Simulations of 3D detectors

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Outline

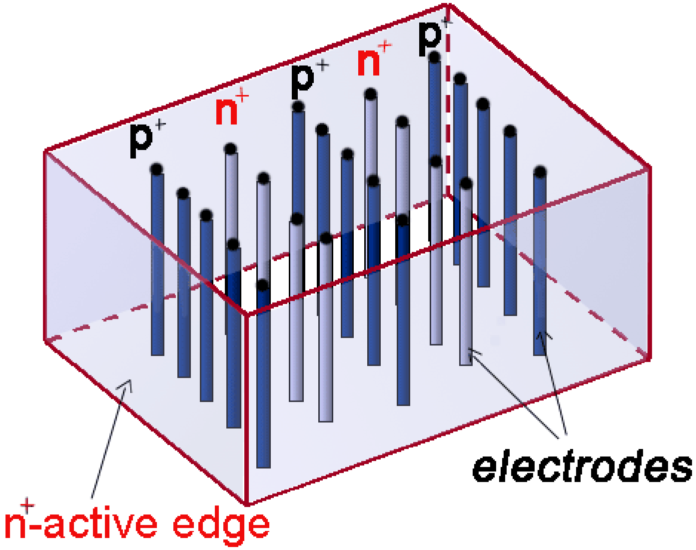
- 3D sensors: properties, state-of-the-art and technology @ FBK

- TCAD simulations for 3D sensors: peculiarities

- Selected simulations :
  - C-V → depletion map
  - SLIM edge
  - Signals from test beam → charge sharing
  - Multiplication effect (?)

3D detectors

First proposed by S. Parker et. al.
in NIMA 395 (1997), 328



Best result:
66% of the original signal after
Fluence = $\mathbf{8.8\times10^{15}\ cm^{-2}}$ 1-MeV $n_{eq.}$
@ 100 V

C. Da Via et. al.: NIMA 604 (2009) 504

ADVANTAGES:

- Electrode distance and active substrate thickness decoupled:
  - Low depletion voltage
  - Short Collection distance
  - Smaller trapping probability after irradiation

→ **High radiation hardness**

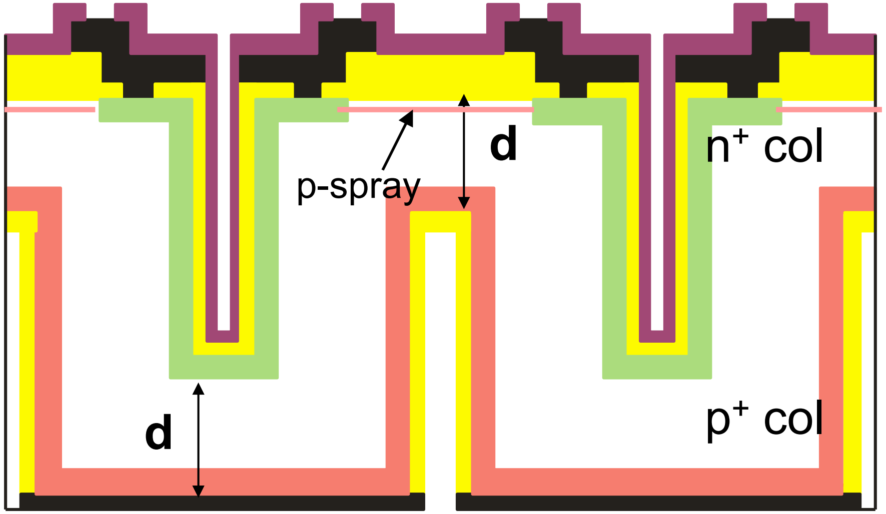
-Active edges:
  - Dead area reduced up to few microns from the edge

DISADVANTAGES:

- Non uniform response due to electrodes
- Complicated technology
- Higher capacitance **(X3)** with respect to planar

Latest 3D technology @ FBK

~ 200-μm *P*-type substrate, *n*-junction columns insulated by p-spray

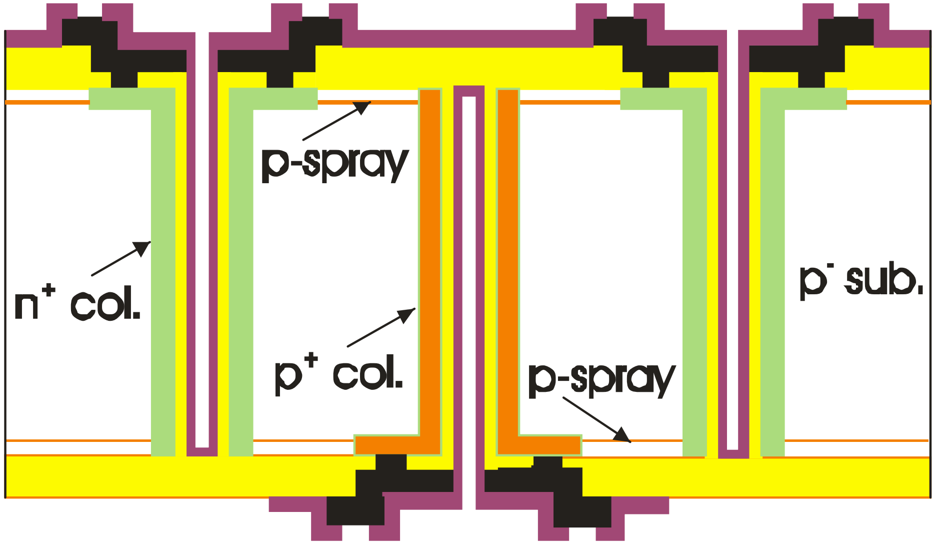


NOT FULL PASSING COLUMNS

- fabrication process reasonably simple
- proved good performance up to irradiation fuence of 10^{15} n_{eq}/cm^2 (even with non optimized gap "d")

but

- column depth difficult to control and to reproduce
- insufficient performance after very large irradiation fluences if "d" is too large



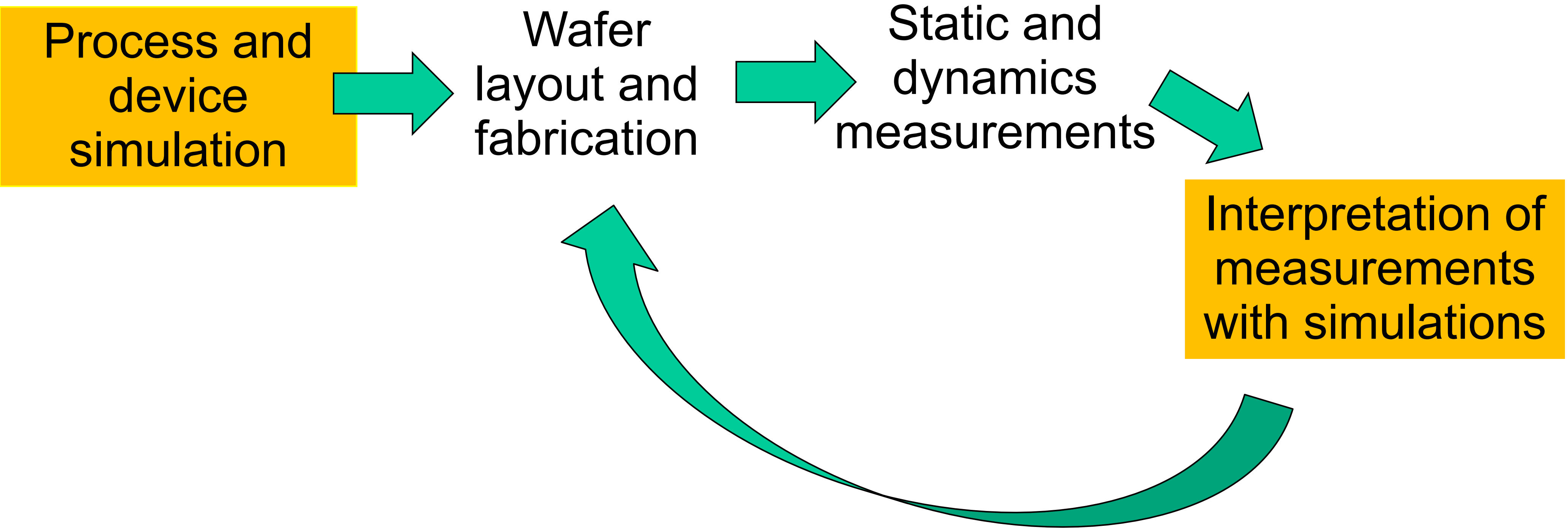
FULL PASSING COLUMNS

- Column depth = wafer thickness
- More complicated process
  → back patterned

From G.-F. Dalla Betta, IEEE NSS 2010, N15-3

The TCAD Simulator

Simulations presented are performed with Synopsis Sentaurus
(former ISE-TCAD) → 1D, 2D and **<u>3D</u>** simulator
solving physical equations (Poisson, drift, diffusion, …)



Process and device simulation

Wafer layout and fabrication

Static and dynamics measurements

Interpretation of measurements with simulations

TCAD Simulator for 3D

Simulation for understanding the properties of different kind of 3D sensors have been the subject of many papers:

- Parker et al.: “3D – A proposed new architecture for solid-state radiation detectors” NIM A395 (1997) 328-343
- Piemonte et al.: “Development of 3D detectors featuring columnar electrodes of the same doping type” NIMA 541 (2008) 441
- Zoboli et al.: “Double-Sided, Double-Type-Column 3-D Detectors: Design, Fabrication, and Technology Evaluation” TNS 55 (2008) 2775
- Pennicard et al.: “Simulations of radiation-damaged 3D detectors for the Super-LHC” NIM A 592 (2008) 16–25

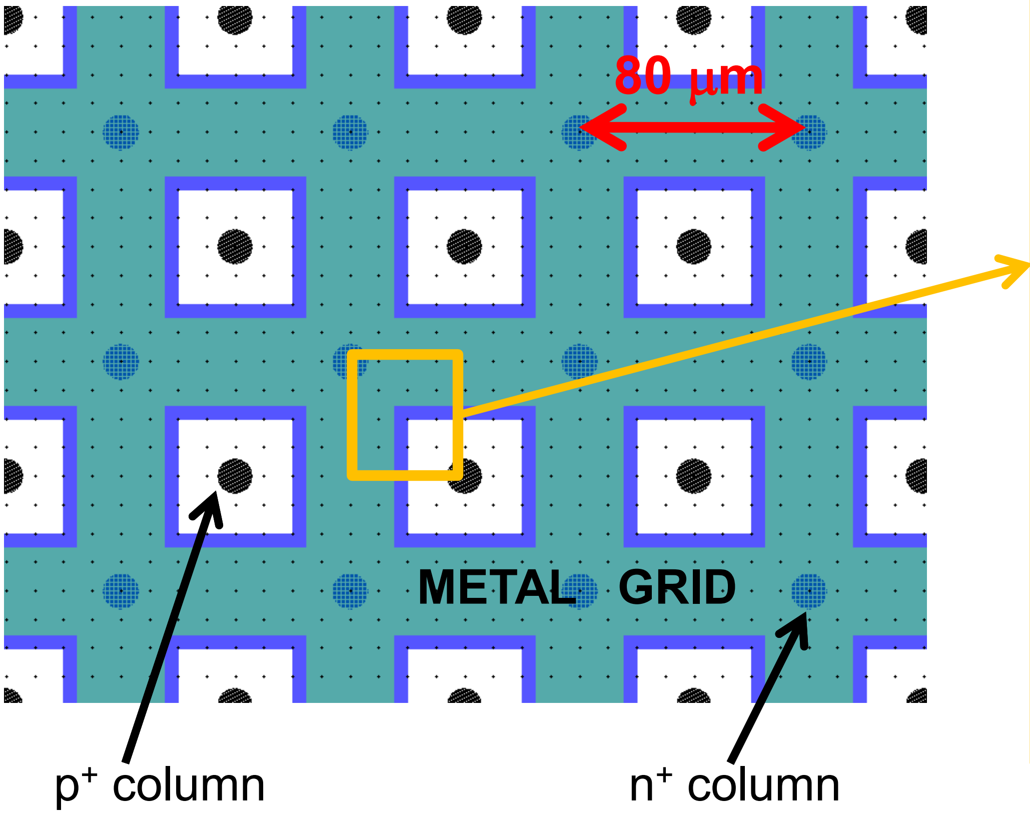
For the different technologies, we studied both static (I-V and C-V) and dynamic behavior (signals from optical and high-energy particles).

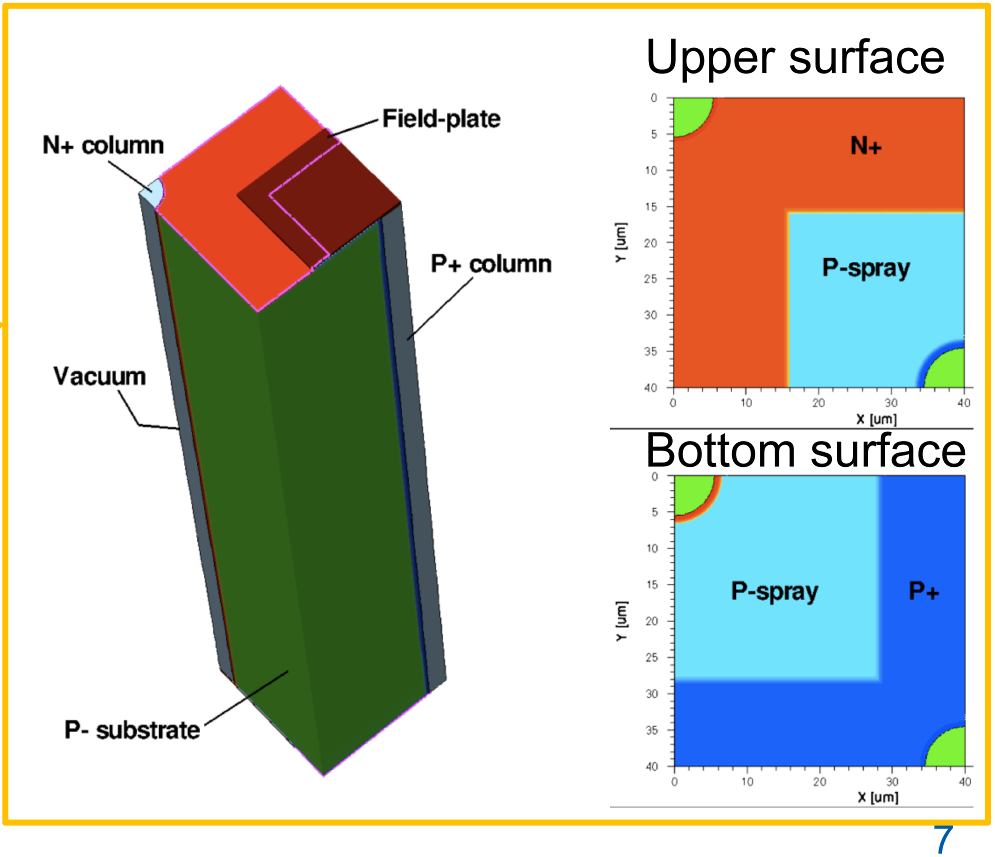
Peculiarity of 3D detector simulations

For a 3D detector, we must use 3D simulations, since properties varies with depth.
→ high number of nodes, long CPU time, …
On the other hand, structures may show regular pattern and the elementary cell can be quite small.

Example of 3D layout

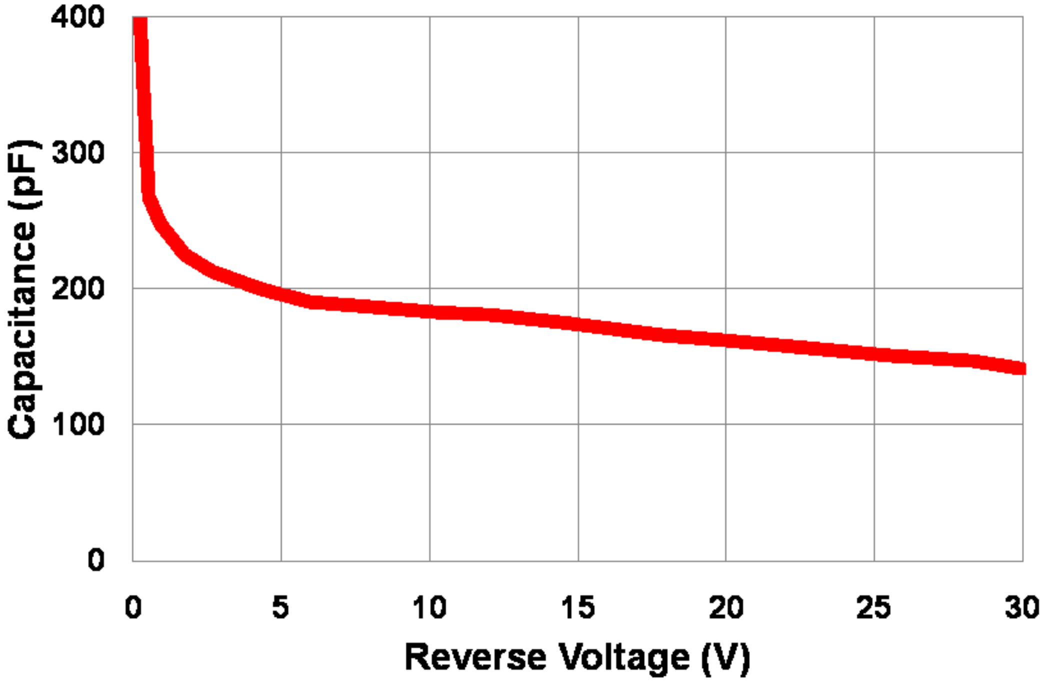
Simulated structure = elementary cell





Example 1. C-V simulation

Capacitance vs V_{bias} of an array of *n* - columns vs *p* - columns (back) of a 3D diode.



C-V curve does not saturate for $V_{bias} > V_{depl}$, like in a standard planar Diode (1D approx),

To understand this effect we simulate:

- elementary cell.
- *p*-spray profile measured with SIMS and inserted in simulation.

From G.-F. Dalla Betta, IEEE NSS 2010, N15-3

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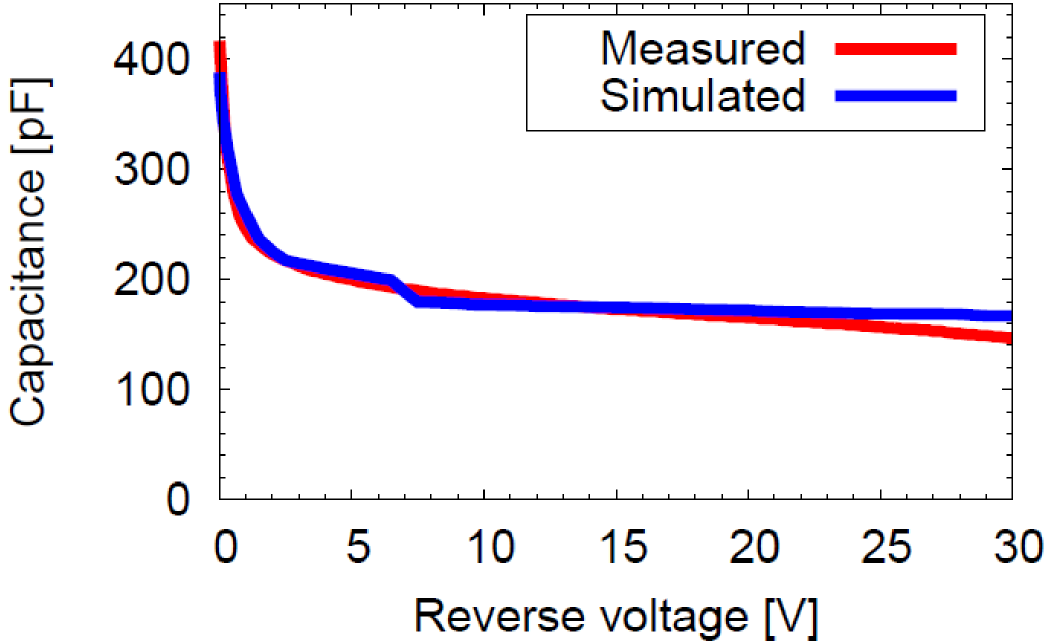

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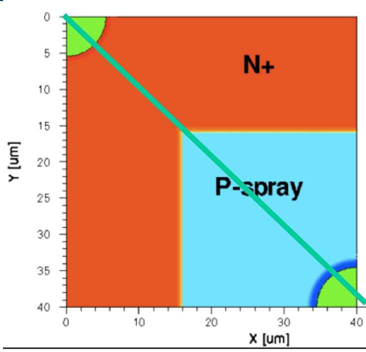
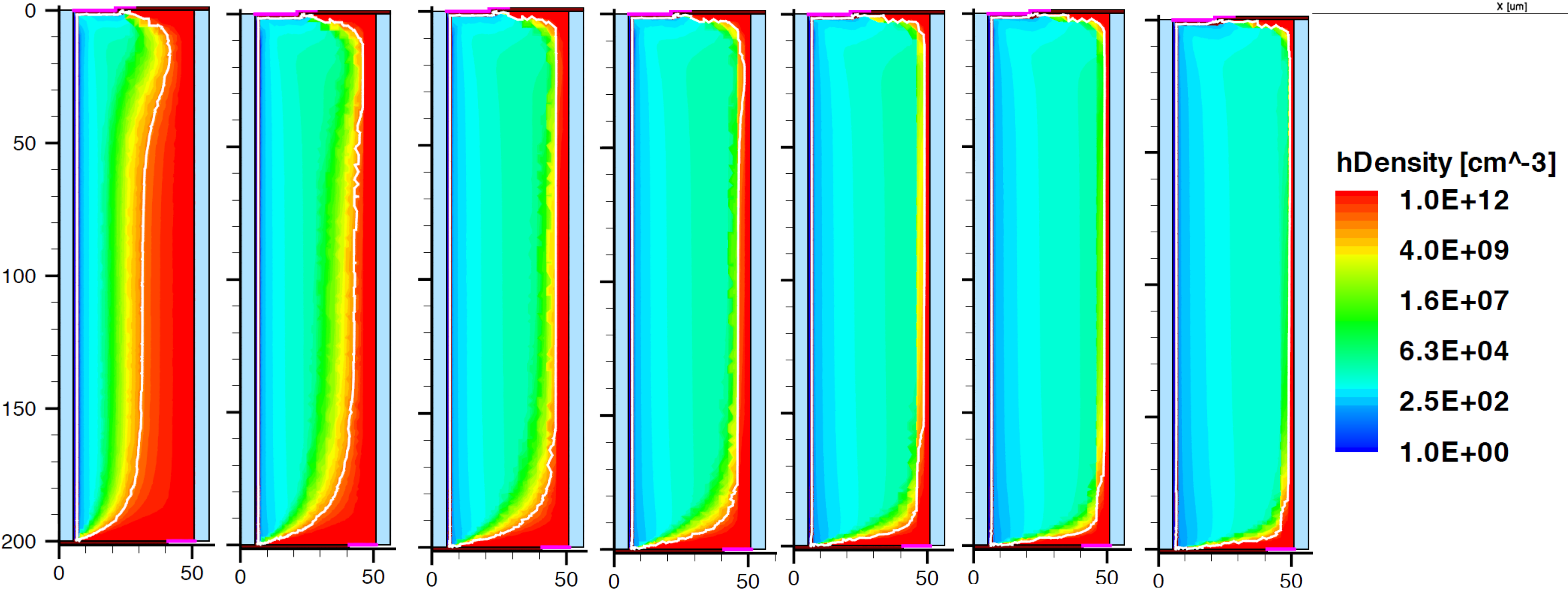
C-V simulation

Hole concentration vs V_{bias}





- At mid-substrate, (hole) depletion already @ V_{bias} = 6 V.
- Important capacitance contribution from *p*-spray which is slowly depleting also at higher voltages.

Example 2. SLIM EDGE

Problem:

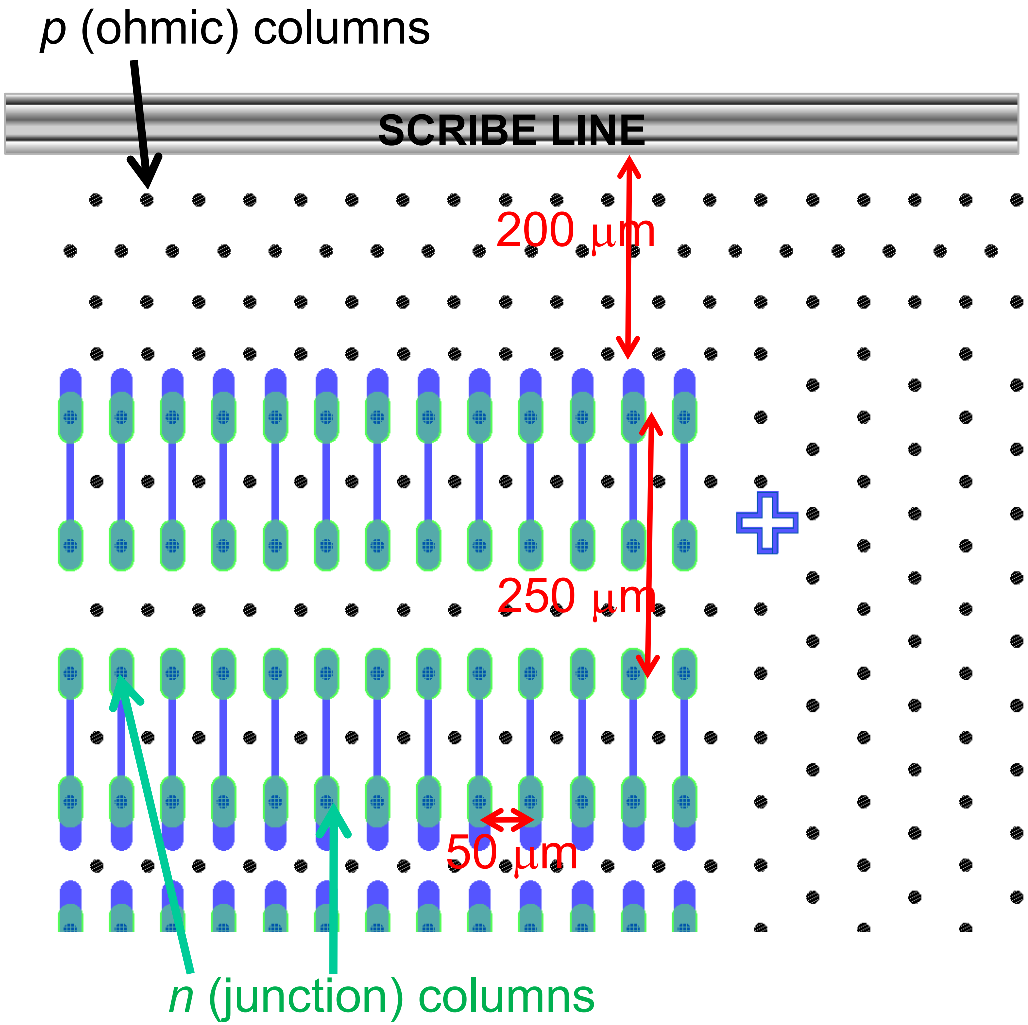
ATLAS IBL requires a max. dead layer of 450 μm along Z for FE-I4 read-out.

Standard Active edge difficult to implement because of support wafer

→SLIM EDGE

- Multiple Ohmic (*p*-col.) fence termination
- Dead area can be as low as~ 200 μm

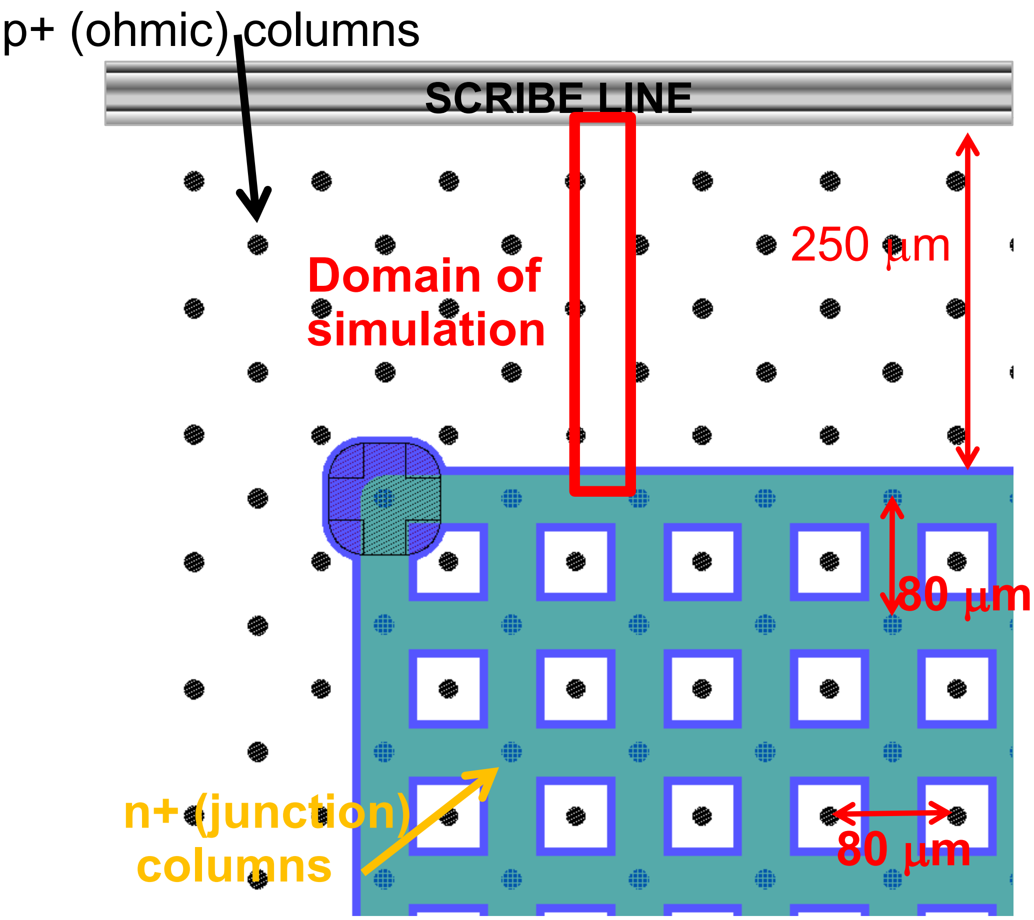
Does it work?

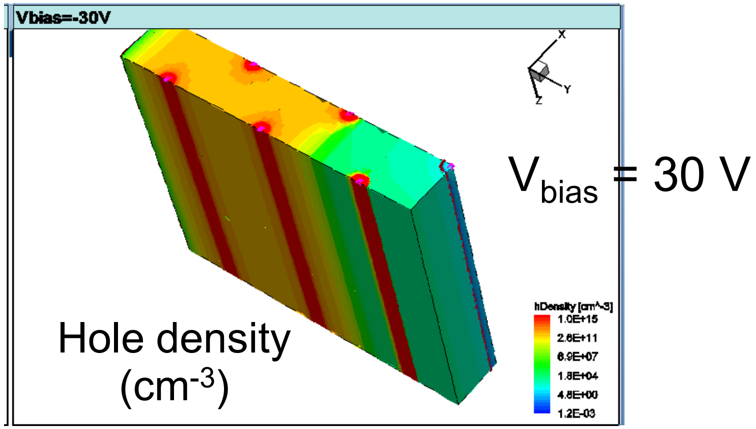


From G. Giacomini, 6th "Trento" WS on 3D and p-type detectors, March 2011

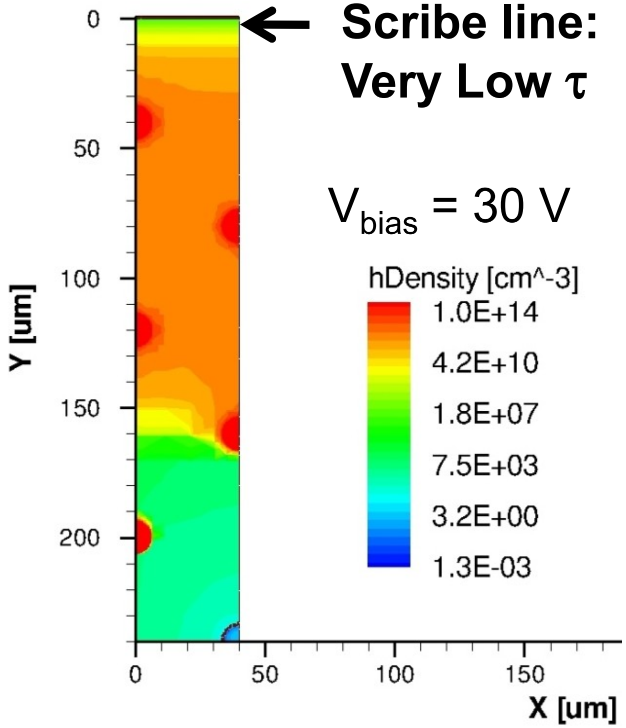
SLIM EDGE

The scribe line is simulated as a low-τ region:
if depletion region touches it → HIGH current!!





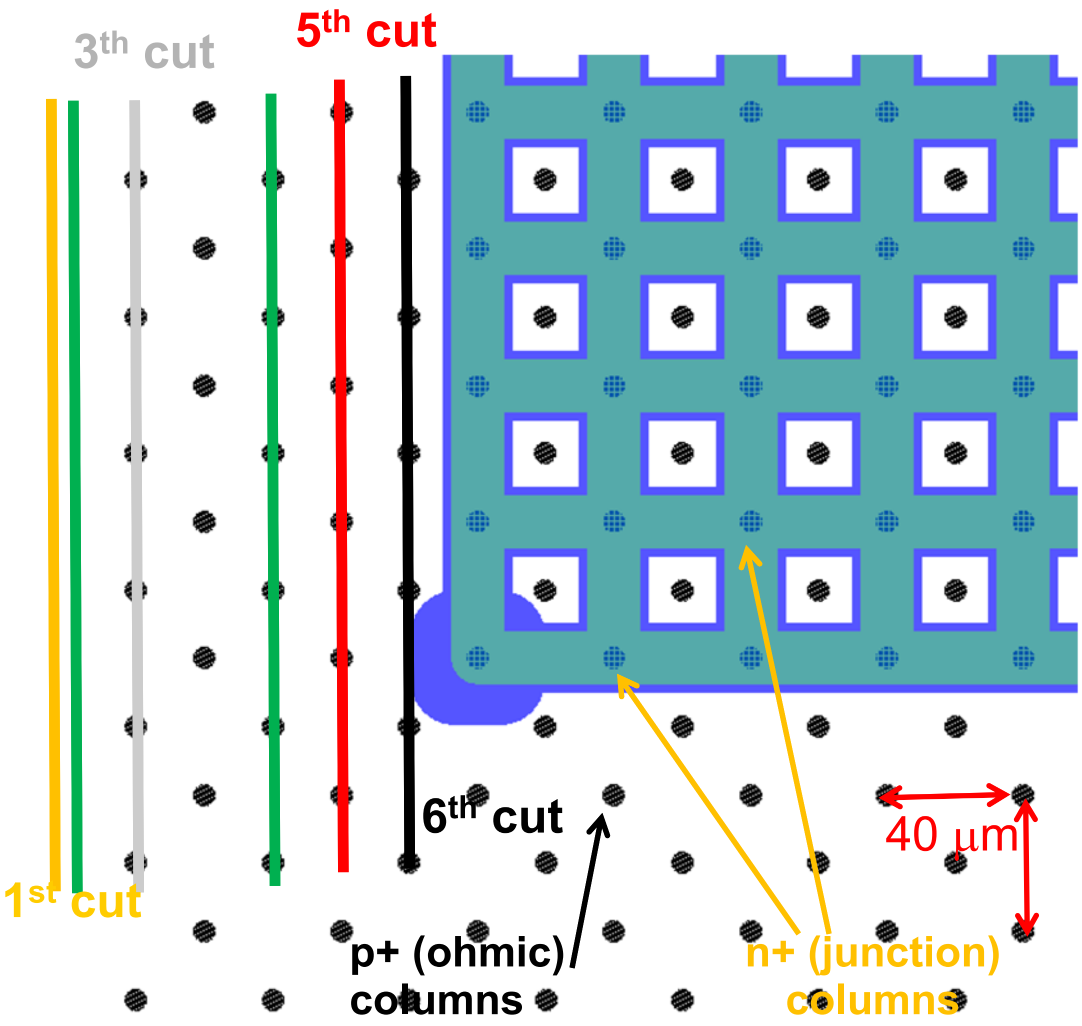
SLICE AT Y = 100 µm

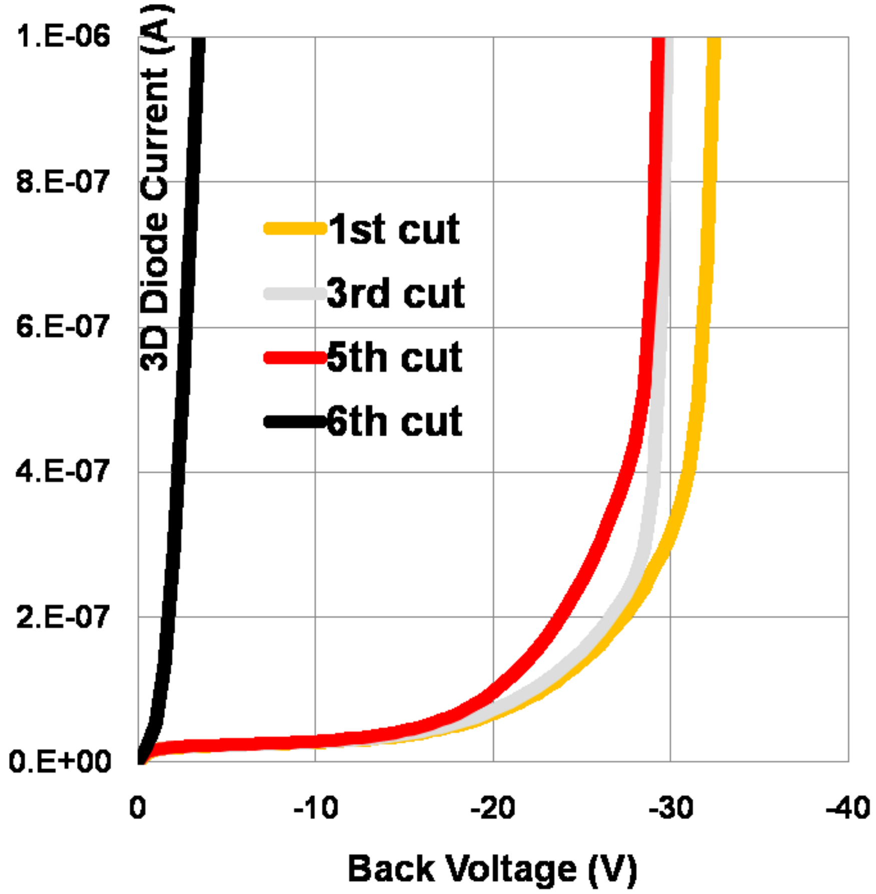


Even for $V_{bias} >> V_{depl}$, depletion region hardly extends beyond second *p*-col row.

SLIM EDGE

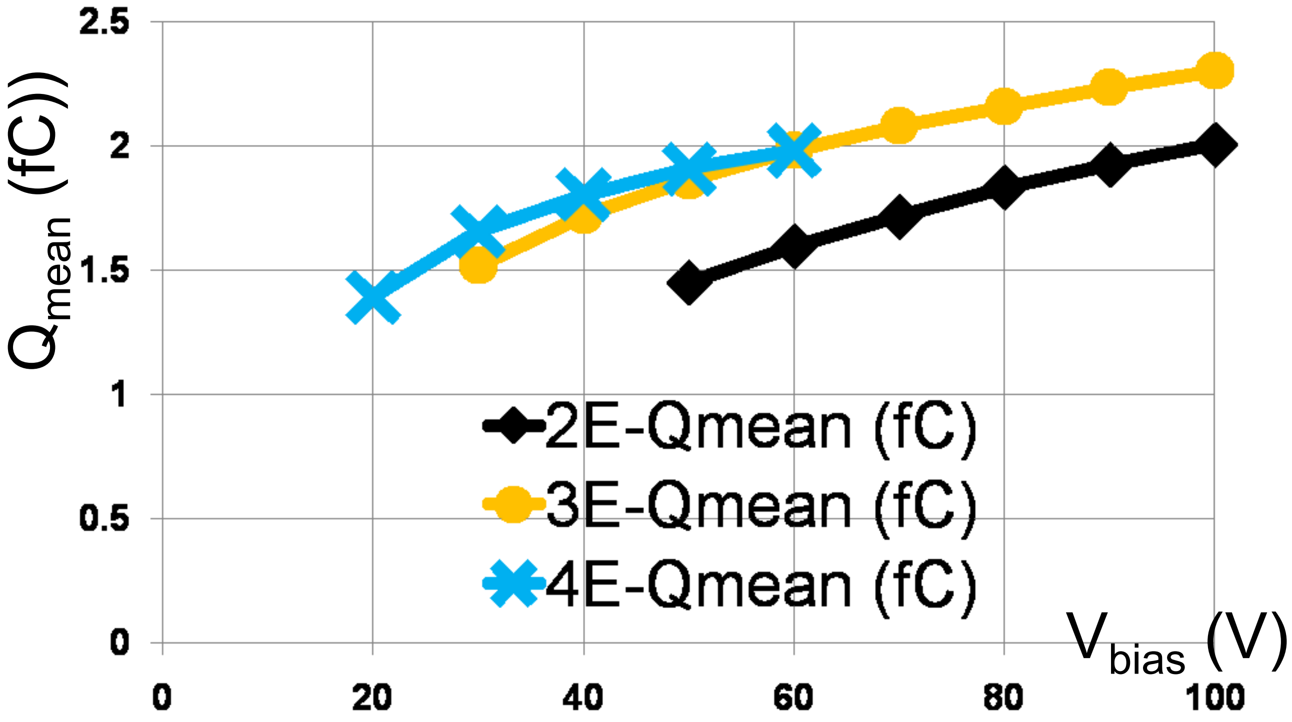
Experimentally, it works:
Dicing away one row at a time and measuring the I-V,
It is shown that one row of ohmic holes is sufficient to “stop” the depletion region



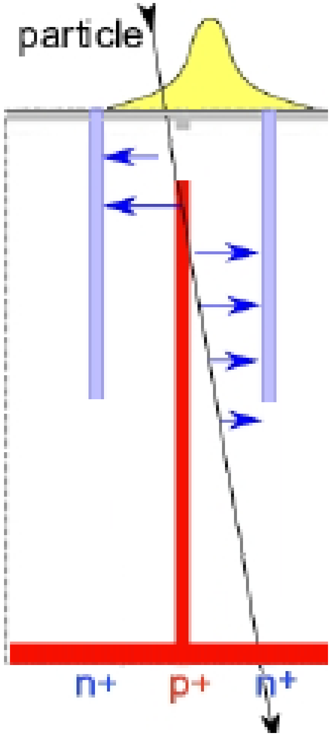


Example 3. Signal from irradiated devices

Old FBK 3D sensor, not full passing columns
proton irradiated @ 1e15 n_{eq}/cm^2



Collimated
Sr source



C. Gallrap et al., "Characterisation of irradiated FBK sensors".
ATLAS 3D Sensor General Meeting, CERN, October 26, 2010.

We want to reproduce this “not intuitive” trend:

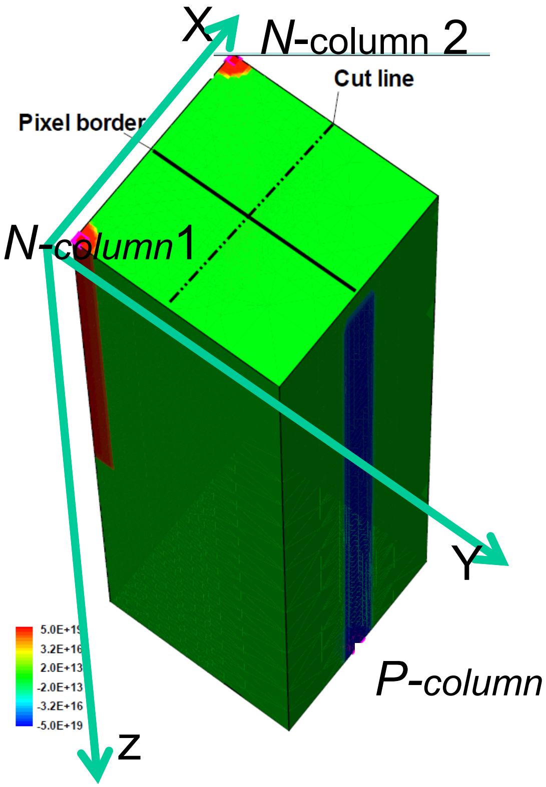
→ 3D is “ideal” only in the columnar overlapping, while only a simulation can predict the collection of electrons generated below the column → fluence dependent

Signal from irradiated devices

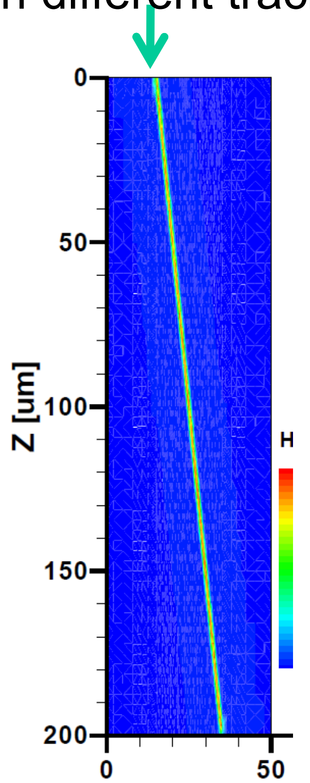
Bulk simulated according to “Perugia” model:
Petasecca TNS 53 (2006) 2971;
Pennicard NIM A 592 (2008) 16–25

Type	Energy (eV)	Defect	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	$E_C - 0.42$	VV	$9.5\ 10^{-15}$	$9.5\ 10^{-14}$	1.61
Acceptor	$E_C - 0.46$	VVV	$5.0\ 10^{-15}$	$5.0\ 10^{-14}$	0.9
Donor	$E_V + 0.36$	C_iO_i	$3.23\ 10^{-15}$	$3.23\ 10^{-14}$	0.9

To simulate the charge sharing:
→ double the elementary cell

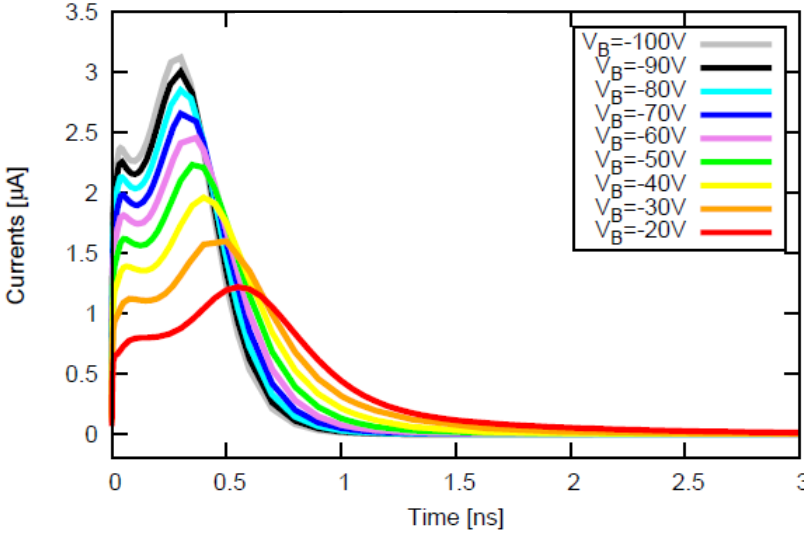


m.i.p. crossing the bulk simulated with
uniform charge release (80 pairs/μm)
and with different track angles

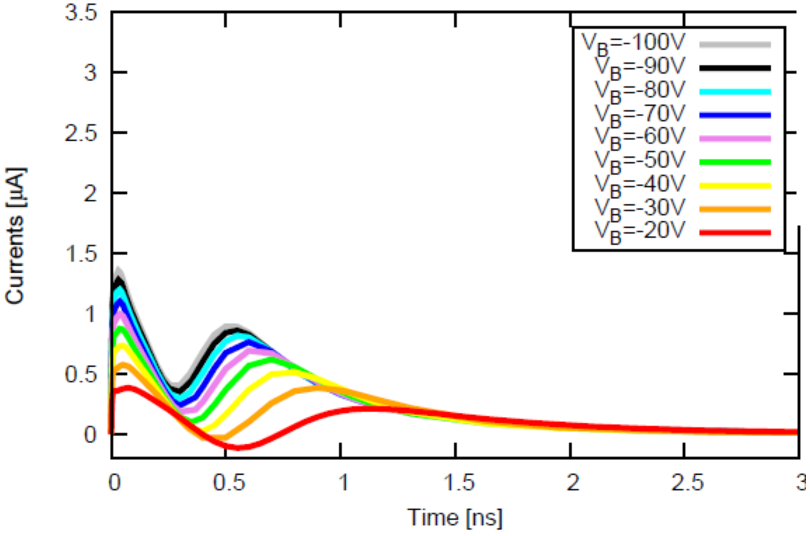


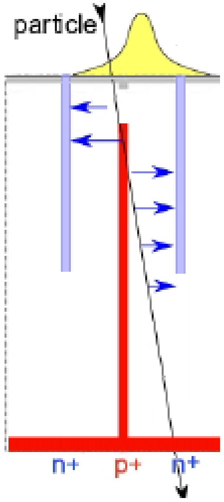
Signal from irradiated devices

Column N1- signals



Column N2- signals

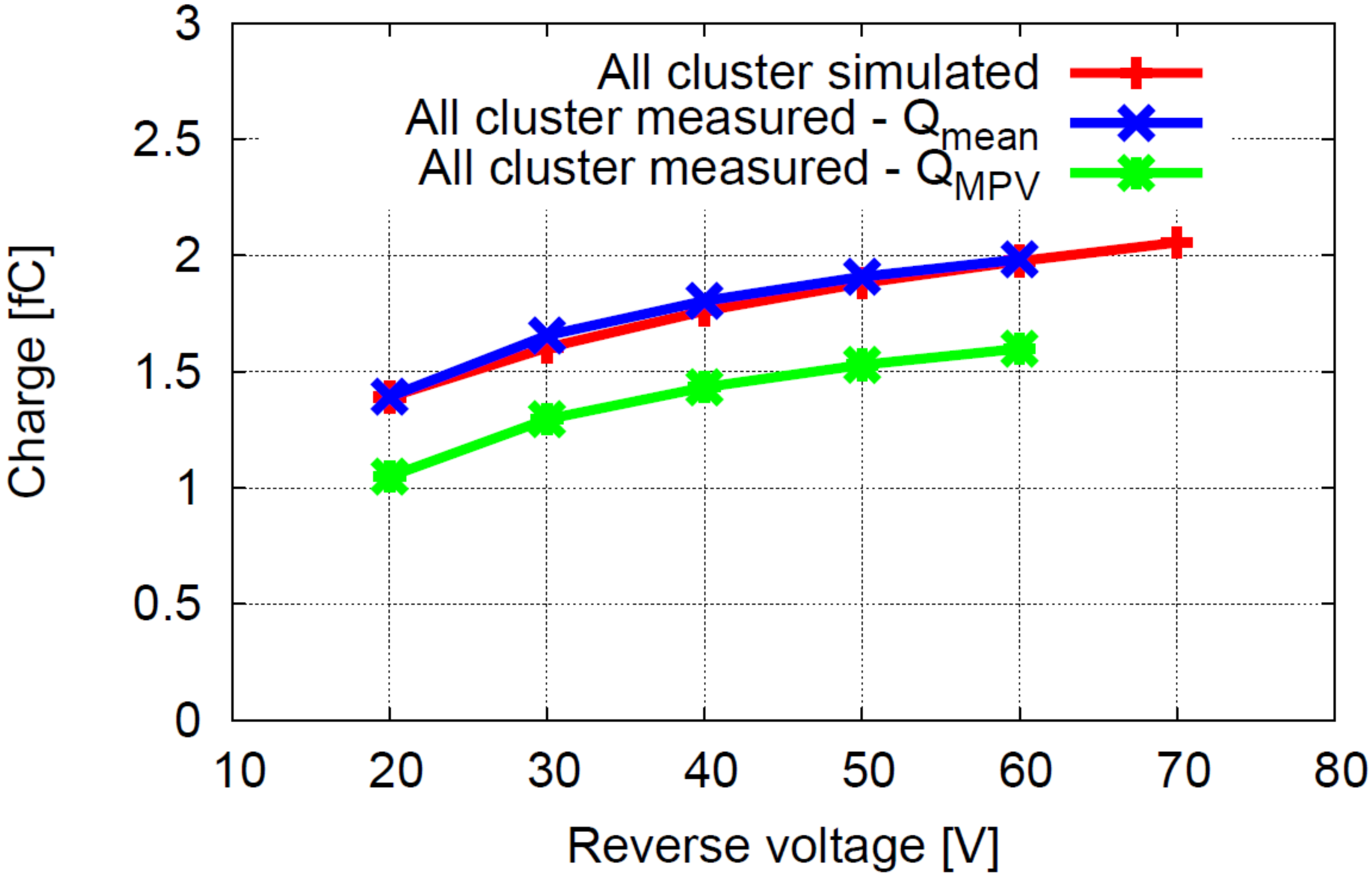




Integrals of currents (= total collected Charge) saturate before 20 ns (no ballistic deficit for ATLAS ROC) and at a value exceeding the threshold of 3200 e- (0.5 fC) (ATLAS threshold)

Signal from irradiated devices

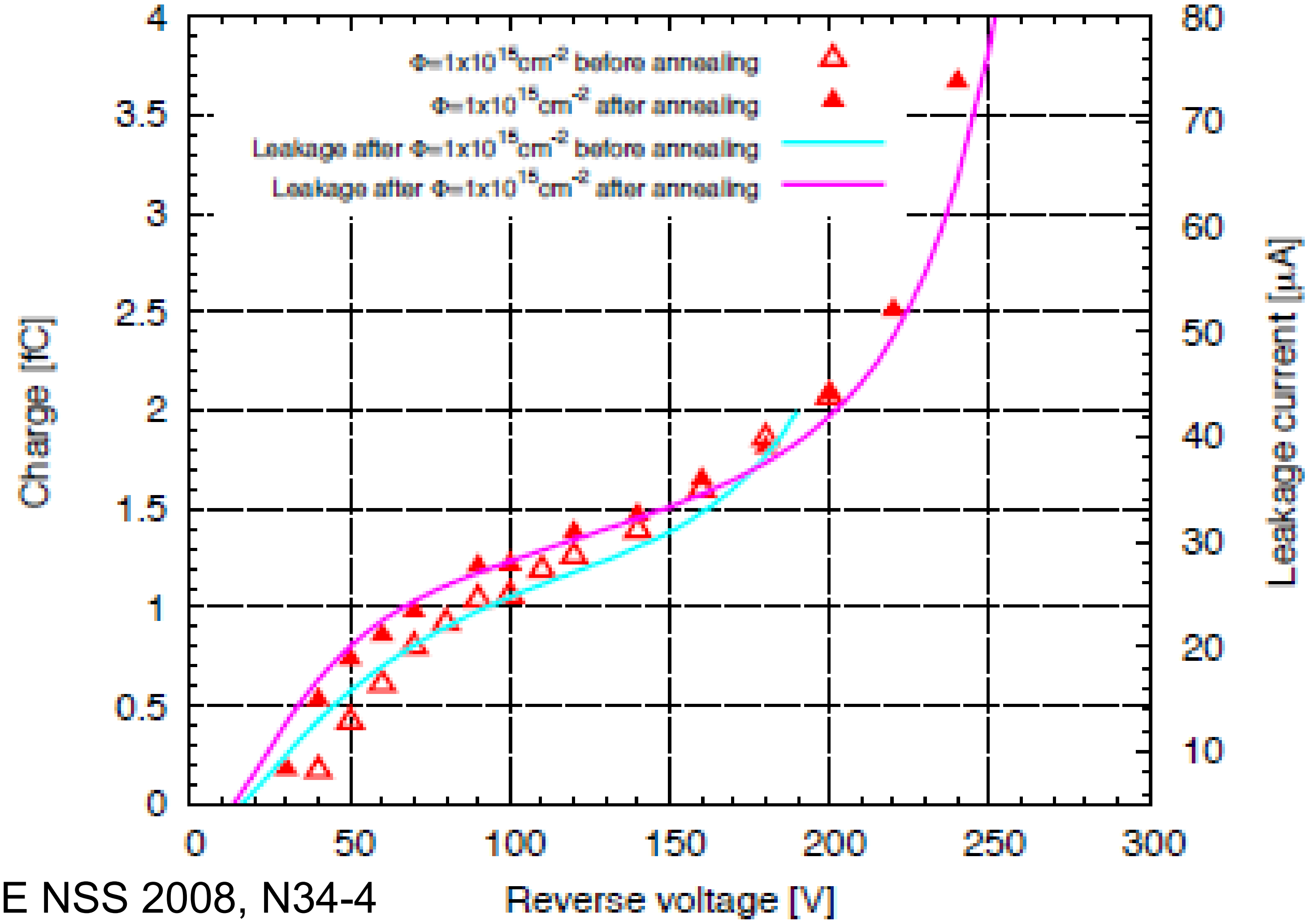
Simulating Cluster size 1 vs Bias voltage and
Simulating Cluster size 2 vs Bias voltage (for few impinging points) and
weighting the simulated results with geometrical/experimental considerations,
we get a simulated curve of the total charge vs V_{bias}, which fits well the irradiation experiment results.



Example 4. Multiplication effects work in progress!

In an irradiated p-on-n strip sensor (Φ= 1e15 n_{eq}/cm^2), already at ~ 150 V, CCE vs V plots shows an anomalous increase of IV and CCE-V.

It is believed that this effect comes from impact ionization

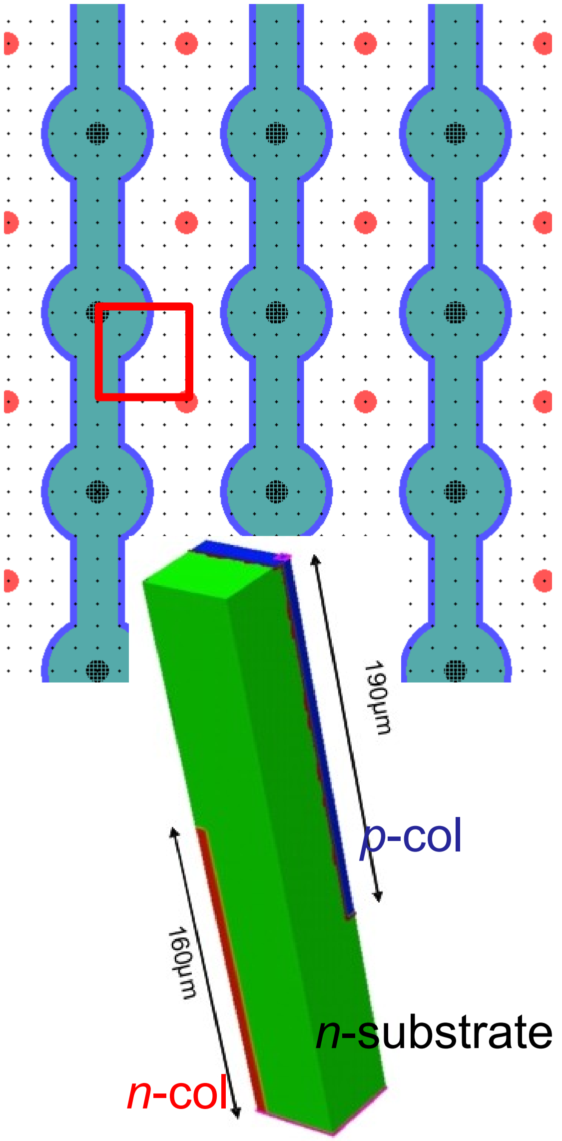


A. Zoboli, IEEE NSS 2008, N34-4

Multiplication effects

work in progress!

irradiated – Φ=1e15 n_{eq}
strip sensor *p*-on-*n*



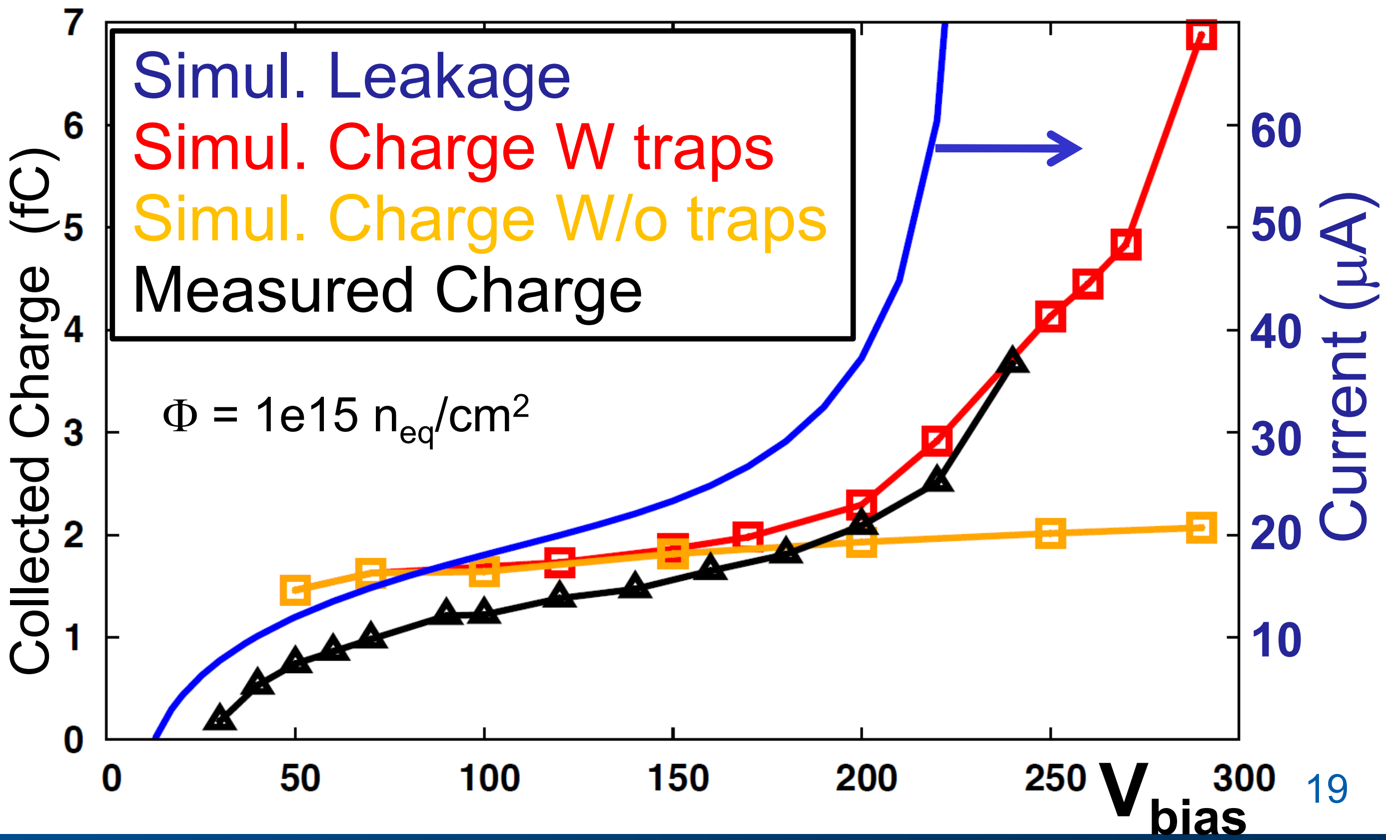
Simulating multiplication with:

- impact ON
- effective bulk doping/oxide charge

→ no multiplication

- impact ON and
- traps from “Perugia” model

→ MULTIPLICATION close to the measured one



CONCLUSIONS

Simulations of 3D are fundamental
because of the complexity of the device.

Different geometries & different Models must be chosen according to the simulation

We showed that simulations are useful both at the design stage as well as to understand peculiar effects.