The gain reduction mechanism in Low Gain Avalanche Detectors investigated with the TPA-TCT

Esteban Currás[1], Marcos Fernández García[1,2], Michael Moll[1], Raúl Montero[3], F. Rogelio Palomo[4], Sebastian Pape[1,5], Christian Quintana[2], Iván Vila[2]

[1]CERN
[2]Instituto de Física de Cantabria
[3]Universidad del Pais Vasco (UPV-EHU)
[4]Universidad de Sevilla
[5]TU Dortmund University

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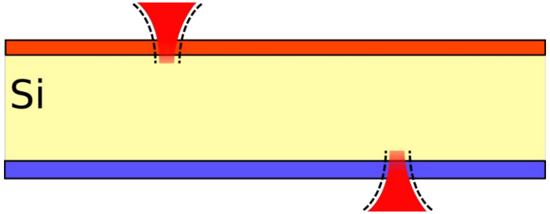
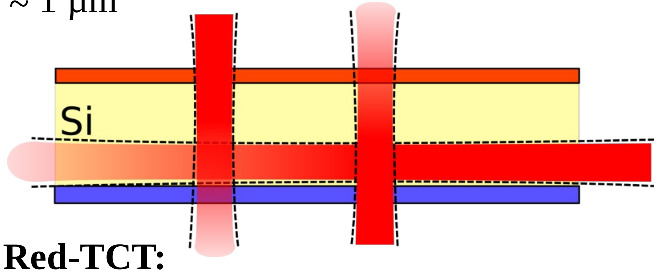
Single Photon Absorption-TCT

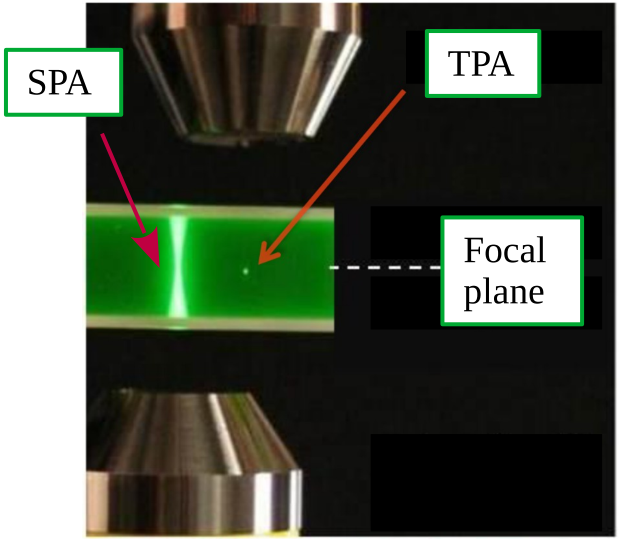
$\lambda \approx 700$ nm



$\lambda \approx 1$ µm



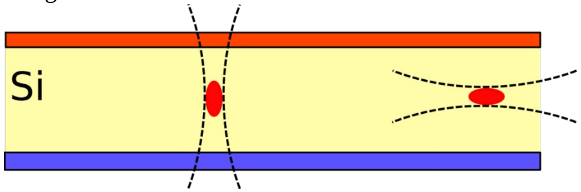
- **Red-TCT:**
  - Full light absorption in ~3-10 µm depth
  - optimal for e/h separation
  - Laser can be micro focused to < 5 µm: **2D resolution**
- **IR-TCT:**
  - To mimic MIPs (continuous laser absorption)
  - Normally 6-10 µm **2D resolution**
  - Edge injection in thick devices allows a depth study



Photography: **Ciceron Yanez**, University of Central Florida

Two Photon Absorption-TCT

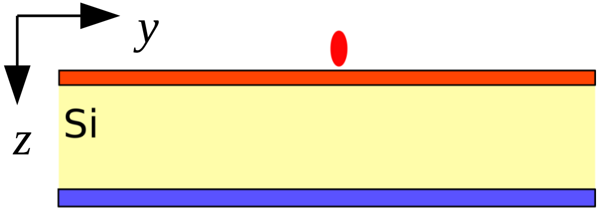
$\lambda > E_g$



- **TPA** excites charge carriers into the CB
- Non-linear effect, depends quadratic on the intensity

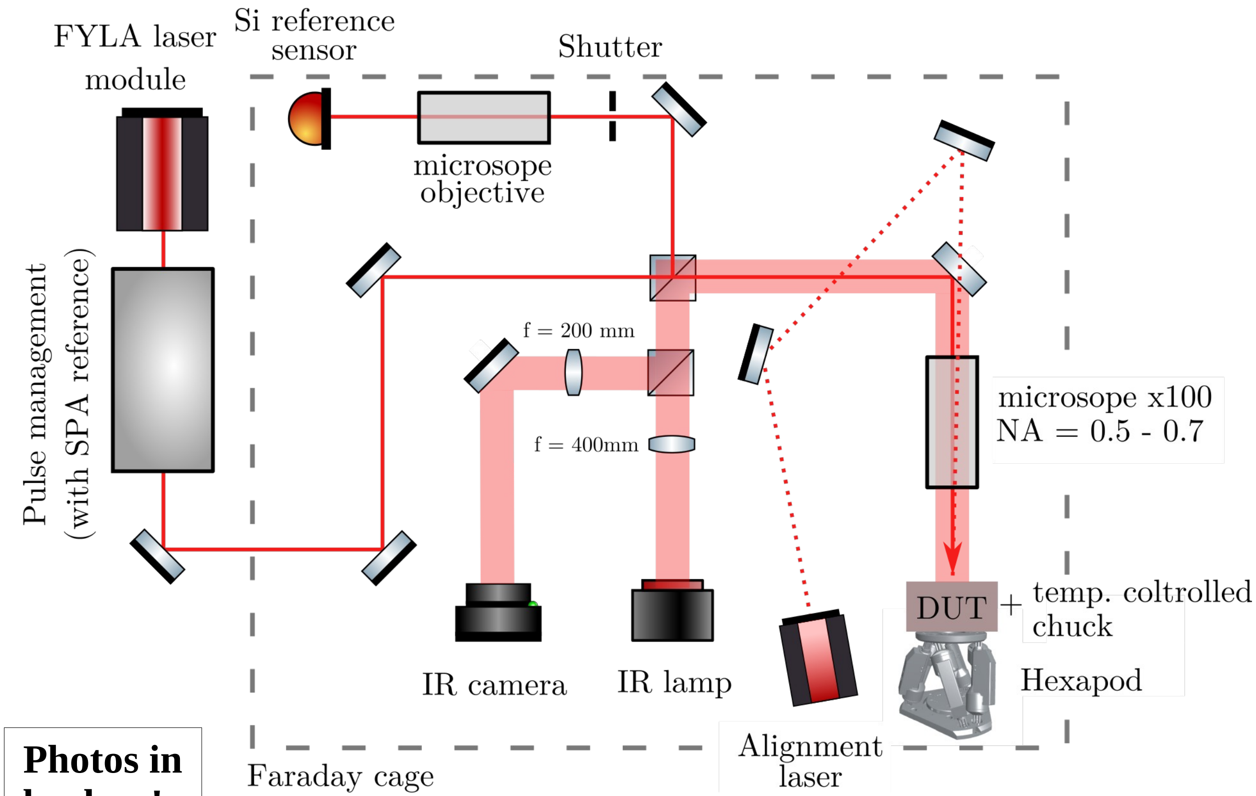
→ main excitation around focal point

- **3D resolution** tool to scan silicon devices:



TPA-TCT: Setup & Calibration

Sketch of the TPA-TCT setup at CERN SSD:

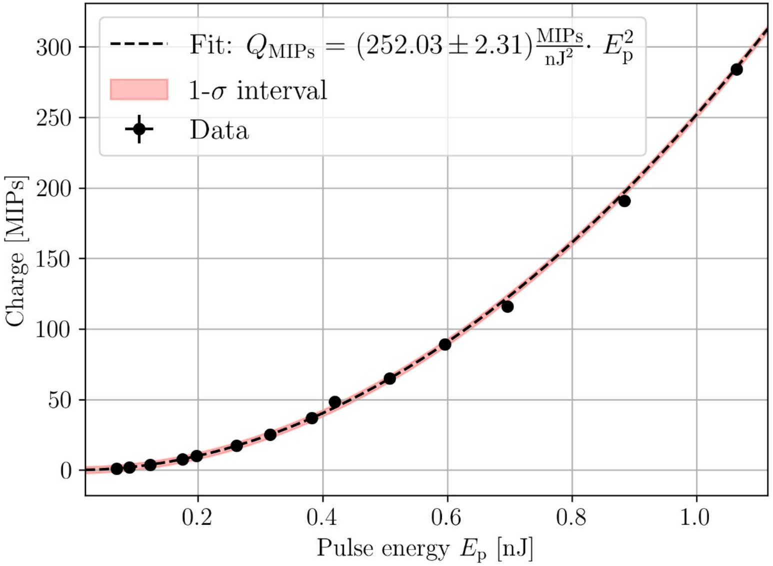


Photos in backup!

M. Wiehe et al.:
Development of a Tabletop Setup for the Transient Current Technique Using Two-Photon Absorption in Silicon Particle Detectors

Calibration:

Pulse energy against generated charge (in a 285 µm PIN; NA = 0.5 at 20°C and 0% humidity):



The pulse energy is measured with a S401C thermal power sensor from Thorlabs.

Impact of the charge carrier density on the gain in LGADs

Excess electrons inside the gain layer build up a temporal counter directed electric field with the holes from the amplification.

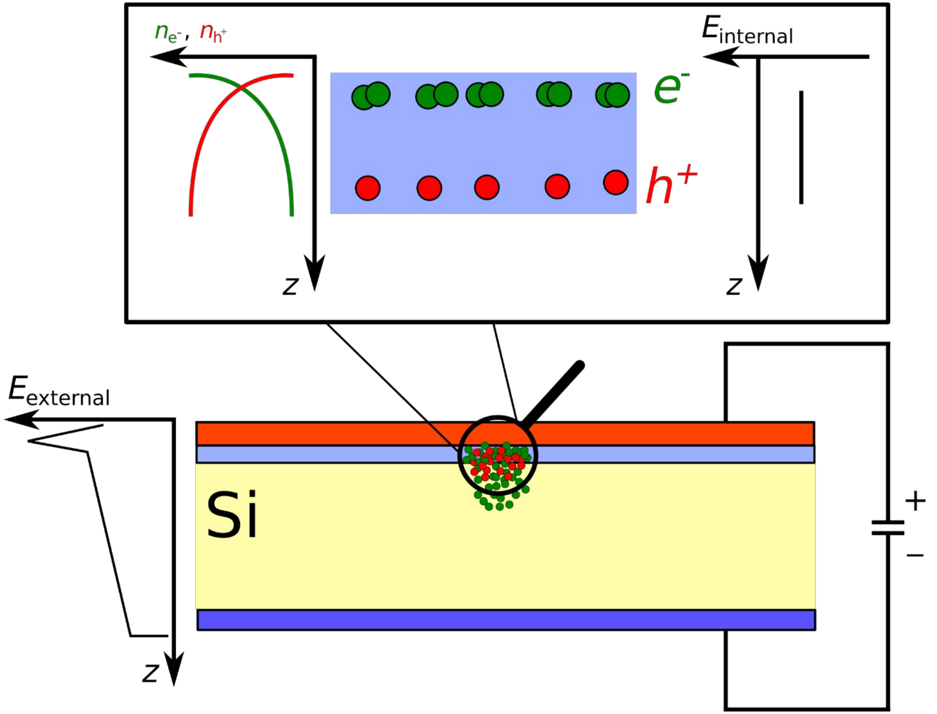
→ Following electrons are in a reduced E-field
→ Lower impact ionisation coefficient
→ Reduced gain

Effect was first found at CERN SSD when comparing IR-TCT and ^{90}Sr source measurements.

Further detail can be found in:

E. Currás, M. Fernández and M. Moll:
Gain suppression mechanism observed in Low Gain Avalanche Detectors (2021)
S. Pape et al.: VCI2022 contribution
G. Kramberger et al.: 39th RD50 workshop contribution

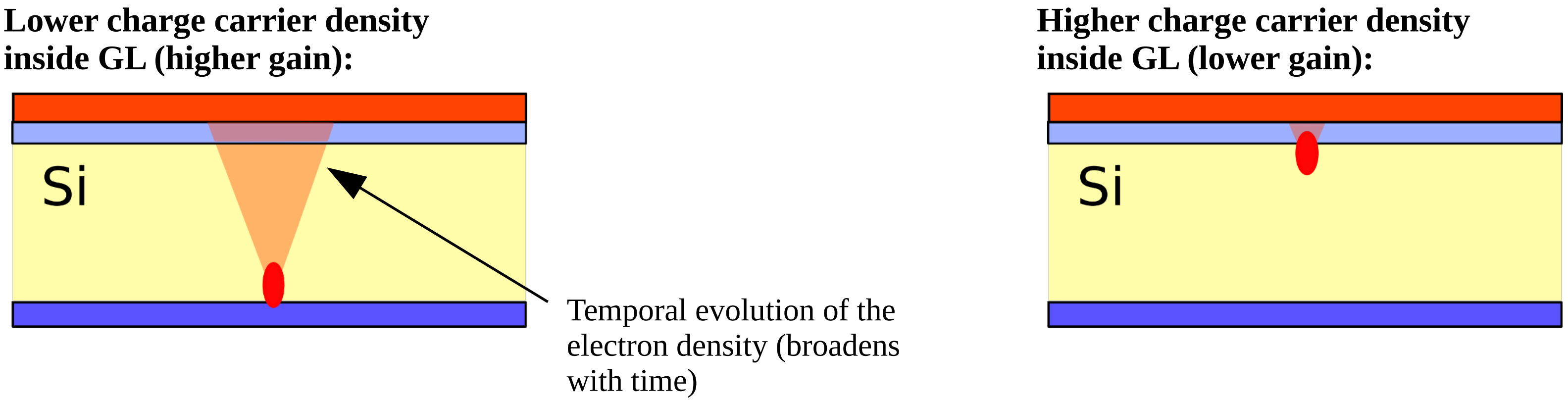
Schematic of the gain reduction by charge carrier density:



Further talk at this conference:
V. Sola: Observation and characterisation of the charge screening effect in LGAD

TPA-TCT: Gain reduction measurement

Gain reduction by charge carrier density can be measured in a **single *z*-scan** using TPA-TCT:



Temporal evolution of the electron density (broadens with time)

Devices under test:

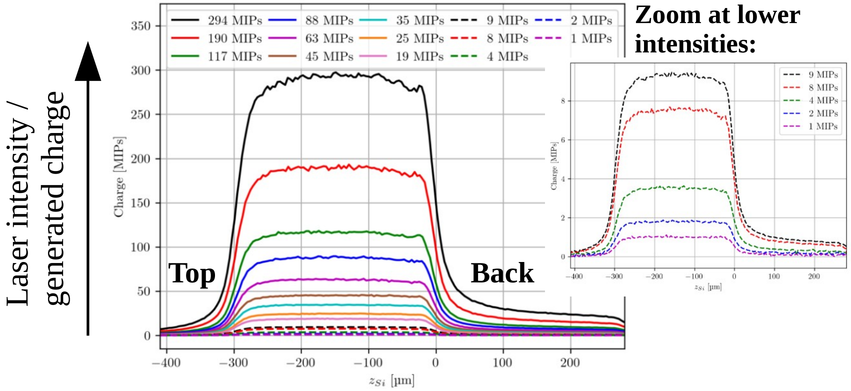
- LGAD: CNM RUN8622 Wafer 5, p-type, 300 µm thick (285 µm active)
- PIN: same details as LGAD

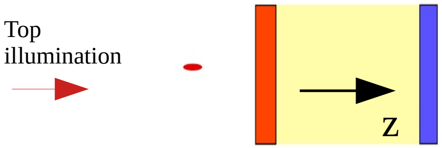
Measurement details:

- Temperature controlled at 20°C
- 0% humidity (dry air)
- Tilt corrected (Details: 38th RD50 talk of M. Wiehe)
- Objective with NA = 0.5
- Light injection from the topside
- Back side biased
- LGAD & PIN at **same bulk voltage** (see backup for more details)

TPA-TCT: Gain reduction measurement

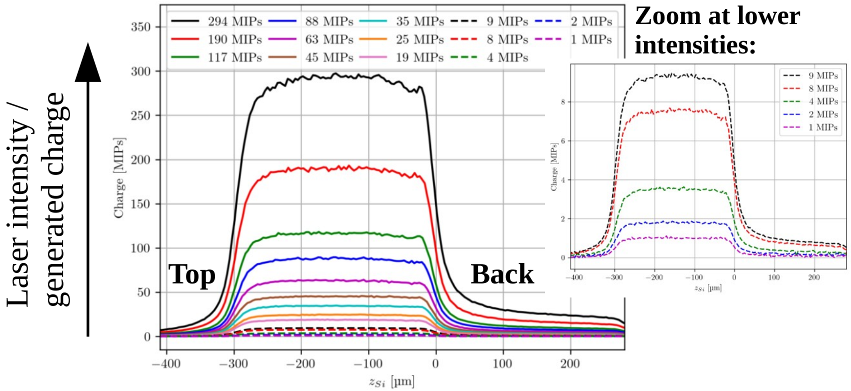
Charge collection in a PIN at different laser intensities **(V_{bulk} = 861 V)**:





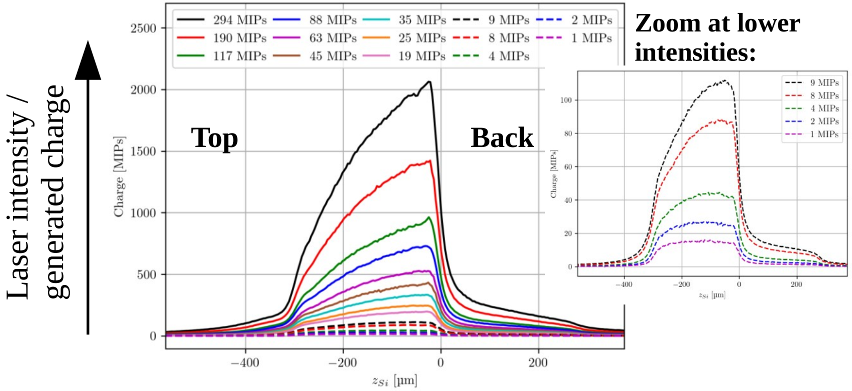
TPA-TCT: Gain reduction measurement

Charge collection in a PIN at different laser intensities **(V_{bulk} = 861 V)**:



Zoom at lower intensities:

Charge collection in a LGAD at different laser intensities **(V_{bulk} = 861 V)**:



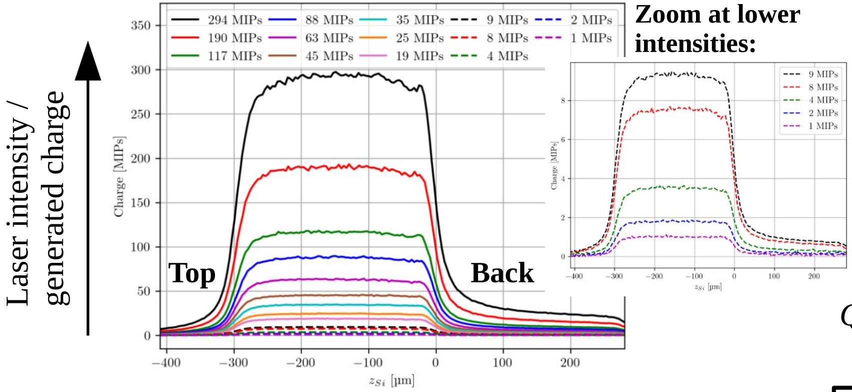
Zoom at lower intensities:

Conclusions:

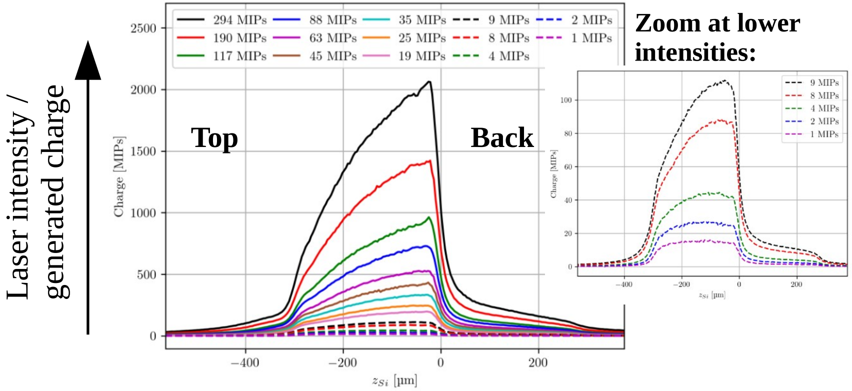
- LGAD collects more charge when initial charge is deposited in the back side
- Shape of $Q_{\text{LGAD}}(z)$ depends on the initially deposited charge
  → not observed in $Q_{\text{PIN}}(z)$

TPA-TCT: Gain reduction measurement

Charge collection in a PIN at different laser intensities (V_{bulk} = 861 V)**:**

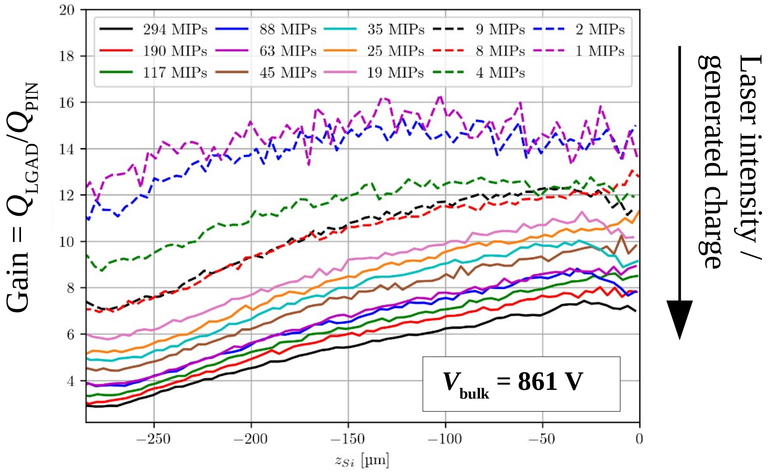


Charge collection in a LGAD at different laser intensities (V_{bulk} = 861 V)**:**



$Q_{\text{LGAD}}(z)/Q_{\text{PIN}}(z)$ yields gain curves

Gain curves:



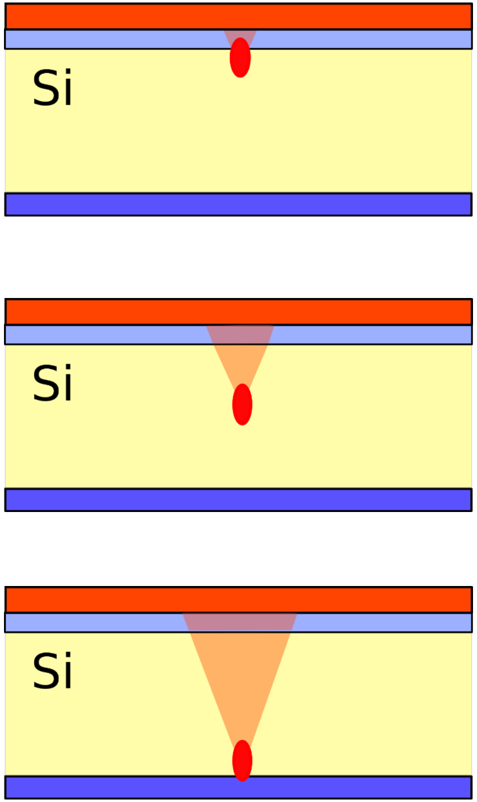
Conclusions:

- LGAD collects more charge when initial charge is deposited in the back side
- Shape of $Q_{\text{LGAD}}(z)$ depends on the initially deposited charge
  → not observed in $Q_{\text{PIN}}(z)$
- Gain is higher when the charge is deposited at the back side compared to the top side
  → higher charge carrier density inside the gain layer, when charge is deposited at the top side
  → higher gain reduction

Influence of a broadening charge carrier density

- Charge carrier density broadens during drift towards collecting electrode
  - ➔ Lowers the charge carrier density that arrives at the gain layer
  - ➔ Deeper deposition ⟶ longer drift time ⟶ higher influence of broadening ⟶ less gain reduction / higher gain

- Needed to compare measurements from different deposition depths



Side note:
For high enough charge carrier densities plasma arises, which prolongs the collection time (influence of plasma on the charge carrier density shape is not considered).
→ The drift time measured at a low laser intensity is taken to model diffusion for all laser intensities

The used broadening model

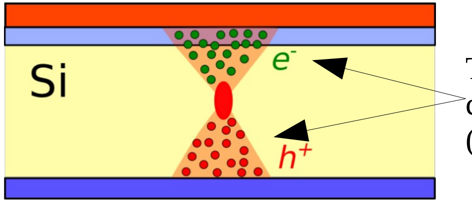
As broadening model, the two dimensional diffusion equation is used. It is numerically solved for a given drift time for the charge carrier density generated by TPA-TCT n_{TPA}:

$$\frac{\partial n_{TPA}(t,r,z)}{\partial t} = D\left(\frac{\partial^2 n_{TPA}(t,r,z)}{\partial r^2} + \frac{\partial^2 n_{TPA}(t,r,z)}{\partial z^2}\right) ,$$

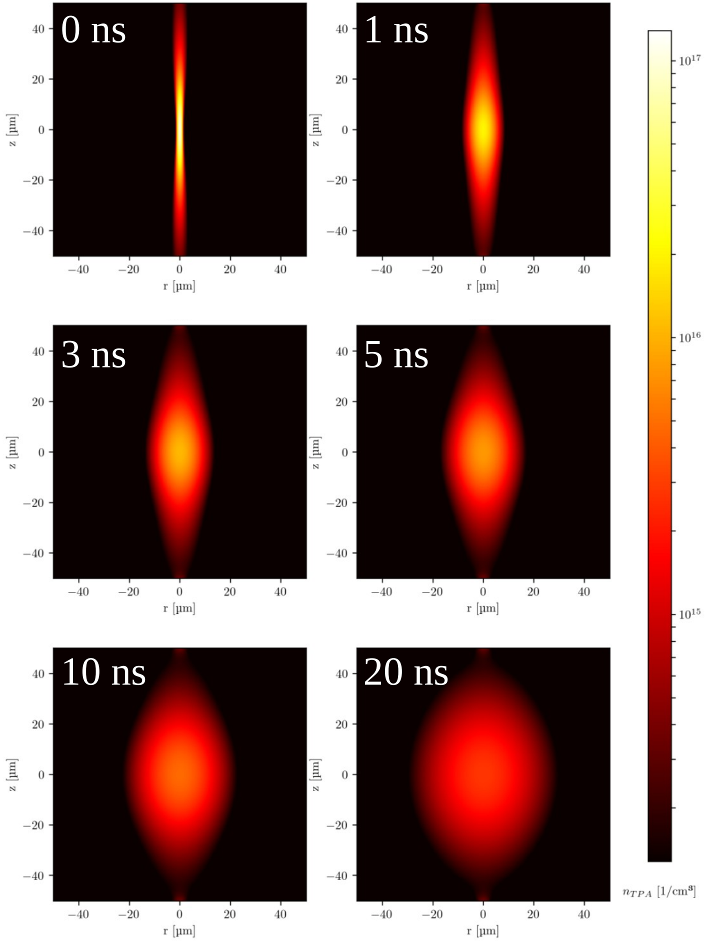
with $$n_{TPA}(0,r,z) = \frac{E_p^2 \beta_2 4 \ln(2)}{\tau \hbar \omega \pi^{5/2} \omega^4(z) \sqrt{\ln(4)}} \exp\left(\frac{-4r^2}{\omega^2(z)}\right) .$$

The diffusion constant of electrons in intrinsic silicon is used:
$D_{\mathrm{intrinsic}} = 36\ \mathrm{cm^2/s}$

Only broadening of the electrons is considered as they are the charge carrier responsible for the gain reduction:

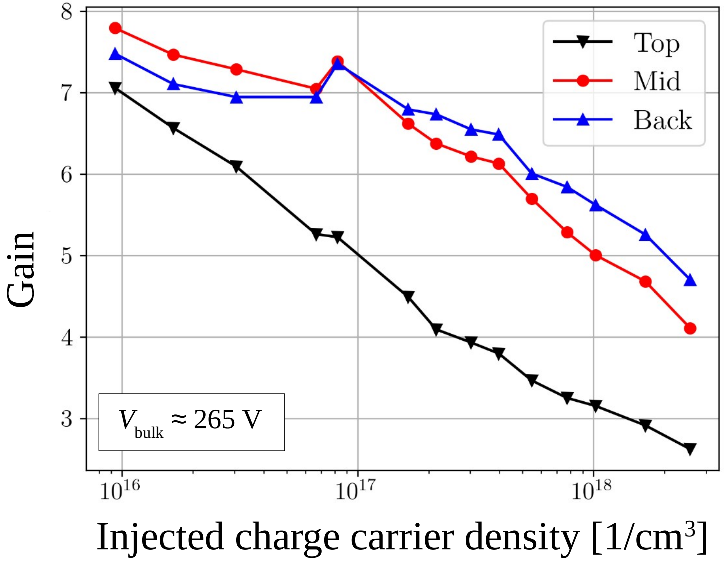


Temporal evolution of the charge carrier density (broadens with time)

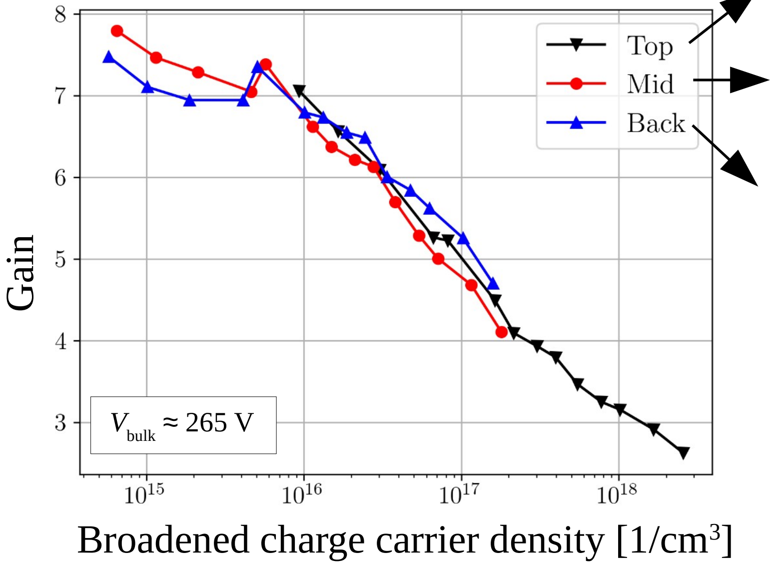


Results: Gain reduction – TPA-TCT

Broadening model **not applied**:



Broadening model **applied**:



$t_{\text{drift}} = 0$ ns

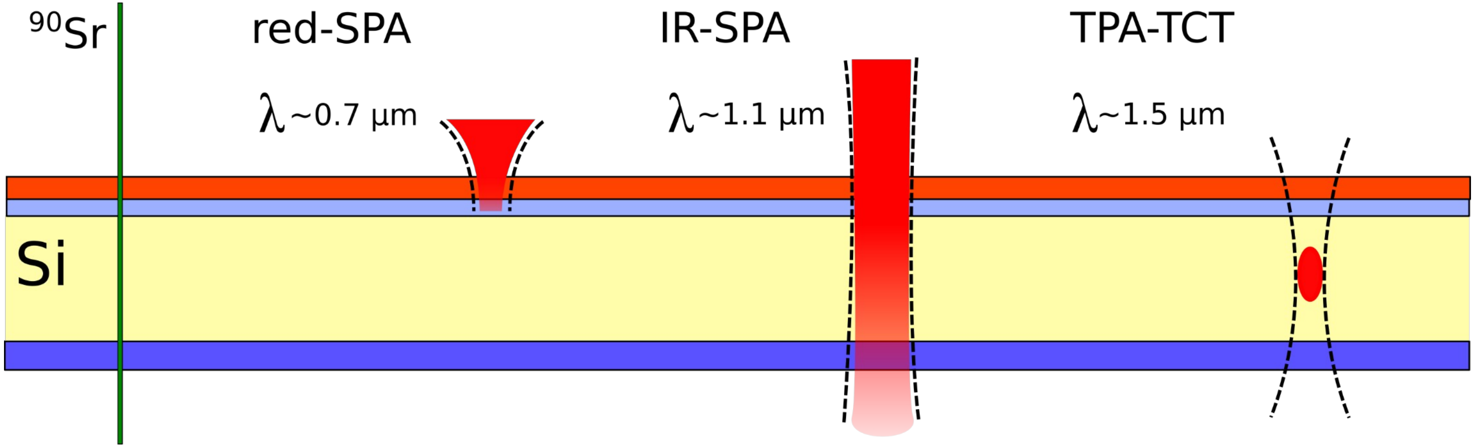
$t_{\text{drift}} = 5.72$ ns

$t_{\text{drift}} = 6.83$ ns

- Gain versus charge carrier density for different deposition depth
- Broadening model brings data into accordance → *right plot*: data agrees for all depth (Top, Mid & Back)
  → different gain for different deposition depth can alone be explained by broadening of the charge carrier density

Comparison of TPA-TCT with SPA-TCT & ^{90}Sr measurements

The here discussed gain reduction mechanism is driven by the excess electron density inside the gain layer.
The excess carrier volumes and carrier distribution provided by the different methods are very different:



Typical excess carrier volumes
(in a 300 µm thick device):

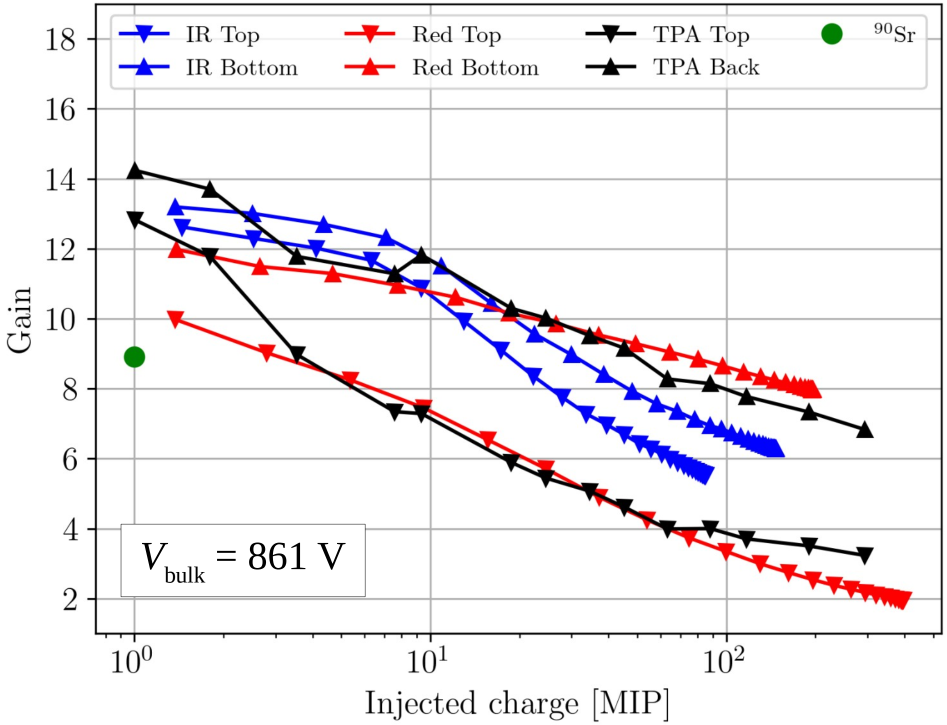
- ^{90}Sr: $V_{Sr} \approx 940\ \mu m^3$
- Red-SPA: $V_{Red} \approx 1100\ \mu m^3$
- IR-SPA: $V_{IR} \approx 100 \times V_{Sr}$
- TPA-TCT: $V_{TPA} \approx 85\ \mu m^3$

→ Difficult to extract the charge carrier density that corresponds to the gain reduction mechanism

→ For the comparison between the methods the data against the generated charge in equivalents of MIPs is presented

Results: Gain reduction by charge carrier density

Results of TPA-TCT, Red-TCT, ^{90}Sr & IR-TCT:

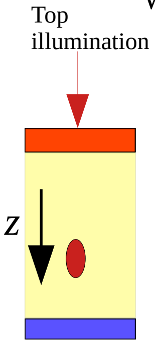


Side note:
The charge is shown as the equivalent of the charge a given amount of MIPs generate in a 285 µm thick PIN device.

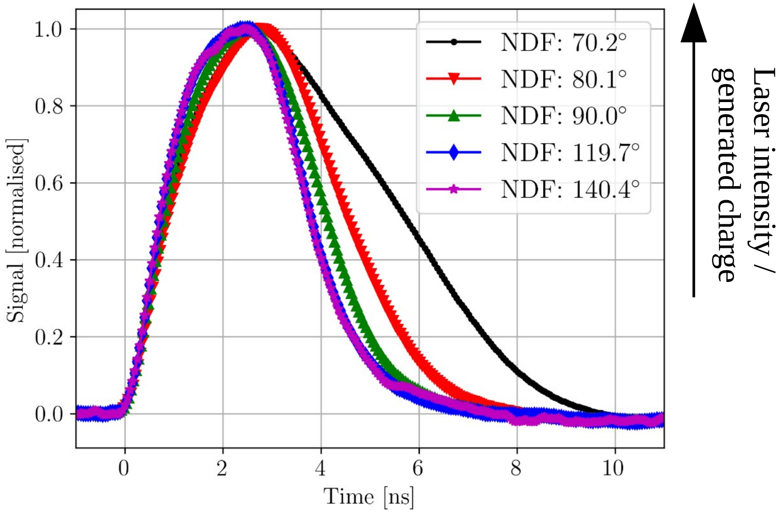
Conclusions:

- All methods show gain reduction
- β-particles of the ^{90}Sr source have the highest gain reduction at 1 MIP
- IR measurements perform very similar, because a comparable charge density is deposited
  → IR Bottom slightly higher gain due to diffusion of the charge carrier density from the back side
- TPA Top and Red Top agree for higher intensities (> 3 MIPs)
- Same holds for TPA Back and Red Bottom
  → result of a similar charge carrier density inside the gain layer

Impact of increasing charge carrier densities on the collection time

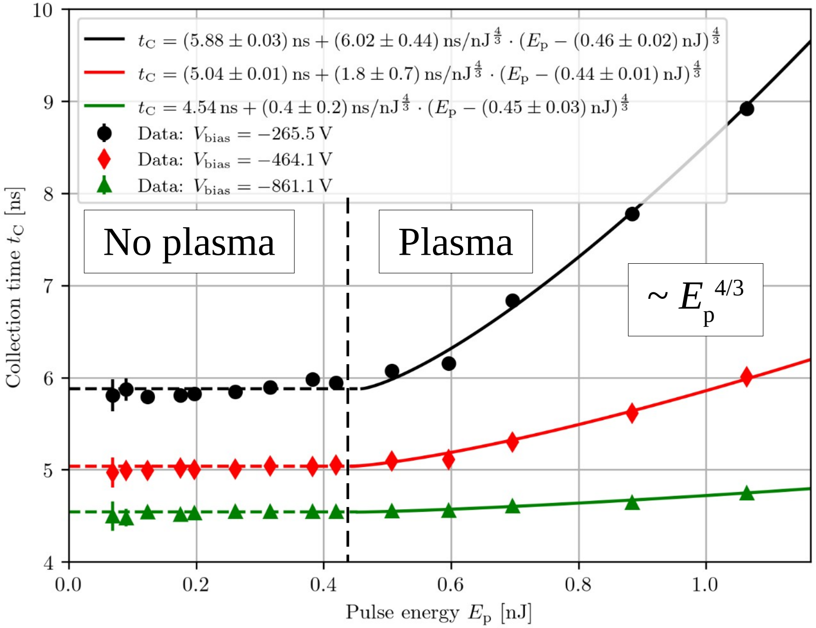


Waveforms taken at same deposition depth, with different laser intensities



Clear prolongation of the collection time observed!

At high enough charge carrier densities, plasma arises, which shields charge carriers inside the plasma from the external electric field
→ delays the beginning of the drift towards the electrodes



Fitting formula derived (by F.R. Palomo) from the Tove-Seibt theory employed to describe the collection time for different laser intensities.

The data agrees well with the model, proving that plasma is a influential effect at high charge carrier densities.

DUT: 300 µm thick p-type PIN,
biased at 265V
Temperature: 20°C
Humidity: 0%

R. Palomo et al.:
Plasma Effects in Silicon Detectors and the Two Photon Absorption Transient Current Technique (RADECS 2021, unpublished)

Summary

- TPA-TCT setup at CERN is fully commissioned
- TPA-TCT used to study LGADs
  → Charge collection behavior of LGADs investigated
- Validated the gain reduction mechanism using TPA-TCT
  → Comparison between ^{90}Sr source, IR-TCT, red-TCT, and TPA-TCT measurements shown
  → results agree within the expectations
- Broadening alone can explain the difference in gain reduction for different depths in TPA-TCT
- Plasma arises at high enough charge carrier densities and prolongs the collection time
  → Effect is understood and a model was developed

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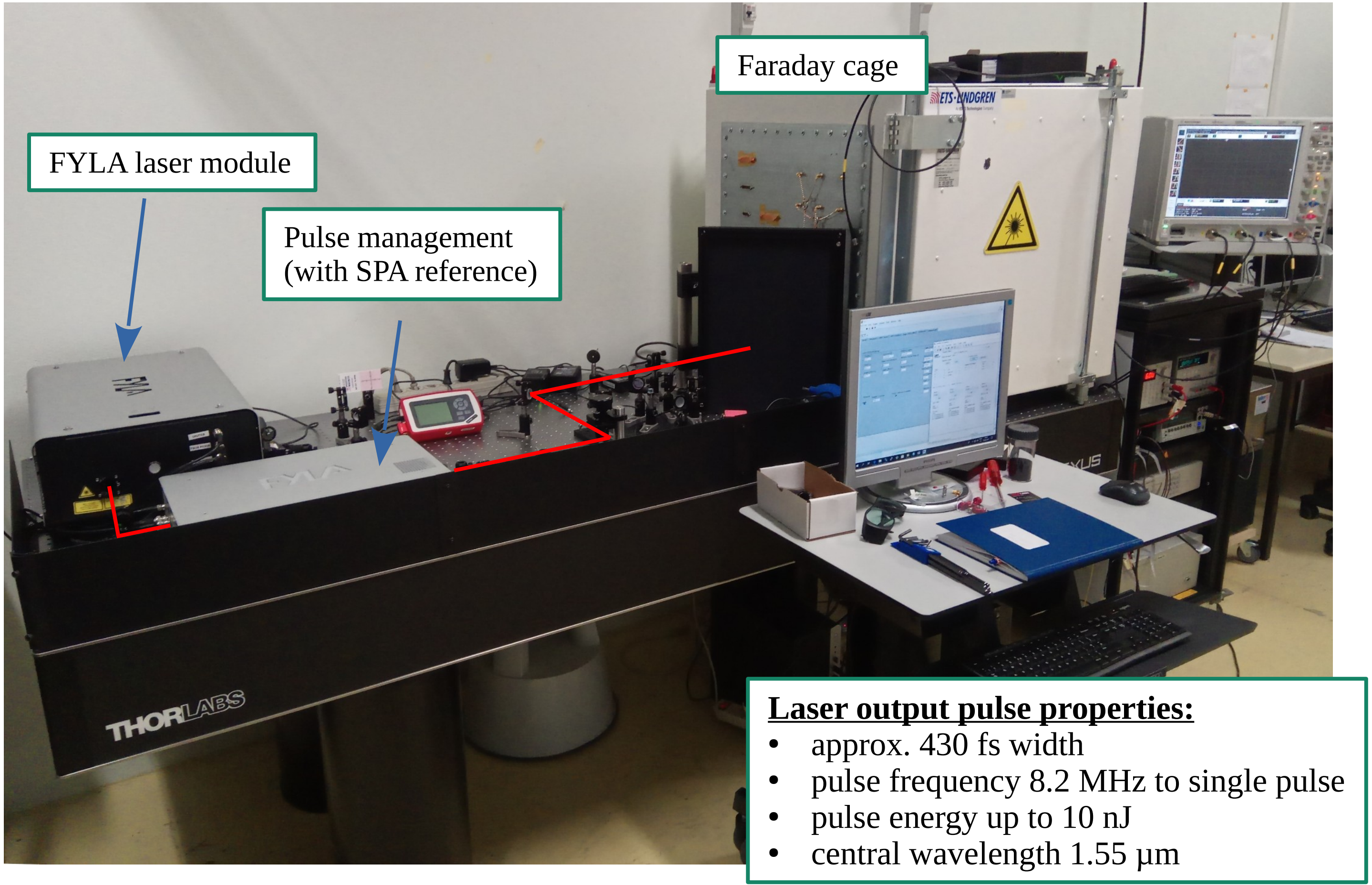
Thank you!

BACKUP

TPA-TCT setup at CERN SSD


FYLA laser module

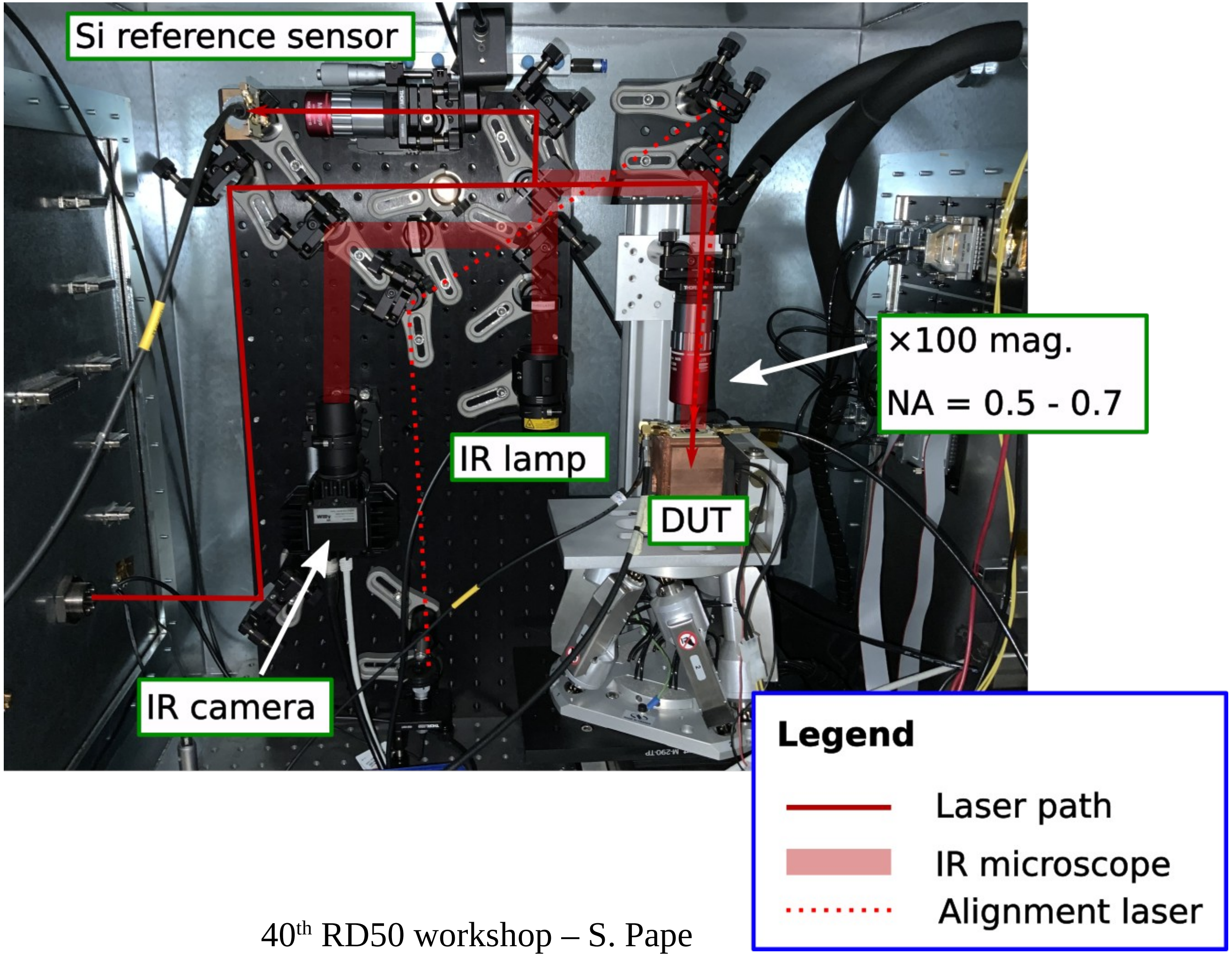
Pulse management
(with SPA reference)

Faraday cage

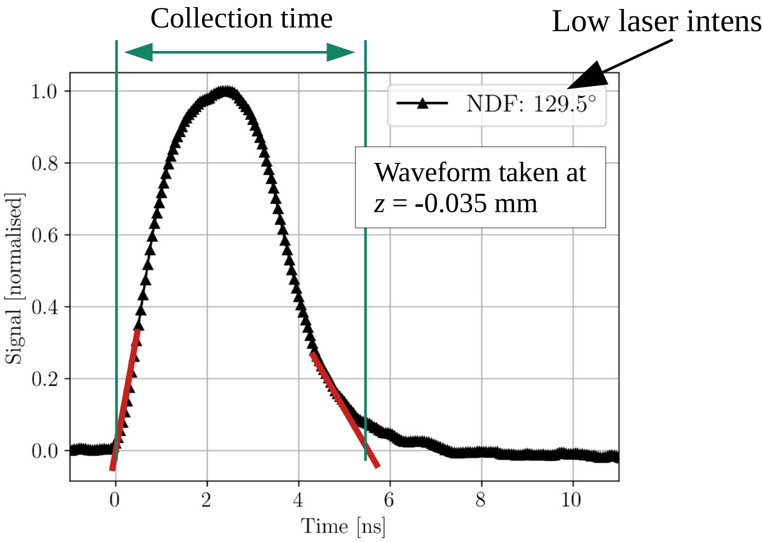
M. Wiehe et al.: *Development of a Tabletop Setup for the Transient Current Technique Using Two-Photon Absorption in Silicon Particle Detectors*

Laser output pulse properties:
- approx. 430 fs width
- pulse frequency 8.2 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm

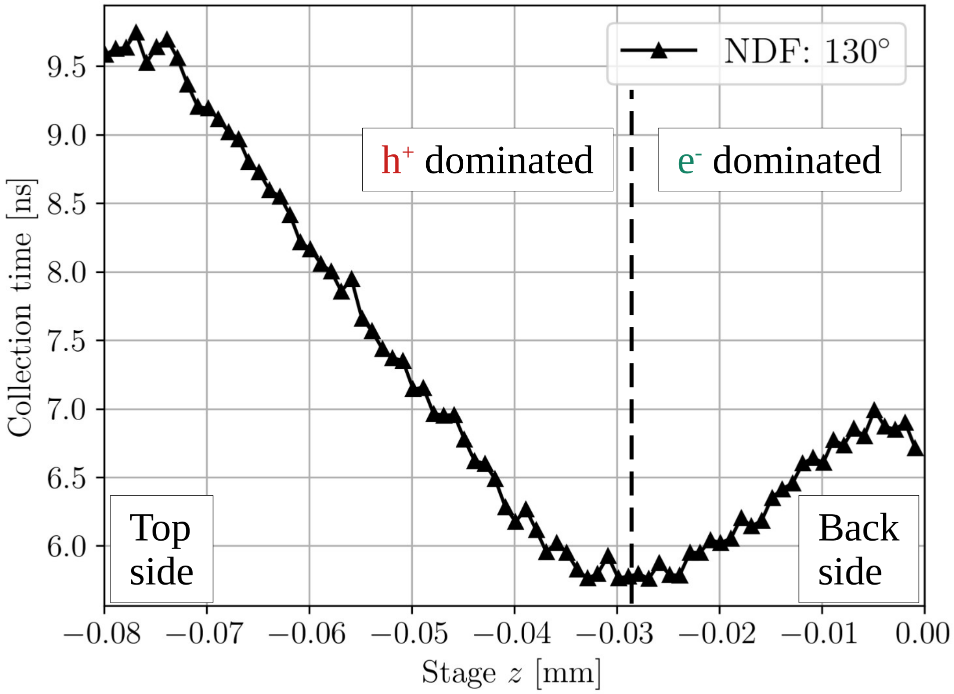
TPA-TCT setup: Inside of the Faraday cage

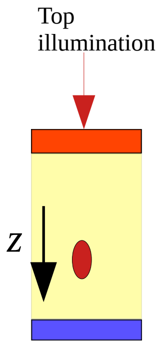


Method to extract the drift time



The collection time for a give depth *z* is obtained by the intersection of the baseline with linear fits towards the rising and the falling edge.





DUT: 300 µm thick p-type PIN,
biased at 861V
Temperature: 20°C
Humidity: 0%

Details of the broadening model

The diffusion equation is discretised and than numerically solved using `python`:

Step 1

$$\frac{\partial n_{TPA}(t,r,z)}{\partial t}=D\left(\frac{\partial^2 n_{TPA}(t,r,z)}{\partial r^2}+\frac{\partial^2 n_{TPA}(t,r,z)}{\partial z^2}\right)$$

↓ Discretisation

Step 2

$$\frac{n_{i,j}^{n+1}-n_{i,j}^{n}}{\Delta t}=D\left[\frac{n_{i+1,j}^{n}-2n_{i,j}^{n}-n_{i-1,j}^{n}}{(\Delta r)^2}+\frac{n_{i,j+1}^{n}-2n_{i,j}^{n}-n_{i,j-1}^{n}}{(\Delta z)^2}\right]$$

↓ Rearranged to calculate the next time step (*Δt*) of the diffusing charge carrier density

Step 3

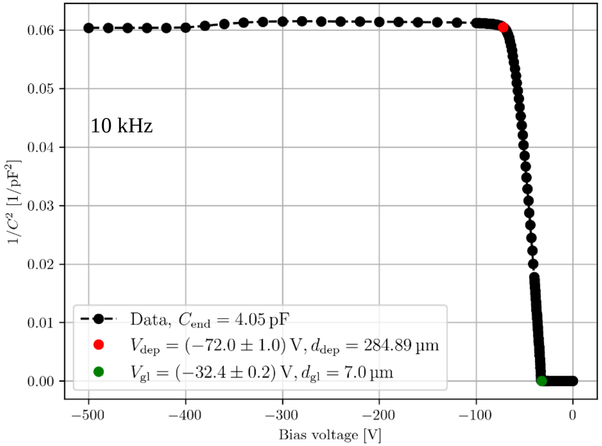
$$n_{i,j}^{n+1}=n_{i,j}^{n}+D\Delta t\left[\frac{n_{i+1,j}^{n}-2n_{i,j}^{n}-n_{i-1,j}^{n}}{(\Delta r)^2}+\frac{n_{i,j+1}^{n}-2n_{i,j}^{n}-n_{i,j-1}^{n}}{(\Delta z)^2}\right]$$

↓

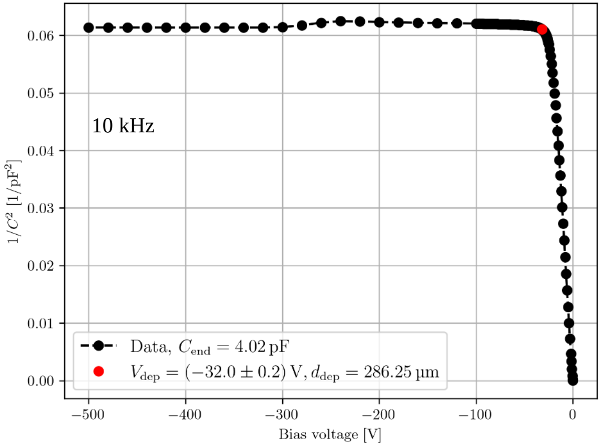
Repeat step 3 until the wanted drift time is reached

Backup: Extraction of the bulk voltage in a LGAD

LGAD CV-characteristic



PIN CV-characteristic

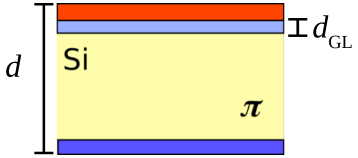


CV-measurements:

- Used to extract $V_{\mathrm{bias,GL}}$ for the LGAD
- PIN CV-data shown for completeness

Device details:

- CNM Run 8622 Wafer 5
- 285 µm thick active volume
- Assumed $d_{\mathrm{gl}} = 2$ µm



$$V_{\mathrm{bias,GL}} = V_{\mathrm{GL}} + d_{\mathrm{GL}} / d \times V_{\mathrm{bias}}$$

$$V_{\mathrm{bulk}} = V_{\mathrm{bias}} - V_{\mathrm{bias,GL}}$$

V_{bias}: bias voltage
$V_{\mathrm{bias,GL}}$: bias voltage in the GL
V_{bulk}: bias voltage in the bulk
V_{GL}: Depletion voltage of the GL

Side note:
This method is an approximation to extract the real bulk voltage in a LGAD.

Bias voltages:

V_{bias} [V]	V_{bulk} [V]	$V_{\mathrm{bias,GL}}$ [V]
900	861.3	38.7
500	464.1	35.9
300	265.5	34.5

Backup: Gain reduction at different bias voltages

- Gain versus charge deposition for different bias voltages
- Higher bias voltage results in higher gain, also while gain reduction is present
- Trend of gain reduction is not visibly influenced by the bias voltage