Update on TCAD simulations of heavily irradiated 3D pixels

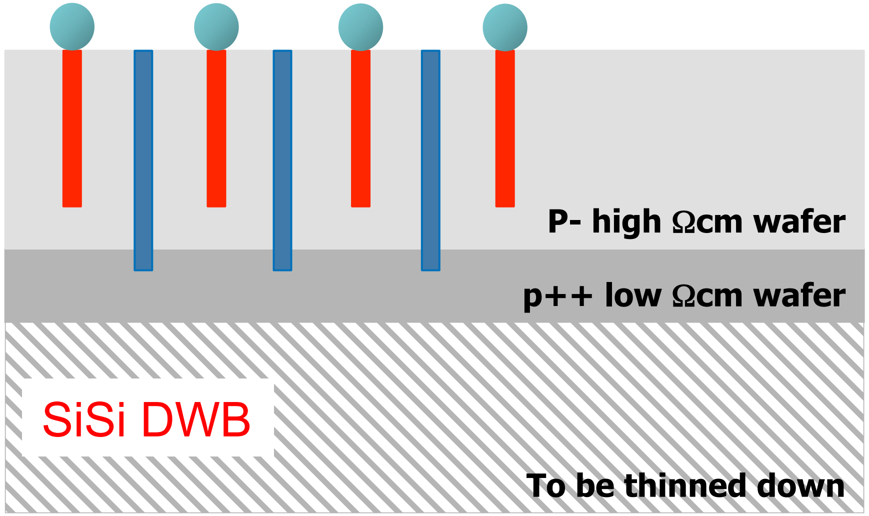
Gian-Franco Dalla Betta,
Roberto Mendicino, DMS Sultan

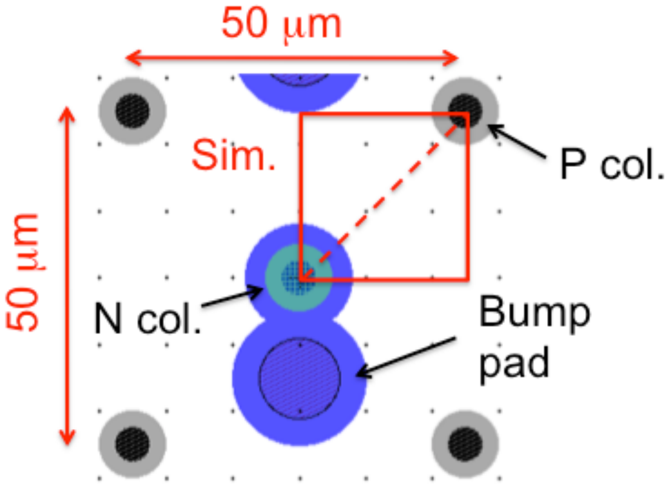
University of Trento and TIFPA INFN, Trento, Italy
gianfranco.dallabetta@unitn.it

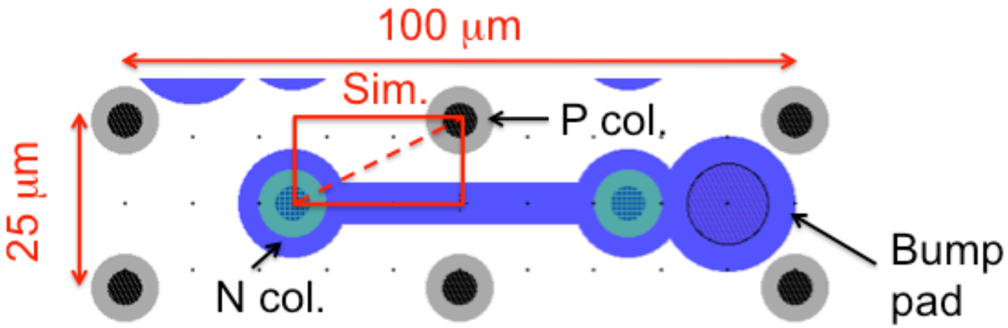
- D7.1 : Simulation of 3D pixel sensor cells [M18] Simulation of new sensor cells for thin 3D sensors with fine pitch, reduced column diameter and inter-column distance. Simulation of charge collection properties of 3D sensors with thinner substrates and determination of optimal thickness for pixel detectors working at HL-LHC. (Task 7.2)
- 1st year summary, work in progress and next steps

New thin 3D on 6” @ FBK

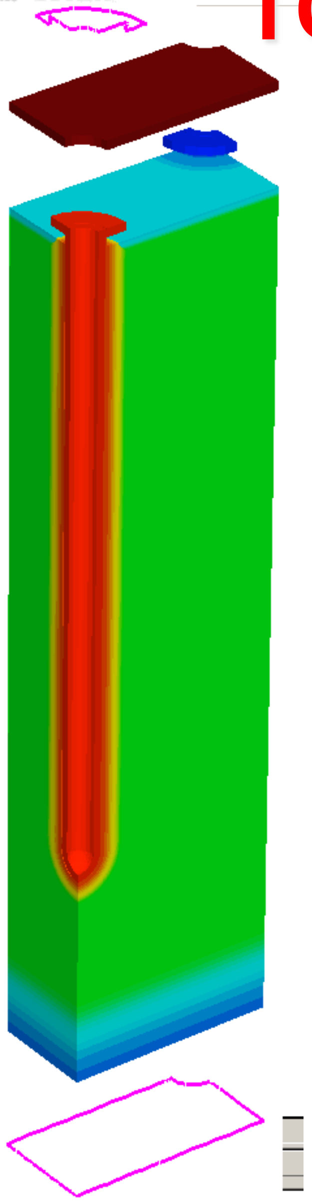
- Single-sided process
- “Thin” active layer: SiSi (or SOI)
- Ohmic columns depth > active layer
- Junction columns depth < active layer
- Reduction of column diameter to 5 um
- Holes partially filled with poly
- Very slim or active edge

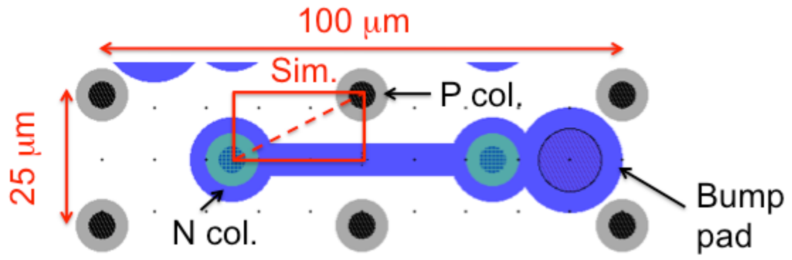




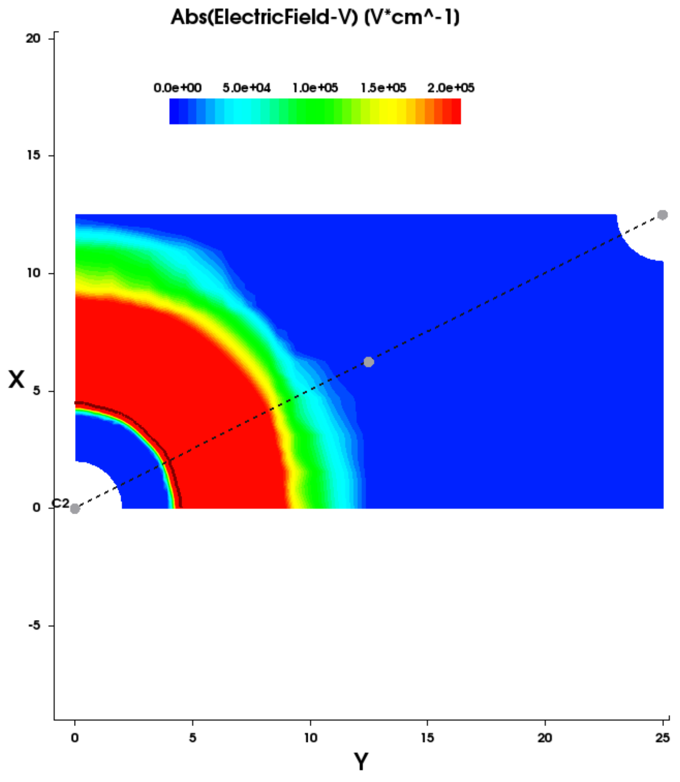


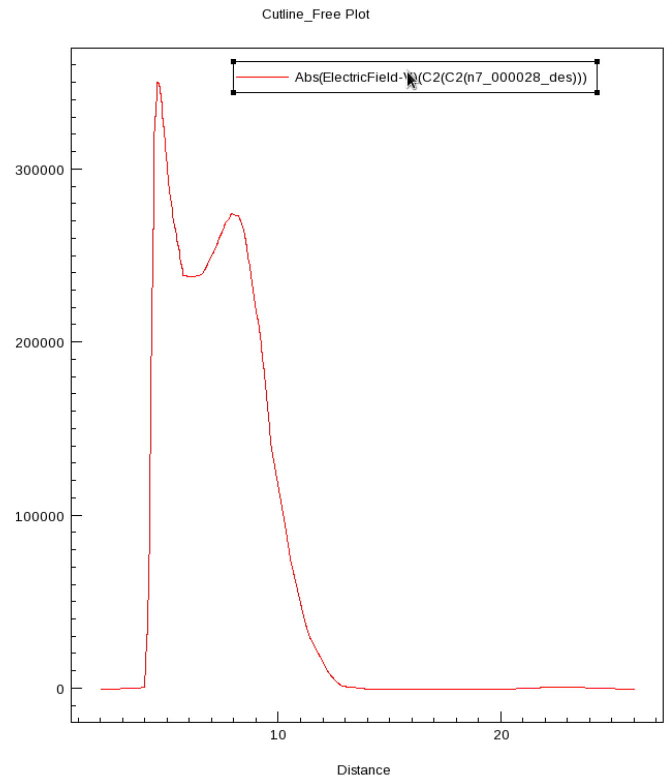
TCAD Simulations: full 3D approach





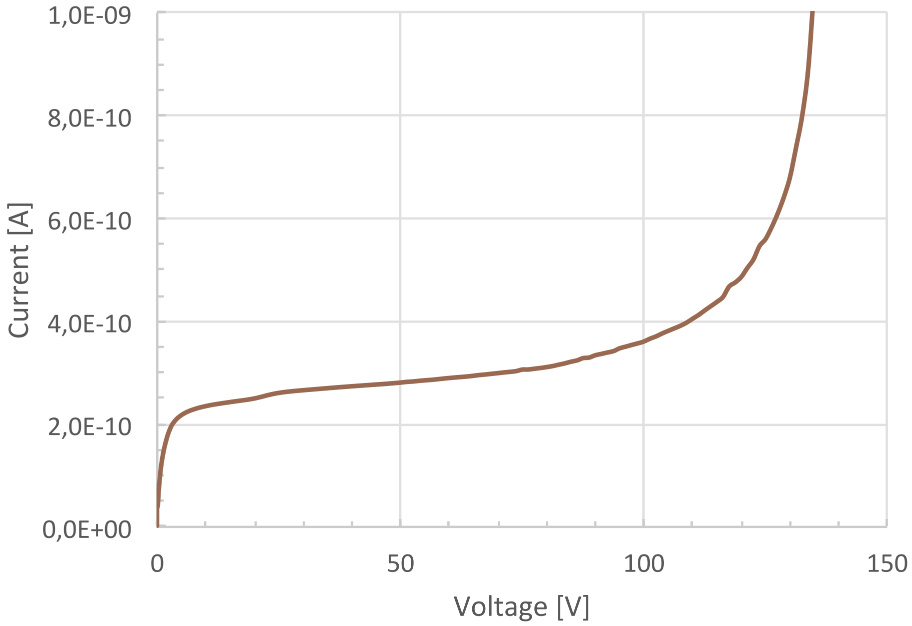
- Domain: 1/8 of pixel
- Thickness: 100um
- n^+ column depth 75um
- All technological details



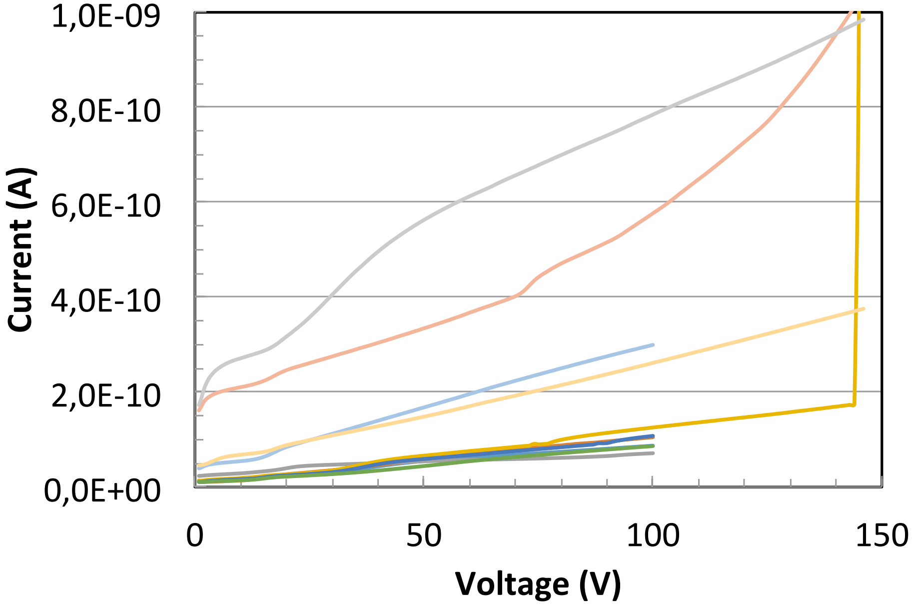


TCAD Simulations: I-V curves

Simulation

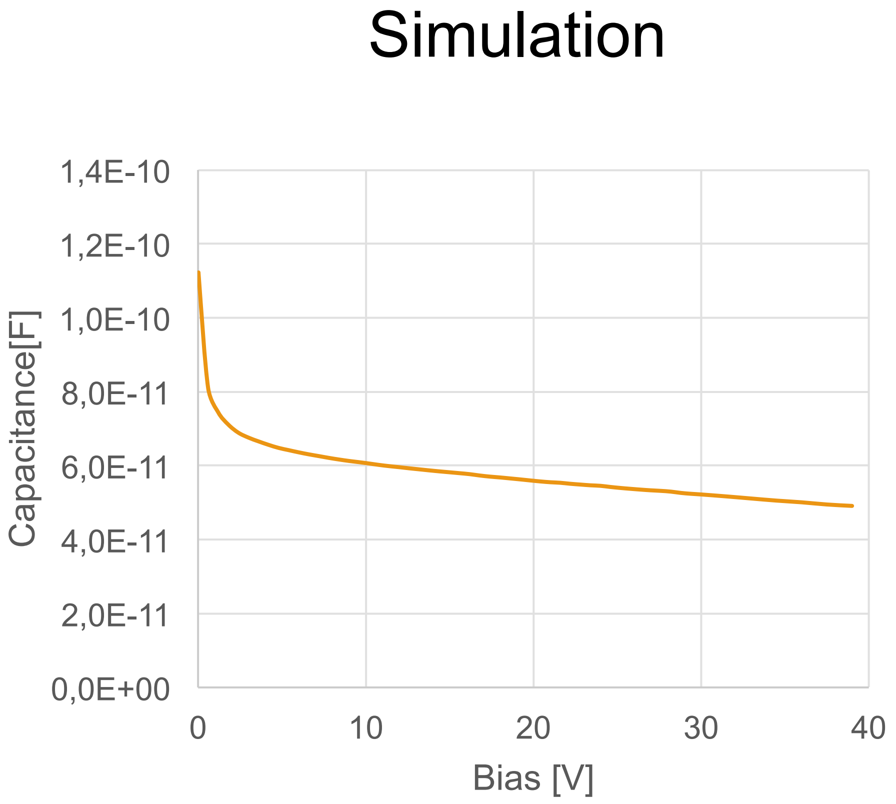


Measurements

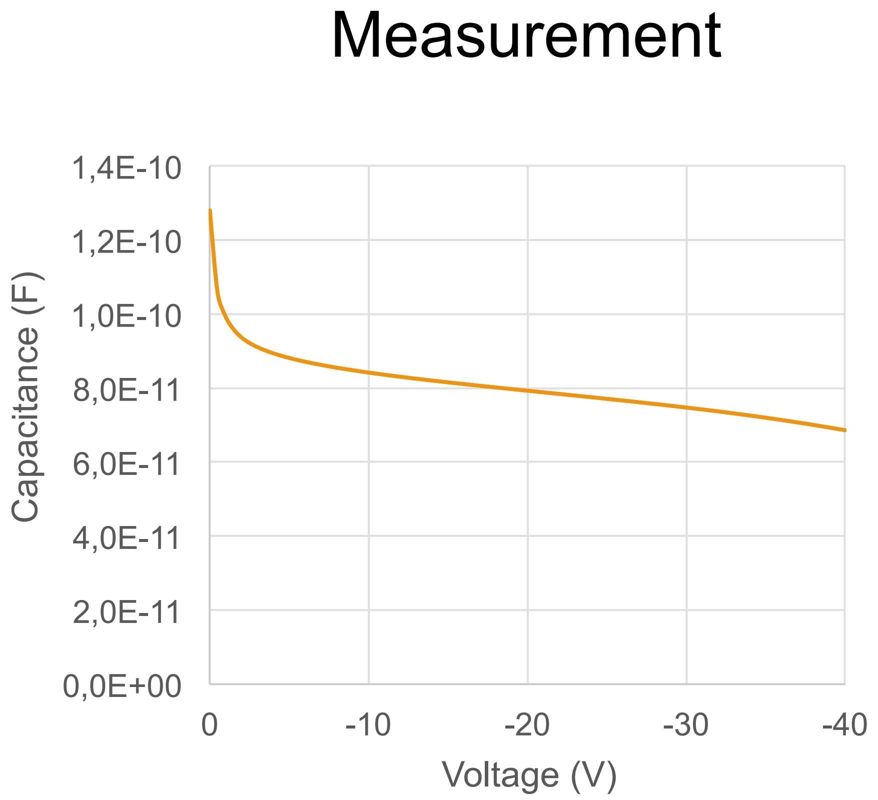


Good agreement for the breakdown voltage, whereas the I-V shape could be improved by better description of surface state effects

TCAD Simulations: C-V curves



Simulation



Measurement

Very good agreement (some parasitics, e.g., from probing pads and diode periphery, not included in the simulation)

Radiation damage model

3-trap level "Perugia" Bulk model: M. Petasecca et al., IEEE TNS 53-5 (2006) 2971

"NEW": parameters as in D. Passeri et al., NIMA 824 (2016) 443

Defect	**E (eV)**	**σ_e (cm²)**	**σ_h (cm²)**	**η (cm⁻¹)**
Acceptor	E_c-0.42	$1.0\text{x}10^{-15}$	$1.0\text{x}10^{-14}$	1.6
Acceptor ($\phi \leq 7\text{x}10^{15}$ cm^{-2})	E_c-0.46	$7.0\text{x}10^{-15}$	$7.0\text{x}10^{-14}$	0.9
Acceptor ($7\text{x}10^{15}$ cm$^{-2} \leq \phi \leq 2.2\text{x}10^{16}$ cm^{-2})	E_c-0.46	$3.0\text{x}10^{-15}$	$3.0\text{x}10^{-14}$	0.9
Donor	E_v+0.36	$3.23\text{x}10^{-13}$	$3.23\text{x}10^{-14}$	0.9

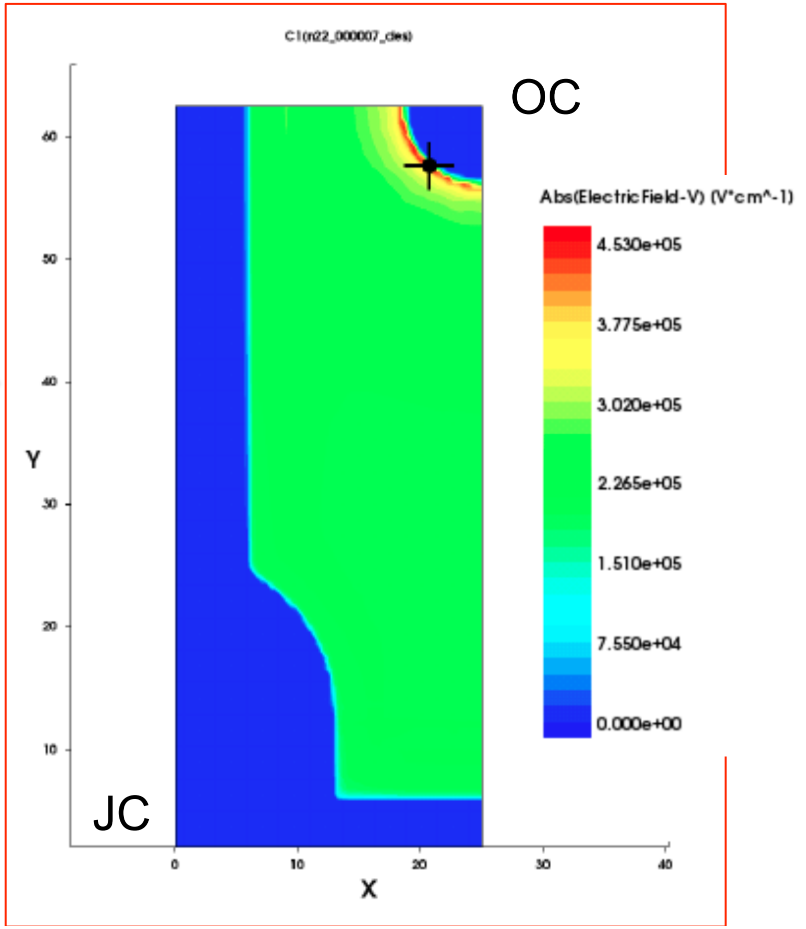
Surface damage model: F. Moscatelli et al., IEEE NSS 2015

Defect	**E (eV)**	**Concentration**
Acceptor	E_c-0.4	40% of acceptor Nit (Nit=0.8 Nox)
Acceptor	E_c-0.6	60% of acceptor Nit (Nit=0.8 Nox)
Donor	E_v+0.6	100% of donor Nit (Nit=0.8 Nox)

Surface isolation and breakdown

Collaboration with Perugia/Bologna and Udine (G. Giugliarelli)

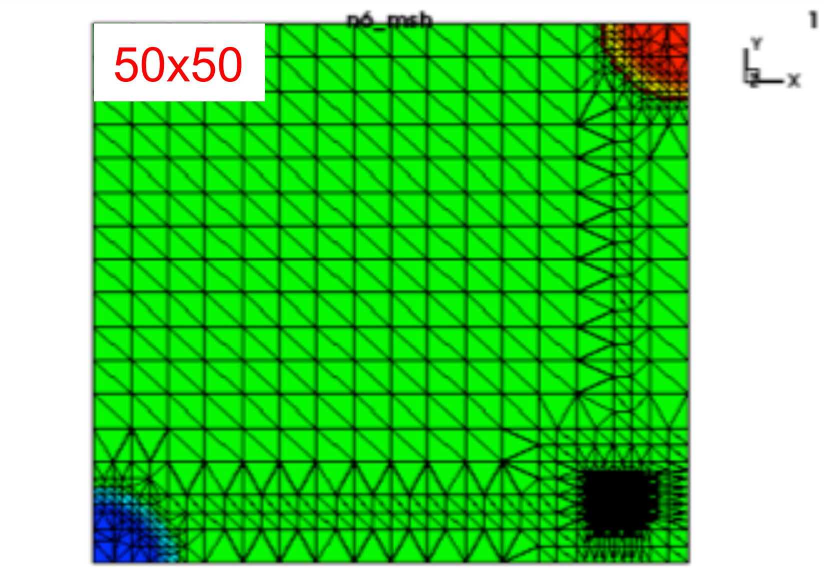
- Applying “Perugia” surface model to irradiated 3D diodes from the IBL production for validation
- At relatively low oxide charge densities ($<10^{12}$ cm^{-2}) good agreement with measured breakdown voltage value (and position)
- At larger oxide charge densities ($\sim 1.5 \times 10^{12}$ cm^{-2}), loss of surface isolation and related error in breakdown voltage prediction
- Need for further parameter tuning before reliable usage for highly irradiated sensor simulation

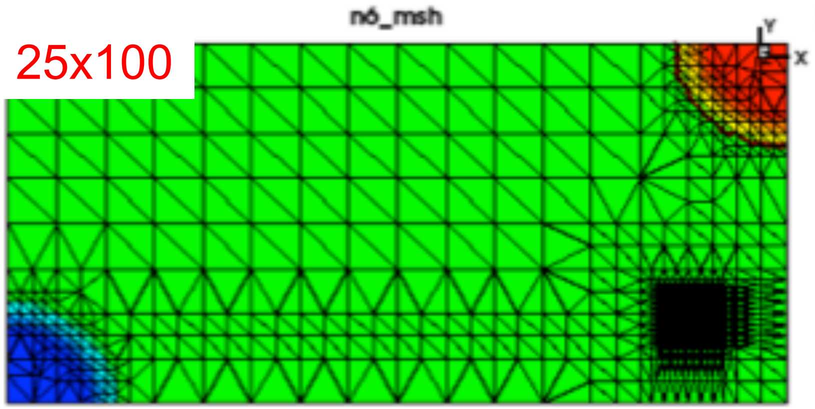


CCE simulation approach

- Simplified simulation domain (~2d):

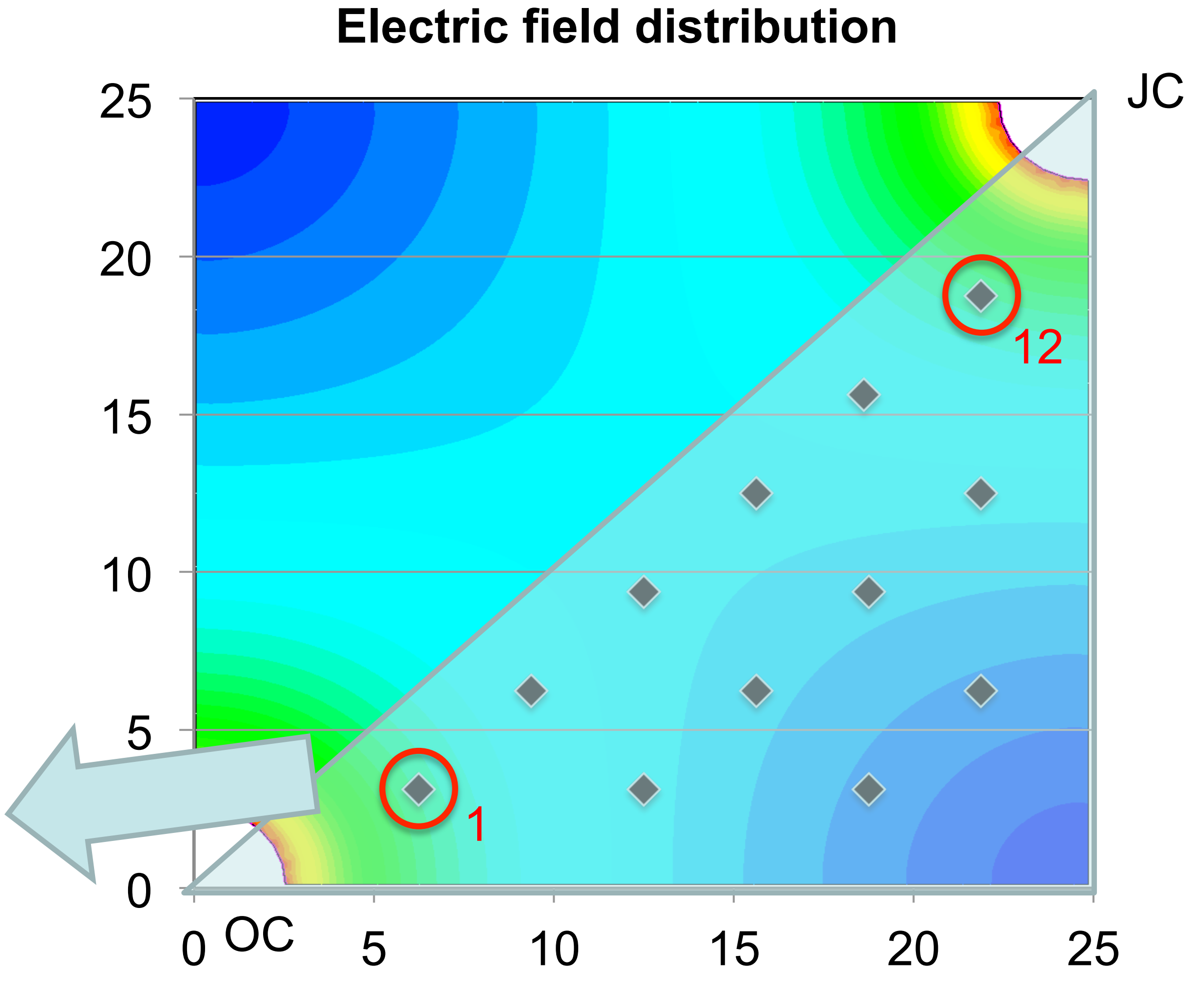
  1 μm thick slice (1/4 or 1/8 of pixel)
- MIP (heavy ion model): vertical hits at several different positions representing different electric field values
- New Perugia radiation damage model
- Avoiding boundaries: no charge sharing
- Subtract leakage current
- 20-ns integration of current signals
- Average charge over all hit positions
- Normalization to injected charge
- Repeat at different bias voltage


50x50


25x100

Simulation points for “50x50” geometry

Pos	x	y
1	6.25	3.125
2	18.75	3.125
3	9.375	6.25
4	15.625	6.25
5	21.875	6.25
6	18.75	9.375
7	18.625	15.625
8	21.875	18.75
9	12.5	3.125
10	12.5	9.375
11	15.625	12.5
12	21.875	12.5

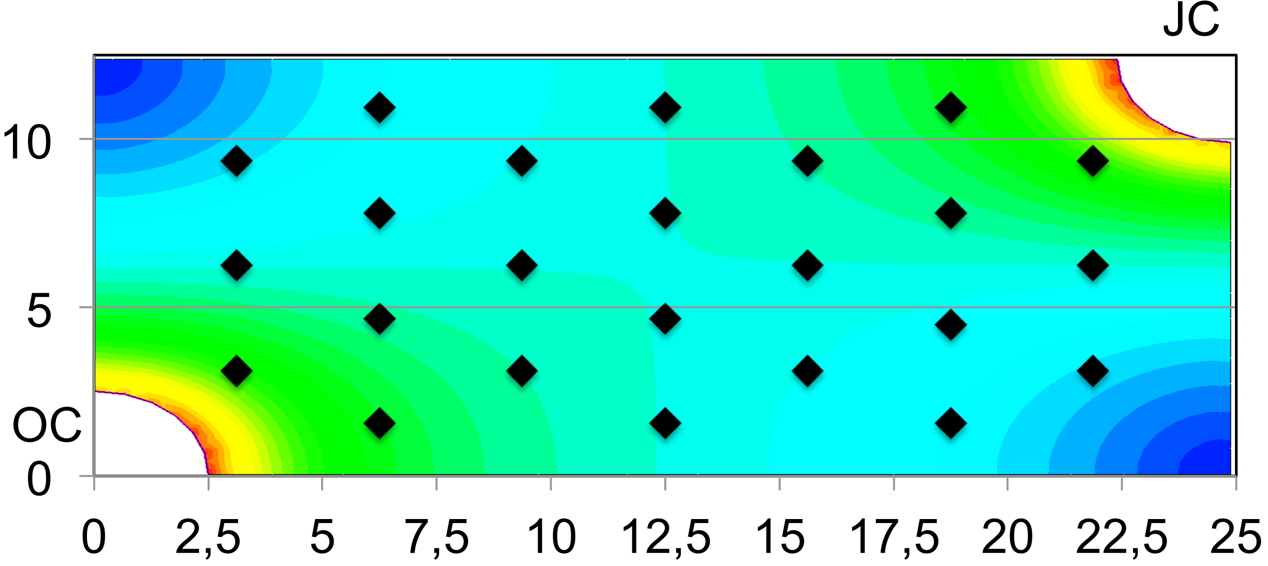


Due to the symmetry it is possible to use half the simulation domain

Simulation points for "25x100" geometry

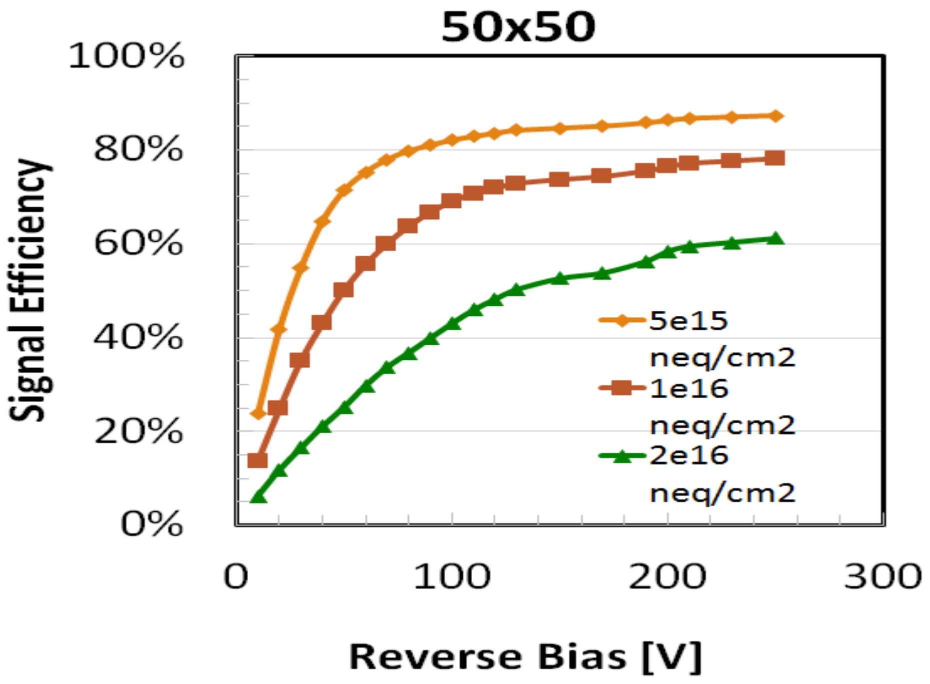
Pos	X	Y
1	6.25	1.5625
2	18.75	1.5625
3	3.125	3.125
4	9.375	3.125
5	15.625	3.125
6	21.875	3.125
7	6.25	4.6875
8	18.75	4.4875
9	6.25	7.8125
10	18.75	7.8125
11	3.125	9.375
12	9.375	9.375
13	15.625	9.375
14	21.875	9.375
15	6.25	10.9375
16	18.75	10.9375
17	3.125	6.25
18	12.5	1.5625
19	12.5	4.6875
20	12.5	7.8125
21	12.5	10.9375
22	21.875	6.25
23	9.375	6.25
24	15.625	6.25

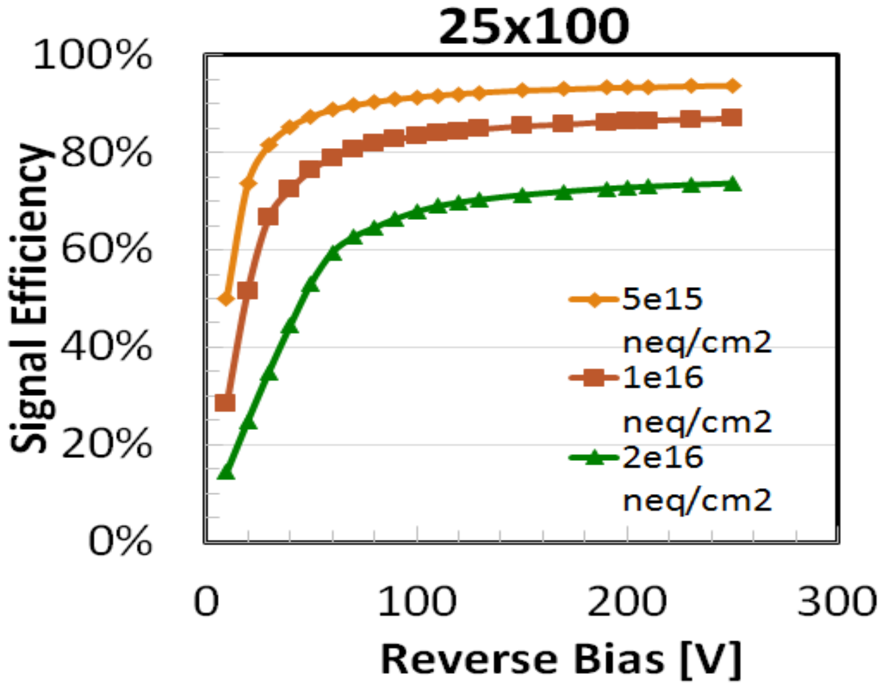
Electric field distribution



In this case it is not possible to use the symmetry principle. The domain is 1/8 of pixel

Average Signal Efficiency

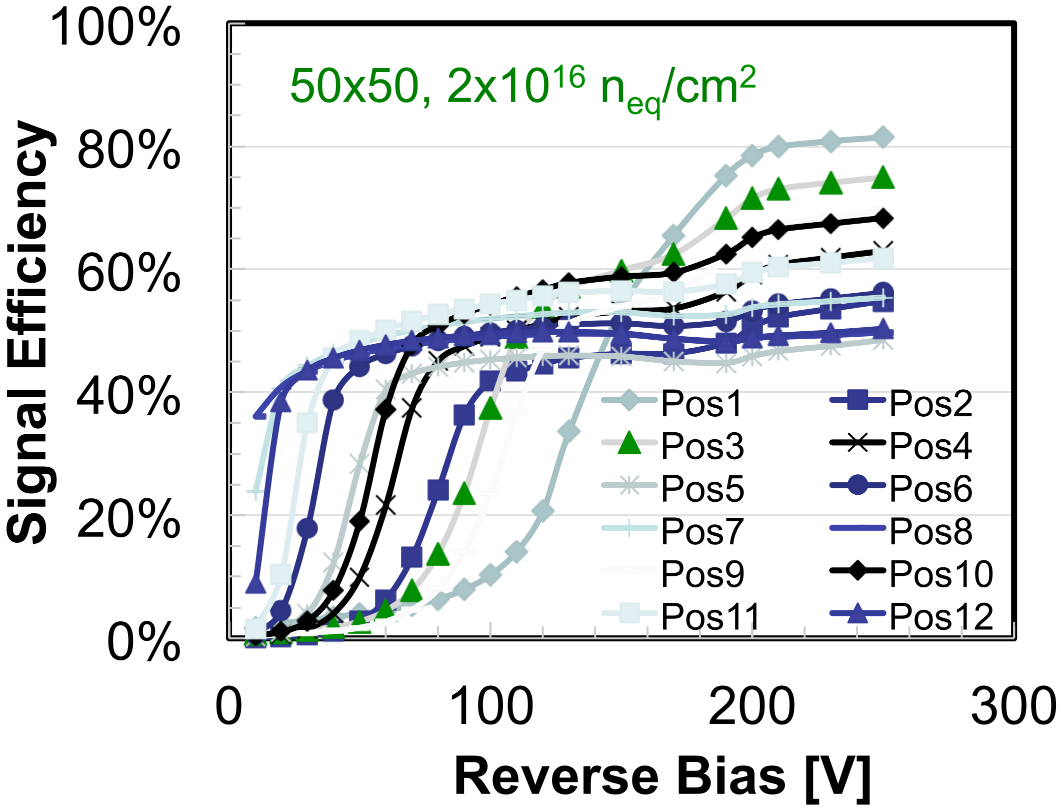


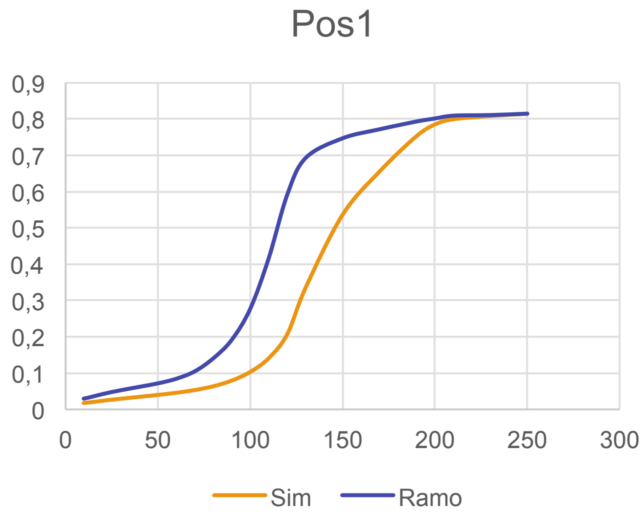


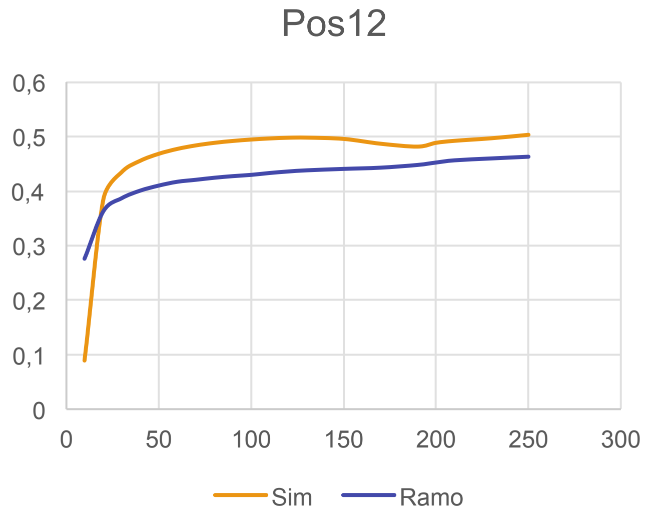
- Very high average signal efficiency
- True values will be smaller due to pixel edge effects
- Significant variations of signal efficiency with hit position, increasing with fluence …

Position dependent Signal Efficiency

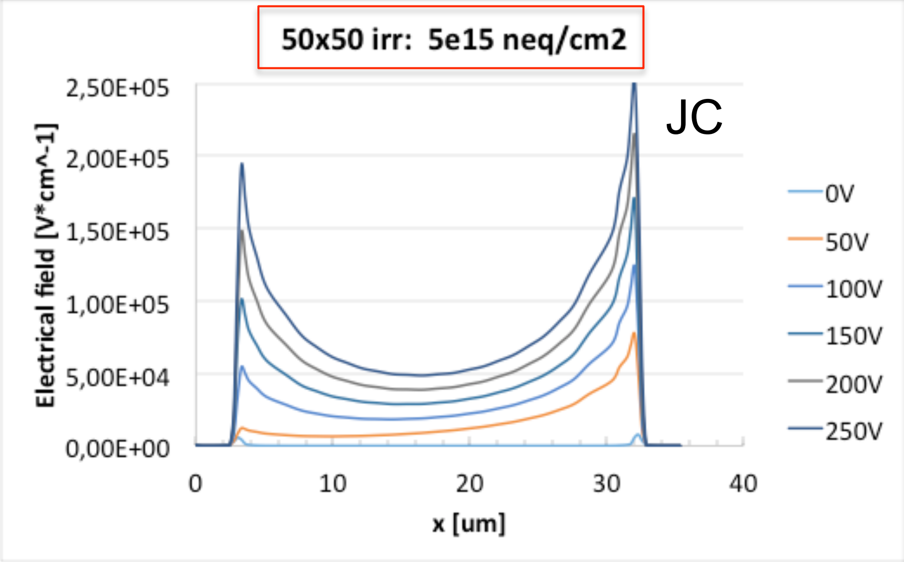
- SE vs Voltage shows different trends for different hit points
- Explained by Ramo’s theorem

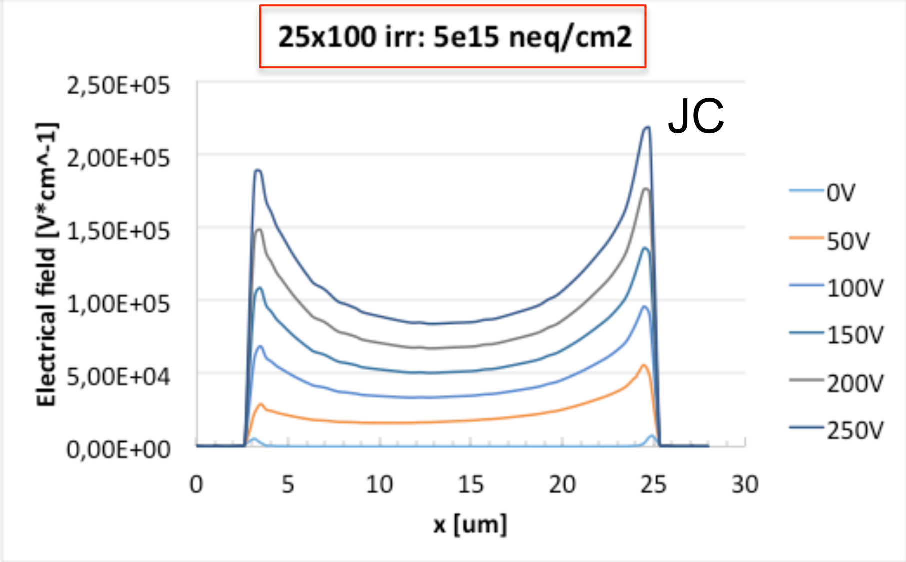


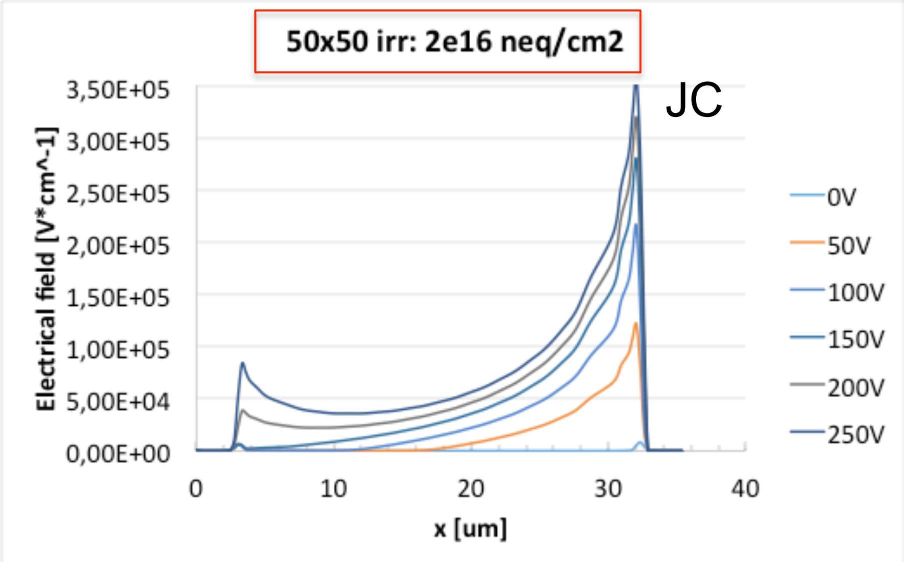


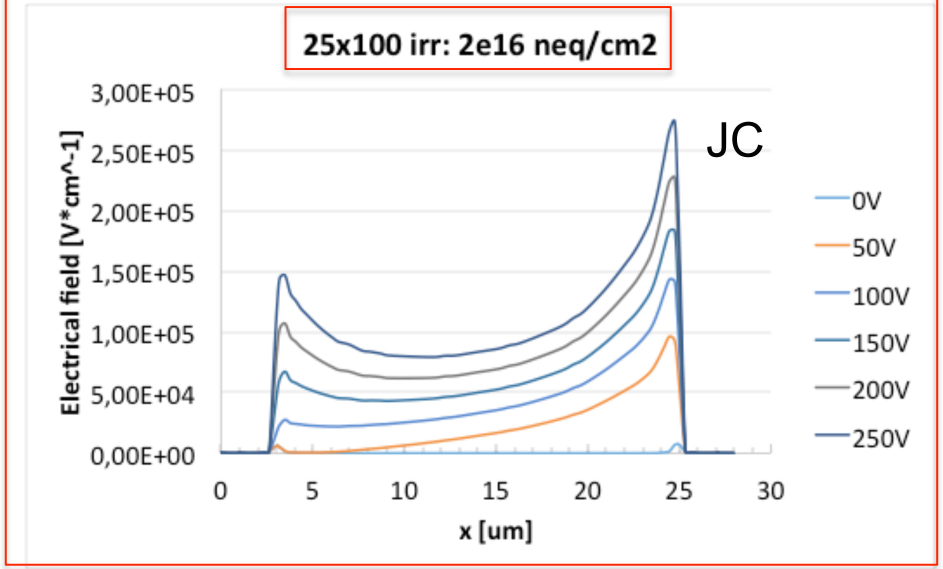


Electric field 1d comparison

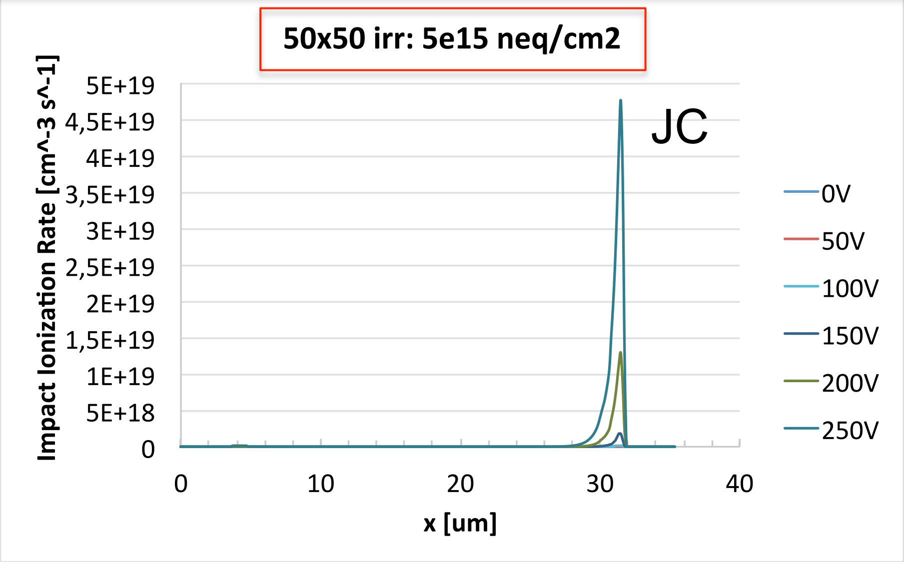

50x50 irr: 5e15 neq/cm2

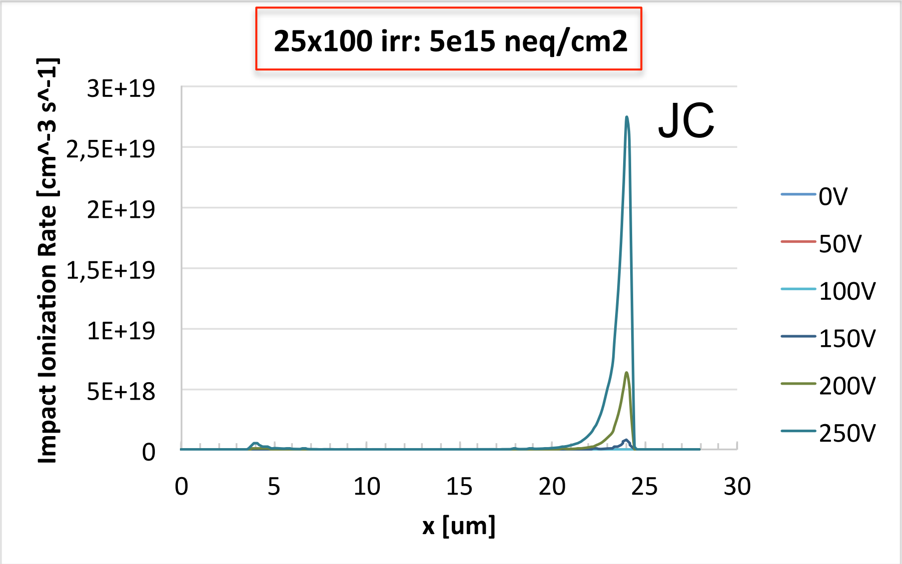

25x100 irr: 5e15 neq/cm2

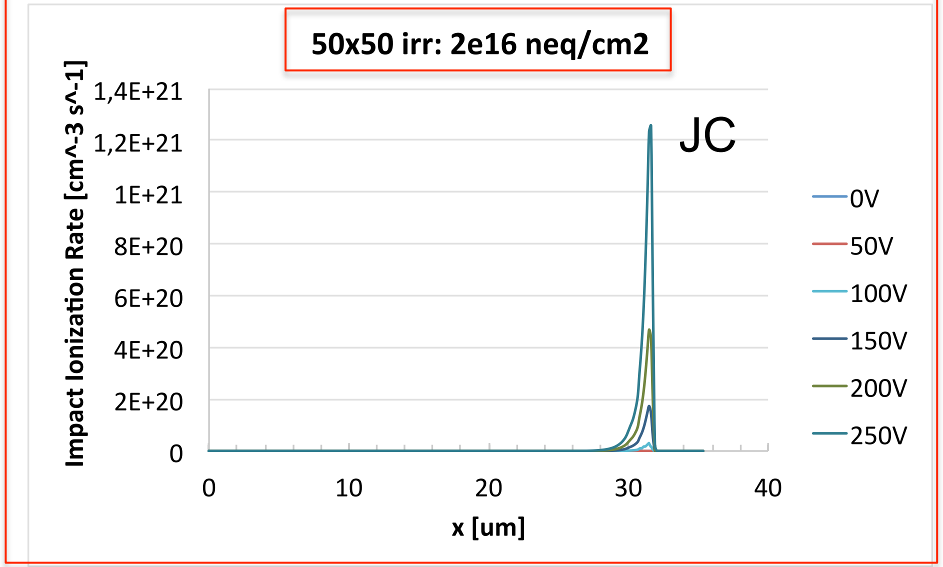

50x50 irr: 2e16 neq/cm2

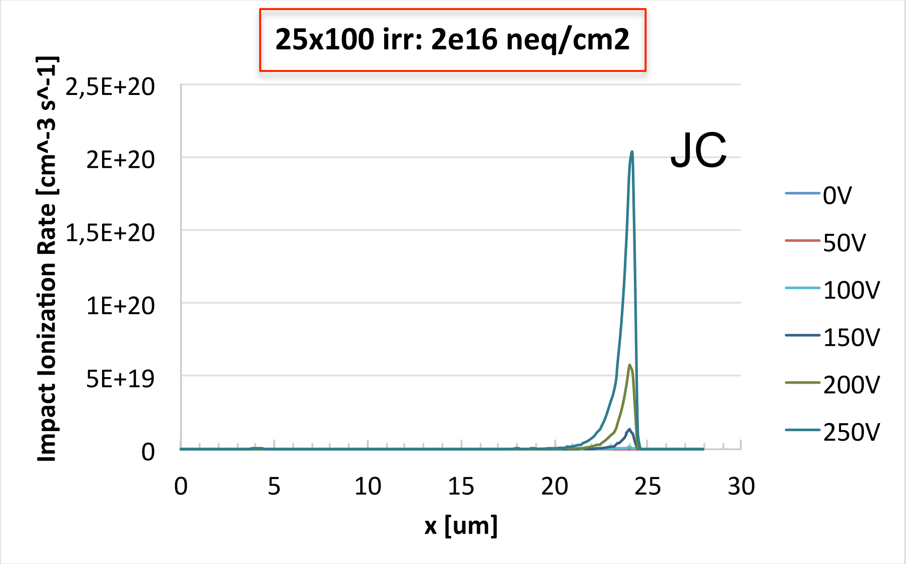

25x100 irr: 2e16 neq/cm2

Impact Ionization Rate 1d comparison

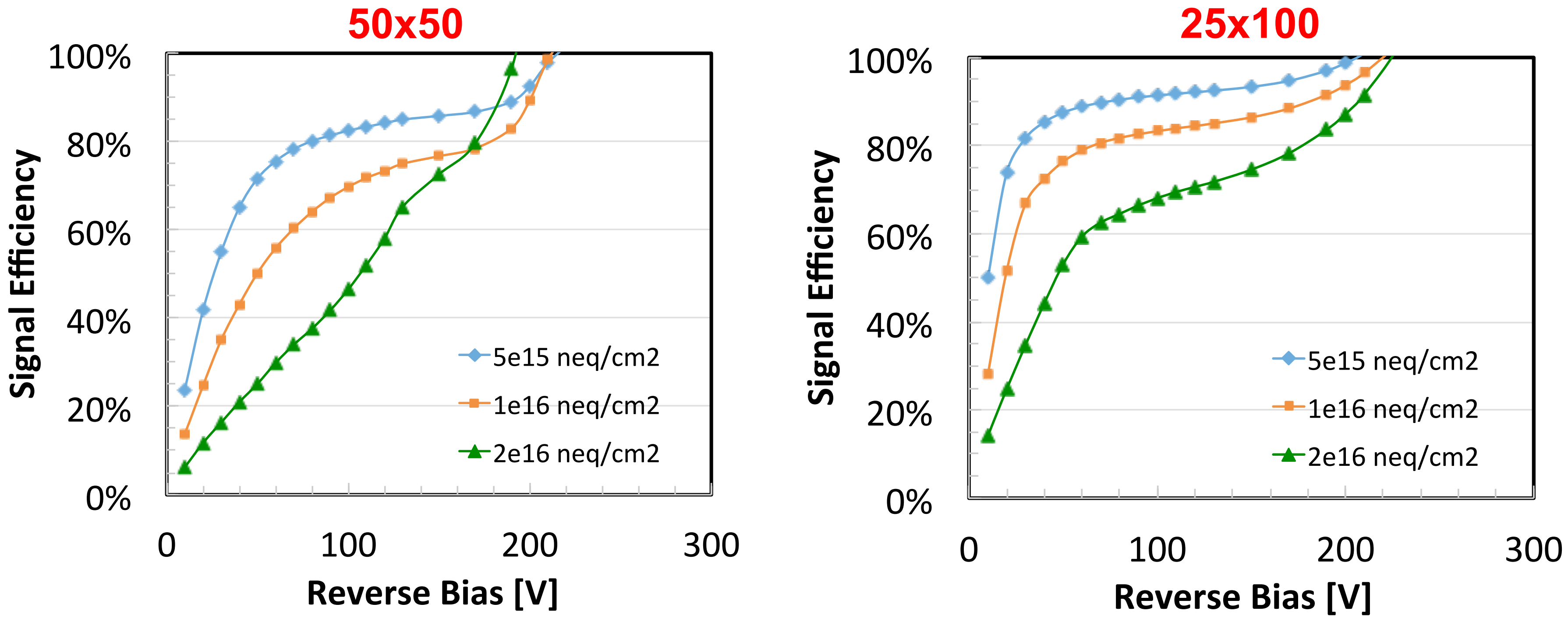

50x50 irr: 5e15 neq/cm2


25x100 irr: 5e15 neq/cm2


50x50 irr: 2e16 neq/cm2

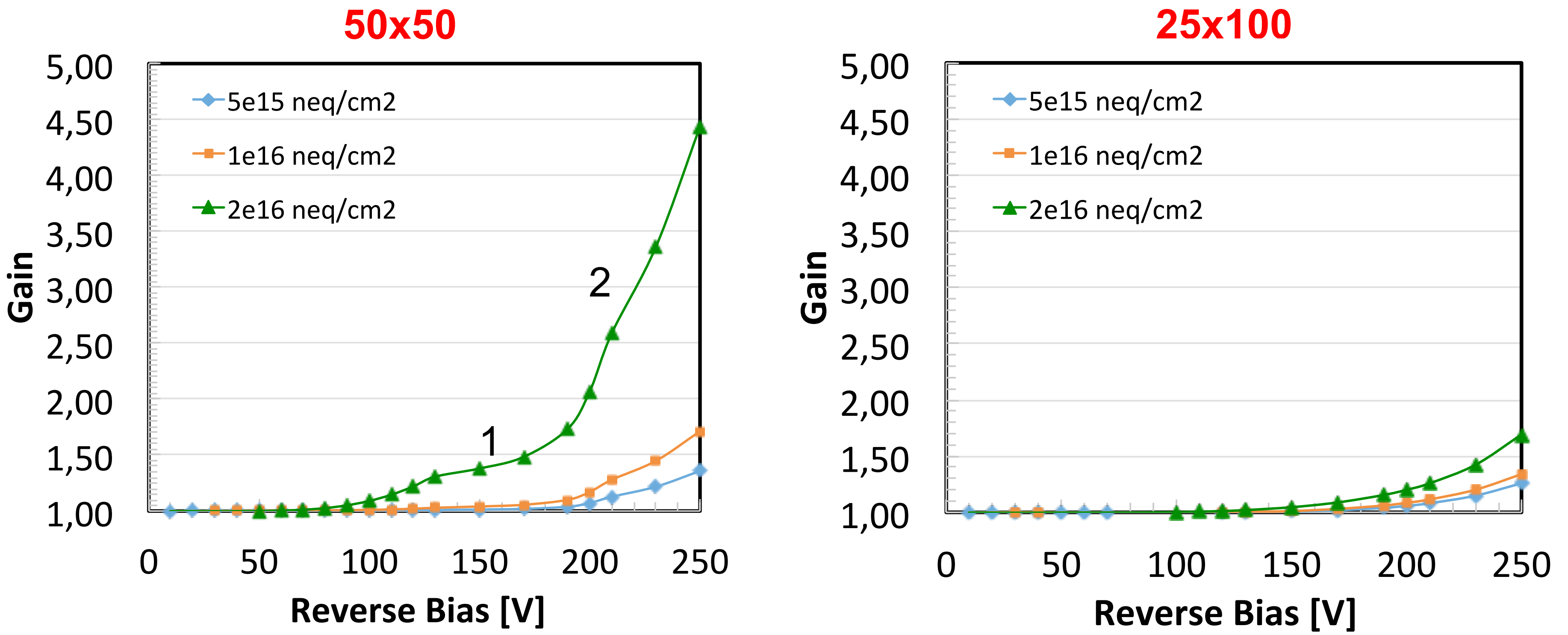

25x100 irr: 2e16 neq/cm2

Average Signal Efficiency with II effects



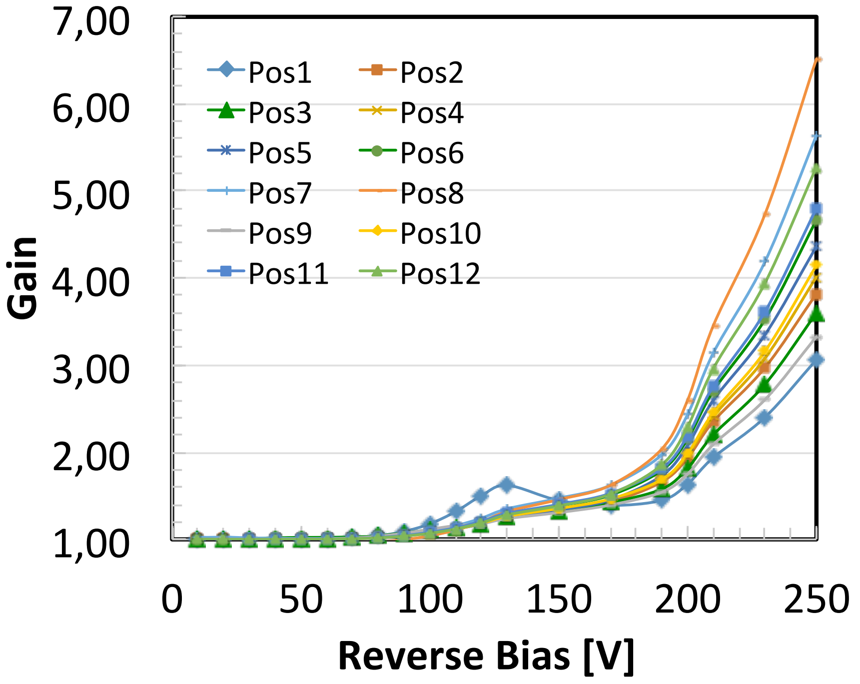
- SE exceeds 100% at high voltage → charge multiplication at JC
- This effect adds up to the previously observed position dependence

Average Gain with II effects



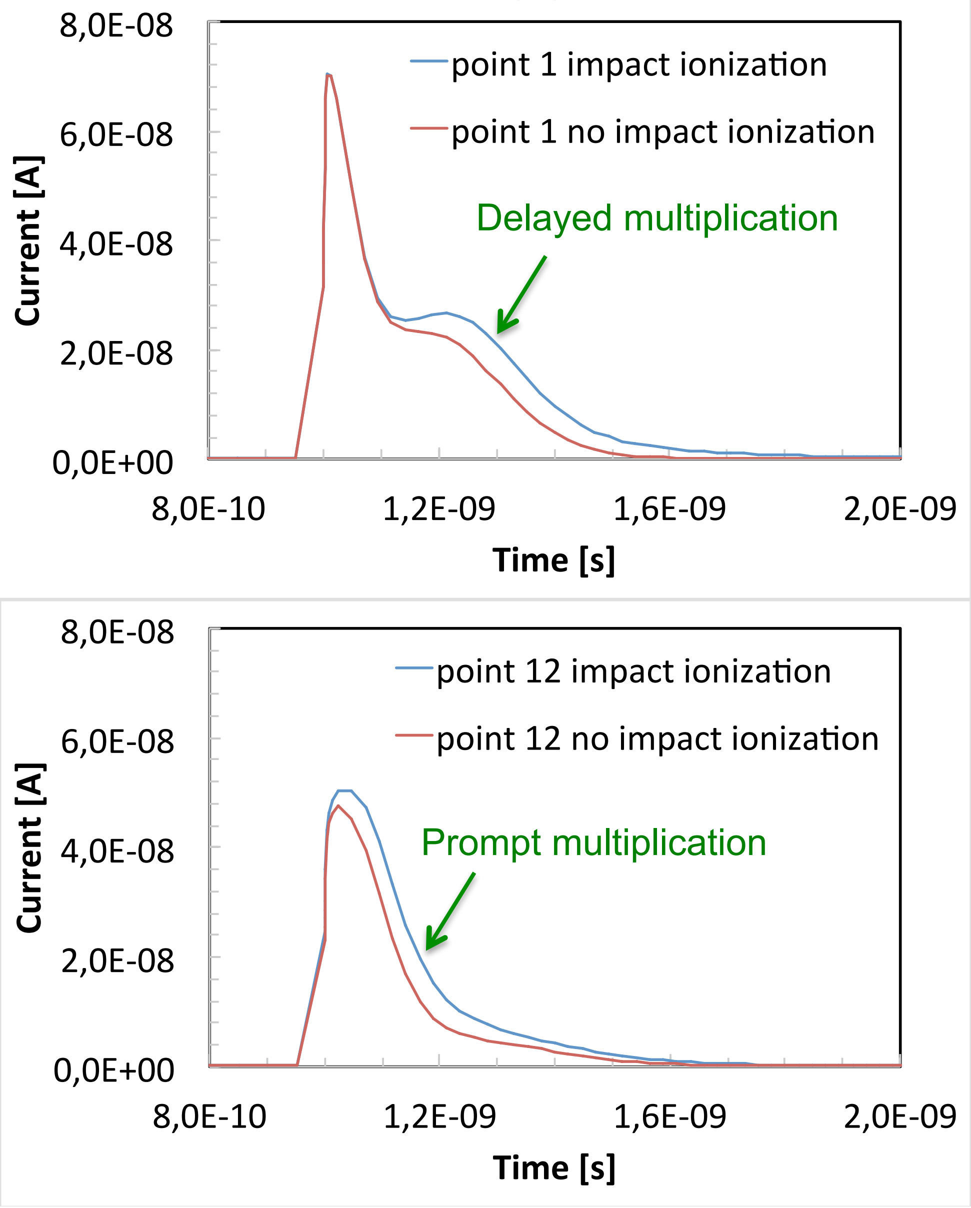
- In most of considered cases the average gain is low
- Gain is quite large only in 50x50 at the largest fluence, for which a two-phase increase with voltage is observed

50x50 at $2x10^{16}$ n_{eq}/cm^2: gain and signals with II



- Large gain spread and different signal shapes with position (to be further investigated)

250V



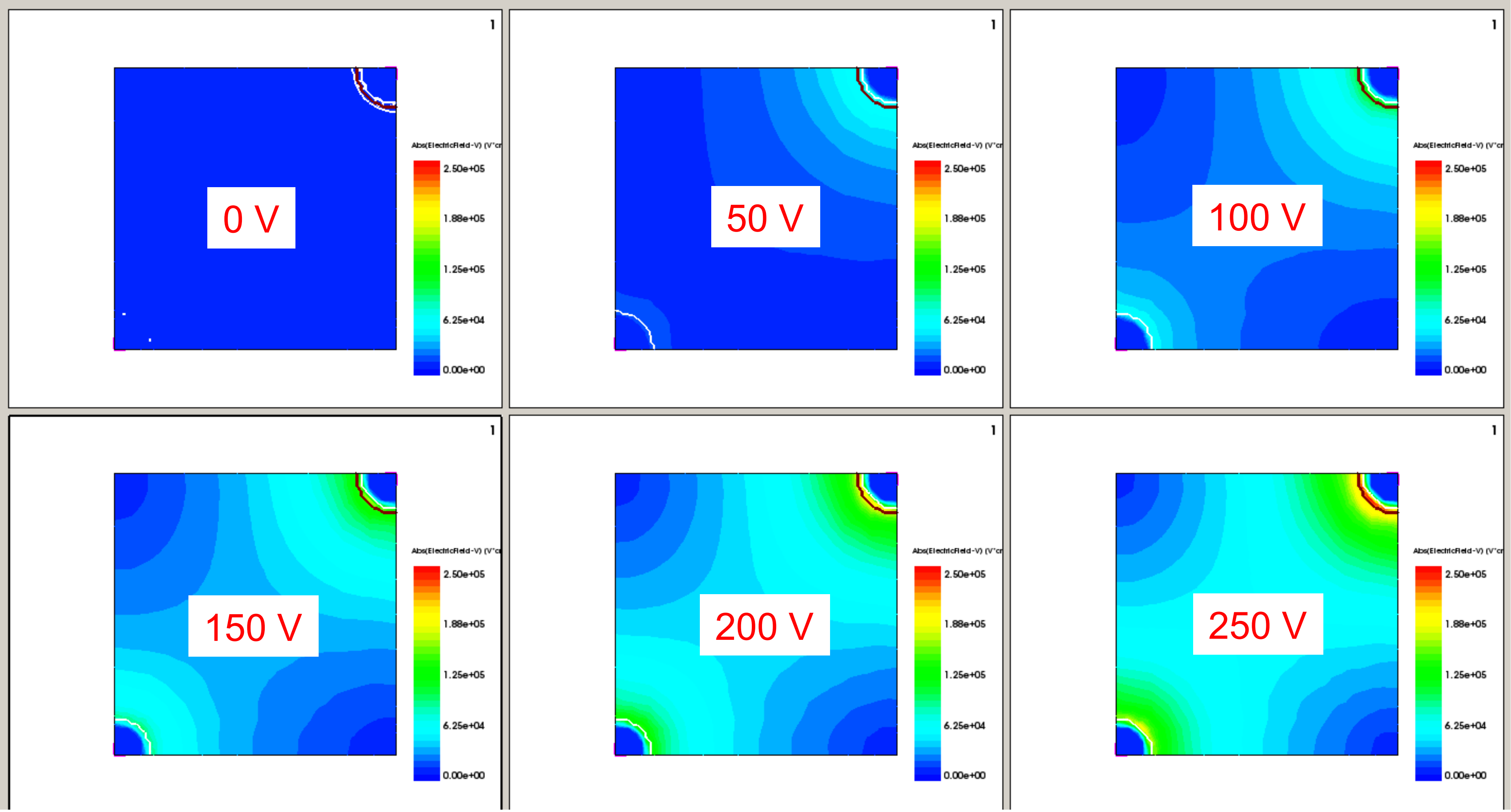
Conclusion and future work

- Simulated electrical characteristics of fresh devices in good agreement with measurements
- Signal efficiency of irradiated pixels show strong position dependence, explained by Ramo’s Theorem
- Charge multiplication predicted by simulations due to very high electric fields
- Next step: full 3D signal simulations (w/o surface effects):
  - inclined tracks, charge sharing
- Surface states model still to be refined for reliable post irradiation simulations

BACK-UP SLIDES

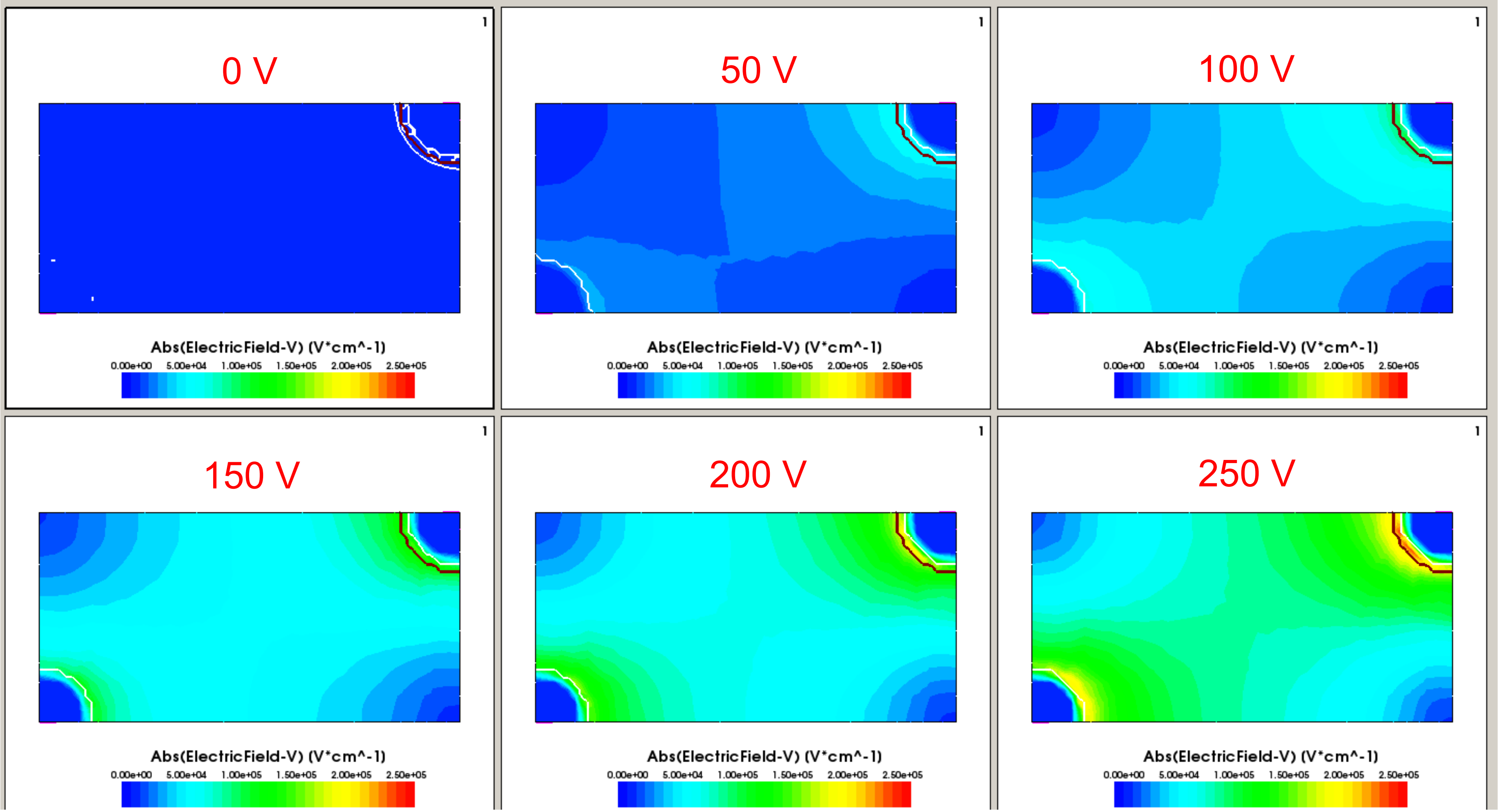
50x50: electric field 2d

$5x10^{15}\ n_{eq}/cm^2$



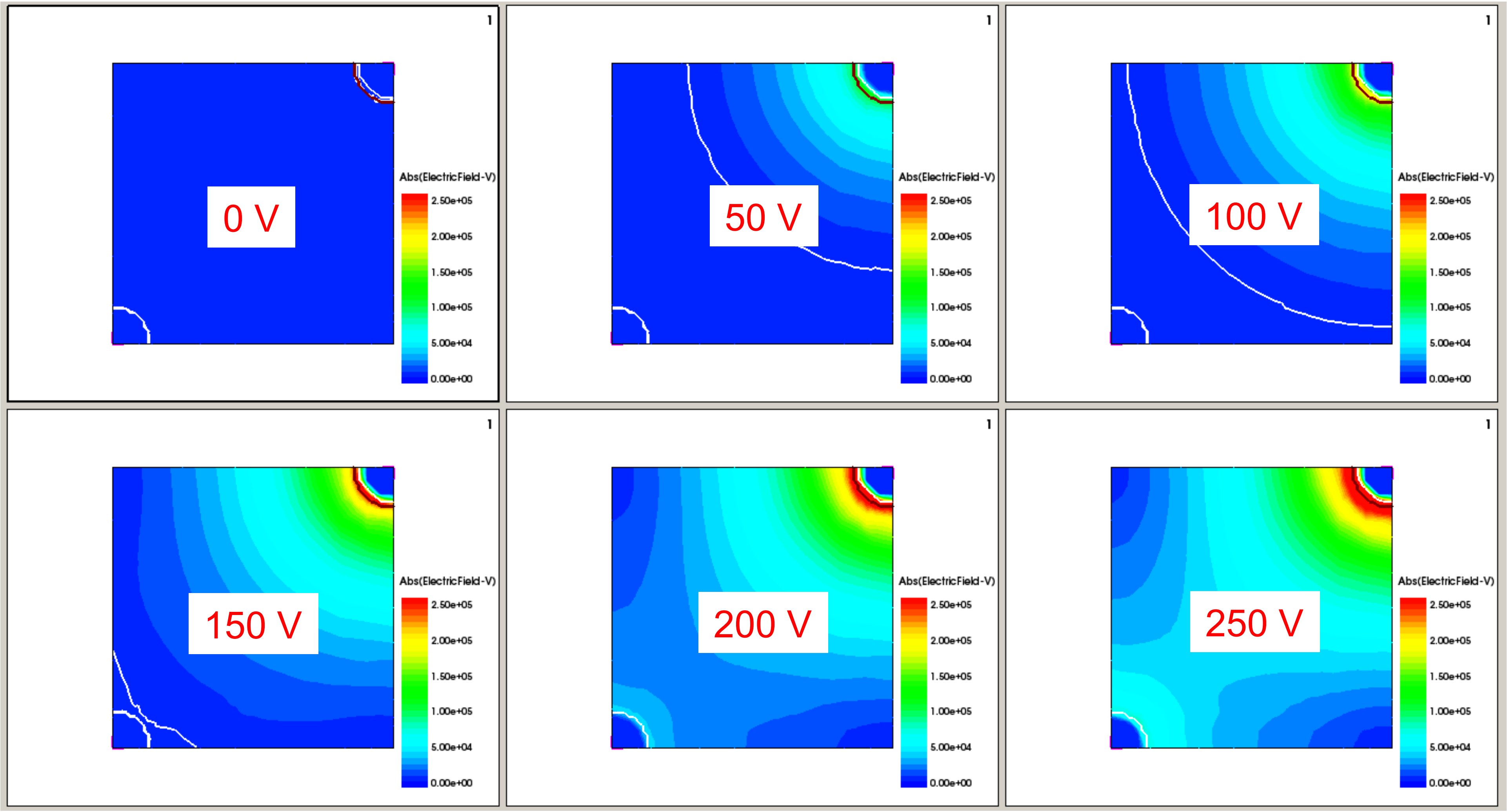
25x100: electric field 2d

$5\times10^{15}\ n_{eq}/cm^2$



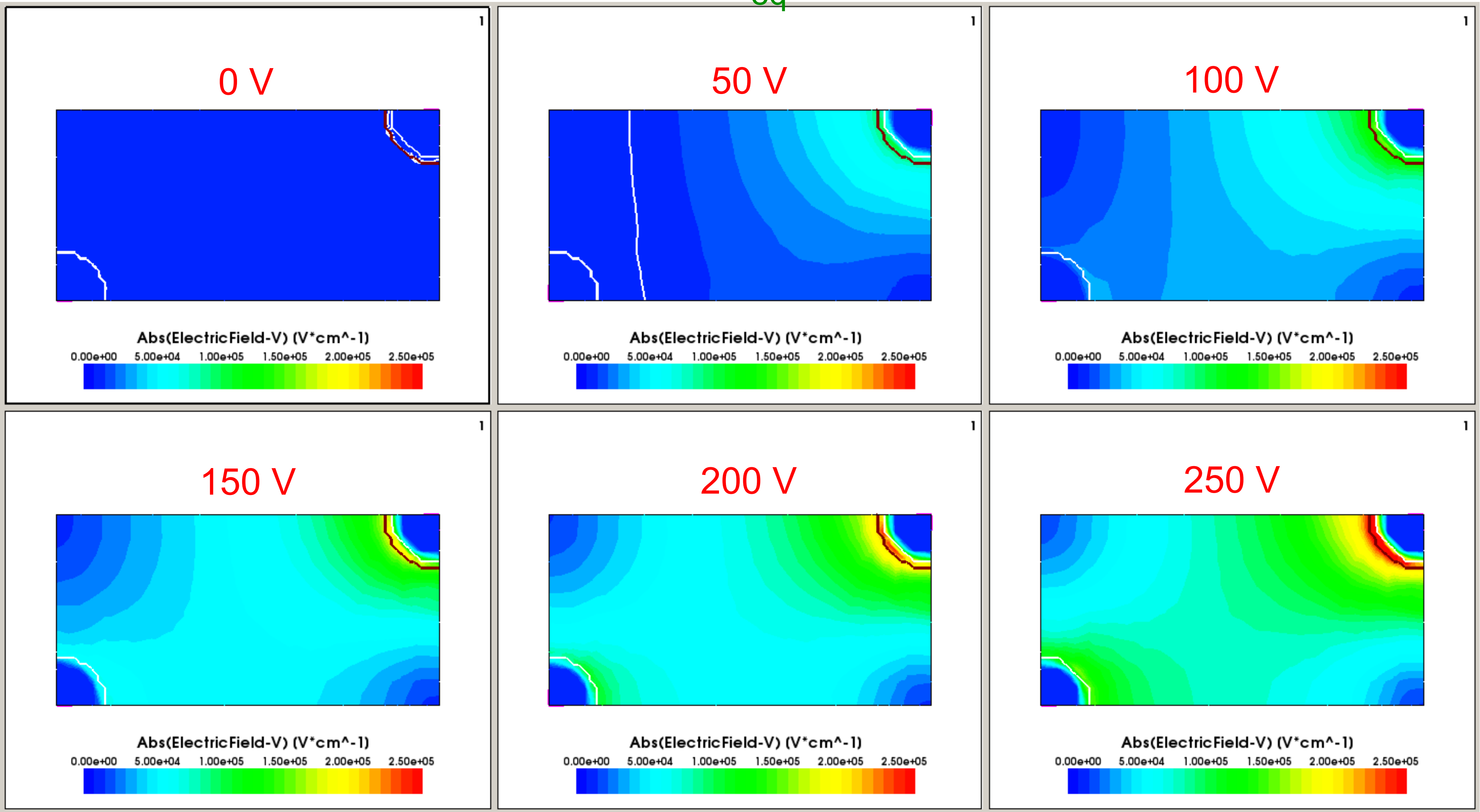
50x50: electric field 2d

$2\times10^{16}\ n_{eq}/cm^2$



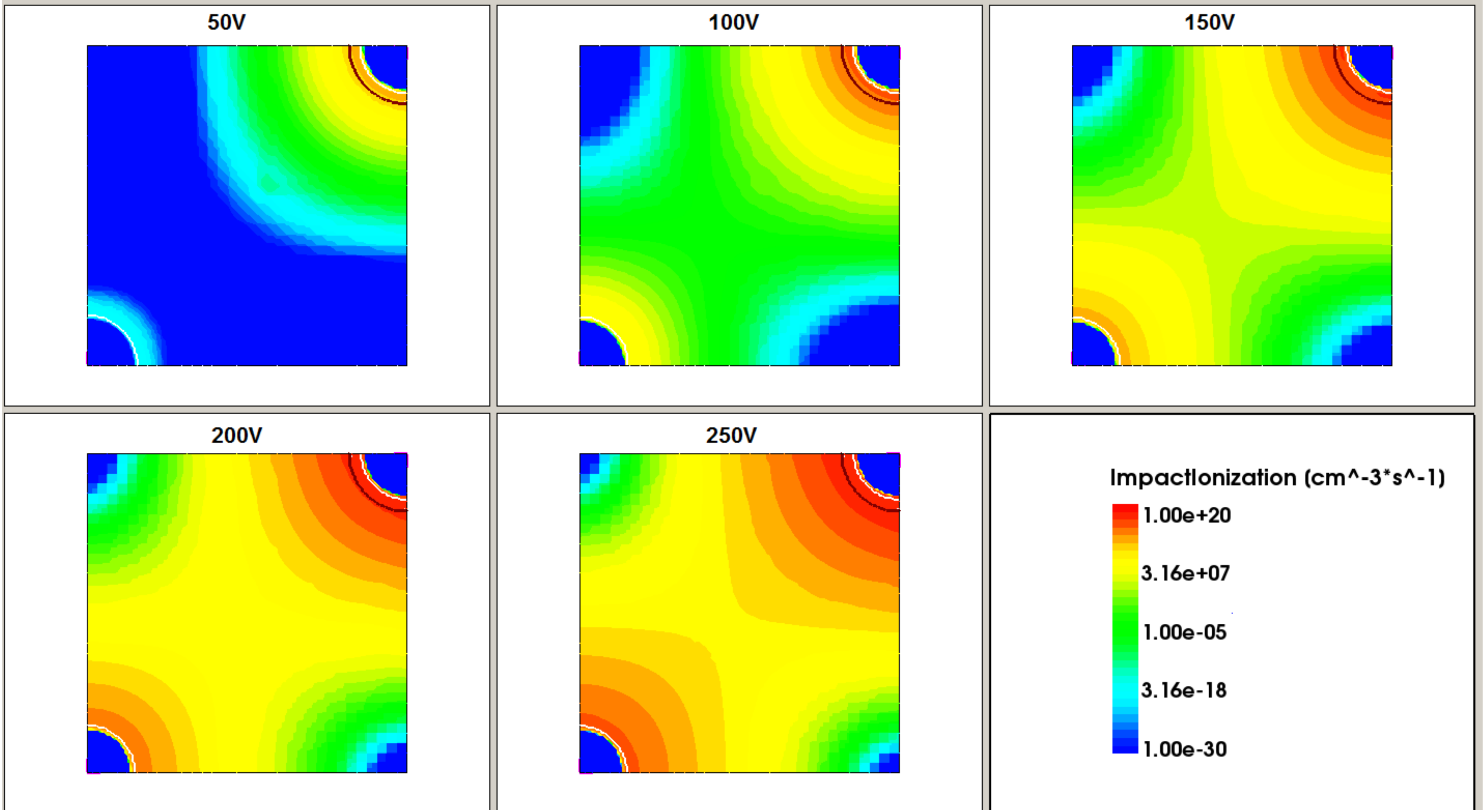
25x100: electric field 2d

$2x10^{16}$ n_{eq}/cm^2



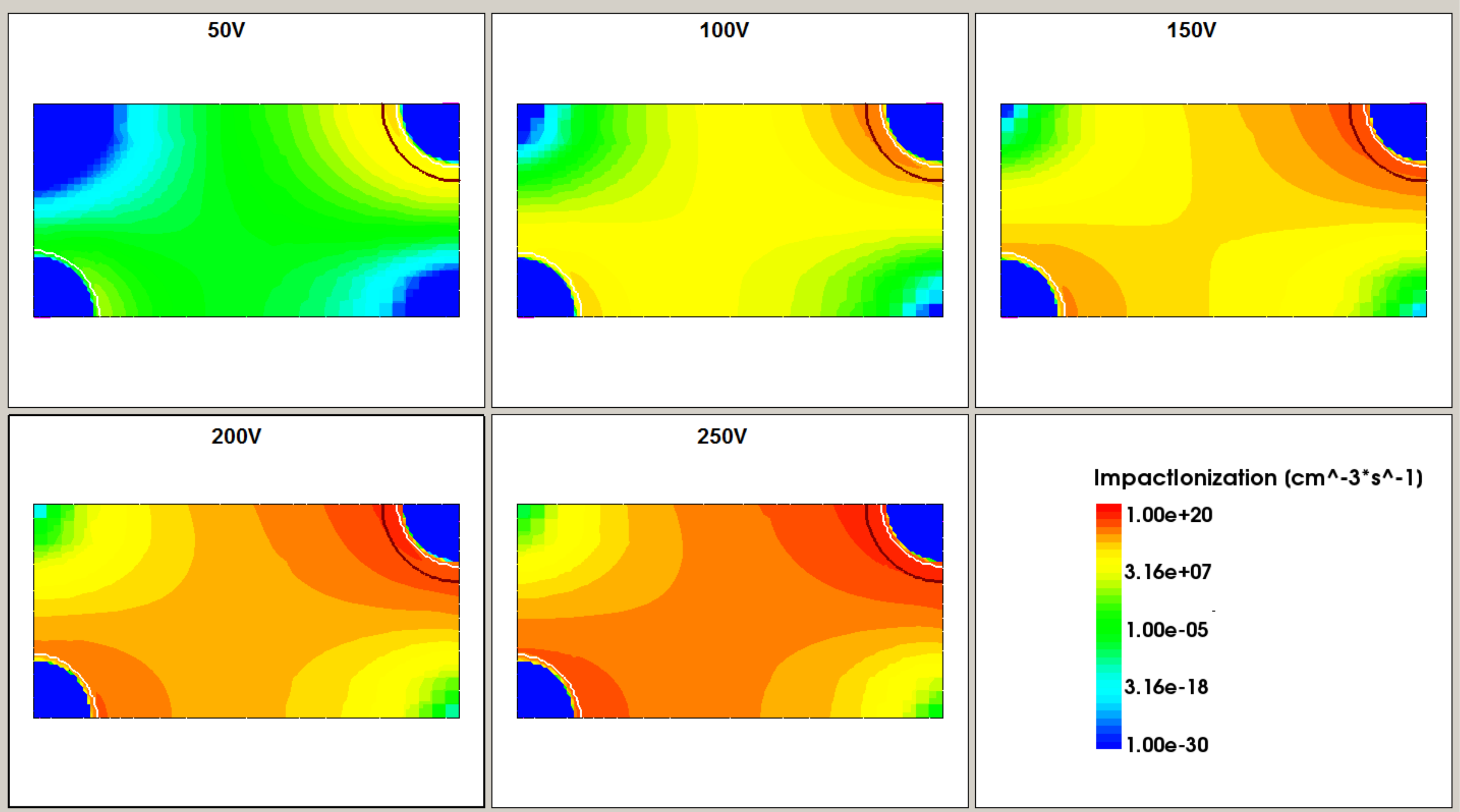
50x50: impact ionization rate 2d

5×10^{15} n_{eq}/cm^2



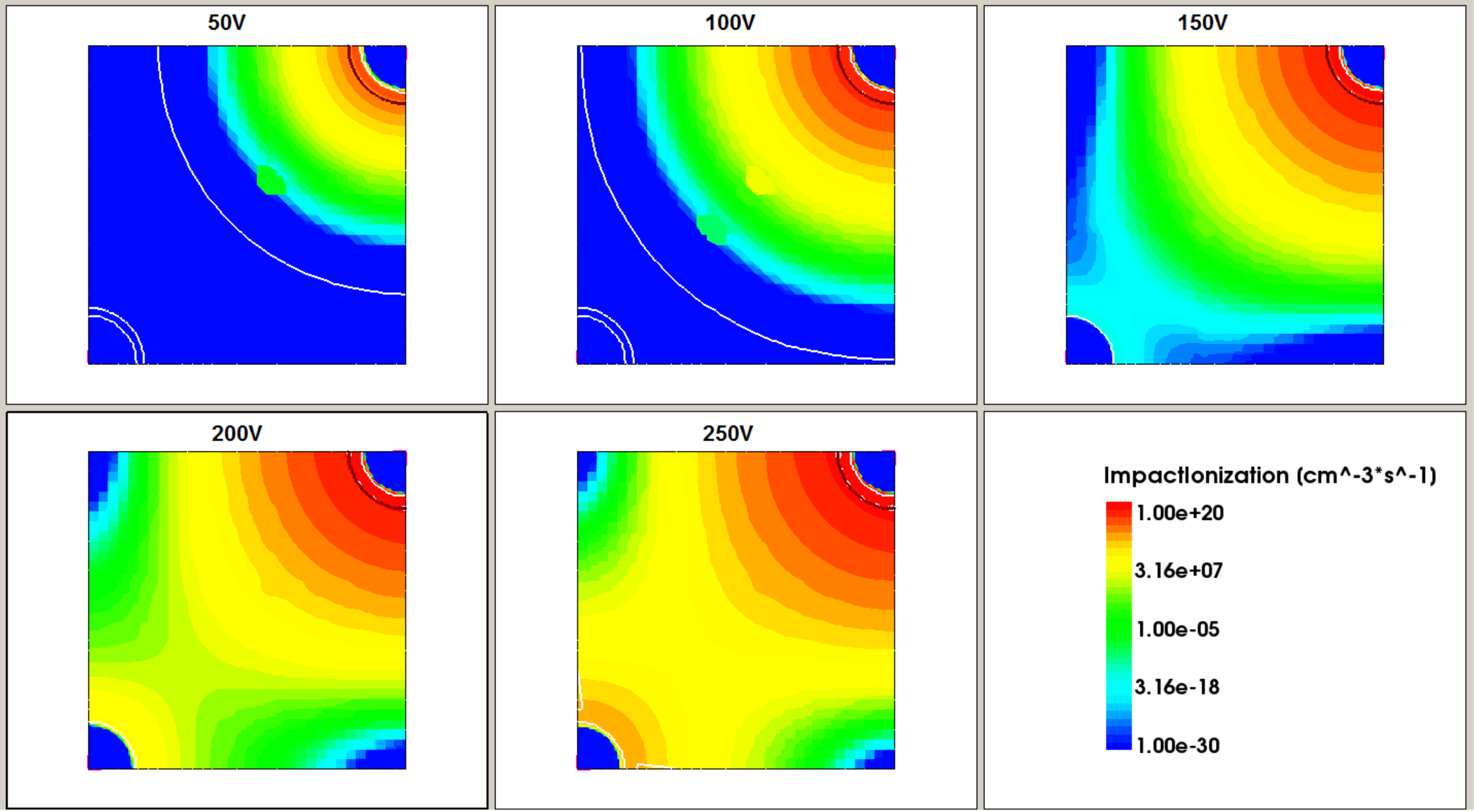
25x100: impact ionization rate 2d

$5\text{x}10^{15}\ n_{eq}/cm^2$



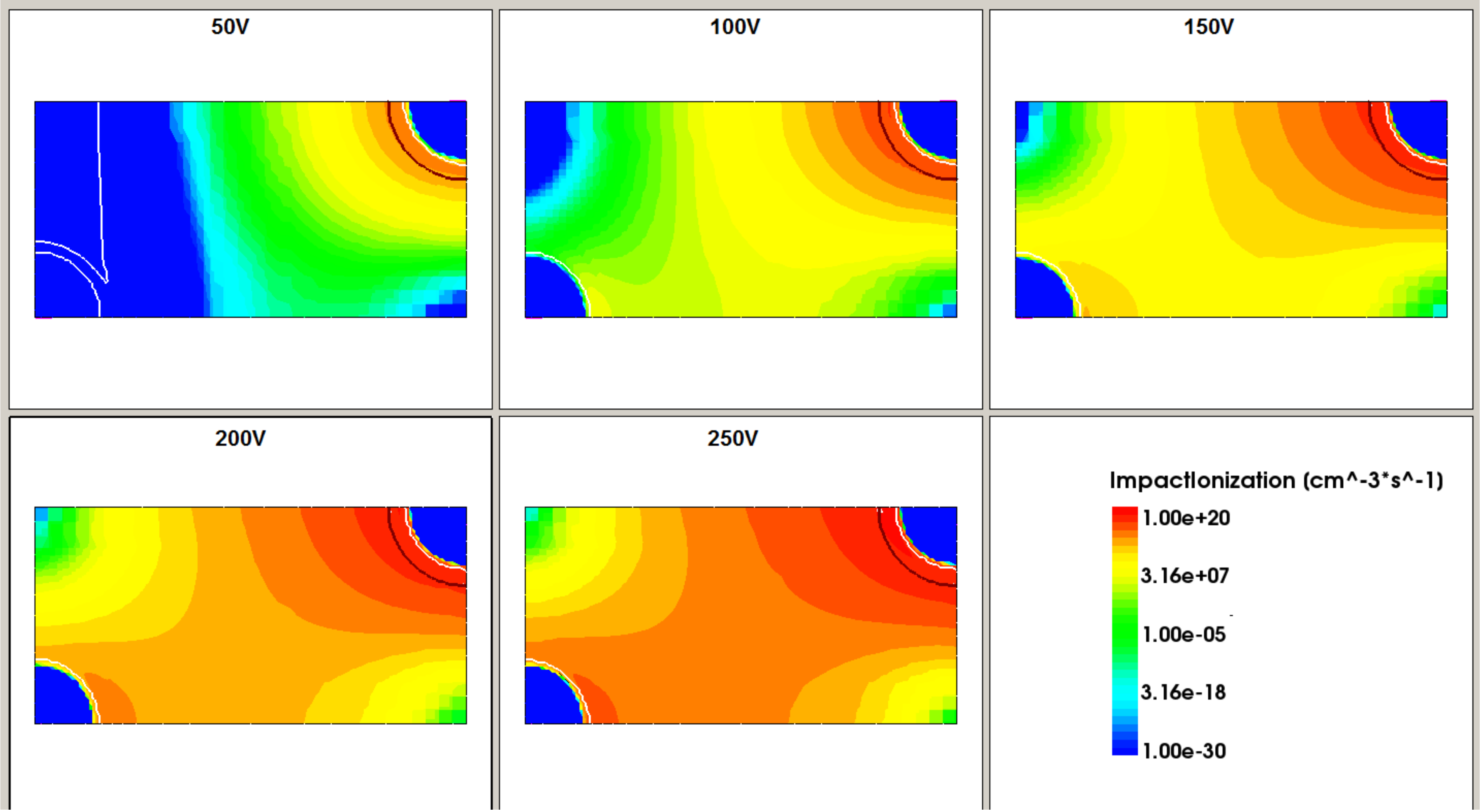
50x50: impact ionization rate 2d

$2\times10^{16}\ n_{eq}/cm^2$

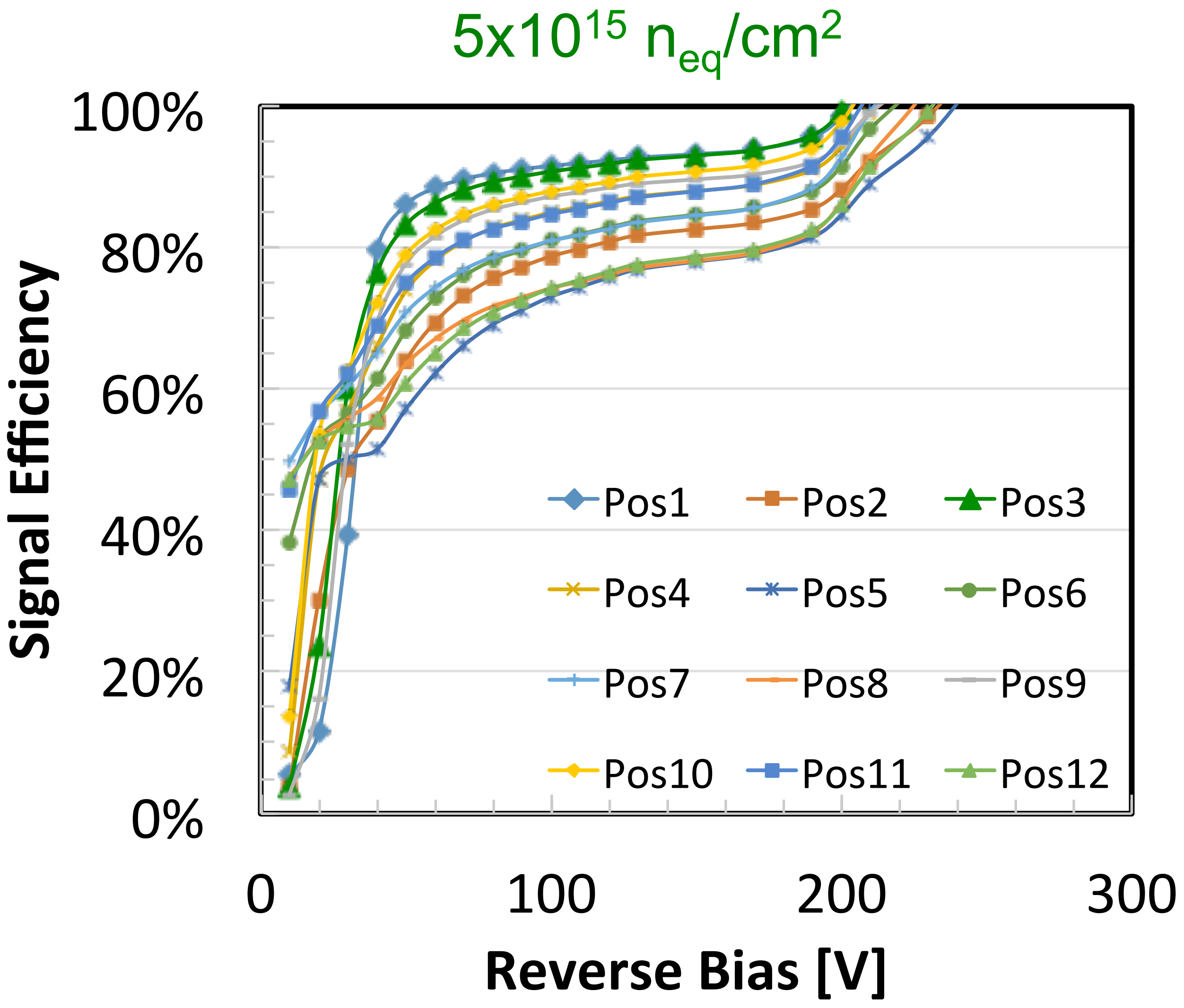


25x100: impact ionization rate 2d

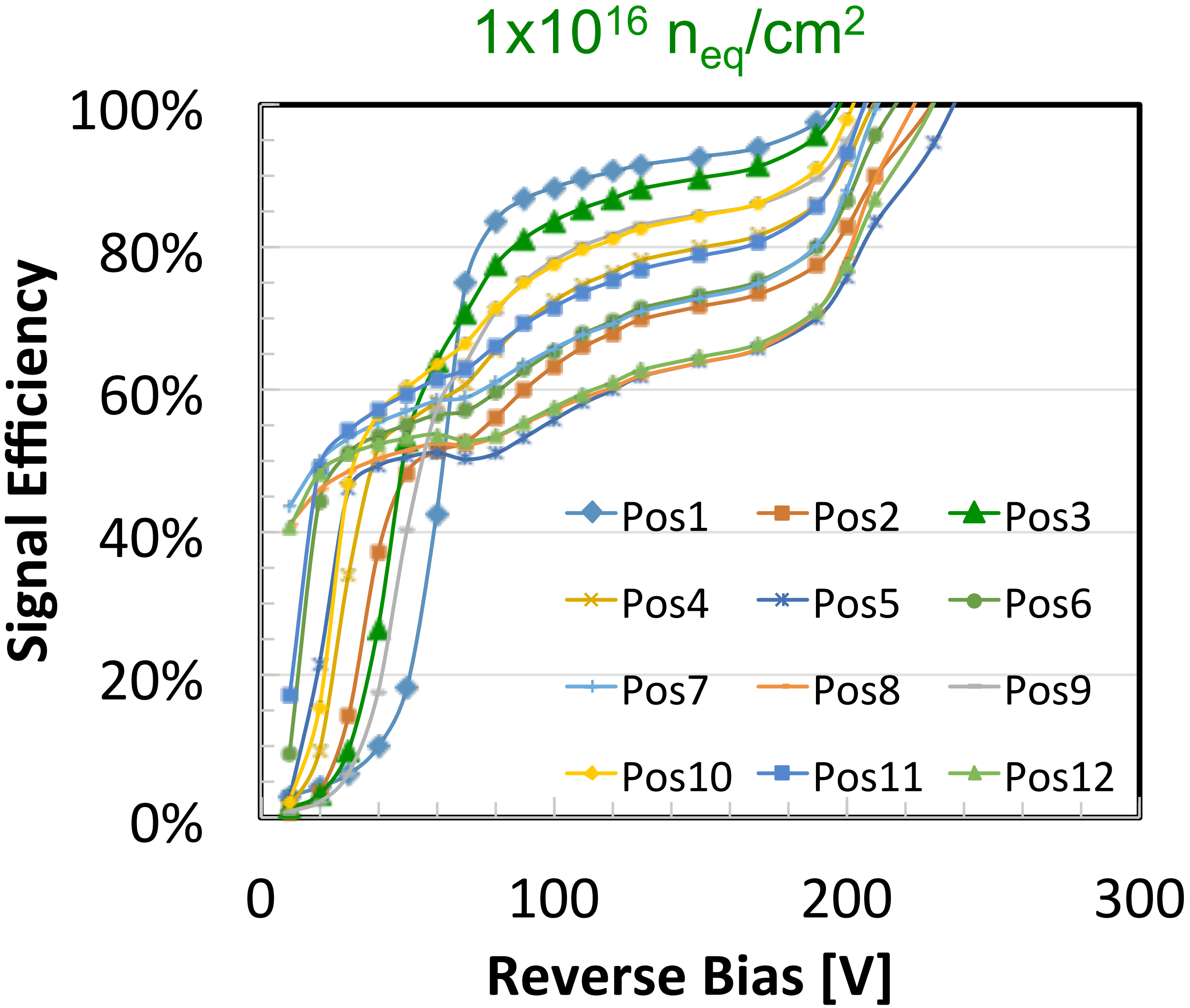
$2\mathrm{x}10^{16}\ n_{eq}/cm^2$



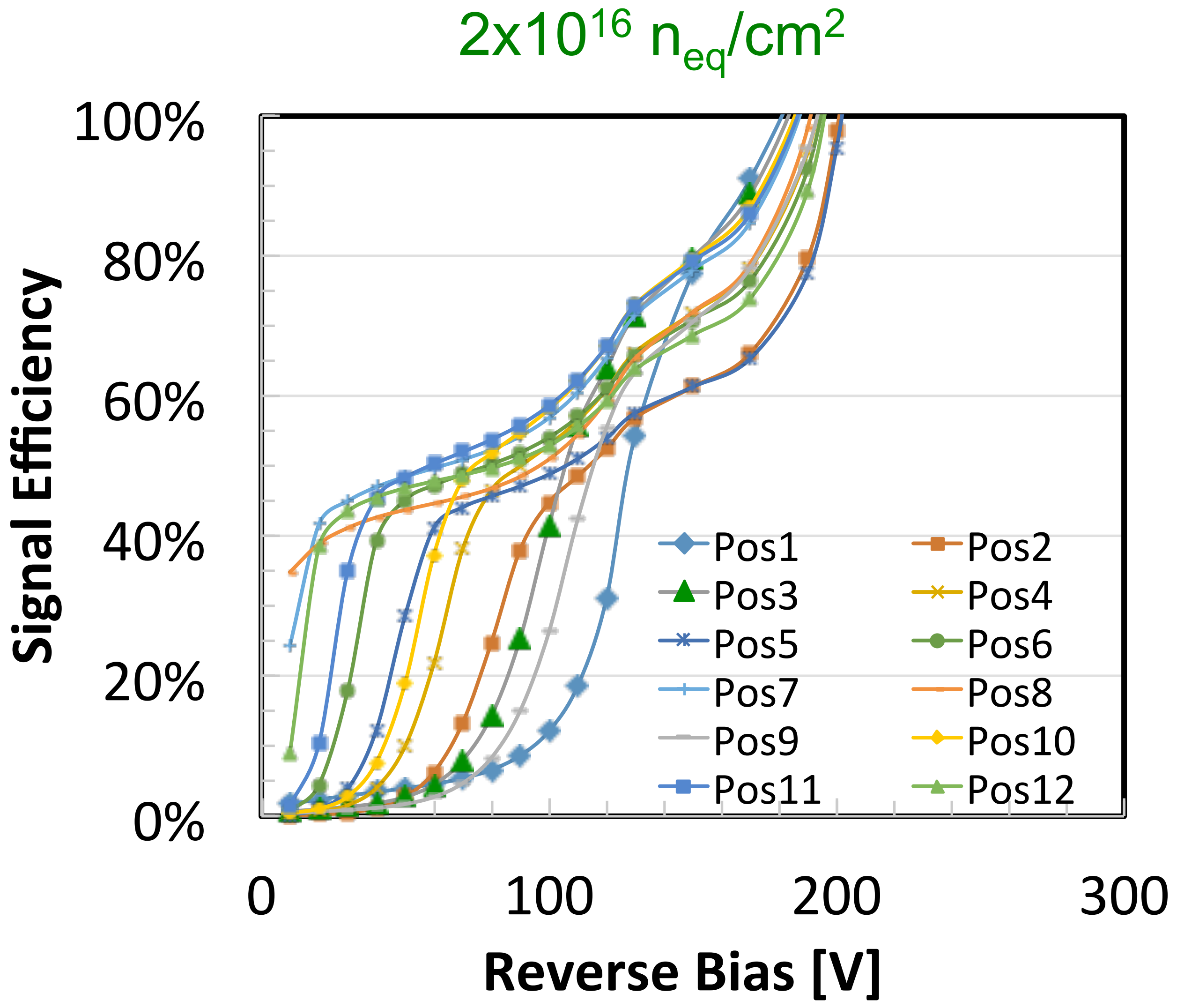
50x50 with II: position dependent SE



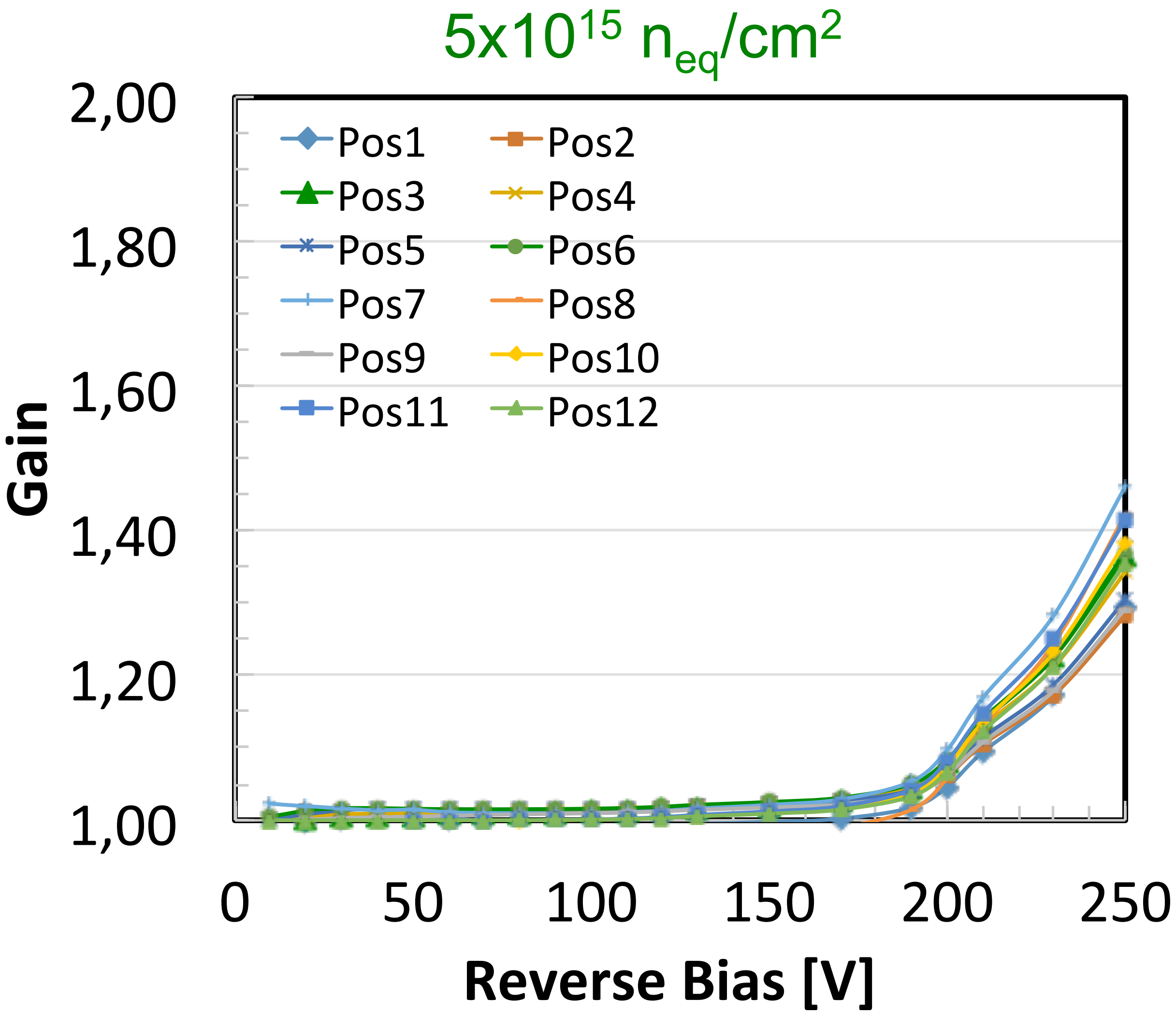
50x50 with II: position dependent SE



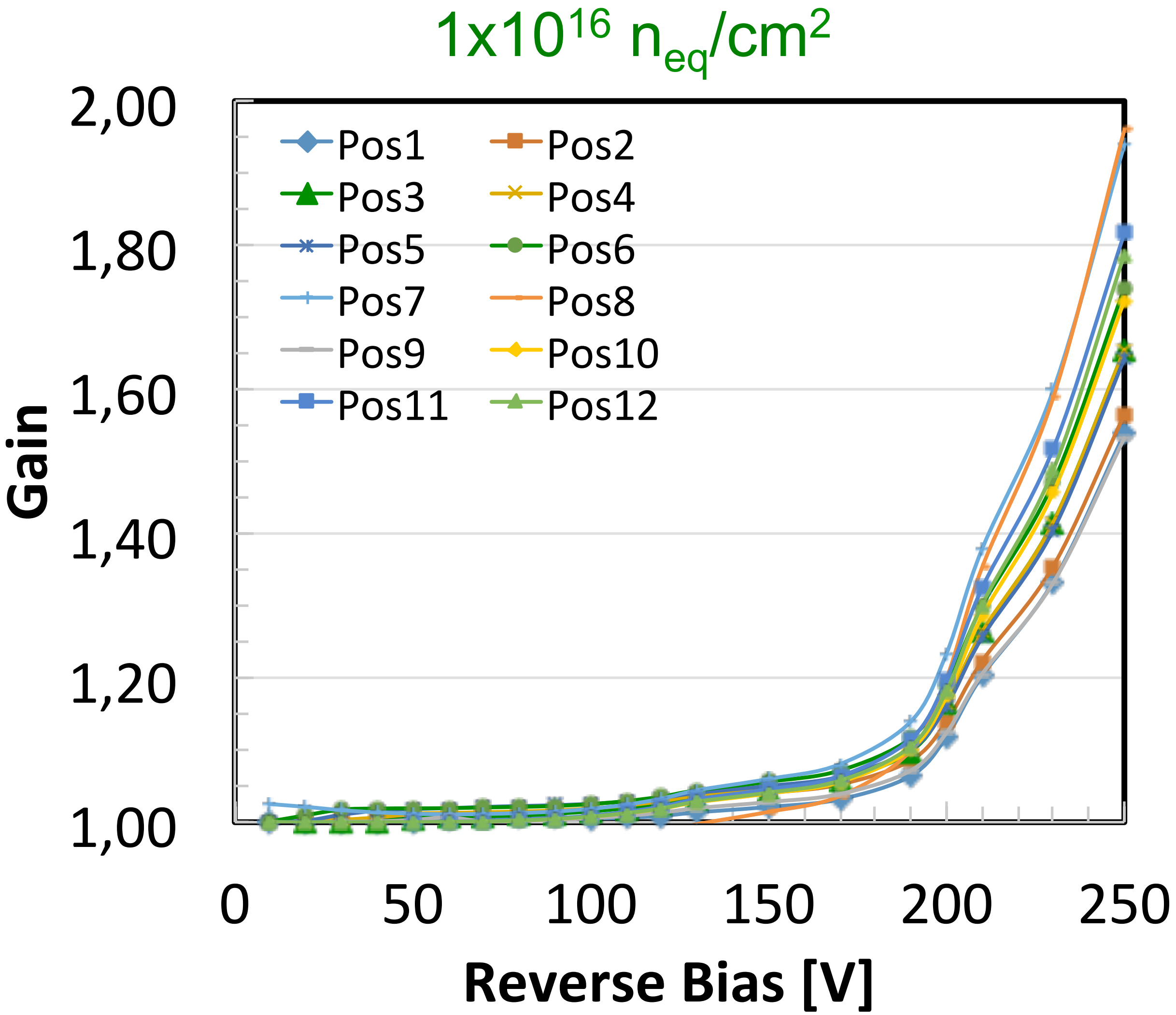
50x50 with II: position dependent SE



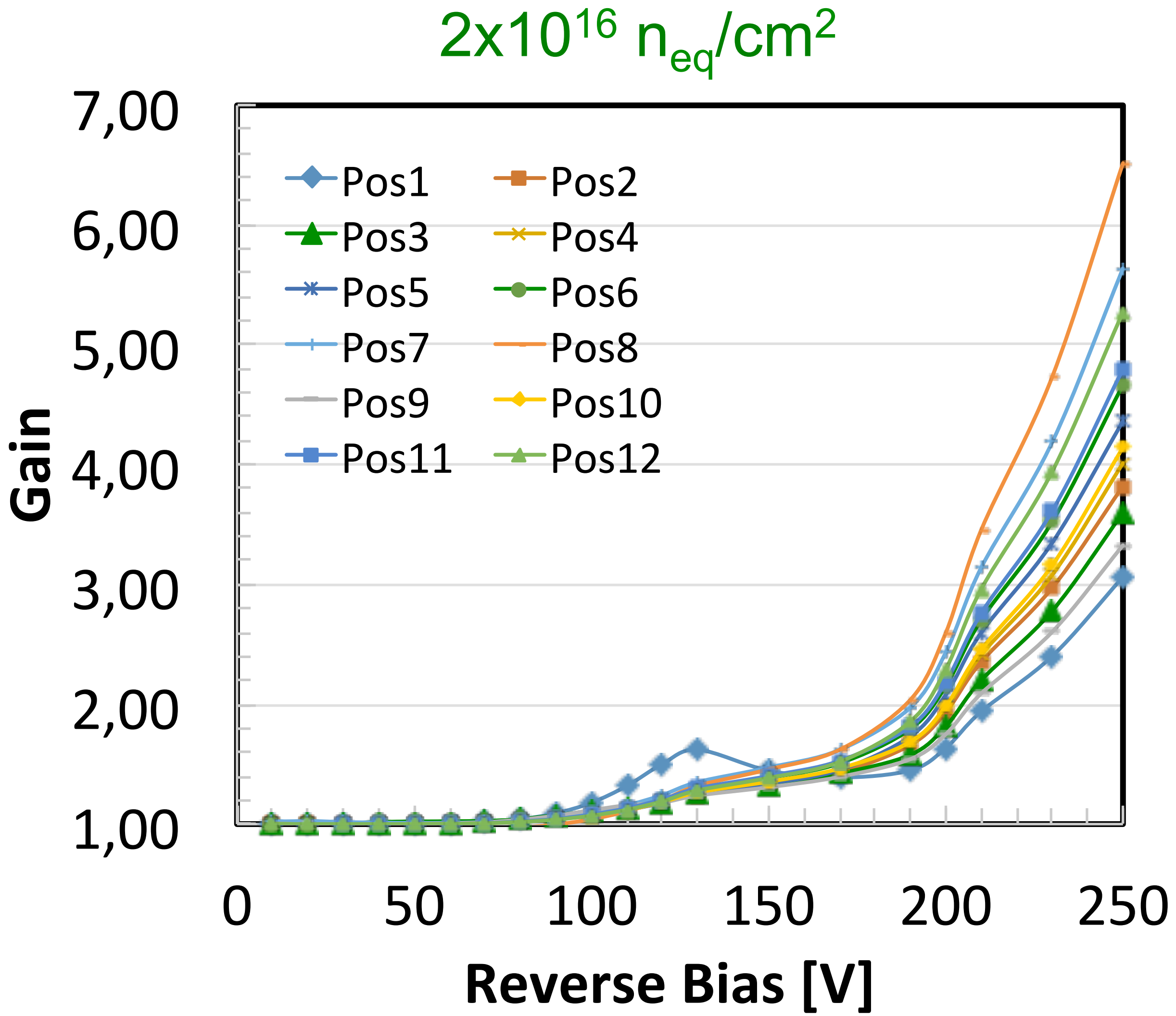
50x50 with II: position dependent gain



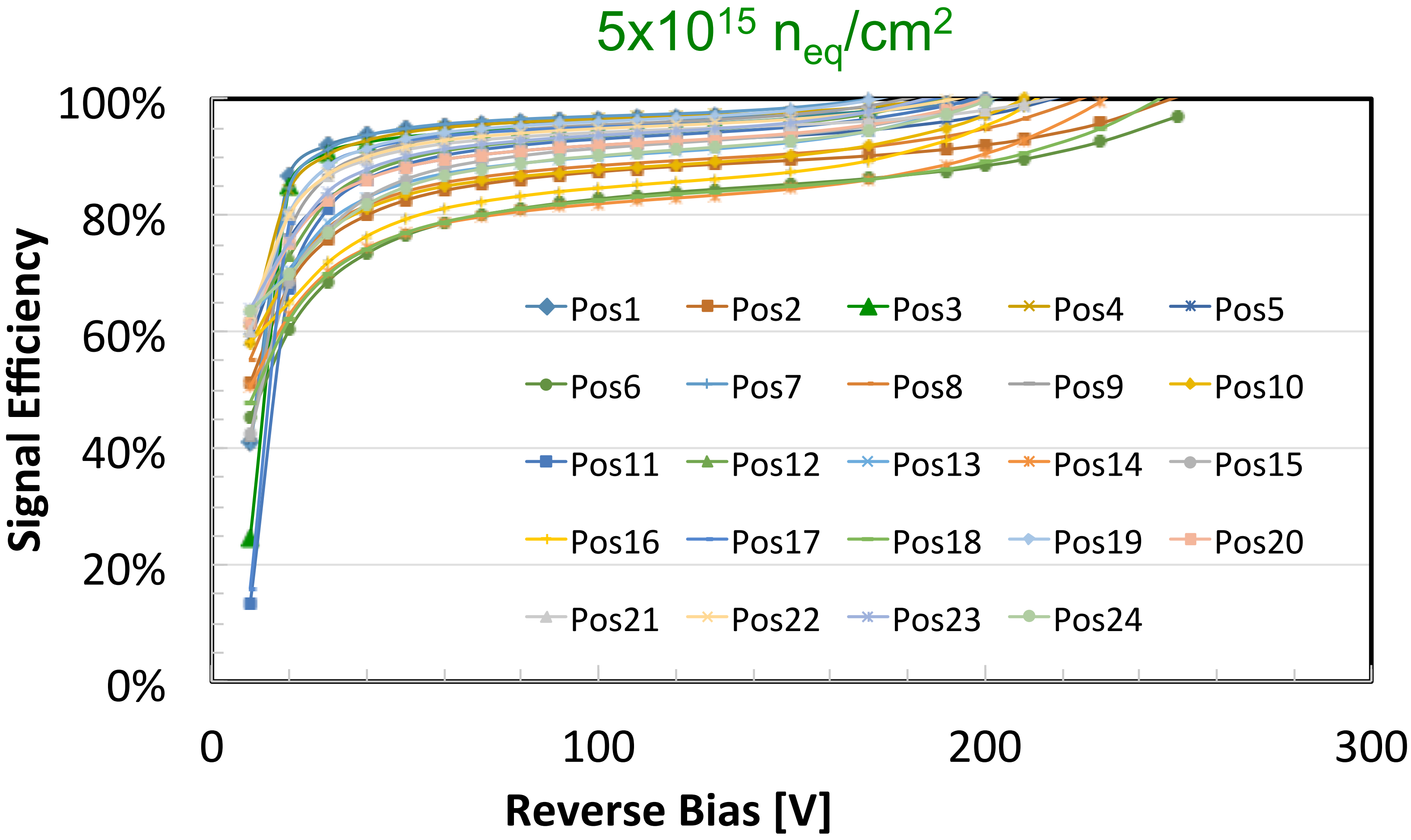
50x50 with II: position dependent gain



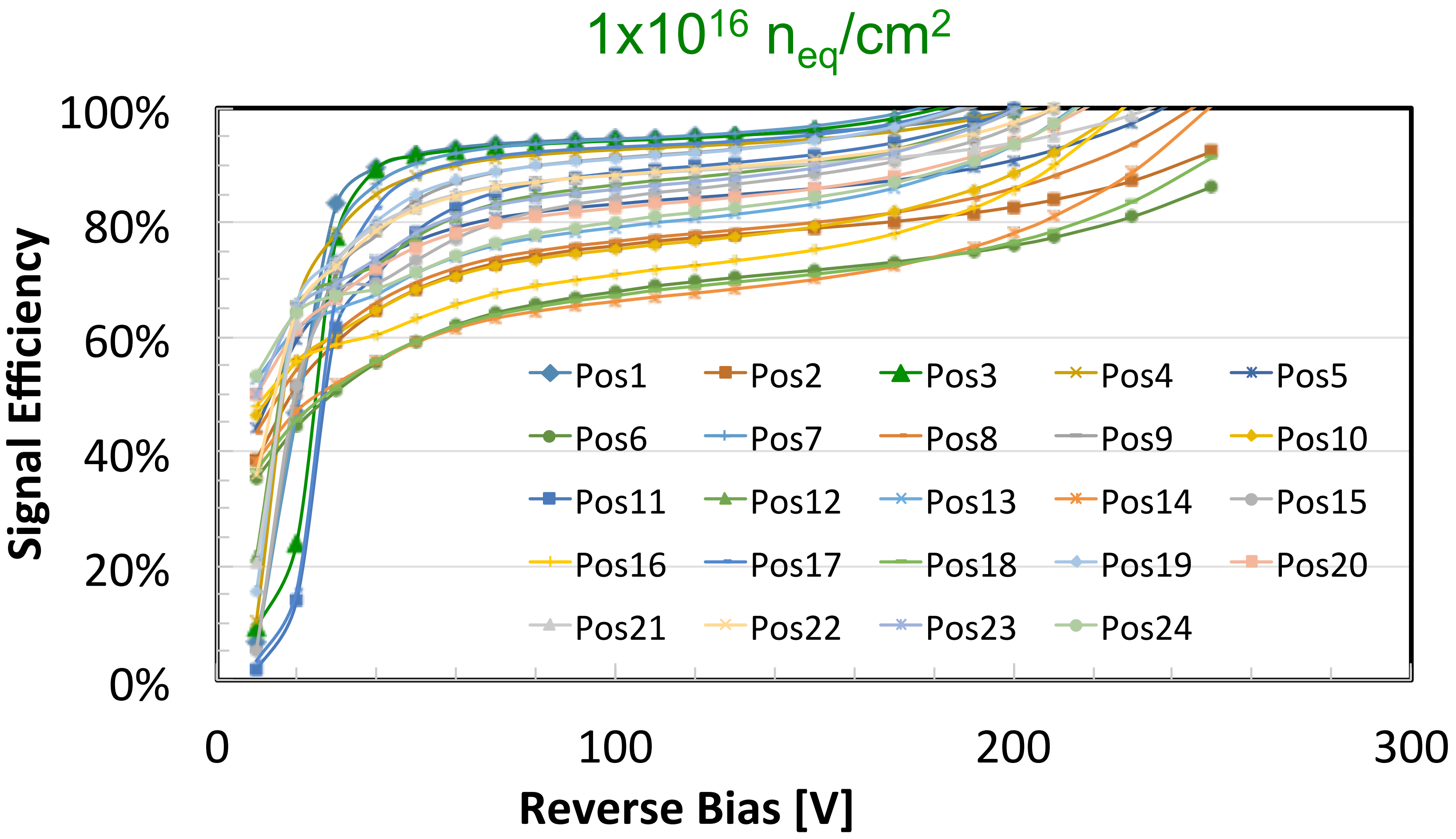
50x50 with II: position dependent gain



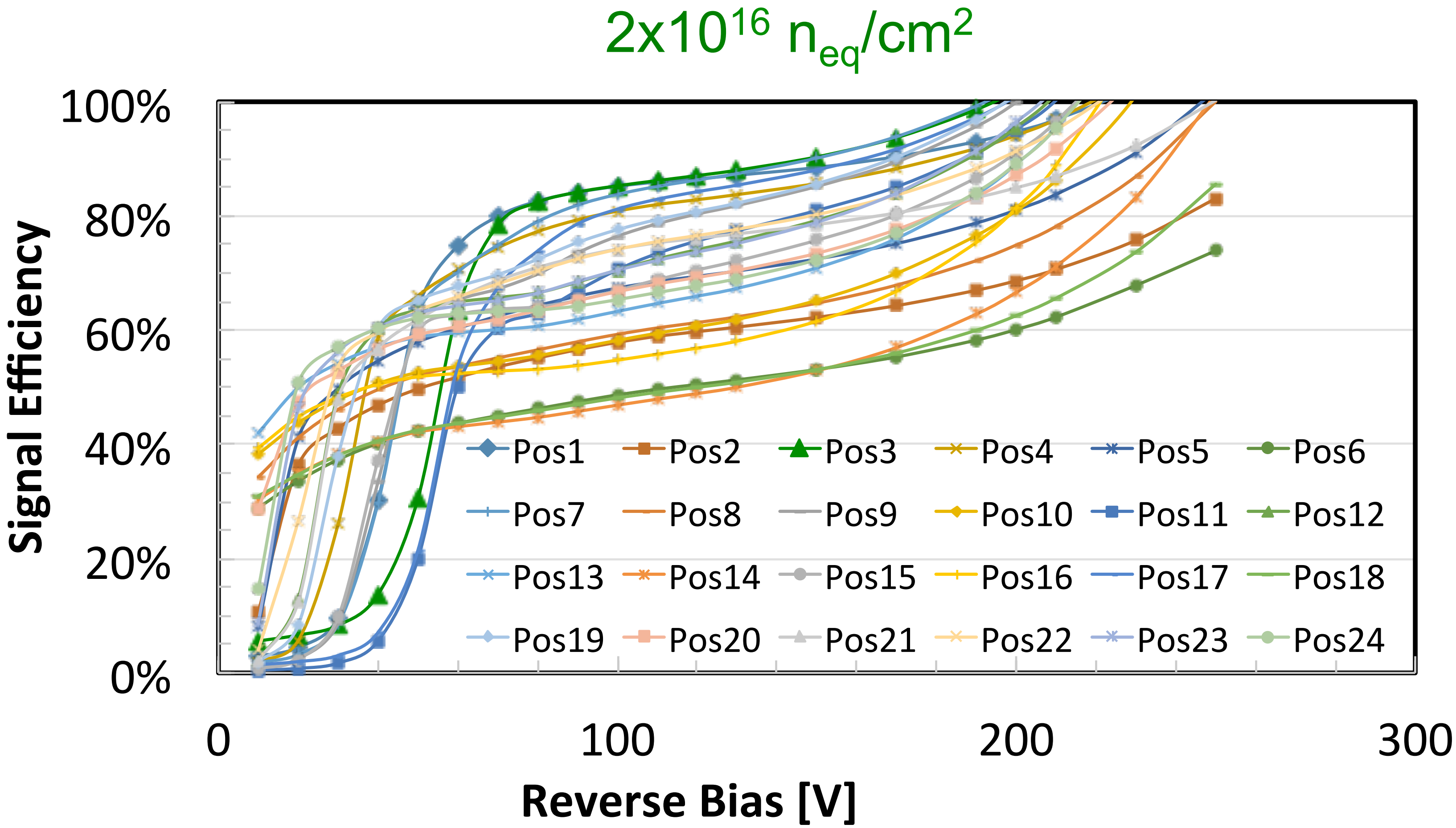
25x100 with II: position dependent SE



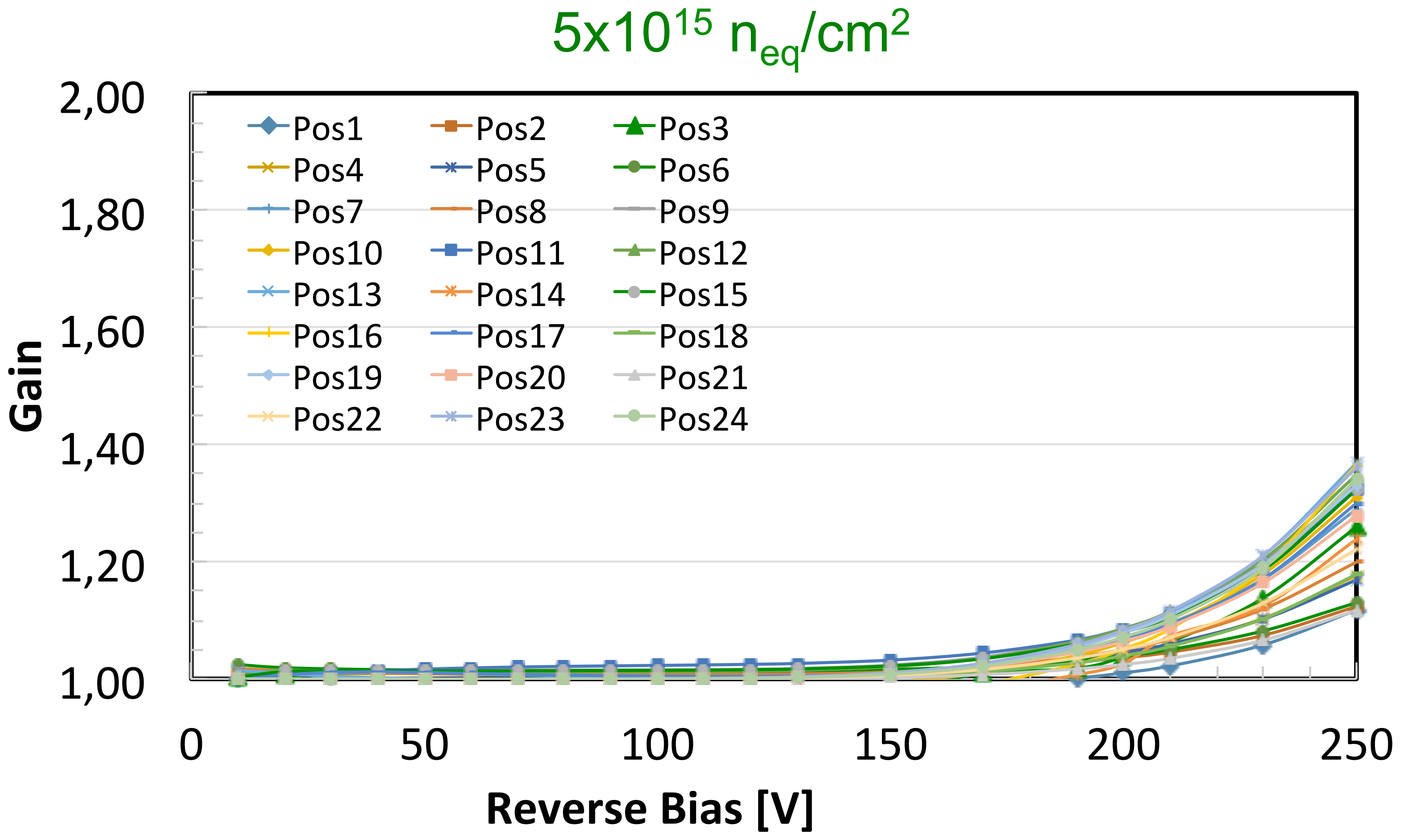
25x100 with II: position dependent SE



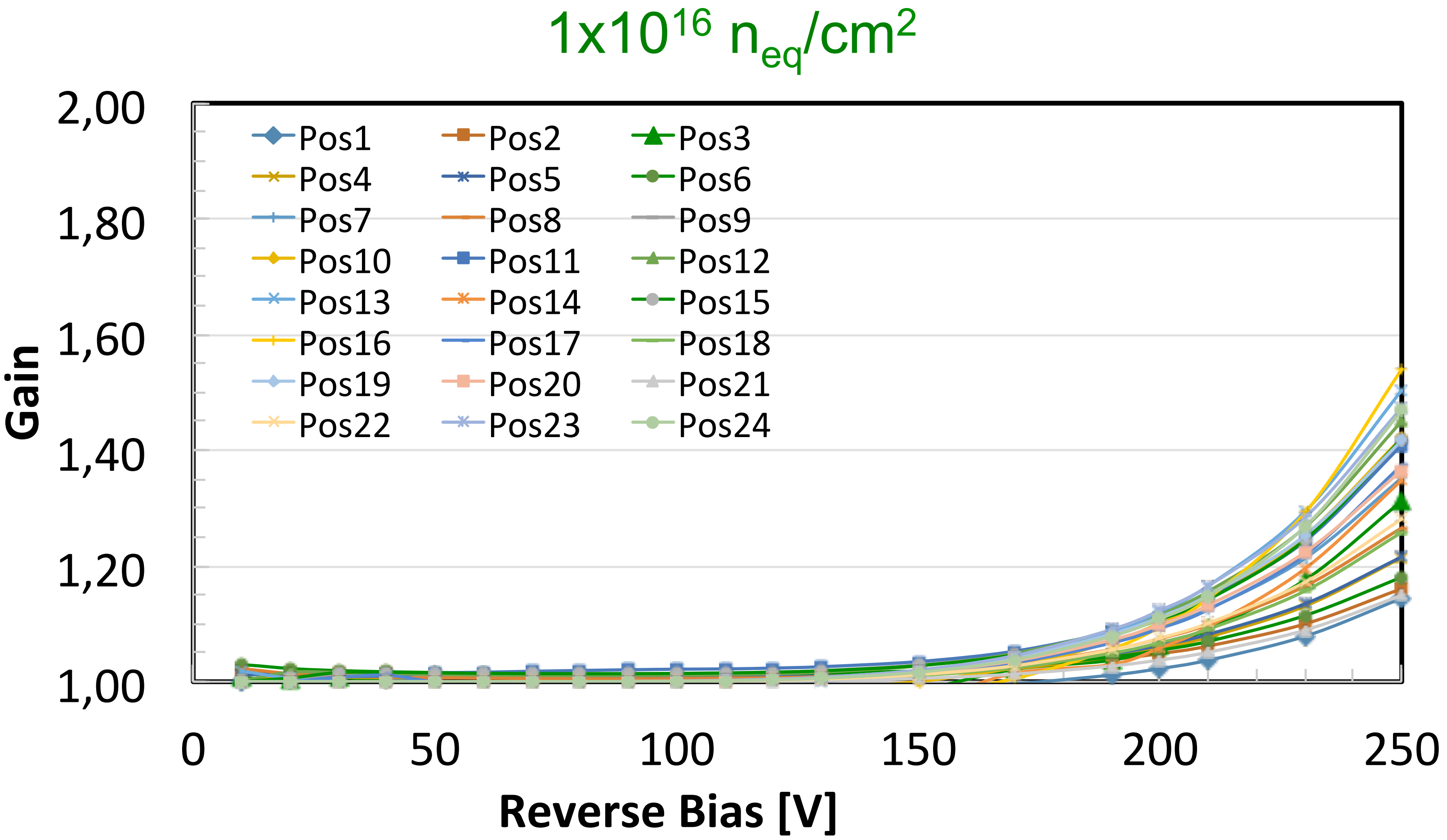
25x100 with II: position dependent SE



25x100 with II: position dependent gain



25x100 with II: position dependent gain



25x100 with II: position dependent gain