TCAD simulation on non-irradiated LGADs

M.Moll and E.Curras-Rivera
for the CERN SSD team

Outline:

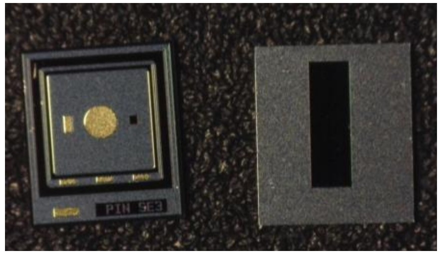
- **Implementing an LGAD device model in TCAD**
  - Tuning of TCAD model against CV/IV and SIMS measurements
  - Extract electric field profiles
- **Study impact ionization models within TCAD**
  - Exploring existing models against experimental data (TCT measurements)
- **Revising the impact ionization parameterizations**
  - Fit impact ionization parameters to experimental data (TCAD and Python scripts)
  - More details in next talk by Esteban Curras Rivera
- **Outlook: Gain reduction in LGADs – First 1D TCAD results**

Part I: Building a TCAD device model

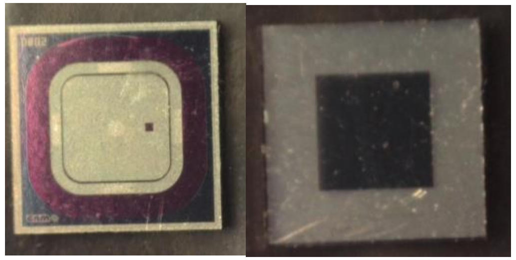
Experimental settings & TCAD simulation

Samples:

- **HPK** LGADs and PAD detectors
  - HPK prototype 2 sensors
  - Area: 1.3 x 1.3 mm^2
  - Thickness: 50 μm
  - 4 different splits (i.e. different gain)



HPK2



CNM 12916

- **CNM** LGADs and PAD detectors
  - CNM run 12916
  - Area: 1.3 x 1.3 mm^2
  - Thickness: 50 μm

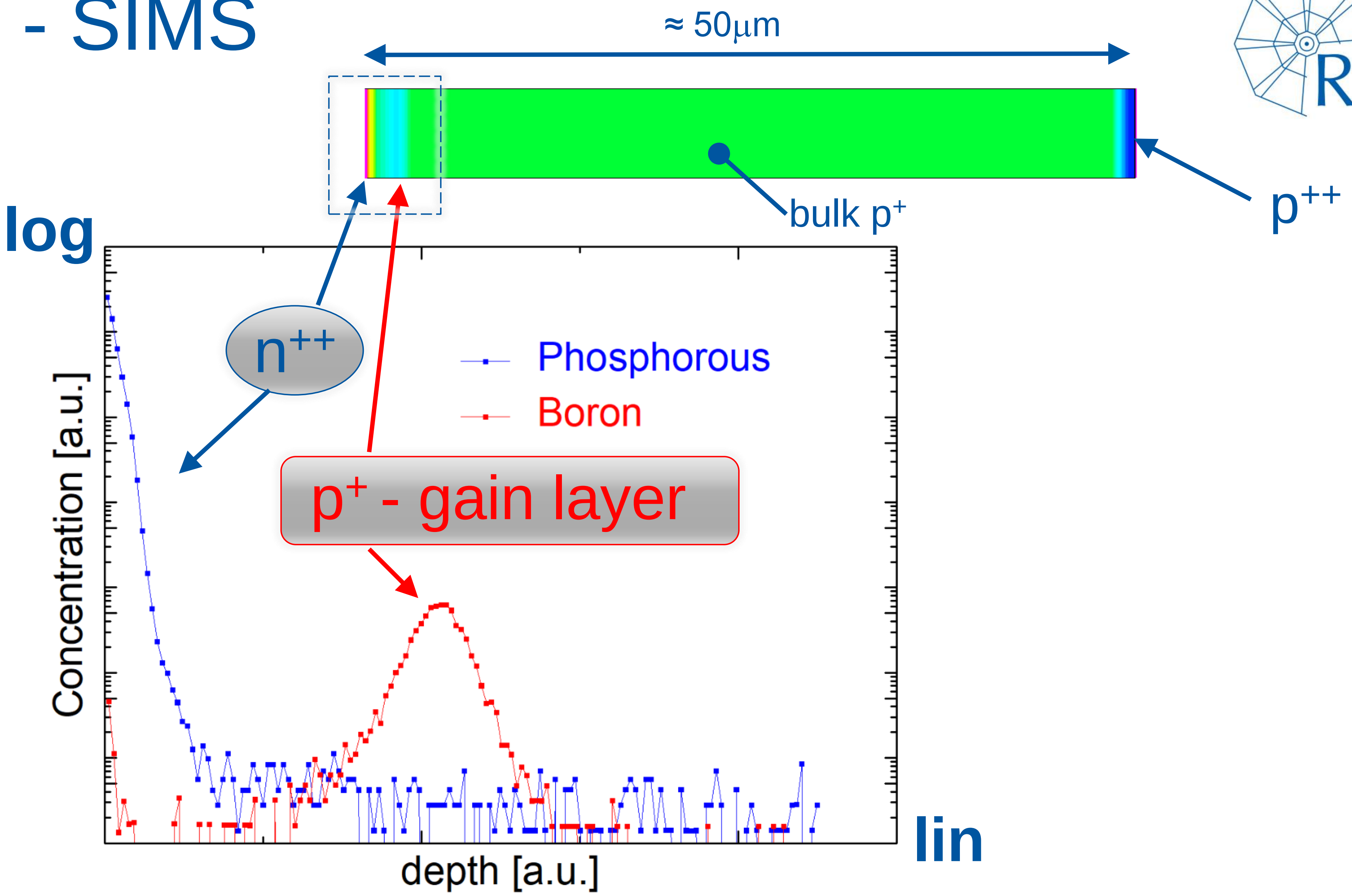
Experiments:

- **Only non-irradiated samples studied**
- CV/IV
  - 10kHz, V_{osc}=0.5V, parallel mode
  - 20°C if not mentioned otherwise
  - guardring connected
- Gain measurements
  - TCT measurements (1060nm, 200ps)
  - Gain = Charge(LGAD)/Charge(Pad)
  - Charge normalisation to MIP with beta source
  - **Details:** E.Curras, CERN EP-RD seminar 12/21

TCAD simulations:

- Synopsys TCAD used for simulations

HPK2 - SIMS



≈ 50µm

bulk p^+

p^{++}

n^{++}

p^+ - gain layer

log

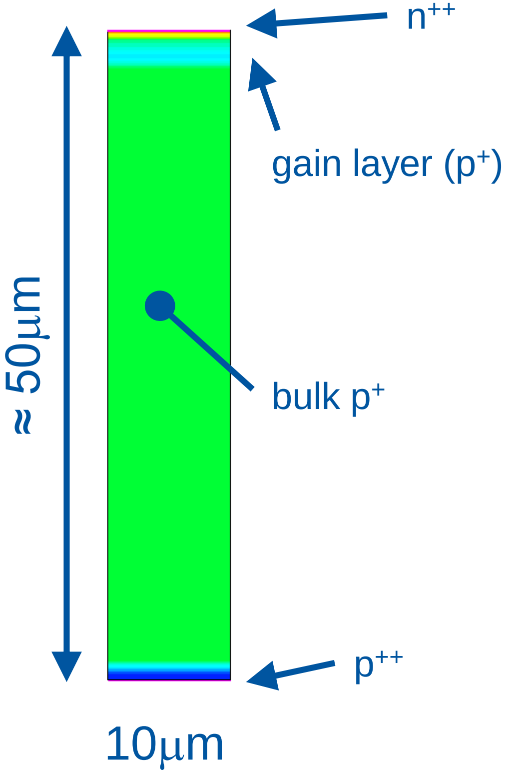
lin

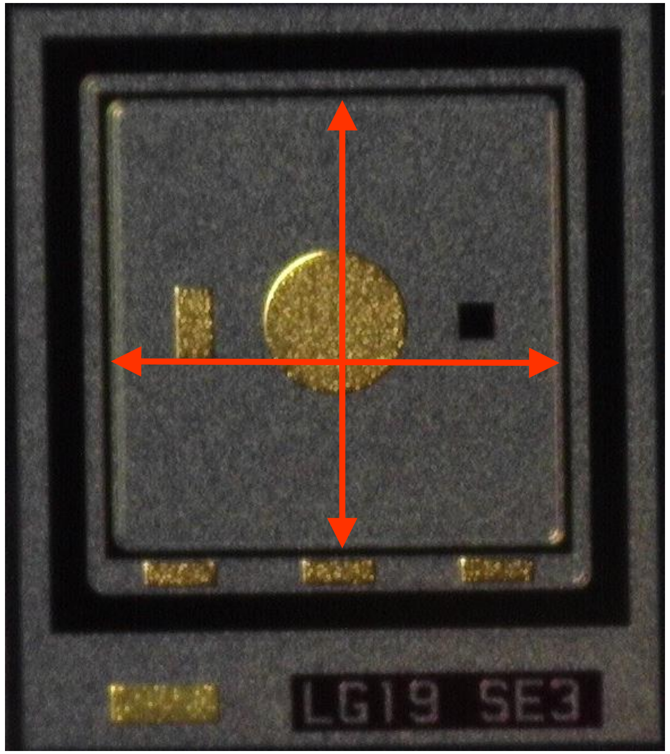
[m.moll 0036]

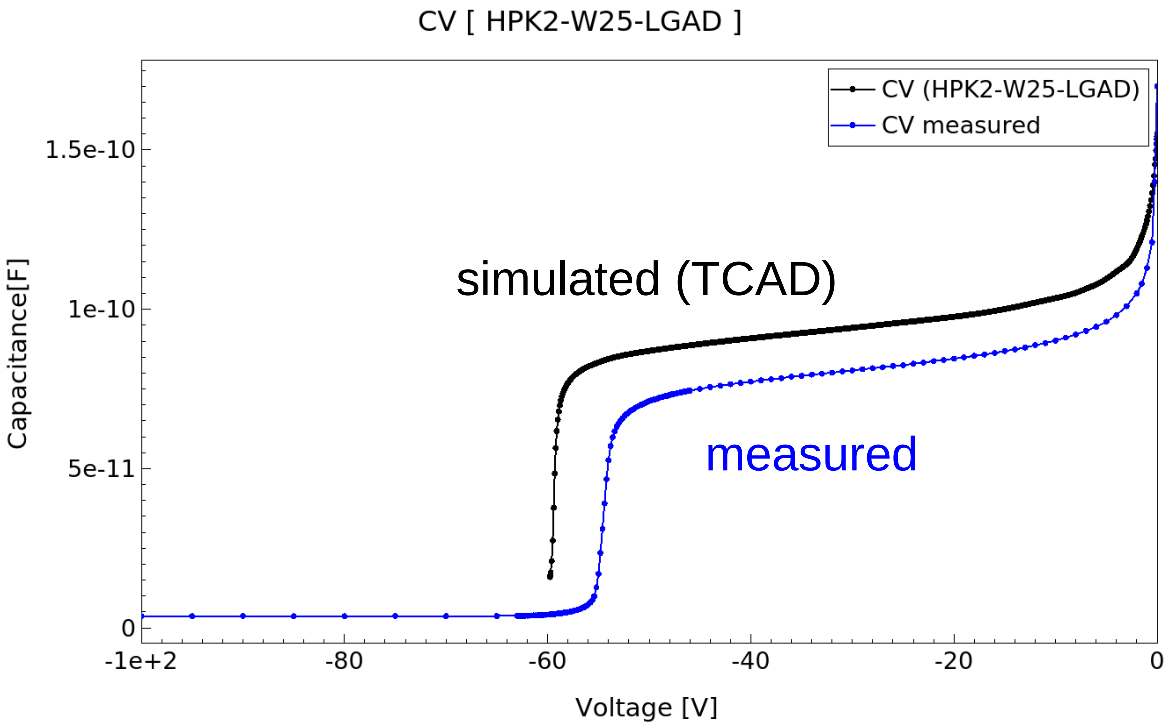
[SIMS: Fresenius, Dresden]

CV: TCAD vs. measurement

- TCAD simulation (1D)
  - Doping profiles as measured by SIMS
  - Assuming parallel plate geometry (1D)
  - Area as deduced from metals on sensor
    - i.e. from middle between pad and guard





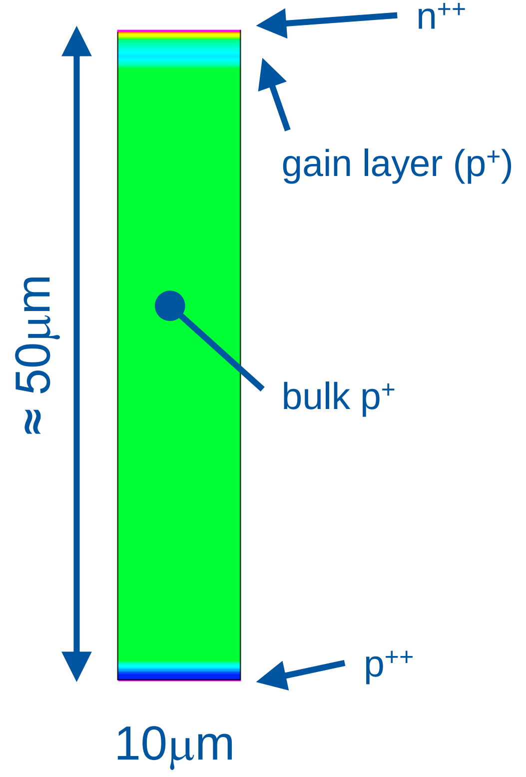


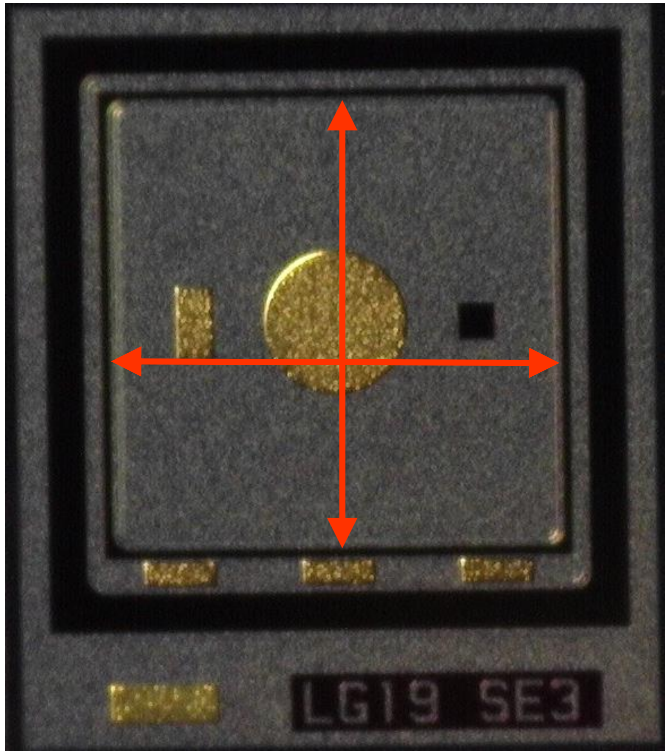
Observation for TCAD simulation:

- Voltage for gain layer depletion too high
- Breakdown during depletion of gain layer
  - Van Overstraeten Model
- Capacitance before V_{GL} too high

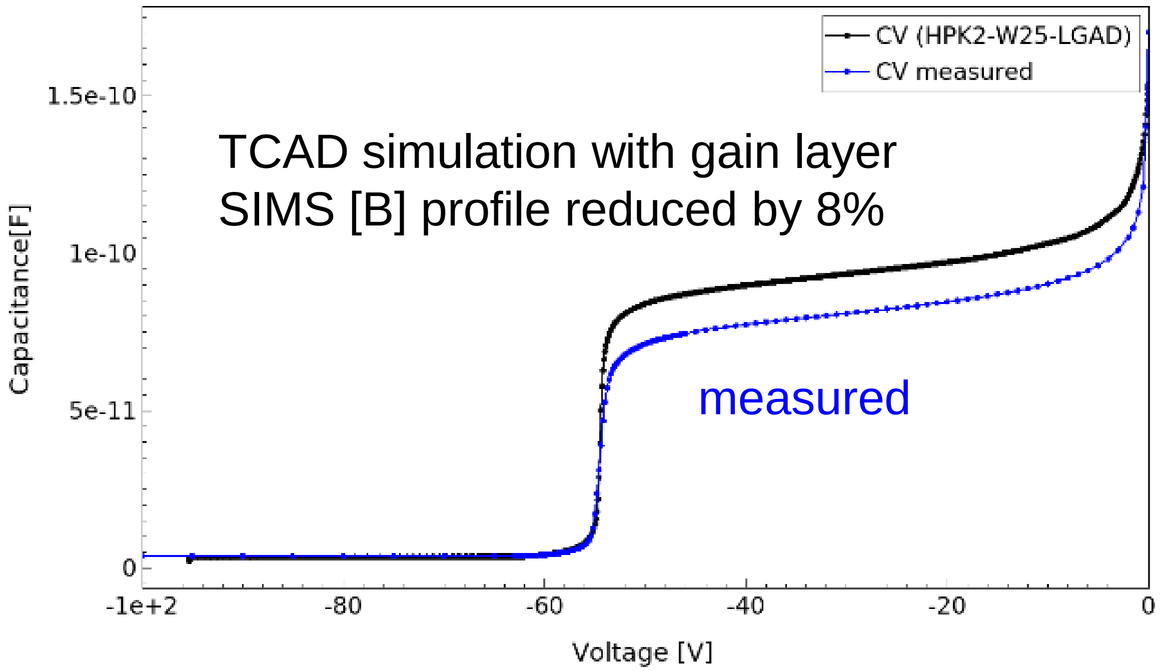
CV: TCAD vs. measurement

- TCAD simulation (1D)
  - Doping profiles as measured by SIMS (x 0.92)
  - Assuming parallel plate geometry (1D)
  - Area as deduced from metals on sensor
    - i.e. from middle between pad and guard





CV [HPK2-W25-LGAD]



TCAD simulation with gain layer
SIMS [B] profile reduced by 8%

measured

Observation for TCAD simulation:

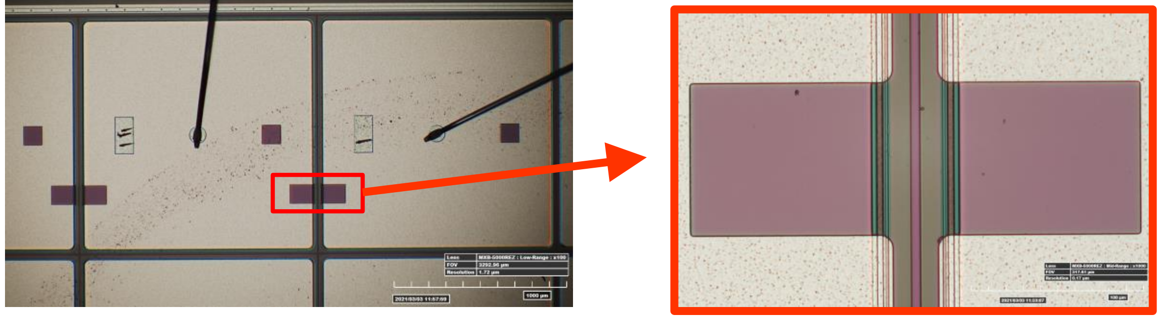
- Capacitance before V_{GL} too high

Conclusion:

- Need to go to more complex geometry (2D)

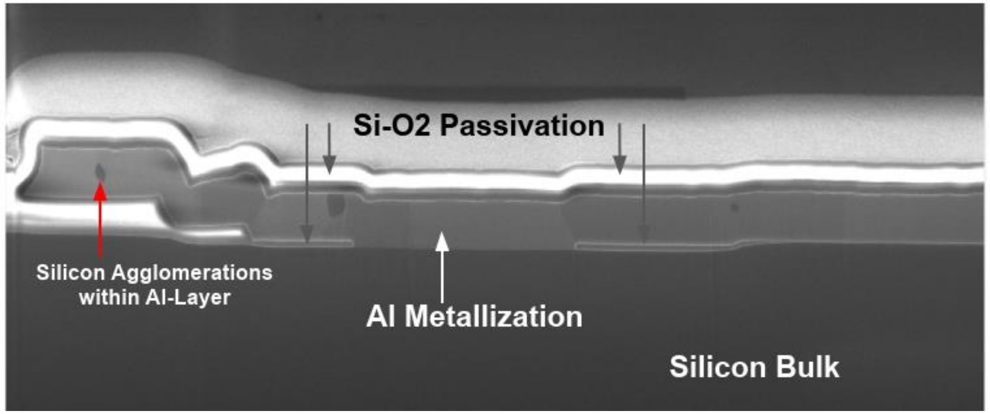
HPK2 – Experimental Input to TCAD model

- High resolution optical imaging of sensor



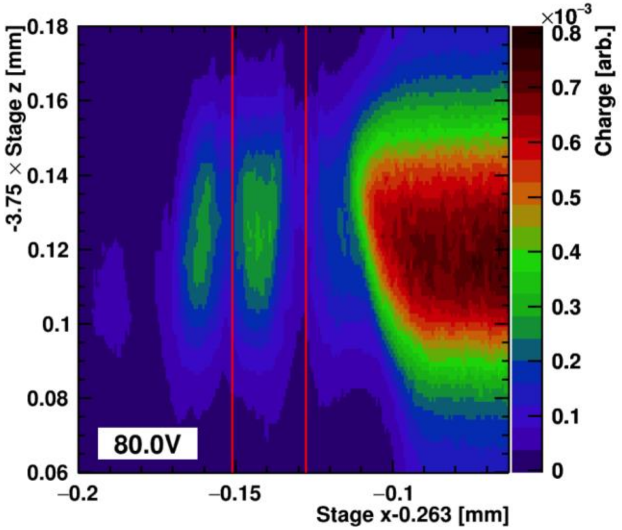
[CERN – QART lab]

- FIB-SEM scans



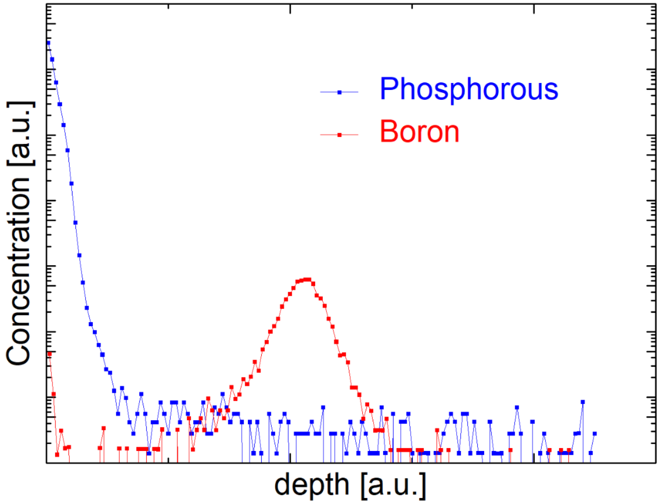
[CERN – EN]

- TPA-TCT scans



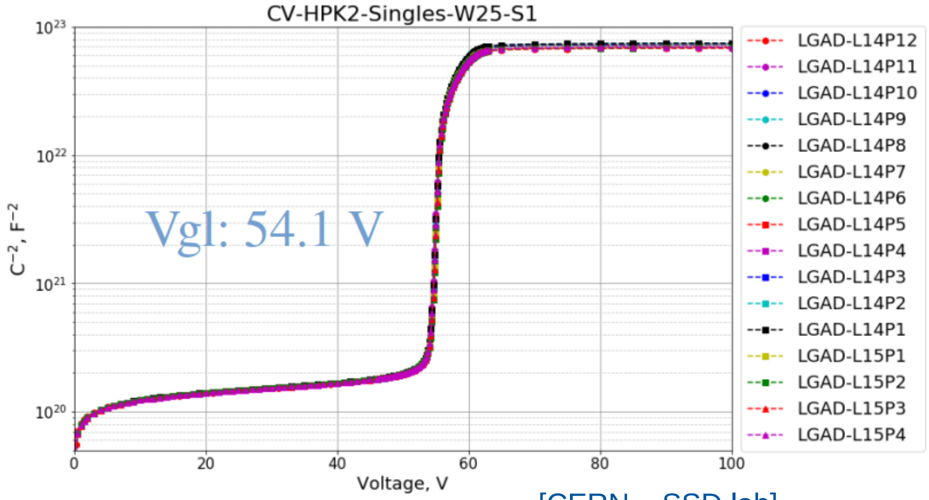
[M.Wiehe, CERN – 38th RD50 Workshop]

- SIMS



[m.moll 0036]

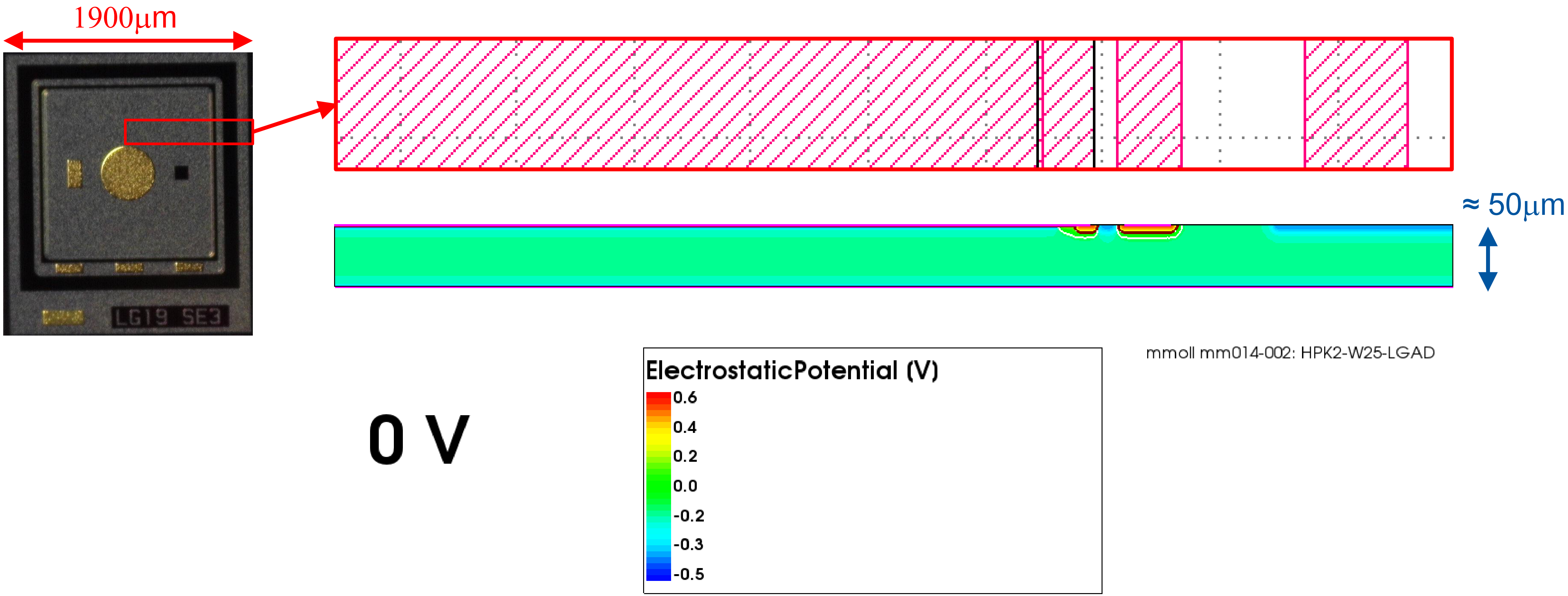
- CV on LGAD/PAD & SRP



[CERN – SSD lab]

HPK2–LGAD - TCAD

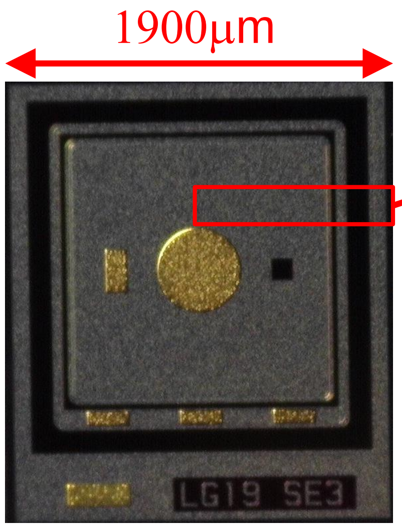
- Lateral field extension

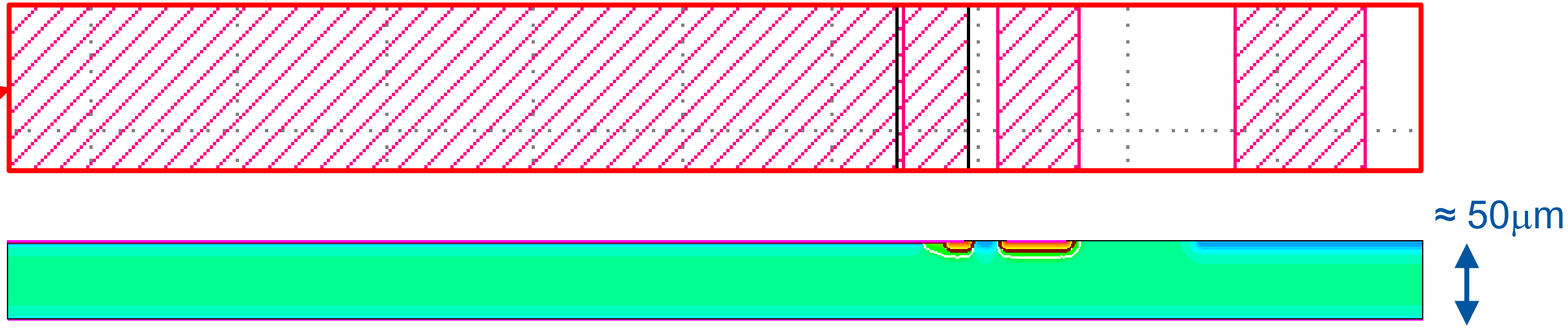


HPK2–LGAD - TCAD

- Lateral field extension

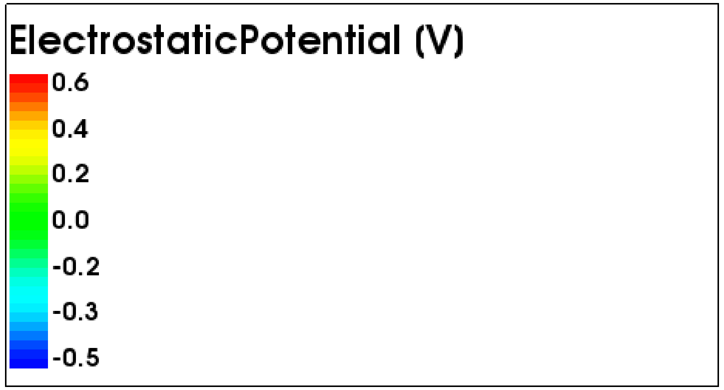
Animated GIF (see pptx version of talk)





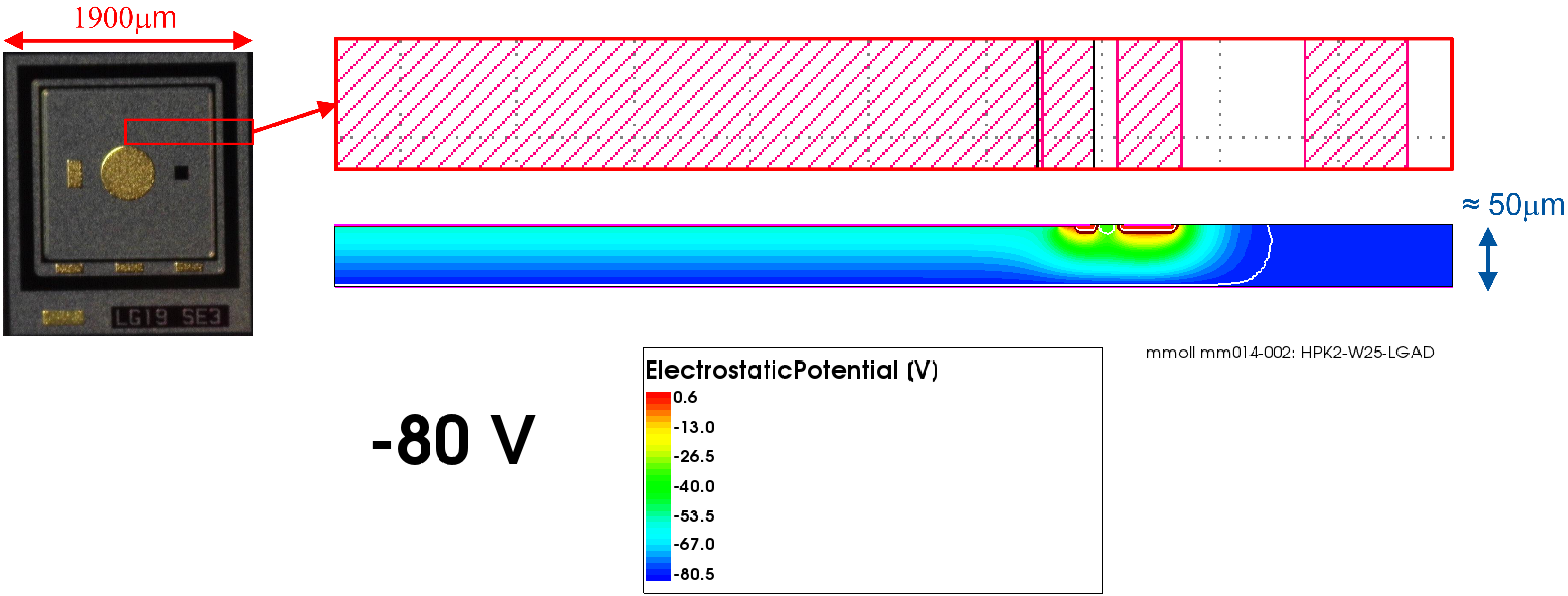
mmoll mm014-002: HPK2-W25-LGAD

0 V



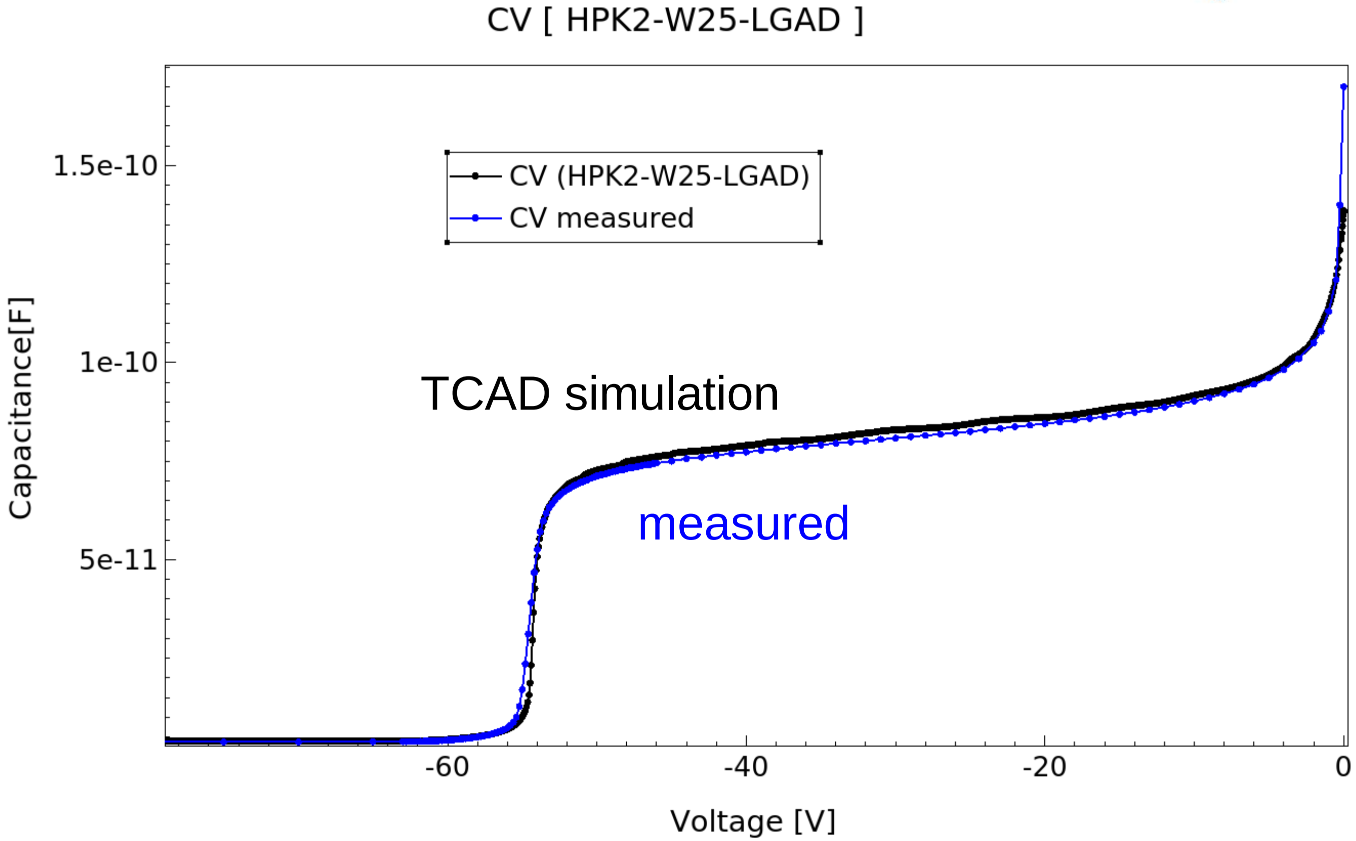
HPK2–LGAD - TCAD

- Lateral field extension



CV: TCAD vs. measurement

- TCAD simulation (2D)
  - Doping profiles based on SIMS
    - with small fetch factor (8% reduction of SIMS data for [B])
  - Simulation of a full device
    - Thickness and backside doping profile from analyses of PAD sensors
    - best guess on periphery geometry as deduced from measurements (TCT, FIB-SEM,TPA-TCT)
      - Note: a p-stop is included here, while device does not seem to have one
    - inclusion of lateral field extension results in time consuming TCAD simulations



Observation for TCAD simulation:

- some fluctuations in simulated data
  - using a too coarse mesh to keep simulation time below one day
- faster drop of capacitance at V_{GL} than in measurement ('measurement artifact', see next slide)
- good agreement
  - The only input data manipulation was a 8% reduction of the measured [B] profile!

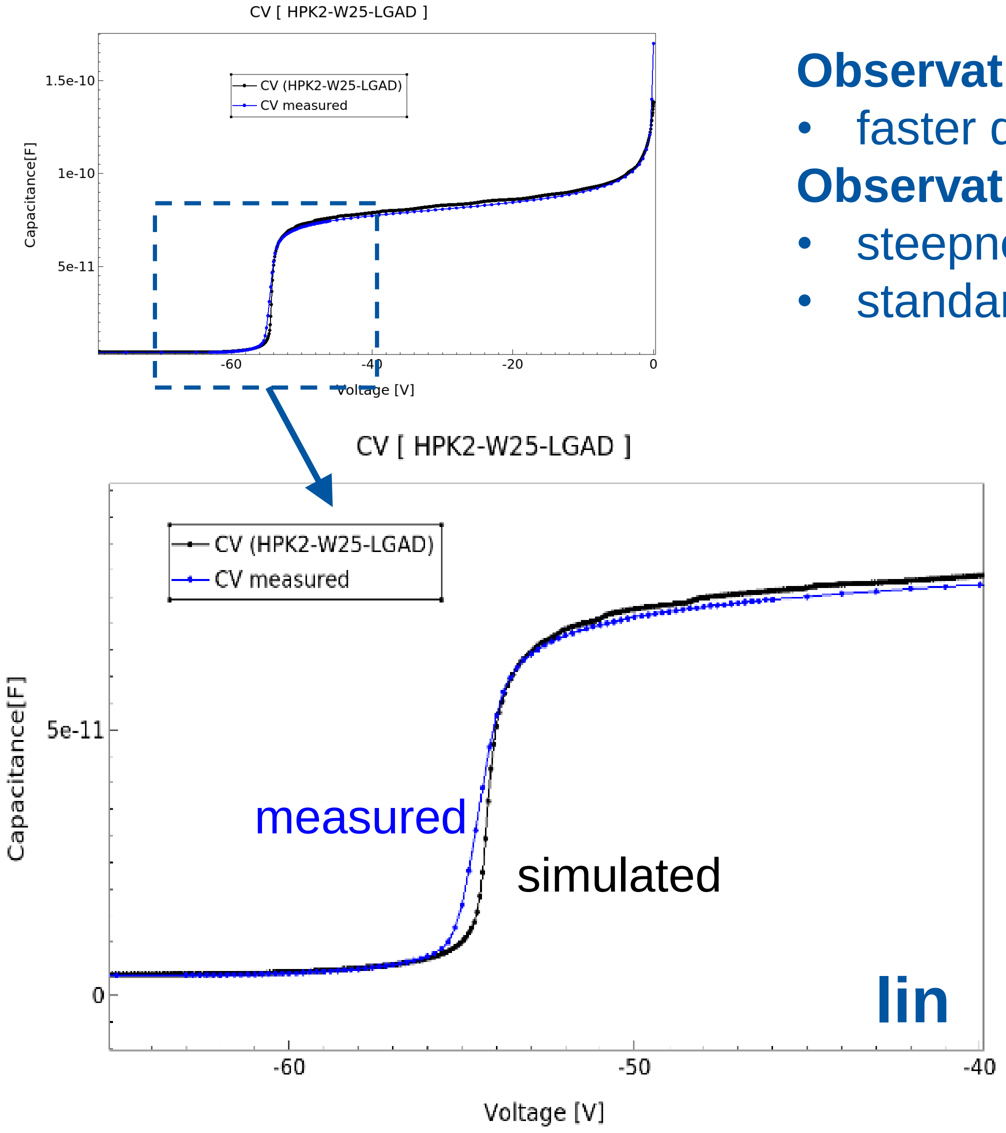
CV: TCAD vs. measurement

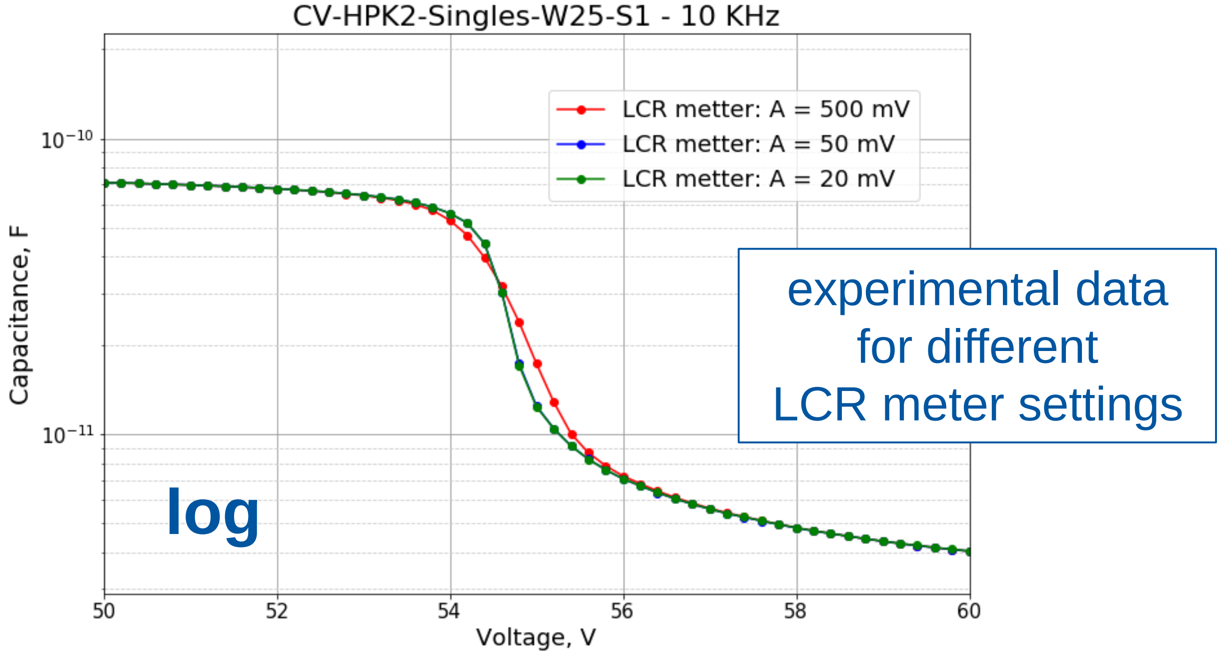
Observation for simulation:

- faster drop of capacitance at V_{GL} than in measurement

Observation for measurement:

- steepness depends on setting of oscillator voltage for LCR meter
- standard: 0.5 V used (i.e. data are averaged over 0.5 V)





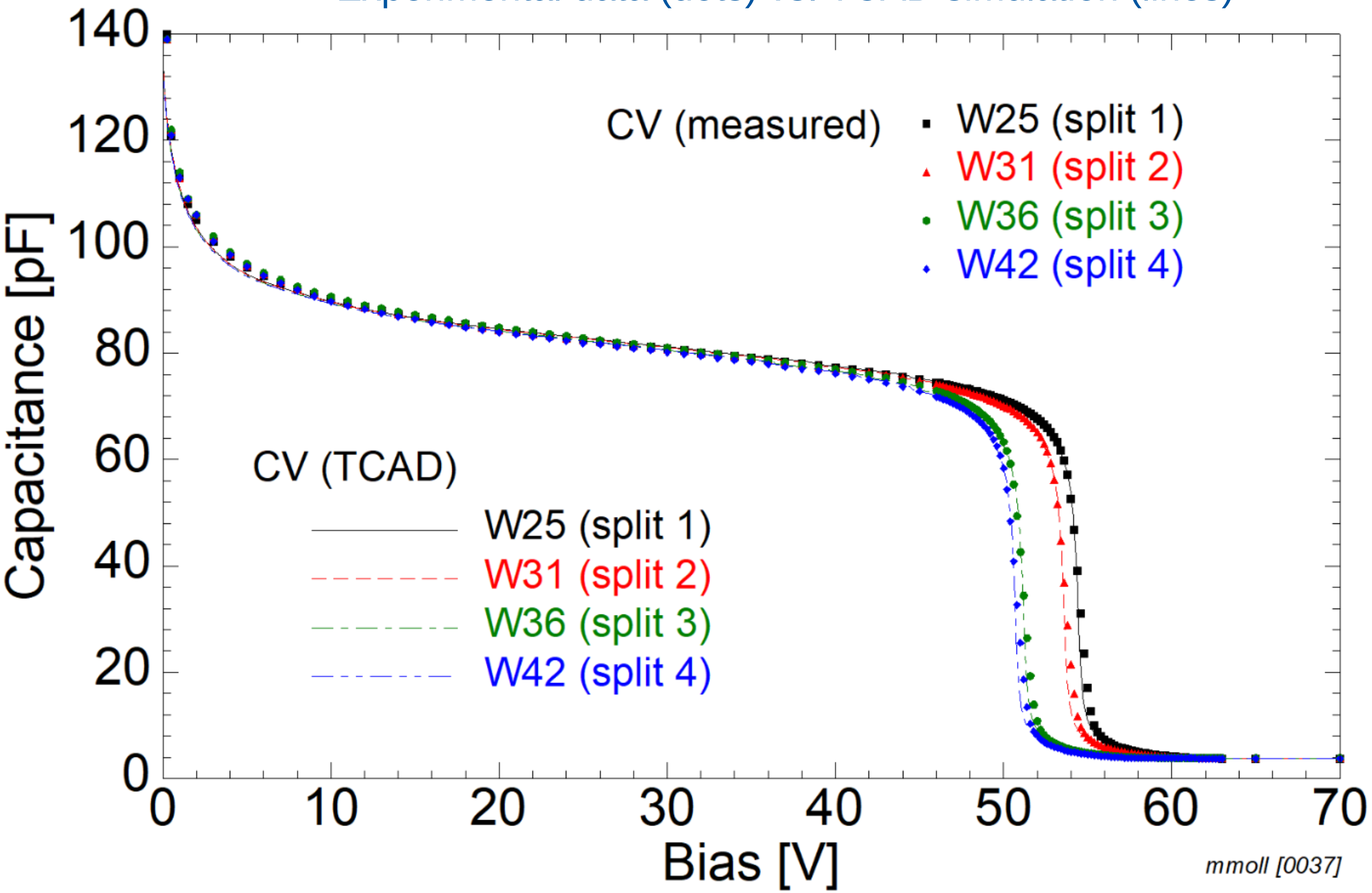
experimental data
for different
LCR meter settings

- **Conclude**: simulation has to be steeper than the measurement

HPK2 sensors: TCAD CV simulation

- Repeat the modeling for all 4 different LGAD splits
  - SIMS only for one split available, the other 3 splits were tuned by the V_{gl} value
  - exploit rotational geometry option of TCAD to get a 3D simulation for faster simulation
- Good agreement

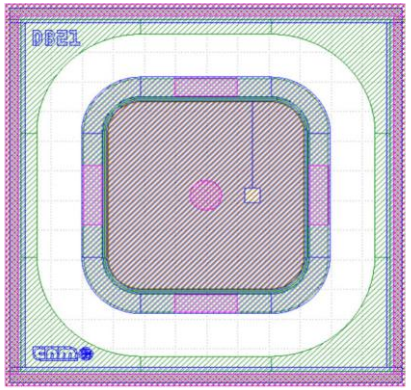
- Experimental data (dots) vs. TCAD simulation (lines)



CNM12916 – Input to TCAD model

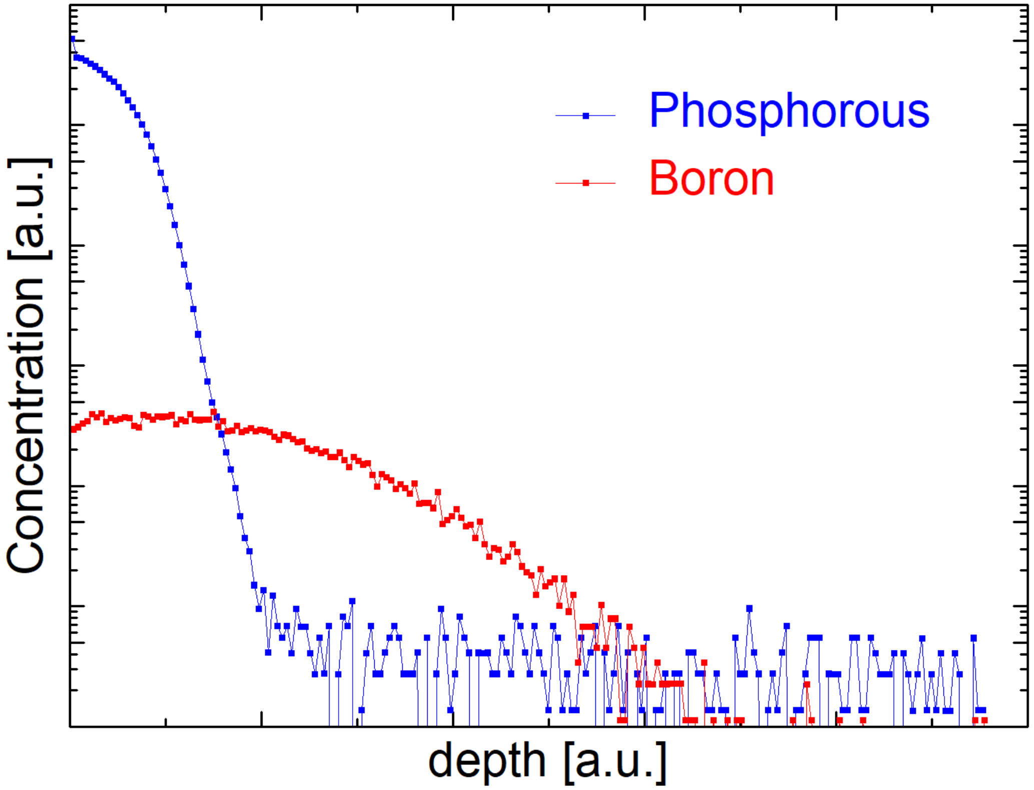
- Information provided by CNM
  - Mask set & relevant processing details!

[A.Doblas, RD50 Workshop Nov.2020]



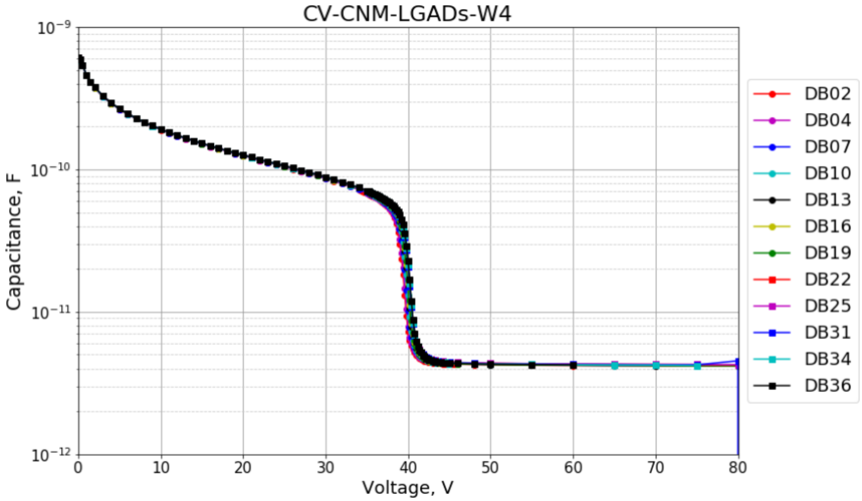
Many thanks to CNM!

- SIMS



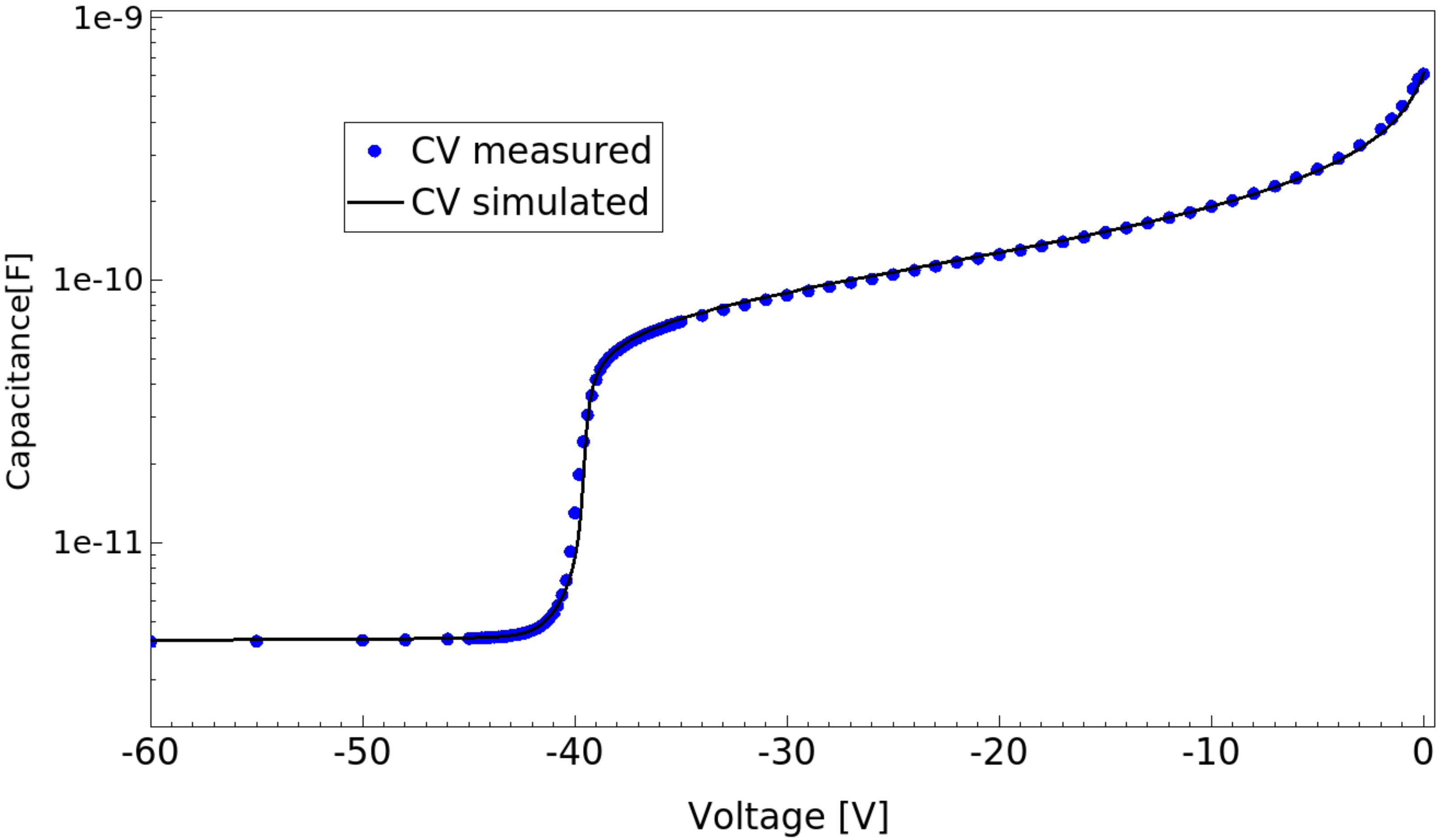
[m.moll 0036]

- CV

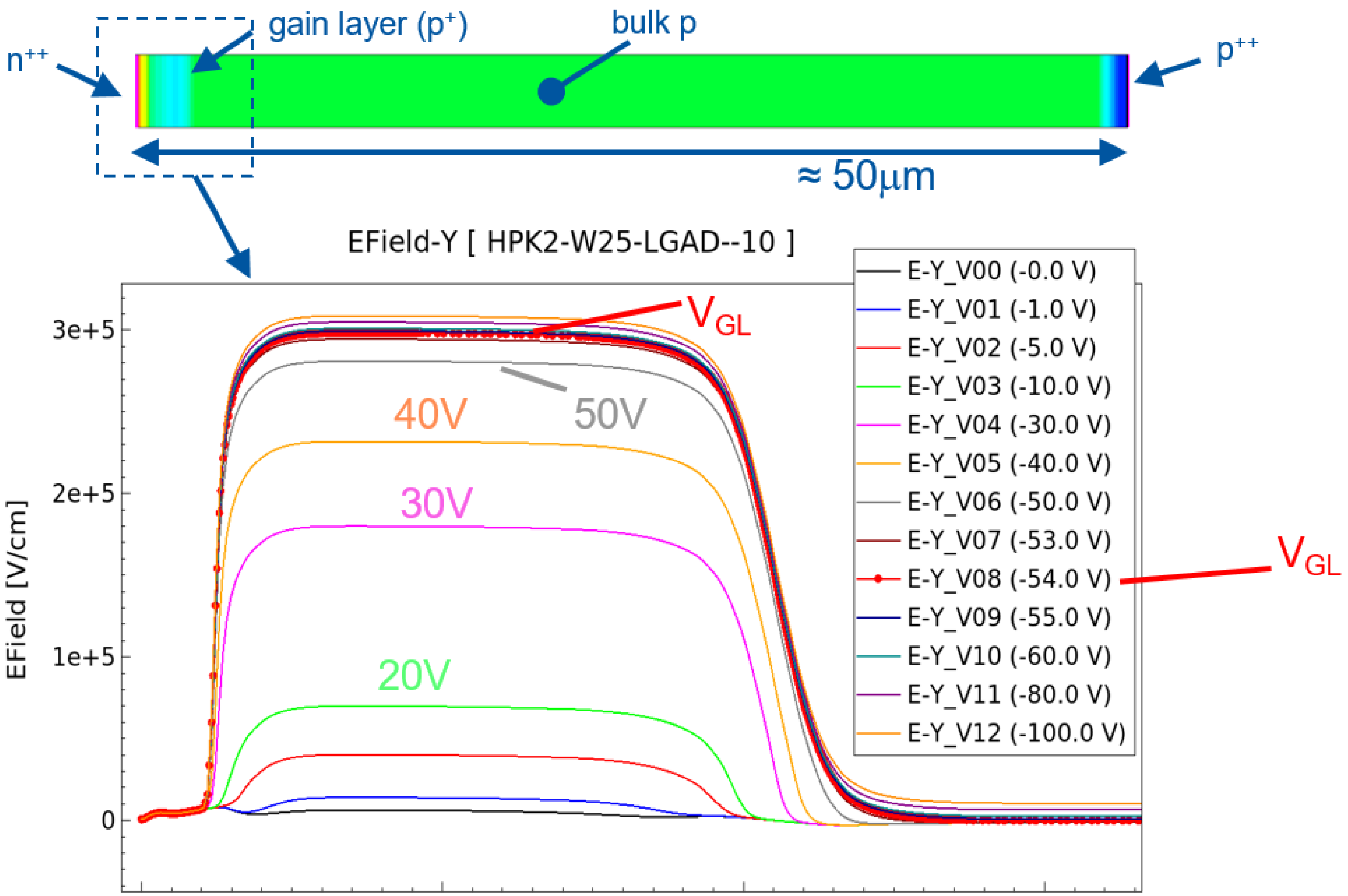


CNM-12916

- TCAD simulation (2D)
  - Doping profiles based on SIMS
    - with small fetch factor (4% reduction of SIMS data for [B])
  - Simulation of a full device
    - Thickness and backside doping profile from analyses of PAD sensors



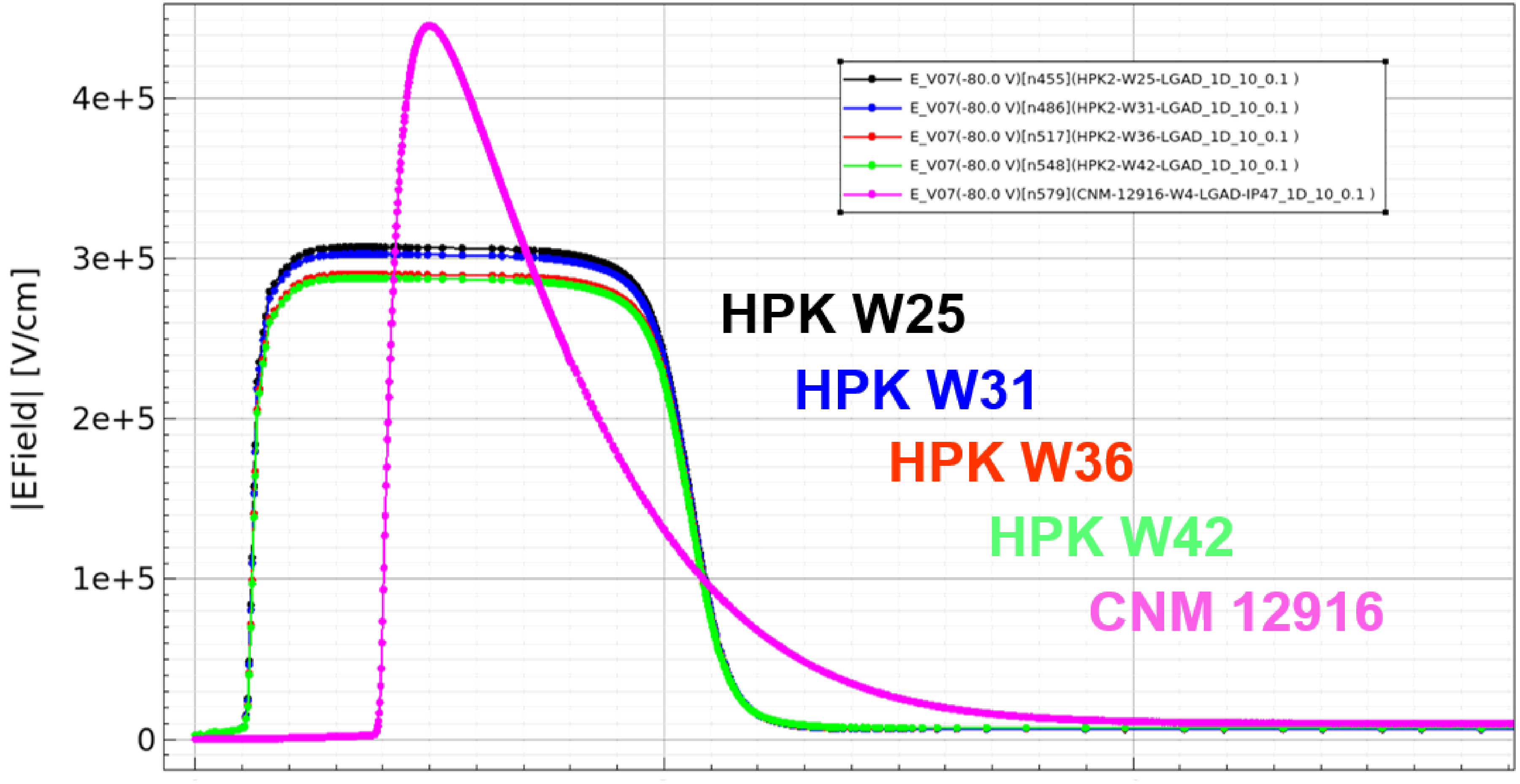
LGAD simulation: Electric Field



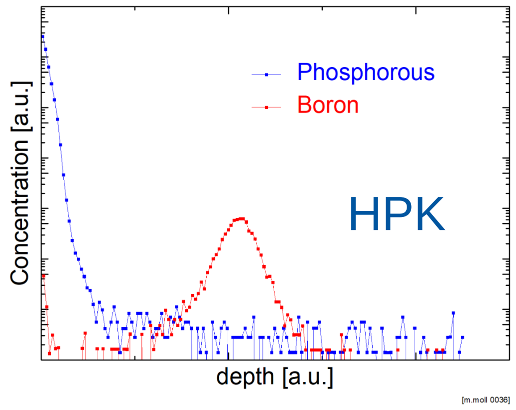
- Voltage ramp from 0V to 100V

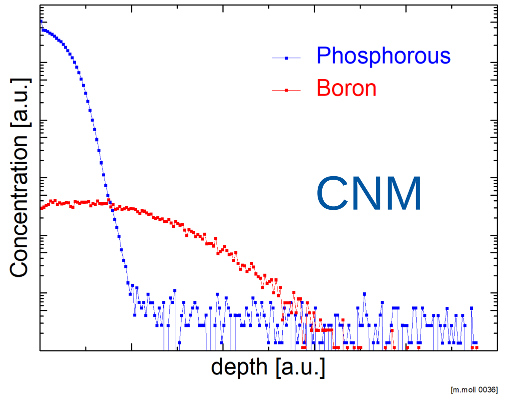
TCAD: Electric Field simulation

- Simulation of field at 80V



Doping profiles



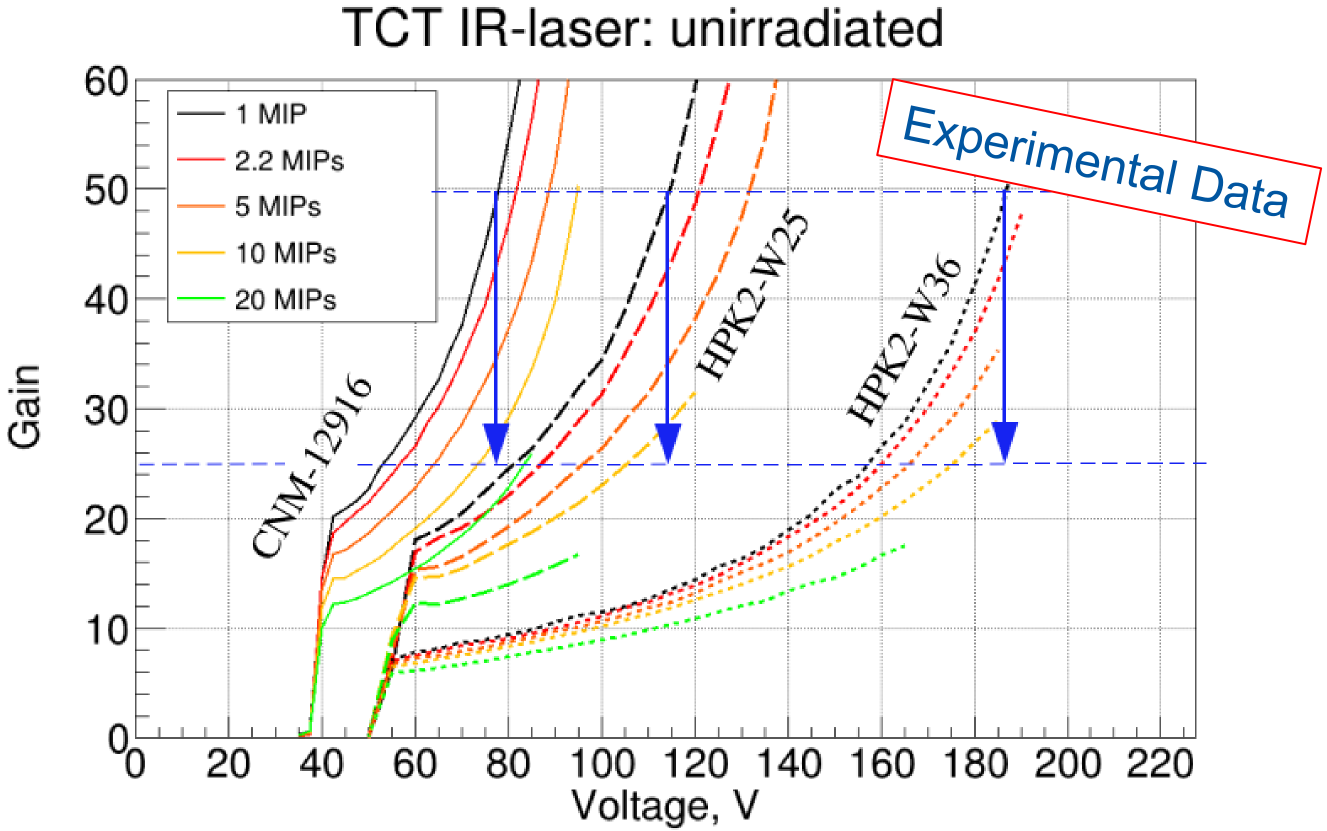


Part II: Impact ionization

Impact Ionization – Experimental Data

- Measurements:
  - IR laser, top illumination
    - pulse length: 200 ps
    - beam spot ≈ 10 um
  - variation of laser intensity
    - MIP unit indicates the most probable charge deposited by a ^{90}Sr beta in same sensor ≈ 0.5 fC ≈ 3100 e/h

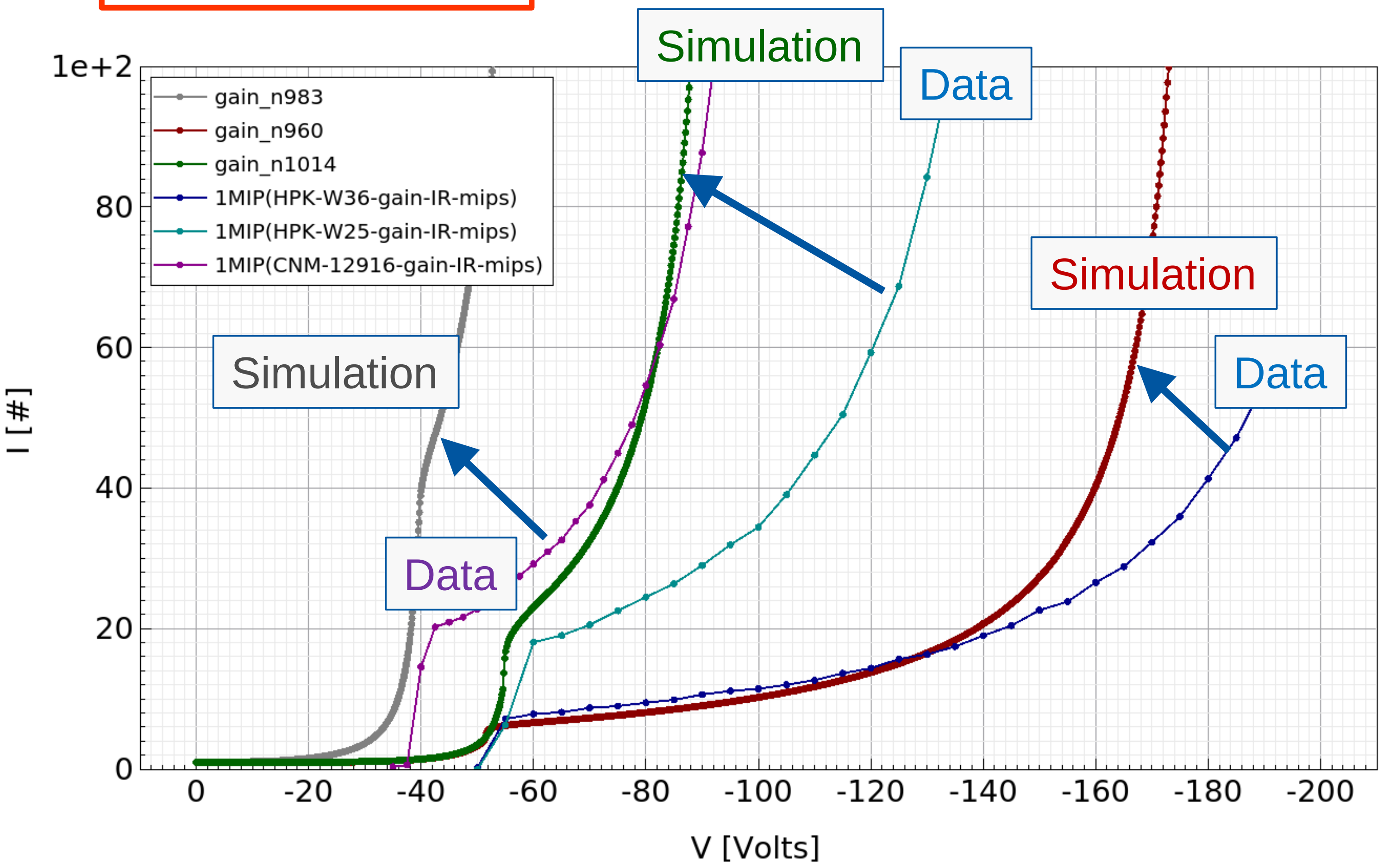
- Observation:
  - Gain reduction mechanism
  - E.Curras at al. "Gain reduction mechanism observed in LGAD"
    - https://doi.org/10.1016/j.nima.2022.166530



Dataset used in the following: Gain measured with a laser intensity giving same charge as 1 MIP (i.e. low charge density, i.e. no gain suppression)

TCAD simulations: Impact Ionization

Overstraeten model



TCAD: Gain obtained from the simulated leakage current

I[#] = IV(with impact ionization) /IV(without impact ionization)
with homogeneous generation rate (SRH model)

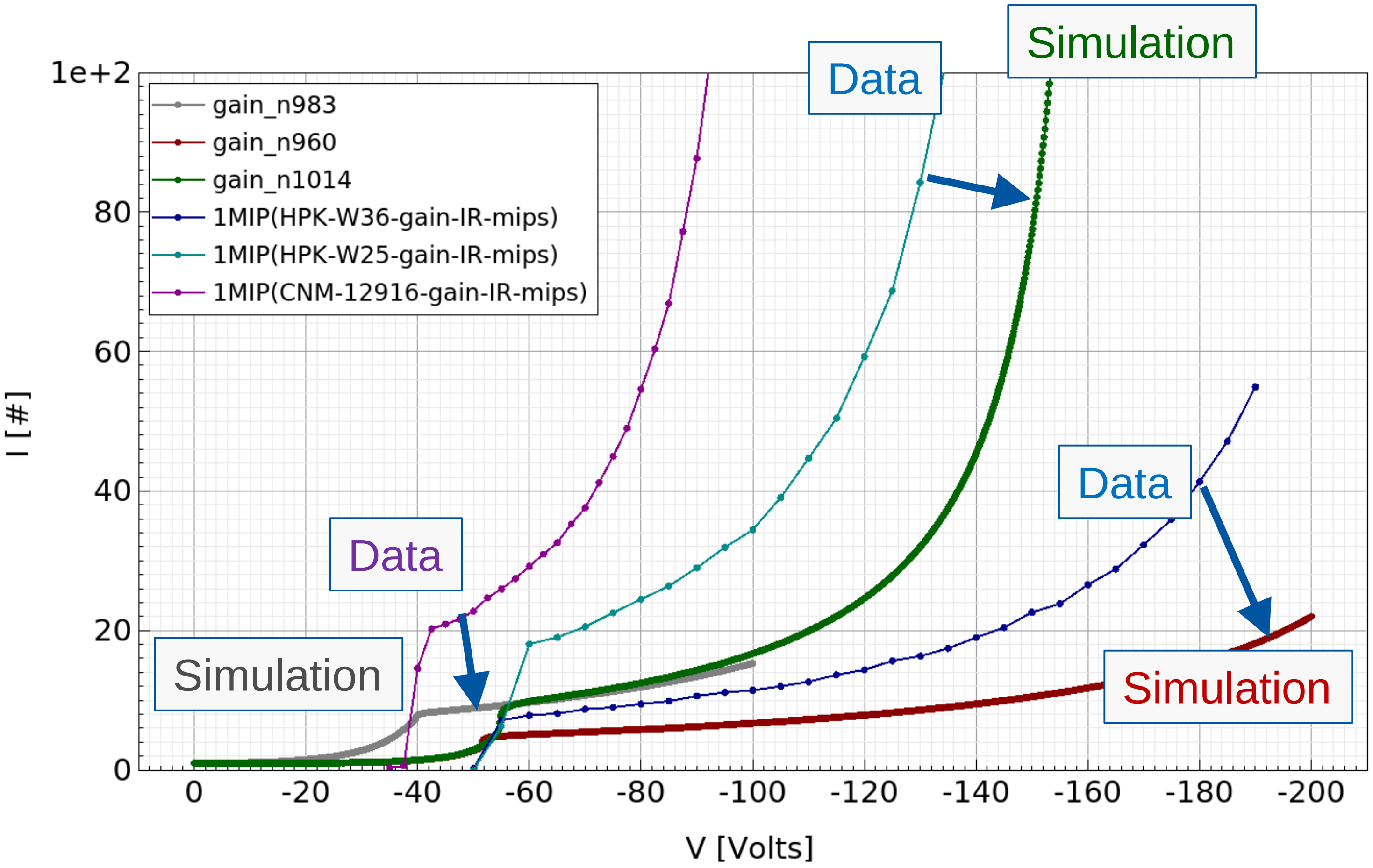
…for fully depleted sensors and for settings where gain reduction effects are not relevant, this gives gain values very close to the ones obtained from TCT simulations

Results only for
'Overstraeten model' shown
…we get a too high gain.

We tried all available Synopsys TCAD local impact ionization models (Okuto, Bologna, …) non reproduced our data nicely

Simulations: Impact Ionization

- Massey model



…implemented as pmi model

$$\alpha_{n,p}(E) = A_{n,p} \cdot \exp\left(-\frac{B_{n,p}(T)}{E}\right)$$

where

⇒ **Massey:**

$A_n = 4.43 \times 10^5\ \mathrm{cm}^{-1}$

$A_p = 1.13 \times 10^6\ \mathrm{cm}^{-1}$

$C_n = 9.66 \times 10^5\ \mathrm{V \cdot cm}^{-1}$

$D_n = 4.99 \times 10^2\ \mathrm{V \cdot cm^{-1} \cdot K^{-1}}$

$B_n(T) = C_n + D_n \cdot T$

$B_p(T) = C_p + D_p \cdot T$

$C_p = 1.71 \times 10^6\ \mathrm{V \cdot cm}^{-1}$

$D_p = 1.09 \times 10^3\ \mathrm{V \cdot cm^{-1} \cdot K^{-1}}$

…with Massey model we got a too low gain

[Massey vs. Overstraeten:
see also M.Mandurrino, 30th RD50 Workshop]

.. obtain our own parameterization

- electric field profiles (as function of voltage) extracted from TCAD
- imported into a Python script to calculate the gain of the device
  - see backup slides and following presentation by Esteban (going from Python to C++)
- fitting the obtained gain to the experimental data by variation of impact ionization parameters (as e.g. also A.Howard, RD50 Workshop Valencia)

$$\alpha_{n,p}(E) = A_{n,p} \cdot \exp\left(-\frac{B_{n,p}(T)}{E}\right)$$

where

⇒ **Massey:**

$\boxed{A_n} = 4.43 \times 10^5\ \mathrm{cm}^{-1}$

$\boxed{A_p} = 1.13 \times 10^6\ \mathrm{cm}^{-1}$

$\boxed{C_n} = 9.66 \times 10^5\ \mathrm{V \cdot cm^{-1}}$

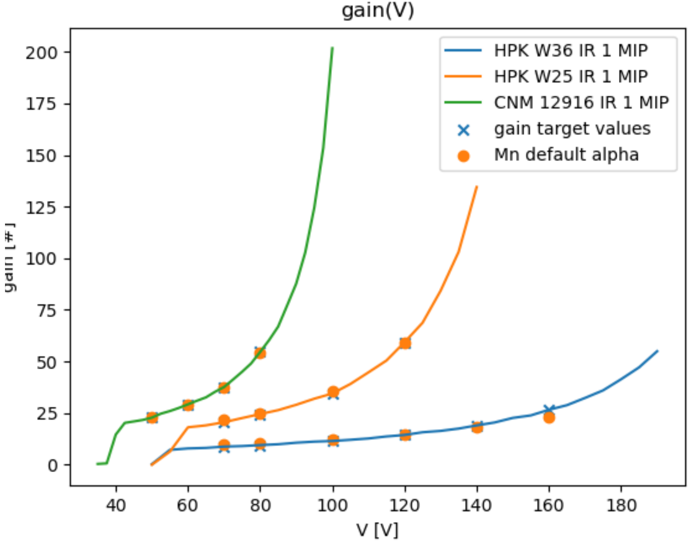
$D_n = 4.99 \times 10^2\ \mathrm{V \cdot cm^{-1} \cdot K^{-1}}$

$B_n(T) = C_n + D_n \cdot T$

$B_p(T) = C_p + D_p \cdot T$

$\boxed{C_p} = 1.71 \times 10^6\ \mathrm{V \cdot cm^{-1}}$

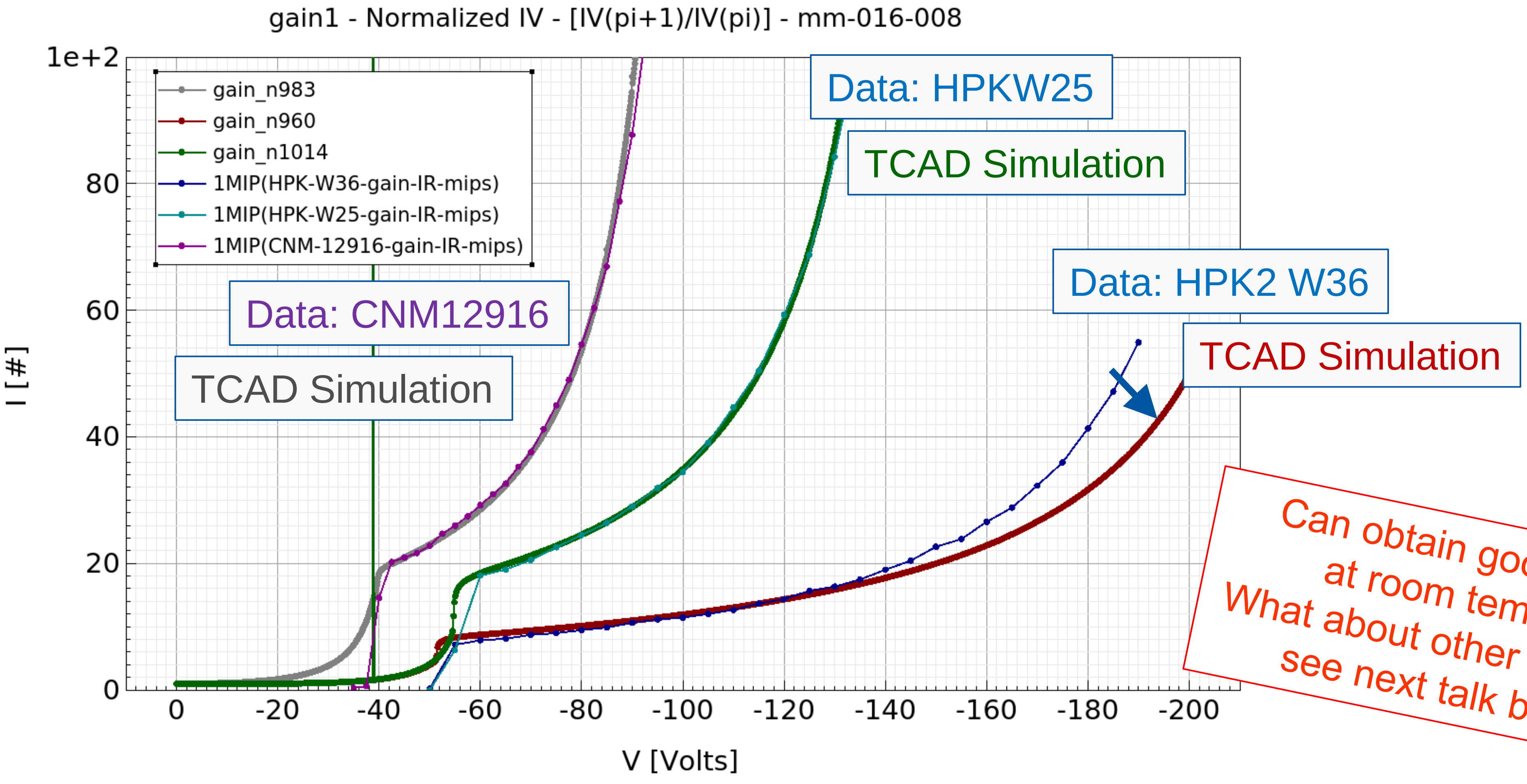
$D_p = 1.09 \times 10^3\ \mathrm{V \cdot cm^{-1} \cdot K^{-1}}$



- all measurements taken at same temperature → 4 parameter fit sufficient
- obtained parameters fed back into TCAD modeling

Fit of the alpha parameterization

- New parameterization for CNM12916 & HPK2 simulation obtained.



Data: CNM12916

TCAD Simulation

Data: HPKW25

TCAD Simulation

Data: HPK2 W36

TCAD Simulation

Can obtain good agreement
at room temperature.
What about other temperatures?
see next talk by Esteban

Part III: Gain suppression

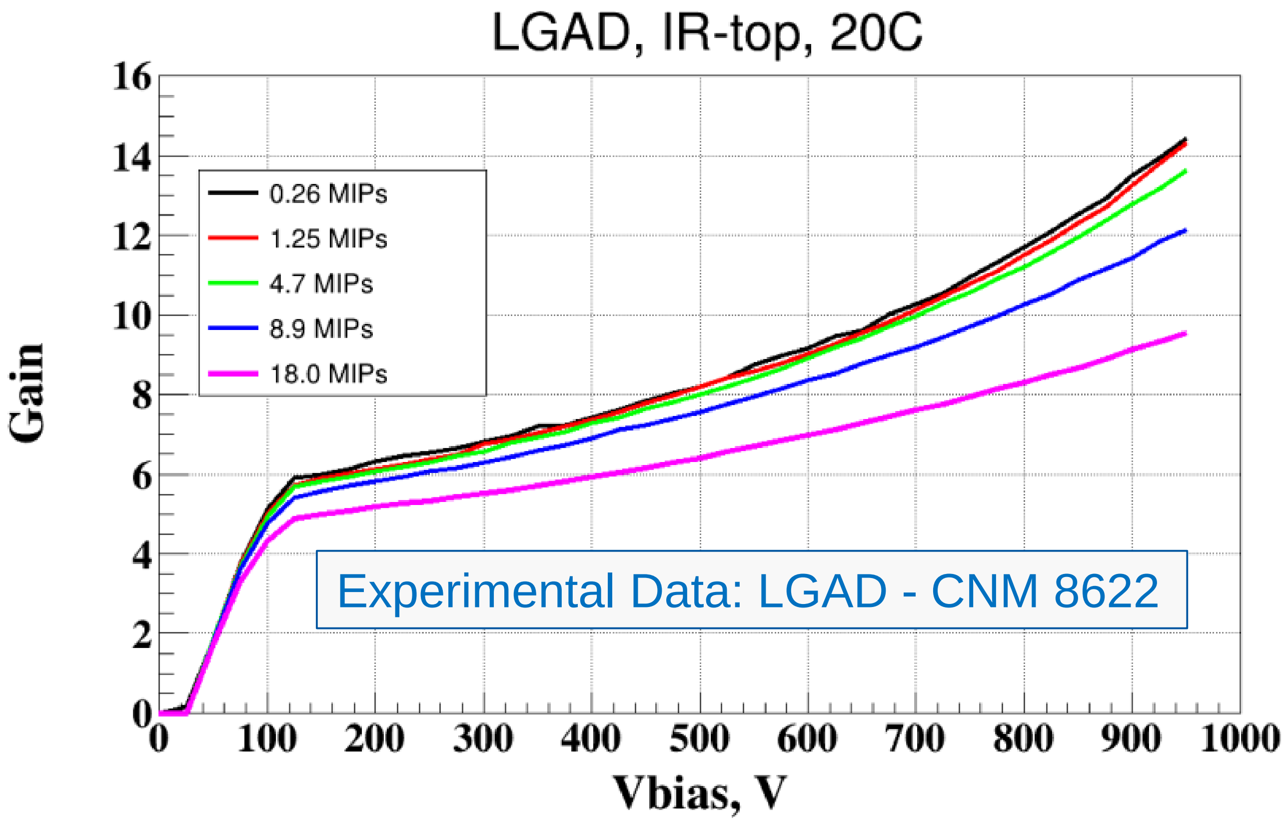
..first results

Gain simulations: CNM 8622 LGADs

- For laser intensities below ‘gain reduction threshold’ and voltages above full depletion, I expect gain deduced from simulation of leakage currents and TCT simulations to be identical.

- Cross check against experimental data:
  - LGAD from CNM 8622, 285 um
  - TCT measurements
    - IR from top at 20°C, beam spot ≈ 10um
  - *Reference:*
    - *E.Curras, “Influence of the ionization density on LGAD gain as measured with TCT, TPA-TCT and Sr-90”, WP1.4. meeting, CERN, 8.3.2022*

- *Note on simulation of CNM8622*
  - *No SIMS available*
  - *CV(f) dependence measured before irradiation!*
  - *thickness from TPA-TCT measurement*
  - ***Doping profile was tailored to match experimental data**:*
    - *(a) The gain layer depletion (V_{gl})*
    - *(b) The gain for low intensity illumination (i.e. without gain suppression)*

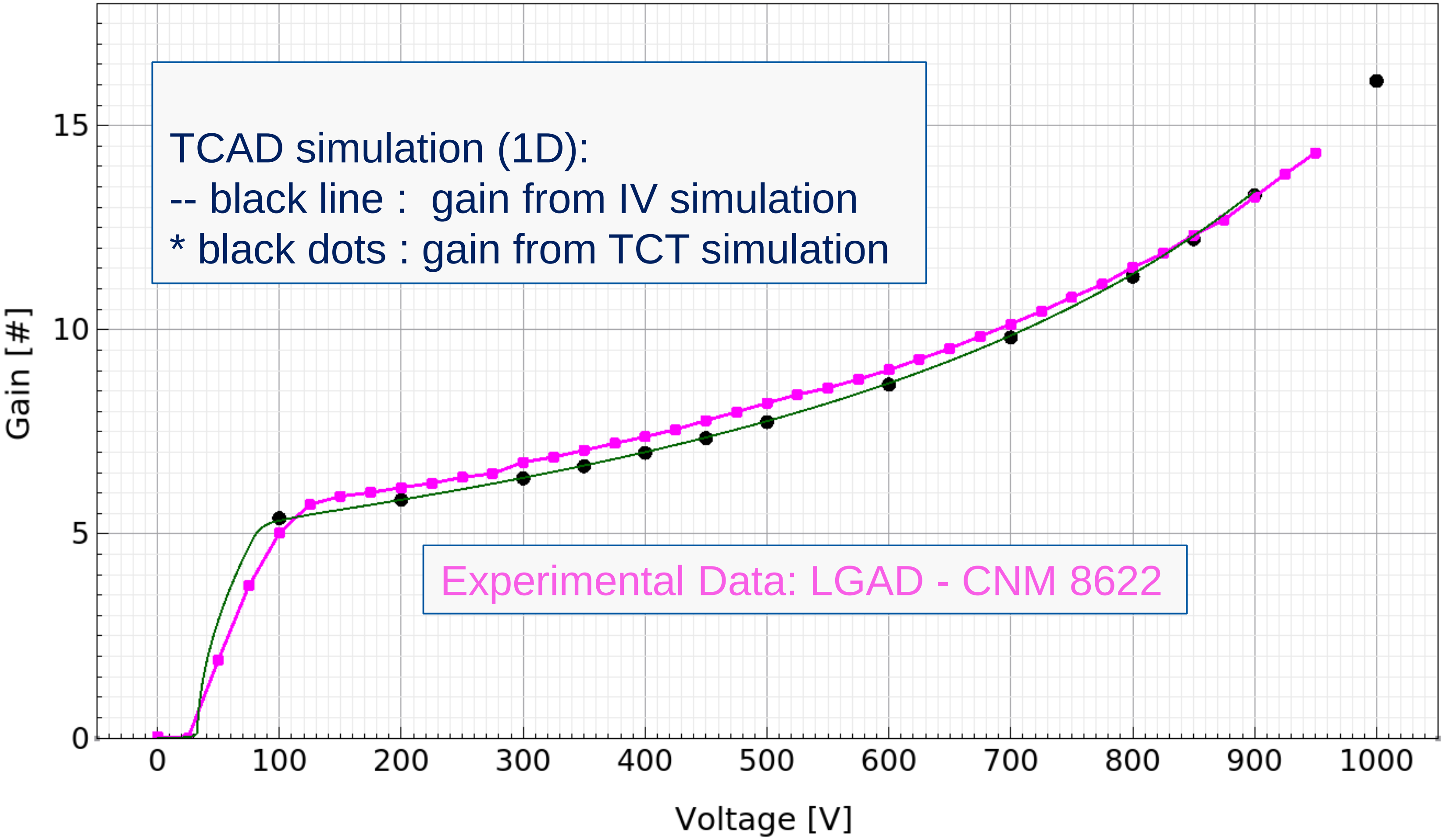


Experimental Data: LGAD - CNM 8622

Gain simulations: TCT vs. Leakage Current

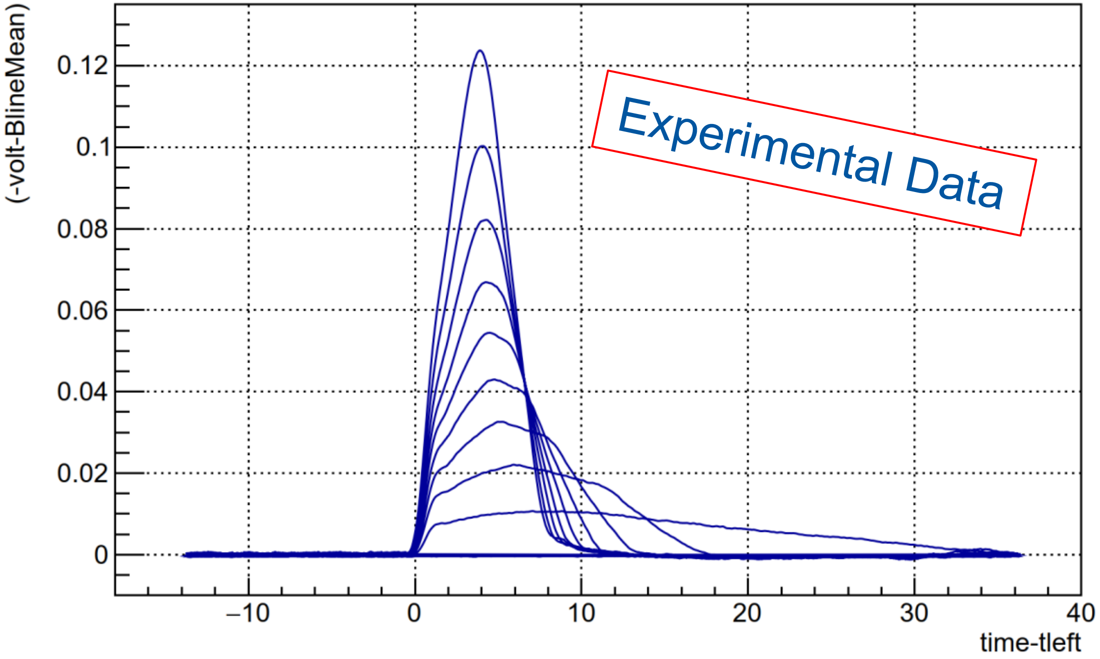
- Experimental data:
  - LGAD from CNM 8622, 285 um
  - TCT measurements
    - IR from top at 20°C,
      beam spot ≈ 10um
  - Gain = Charge(LGAD)/Charge(PIN)

- *Simulated ("1D")*
  - *IV (LGAD with gain)*
    / IV(LGAD without gain)
  - *TCT (LGAD with gain)*
    / TCT(LGAD without gain)
    - *Low light intensity (no gain suppression)!*

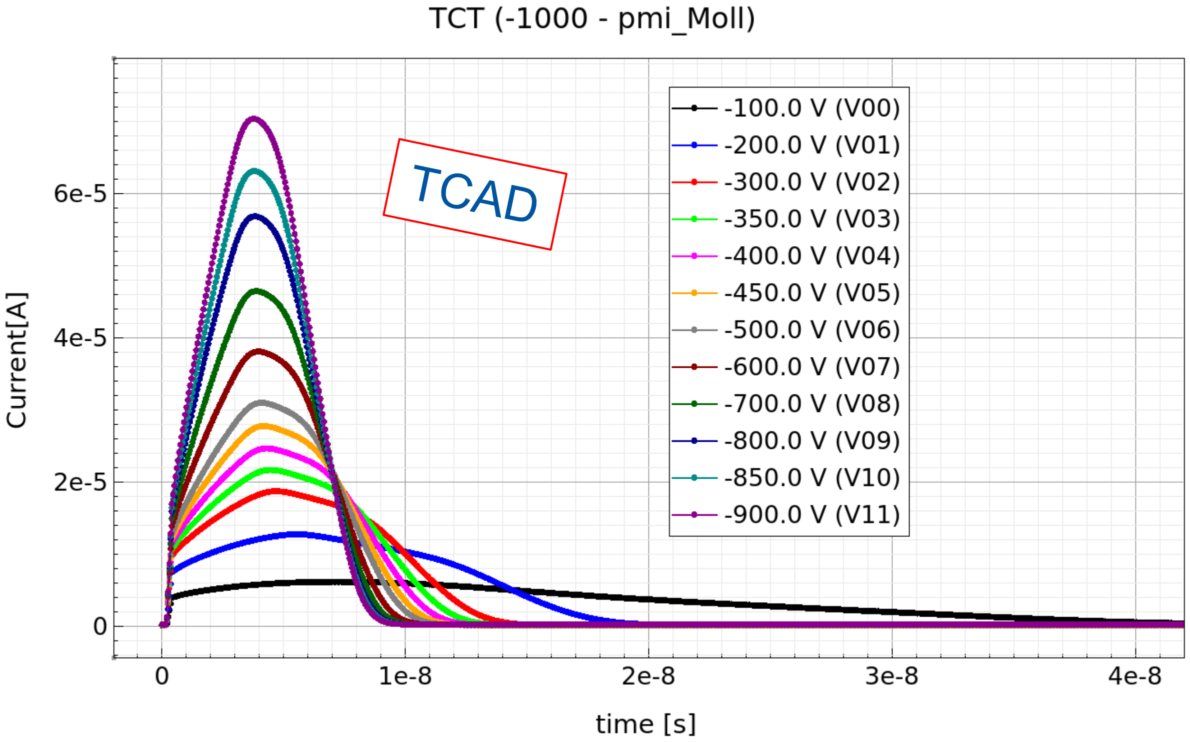


TCT – LGAD 8622 – low intensity

- Experimental data [IR front – RT -1.25 MIP]
  - 100V - 900 V

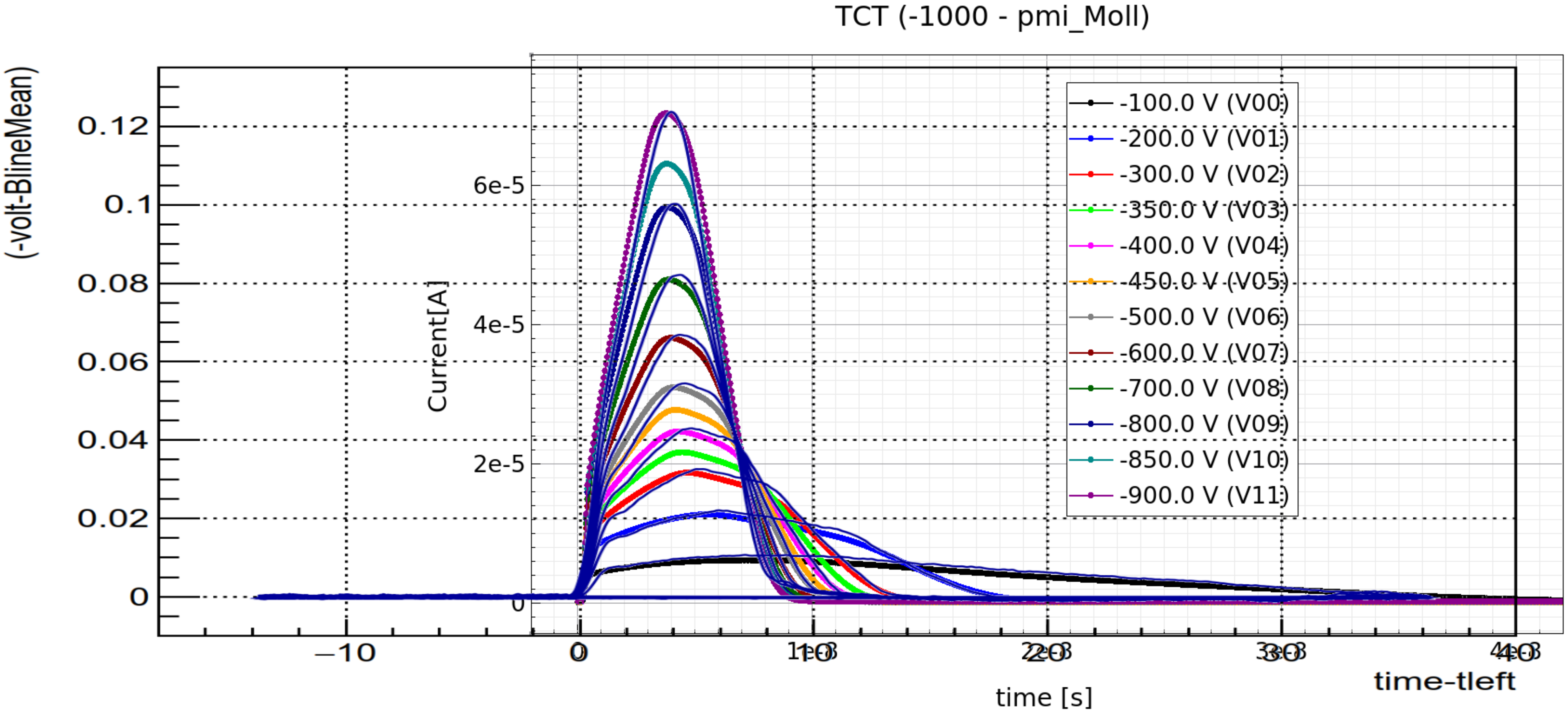


- TCAD simulation [IR – front - RT low intensity]
  - 100 - 900 V



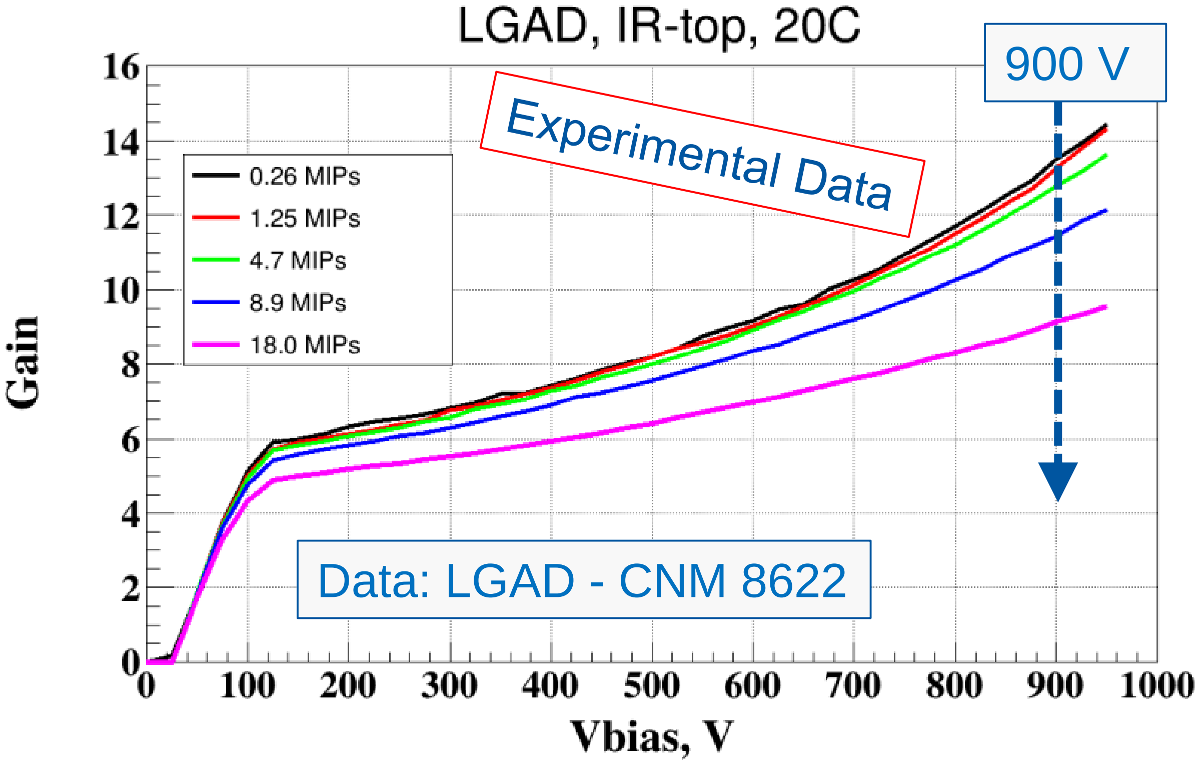
TCT – LGAD 8622 – low intensity

- Experimental data [IR – RT -1.25 MIP]
  - 100 - 900 V
- TCAD [IR – front - RT low intensity]
  - 100 - 900 V



TCT: Variation of laser pulse intensity

- TCT: IR and red laser pulses, top and bottom illumination

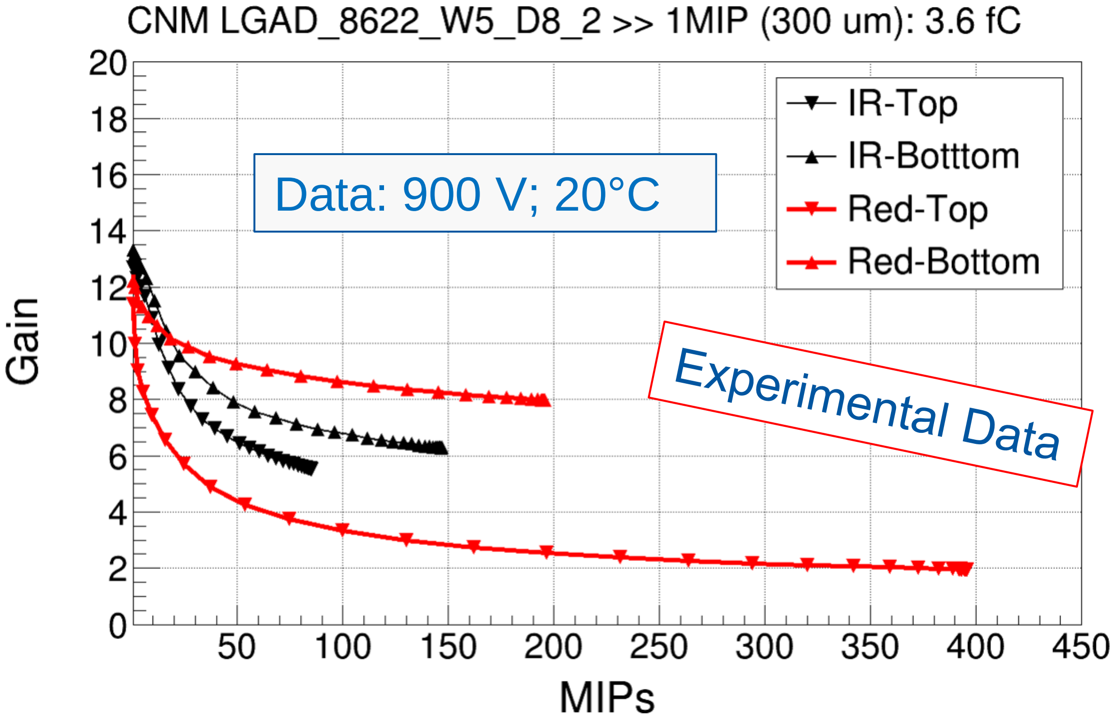


900 V

Experimental Data

Data: LGAD - CNM 8622

[Data: E.Curras, CERN WP1.4. meeting, 8.3.2022]



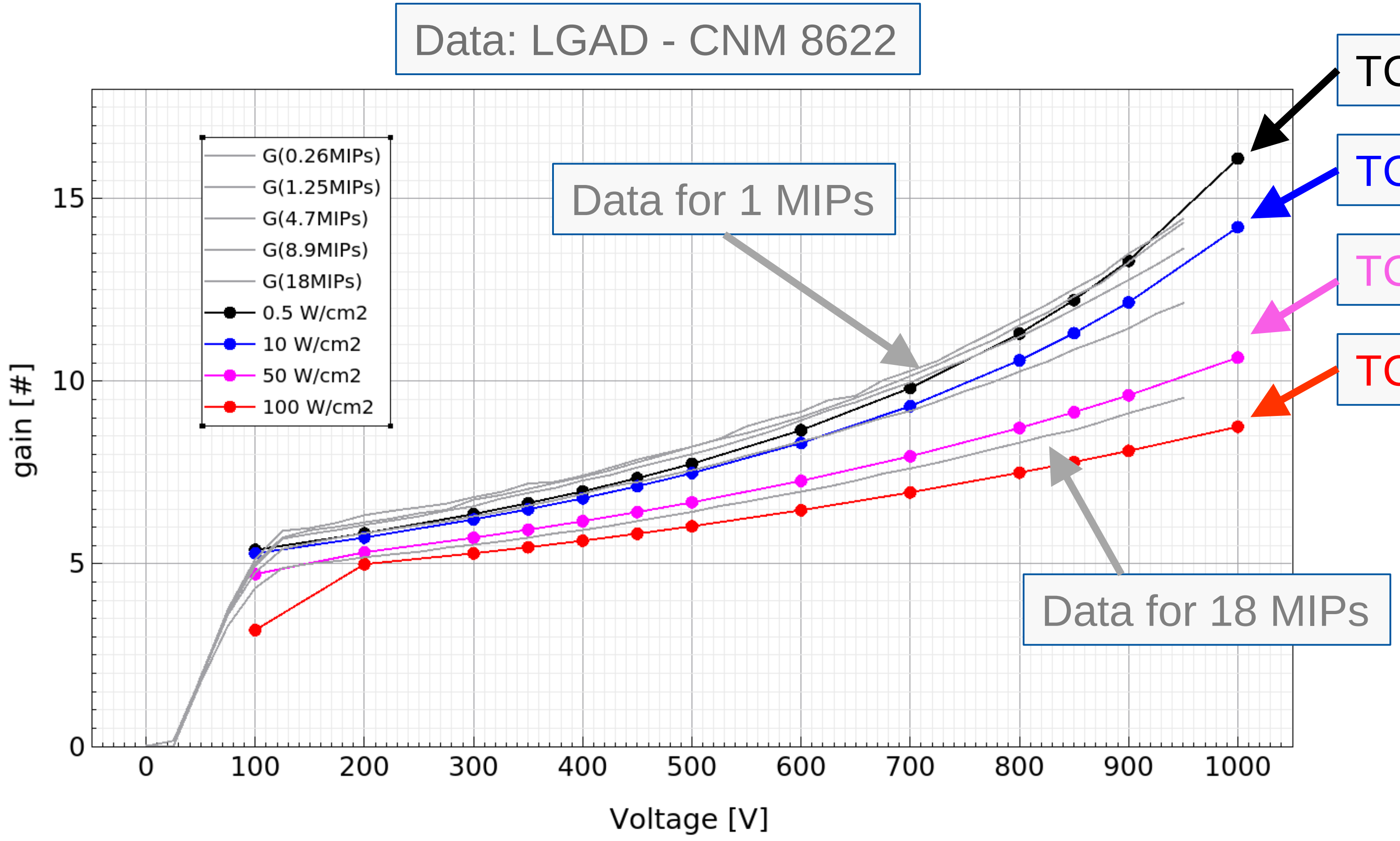
Data: 900 V; 20°C

Experimental Data

increasing laser intensity

TCT – LGAD 8622 – gain suppression

- Experimental data: IR front, RT, 0.3 to 18 MIP equivalent intensity
- Simulation (1D!): IR front, RT, 0.5 to 100 W/cm^2 intensity, 200ps



Data: LGAD - CNM 8622

Data for 1 MIPs

Data for 18 MIPs

TCAD - 0.5 W/cm^2 (and below)

TCAD - 10 W/cm^2

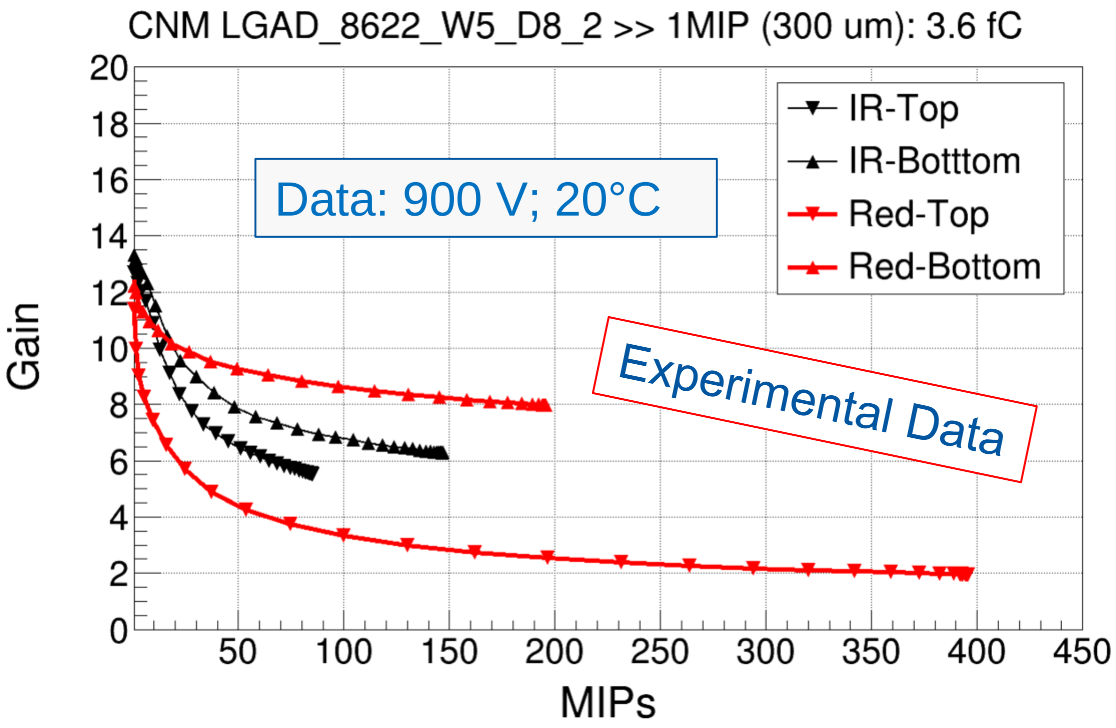
TCAD - 50 W/cm^2

TCAD - 100 W/cm^2

- MIP equivalent
  - Very rough estimate assuming:
    - 1 MIP = 80 x 285 e-h = 22800 e-h = 3.7fC
    - beam spot is circle with r = 5um
  - 100 W/cm^2 = 1 MIP
- 1D simulations show ~25 times stronger gain reduction.
- Overestimation expected, as this is a 1D simulation of IR-TCT with **no** lateral diffusion of charge in a 285 um thick device!

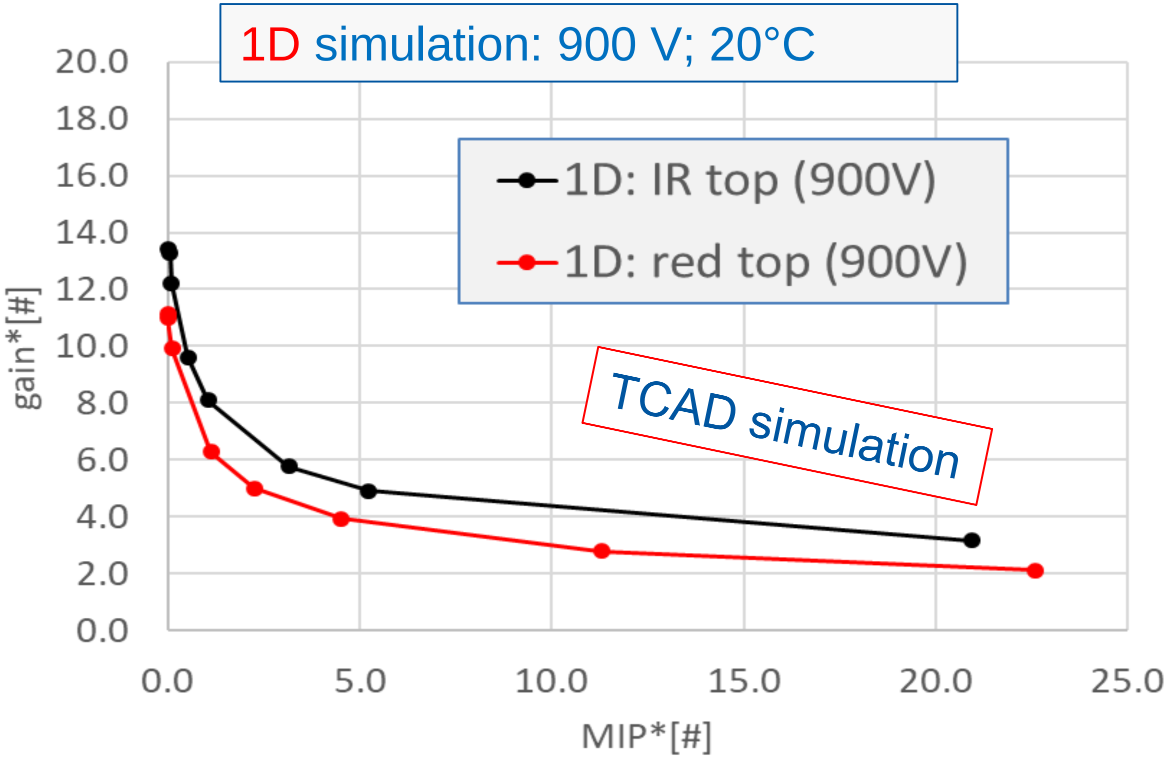
TCT: Variation of laser pulse intensity

- TCT: IR and red laser pulses, top and bottom illumination



increasing laser intensity

[Data: E.Curras, CERN WP1.4. meeting, 8.3.2022]



gain* = I(with gain)/I(without gain)
MIP* = Intensity to create charge of 1 MIP

Conclusions

- TCAD model (i.e. doping profiles) for HPK2, CNM12916, CNM8622 produced
  - Based on SIMS, TPA-TCT, geometry and CV measurements
- Impact ionization models in Synopsys TCAD with default parameters studied
  - Experimental data: LGAD gain measured with TCT
  - Non of the models gave a good agreement with our experimental data
- Method developed to fit impact ionization model parameters outside of TCAD using the E-Field profile from TCAD simulation
  - Good agreement of gain measured vs gain simulated by TCAD (after tuning parameters)
  - …next talk: Can we get temperature dependent data to match as well?
- Gain suppression in LGADs
  - 1D TCAD simulations reproduce (qualitatively) the observed gain suppression effect

Annex

Ionization coefficients α_n and α_p

$$G_{\text{ii}} = \frac{1}{q}(\alpha_n|\vec{J}_n| + \alpha_p|\vec{J}_p|)$$

- Synopsys manual

van Overstraeten – de Man Model

$$\boxed{\alpha(F_{\text{ava}}) = \gamma a \exp\left(-\frac{\gamma b}{F_{\text{ava}}}\right)}$$

$$\gamma = \frac{\tanh\left(\frac{\hbar\omega_{\text{op}}}{2kT_0}\right)}{\tanh\left(\frac{\hbar\omega_{\text{op}}}{2kT}\right)}$$

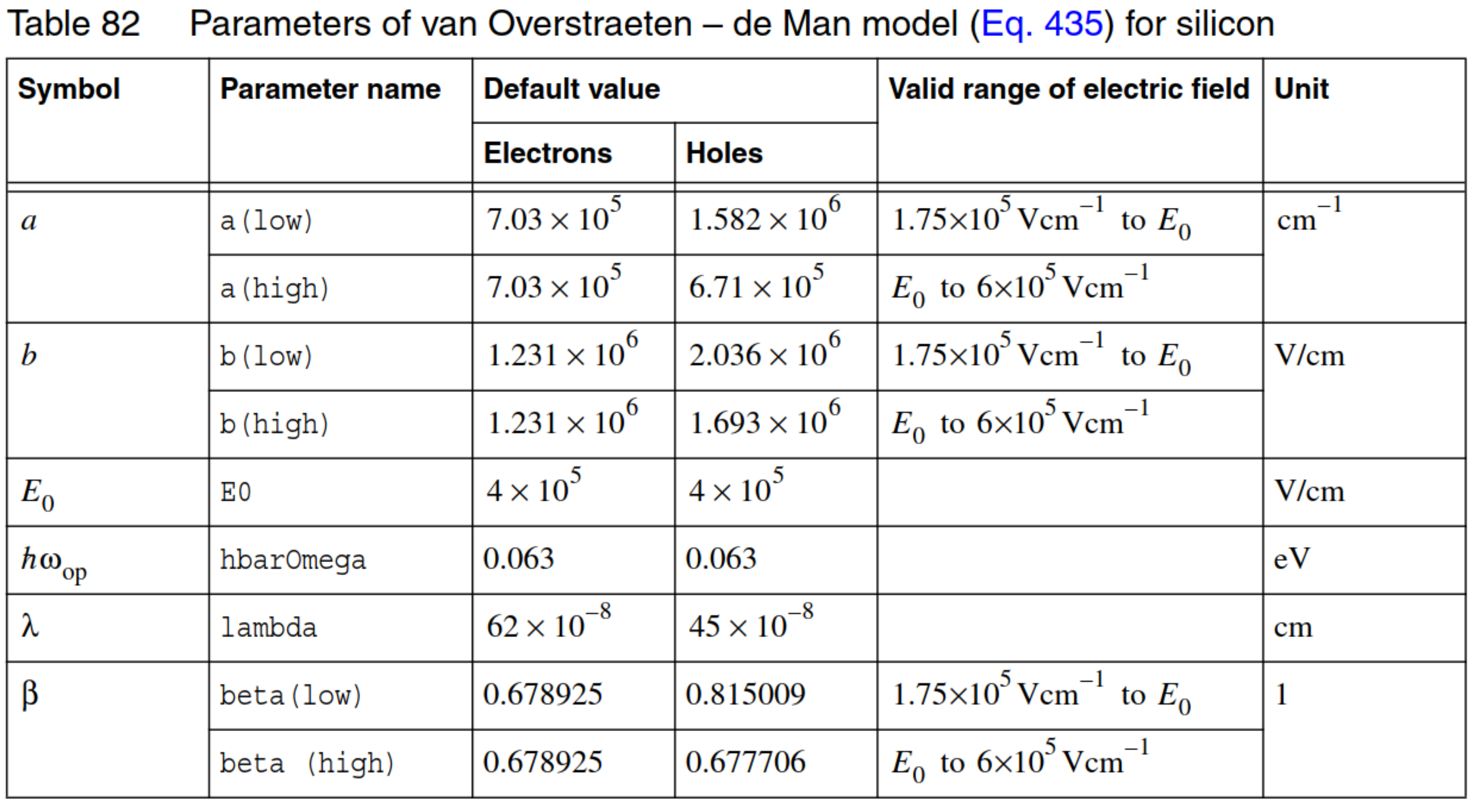
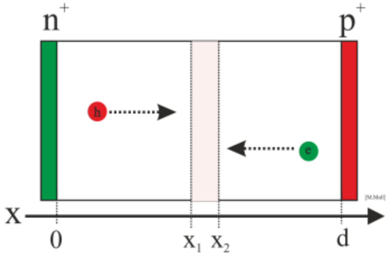


Table 82 Parameters of van Overstraeten – de Man model (Eq. 435) for silicon

Symbol	Parameter name	Default value		Valid range of electric field	Unit
		Electrons	Holes		
a	`a(low)`	7.03×10^5	1.582×10^6	$1.75\times10^5\,\text{Vcm}^{-1}$ to E_0	cm^{-1}
	`a(high)`	7.03×10^5	6.71×10^5	E_0 to $6\times10^5\,\text{Vcm}^{-1}$	
b	`b(low)`	1.231×10^6	2.036×10^6	$1.75\times10^5\,\text{Vcm}^{-1}$ to E_0	V/cm
	`b(high)`	1.231×10^6	1.693×10^6	E_0 to $6\times10^5\,\text{Vcm}^{-1}$	
E_0	`E0`	4×10^5	4×10^5		V/cm
$\hbar\omega_{\text{op}}$	`hbarOmega`	0.063	0.063		eV
λ	`lambda`	62×10^{-8}	45×10^{-8}		cm
β	`beta(low)`	0.678925	0.815009	$1.75\times10^5\,\text{Vcm}^{-1}$ to E_0	1
	`beta (high)`	0.678925	0.677706	E_0 to $6\times10^5\,\text{Vcm}^{-1}$	

Impact Ionization

- Consider multiplication of electrons and holes



charge generation [As/cm^3]

$$\boxed{-\frac{dJ_n}{dx} = \alpha_n J_n + \alpha_p J_p + g(x) = \frac{dJ_p}{dx}}$$

$$J = J_n(x) + J_p(x)$$

$$\begin{aligned} -\frac{dJ_n}{dx} &= (\alpha_n - \alpha_p)\, J_n + \alpha_p J + g(x) = \frac{dJ_p}{dx} \\ &= (\alpha_p - \alpha_n)\, J_p + \alpha_n J + g(x) \end{aligned}$$

- Solution for the total current:

$$\boxed{J = M_n J_n(d) + M_p J_p(0) + \int_0^d g(x) M(x) dx}$$

with

$$\boxed{M(x) = \frac{\exp\left(-\int_x^d (\alpha_n - \alpha_p)\, d\eta\right)}{1 - \int_0^d \alpha_n \exp\left(-\int_\xi^d (\alpha_n - \alpha_p)\, d\eta\right) d\xi}}$$

- The term in the denominator is called **electron ionization integral**
  - Sensor breaks down when it approaches 1

$$\boxed{I_{n,ion} = \int_0^d \alpha_n \exp\left(-\int_\xi^d (\alpha_n - \alpha_p)\, d\eta\right) d\xi}$$

see e.g. McIntyre IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 46, NO. 8, AUGUST 1999