TCAD simulations of TPA-TCT measurements on PINs and LGADs

- hunting for sharks -

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Outline:

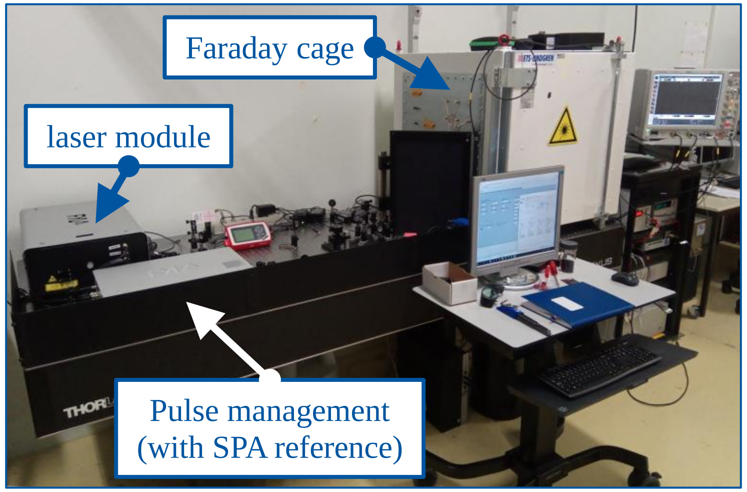
- Implementation of TPA-TCT TCAD simulations
- Experimental data and TCAD simulations
  - PIN diodes
  - LGADs
- Simulation of gain reduction in LGADs
- Conclusion and Outlook

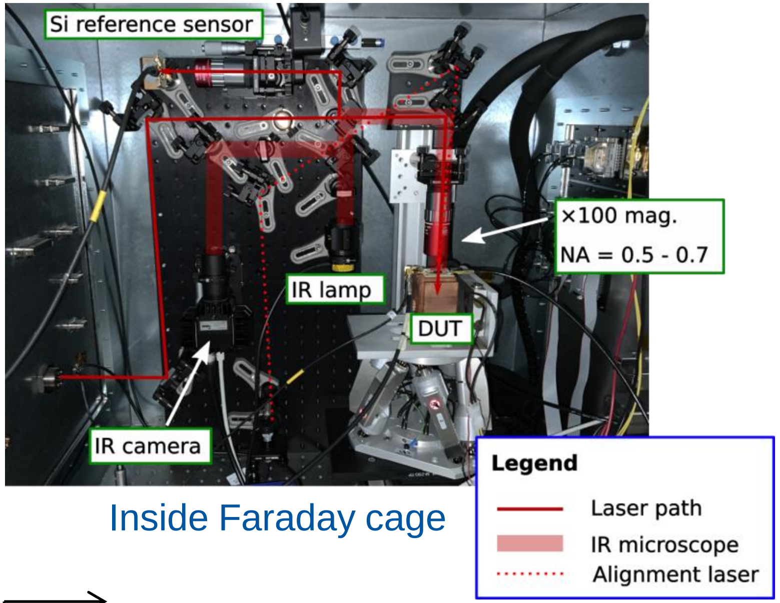
TPA : Two Photon Absorption
TCT : Transient Current Technique
PIN : p-type intrinsic n-type
LGAD : Low Gain Avalanche Diode
shark : Sharks are a group of elasmobranch fish characterized by a cartilaginous skeleton, five to seven gill slits on the sides of the head, and **pectoral fins** that are not fused to the head.

Experimental Details

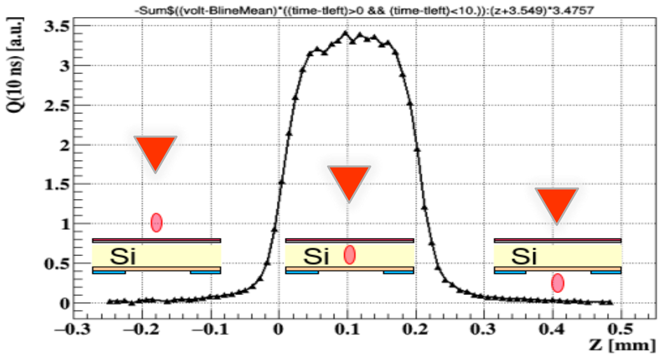
TPA-TCT setup

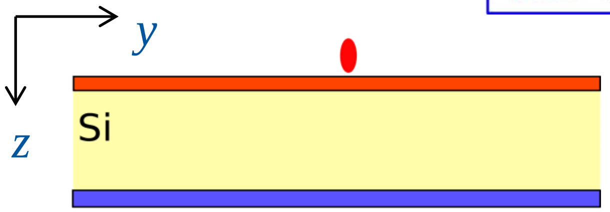
- Located in CERN EP-DT Solid State Detectors (SSD) lab
- Fyla fs laser, 1550 nm, 430 fs pulses up to 10 nJ, 8MHz to single pulse, SPA and TPA reference systems, x100 objectives with NA = 0.5 or 0.7





Inside Faraday cage





"z-scan" = illumination from the top!

Sensors

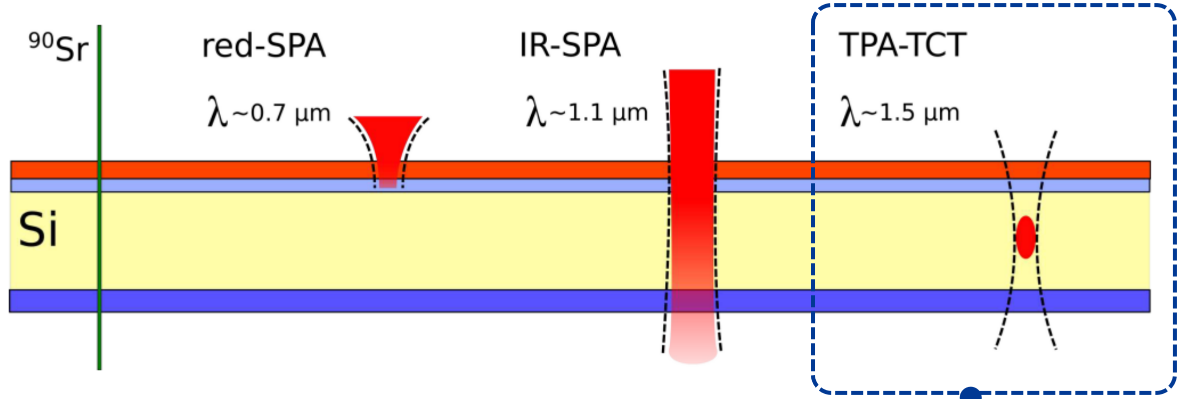
- All used sensors
  - FZ p-type, high resistivity, not irradiated!
- CiS (CIS16)
  - PIN diode (300 um)
- CNM 7859, 8622 and 8665
  - PIN diodes / LGAD (≈ 290 um)

Simulations

- TCAD: Synopsys vs. U-2022.12-SP1
  - 2D with rotational symmetry used
- LGAD and Impact Ionization models
  - see [Curras and Moll IEEE TED 2023]
- TPA charge generation
  - with analytic charge generation model (see following slides)
- Electronics shaping
  - folding TCAD output with 'transfer function' (see following slides)

TCT: Excess charge generation

- Various options to produce excess charge in silicon sensors for Transient Current Technique analyses



[S.Pape, VCI2022]

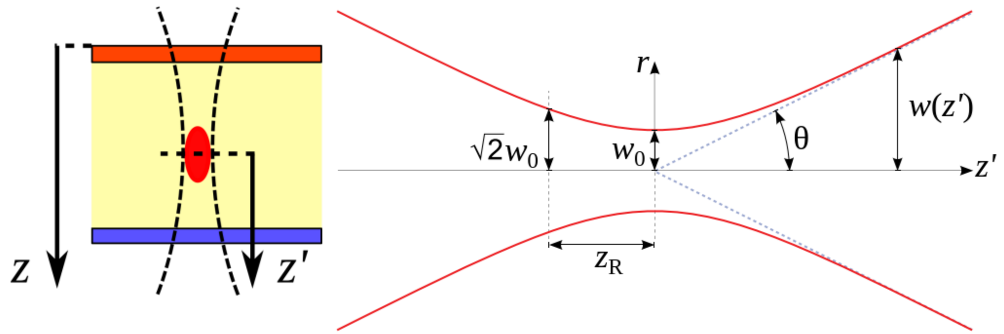
- Typical excess carrier volumes (in a 300 µm thick sensor)
  - ^{90}Sr — V_{Sr} ≈ 940 µm^3
  - SPA (red) — V_{red} ≈ 1100 µm^3
  - SPA (infrared) — V_{IR} ≈ 100 × V_{Sr}
  - TPA — V_{TPA} ≈ 85 µm^3

TPA-TCT: model of excess carrier generation

- Gaussian beam in space and time
  - with pulse length of 430 fs charge generation is “instantaneous”
  - charge distribution in space characterized by:
    - beam waist w_0
    - Rayleigh length z_R

$$z_R = \frac{\pi n w_0^2}{\lambda}$$

$$w(z') = w_0 \sqrt{1 + \left(\frac{z'}{z_R}\right)^2}$$



[Sketch: S.Pape, Thesis 2024]

- Charge generation goes with (irradiance)^2
  - 2 photons needed for one electron hole pair ($2\hbar\omega$)
  - Charge carrier density:

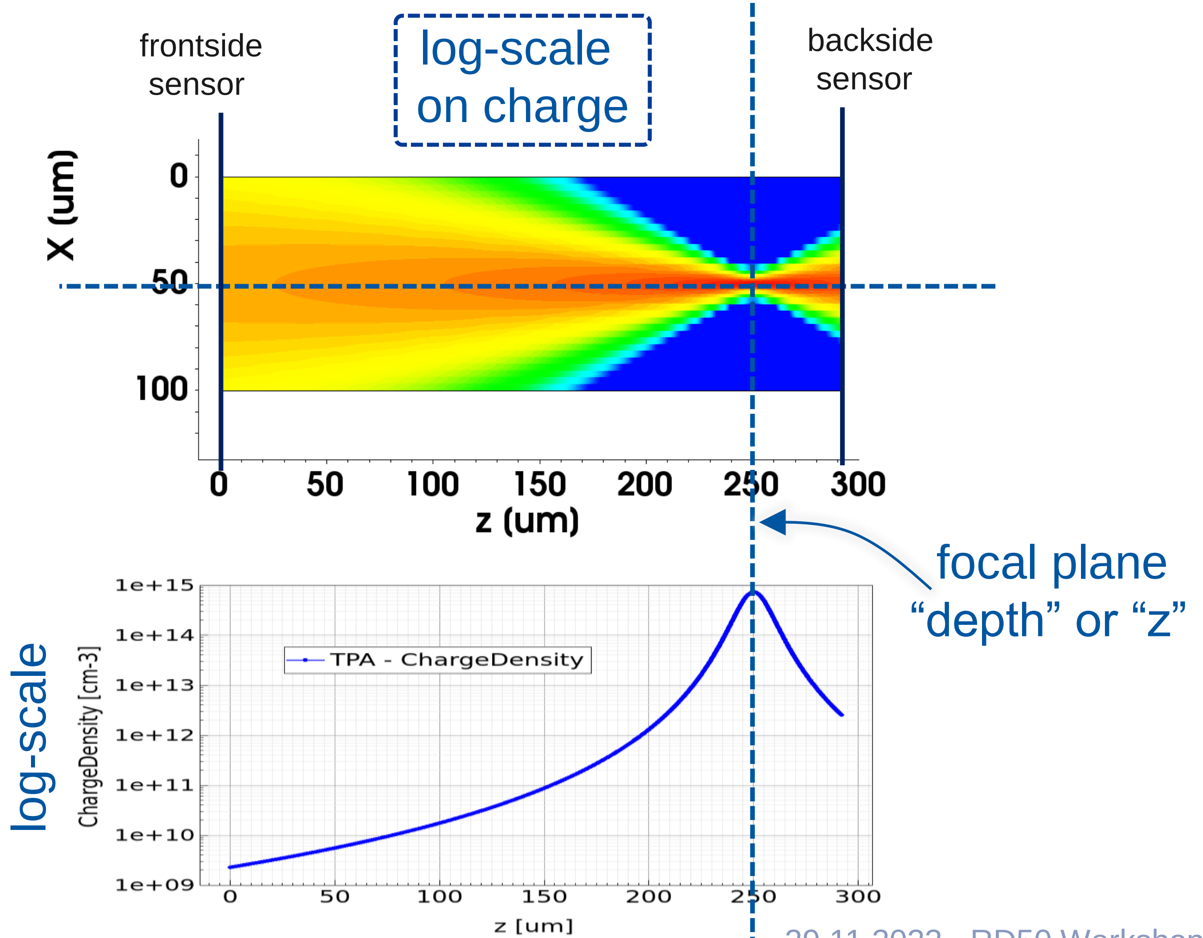
$$n_{\mathrm{TPA}}(r, z') = \frac{E_\mathrm{p}^2 \beta_2 4 \ln 2}{\tau \hbar \omega \pi^{5/2} \sqrt{\ln 4}} \frac{1}{w^4(z')} \exp\left(-\frac{4r^2}{w^2(z')}\right)$$

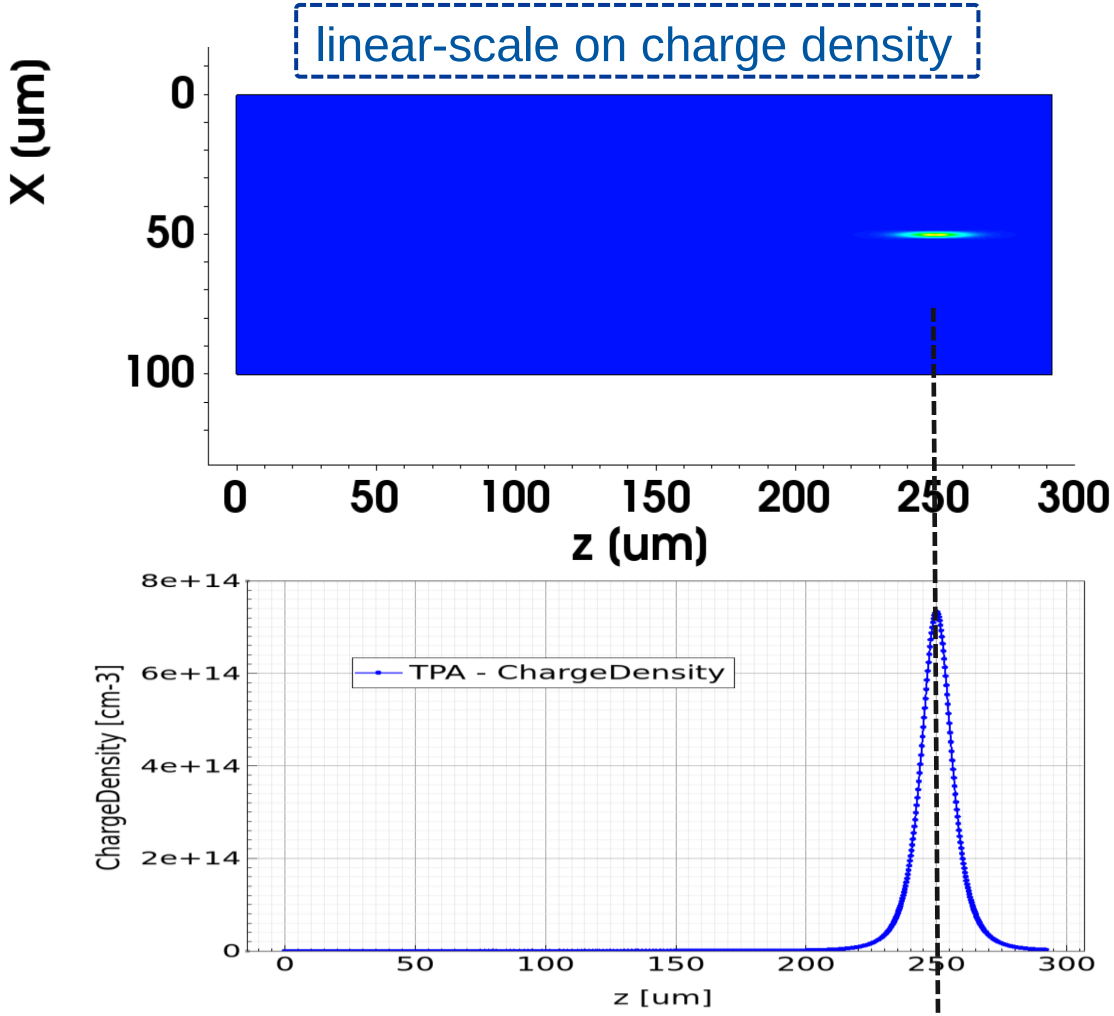
- E_p pulse energy
- τ FWHM of pulse in time
- β_2 two photon absorption coefficient
- n refractive index
- λ wave length

TCAD: TPA-TCT excess charge generation

- TPA charge generation example:
  - Sensor: CNM 7859 PIN (290 um)
  - Beam: NA=0.5; w_0=1.3um, z_R=10.5um; Q≈*5fC*
  - Focal plane: 250 um depth

$$n_{\mathrm{TPA}}(r,z') = \frac{E_{\mathrm{p}}^2 \beta_2 4 \ln 2}{\tau \hbar \omega \pi^{5/2} \sqrt{\ln 4}} \frac{1}{w^4(z')} \exp\left(-\frac{4r^2}{w^2(z')}\right)$$





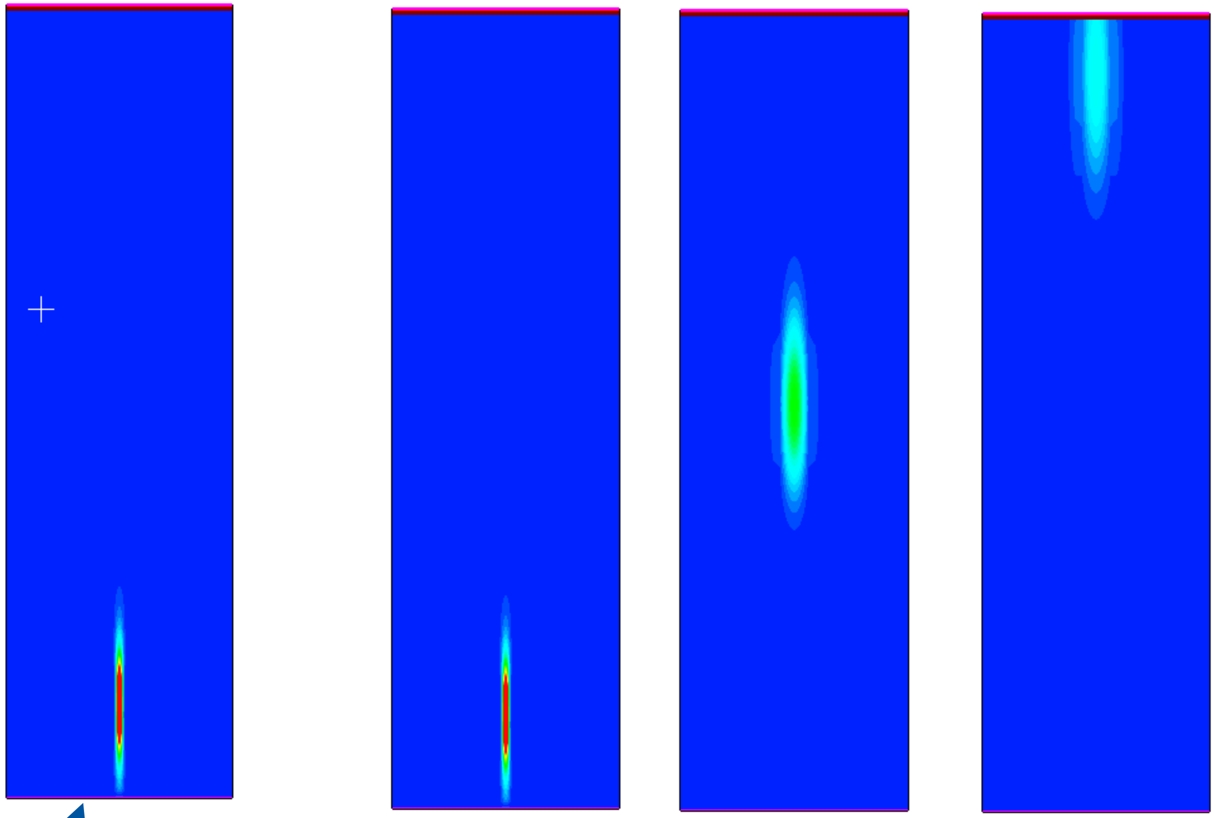
Simulation of TPA-TCT

- Charge cloud generated around focal depth of 250 μm (at t=1.0 ns)
- Visualisation of electron cloud moving through PIN detector (holes not shown)

frontside (n^+)
p-type sensor

1.02e-9 s

backside (p^+)
p-type sensor

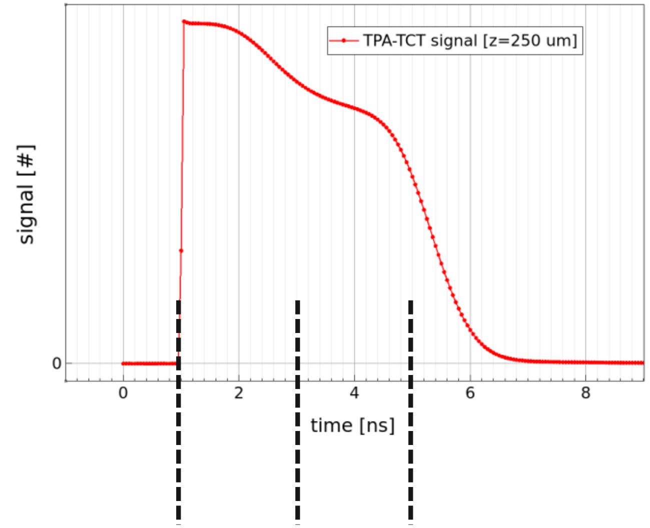


1.0 ns charge cloud generated at z = 250 μm

3.0 ns

5.0 ns

Transient Current (TC)
induced by electrons and holes

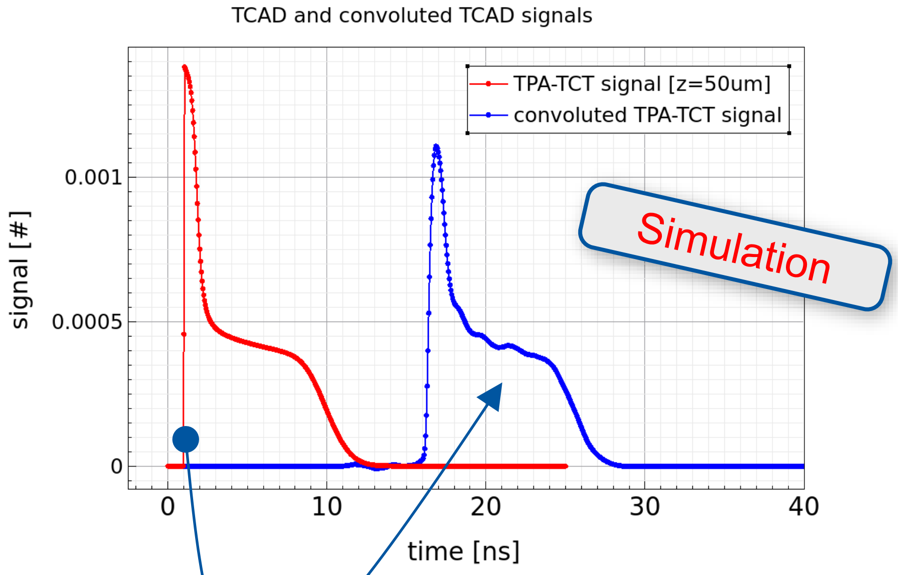


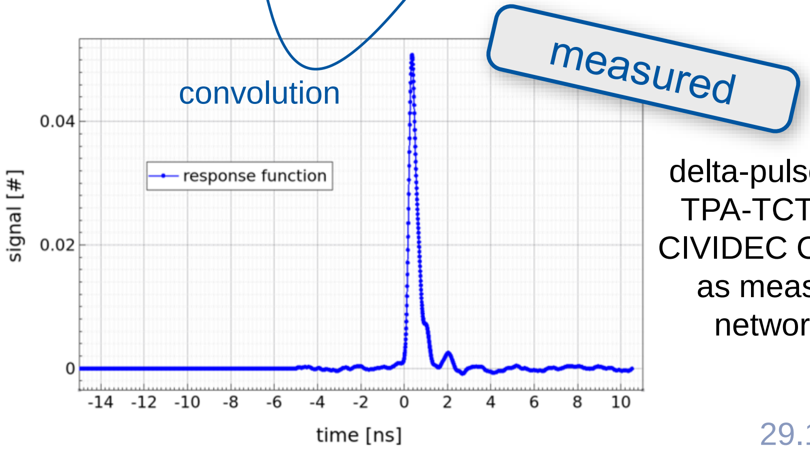
1.0 ns **3.0 ns** **5.0 ns**

Note: This example is calculated in 2D for better visibility, all shown transients calculated from 3D simulations.

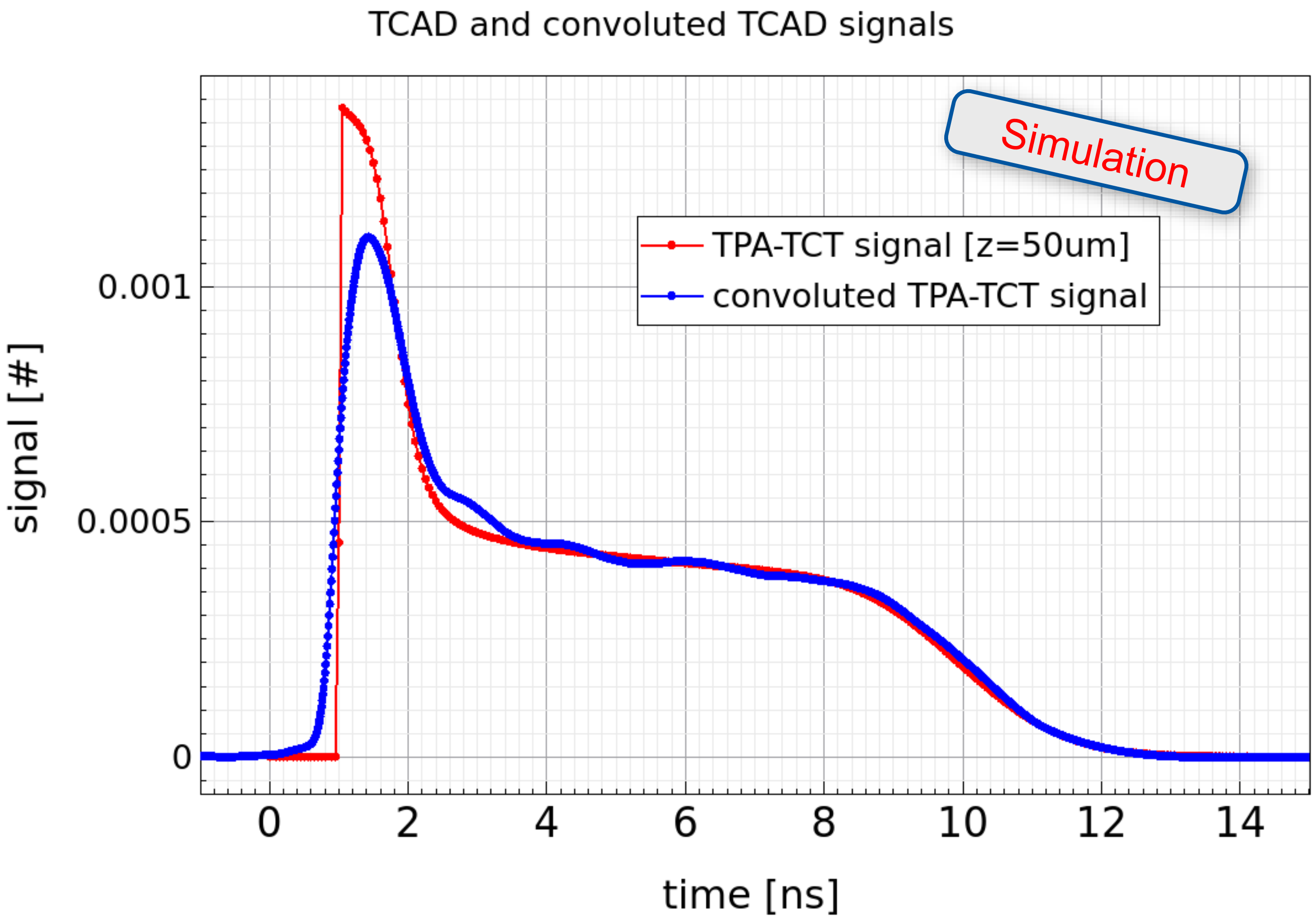
Simulation: Convolution with ‘transfer function’

- Simulated TPA-TCT signal is convoluted with a measured ‘transfer function’
  - **Sensor:** CNM 7859 PIN (290 um); **Beam:** NA=0.5; w_0=1.3µm, z_R=10.5µm; Q≈5fC; **Focal plane:** z=50 µm depth





delta-pulse response of TPA-TCT system with CIVIDEC C2HV amplifier as measured with a network analyser



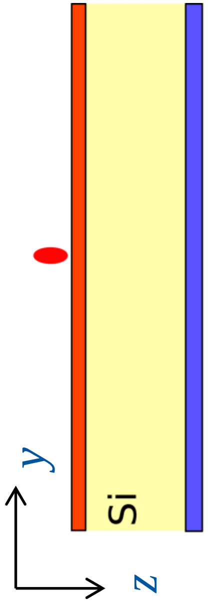
TPA-TCT on PIN diodes

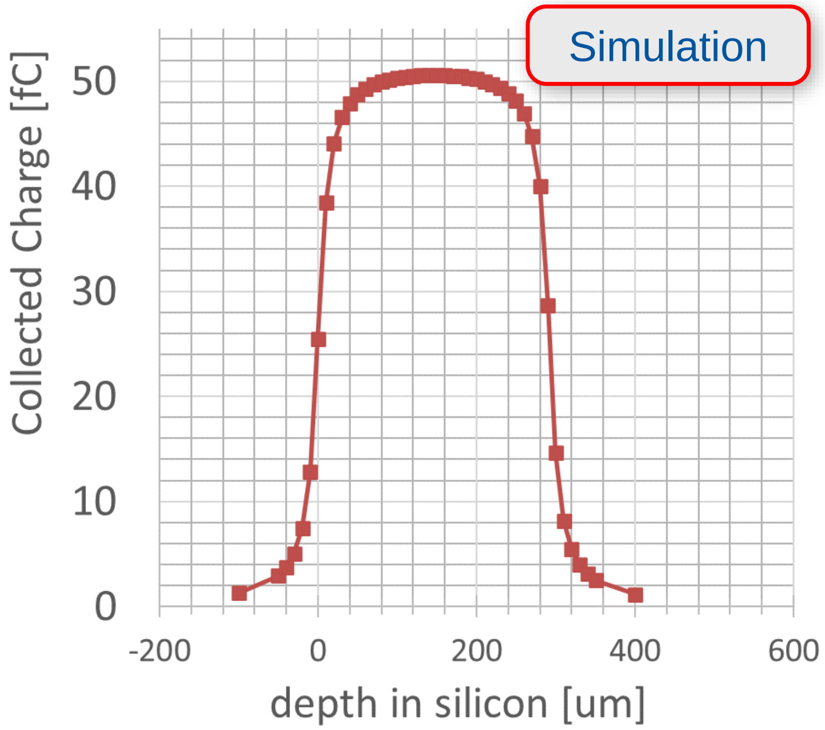
Experiment vs. Simulation

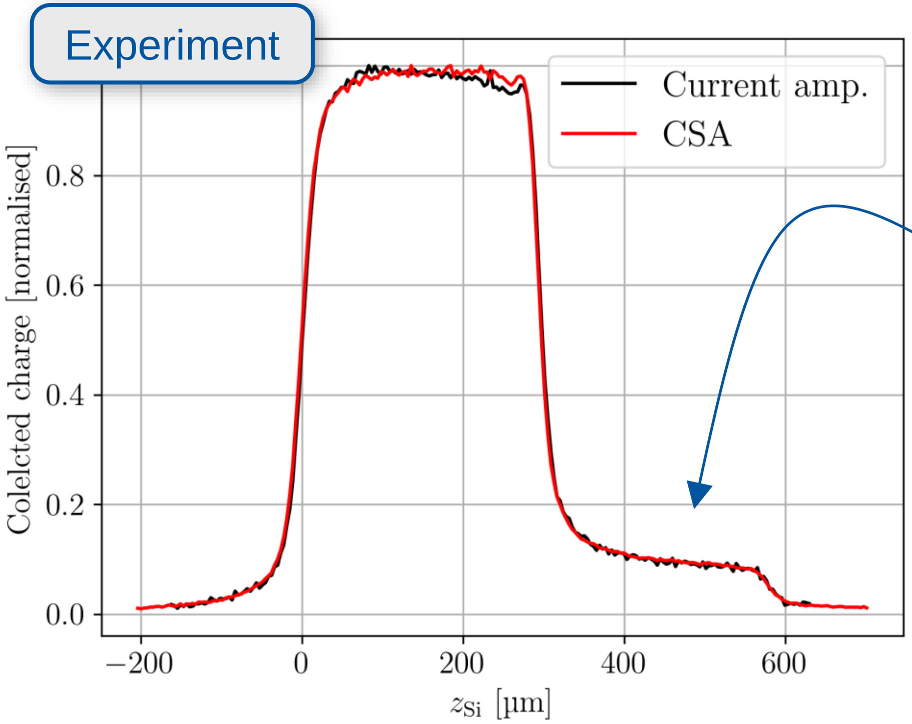
… gaining confidence into the simulations

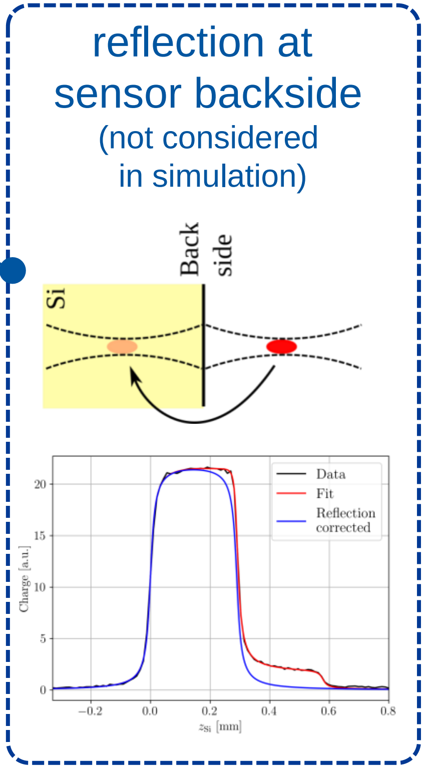
PIN-Diode – TPA-TCT z-scan

- Experimental and simulation settings
  - Sensor: CNM 7859 WL-A63-PIN4 (p-type, 290μm) operated at 200V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with z_R=10.5μm, w_0=1.3μm







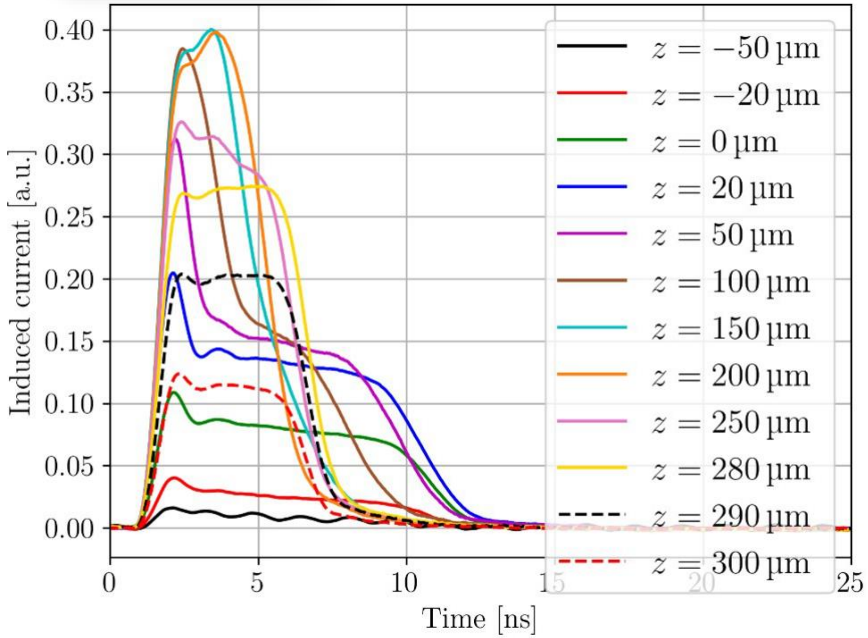


[S.Pape, PhD thesis, 2024]

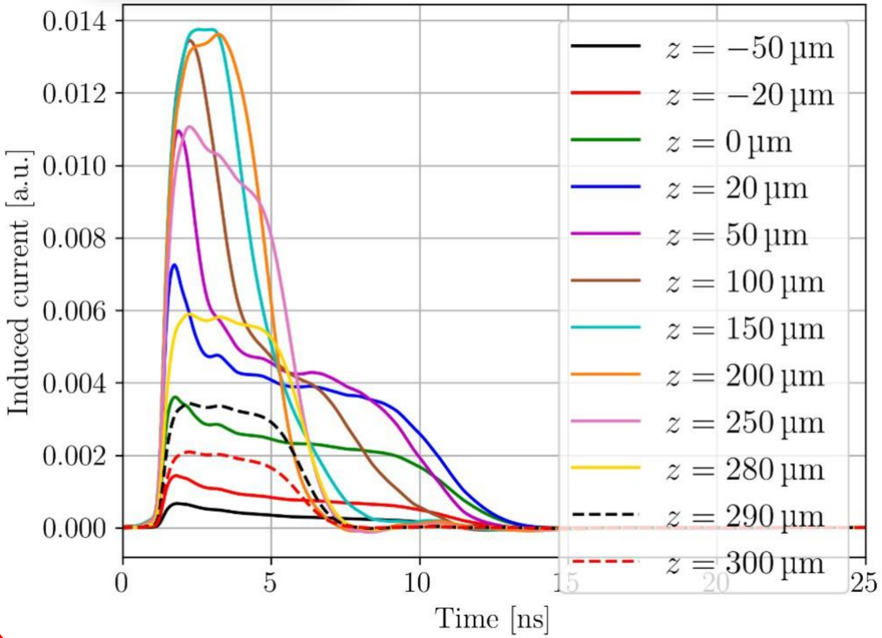
PIN-Diode – TPA-TCT z-scan

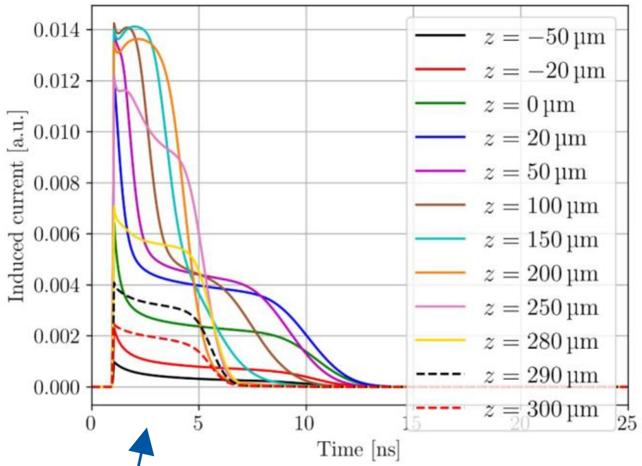
- TPA-TCT transients after charge injection at various depth (“z-scan”)

Experiment



Simulation





- raw TCAD transient
- convoluted data

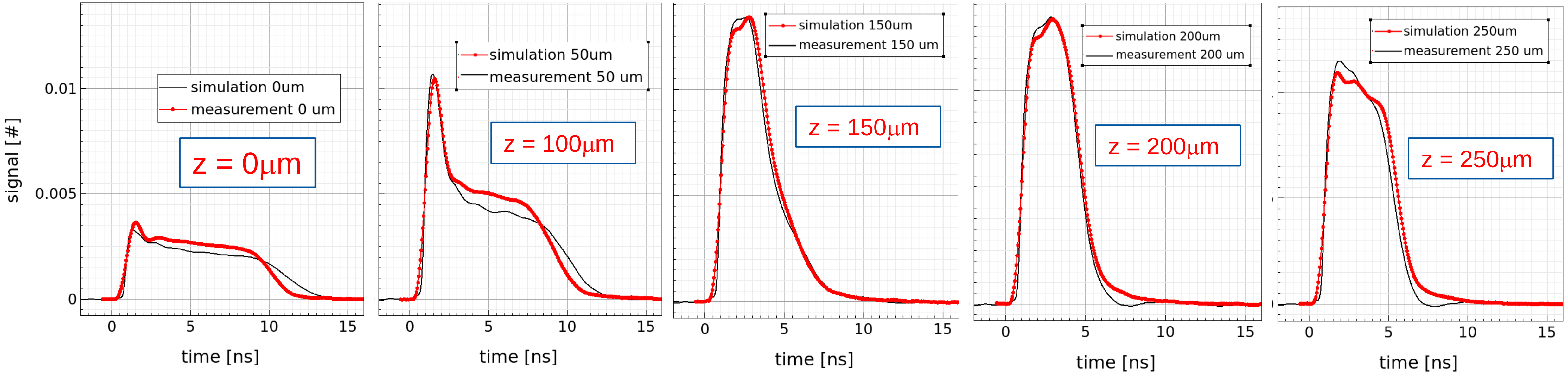
- z < 280 um : **very good agreement** between experiment and simulation
- z > 280 um : for injection close to the backside the experimental transients are influenced by reflection
  - higher signal in experiment due to reflection at back side
- z > 290 um : no signal in simulation while in the experiment we get a signal
  - even beyond the sensor thickness a signal is obtained in the experiment because of the reflection at the back side

PIN-Diode – TPA-TCT z-scan

- TPA-TCT transients (simulation & data) after charge injection at various depth (“z-scan”)
  - same data as previous slide

red points = simulated data

black lines = measured data



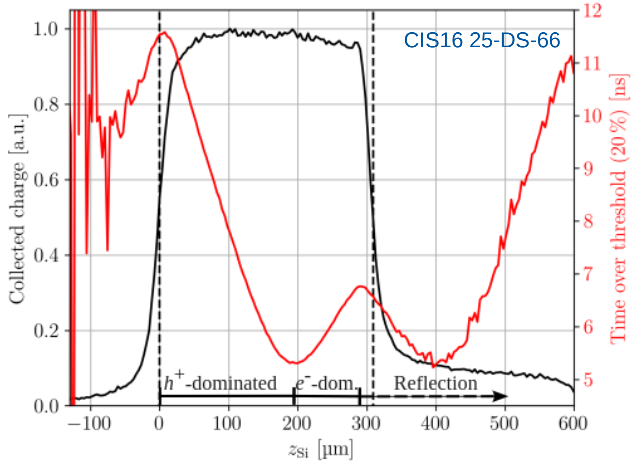
- **Note:** same scaling factor for signal heights used for all simulated data!
- ….. some room for improvement, but quite good agreement

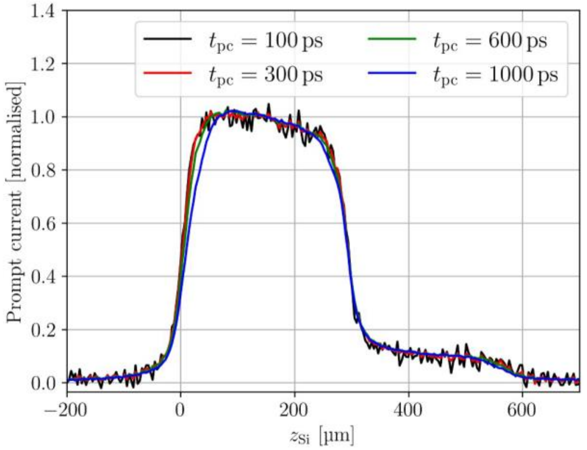
Details: see talk of Sebastian Pape

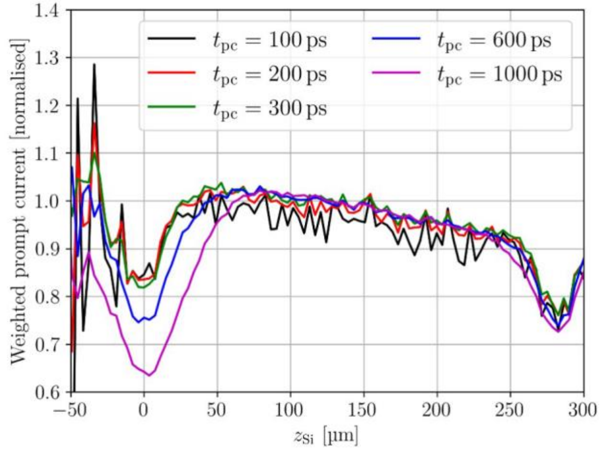
PIN-Diode – TPA-TCT z-scan

- Experimental and simulated transients undergoing the same analyses procedures

Experiment



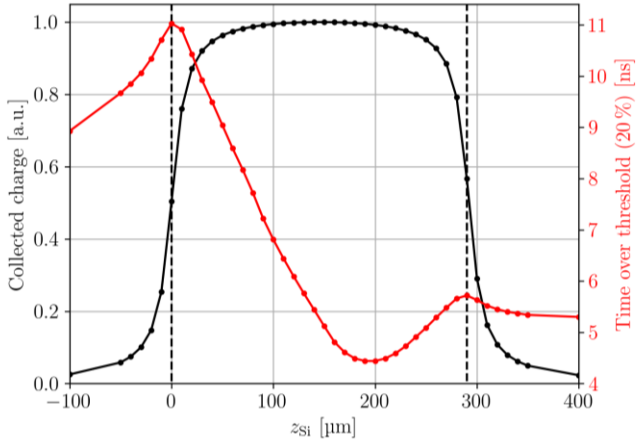


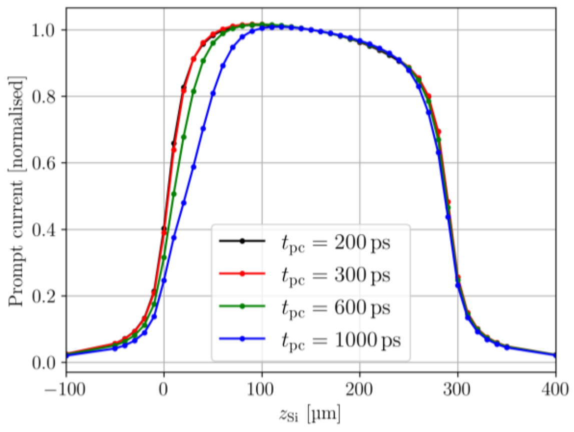


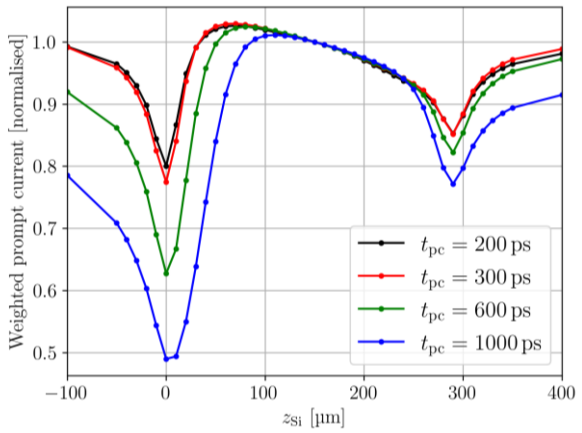
[S.Pape, PhD thesis, 2024]

Collected Charge (CC) & Time over Threshold (ToT) | Prompt Current (PC) Analyses | Weighted Prompt Current (WPC) Analyses

Simulation







TPA-TCT on LGADs

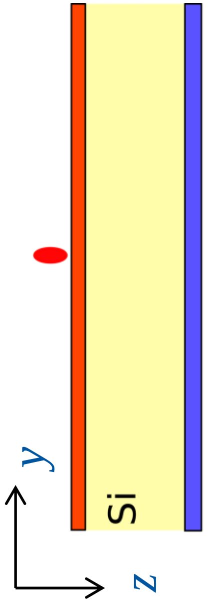
Experiment vs. Simulation

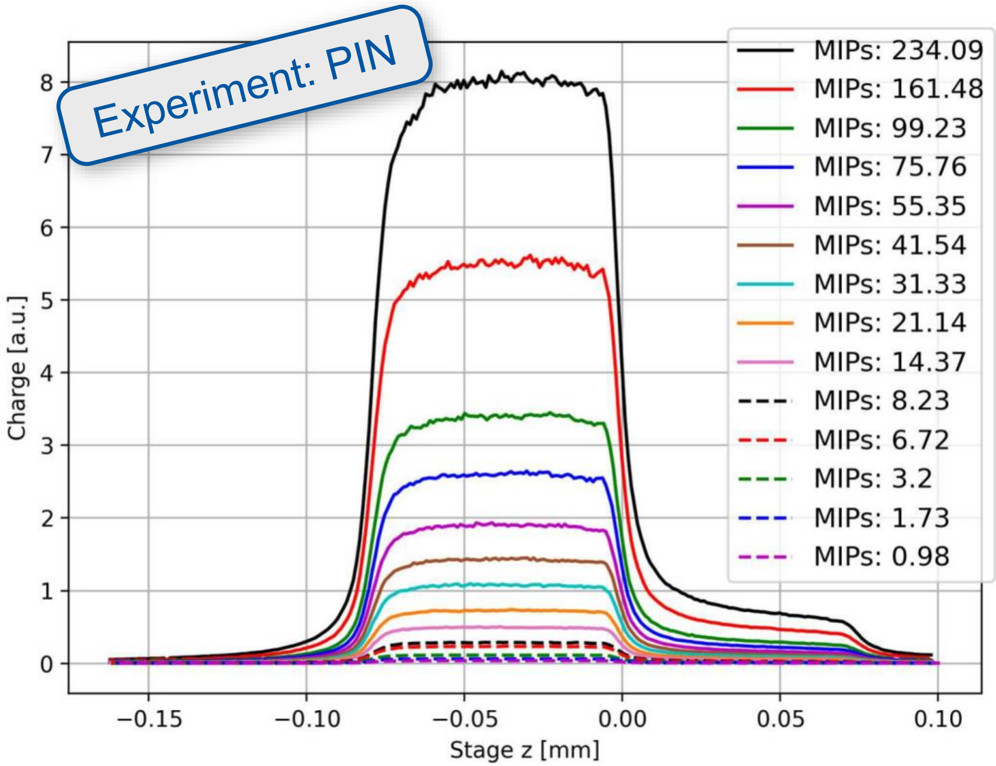
… finally, we arrive to the SHARKS

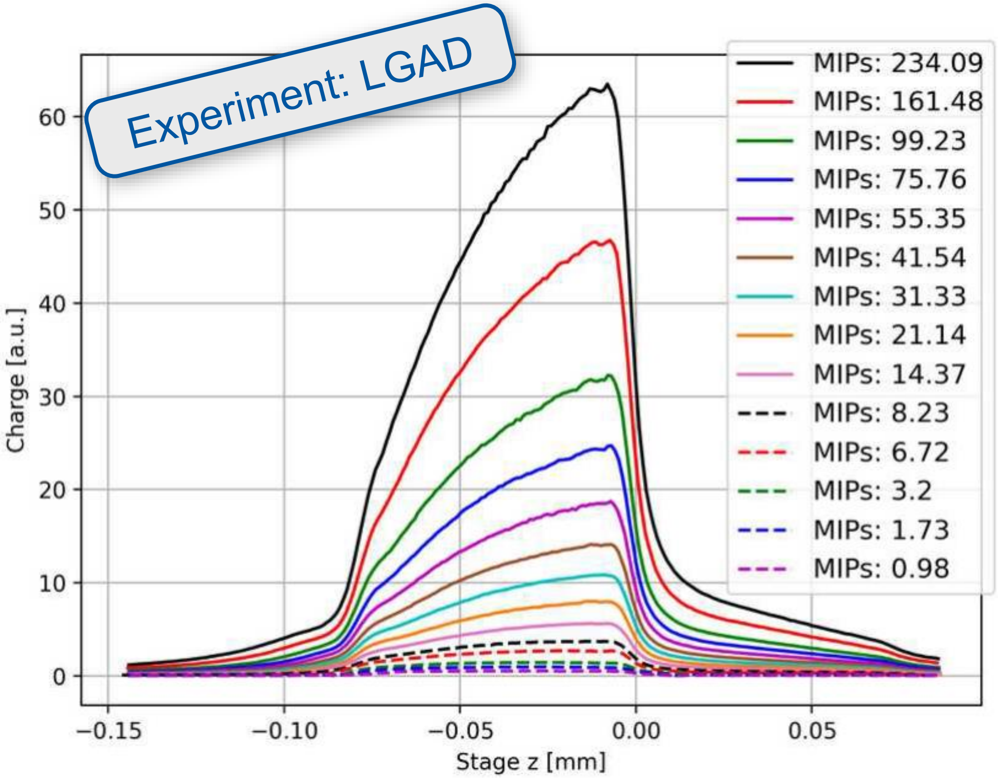
PIN and LGAD – TPA-TCT z-scan

- TPA-TCT measurements on CNM 8622 devices (illumination from top)
  - **PIN:** p-type, 280μm, operated at 200V, 20°C; **LGAD:** 280μm, operated at 900V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with z_R=11.9μm, w_0=1.3μm

1 MIP ≈ 3.6 fC







PIN diode: Beam intensity has no influence on charge collection profile

LGAD: Beam intensity has influence on charge collection profile: "shark fin effect"

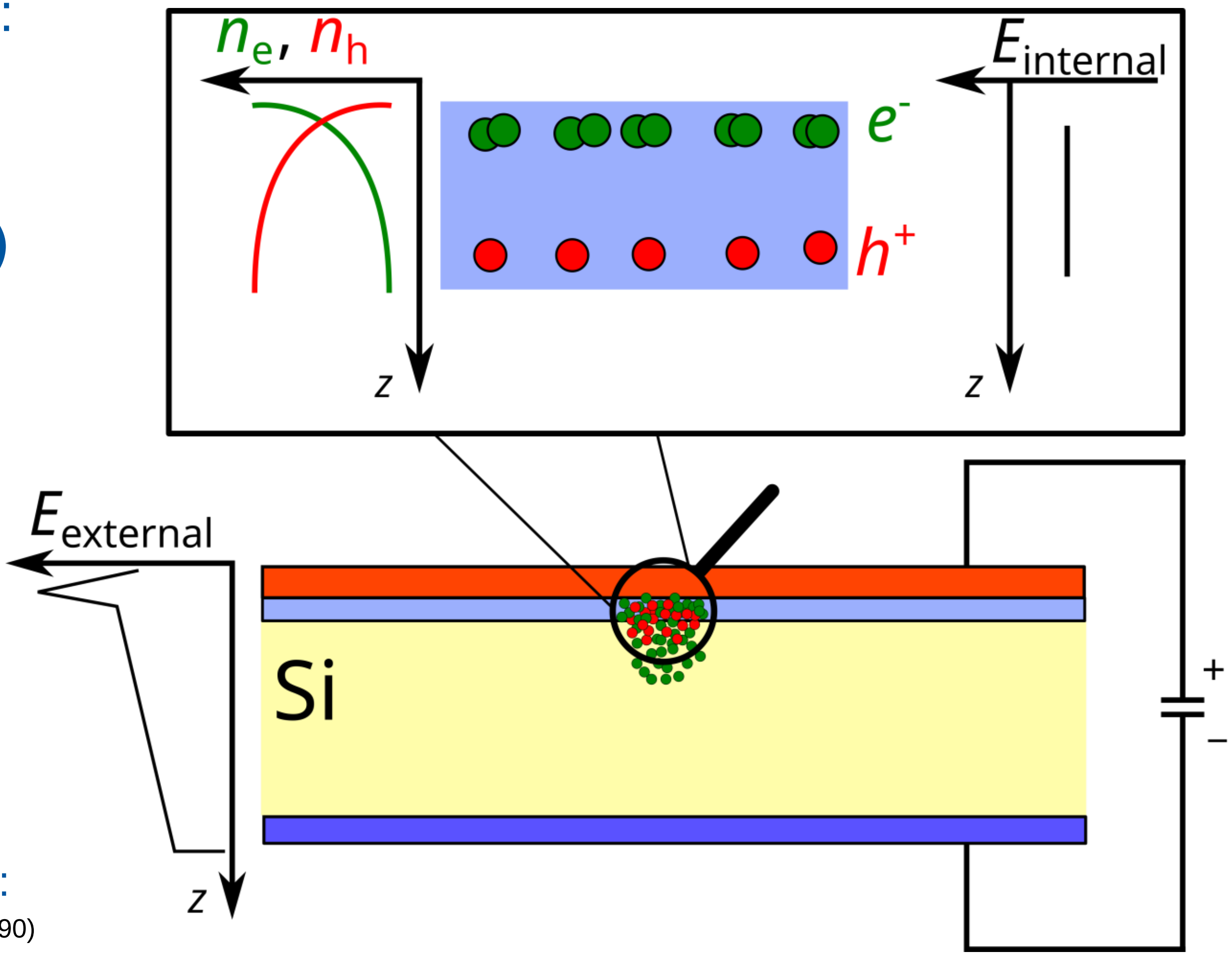
[S.Pape, RD50 Workshop Nov.2021]

[S.Pape et. al, NIMA 2022]

Reminder: LGAD gain suppression

LGAD gain depends on operational parameters:

- Applied voltage
- Temperature
- **Charge carrier density ("gain suppression")**
  - *Excess charge carriers enter the gain layer (i.e the high field region) and undergo impact ionization.*
  - *The charge carriers build up a temporal counter directed electric field that reduces the field strength in the gain layer.*
  - *Following charge carriers entering the gain layer see a lower field and produce less impact ionization.*
  - *The gain depends on the amount of charge carriers being amplified. The higher the free charge carrier density in the gain layer the lower is the gain.*
  - ***Gain depends on the excess charge carrier density***

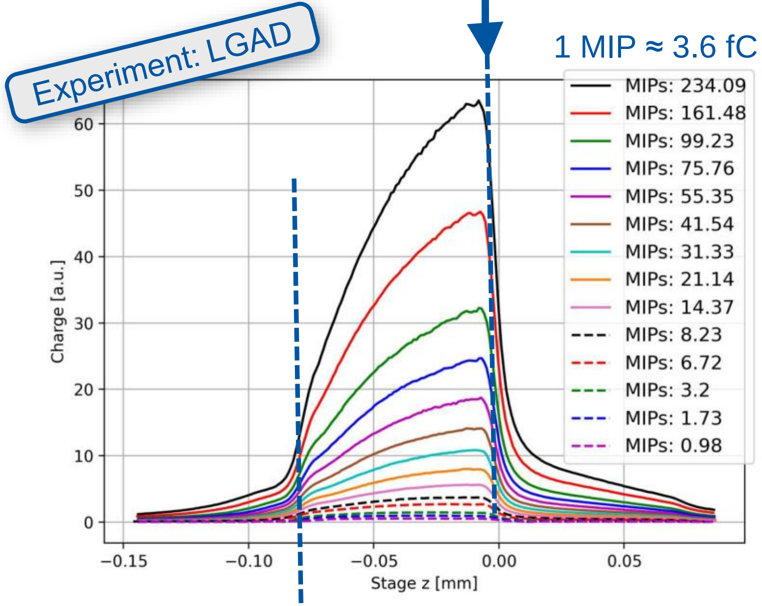


[S.Pape, CERN EP-DT Training Seminar, 6.6.2023]

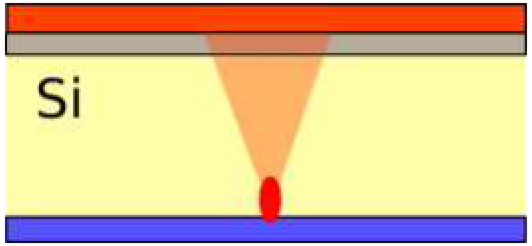
- More details on LGAD impact ionization and gain suppression:
  - Curras et al., *NIMA 2022*, **Gain reduction mechanism in LGAD** (first observation, IR-TCT, Sr90)
  - Curras and Moll, IEEE TED 2023 (impact ionization coefficients)
  - Kramberger et al., NIMA 2023, (IR-TCT, modelling)
  - S.Pape et al. NIMA 2022 (TPA-TCT); Femke de Wit, Bachelor thesis 2023 [link] ; Sebastian Pape, PhD thesis 2024 [soon]

LGAD gain suppression in TPA-TCT

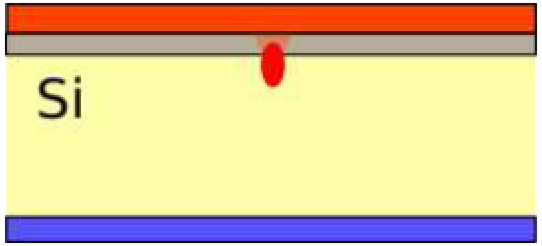
focus close
to backside



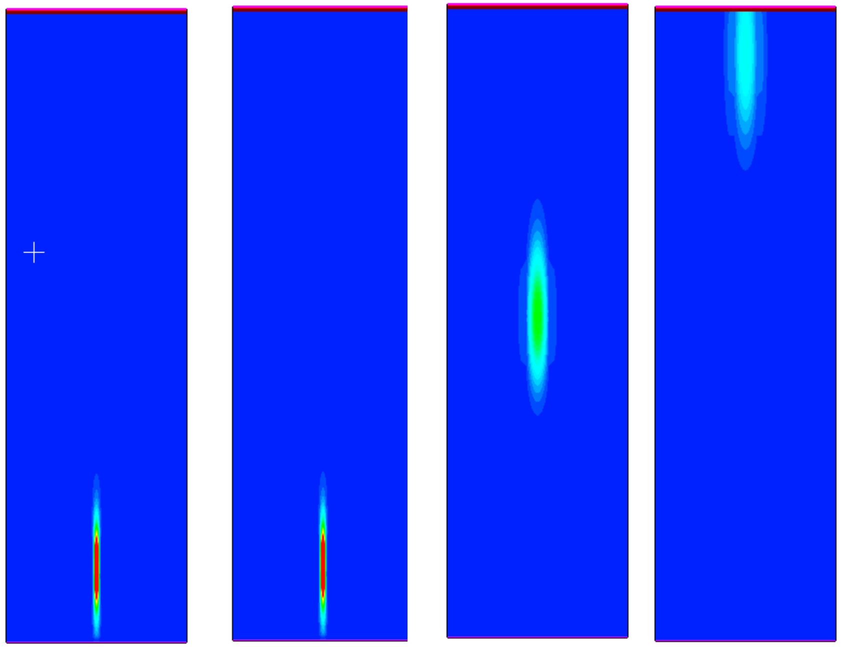
focus close
to frontside



lower charge density
at gain layer
= less gain suppression



high charge density
at gain layer
= high gain suppression



charge injected
250μm depth

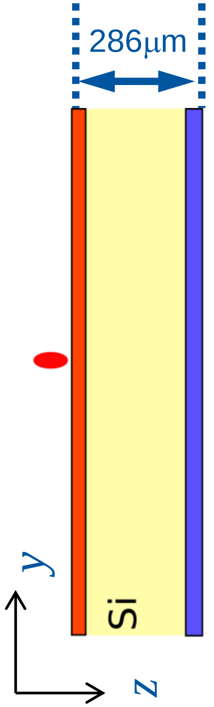
+2.0 ns

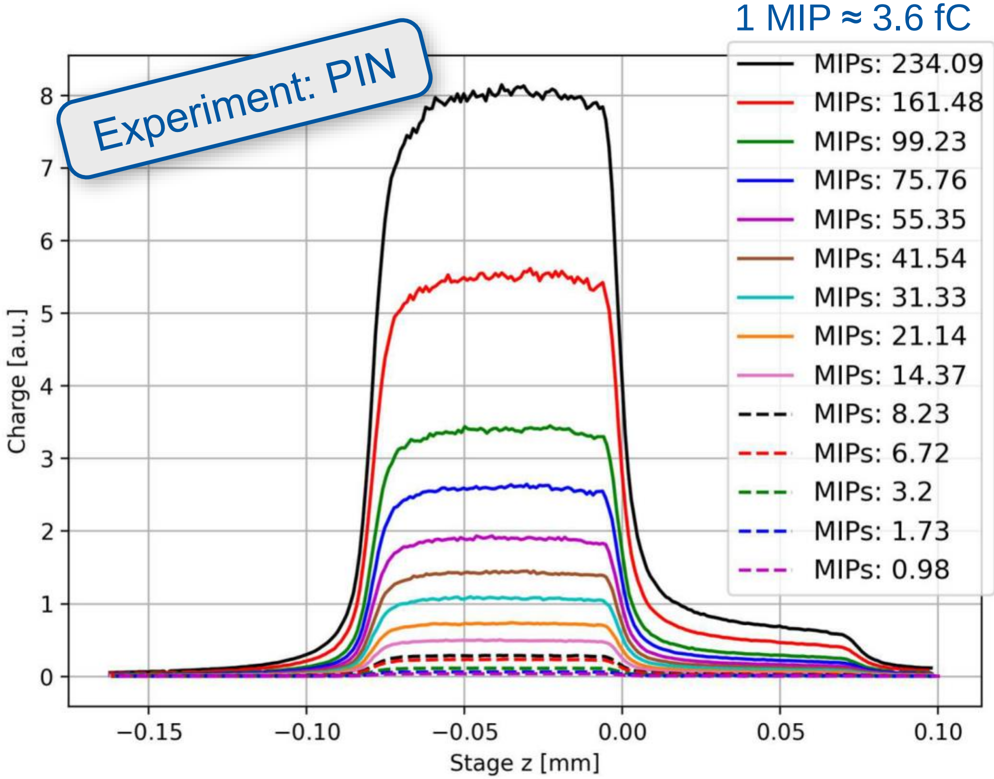
+4.0 ns

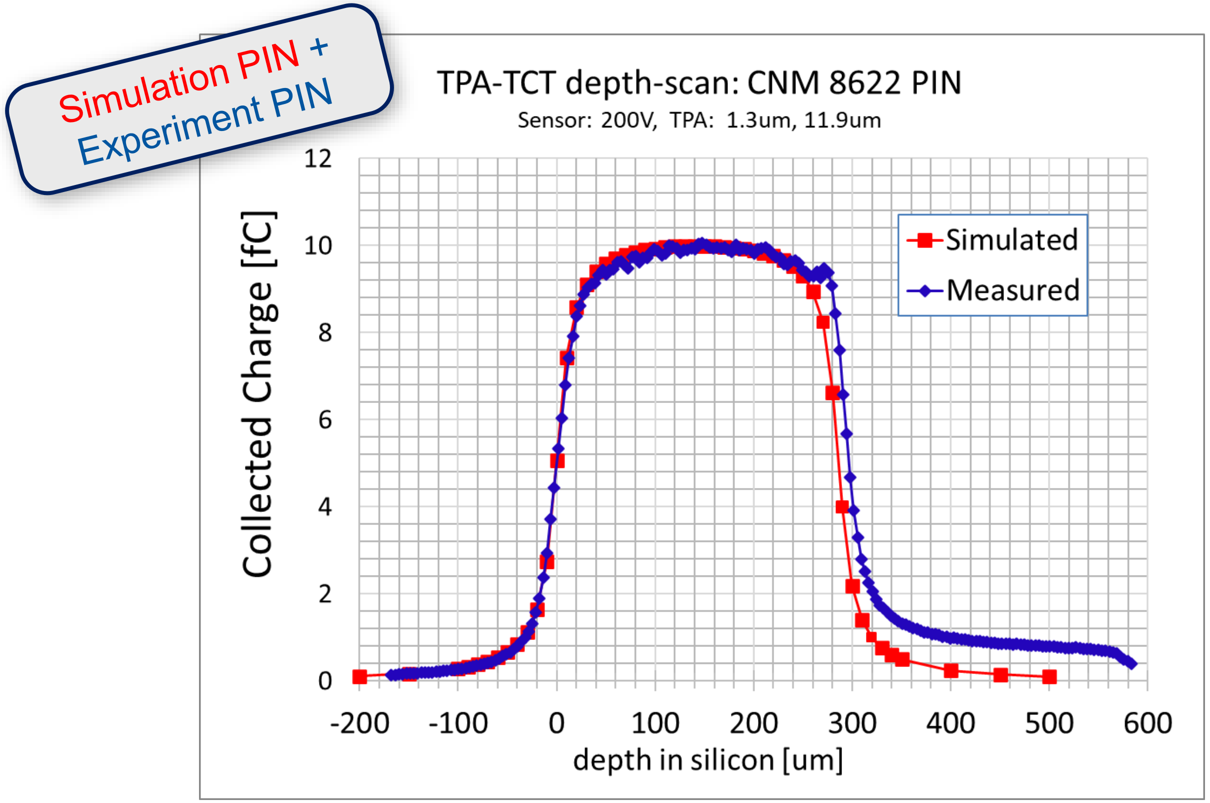
- More details on experimental results:
  - Sebastian Pape, 27.11.2021, RD50 Workshop
  - S.Pape et. al, NIMA 2022
  - S.Pape, PhD thesis 2024

PIN – TPA-TCT z-scan

- TPA-TCT measurements on CNM 8622 devices (illumination from top)
  - **PIN:** p-type, 286µm, operated at 200V, 20°C
  - **TPA-TCT optics**: NA=0.5 (x100) resulting in a beam with z_R=11.9µm, w_0=1.3µm







PIN diode: Beam intensity has no influence on charge collection profile

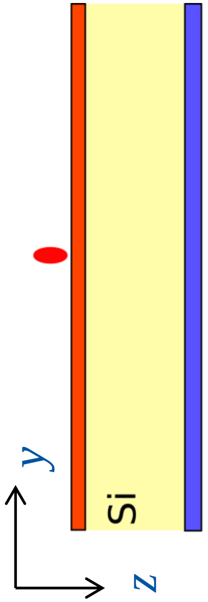
PIN: Reflection at back side not included in simulation.

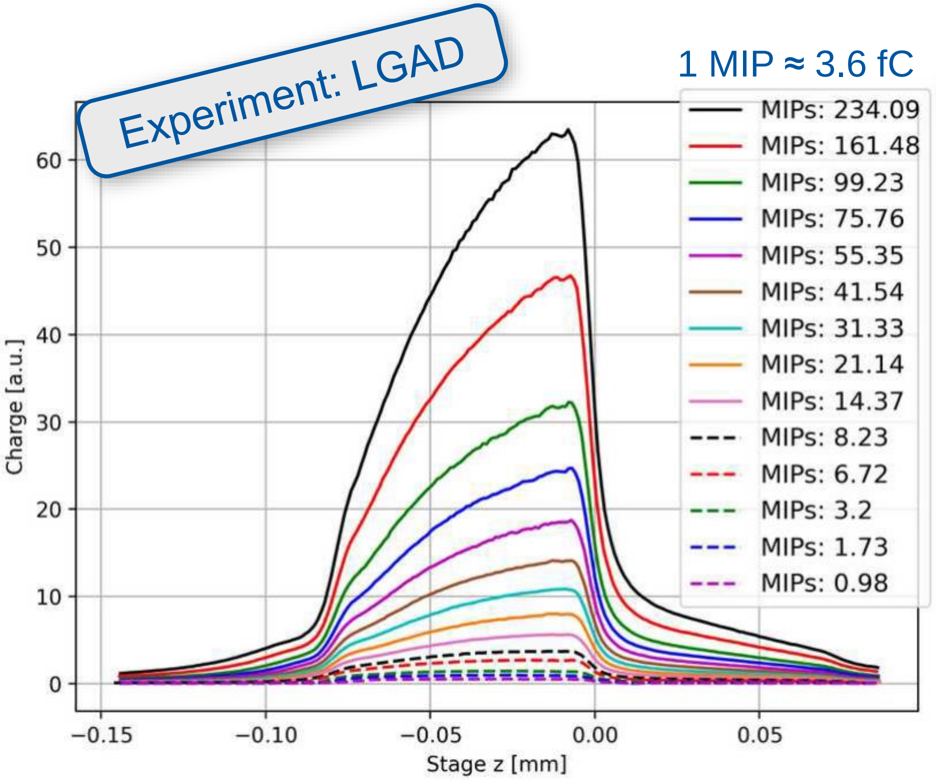
[S.Pape, RD50 Workshop Nov.2021]

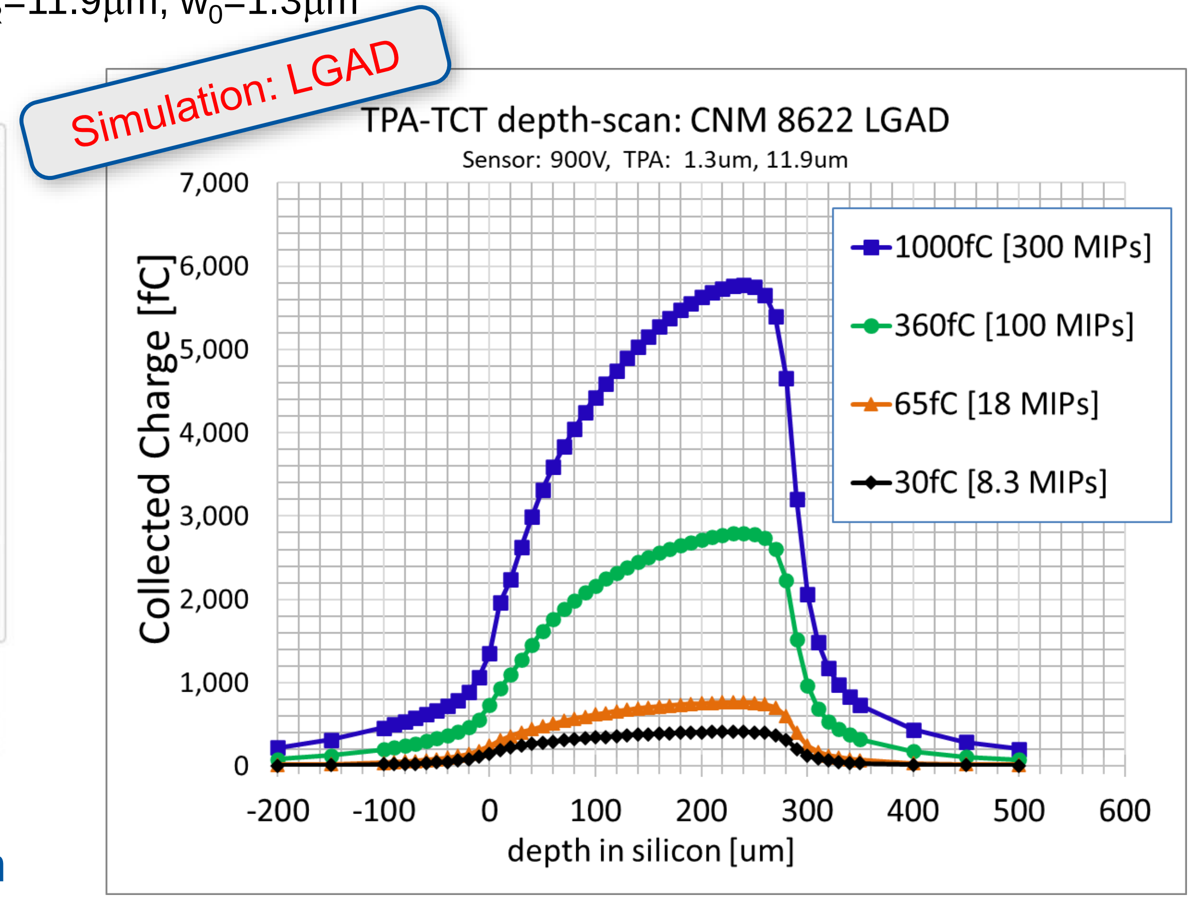
[S.Pape et. al, NIMA 2022]

LGAD – TPA-TCT z-scan

- TPA-TCT measurements and simulations on CNM 8622 devices (illumination from top)
  - **LGAD:** 280μm, operated at 900V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with z_R=11.9μm, w_0=1.3μm







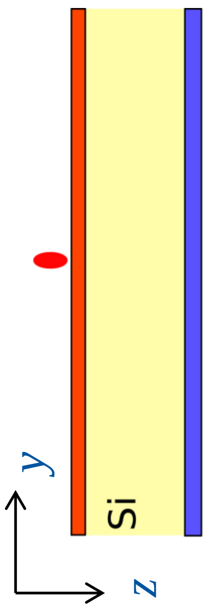
LGAD: Beam intensity has influence on charge collection profile: "shark fin effect"

[S.Pape, RD50 Workshop Nov.2021]

[S.Pape et. al, NIMA 2022]

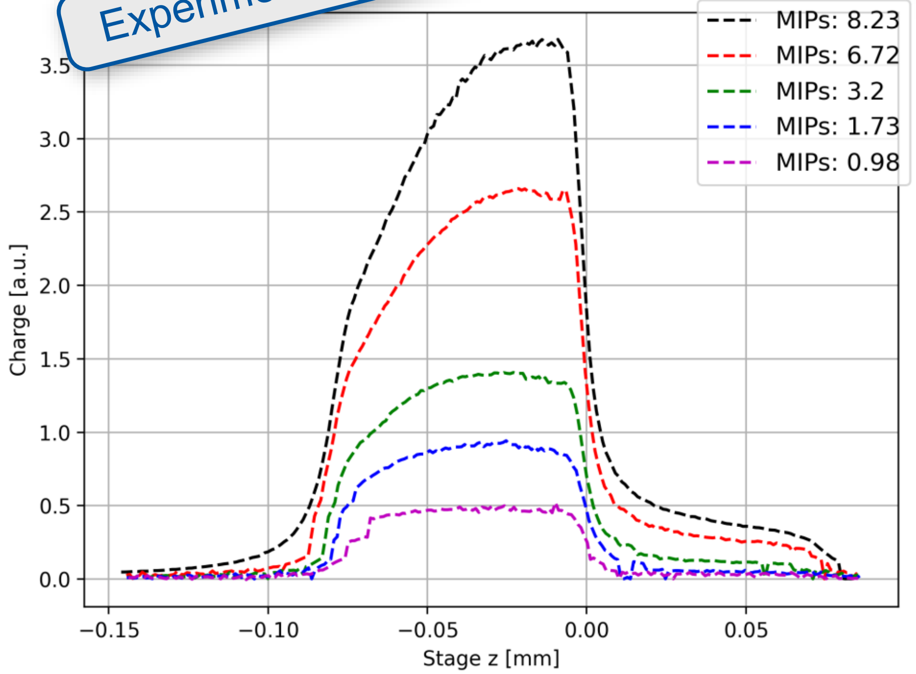
LGAD – TPA-TCT z-scan

- TPA-TCT measurements and simulations on CNM 8622 devices (illumination from top)
  - **LGAD:** 280µm, operated at 900V, 20°C
  - TPA-TCT optics: NA=0.5 (x100) resulting in a beam with z_R=11.9µm, w_0=1.3µm

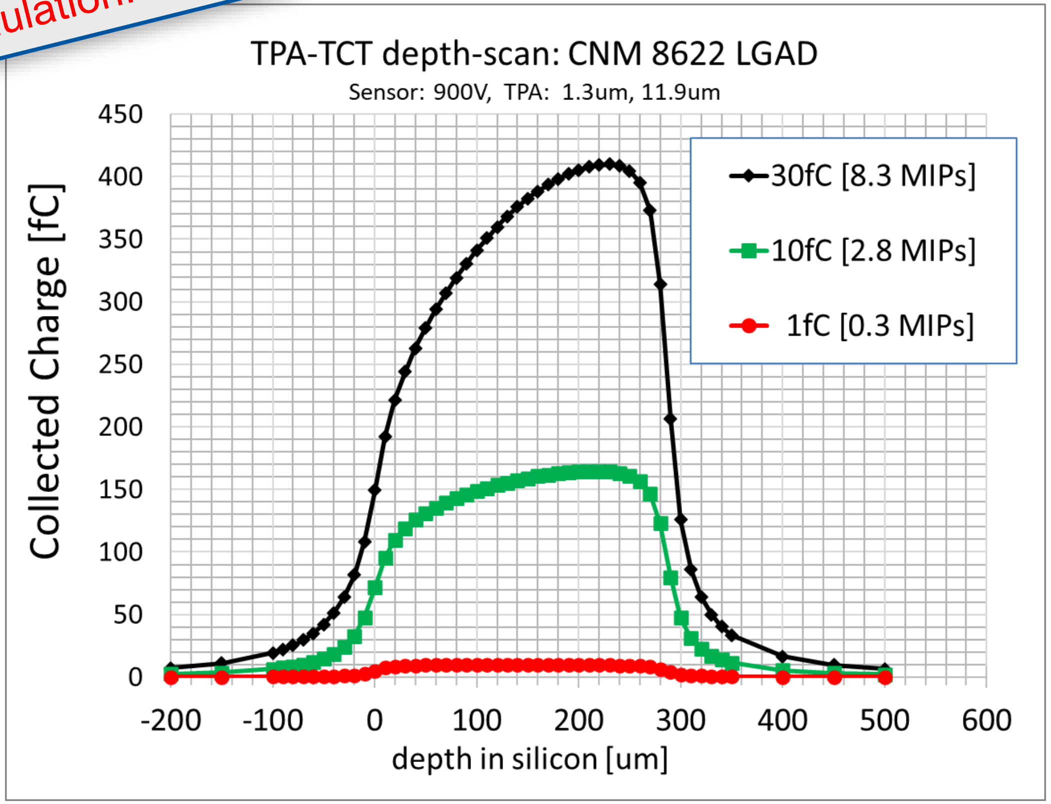


Experiment: LGAD

1 MIP ≈ 3.6 fC



Simulation: LGAD



LGAD: Beam intensity has influence on charge collection profile: "shark fin effect"

[S.Pape, RD50 Workshop Nov.2021]

[S.Pape et. al, NIMA 2022]

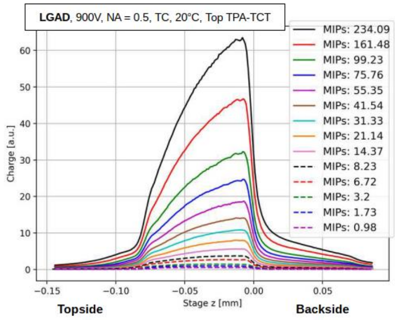
Gain as function of depth

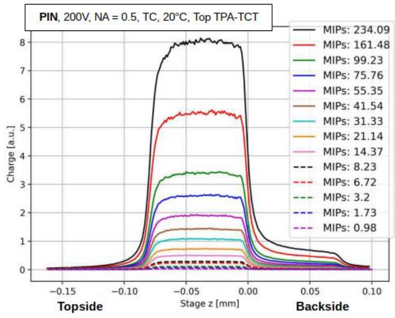
- Experimental Data
  - Sebastian Pape, 27.11.2021, RD50 Workshop
  - gain(z) = $Q_{LGAD}(z)/Q_{PIN}(z)$
  - 1 MIP = 3.6 fC

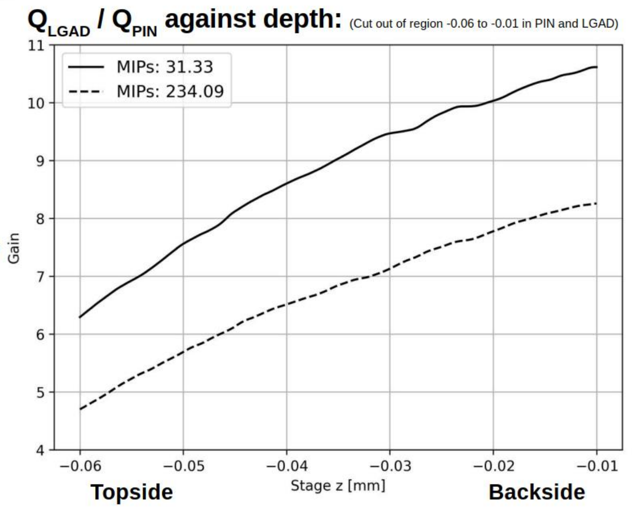
Experiment: LGAD, PIN

Simulation: LGAD, PIN

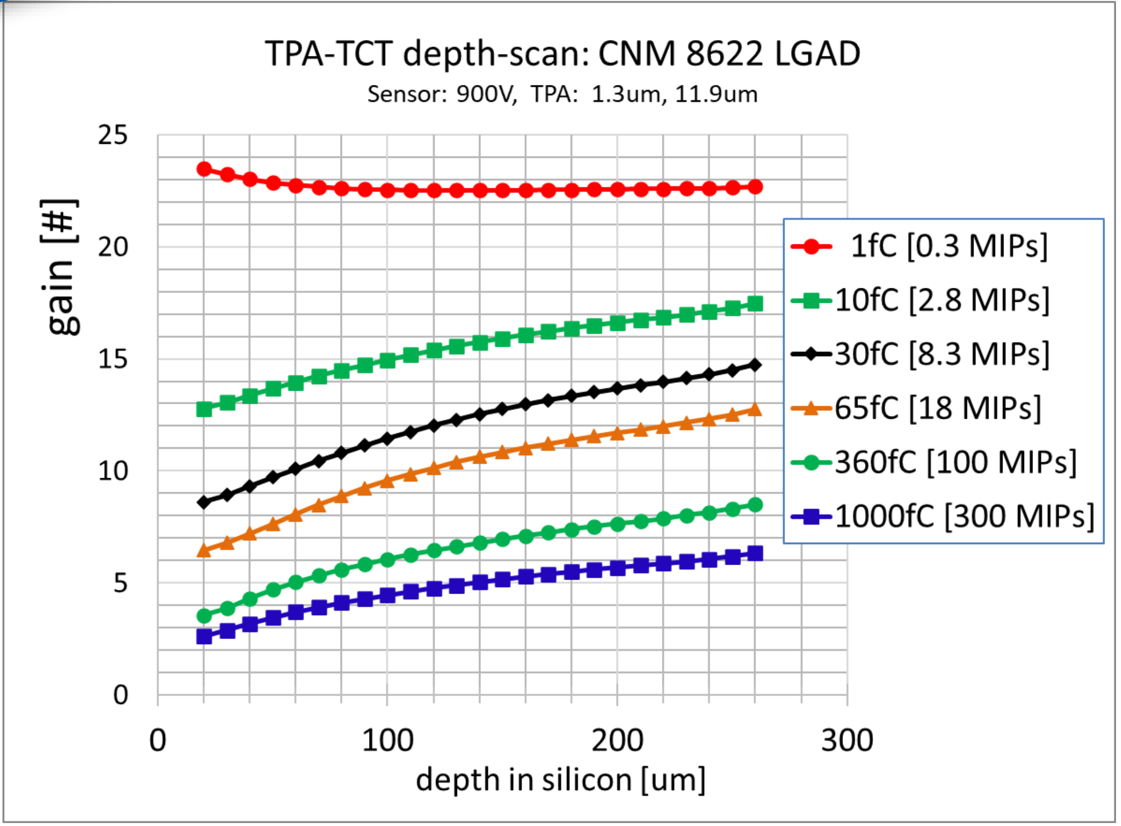
- TCAD simulation
  - CNM 8622 $Q_{LGAD}(z)/Q_{PIN}(z)$







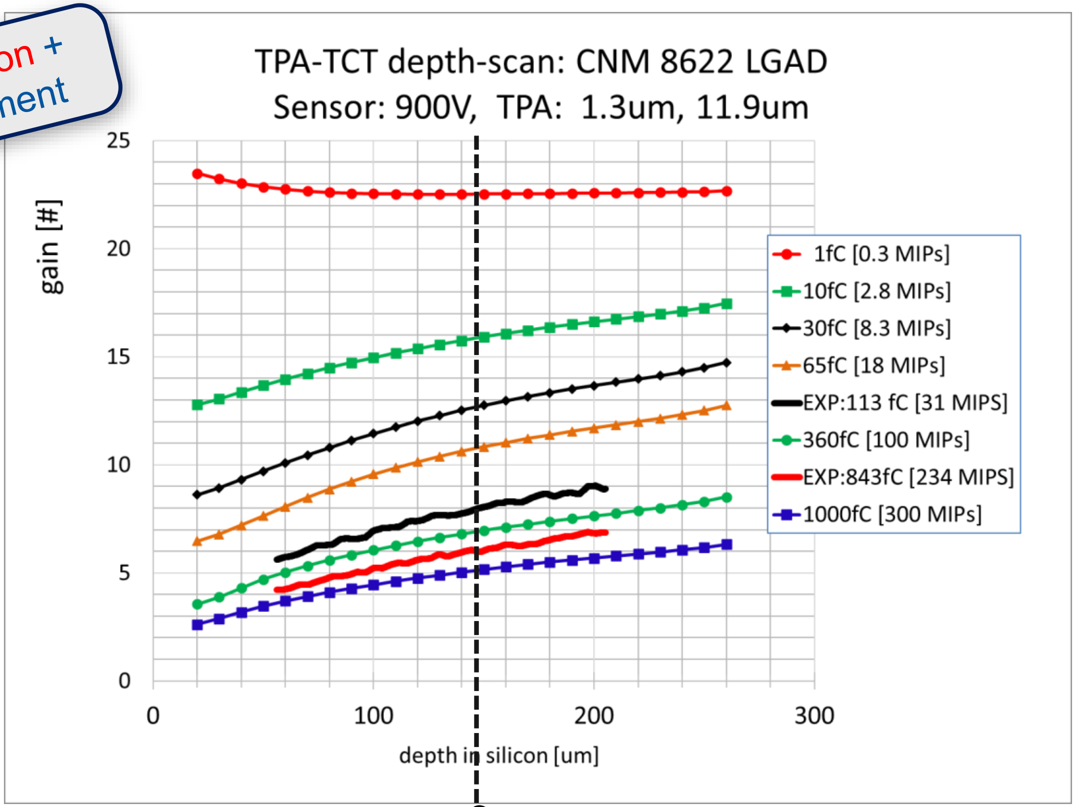
→ Gain suppression increases with the charge carrier density
→ lower in the backside because charge density decreases due to diffusion

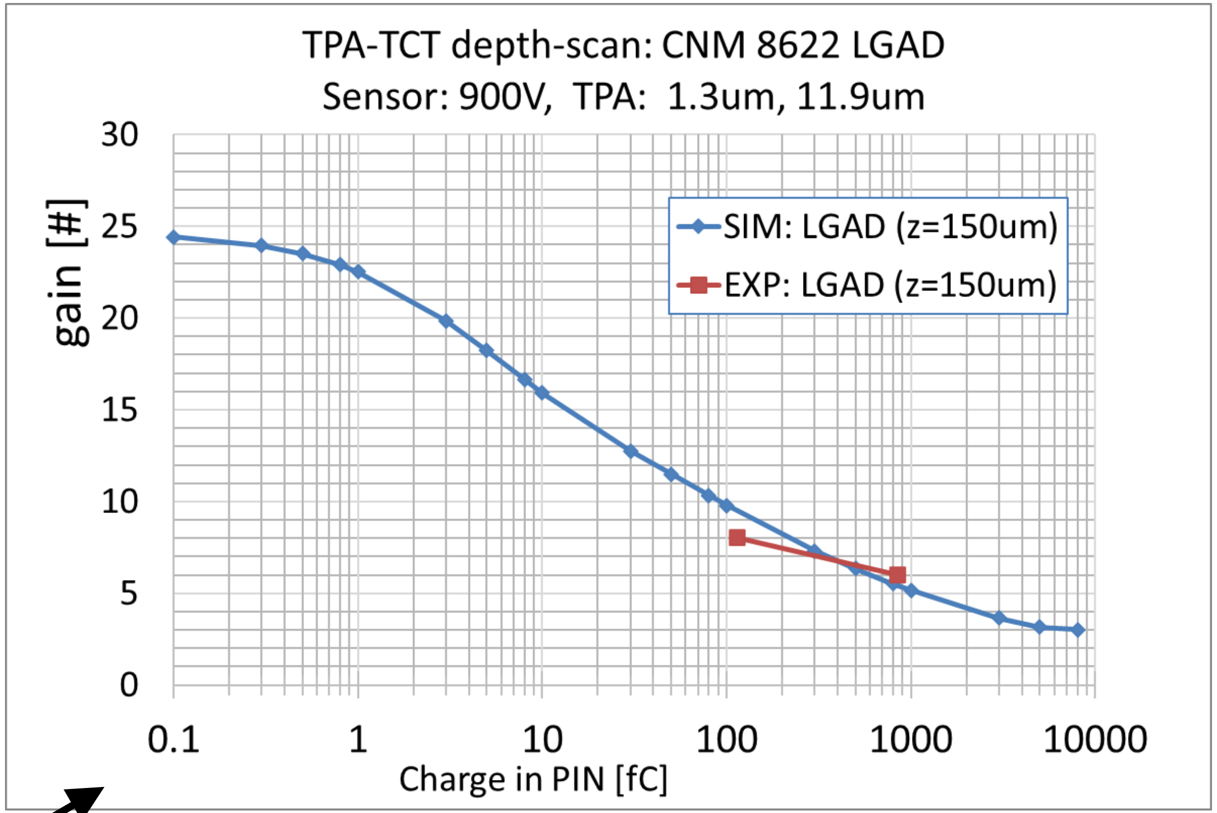


Gain as function of depth

- Experimental and Simulated Data
  - gain(z) = $Q_{LGAD}(z)/Q_{PIN}(z)$ (collected within 25ns)
  - 1 MIP = 3.6 fC

Simulation + Experiment





Carriers deposited at z=150 um

Gain as function of depth

- Experimental and Simulated Data
  - gain(z) = $Q_{LGAD}(z)/Q_{PIN}(z)$ (collected within 25ns)
  - 1 MIP = 3.6 fC

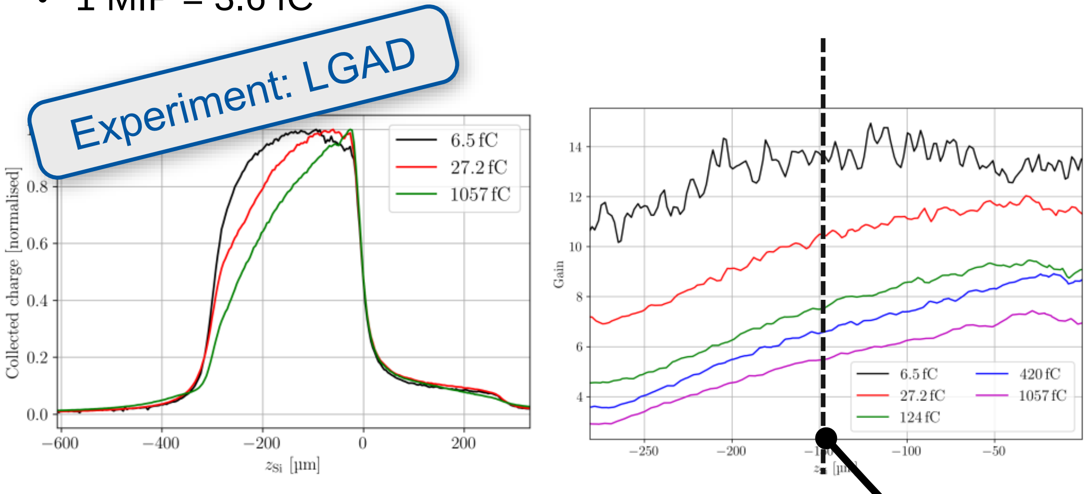
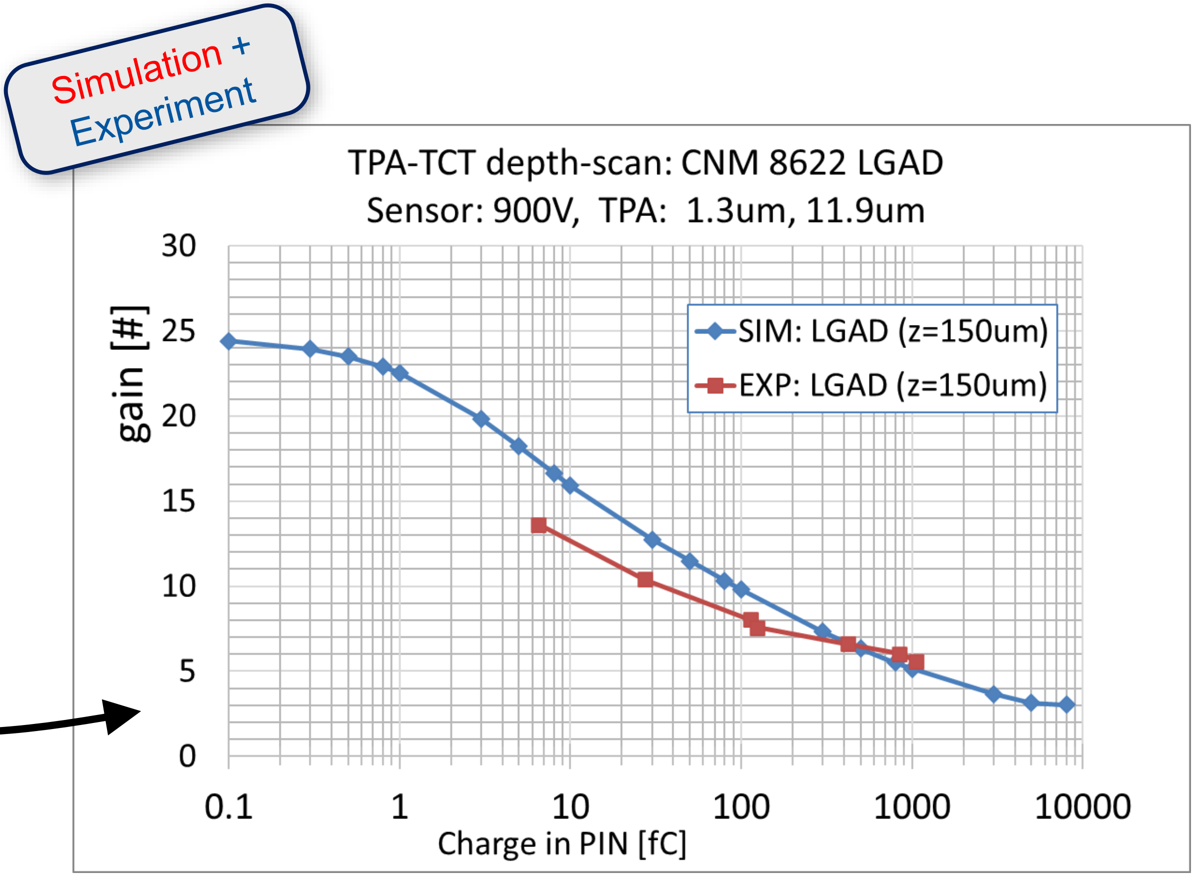


Figure 4.2.2: Gain reduction mechanism observed in the CNM LGAD 8622-W5-D8-2 by in-depth scans (a) and gain profiles (b) at different laser intensities. The laser intensity is given in units of the generated charge, which is extracted from measurements in a pad detector. The top side is located at ≈ −300 µm and the coordinates in the z-axis of both plots match. The gain reduction becomes more pronounced when charge is generated inside or close to the top side junction. All measurements are performed with a bias voltage of 900 V.

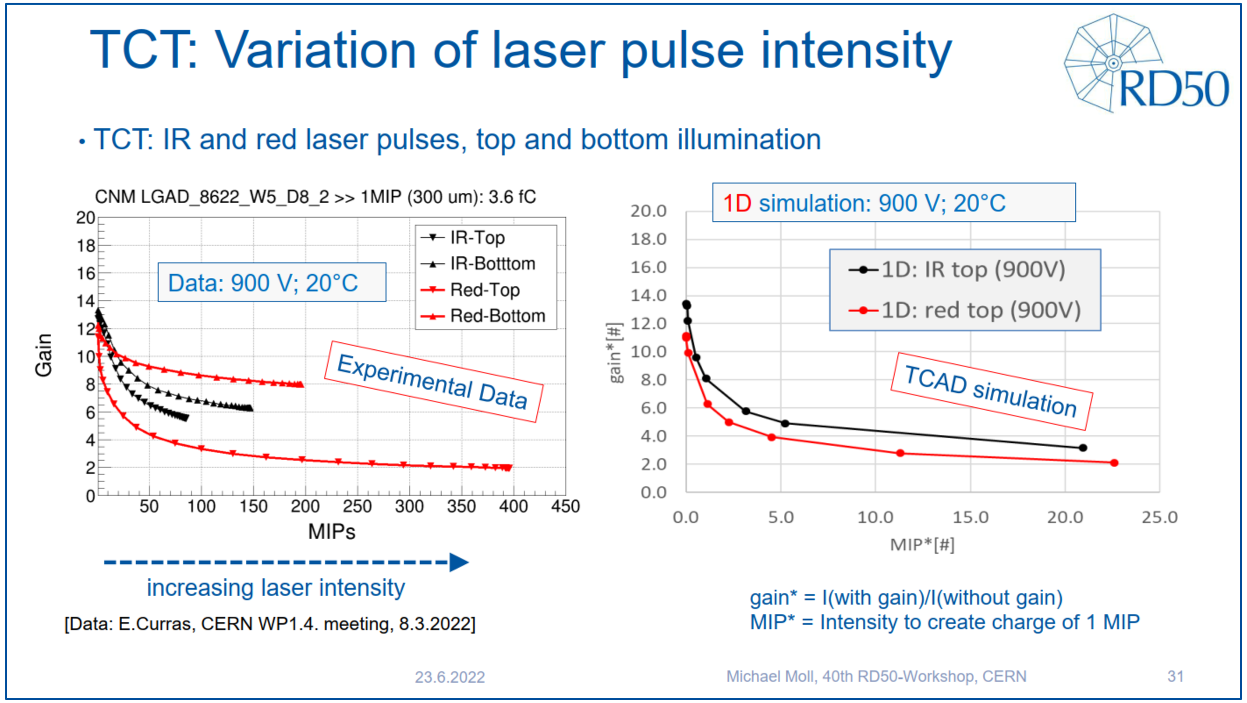


Carriers deposited at z=150 um

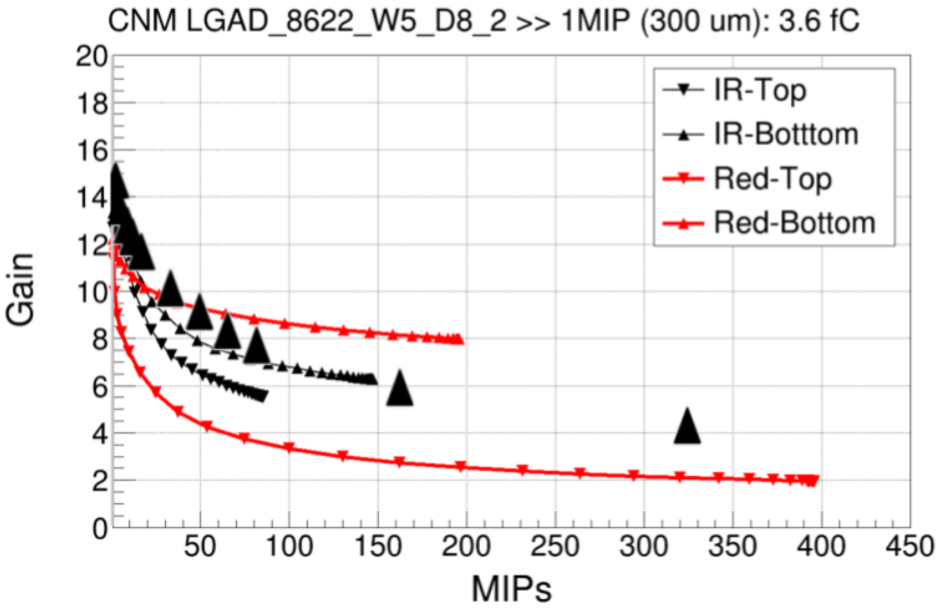
Outlook: SPA-TCT (Infrared)

- Study of LGAD gain suppression using SPA-TCT

- June 2022 RD50 Workshop
  - 1D simulation on gain suppression: Factor >10 mismatch in laser intensity between simulated and experimental data

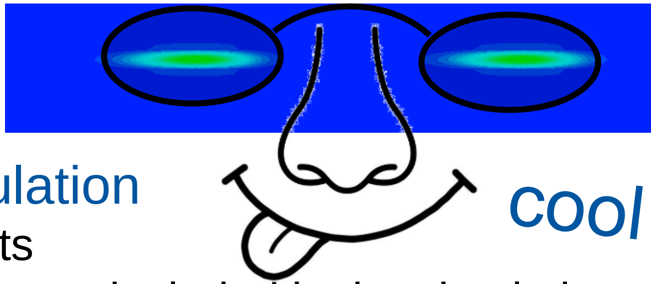


- Repeated simulation with 3D laser beam
  - 1064nm, z_R=50um, w0=8um, absorption length 1.5 mm
  - Good agreement (preliminary data)



large triangles = TCAD simulation

Conclusions/Outlook



- TPA generated charge profiles included in TCAD simulation
  - good agreement between measured and simulated transients
  - reflections of the beam are seen in the experimental data but not included in the simulations
  - simulations help to understand several features of z-scans on PIN diodes (see Sebastian Pape talk)
  - Simulated transients undergo same analyses procedures as measured transients:
    - Access to: Time-over-Threshold (ToT), Prompt-Current (PC), Weighted Prompt-Current (WPC),…
    - Simulations proved already a powerful tool to understand several features of z-scans on PIN diodes

- TCAD simulations reproduces the “shark-fin” effect for LGADs
  - confirmation that diffusion is the origin of the effect
  - gain suppression can be successfully simulated in TCAD simulators with ‘standard physics models’
  - absolute values of gain suppression in this work agree within 20% with experimental results

- OUTLOOK
  - Consolidation of simulations: study LGAD transients, meshing integrity, absolute numbers of charge generated
  - Gain suppression in LGADs as seen with infrared and red lasers
  - Development of an analytic model for LGAD gain suppression in Monte Carlo solvers
    - very tricky, see Femke de Wit thesis [link]
  - Study of plasma effects in PIN diodes (experimental results covered by TCAD simulations??)