SIM-Détecteurs 2014

École de simulation de détecteurs silicium

LPNHE - Paris

du 15 au 17 septembre 2014

Simulations des senseurs à pixel avec Silvaco

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https://indico.in2p3.fr/event/SIMdetecteurs2014

Bruno Mazoyer - LAL Orsay

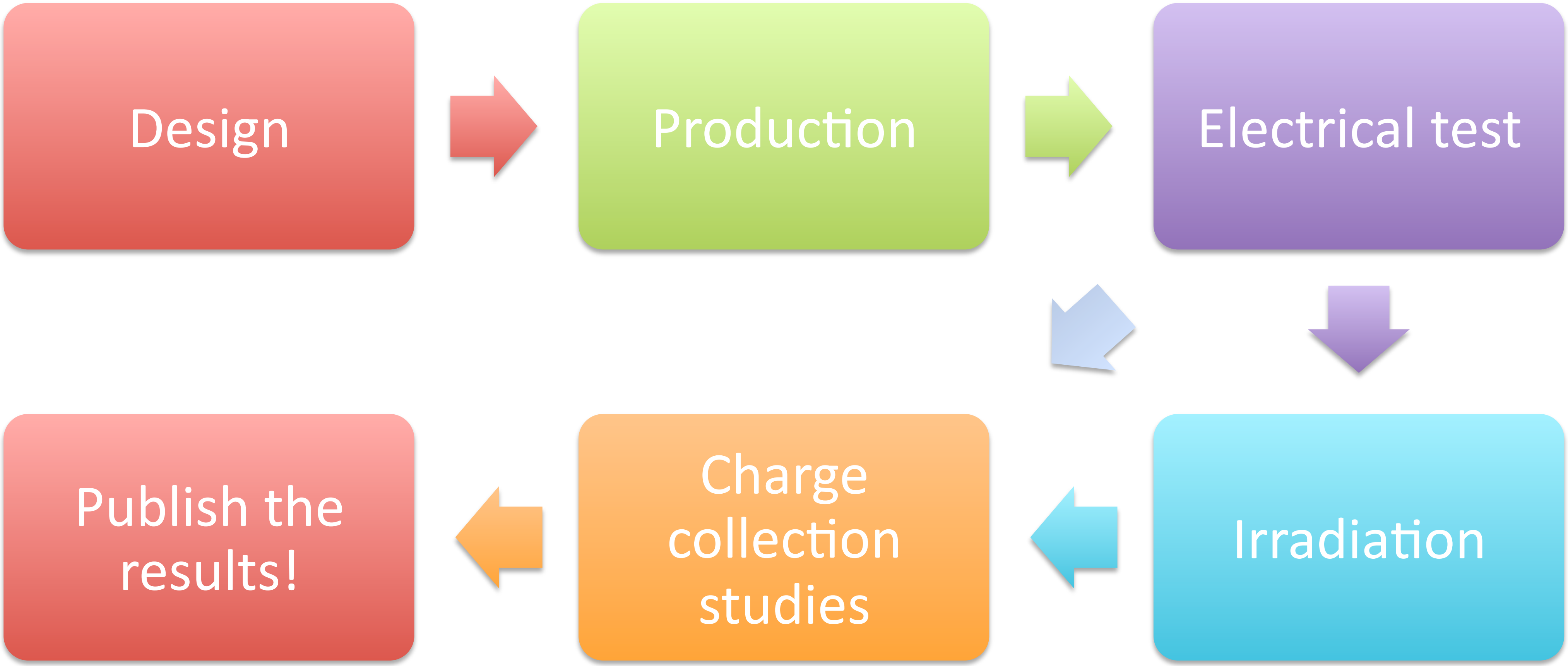
Outline

- Introduction & motivations
- Pixels for high luminosity colliders
- Selected results
  - Edgeless sensors
  - Radiation damage models
  - Electric field measurement
- Comments and conclusions

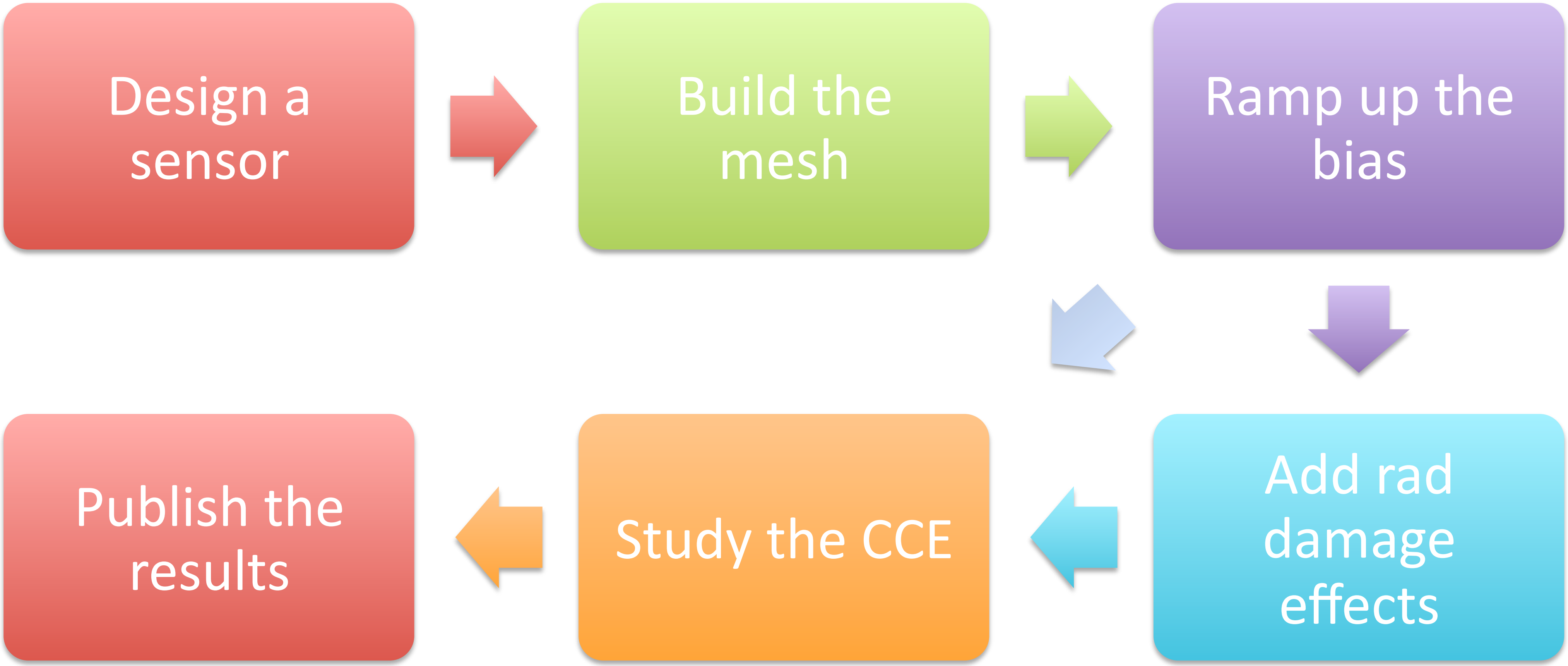
SILVACO

INTRODUCTION & MOTIVATIONS

Normal work flow for a HEP silicon sensors



TCAD simulation work flow



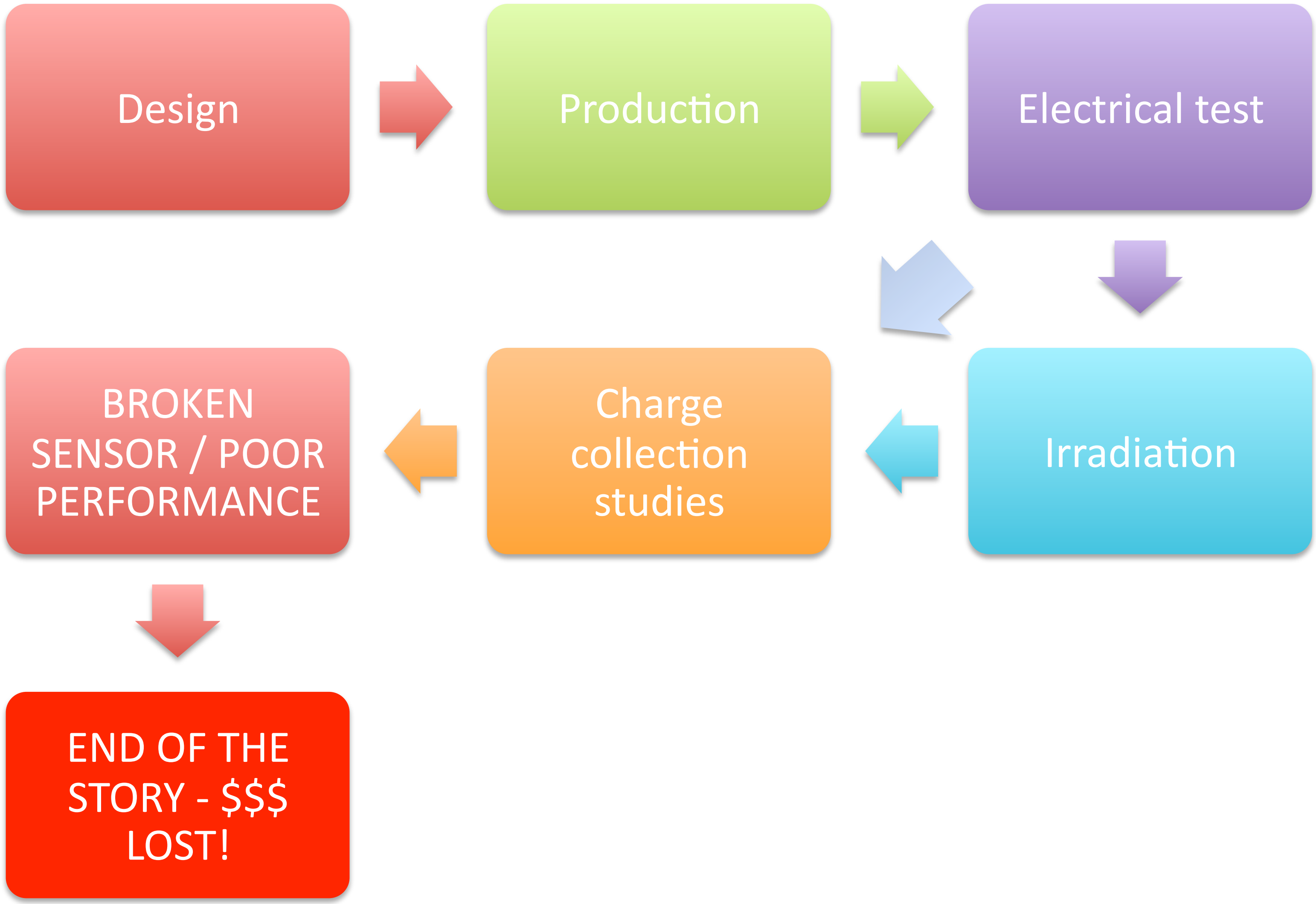
So why bother with simulations?

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

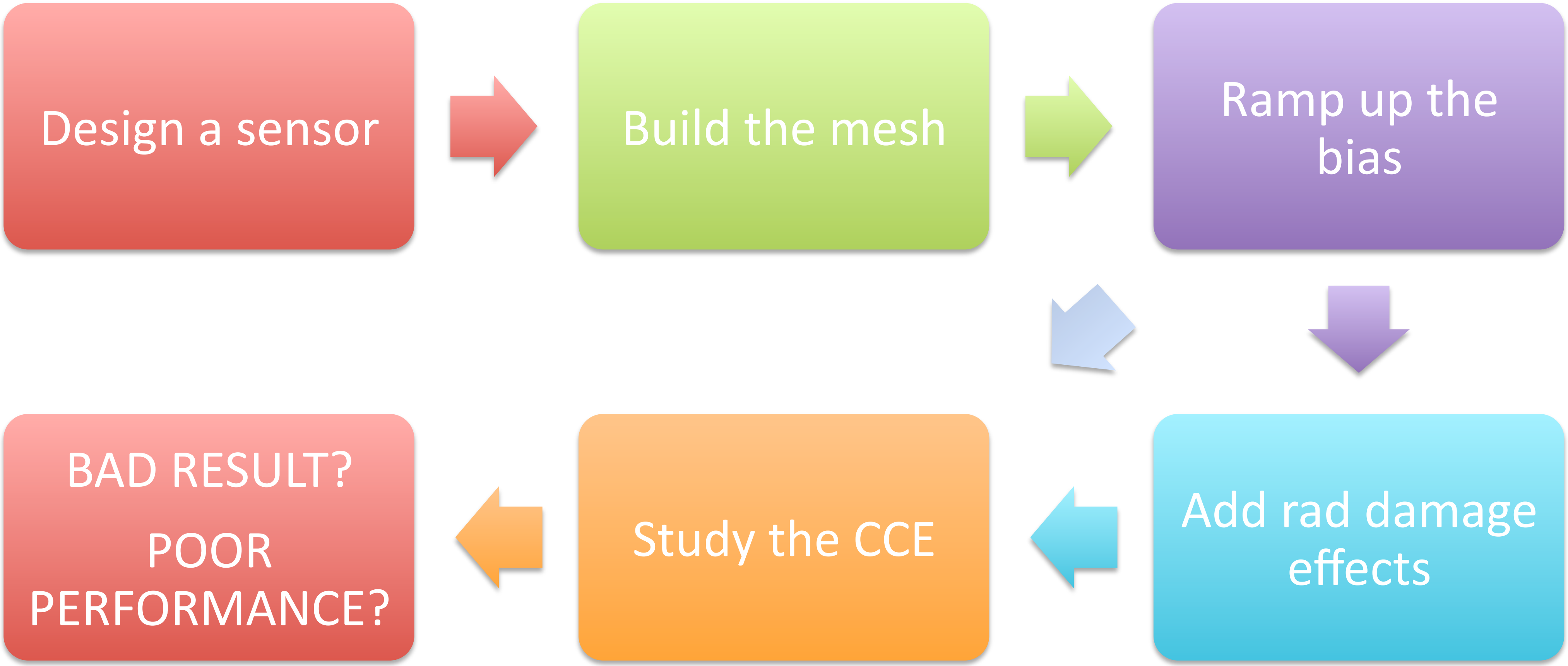
So why bother with simulations?

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

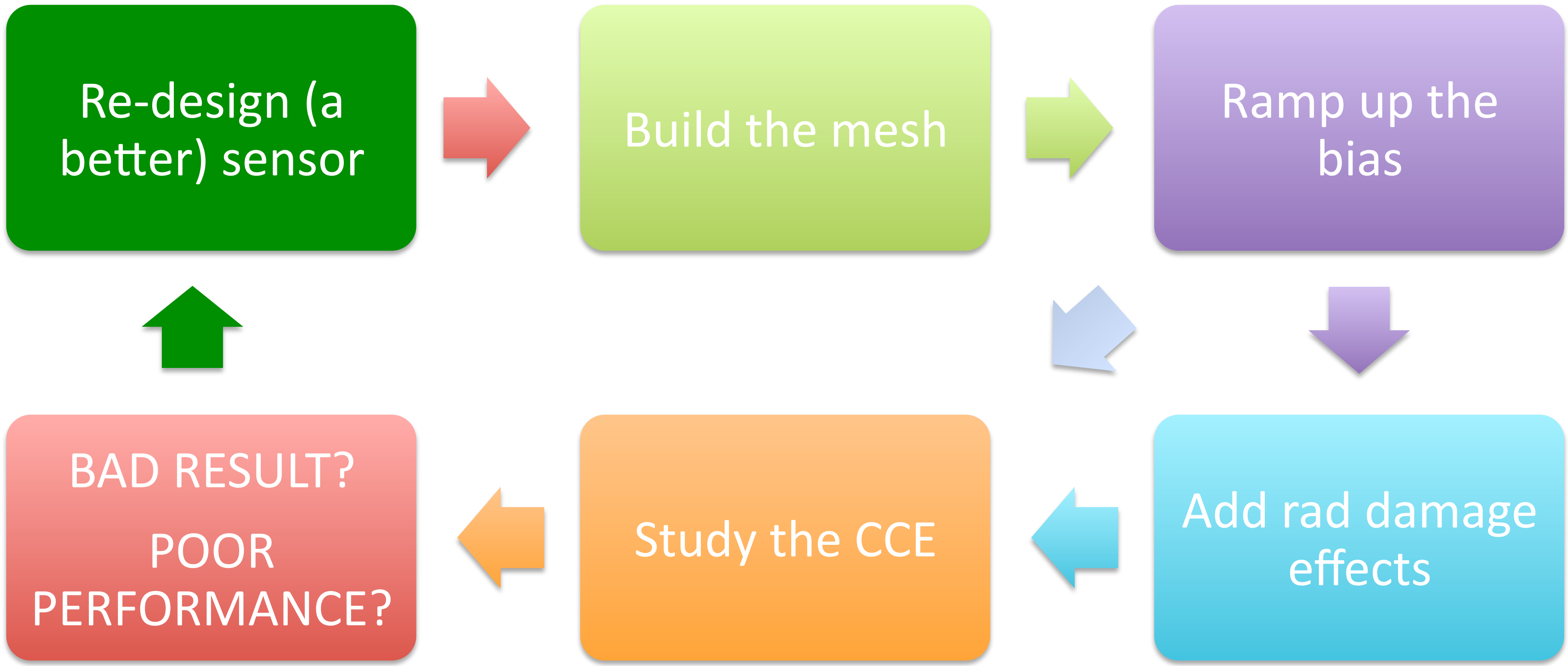
Possible work flow for real sensors



TCAD simulation work flow



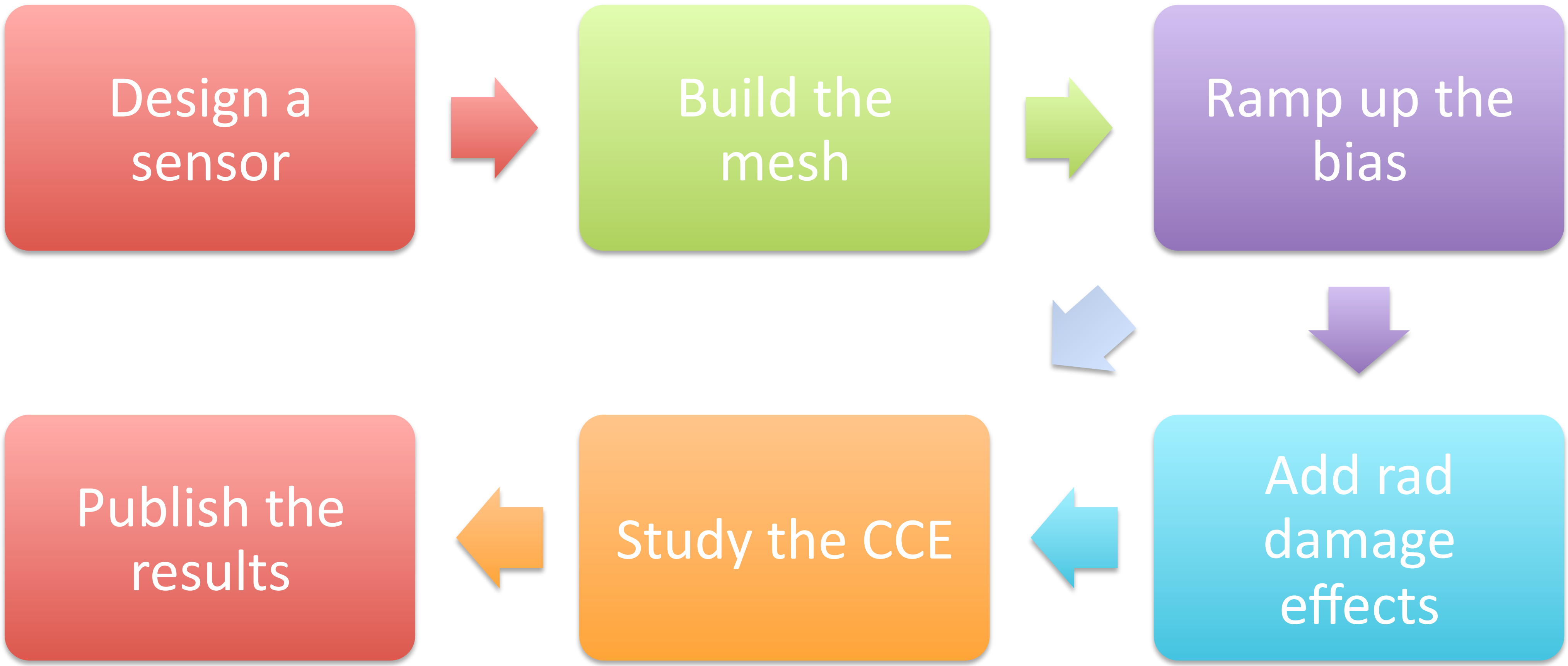
TCAD simulation work flow



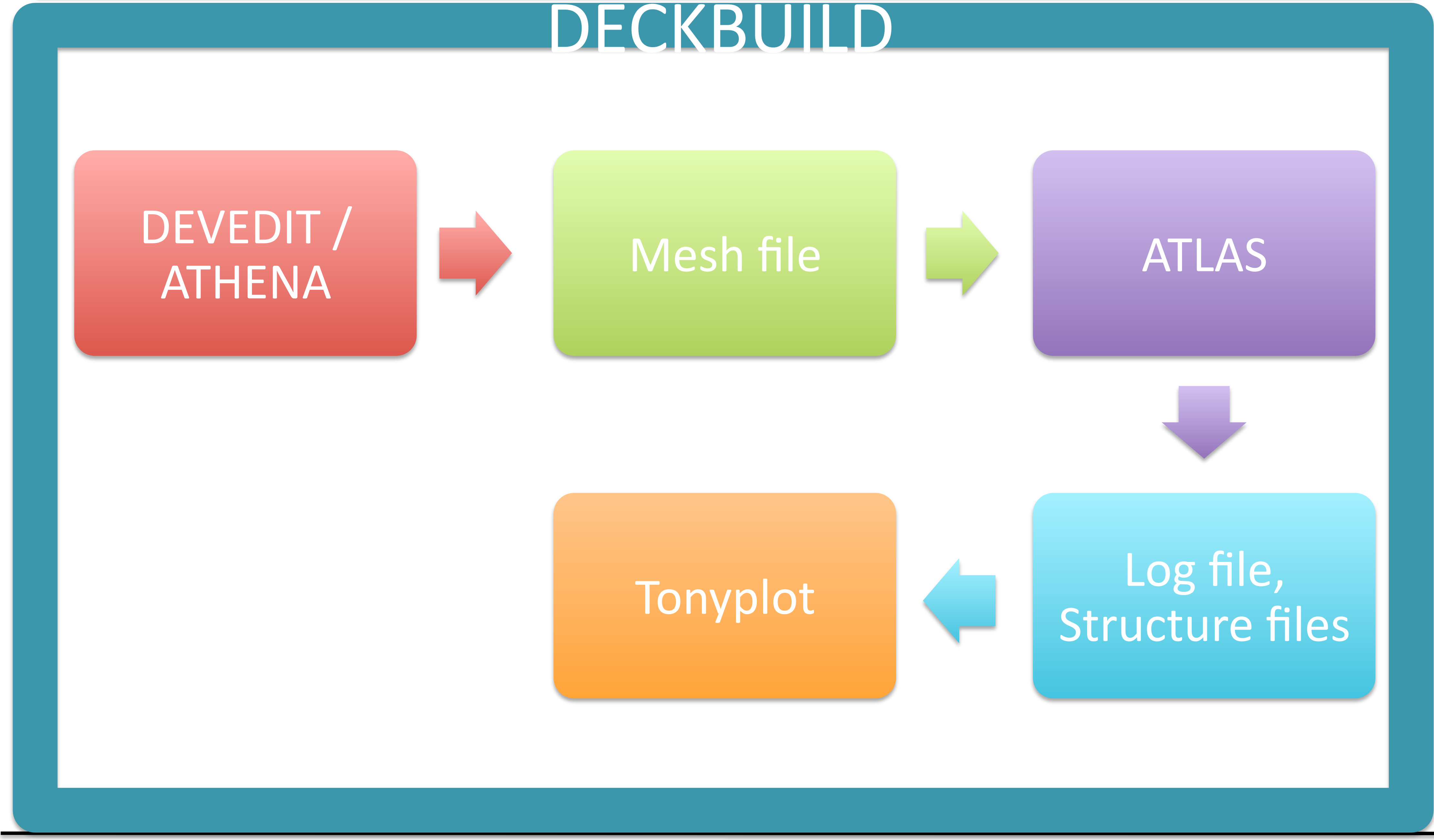
Simulations benefits

- 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!

TCAD simulation work flow



Packages


DECKBUILD
DEVEDIT / ATHENA
Mesh file
ATLAS
Log file, Structure files
Tonyplot

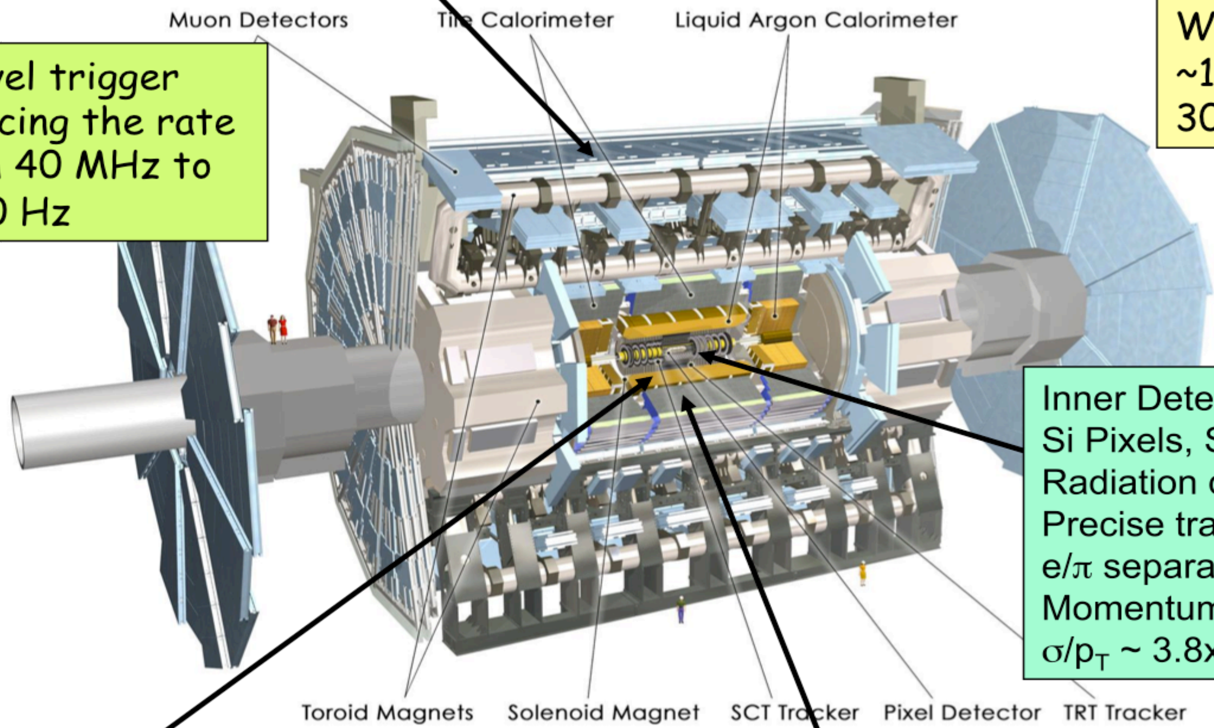
PIXELS FOR HIGH LUMINOSITY COLLIDERS

The ATLAS experiment

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



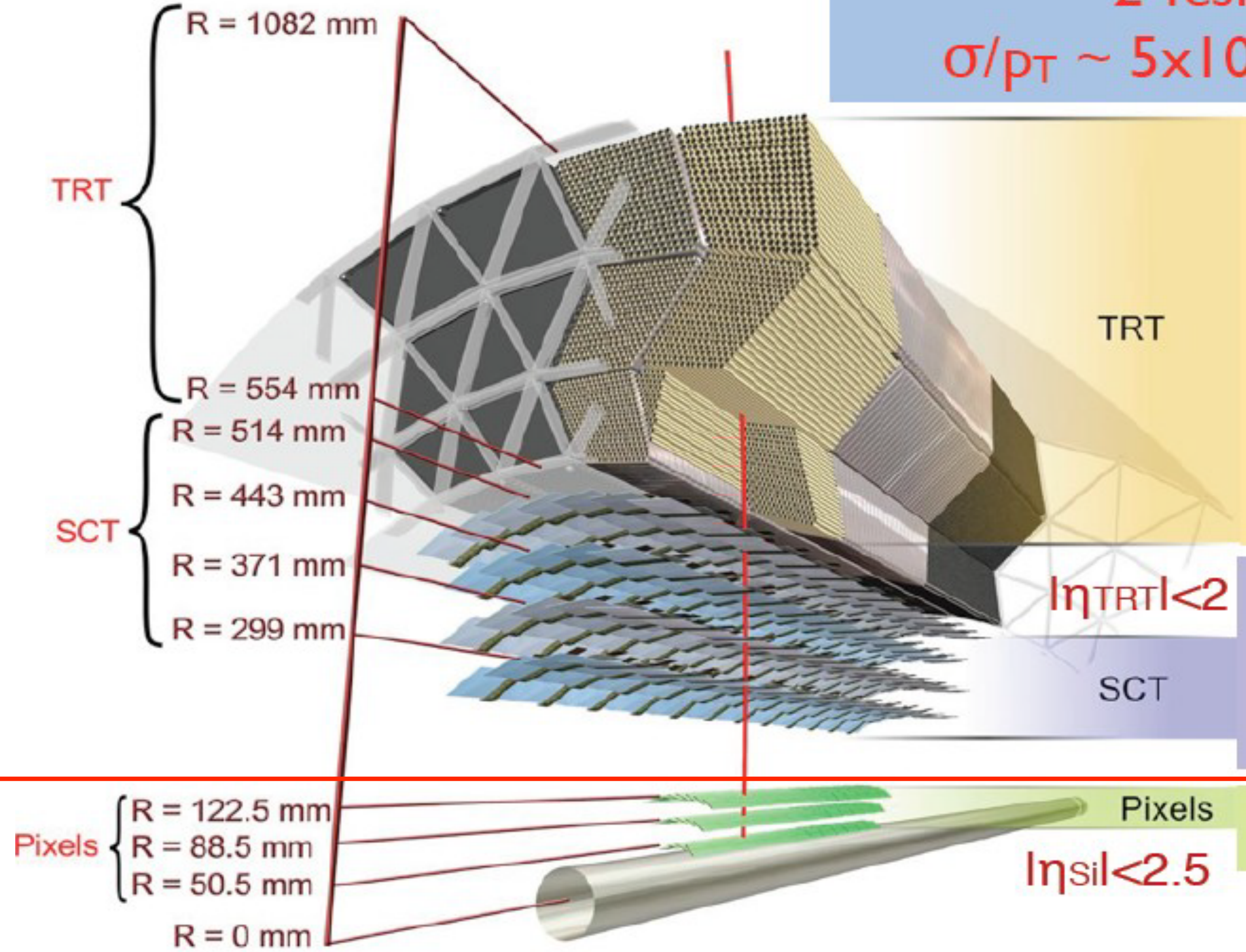
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\ p_T\,(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

36

The ATLAS Inner Detector



2 Tesla Solenoid

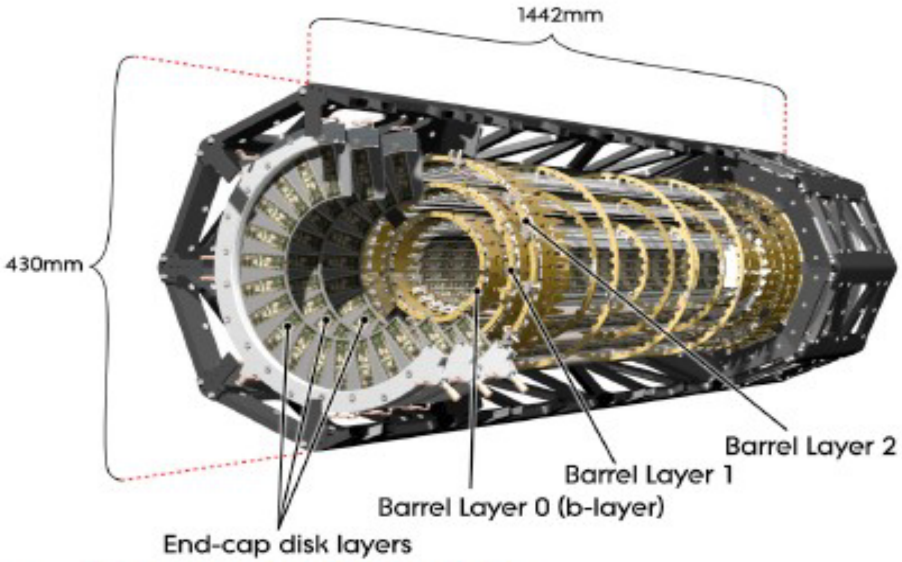
$\sigma/p_T \sim 5\times10^{-4}\, p_T/\mathrm{GeV} \oplus 0.01$

Transition Radiation Tracker (TRT) (350k channels) with e/π separation

SemiConductor Tracker (SCT) ~6M silicon strips

Pixels: 80M channels

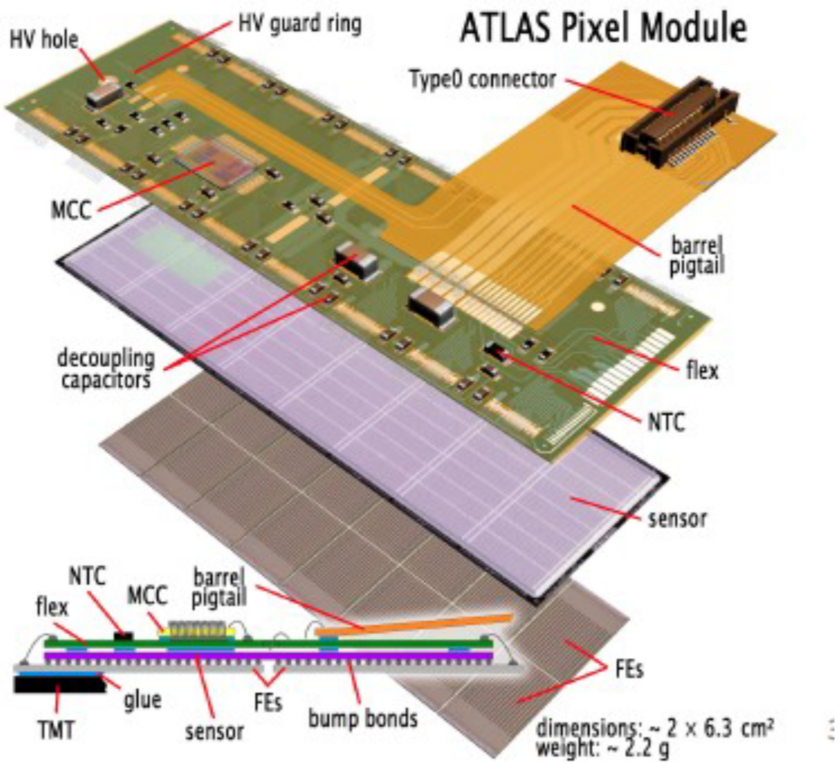
The ATLAS pixel detector



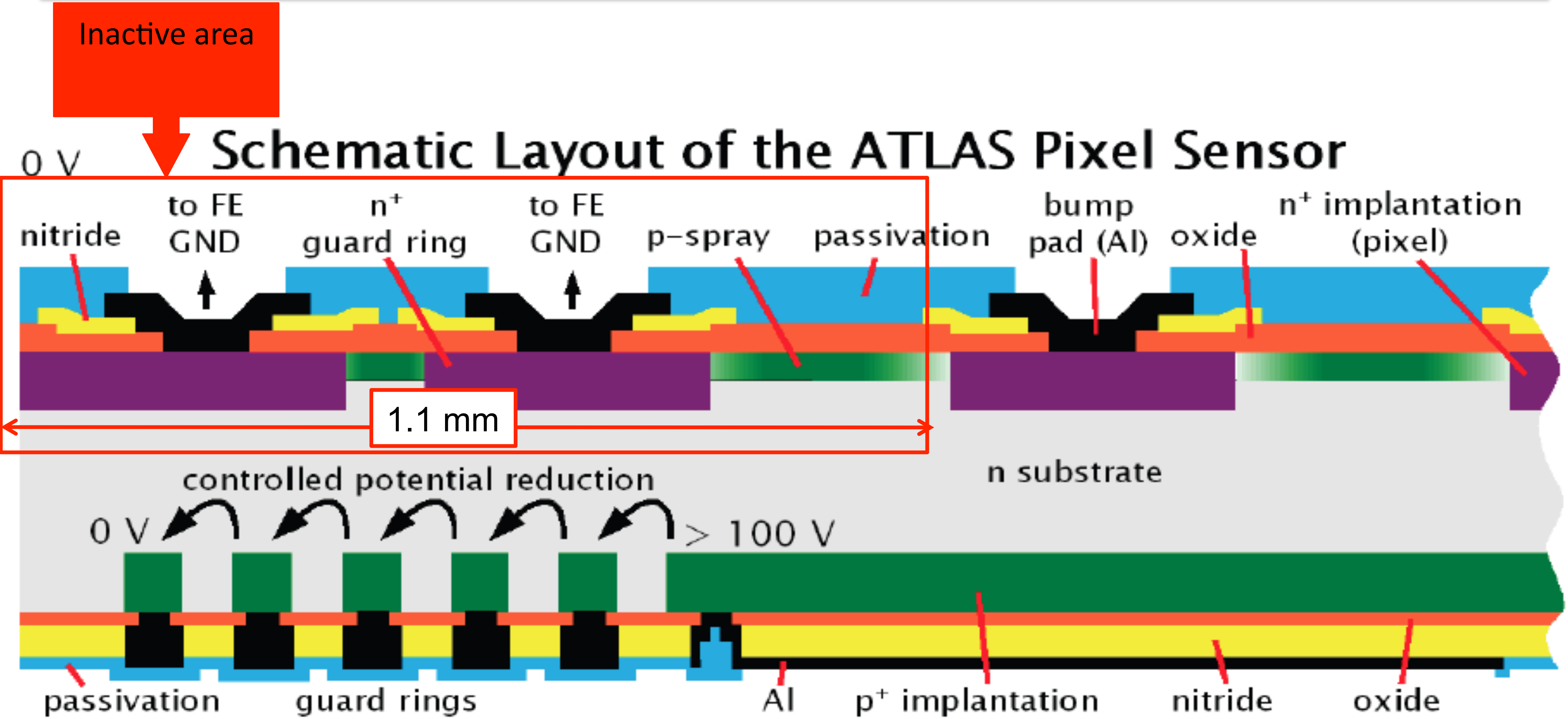
- **ATLAS Pixel Module**
  - 16 front-end chips (FE-I3) module with a Module Controller Chip (MCC)
  - 46080 R/O channels 50 µm x 400 µm (50 µm x 600 µm for edge pixel columns between neighbour FE-I3 chips)
  - Planar n-in-n DOFZ silicon sensors, 250um tick
  - Designed for 1 x 10^{15} 1MeV fluence and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

IPRD10, Siena 9.6.2010 - Alessandro La Rosa (CERN)

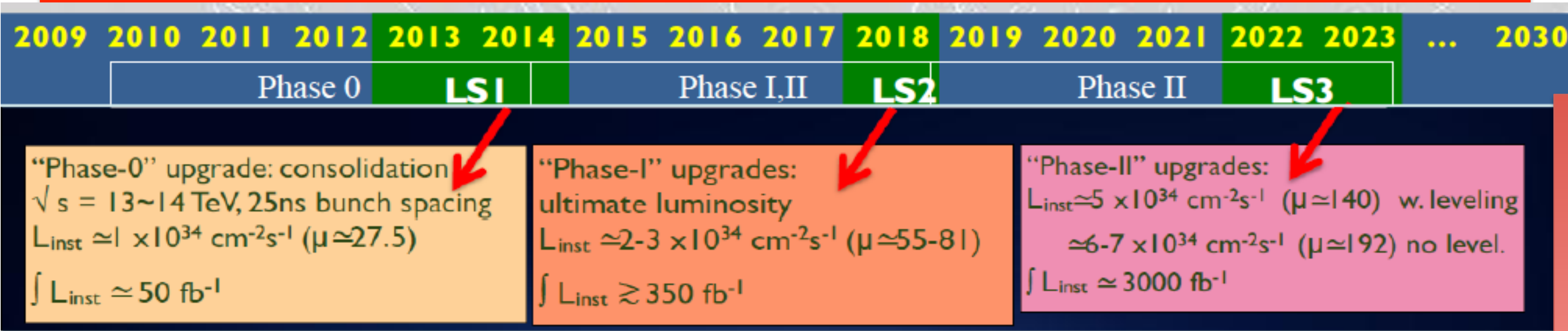
- ATLAS Pixel Detector
  - 3 barrels + 3 forward/backwarc disks
  - 112 stave and 4 sectors
  - 1744 modules
  - 80 million channels



The Atlas Pixel sensors



LHC & ATLAS upgrades for the High Lumi era



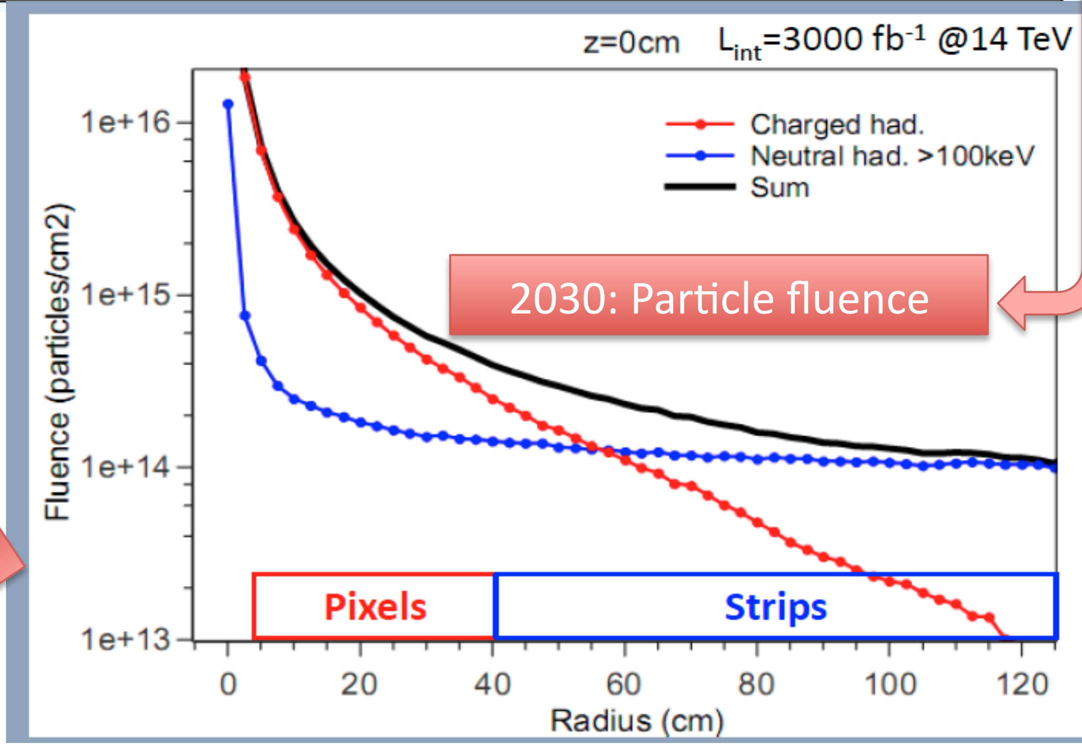
ATLAS has devised a 3 stage upgrade program to optimize the physics reach at each Phase

<u>Foreseen Tracker Upgrades</u>

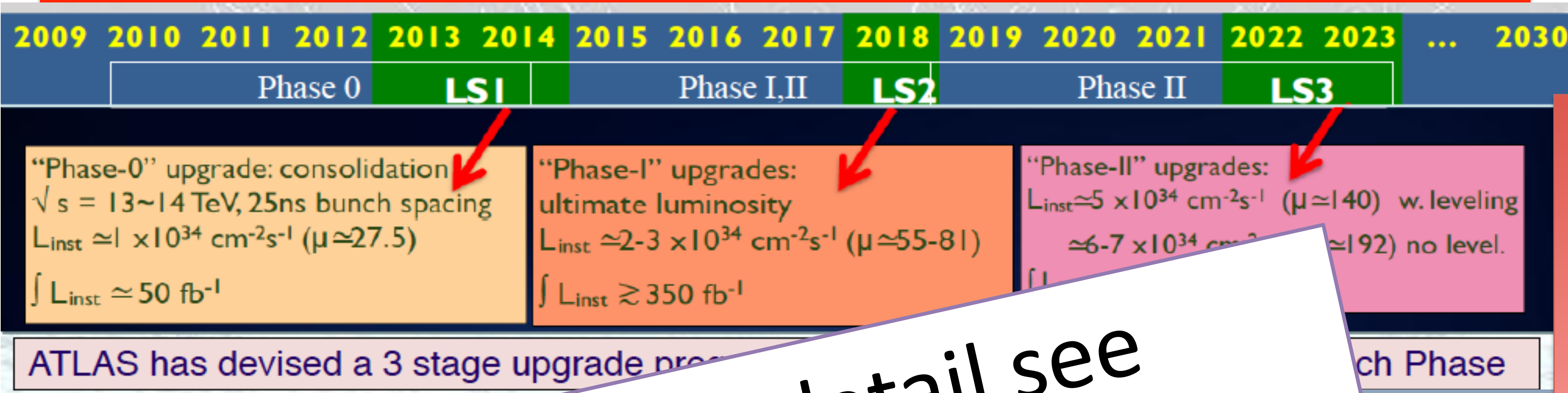
LS1: new Insertable pixel B-layer (IBL)

(LS2: Fast Tracking (FTK))

LS3: All new Tracking Detector



LHC & ATLAS upgrades for the High Lumi era



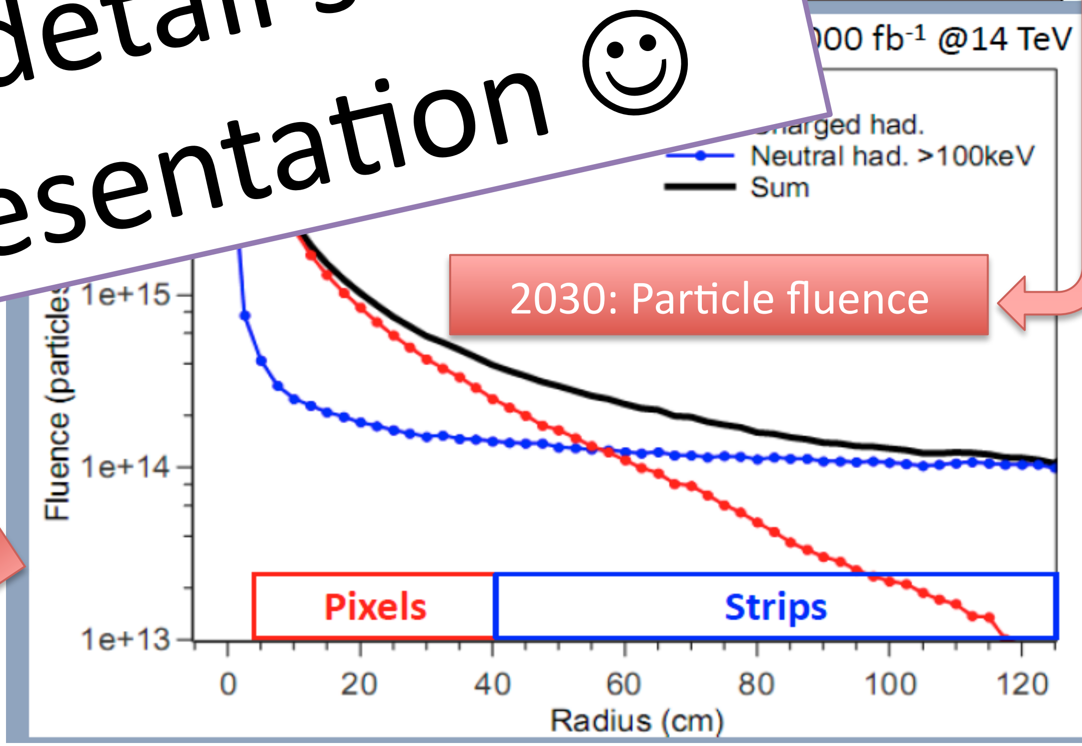
For more detail see Michael's presentation ☺

For

LS1: new In ayer (IBL)

(LS2: Fast Tracking (FTK))

LS3: All new Tracking Detector



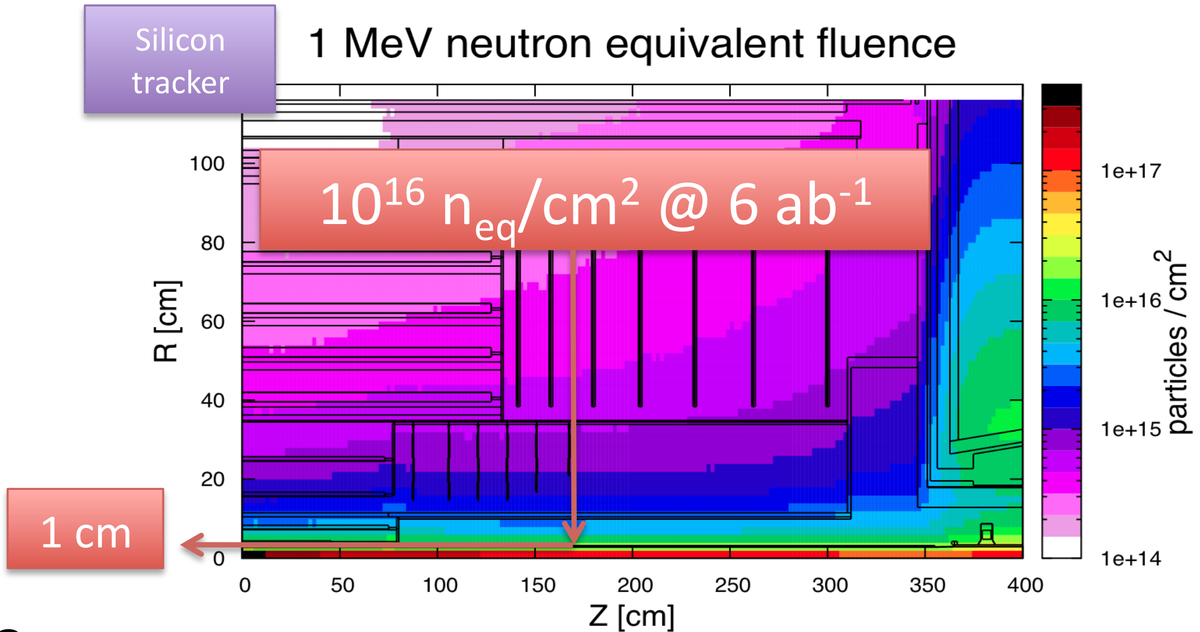
Pixels for the future LHC experiments

- **Thin**: reduce the material budget, cope with charge trapping
- **Cheap**: large area to be instrumented – O(10 m^2)
- **Efficient**: very limited module tiling in the innermost layers

RAD HARD

&

SLIM EDGE DETECTORS



Detector:	Silicon area [m^2]	Channels [10^6]
Pixel barrel	5.1	445
Pixel end-cap	3.1	193
Pixel total	**8.2**	**638**
Strip barrel	122	47
Strip end-cap	71	27
Strip total	**193**	**74**

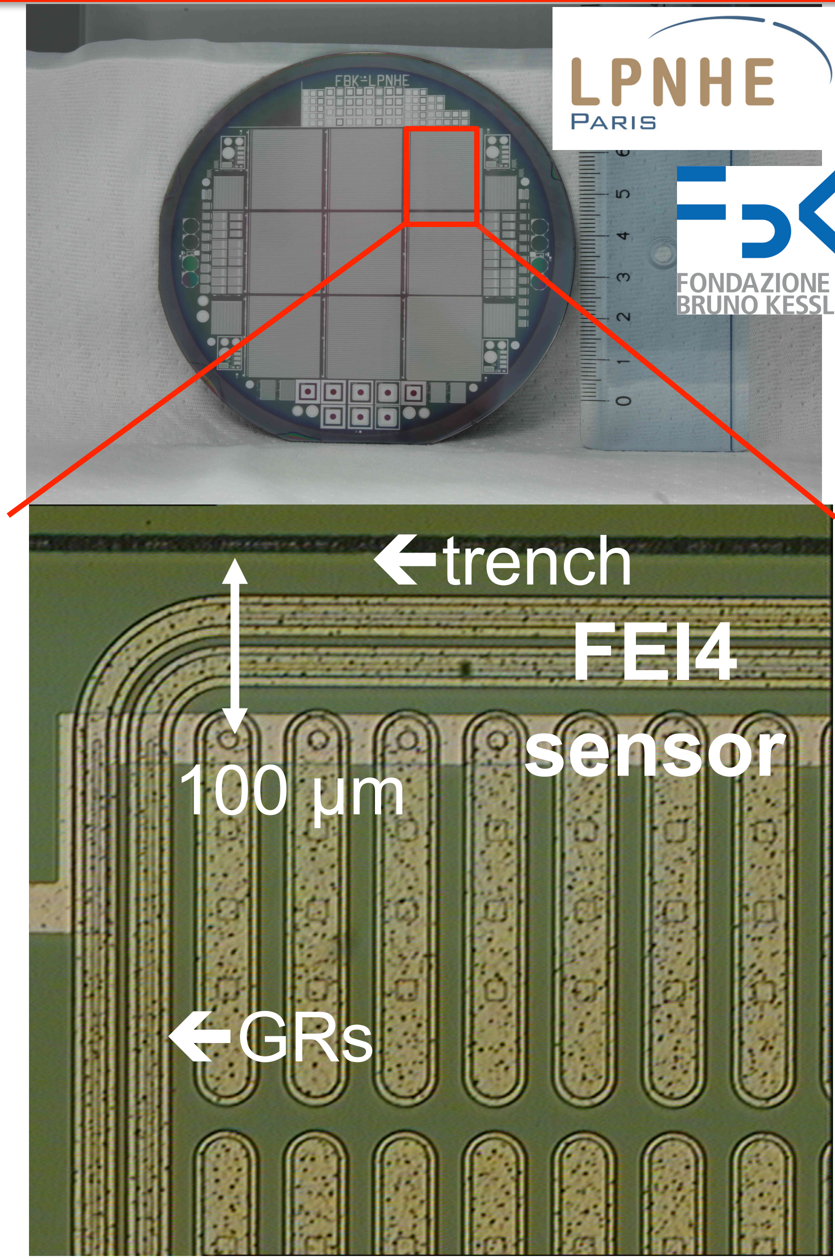
Table 6.6: Inner tracker active area and channel count.

SELECTED RESULTS

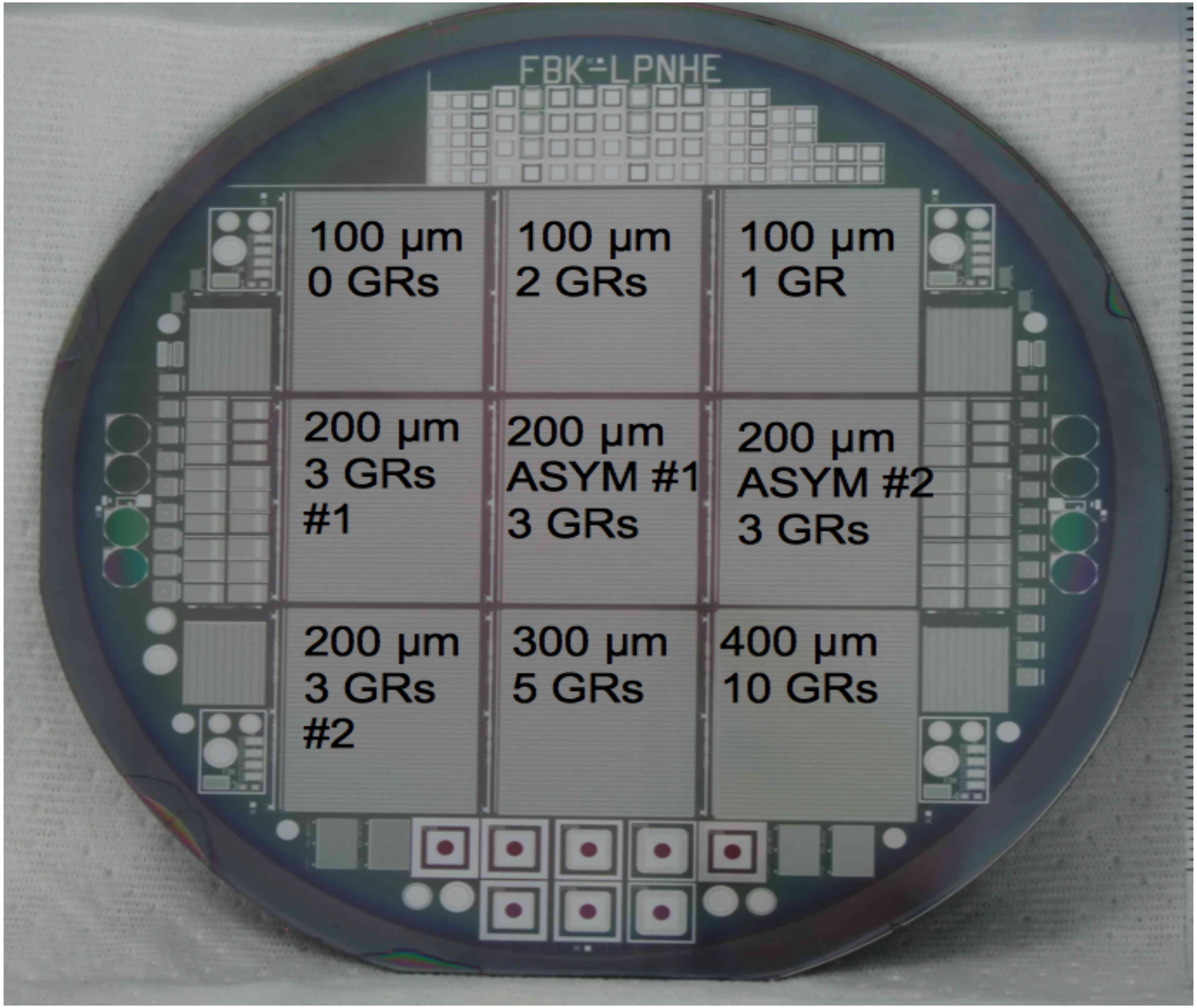
EDGELESS SENSORS

Edgeless pixels via Deep Reactive Ion Etching

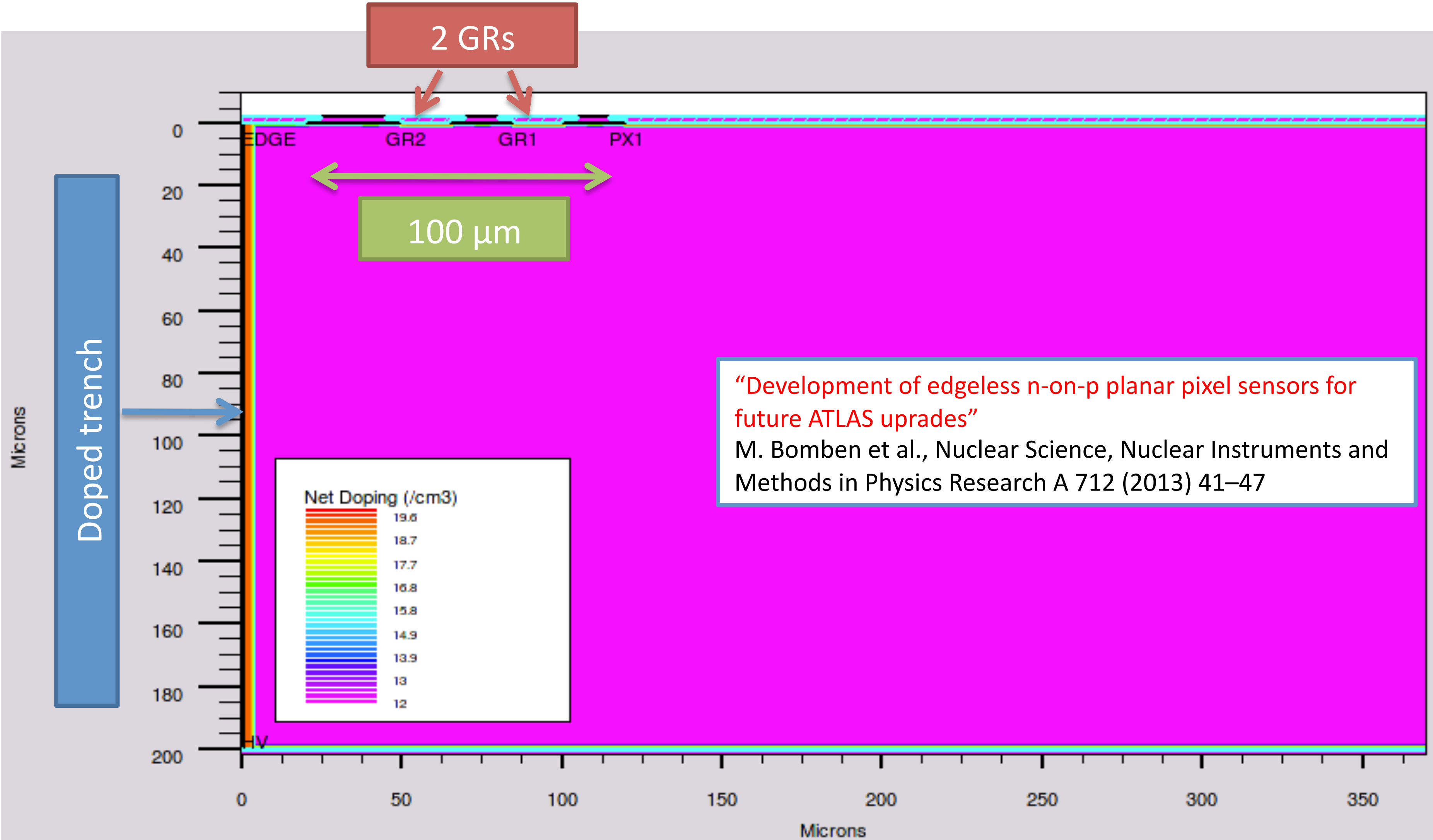
- Joint **FBK-LPNHE** project
  - Goal: make the **border** a **damage free ohmic contact**
- **How: DRIE**
- **Target: intermediate layers**
- **200 µm thick n-on-p** production
  - 500 µm support wafer
  - Polarization via bias tab
- **Pixel-to-trench distance as low as 100 µm**



Edgeless designs



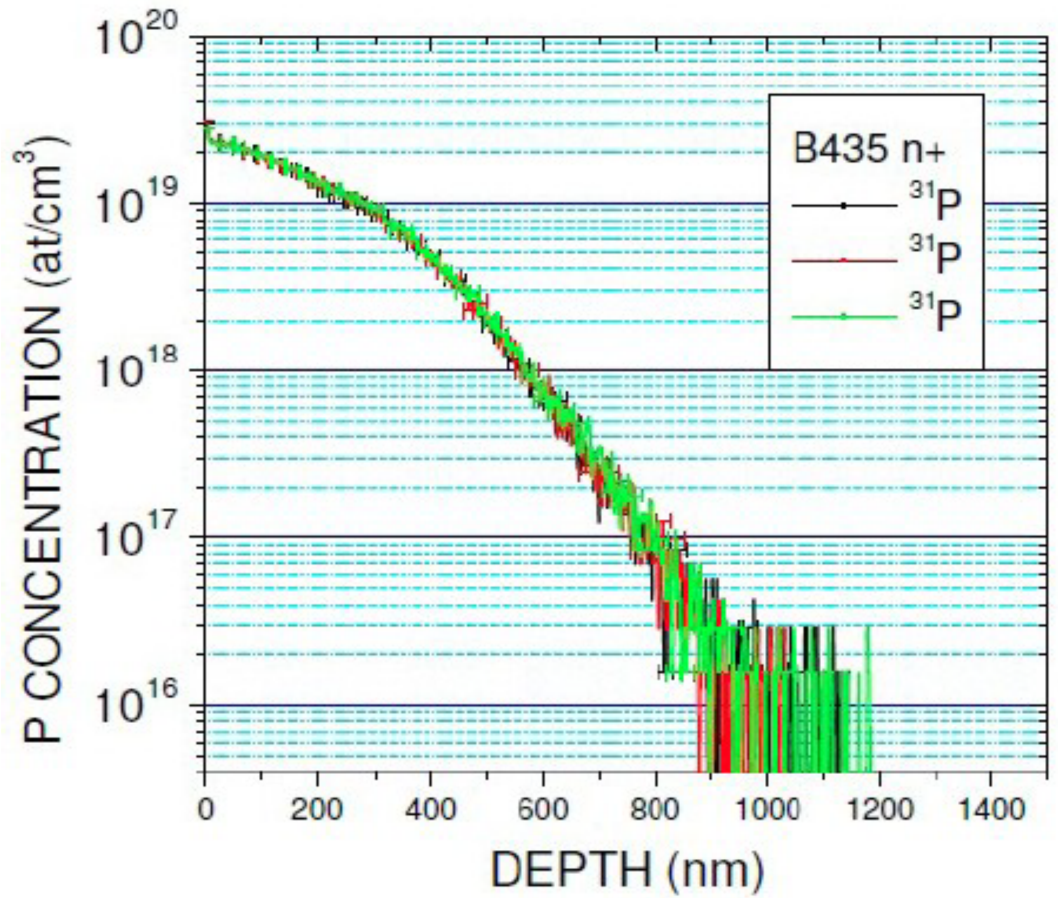
A concrete example: Active Edge sensors

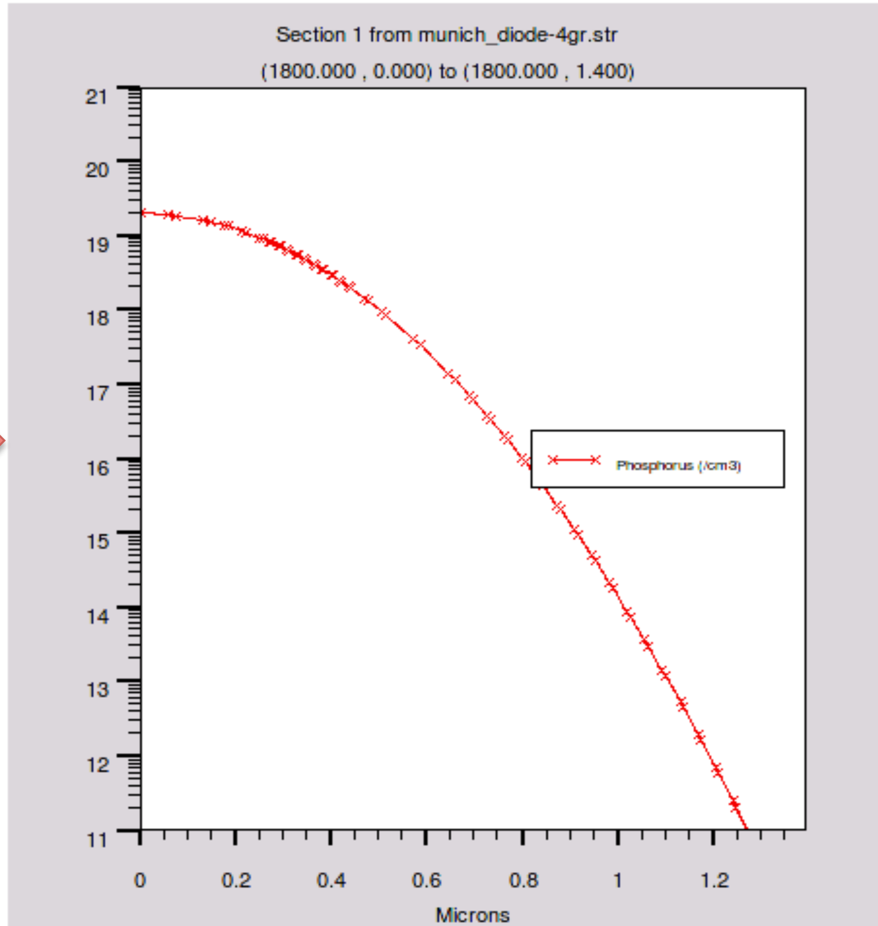


"Development of edgeless n-on-p planar pixel sensors for future ATLAS uprades"
M. Bomben et al., Nuclear Science, Nuclear Instruments and Methods in Physics Research A 712 (2013) 41–47

Intermezzo: TCAD inputs

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

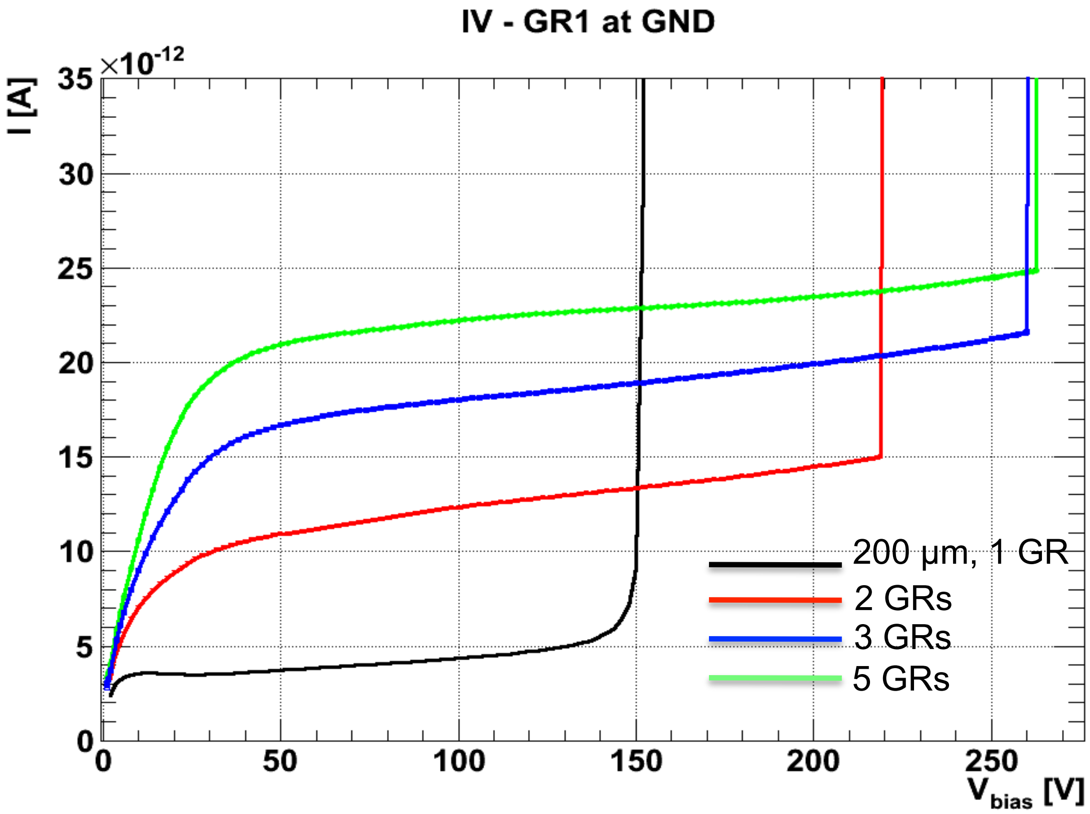




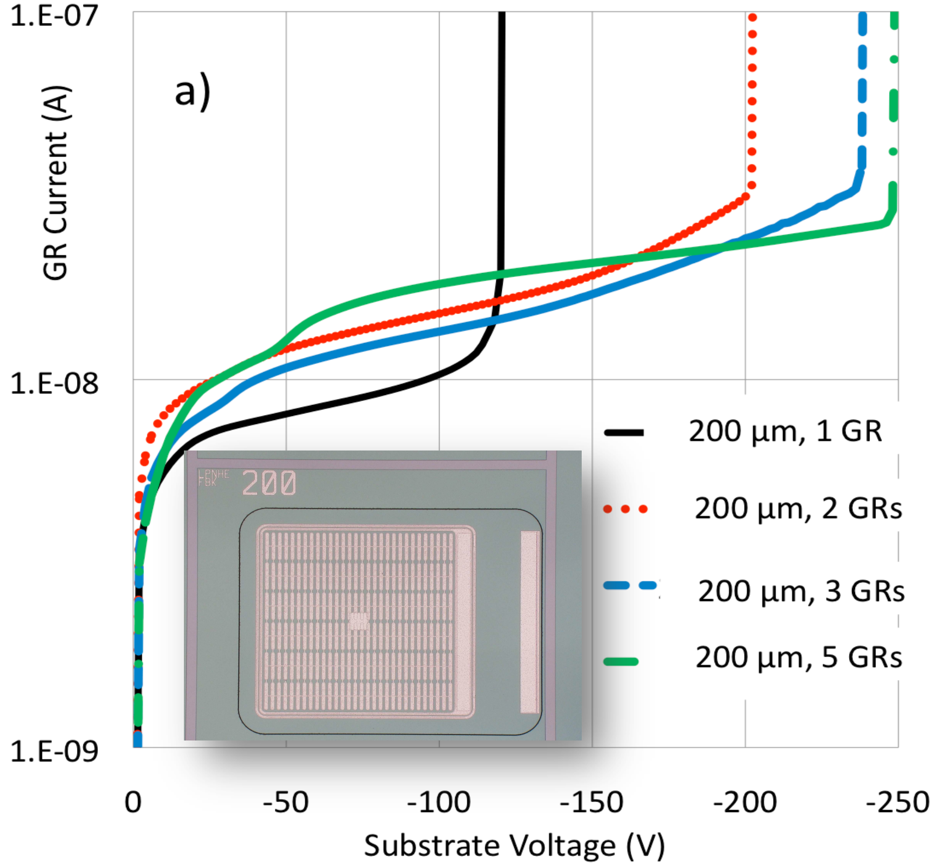
IV on test structures

Crucial parameters: p-spray implant characteristics

SIMULATIONS



DATA



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

Charge collection efficiency with MIP

- We can profit of SEU module to study the drift of charge released along a track

```
# Specify the charge track: normal incidence through the drain
singleeventupset entry="1800.0,0" exit="1800,300" pcunits b.density=1.6e-4 \
                 radialgauss radius=5  t0=2.e-11 tc=0
# Log file for transient
log outf="$'log_file_name'-SEU.log"
```

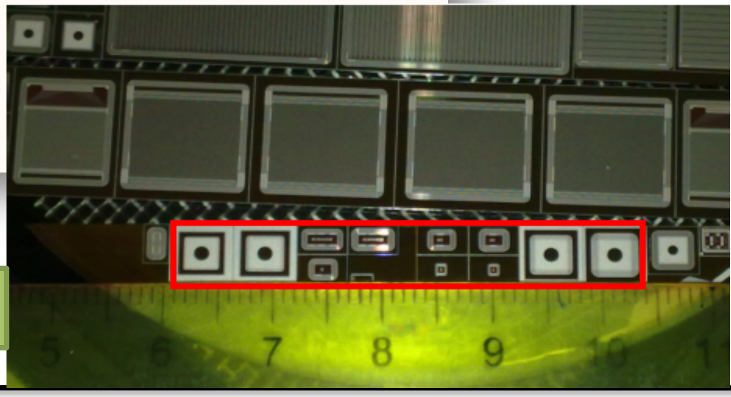
- Entry and exit point
- Charge per length unit
- Track time of arrival

```
# Early transient
method tstep.incr=1.25 dt.max=2.0e-13
solve tfinal=2.0e-12 tstep=2.5e-15 prev
save outf="$'file_name'-before-seu.str"

# SEU peak
#method mestep
solve tfinal=7.0e-12 tstep=2.0e-13 prev
save outf="$'file_name'-during-seu.str"

# Response to particle strike
#method lte.timestep tstep.incr=1.25 dt.max=2.5e-11
solve tfinal=3e-10 tstep=2.0e-13 prev
save outf="$'file_name'-particle.str"
```

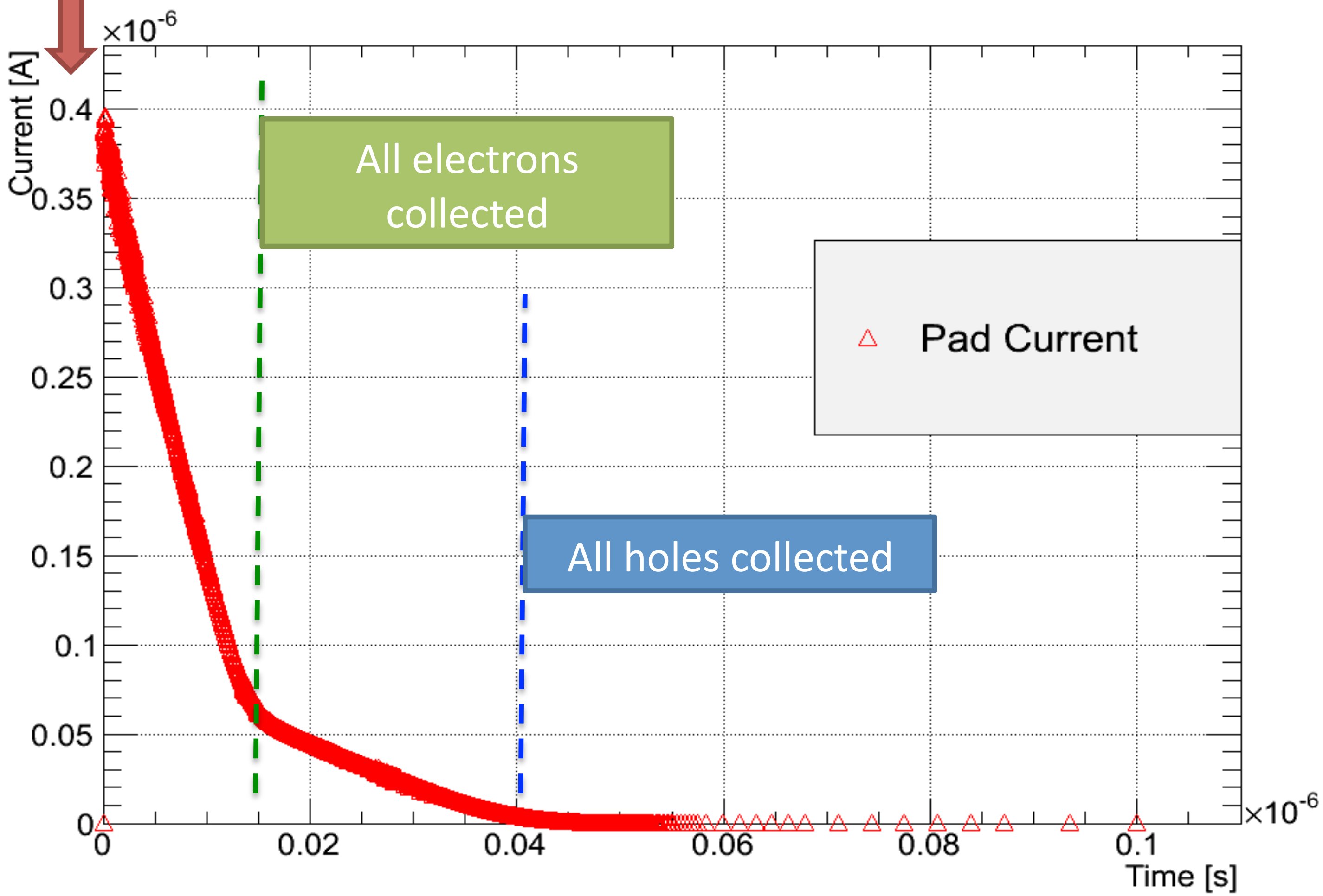
- Solution in the time-domain



In the following: results for n-on-p diodes

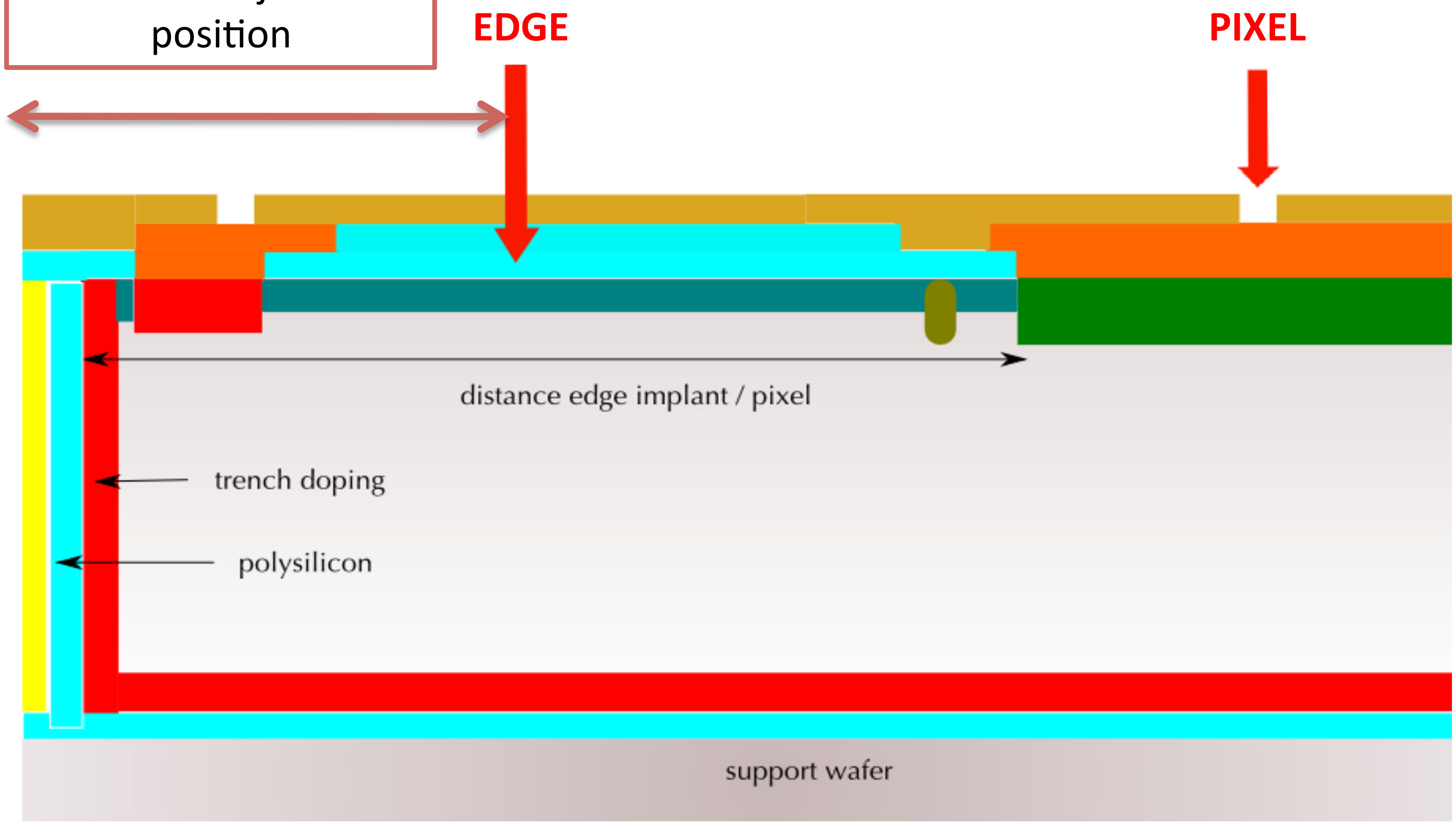
Response to a MIP

Expected Initial current ~ λ ($<v_e>+<v_h>$) = 3.9×10^{-7} A

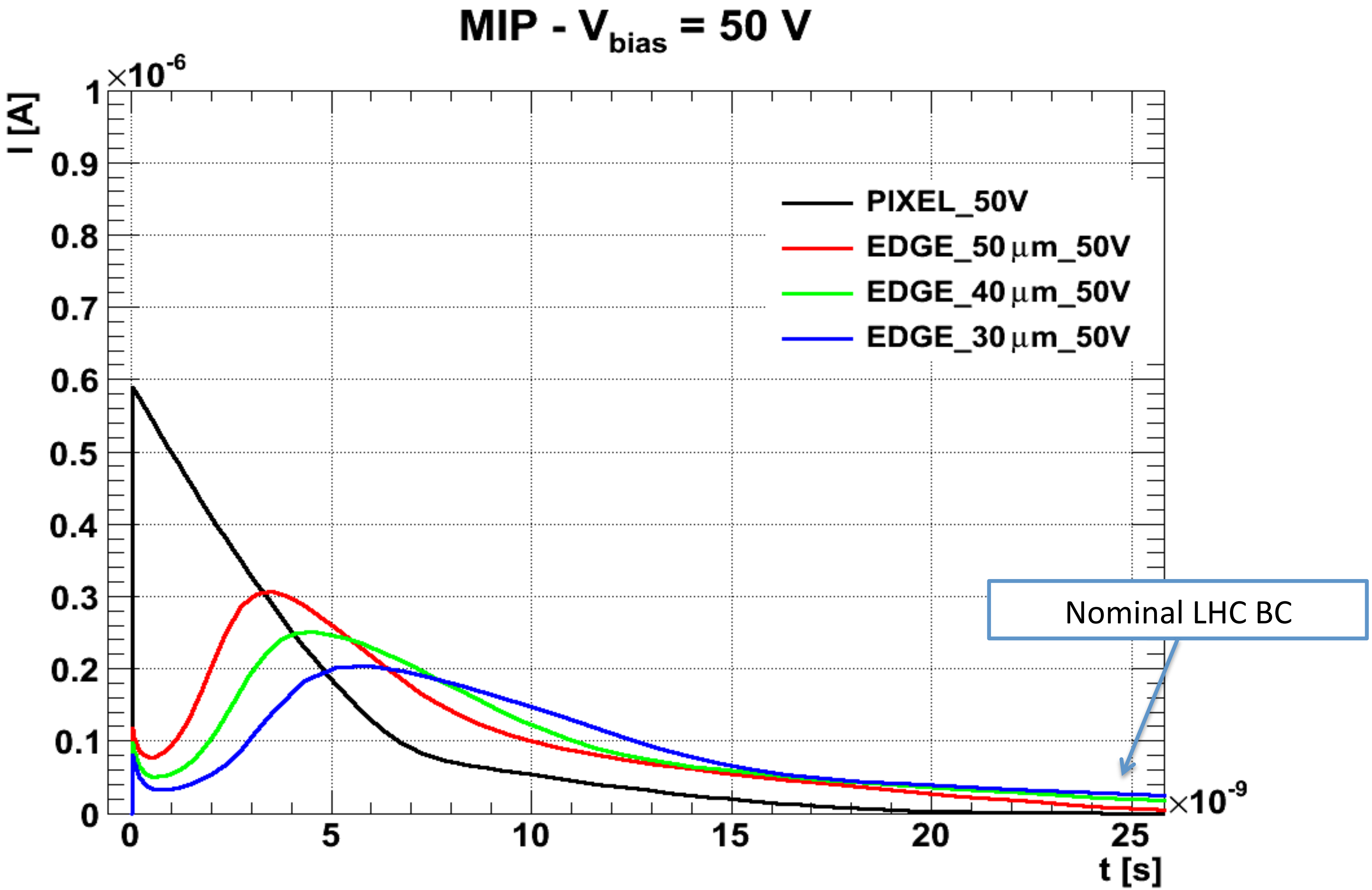


Charge collection efficiency studies (CCE)

Study the collection time wrt injection position

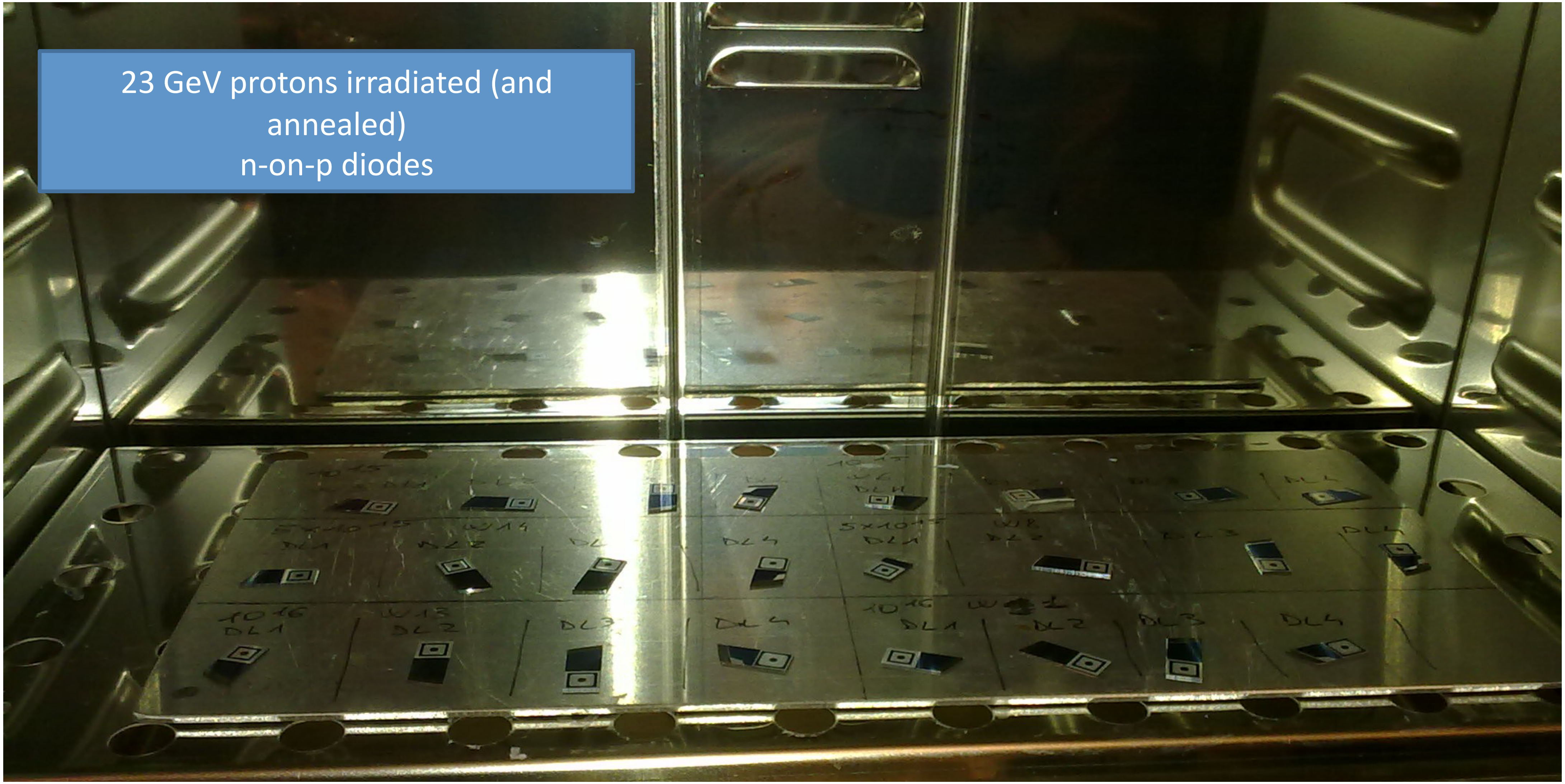


Signal at 50 V for unirradiated sensors (zoom)



RADIATION DAMAGE MODELS

Radiation damage: data vs simulations



23 GeV protons irradiated (and annealed)
n-on-p diodes

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	9.5×10^{-15}	9.5×10^{-14}	1.613
A	E_C -0.46	5.0×10^{-15}	5.0×10^{-14}	0.9
D	E_V +0.36	3.23×10^{-13}	3.23×10^{-14}	0.9 (1)

"Simulations of radiation-damaged 3D detectors for the Super-LHC",
D. Pennicard et al., Nucl. Instrum. and Meth. A 592 (2008) 16-25

ATLAS: an example for radiation damage

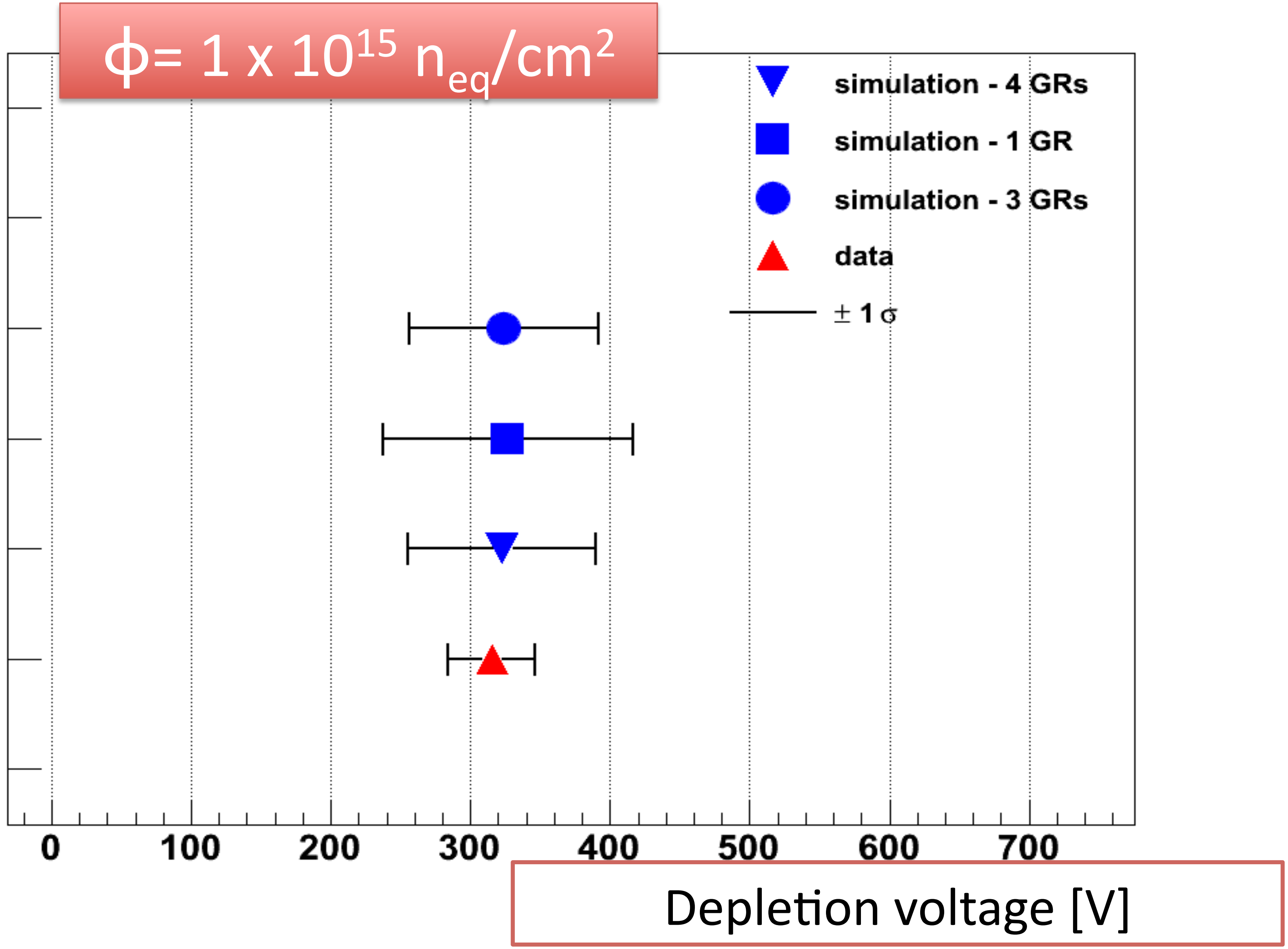
```
ATLAS> trap acceptor e.level=0.495 density=1e+13 degen=1 sign=1e-15 sigp=1e-15

Mesh
 Type:                non-cylindrical
 Total grid points:   37668
 Total triangles  :   74496
 Obtuse triangles :   0  (0 %)
ATLAS> trap donor e.level=0.48 density=1e+13 degen=1 sign=1e-15 sigp=1e-15
ATLAS> ## else
ATLAS>
ATLAS>    ##   if.end
ATLAS>
ATLAS> ## if.end
ATLAS>
ATLAS>
ATLAS> # MODELS, IMPACT, INTERFACE & METHOD
ATLAS> models bipolar temperature=290 print
ATLAS> impact selb
ATLAS>
ATLAS> interface Qf=3e+12 x.min=1
ATLAS> interface Qf=3e+12 x.max=1
ATLAS> interface S.N=5 S.P=5
ATLAS>
ATLAS>
ATLAS> ### altering default recombination lifetime for bulk
ATLAS> MATERIAL region=2 TAUP0=7.80896e-08 TAUN0=9.43913e-08 ETRAP=0.09
ATLAS>
ATLAS> method gummel newton climit=1e-5
```

Carriers traps

Interface models

Depletion voltage – data vs simulations



Silicon/SiO_2 interface defects

- Ionizing energy loss in the oxide creates defects at the **Surface**:

→ Increase in interface/oxide charge

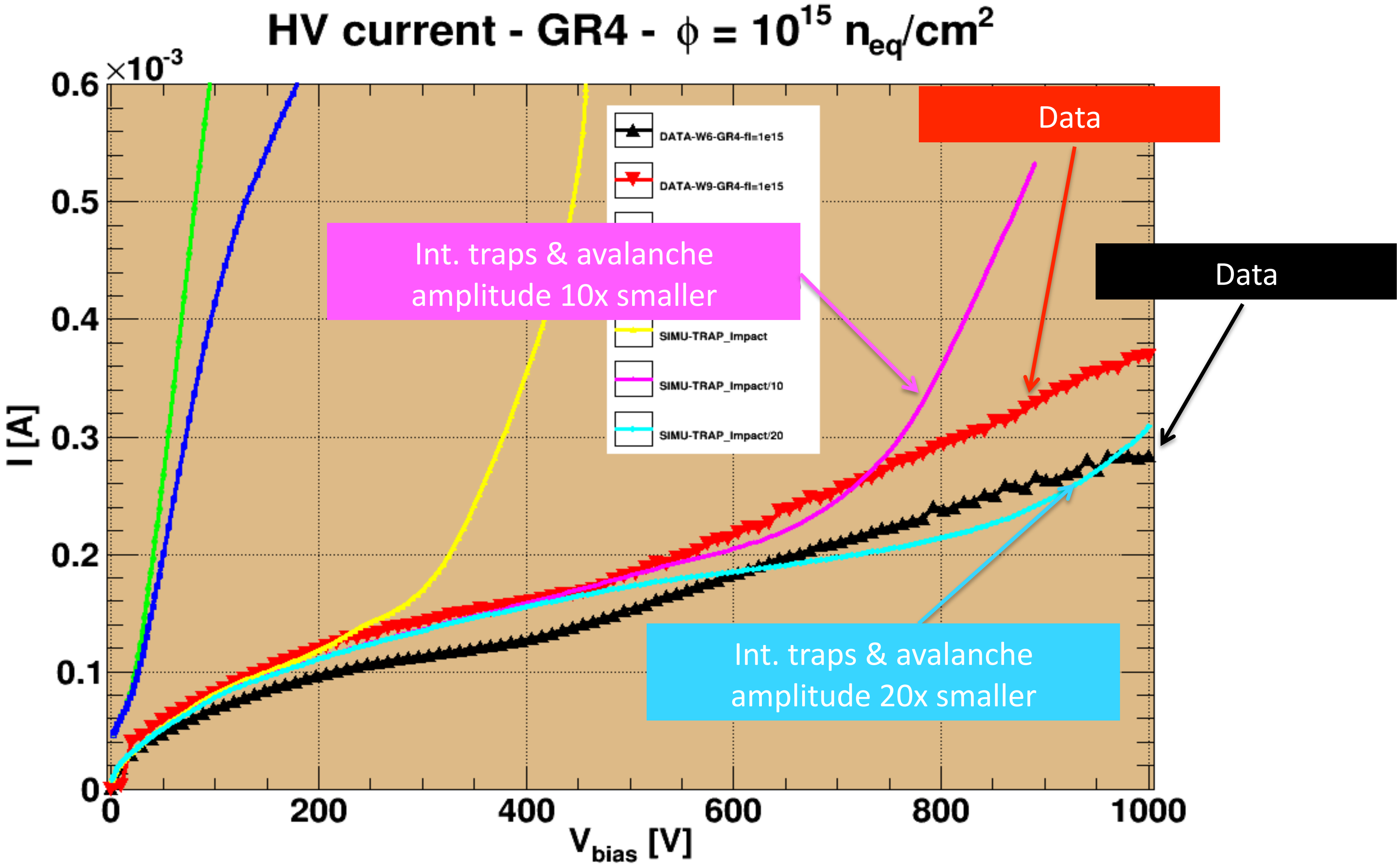
→ Defects at the interface silicon oxide

Type	$E_C - E_{it}$ (eV)	$\sigma_e(\mathrm{cm}^2)$	$\sigma_h(\mathrm{cm}^2)$	$N(10^{11}\mathrm{cm}^{-2})$
A	0.391	1.2×10^{-15}	1.2×10^{-15}	10
A	0.598	6.0×10^{-16}	6.0×10^{-16}	5
A	0.462	2.5×10^{-17}	2.5×10^{-17}	5

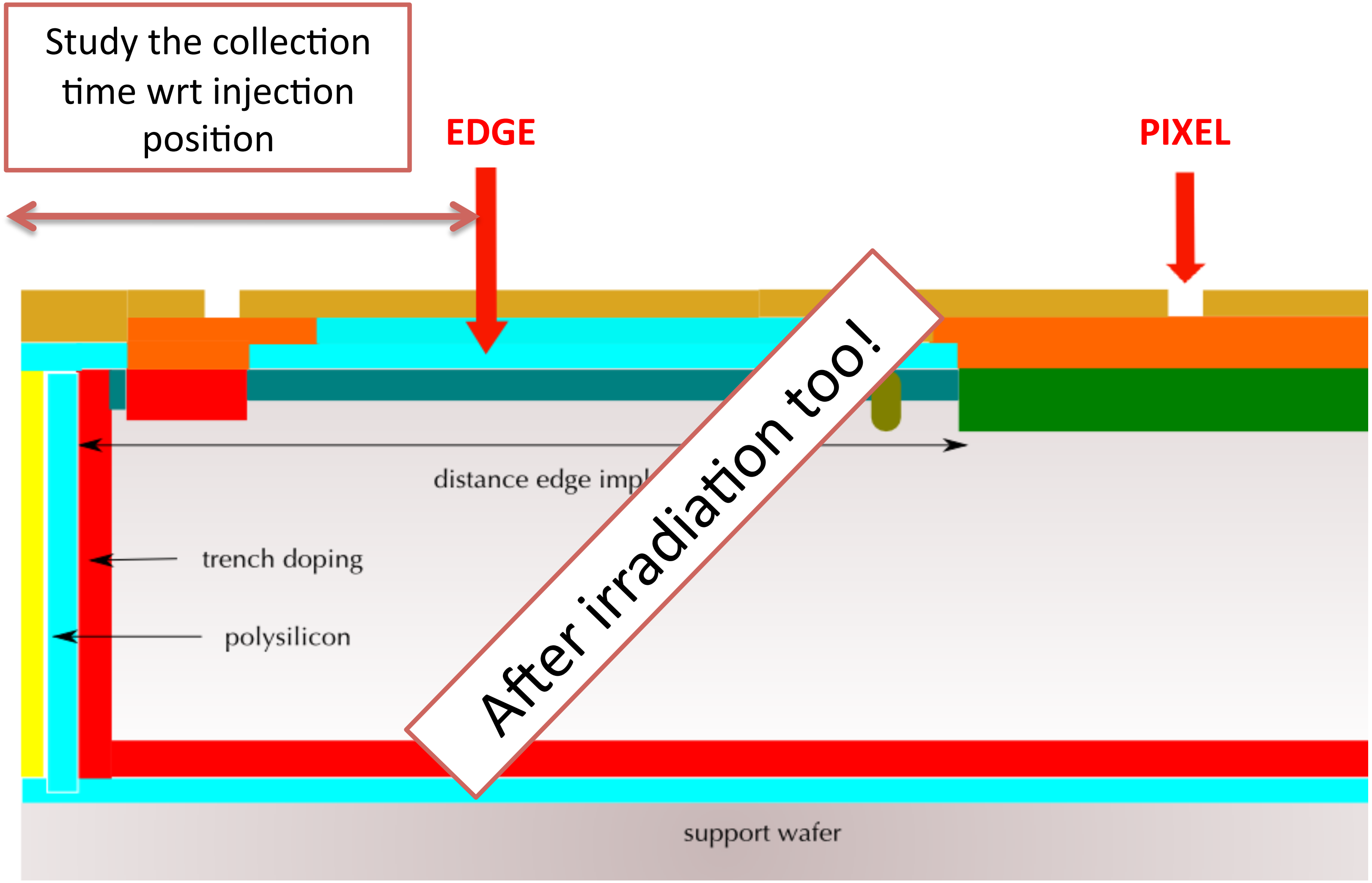
(2)

"Study of surface radiation damage in silicon sensors",
J. Zhang, 18th RD50 Workshop, Liverpool, 23-25/5/2011

Leakage current – data vs simulations

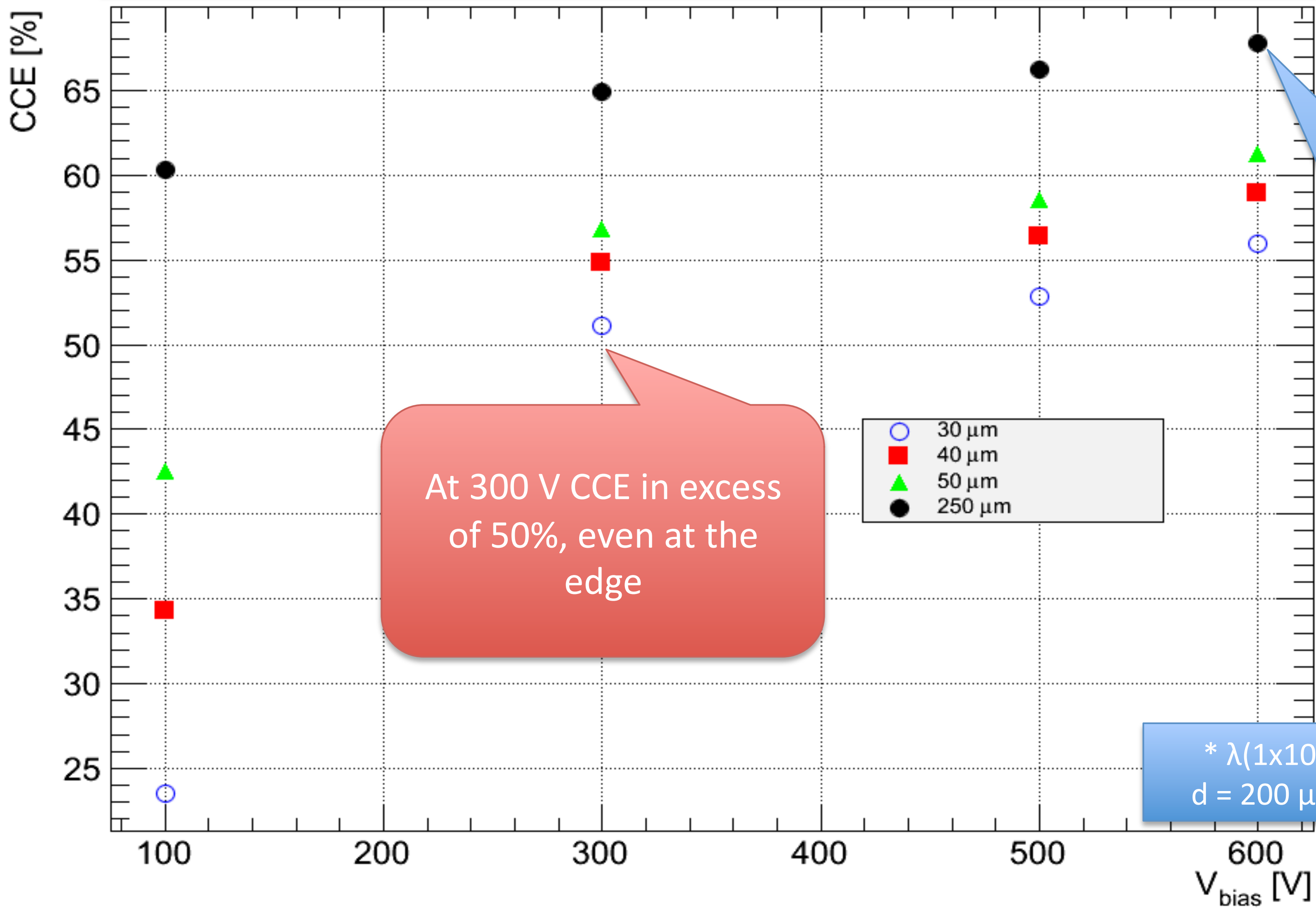


Charge collection efficiency studies (CCE)



Charge collection efficiency studies (CCE)

$\phi = 1 \times 10^{15}\ n_{eq}/cm^2$



At 300 V CCE in excess of 50%, even at the edge

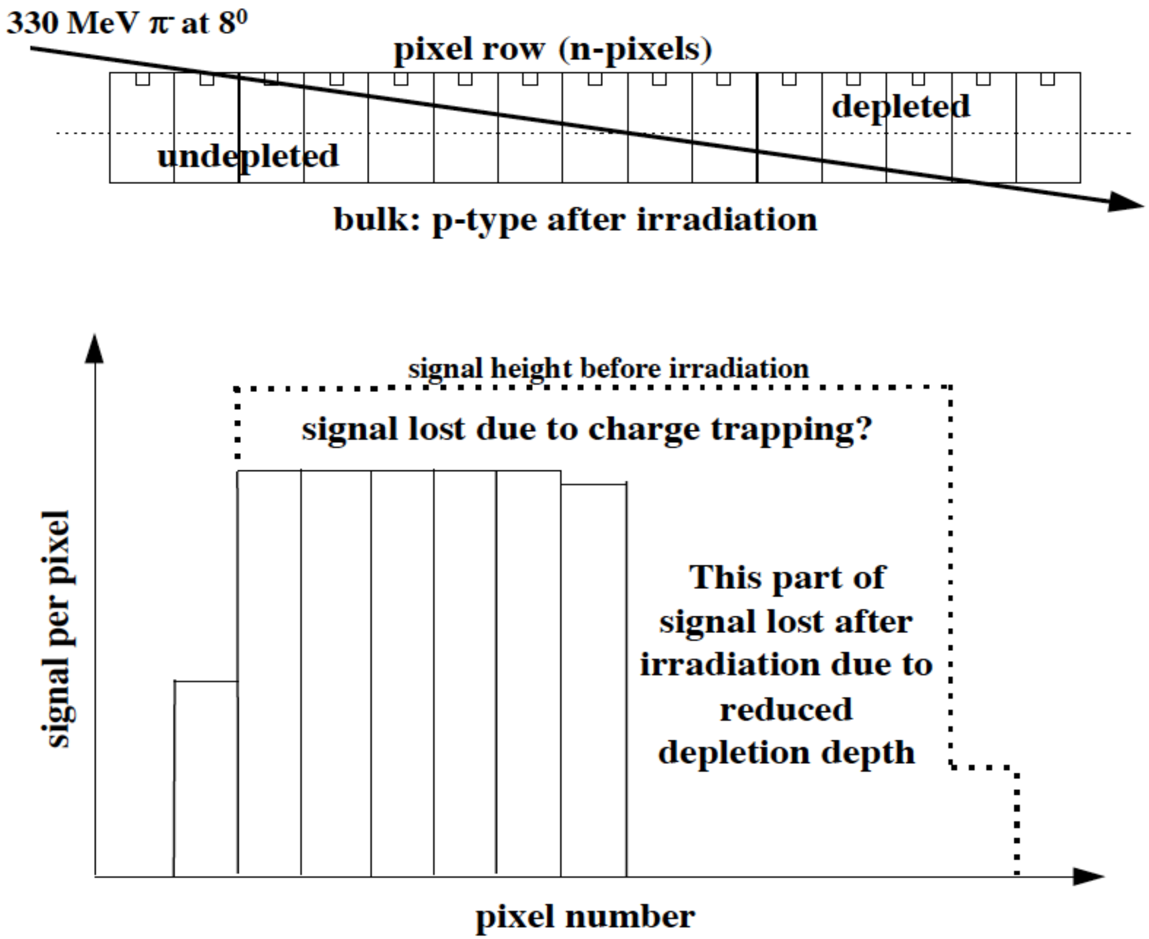
$CCE^{TH} = \lambda/d[1-e^{-d/\lambda}] \sim 67\%$*

* $\lambda(1x10^{15}n_{eq}/cm^2) \approx 240\mu m$
d = 200 μm (sensor thickness)

ELECTRIC FIELD MEASUREMENT

Grazing angle technique

- Technique developed by Henrich, Bertl, Gabathuler & Horisberger (CMS note 1997/021)



- Tracks enter at shallow angle wrt to the detector surface
- Charge collection efficiency as a function of the bulk depth
  - (Analog readout)

Extract electric field from TCAD sims & tb data

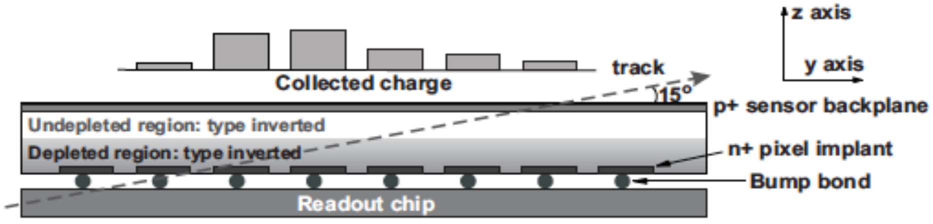
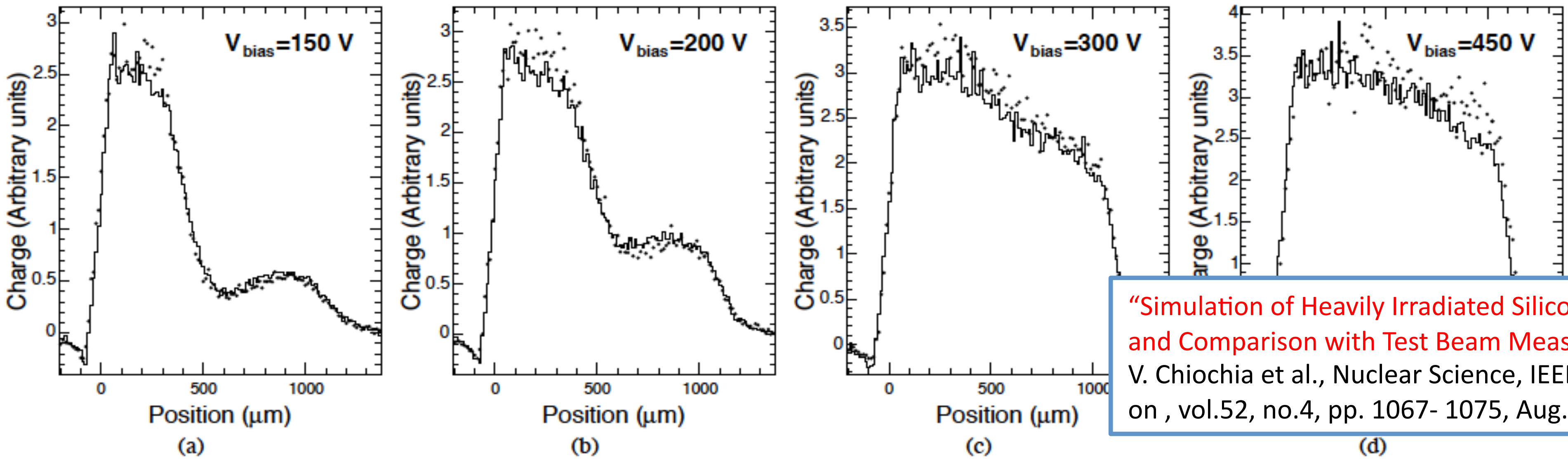


Fig. 2

THE GRAZING ANGLE TECHNIQUE FOR DETERMINING CHARGE COLLECTION PROFILES. THE CLUSTER LENGTH IS PROPORTIONAL TO THE DEPTH OVER WHICH CHARGE IS COLLECTED.

- Study of Charge Collection as a function of charge deposition depth
- **Parameterization of the Electric Filed in simulations**
- **Comparison data/simulation**



"Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements"
V. Chiochia et al., Nuclear Science, IEEE Transactions on , vol.52, no.4, pp. 1067- 1075, Aug. 2005

Fig. 10

THE MEASURED CHARGE COLLECTION PROFILES AT BIAS VOLTAGES OF 150 V, 200 V, 300 V, AND 450 V ARE SHOWN AS SOLID DOTS FOR FLUENCES OF 6×10^{14} N_{eq}/CM^2. THE BF SIMULATION IS SHOWN AS THE SOLID HISTOGRAM IN EACH PLOT.

Level of detail attained: DP effect

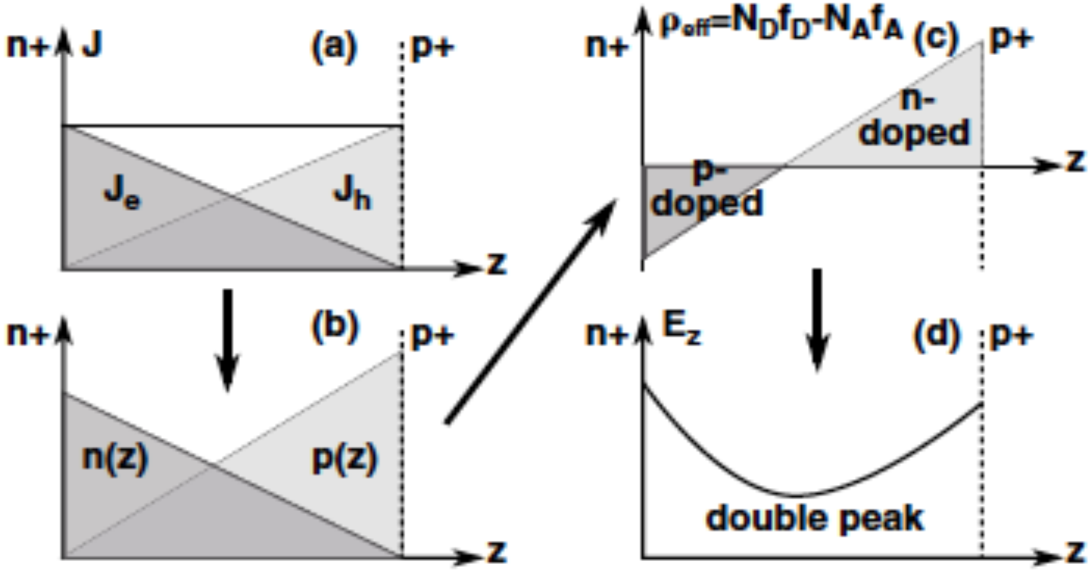
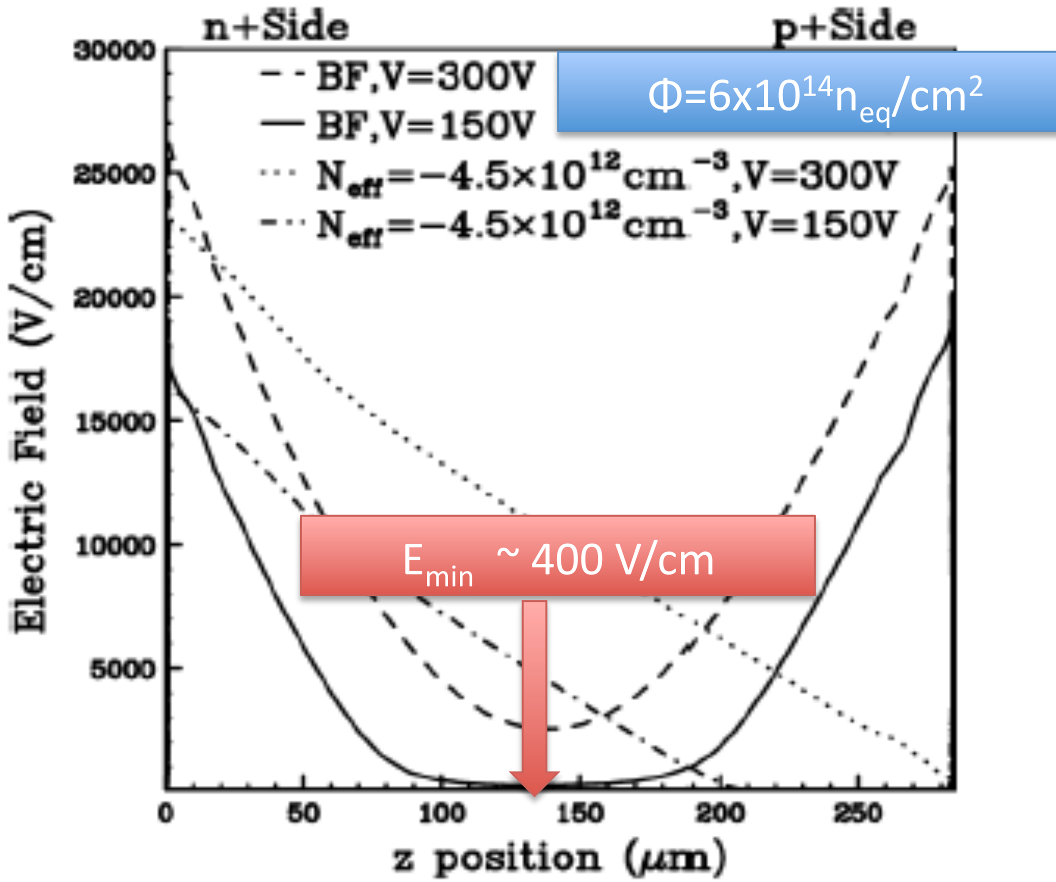
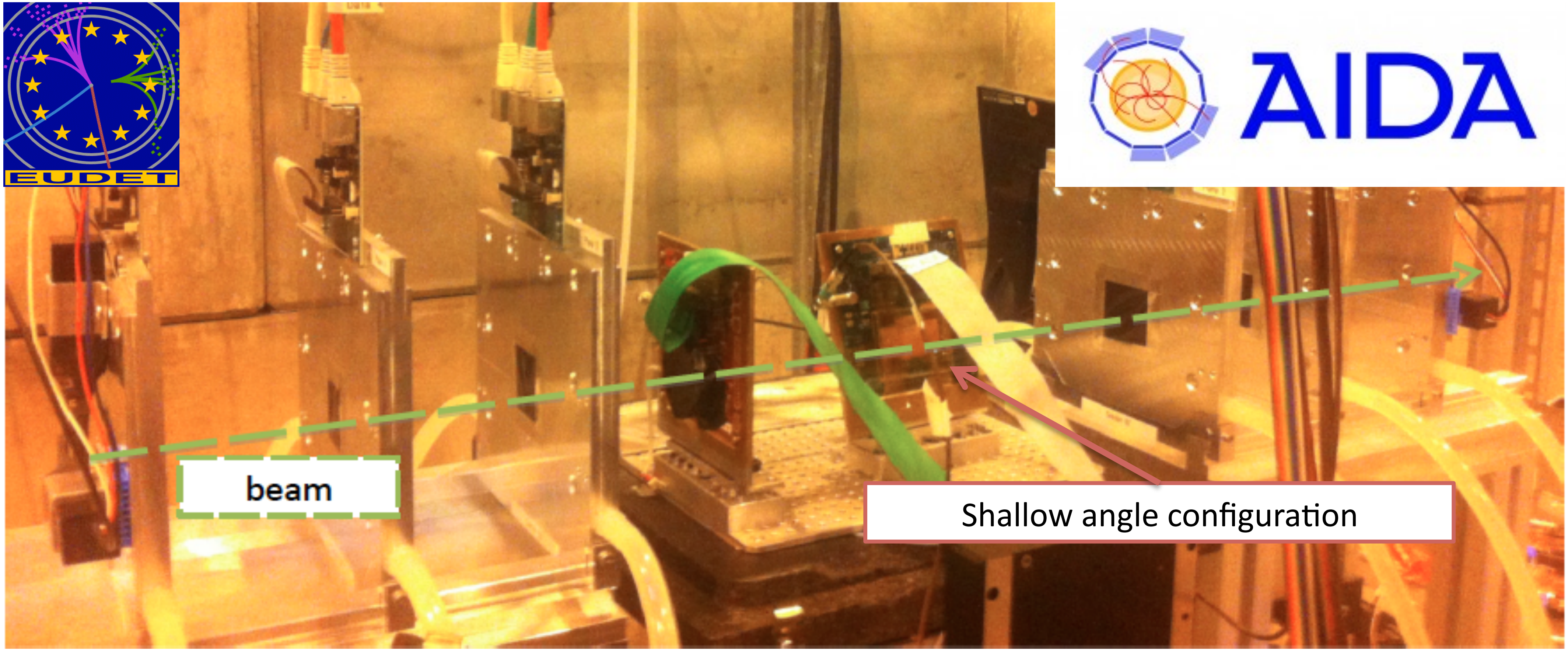


Fig. 6
AN ILLUSTRATIVE SKETCH OF THE EVL MODEL FOR A REVERSE BIASED DEVICE [20].



- They vary the input parameters of the model to reproduce the profiles they observe in data
- Max fluence investigated: $6x10^{14}$ n_{eq}/cm^2
- **Time to look at high fluences!**

Project: RD50 testbeam

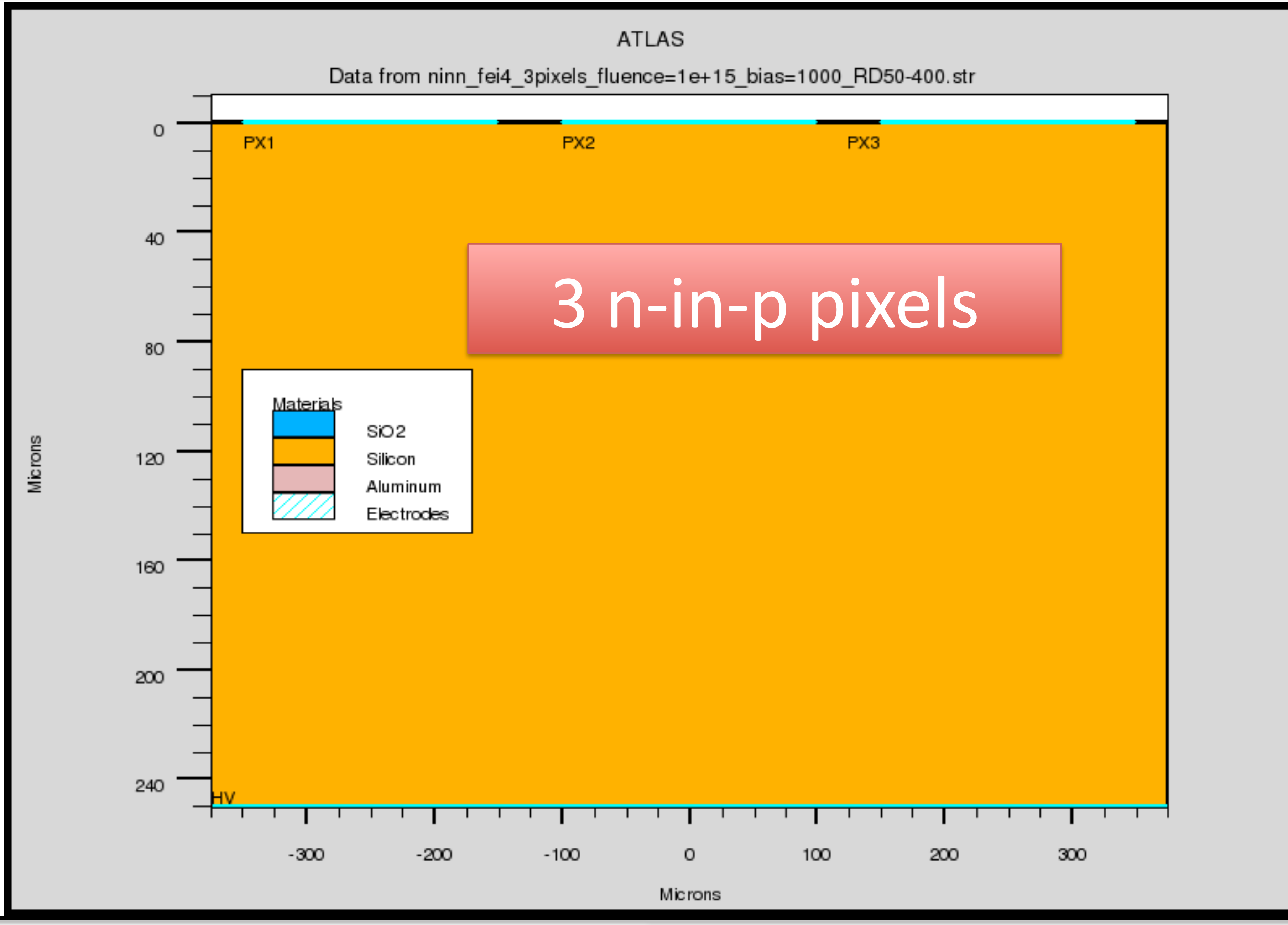


- 1 week of beamtime at CERN SpS (120 GeV/c π)
- DUTs: Highly irradiated pixels
- TCAD simulations for different radiation damage models

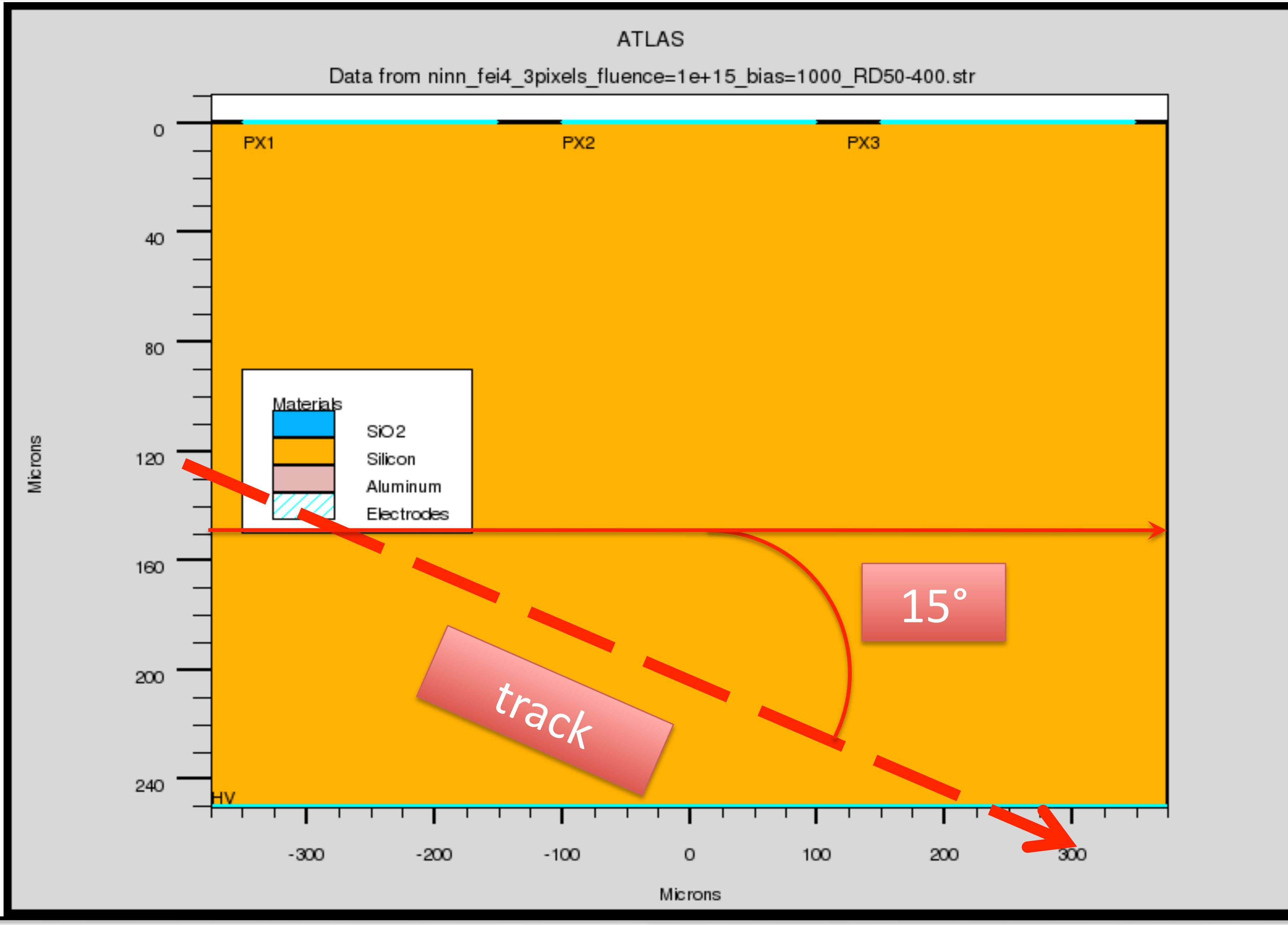
Possible measurements

- Irradiation fluences: $1 \div 6 \times 10^{15}\ n_{eq}/cm^2$
- Different geometries (strips and pixels)
- Different materials (DOFZ vs MCz), type (n vs p)
- Different radiations (n, p, π)
- Charge multiplication? (Dream: only if $\sigma_{trk} \sim 1\mu m$)

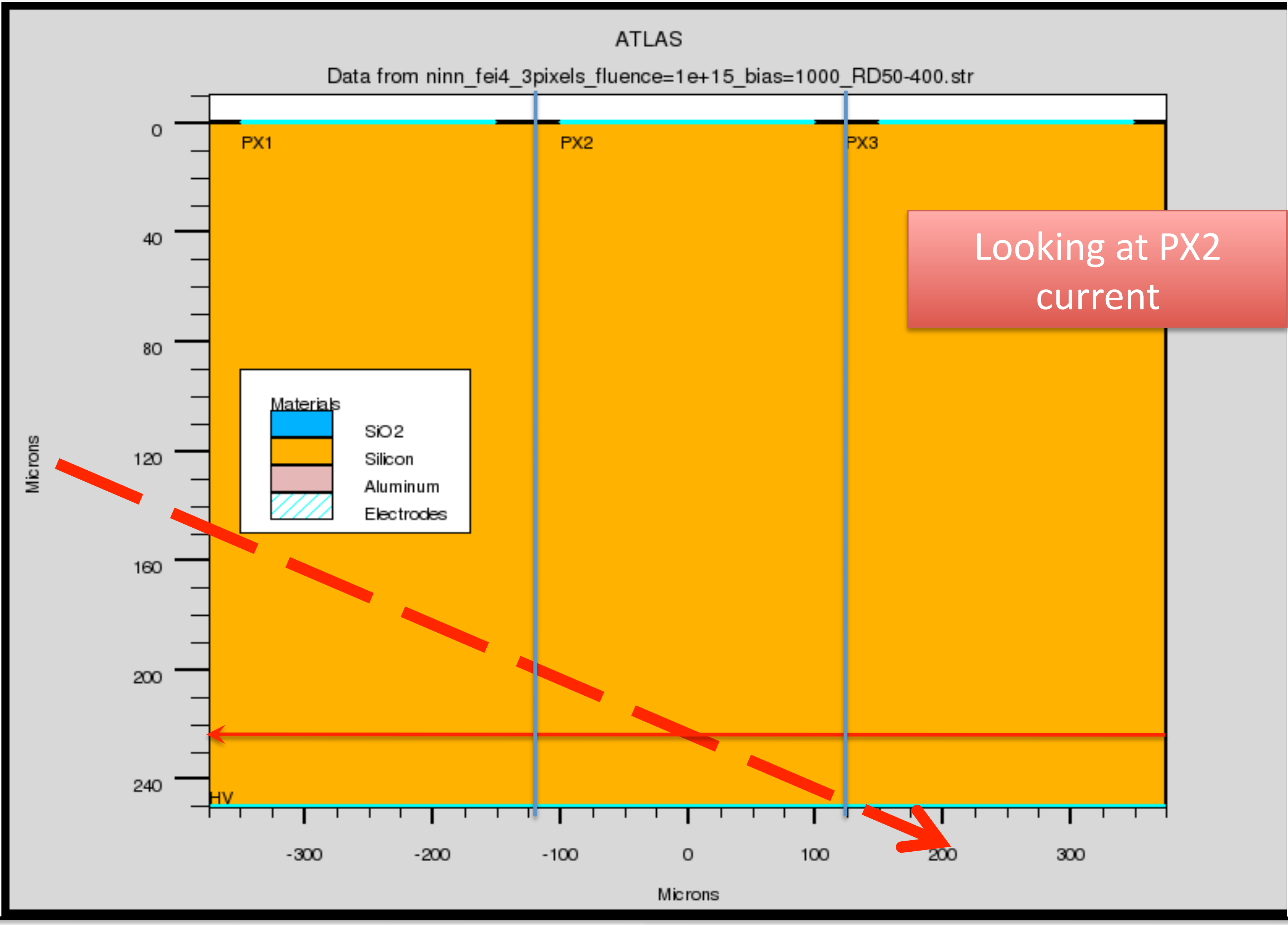
Simulated structure



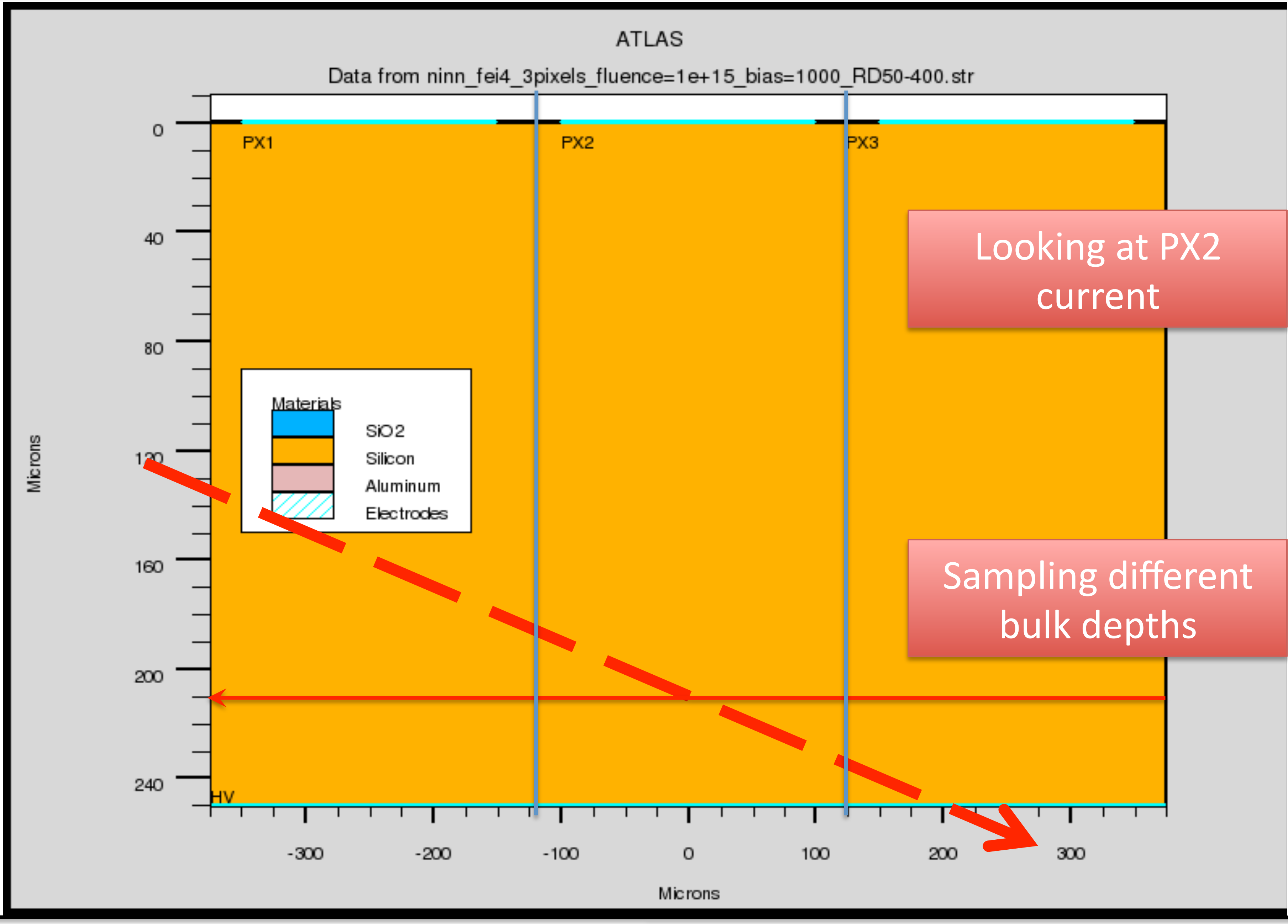
Collected charge vs track entry point



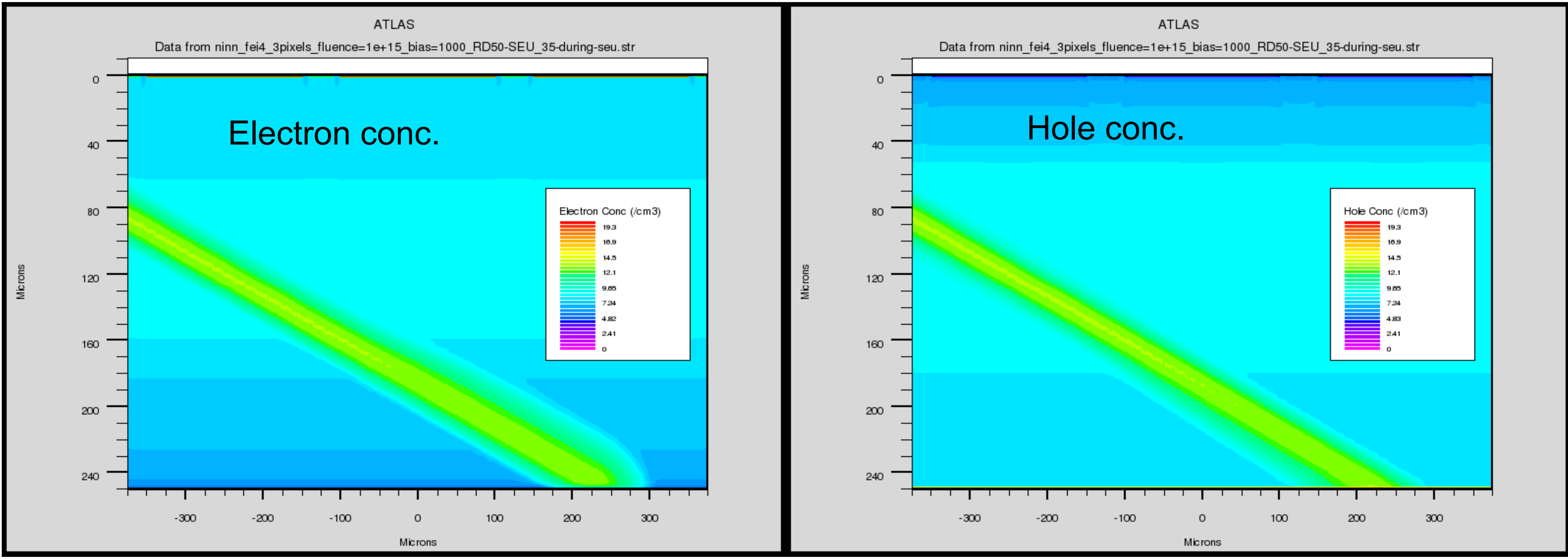
Scanning the bulk depth



Scanning the bulk depth

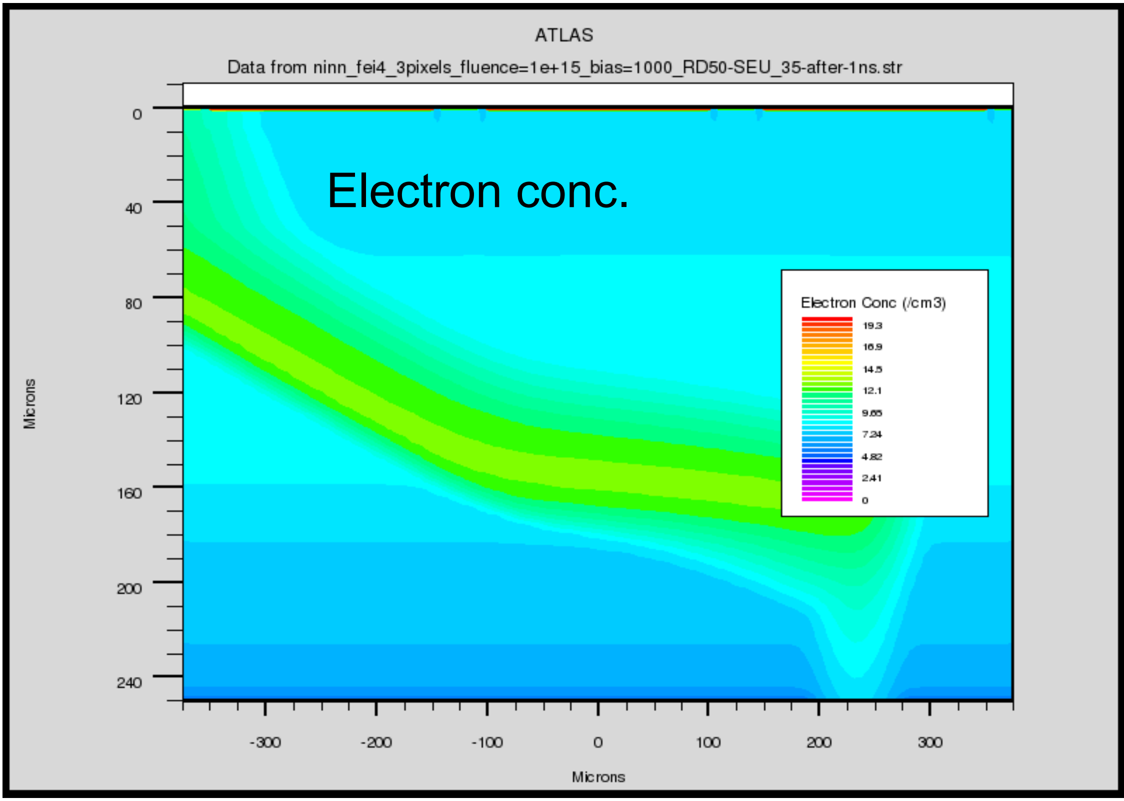


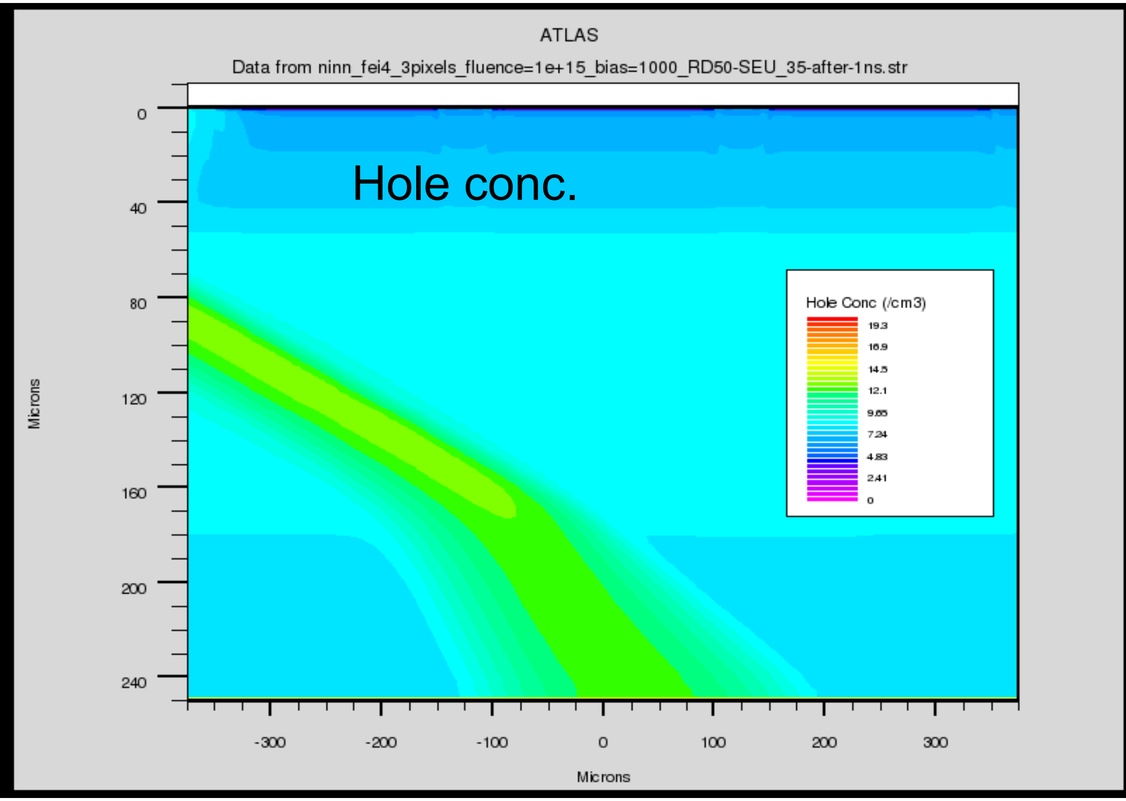
Ionizing particles and carrier distributions



- Carrier distribution during the particle strike

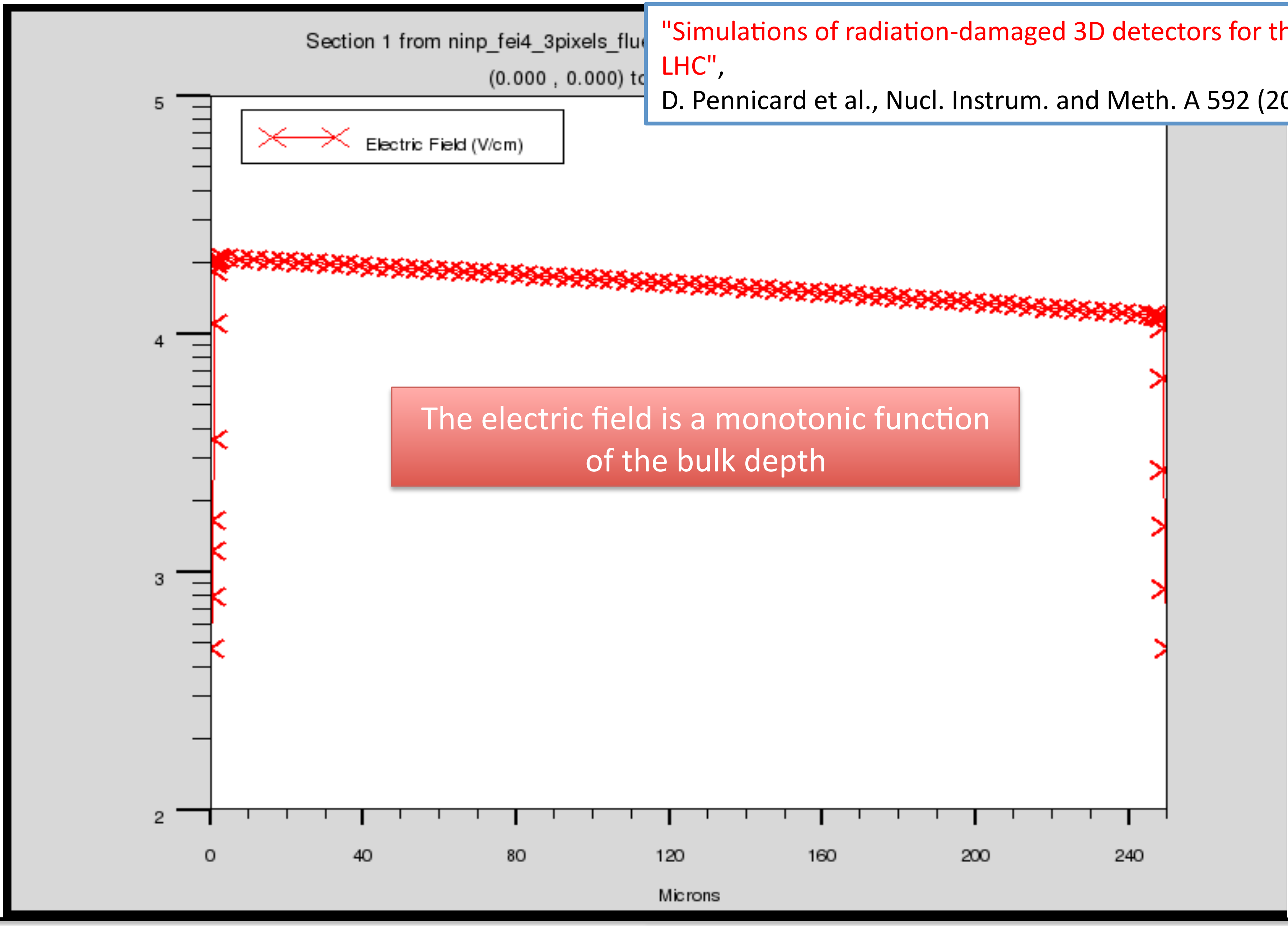
Ionizing particles and carrier distributions





- Carrier distribution 1 s after the particle strike

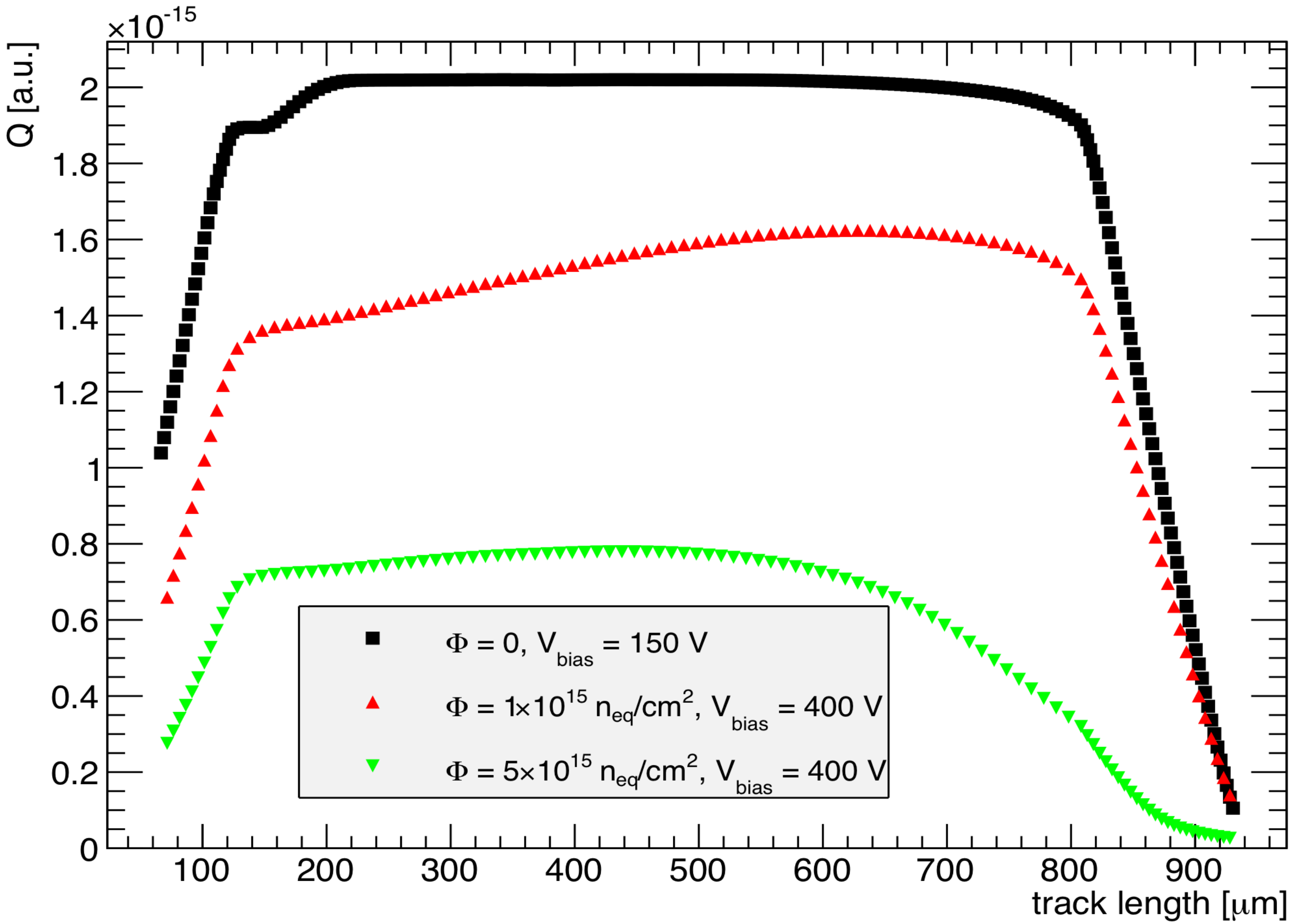
Radiation damage model I - Pennicard



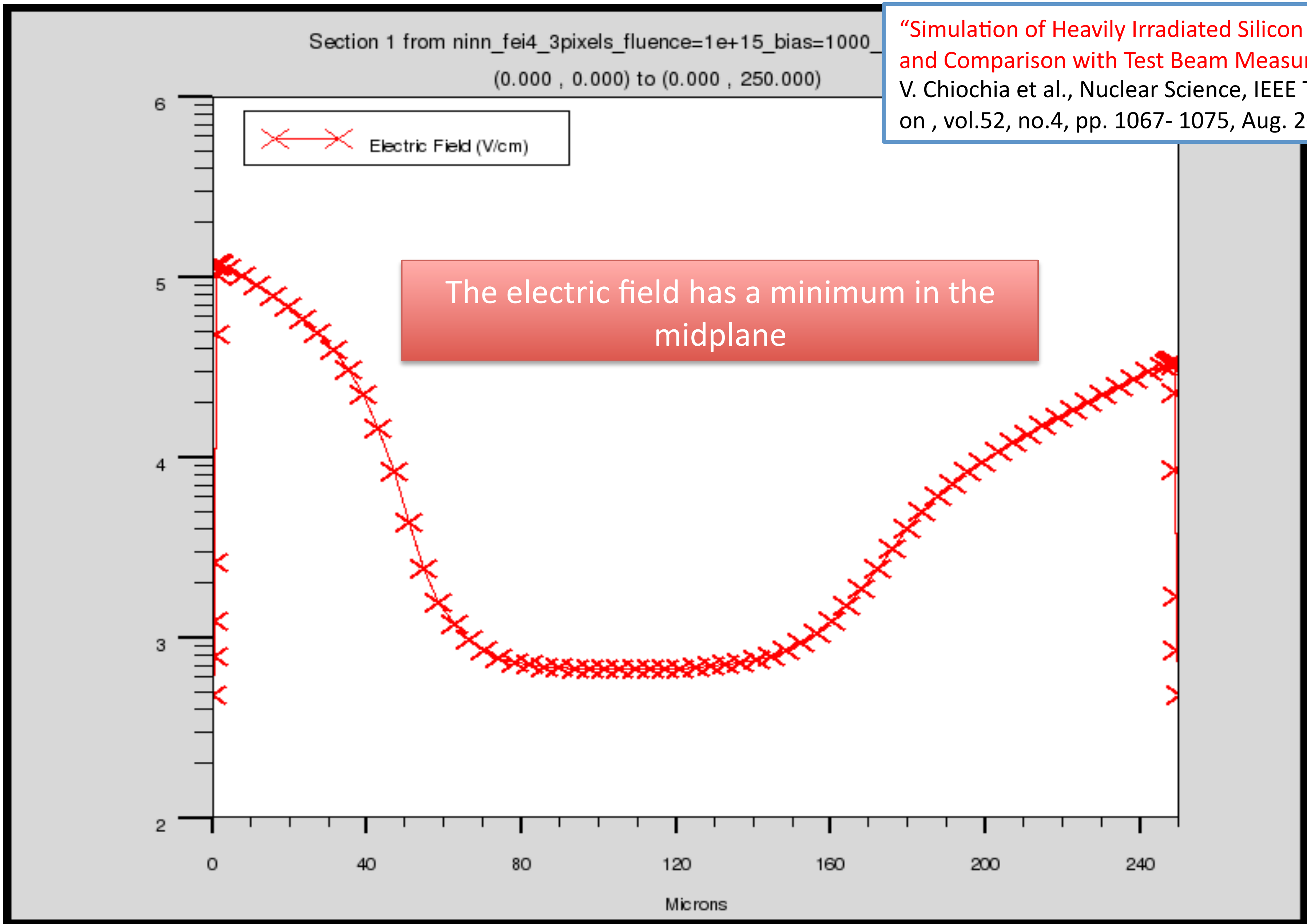
"Simulations of radiation-damaged 3D detectors for the Super-LHC",
D. Pennicard et al., Nucl. Instrum. and Meth. A 592 (2008) 16-25

The electric field is a monotonic function of the bulk depth

Charge profile for Pennicard model

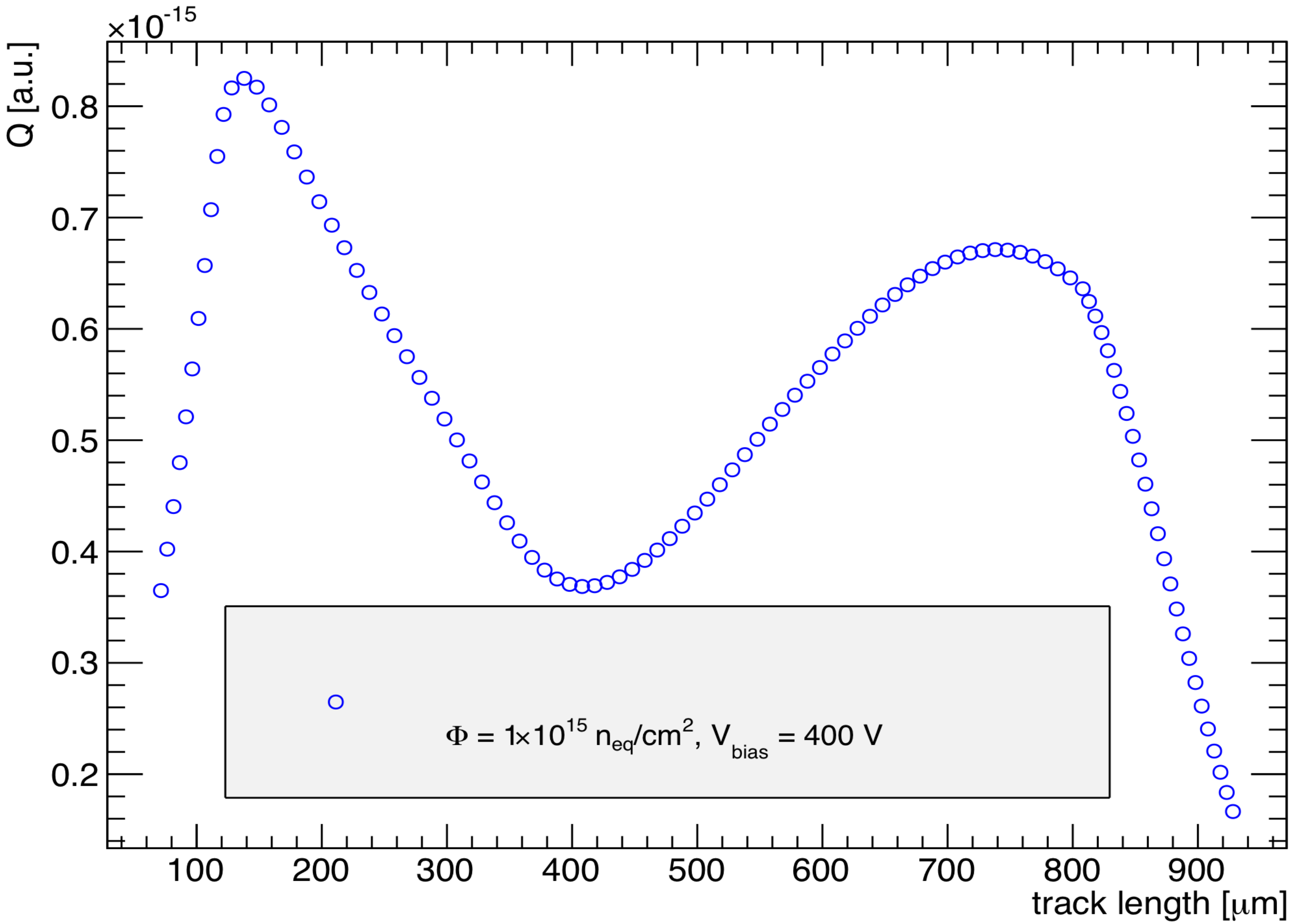


Radiation damage model II - Chiochia



"Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements"
V. Chiochia et al., Nuclear Science, IEEE Transactions on , vol.52, no.4, pp. 1067- 1075, Aug. 2005

Charge profile for Chiochia model



COMMENTS AND CONCLUSIONS

TCAD simulations for HEP sensors: my view

- Thanks to TCAD you can make powerful predictions on new sensors
- TCAD could save you money and time
- … but to learn it and produce reliable results might take some time
- Better to have a good knowledge of semiconductor physics before using TCAD

TCAD simulations: time needed

- The CPU time increases with number of meshing points
- E.g. : 1 minute per bias point for ~ 100k nodes mesh on a 8 core 3GHz machine
- For irradiated sensors it took me ~ 1/2 week to get full depletion
- Another example: time-domain solution. For the same structure above you need to solve for ~ 10 ns in time steps of ps, with ~ 1 minute per point
  ➔ it took me 1÷2 days

➢ Look for optimizations & compromises!

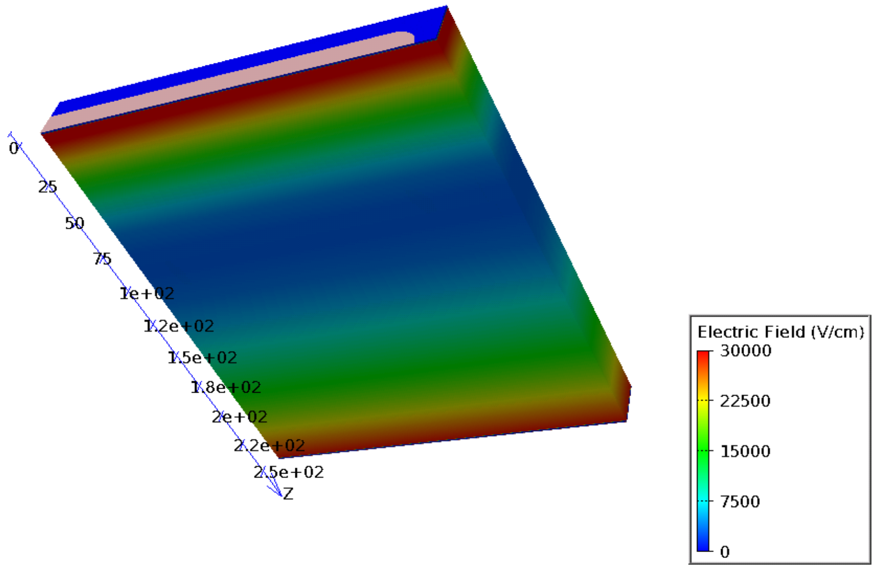
Conclusions

- 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
- The program is rather complex, and if you don't know what you are doing is easy to get a bit lost
- So, if you want to use TCAD, it is recommended to have a good knowledge of semiconductor physics, and good data inputs

One last thing

- It could be nice and funny to work with TCAD simulations ☺
- So if you are interested in working with TCAD simulations, feel free to contact me: marco.bomben@cern.ch

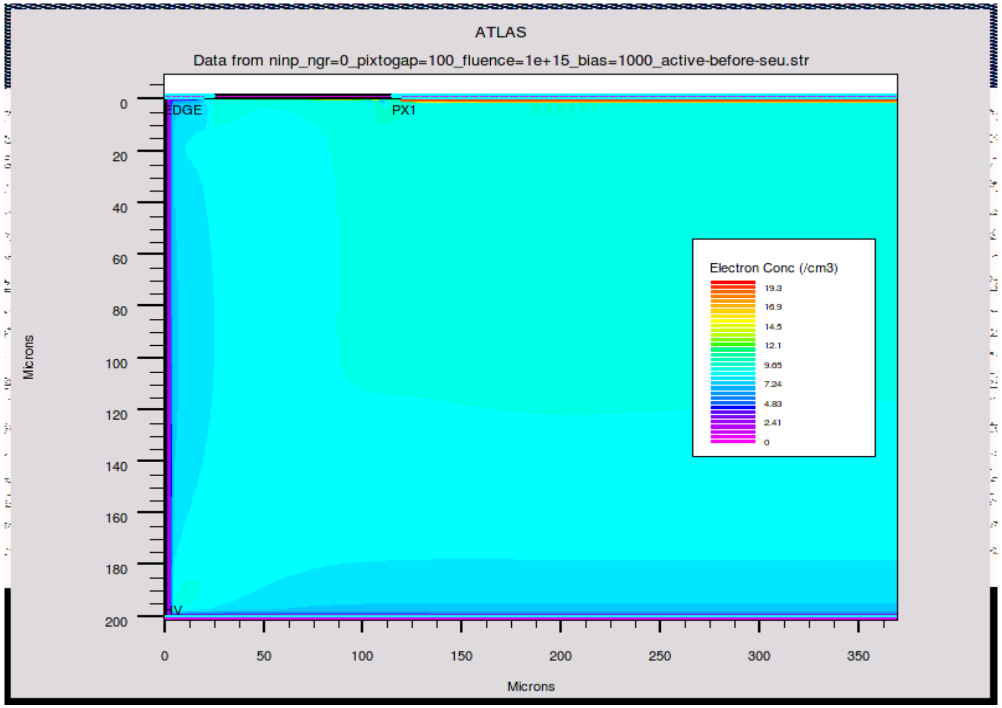
➢ Thank you!



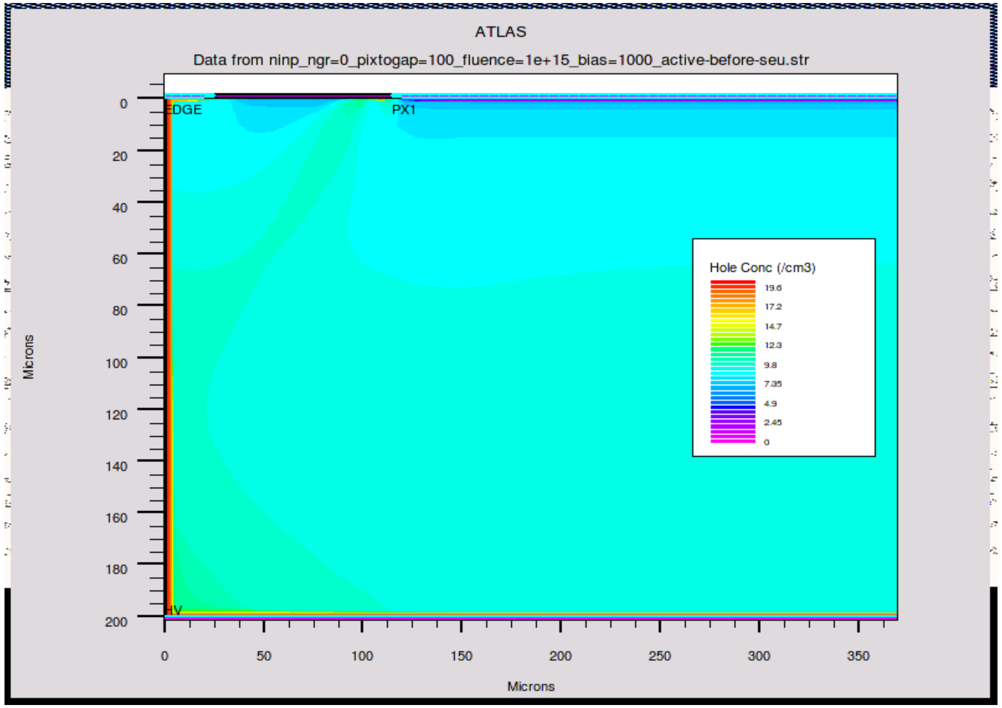
BACKUP MATERIAL

Before strike

Electrons



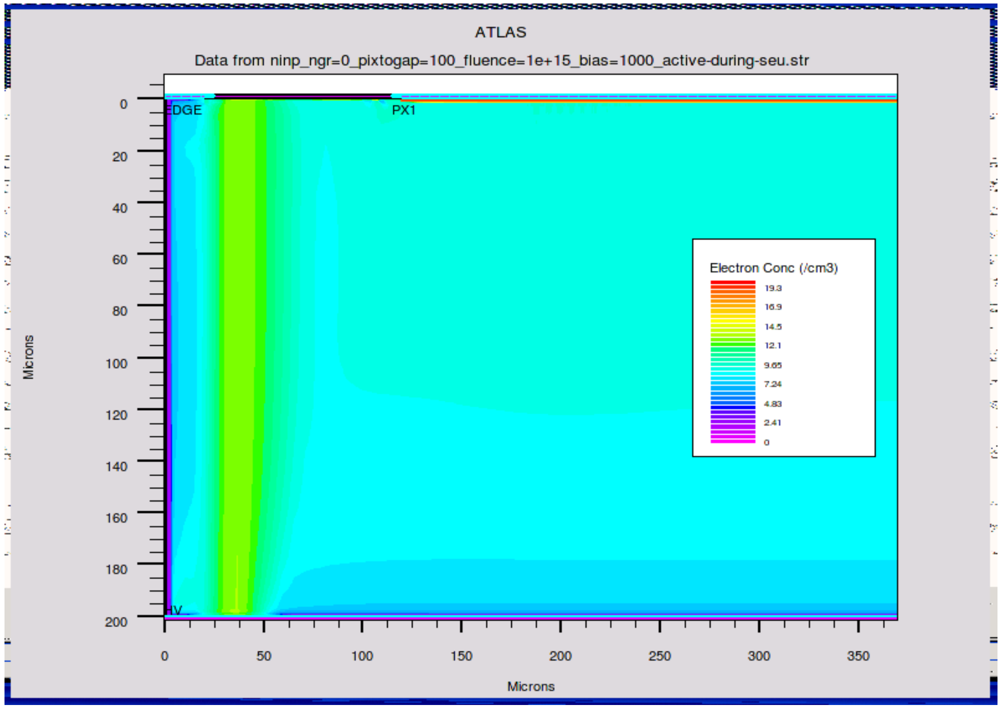
Holes

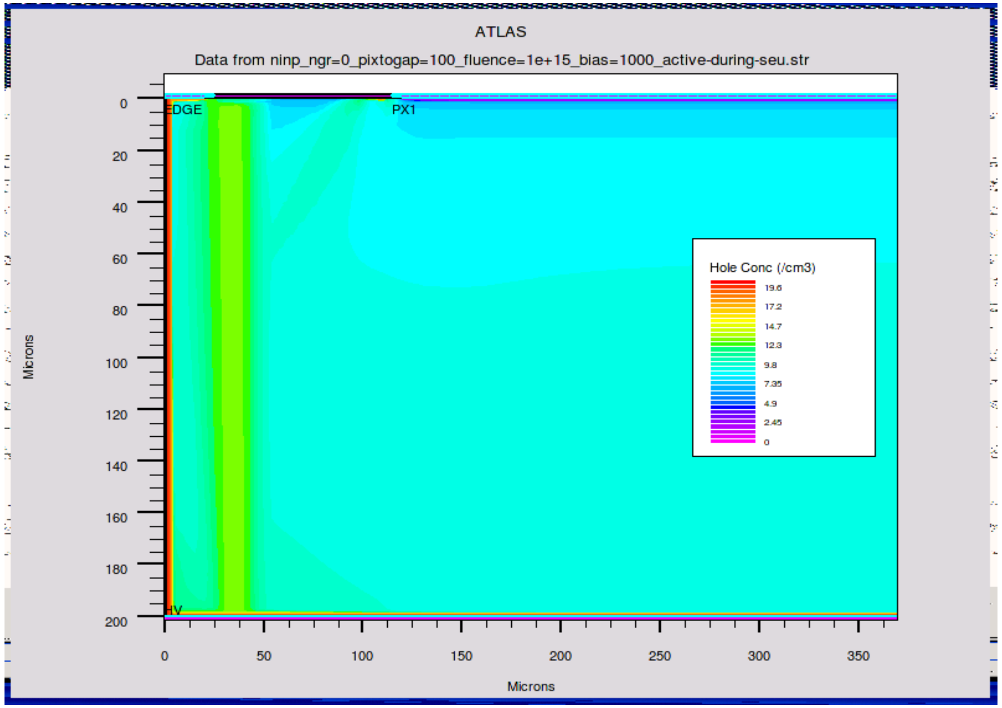


30 ps after particle hit

Electrons

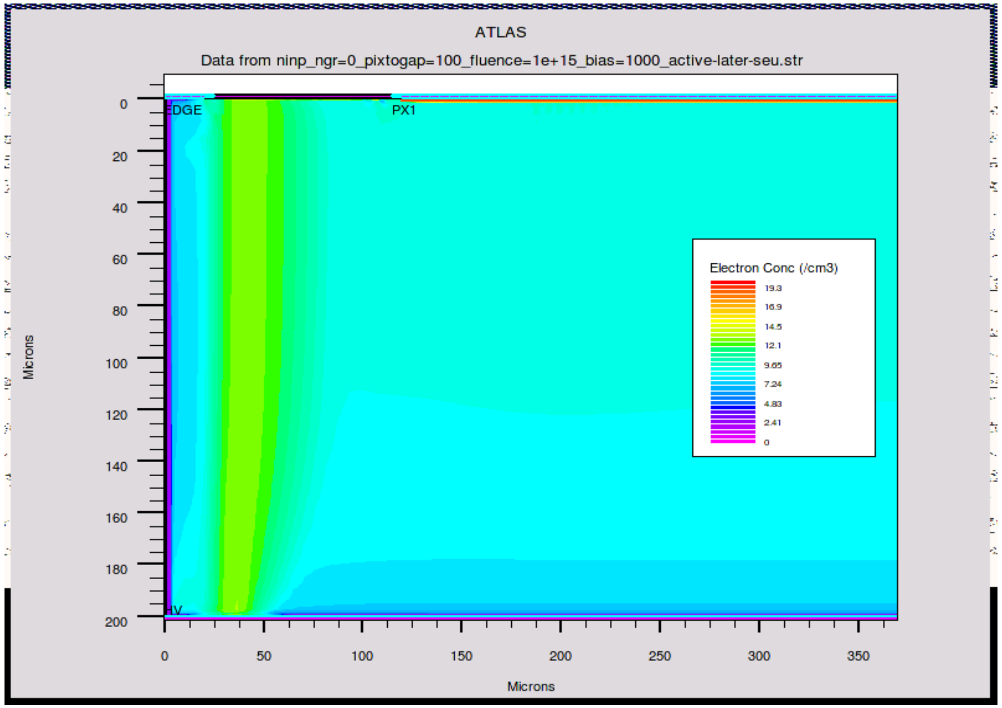
Holes



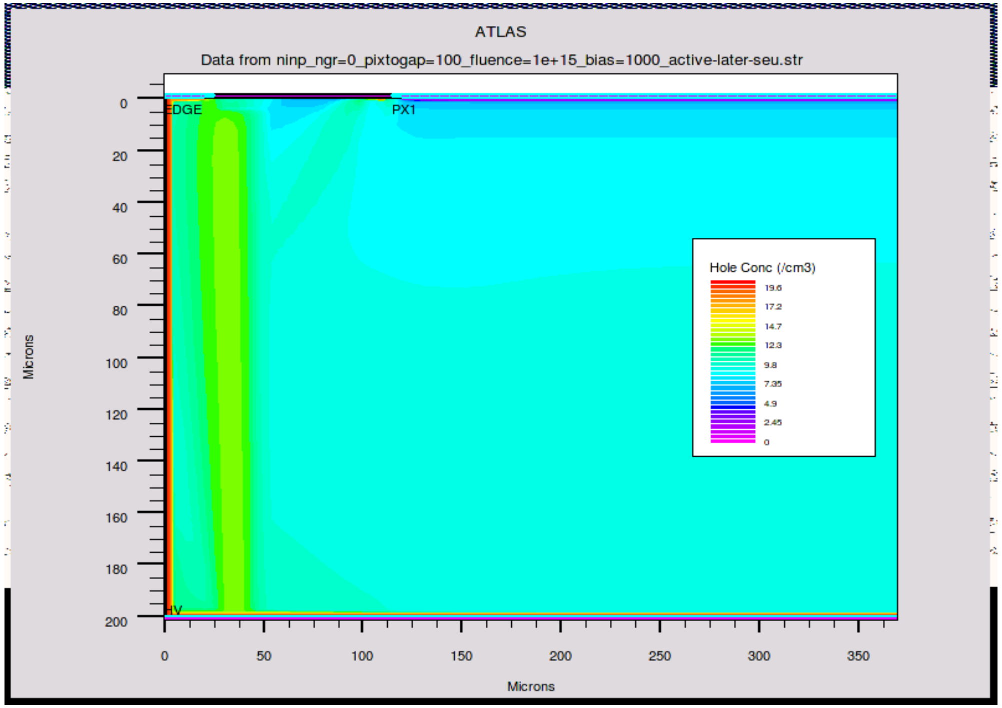


80 ps after particle hit

Electrons

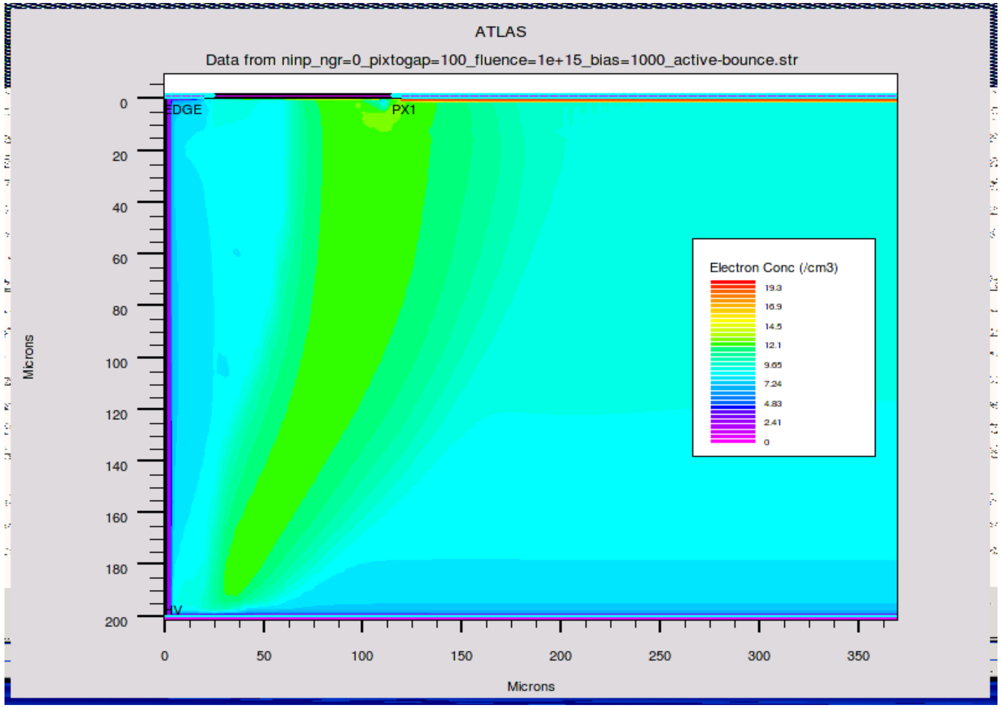


Holes

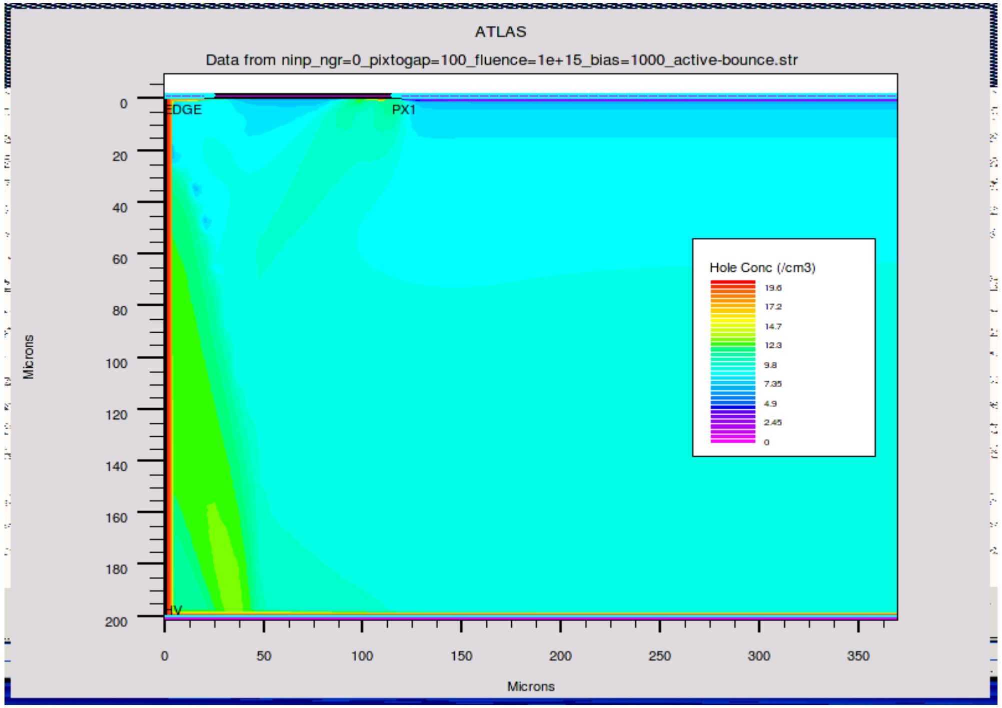


780 ps after particle hit

Electrons

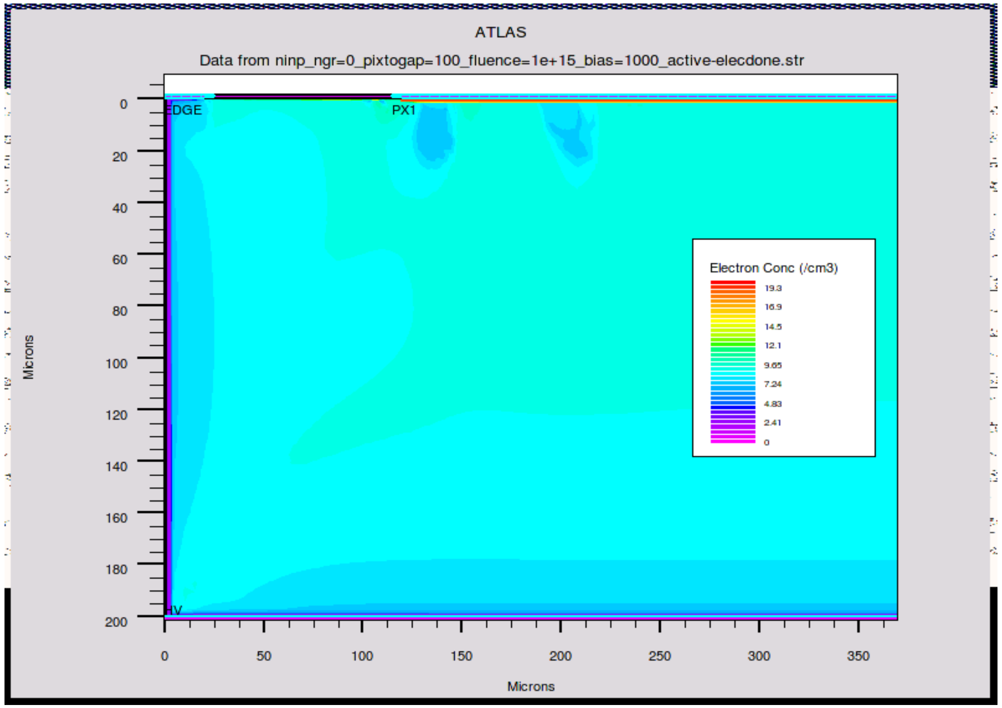


Holes

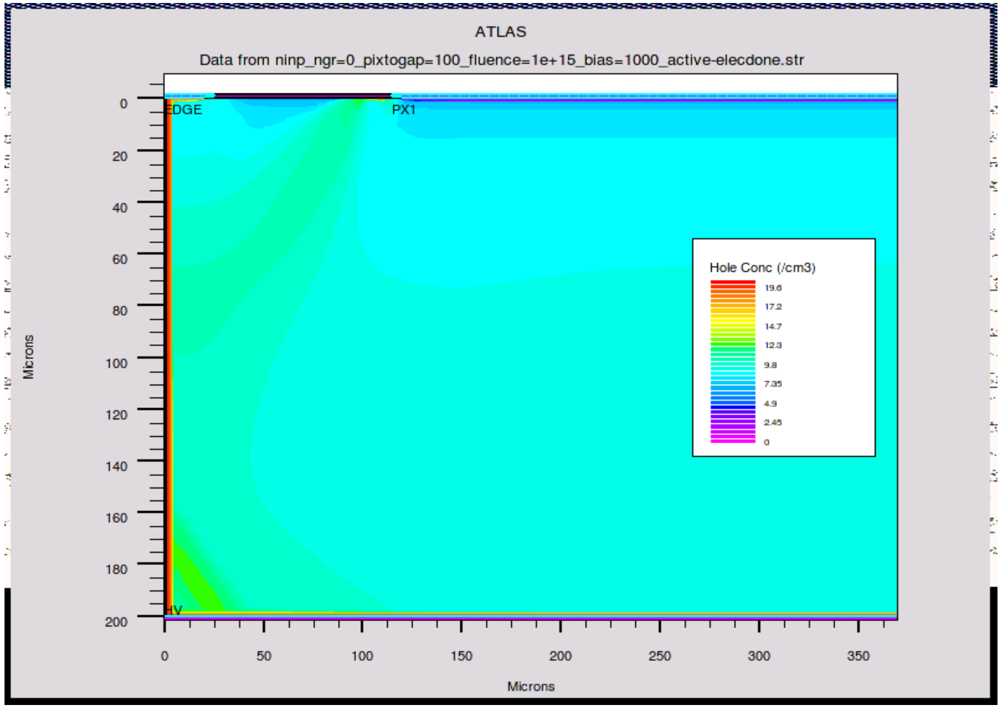


4 ns after particle hit

Electrons

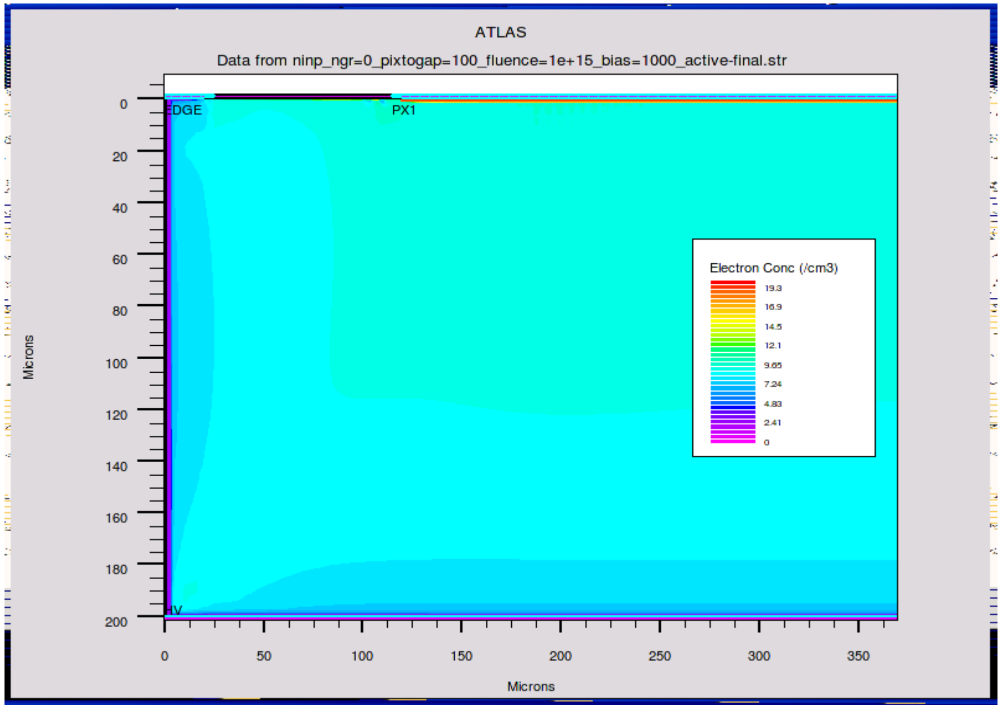


Holes

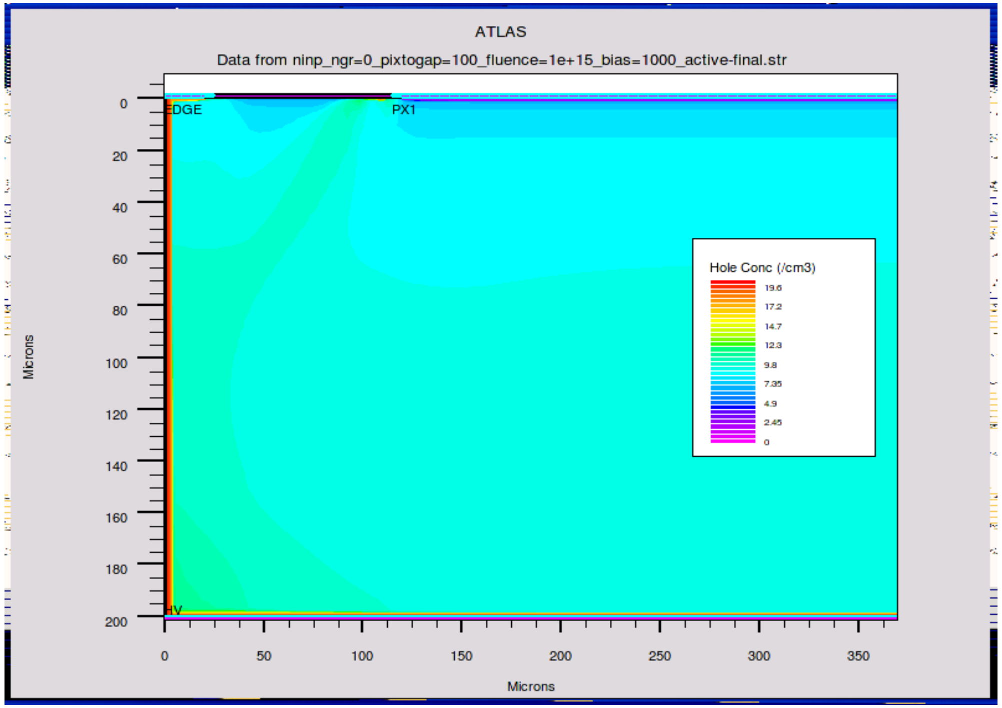


100 ns after particle hit

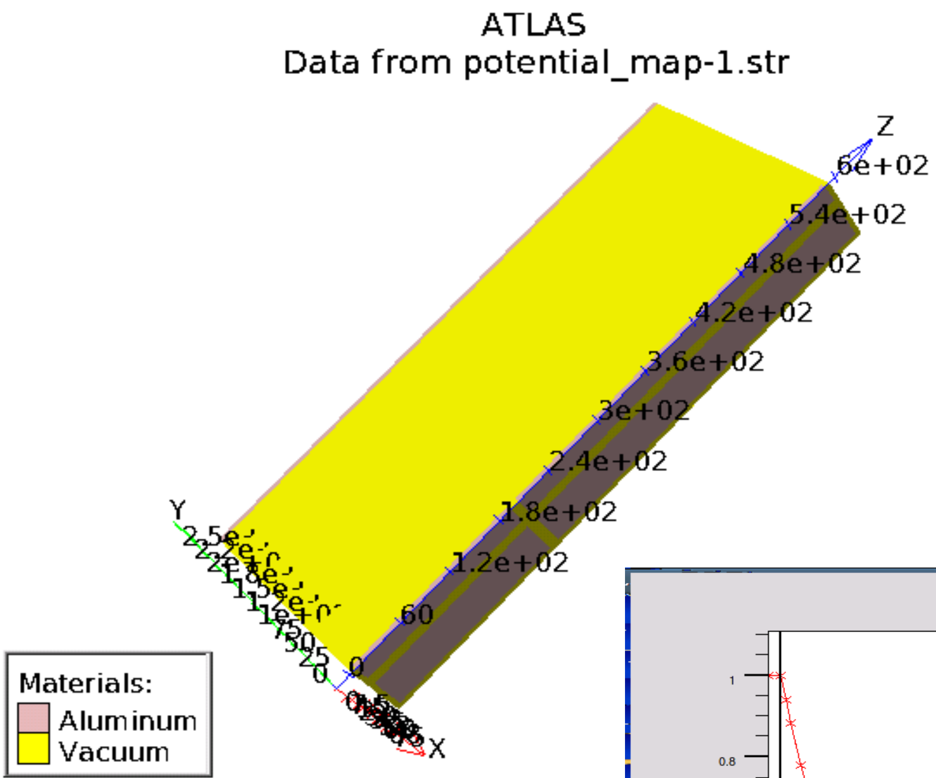
Electrons

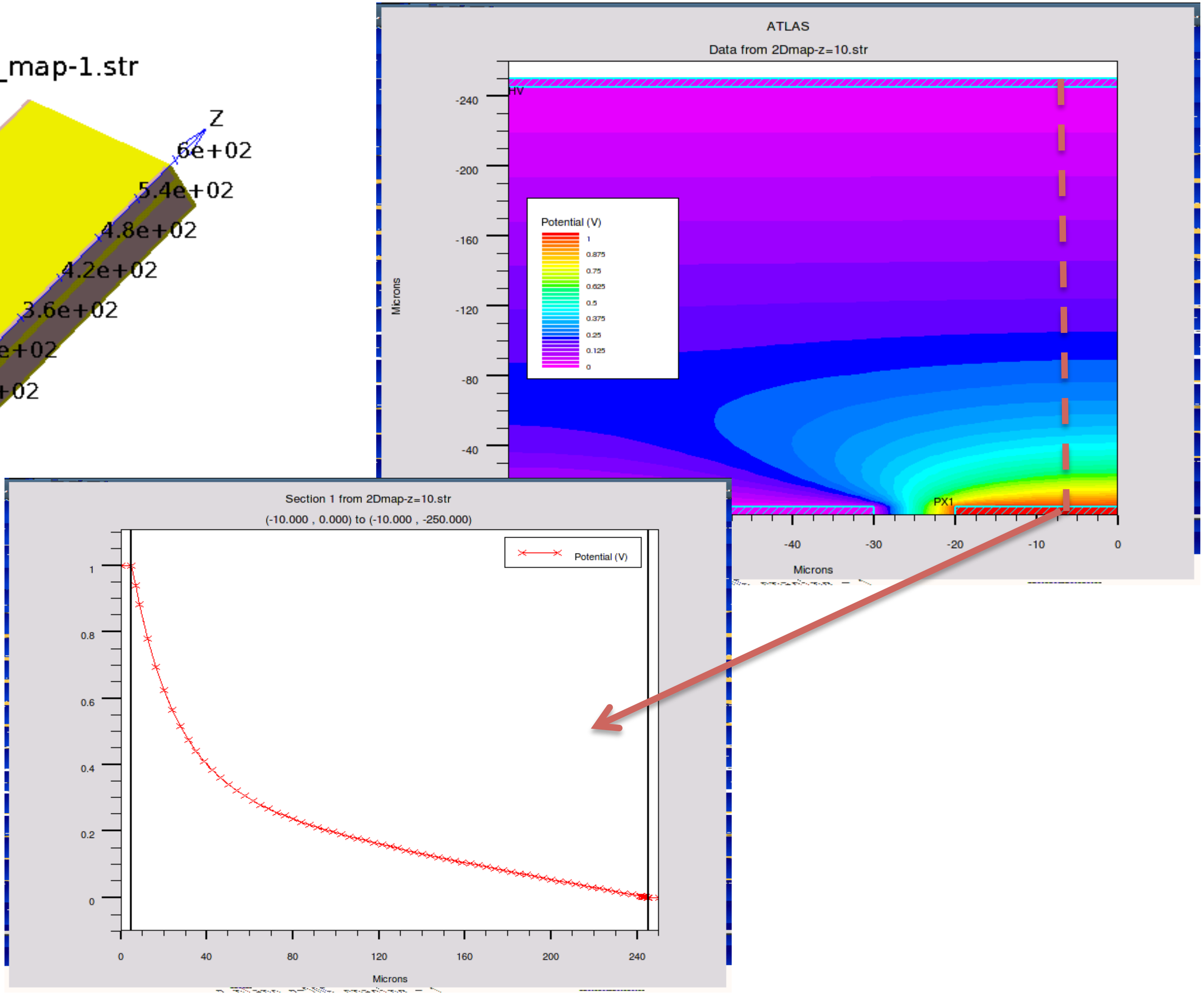


Holes

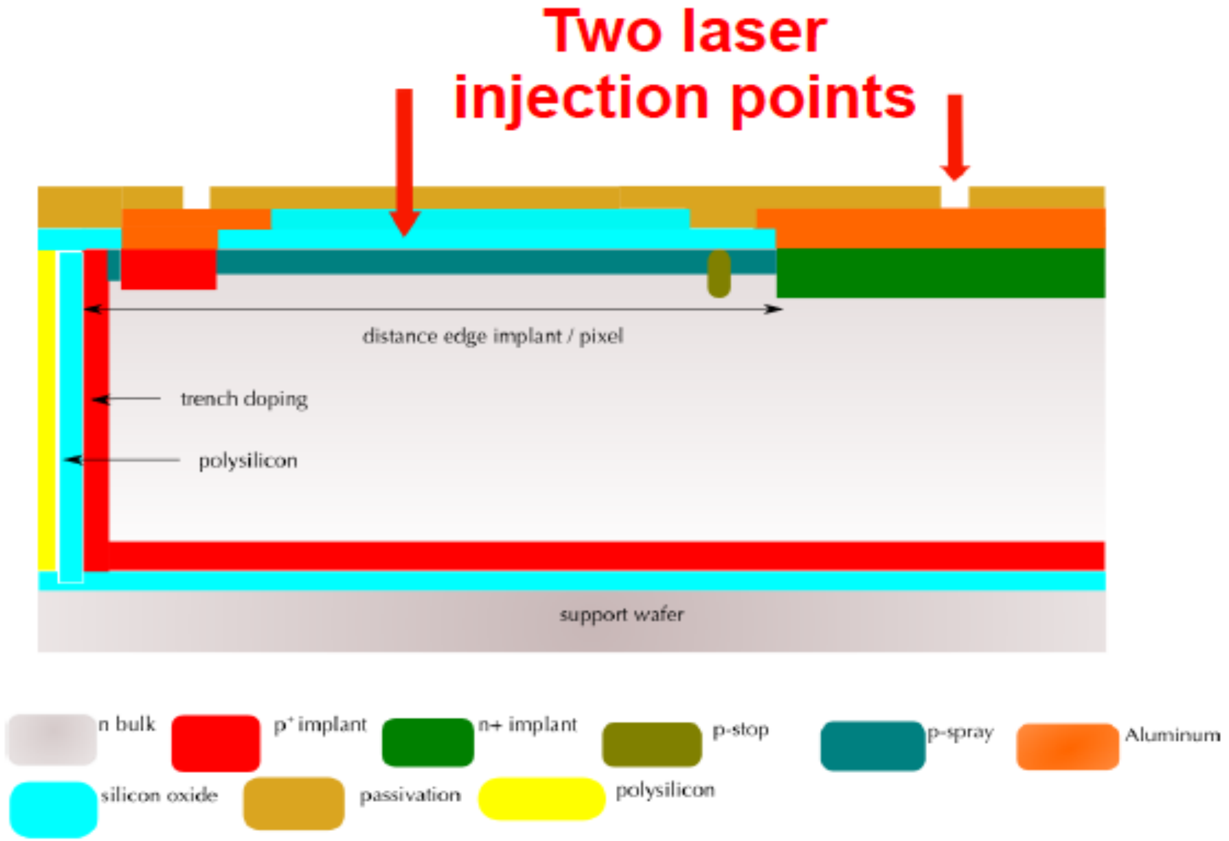


Digitizer inputs from TCAD: ramo potential





Simulation of CCE studies with laser




```
ATLAS> # BEAM DEFINITION
ATLAS> beam num=1 x.origin=200 y.origin=-2.0 angle=90 wavelength=1.06 rays=101 gaussian
 mean=0 xsigma=5
```

```
ATLAS> solve     b1=18 ramp.lit ramptime=1e-9 tstop=10e-9 tstep=2e-10
```

```
ATLAS> solve     b1=0 ramp.lit ramptime=1e-9 tstop=50e-9 tstep=5e-10
```