Gain suppression mechanism in LGADs and SEE studies in a RD53B chip measured with the TPA-TCT method

Esteban Currás[1], Marcos Fernández García[1,2], Michael Moll[1], Raúl Montero[3], Rogelio F. Palomo[4], Sebastian Pape[1,5], Ivan Vila[2], Moritz Wiehe[1,6]

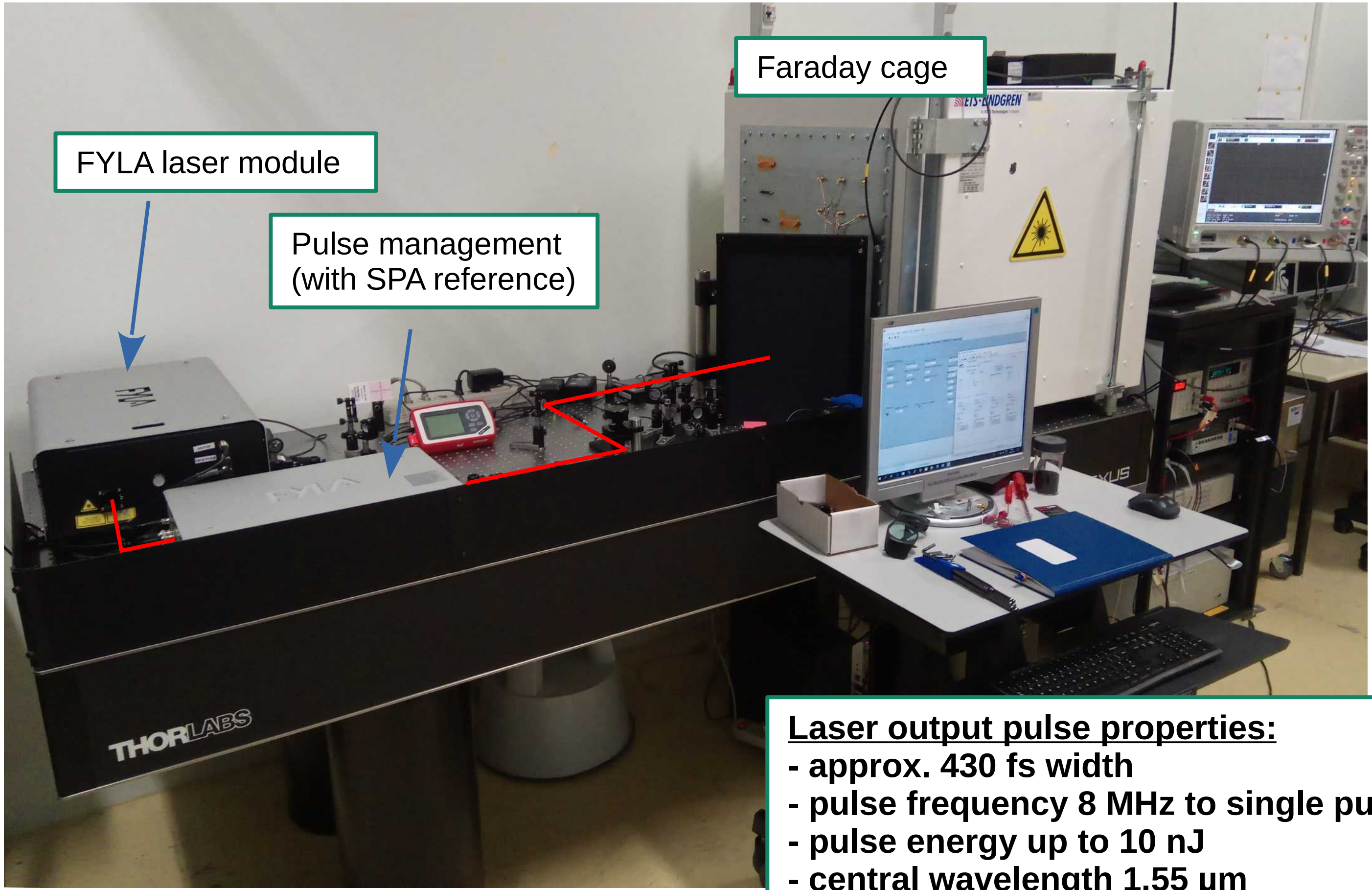
[1]CERN
[2]Instituto de Física de Cantabria
[3]Universidad del Pais Vasco (UPV-EHU)
[4]Universidad de Sevilla
[5]TU Dortmund University
[6]Universität Freiburg

Federal Ministry of Education and Research

Outline

- The TPA-TCT setup at CERN SSD
- Gain suppression mechanism in Low Gain Avalanche Detectors
- Setup extension to thin devices
- SEE studies in a RD53B chip

Setup



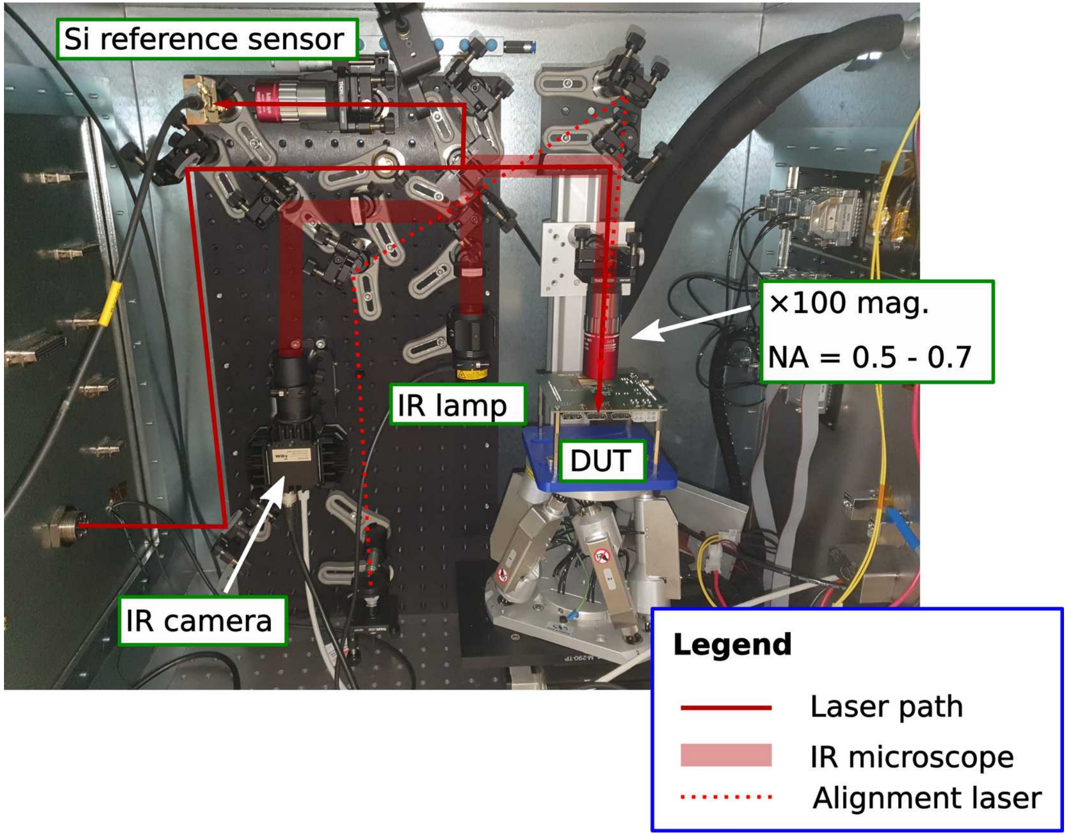
M. Wiehe et al.: *Development of a Tabletop Setup for the Transient Current Technique Using Two-Photon Absorption in Silicon Particle Detectors*

<u>Laser output pulse properties:</u>
- **approx. 430 fs width**
- **pulse frequency 8 MHz to single pulse**
- **pulse energy up to 10 nJ**
- **central wavelength 1.55 µm**

WE LASER
THE NEW INDUSTRY

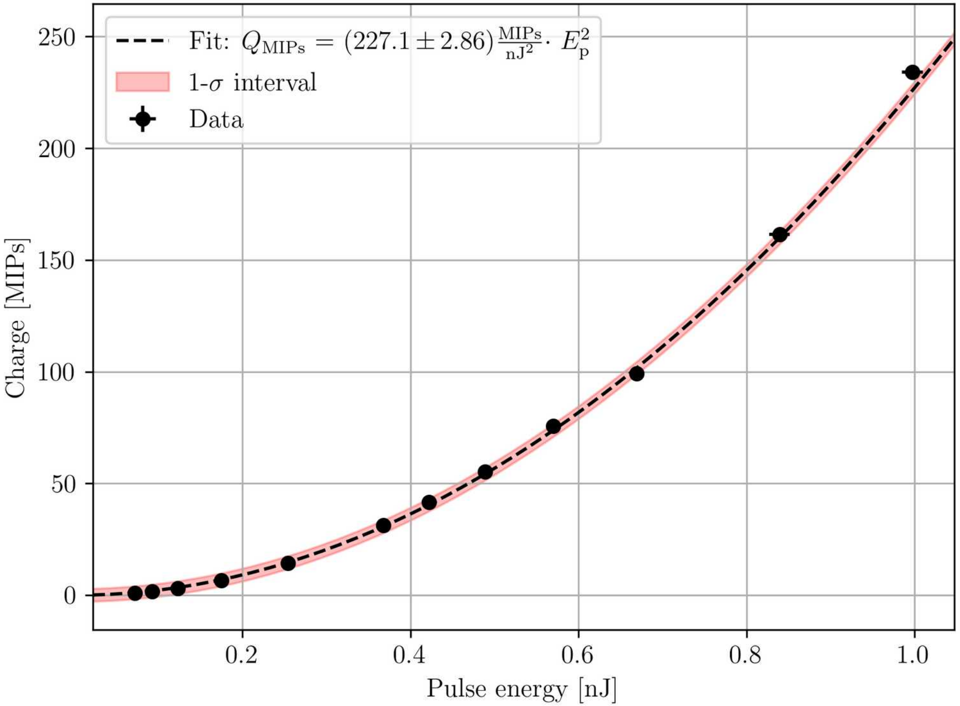
Setup

Inside of the Faraday cage:



Calibration:

Pulse energy vs generated charge (in a 300µm PIN with NA = 0.5 at 20°C and 0% humidity):



Gain suppression mechanism

Gain suppression in gain devices

Comparison of β-source and TCT measurements of LGADs at CERN-SSD have shown that their gain depends on the charge density in the gain layer. This had not been realized until now.

1.) Low charge density in the GL will lead to a higher gain: there will be a negligible gain suppression.

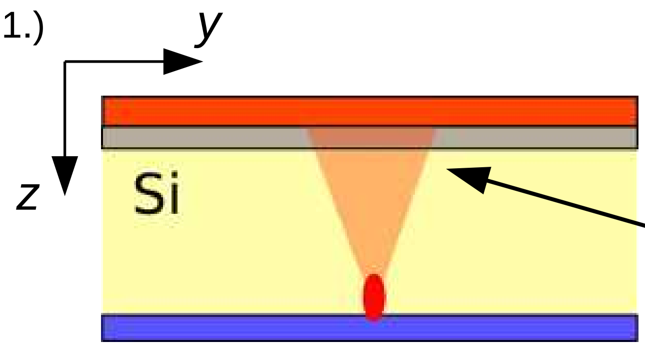
2.) High charge density in the GL will lead to a reduction in the gain: drop in the GL E-field (less amplification).

E. Currás - 38th RD50 Workshop

E. Currás, M. Fernández and M. Moll:
Gain suppression mechanism observed in Low Gain Avalanche Detectors (2021)

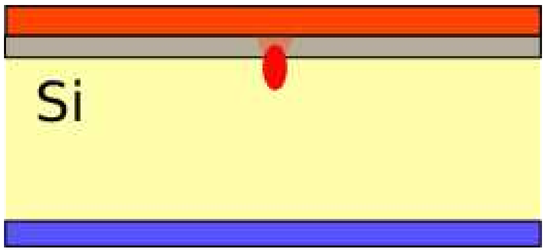
Idea behind gain suppression in TPA-TCT:

1.)



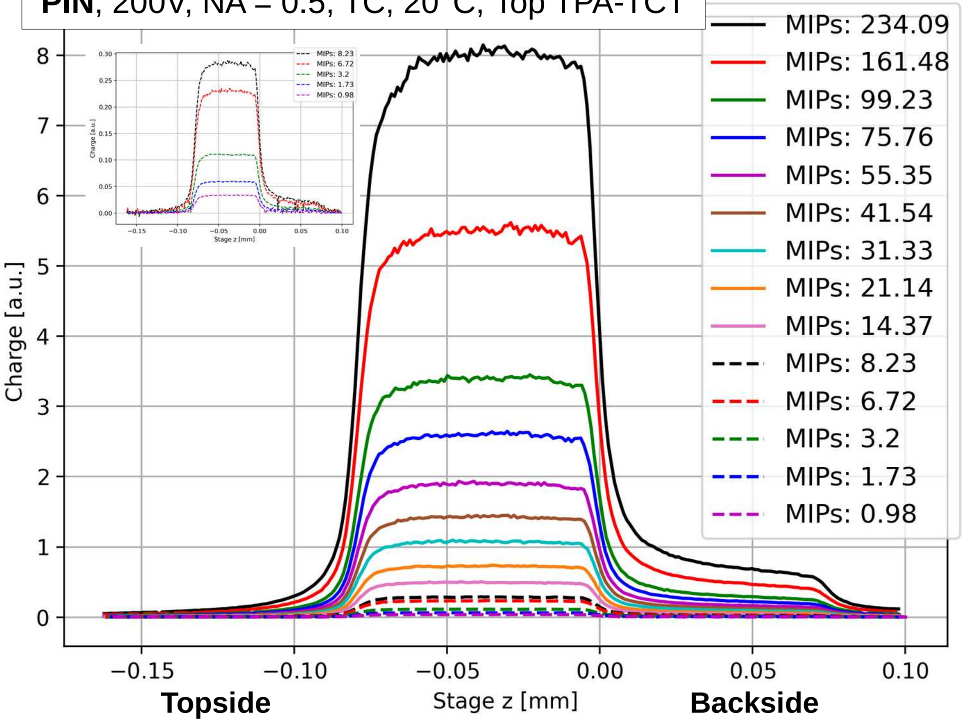
Shaded red:
schematic evolution of the charge density with time

2.)



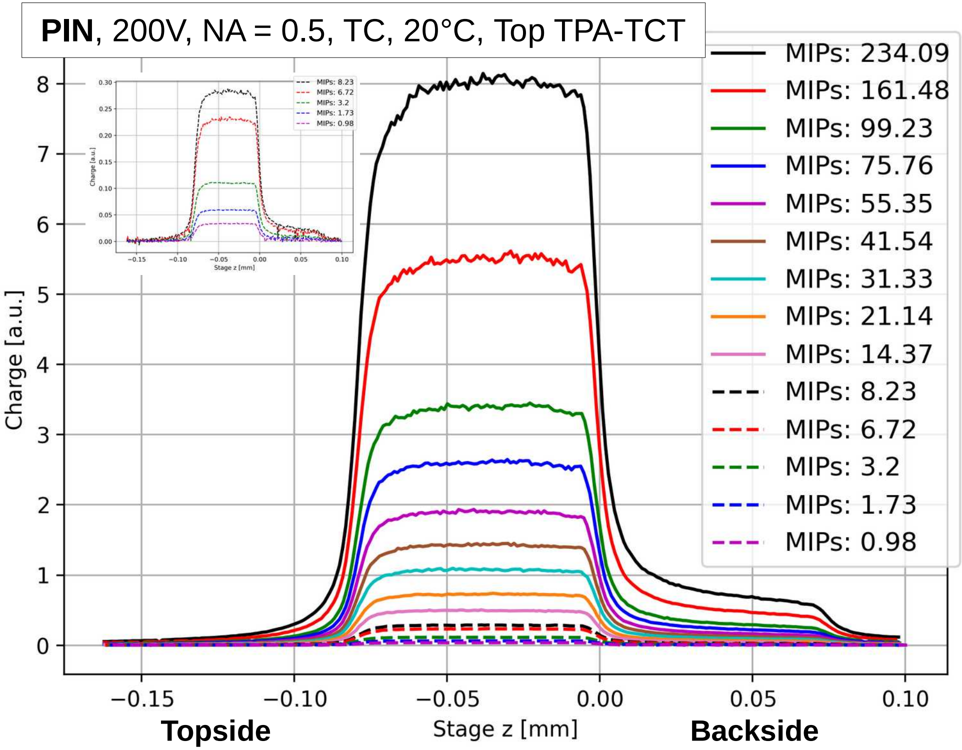
Charge collection: 280µm CNM PIN

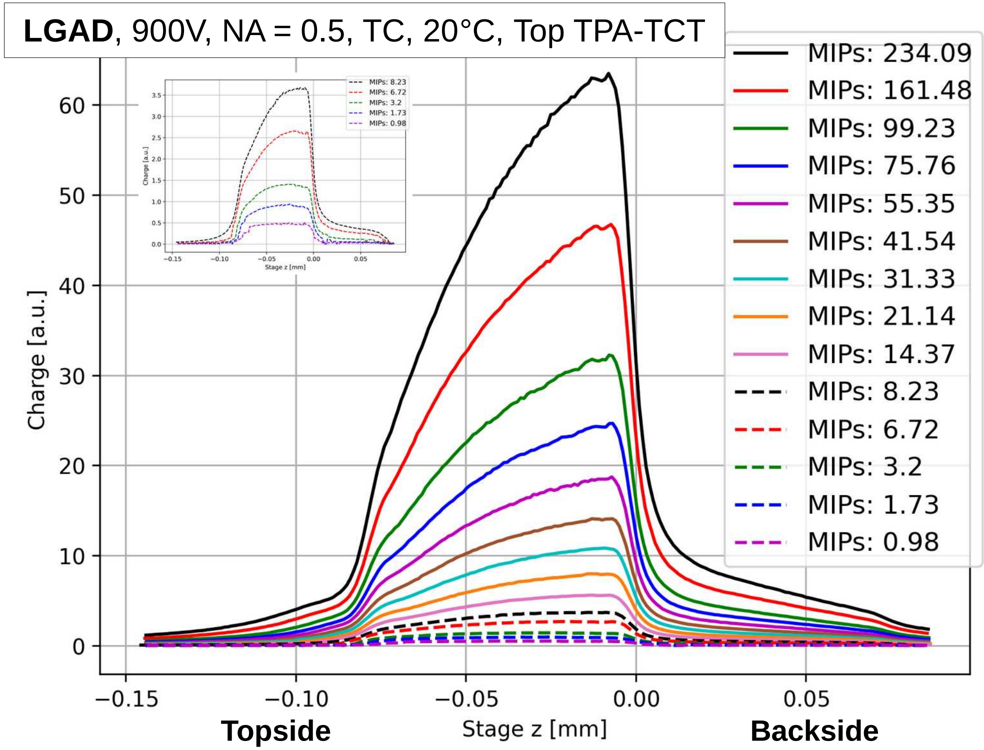
PIN, 200V, NA = 0.5, TC, 20°C, Top TPA-TCT



Charge collection measurement in a PIN:
→ behaves as expected
→ Charge collection profile shape does not depend on the laser intensity / charge density.

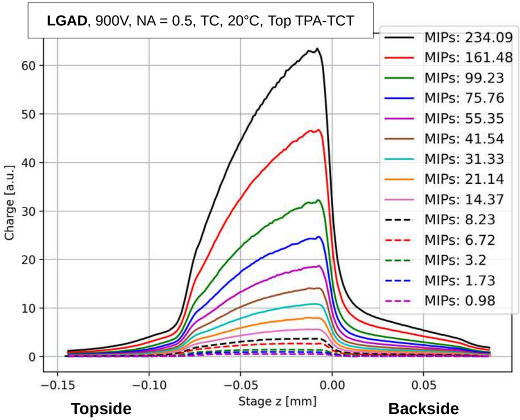
Charge collection: 280µm CNM PIN & LGAD

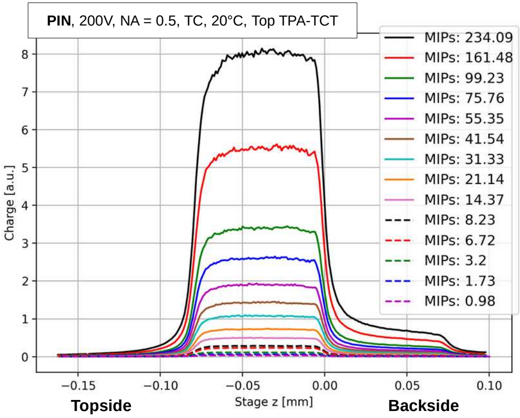




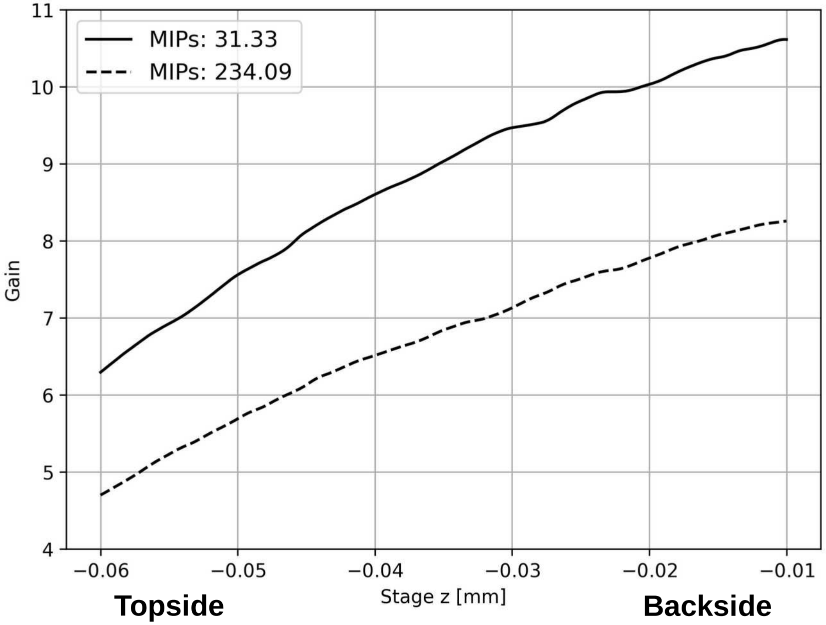
→ Charge collection in a LGAD depends on laser intensity / charge density
→ Gain suppression mechanism

Gain suppression: 280µm CNM LGAD





Q_{LGAD} / Q_{PIN} against depth: (Cut out of region -0.06 to -0.01 in PIN and LGAD)



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

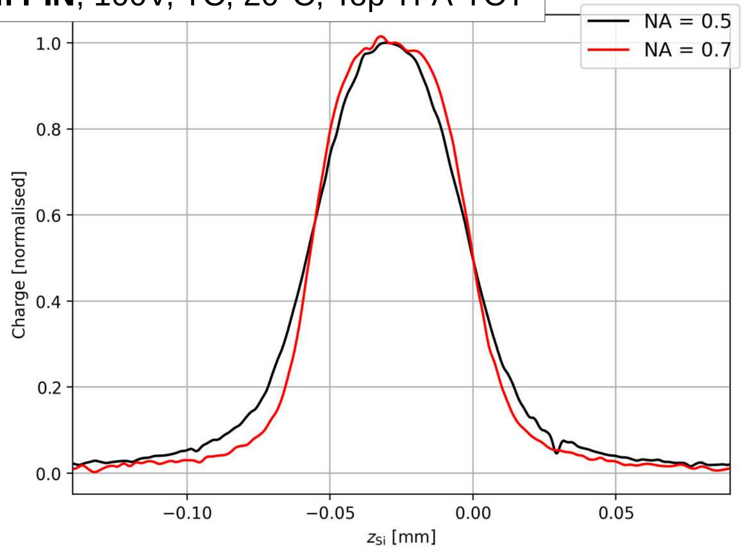
Setup extension to thin devices

Highly focusing optics

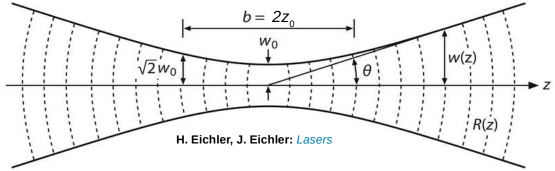
It is found that for **thin devices** (50 - 70µm) a higher focusing objective (NA = 0.7) improves the resolution, due to a smaller volume of charge generation. However, for thick devices a objective with NA = 0.5 is preferably used.

Charge collection in a 50µm PIN measured with different NA:

~50µm PIN, 100V, TC, 20°C, Top TPA-TCT



Beam parameter:

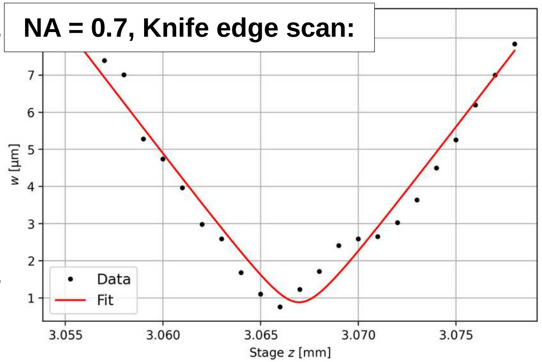


NA = 0.5: W_0 = 1.3 µm, $z_{0,Si} \approx 12$ µm

NA = 0.7: W_0 = 0.9 µm, $z_{0,Si} \approx 6$ µm

S. Pape - 38th RD50 Workshop

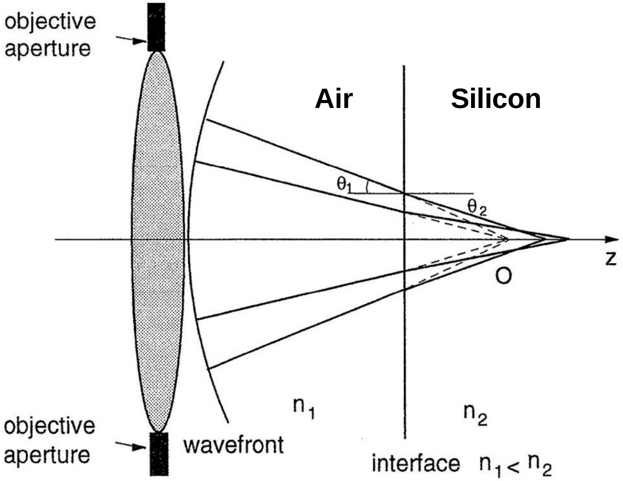
NA = 0.7, Knife edge scan:



Rayleigh length for NA = 0.7 is approx. two times smaller
→ Volume of charge generation along the beam axis by a factor of two smaller

Aberration due to refractive index mismatch

Min Gu: *Advanced Optical Imaging Theory*



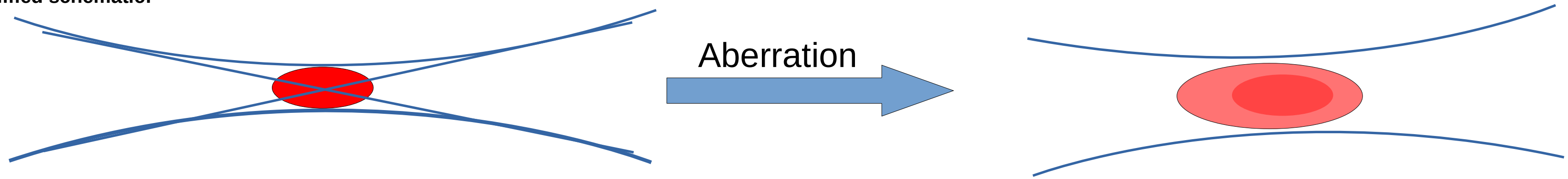
Aberration: light rays of different incident angles are focused at different positions on the axis

→ **The effect is linear with depth**

Mismatch of refractive indices at the top air-silicon interface (n_1 = 1, n_2 = 3.4757)

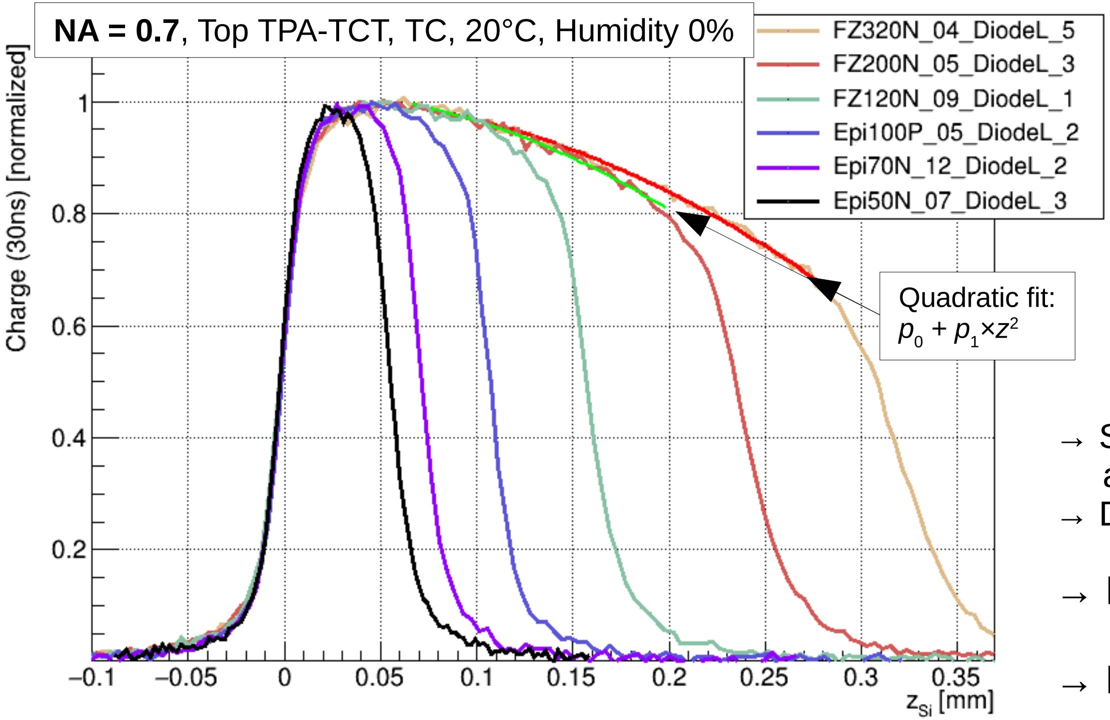
Aberration → defocused focal spot → lower intensity → less charge generation → linear effect → quadratic decrease in collected charge

Simplified schematic:



Charge Collection: numerical aperture 0.7

Measurements performed with an objective with a **numerical aperture** of **0.7** (**not observed with NA = 0.5**).
Charge collection in PINs (HPK devices) with difference thicknesses:



- Orange: 320µm
- Red: 200µm
- Green: 120µm
- Blue: 100µm
- Purple: 70µm
- Black: 50µm

→ Spherical aberration occurs with NA = 0.7 and leads to a distortion of the focal spot in depth

→ Distortion visible for devices thicker than 70µm

→ **Highly focusing objective (NA = 0.7) especially useful for thin devices**

→ **Enables a more precise study of thin (segmented) silicon devices**

NA=0.7 → scaling factor 4.12

SEEs in the RD53B chip

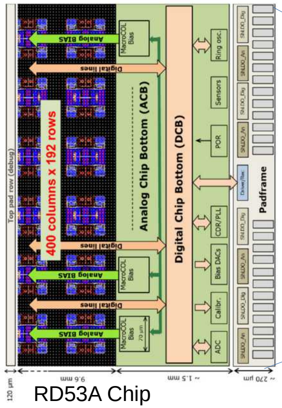
SEEs in RD53B Chip

Investigate SEEs in the RD53B chip
in cooperation with CERN EP-ESE

Measurements were before performed with a commercial TPA tool for SEE studies
(Pulse Scan setup at Leuven).

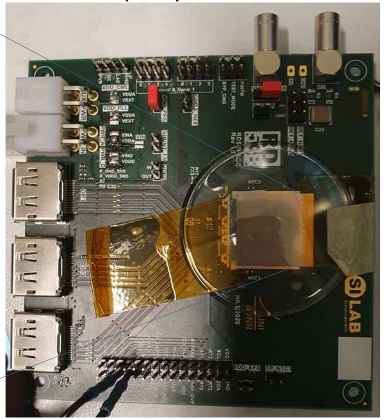
Test CERN SSD TPA-TCT setup in comparison to the commercial SEE setup

Simulations of the core bandgap region found SET → verified experimentally

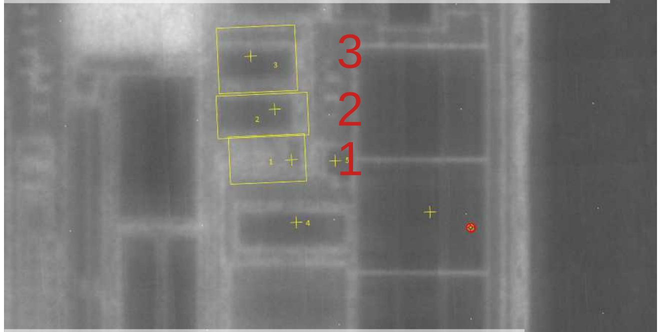


RD53A Chip

RD53 chip + pixel sensor

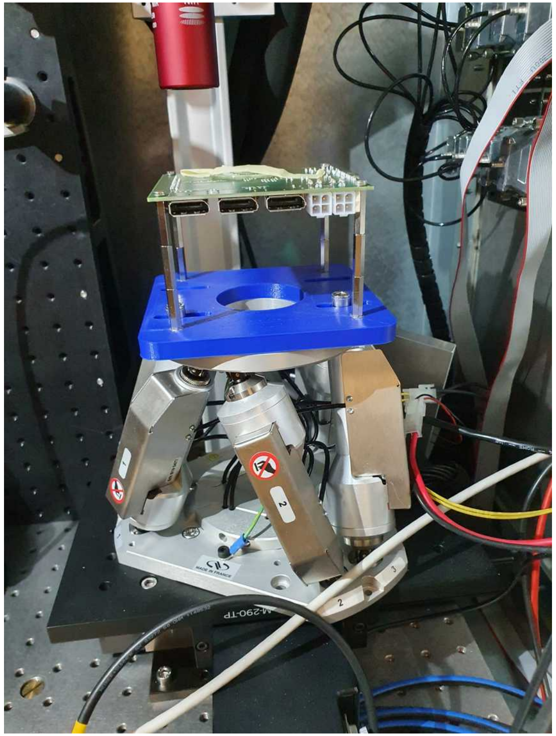


Transistors of the core bandgap (for Bias DAC) in the digital chip bottom:



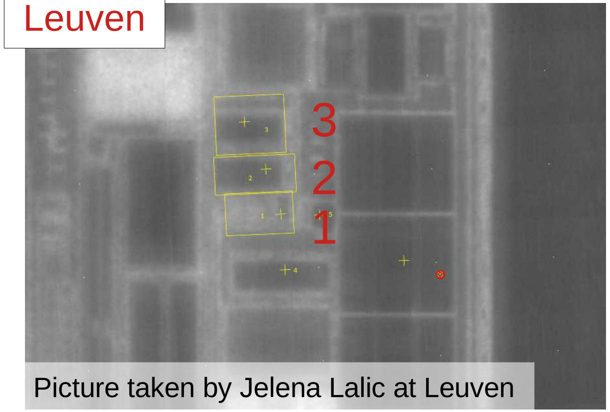
Picture taken by Jelena Lalic at Leuven

RD53B chip mounted in the CERN SSD setup with a custom made holder:



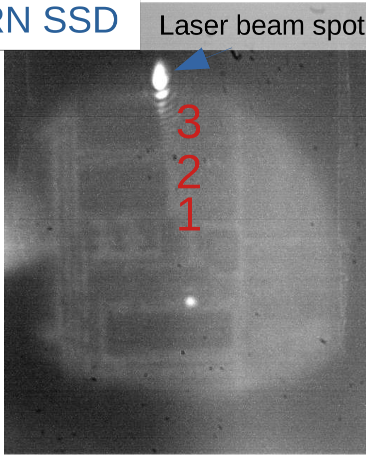
SEEs in RD53B Chip: Leuven & CERN SSD

Leuven



Picture taken by Jelena Lalic at Leuven

CERN SSD

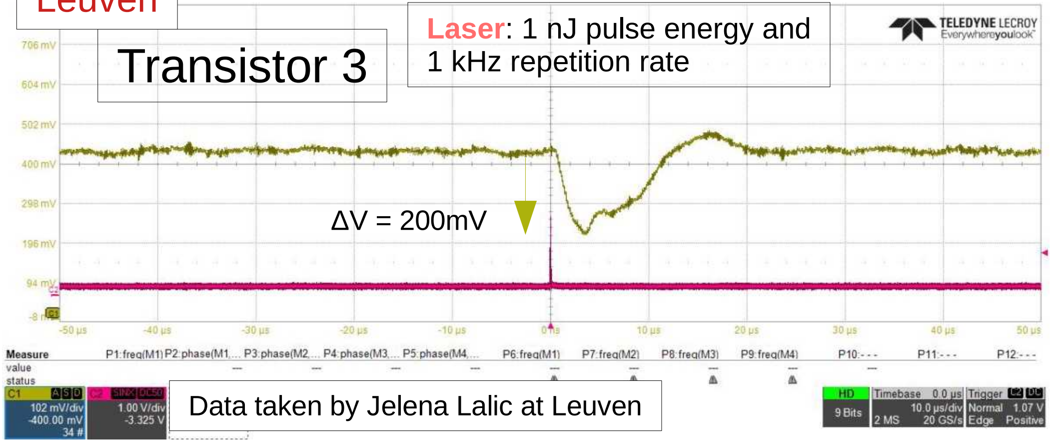


Charge injection in the transistor leads to SET event down the chain

CERN SSD setup reproduced first studies performed at Leuven.

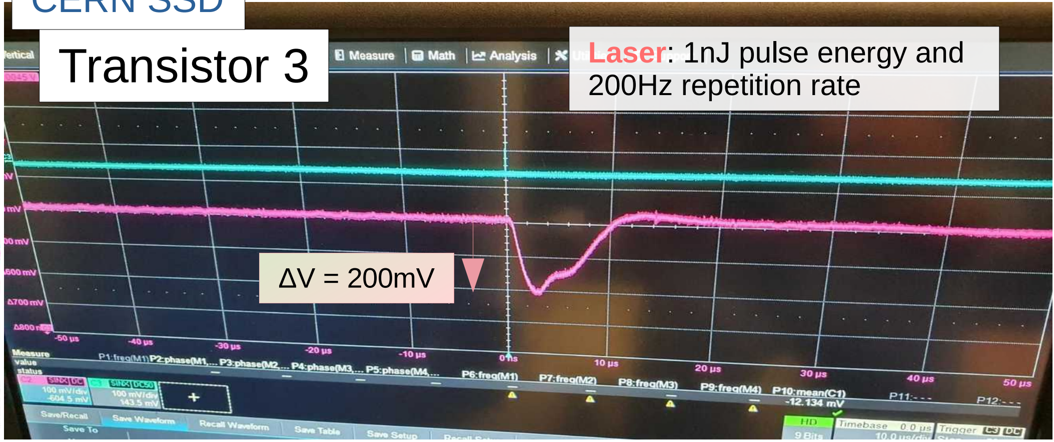
Not even full intensity used!
→ factor two in additional pulse energy possible

Leuven



Data taken by Jelena Lalic at Leuven

CERN SSD



Summary

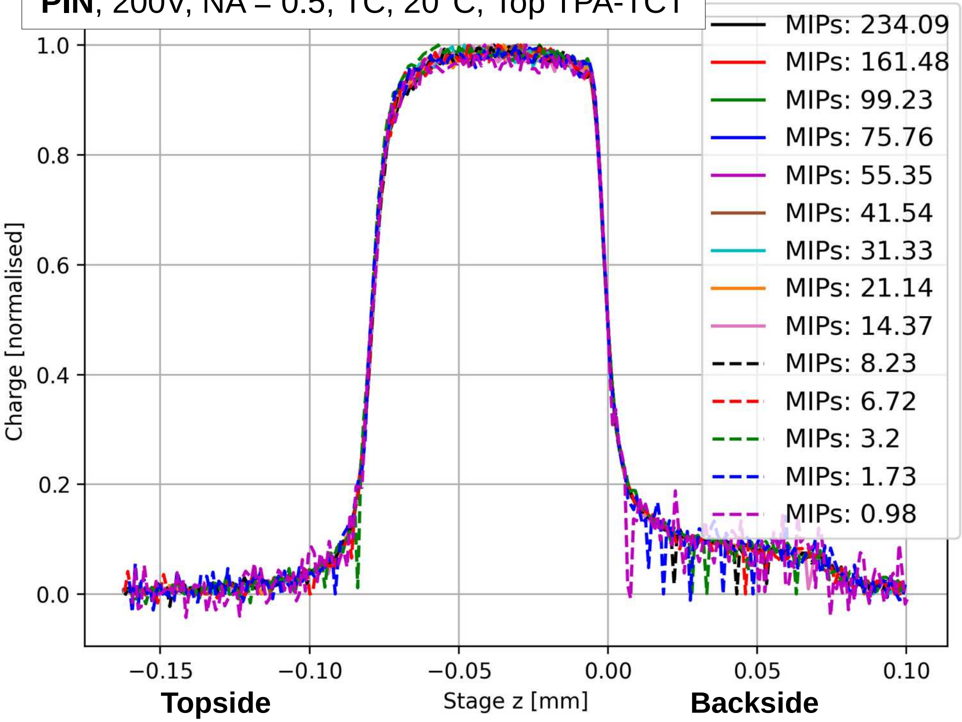
- Gain suppression mechanism was again verified using the TPA-TCT method
  - In depth study was performed → further analysis ongoing
- Highly focusing objectives (NA = 0.7) enable a more precise study of thin devices
  - NA = 0.7 limits the use to thin devices (approx. ≤70µm), due to spherical aberration
→ spherical aberration **not observed with NA = 0.5**
- CERN SSD TPA-TCT setup suitable to perform SEE studies
  - Measurements performed in cooperation with CERN EP-ESE
  - First measurements at CERN SSD reproduced results from RD53

Thank you for your attention!

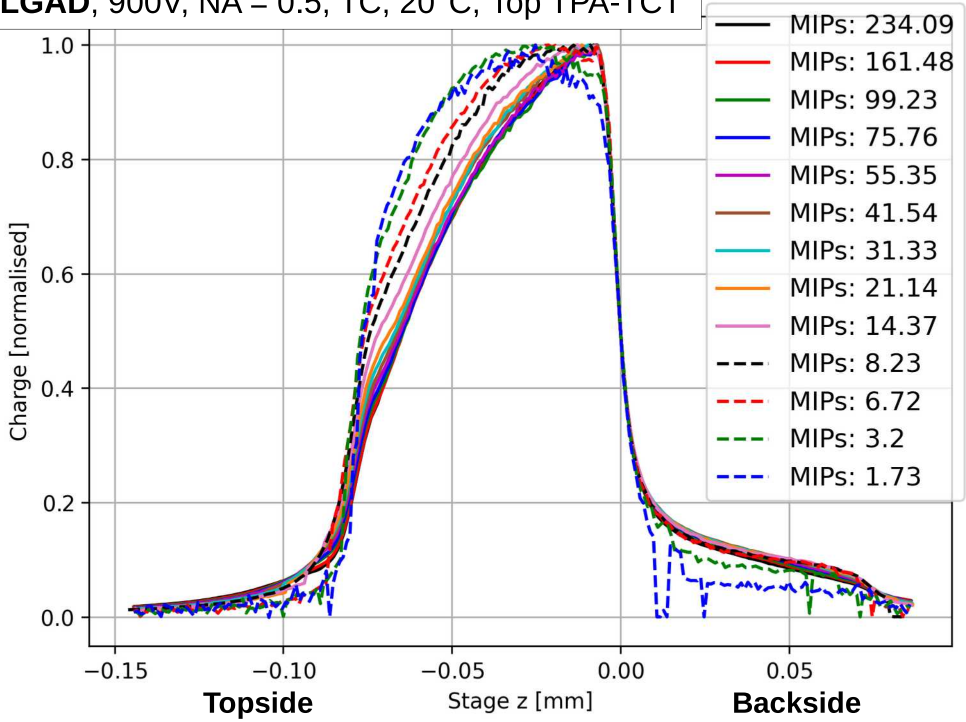
Backup

Charge collection: 280µm CNM PIN & LGAD

PIN, 200V, NA = 0.5, TC, 20°C, Top TPA-TCT

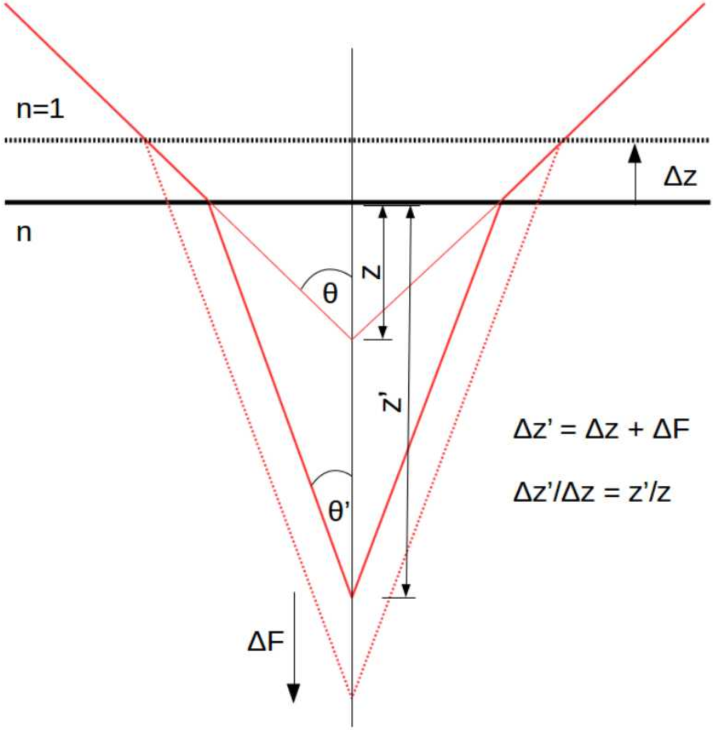


LGAD, 900V, NA = 0.5, TC, 20°C, Top TPA-TCT



→ Charge collection in a LGAD depends on laser intensity / charge density
→ Gain suppression mechanism

Refraction in silicon



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

Beam moves different in silicon than in air, due to refraction!

$n_{Si} = 3.4757$

Conversion of movement in air to movement in silicon depends on the focusing:

$$z' = z\sqrt{\frac{n^2 - NA^2}{1 - NA^2}}$$

$$z' = z\sqrt{\frac{z_0 \pi n^3}{z_0 \pi n - \lambda n^2 + \lambda}}$$

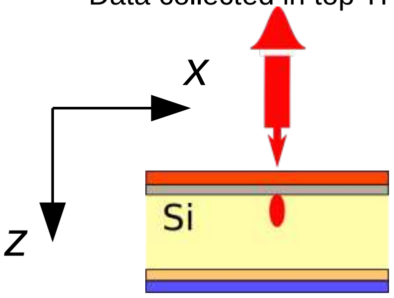
Measured: NA = 0.5 → $z'/z = 3.754$
NA = 0.7 → $z'/z = 4.12$

Prompt current method to extract the drift velocity

$\sim v_{Drift}(z) = \mu(z) \approx -\mu\,\mathrm{I}(\sim 0\mathrm{s})$

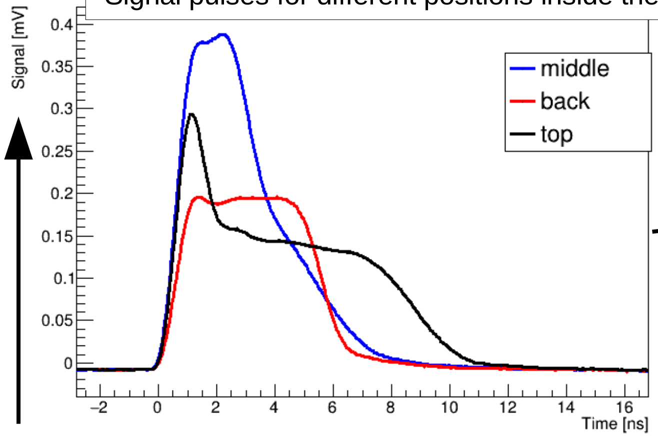
The drift velocity for a given *z* equals the charge carrier mobility (here holes) times the electric field at a given *z* value
The electric field at a given *z* is correlated to the current signal at the time the laser generated the charge
(Signal height and rise time contains information about electric field at the position where the charge is generated)

Data collected in top TPA-TCT:

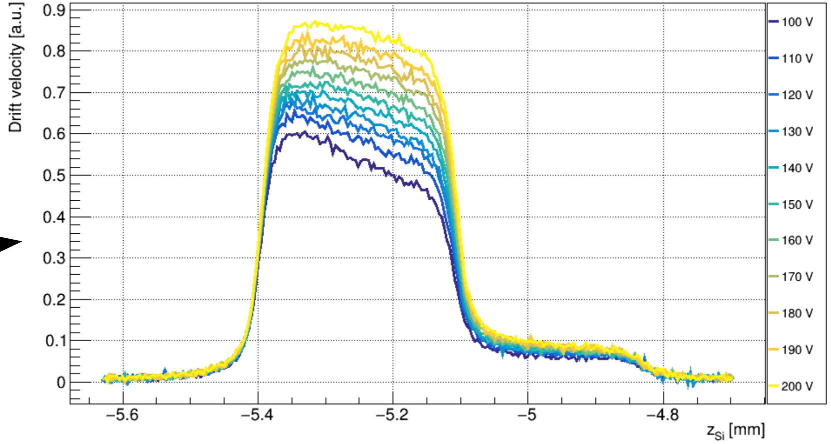


Integrate the first **600ps** of a signal pulse from a given *z*
→ estimator for the drift velocity $v_{Drift}(z)$,
due to the above mentioned relation

Signal pulses for different positions inside the DUT



Integrate the first 600ps signal for every *z* position of the beam's focal point



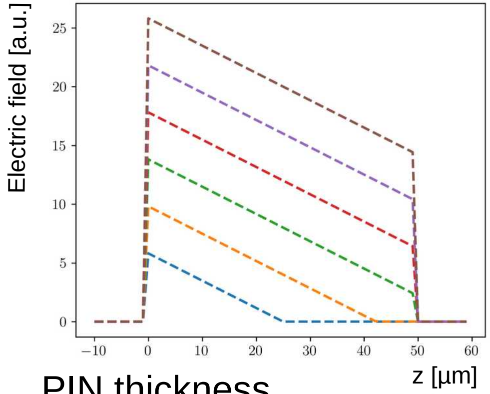
More details presented in: **G. Kramberger et al.:** *Investigation of Irradiated Silicon Detectors by Edge-TCT*

Recorded with 50 Ω scope input → voltage signal = 50Ω×current signal

Resolution: Charge profiles

f(t) *(PIN E-field)*:

Schematic depletion of a PIN:



PIN thickness
in µm (here 50µm)

detector thickness d

depletion voltage V_{dep}

$$\boxed{V_{dep} = \frac{e}{2 \cdot \varepsilon} \cdot \left| N_{eff} \right| \cdot d^2}$$

effective space charge density N_{eff}

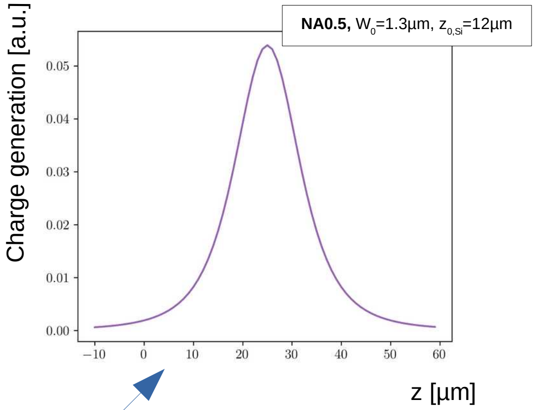
M.Moll, SSD Meeting 01.03.2021

$$\boxed{E(x) = \frac{1}{d} \cdot (V - V_{dep}) + \frac{2}{d} \cdot V_{dep} \cdot \left(1 - \frac{x}{d}\right)}$$

g(t) *(Laser scanning function)*:

$$n_{tpa}(r,z) = \frac{E_p^2\, \beta_2\, 4\ln 2}{\tau\, \hbar\omega\, \pi^{\frac{5}{2}}\, w^4(z)\, \sqrt{\ln 4}} \exp\left[-\frac{4r^2}{w^2(z)}\right]$$

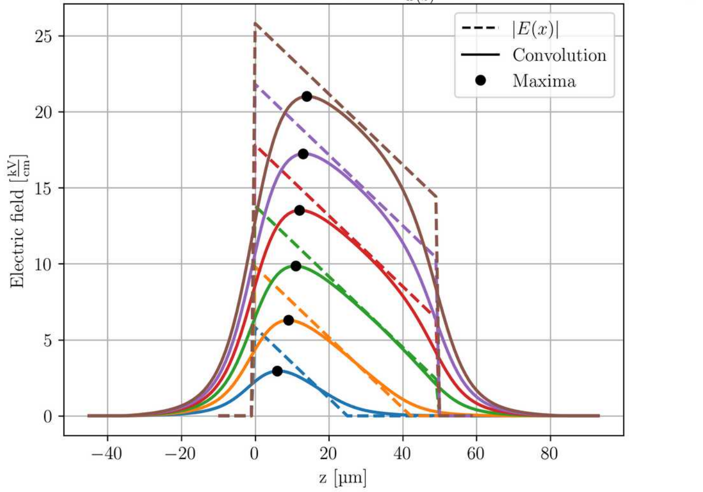
~$1/w^4$



$1/w^4$ normalized by its integral

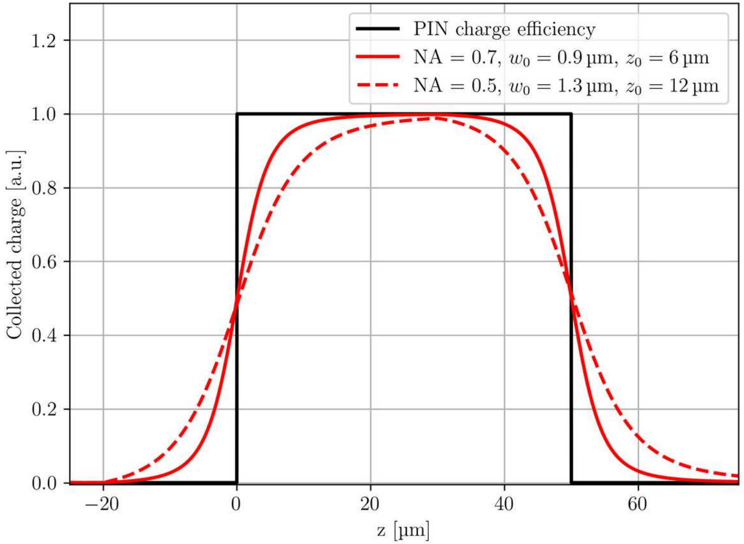
$$(f * g)(t) := \int_{-\infty}^{\infty} f(\tau) g(t-\tau)\, d\tau$$

Convolution of the electric field $|E(x)|$ with $\frac{1}{w(z)^4}$ ($w_0 = 1.3\,\mu m$, $z_R = 12\,\mu m$)

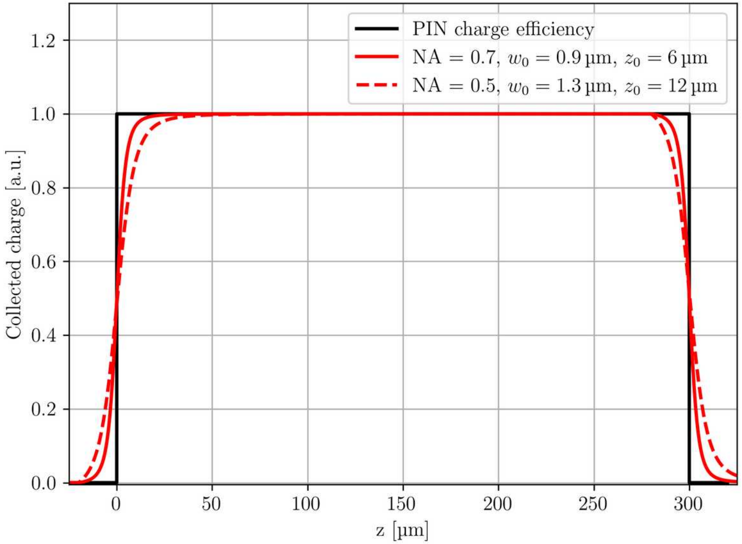


Theoretical comparison: NA 0.5 and NA 0.7

50µm device



300µm device



Spherical aberration not considered!