# Edge-TCT simulation of LGADs in RASER

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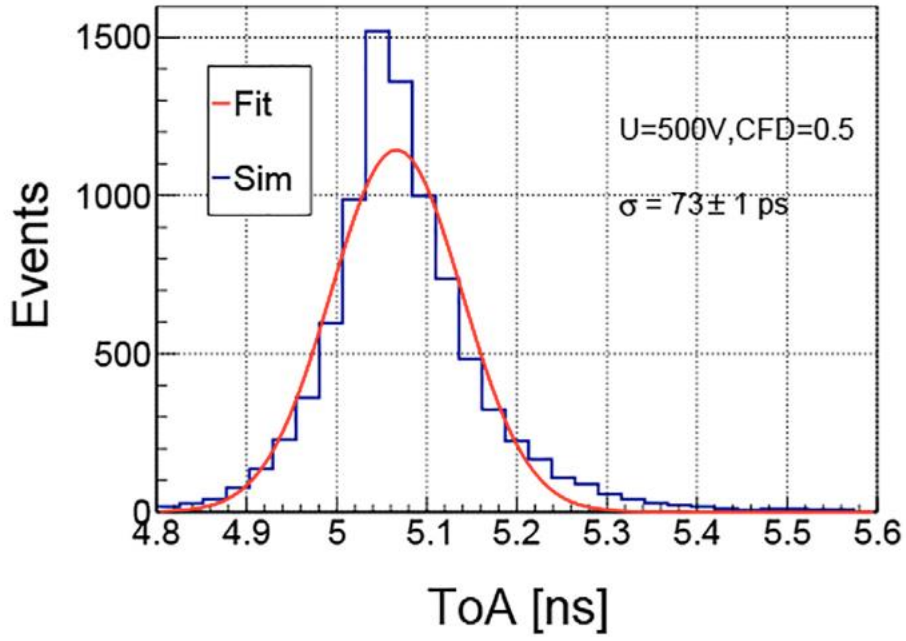
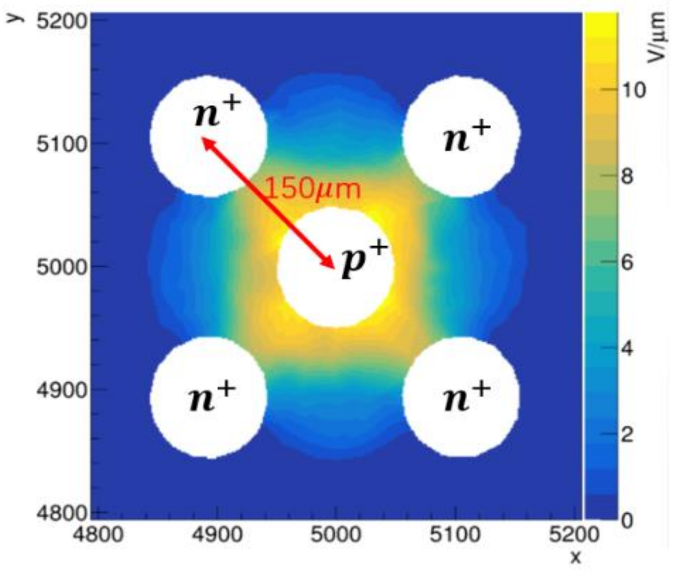
# What is RASER

- Simulation software of RAdiation SEmiconductoR
- Developed by RASER team
- Programmed by python
  - Under the ROOT framework
  - Geant4 and FEniCS dependent
- Designed to estimate time resolution of SiC detectors
- Recent works on this $41^{st}$ workshop:
  - 4H-SiC devices simulation with DEVSIM
  - SiC for Proton Beam Monitor

# Published Results from RASER




Time resolution of NJU 5mm × 5mm 4H-SiC-PIN
Simulation 73±1ps Experiment 94±1ps
[Front. Phys. 10:718071.](#)




Predictions of SiC 3D Detector
Time resolution up to 25ps
[Micromachines 2022,13,46.](#)

# Edge-TCT Experiment Setup

Layout

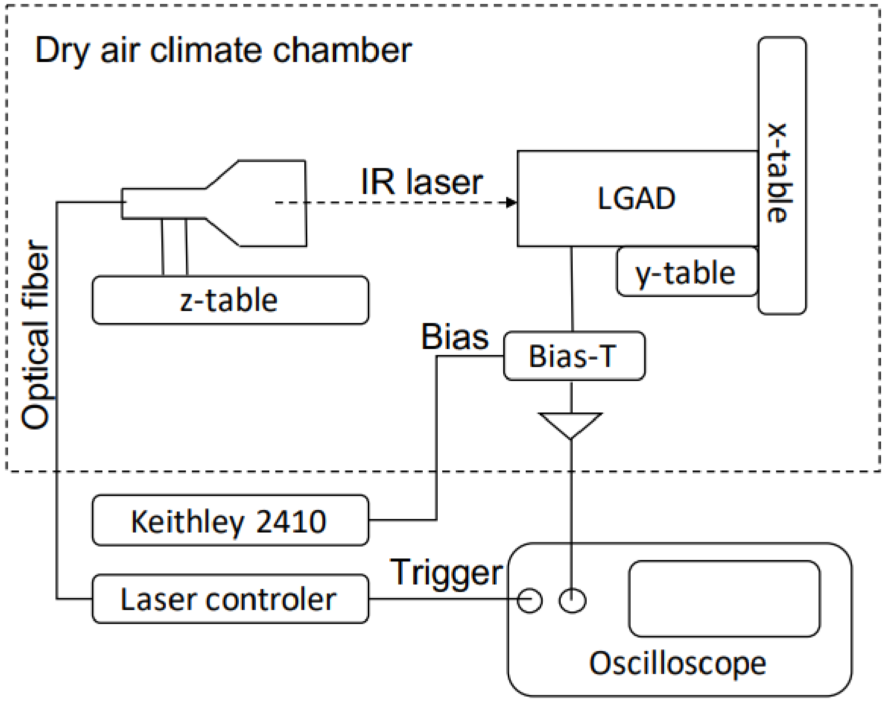
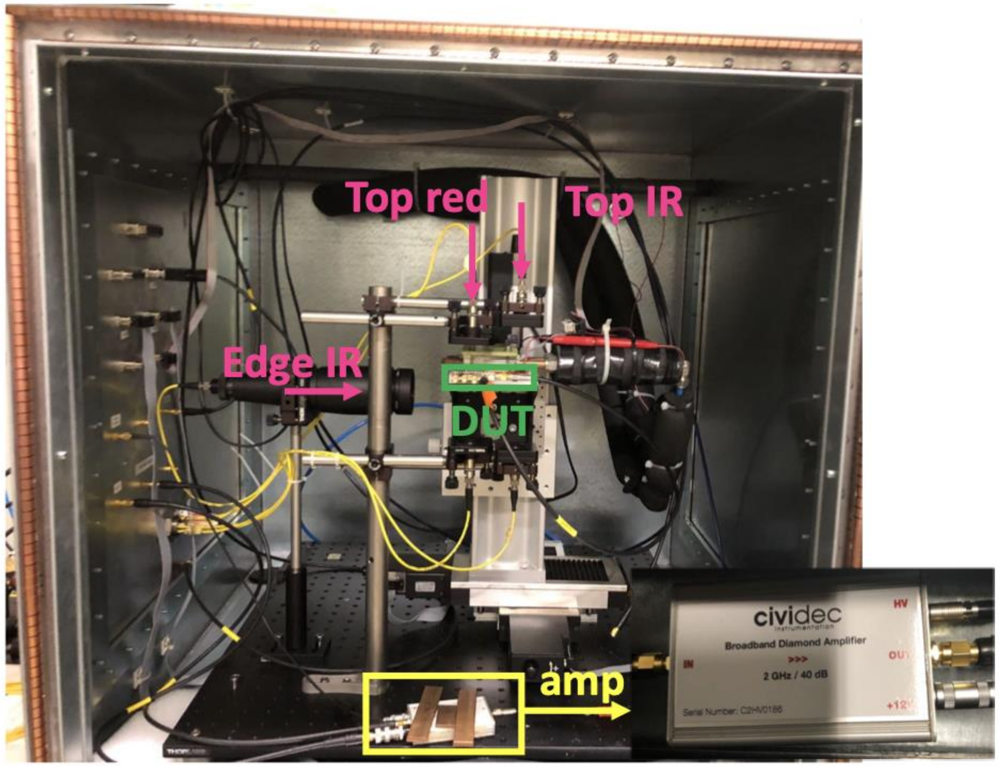


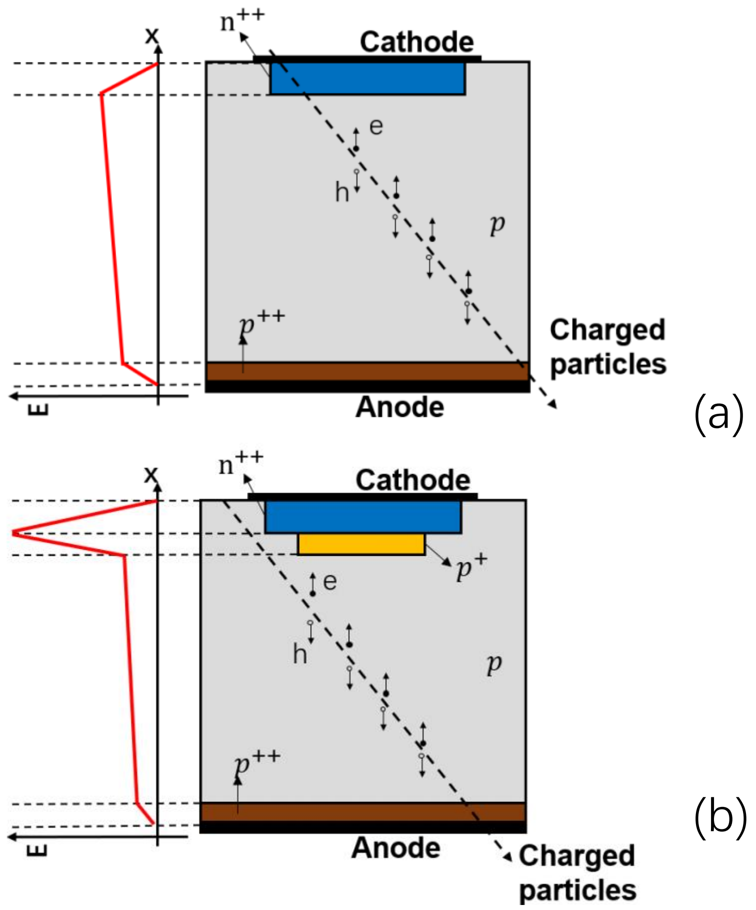

Photo of facilities




Experiment carried out at CERN RD50 group in 2019. Tested at 200V bias in room temperature.
Data from edge IR is selected to detect LGAD velocity profile.
X,Y,Z-table portable to change the focus. Scan step 1μm.

# HPK 3.1-50 PIN & LGAD Parameterization

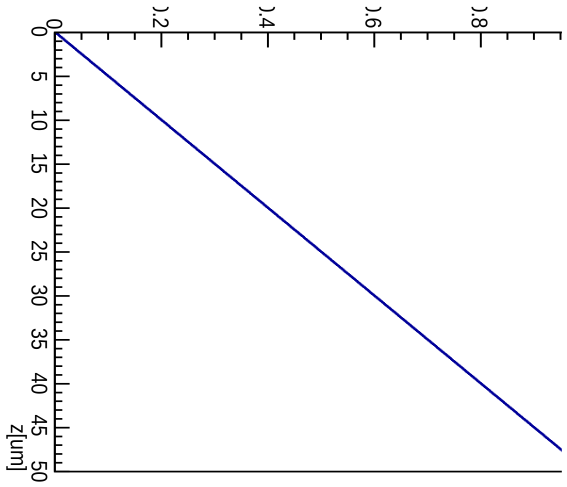
- Planar structure
  - $1.3\times1.3\ mm^2$ pad size and 50 μm thick
  - p bulk doping $1.0\times10^{12}\ cm^{-3}$
- Gain layer of LGAD
  - p+ doping $\begin{cases} 1.0\times10^{12}cm^{-3},\ 0\mu m<z<1\mu m \\ \sim2.0\times10^{16}cm^{-3},\ 1\mu m<z<2\mu m \end{cases}$
    - estimated from CV test
  - gain ~65 times
    - from fine tuning of doping profile

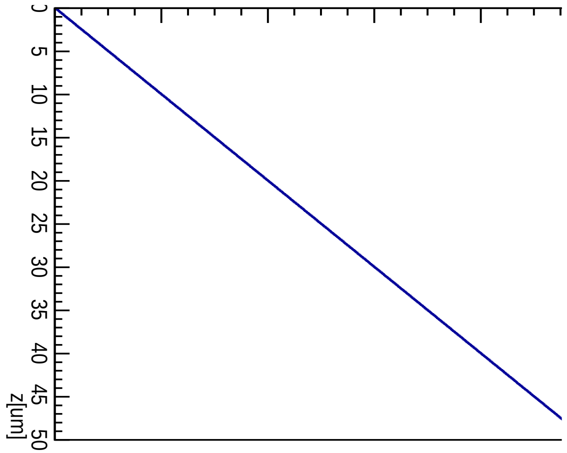



Sketch of (a) PIN and (b) LGAD.

# Electric Field & Weighting Field

- PDE solver: FEniCS
- Equation of electric potential: $\nabla^2 U(x) = -eN_{eff}(x)/\varepsilon$
  - Only consider the space charge region
  - In full depleted detector
  - Ignoring free carriers
- Equation of weighting potential: $\nabla^2 U_w = 0$
  - $U_w(boundary) = \begin{cases} 1, reading\ electrode; \\ 0, other\ electrodes \end{cases}$
  - Could be estimated as 1/d in planar detectors




Field intensity in (a) PIN (b) LGAD.

# Laser Model & Parameters

- Light intensity of Gaussian beam:

$$I(r,z;t) = I(0,0;0)\frac{w_0}{w(z)}\exp\frac{-2r^2}{w^2(z)}\exp\frac{-4t^2\ln 2}{\tau^2}$$

$$w(z) = w_0\sqrt{1+(2z/L)^2}$$

$$\lambda = 1064\text{nm}, w_0 = 8\mu\text{m}, \tau = 350\text{ps}$$

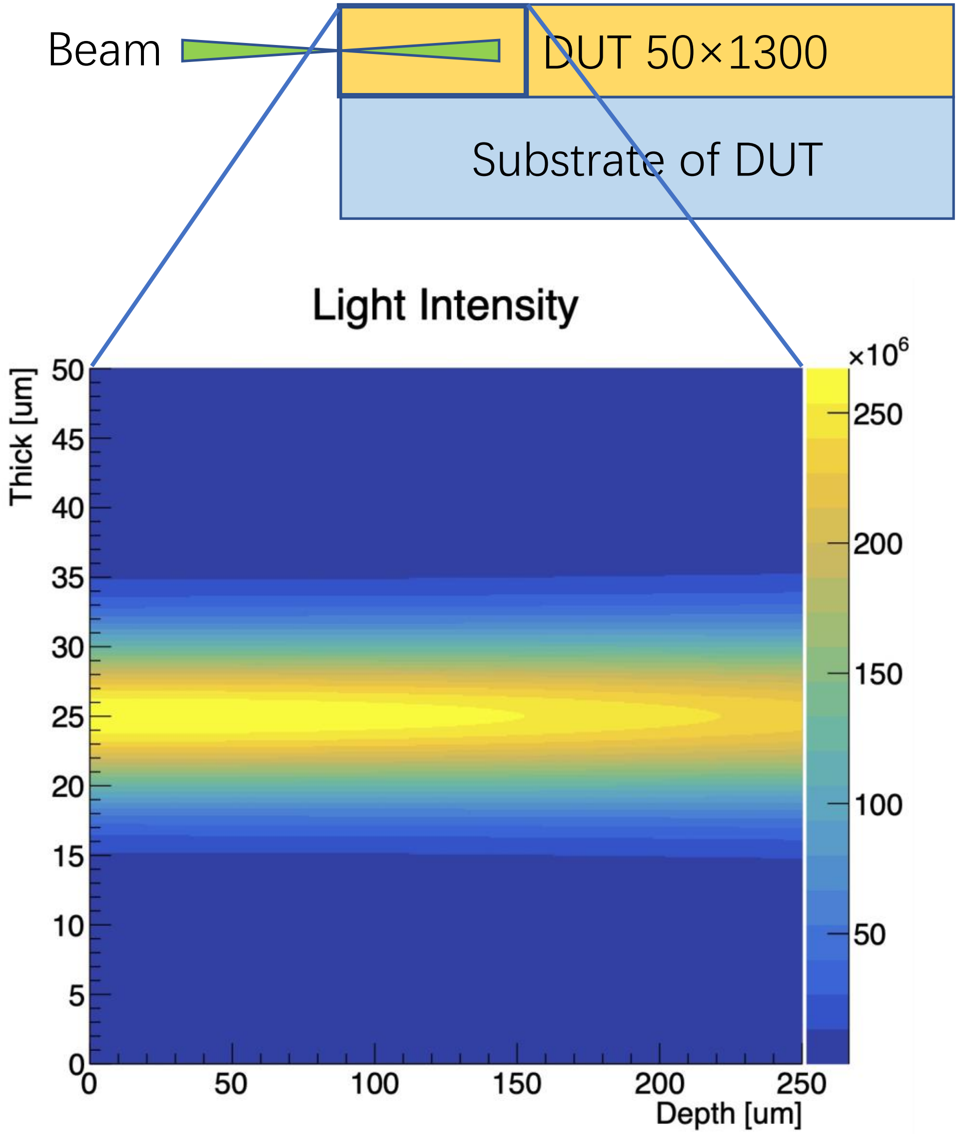
- Absorption & refraction :

$$I'(r,z';t) = I_0(r,z;t)\exp(-\alpha(\lambda)z'), z' \approx nz$$

$$\alpha(1064\text{nm}) = 9.87\text{cm}^{-1}$$

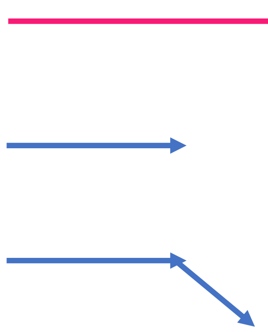
- Excitation:

$$dN_{e-h\,pairs}(dVdt) = I'dVdt/h\nu$$



# Carrier Movement

- Assuming lifetime long enough
  - carriers end their drift when they have reached the electrodes
  - no recombination considered
- Discretization: Compound of directional drift and diffusion
  - $dx = vdt + Dx(dt)$
  - $v = \mu E$ $\mu$. the mobility model
  - $Dx \sim N(0, (Ddt)^2), D = \mu k_B T/q$



$\vec{E}$

$\mu \vec{E} dt \parallel \vec{E}$

$d\vec{x} = \mu \vec{E} dt + D\vec{x}(dt) \nparallel \vec{E}$

# Signal Collection, Electronics & Noise

- Shockley-Ramos Theorem

$$I_q(t) = q\vec{v}_q(t) \cdot \nabla U_w(\vec{x}_q(t))$$

- Discretization & sum up

$$I_q(t)dt = q\vec{v}_q \nabla U_w dt = q\frac{d\vec{x}_q}{dt}\frac{dU_w}{dx}dt = qdU_w(\vec{x}_q(t))$$

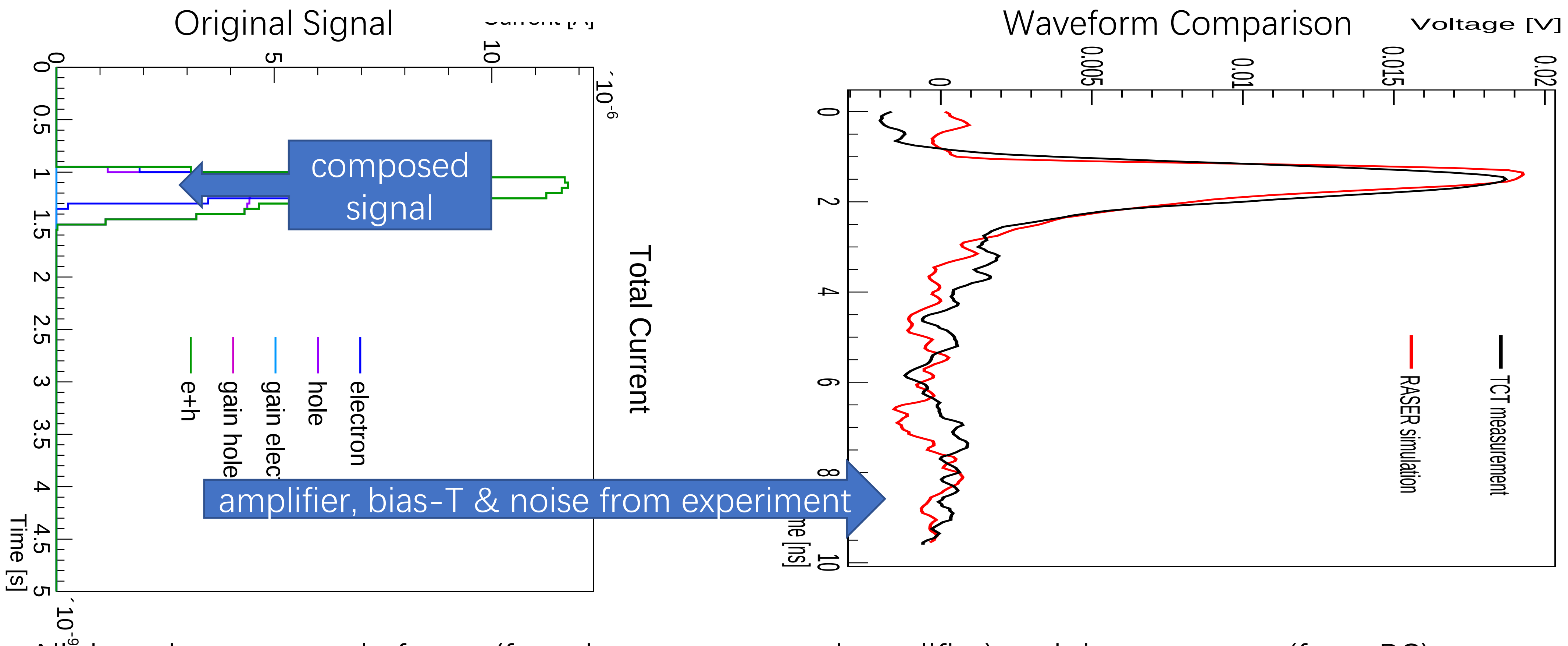
$$\bar{I}_{(t_1,t_2)}(t_2 - t_1) = \sum_q \sum_{t\in(t_1,t_2)} I_q(t)dt$$

- RC shaping

$$I_{out}(t) = I_{in}(t) \otimes h(t) \quad h(t) = A \cdot \frac{1}{\tau}e^{-t/\tau}$$

- Synthesized waveform = Signal + Noise

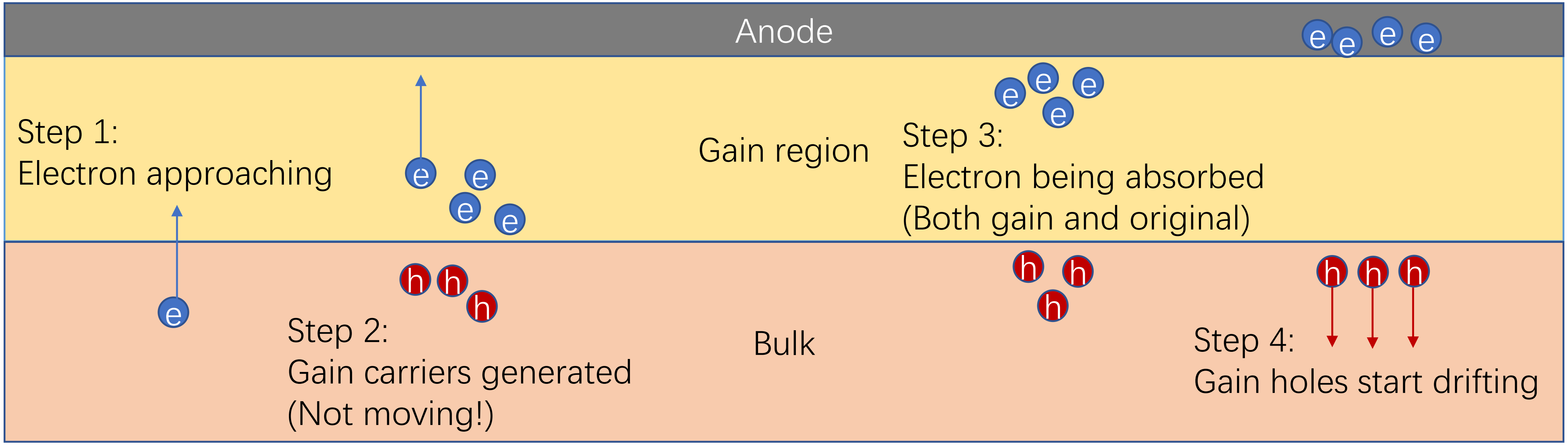
# Waveform Simulation: PIN




All data share one scale factor (from beam power and amplifier) and time constant (from RC).
A waveform of zero-input from experiment is applied into waveforms from simulation as noise.
The software gives a good fit between calculation and test.

# Multiplication: Simplified Approach

- One carrier generates (Gain) pairs of carriers
- Secondary electrons absorbed by anode instantly
- Secondary holes released when the original carrier captured



# Gain Rate Model

- Ionization rate: van Overstraeten's model[1] pp.705-718

$$\alpha_{p,n}(T;E) = \frac{\tanh(\hbar\omega/2k_{T_0})}{\tanh(\hbar\omega T_0/2k_{T_0}T)} a_{p,n} \exp(-b_{p,n}/E)$$

$a_n = 7.03 \times 10^5 cm^{-1}, b_n = 1.232 \times 10^6 cm^{-1}; a_p = 6.71 \times 10^5 cm^{-1}, b_p = 1.693 \times 10^6 cm^{-1}$

$a_p = 1.582 \times 10^6 cm^{-1}, b_p = 2.036 \times 10^6 cm^{-1}$ when $E < 4 \times 10^5\ V/cm$

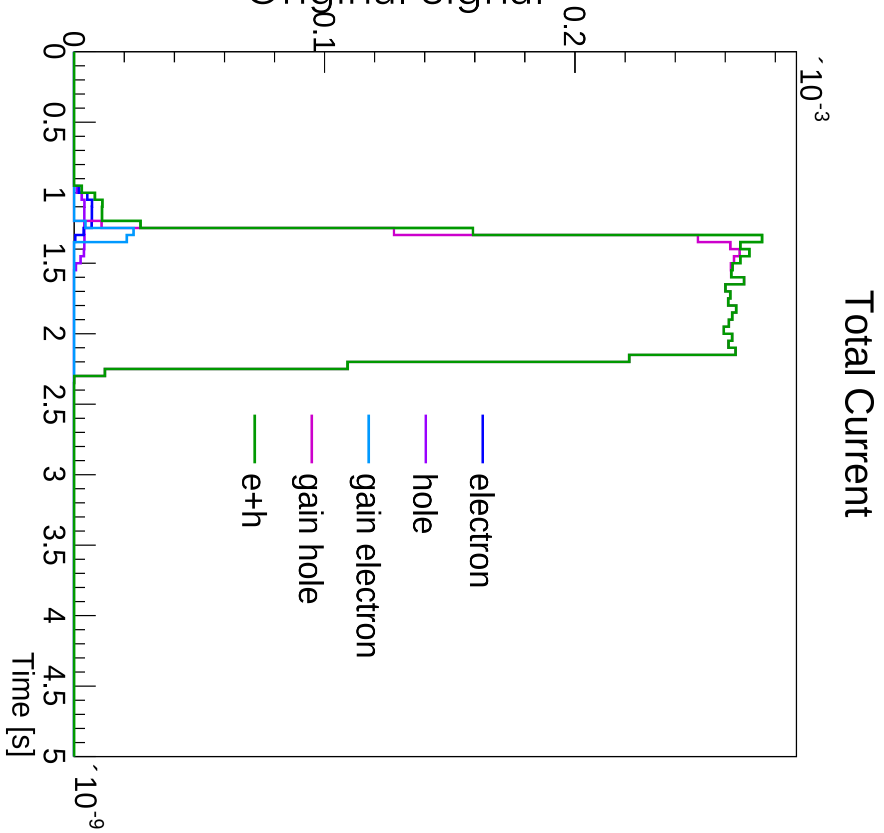
- Baliga's derivation[2] pp.92-93

$$M(x) = \frac{\exp\left[\int_0^x (\alpha_n - \alpha_p)dx\right]}{1 - \int_0^W \alpha_p \exp\left[\int_0^x (\alpha_n - \alpha_p)dx\right] dx}$$

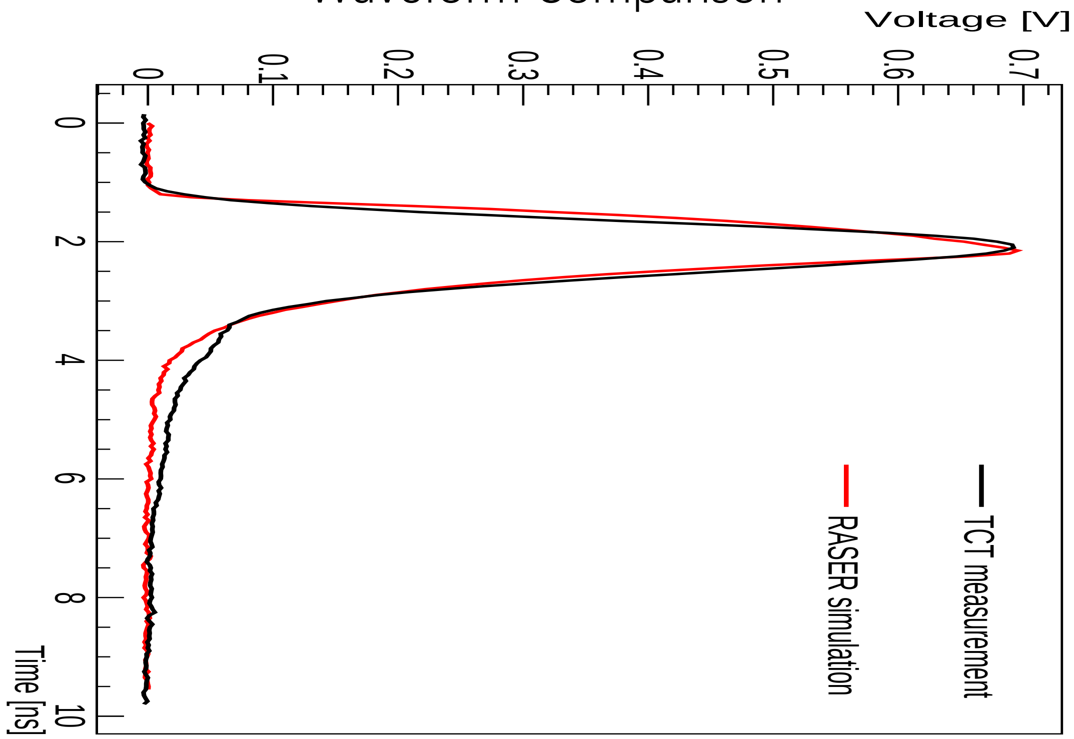
  - Gain = M(d_gain)
  - In bulk $\exp\left[\int_0^x (\alpha_n - \alpha_p)dx\right] \ll 1$ thus multiplication negligible

# Waveform Simulation : LGAD

Original Signal

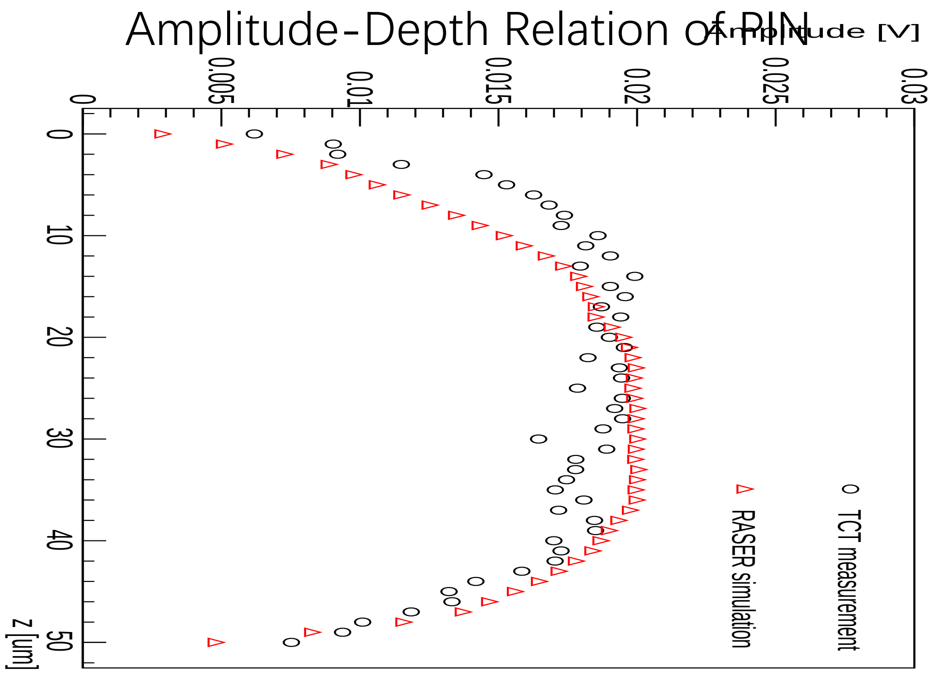


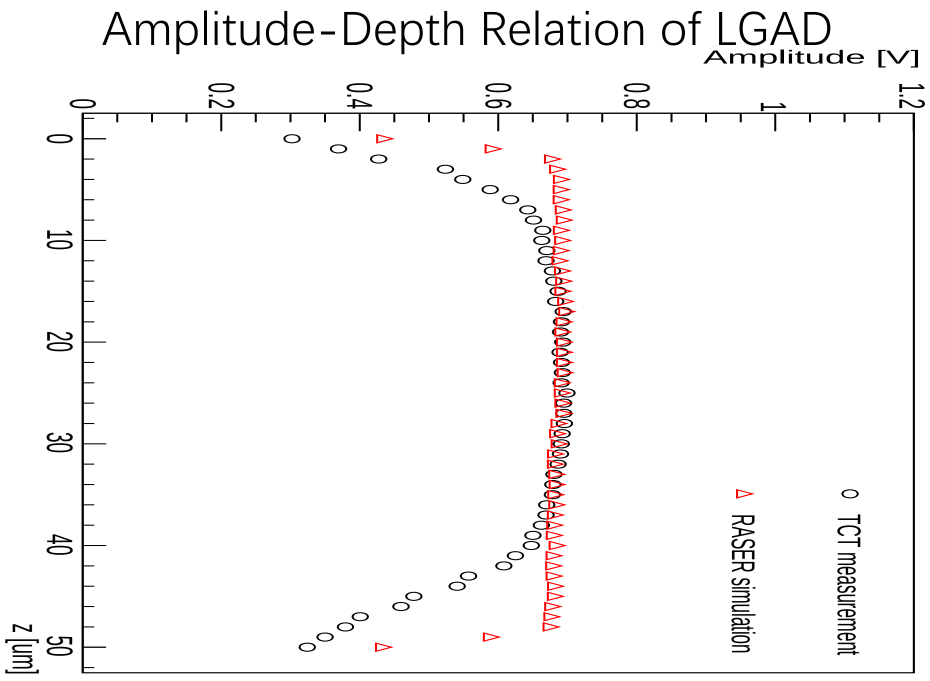

Waveform Comparison




Gain holes contribute to the absolute majority of the signal.
Difference of laser power from PIN test (1.59 times) is considered.

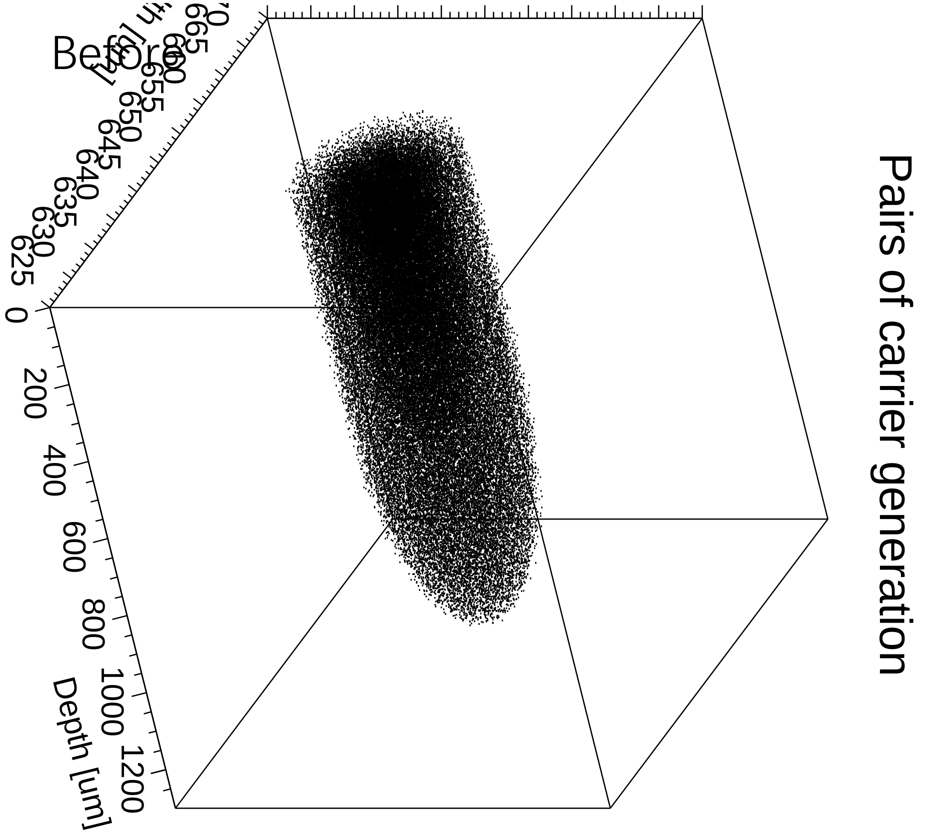
# Amplitude-Depth Relation Comparison

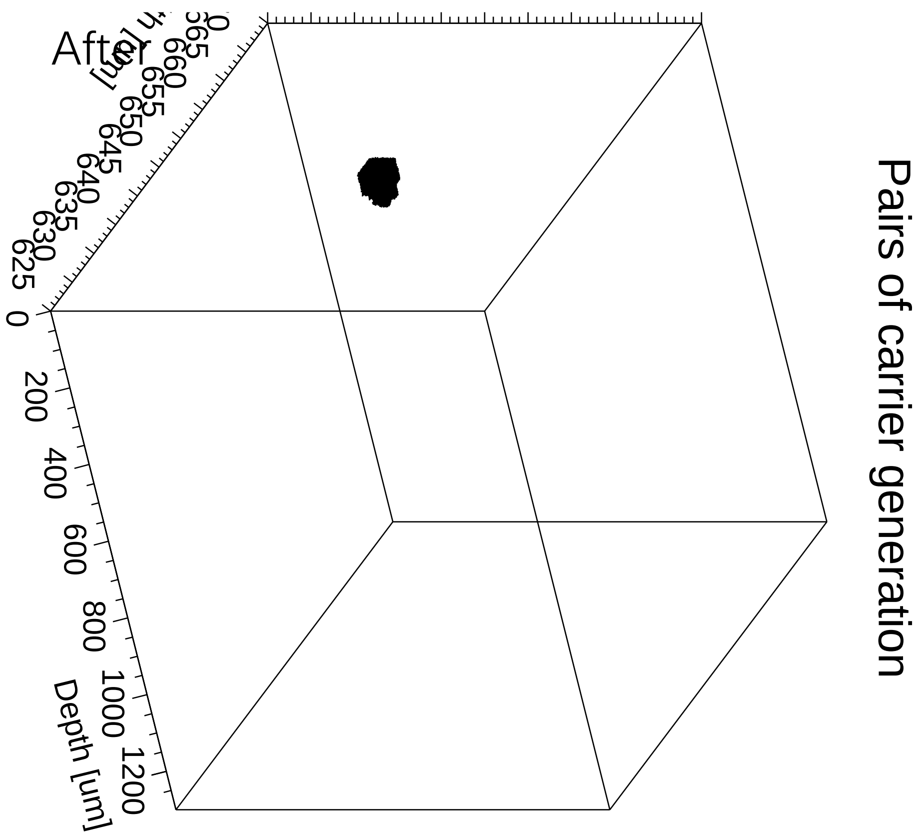



Related with volume of beam covered, or numbers of photons inside the bulk.
The overall pattern is well obtained by the simulation of edge scan.
Difference in LGAD might be induced by cutoff of low photon density areas.

# Cutoff of Low Photon Density Areas

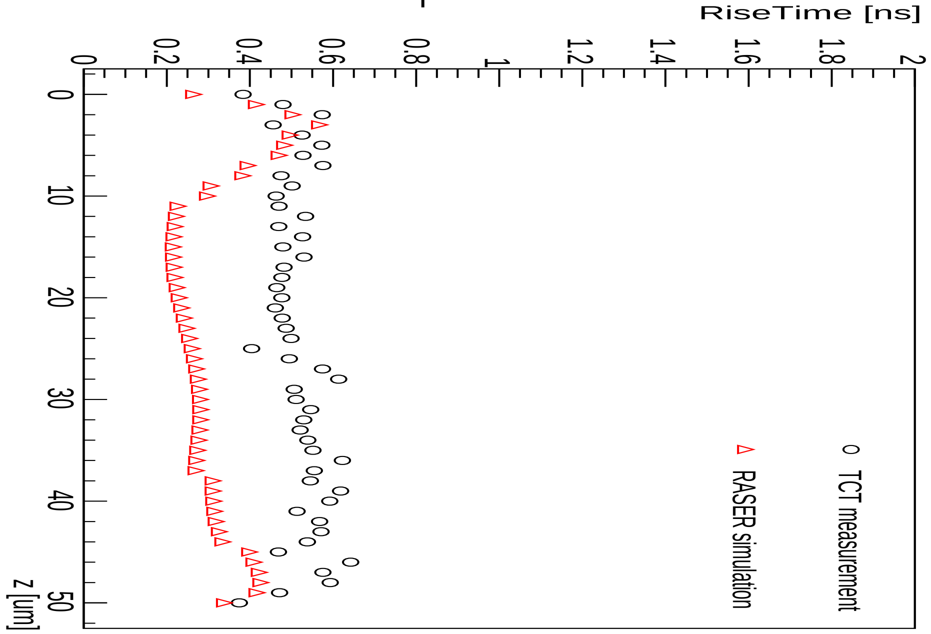


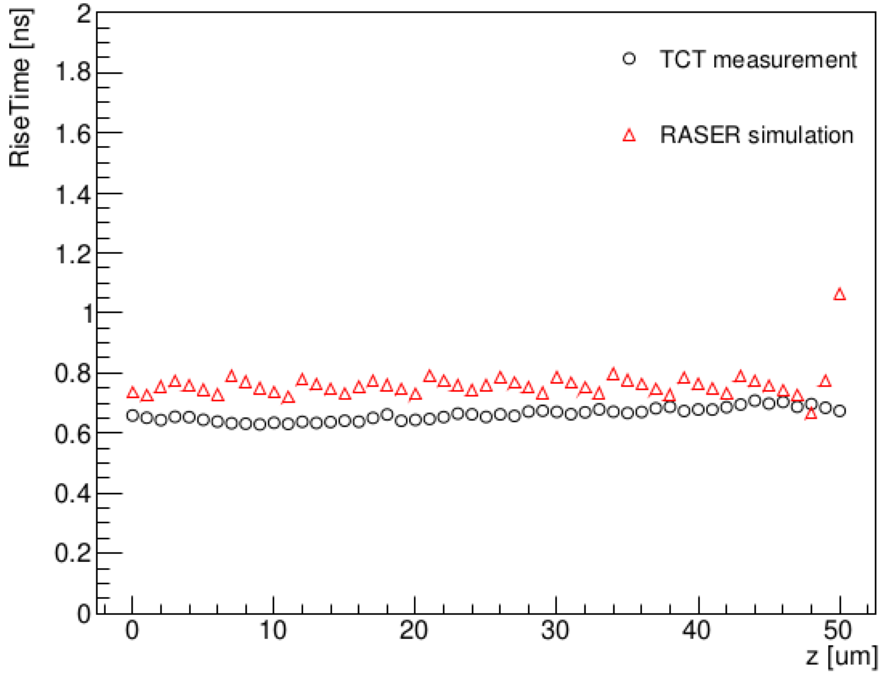

Reduce run time, equivalent to laser with smaller beam width
Limit of cut: 100 photons per block, block size: (1*1*5μm)*50ps

# Rise Time (0.2 to 0.8 Amplitude)

Rise Time-Depth Relation of PIN



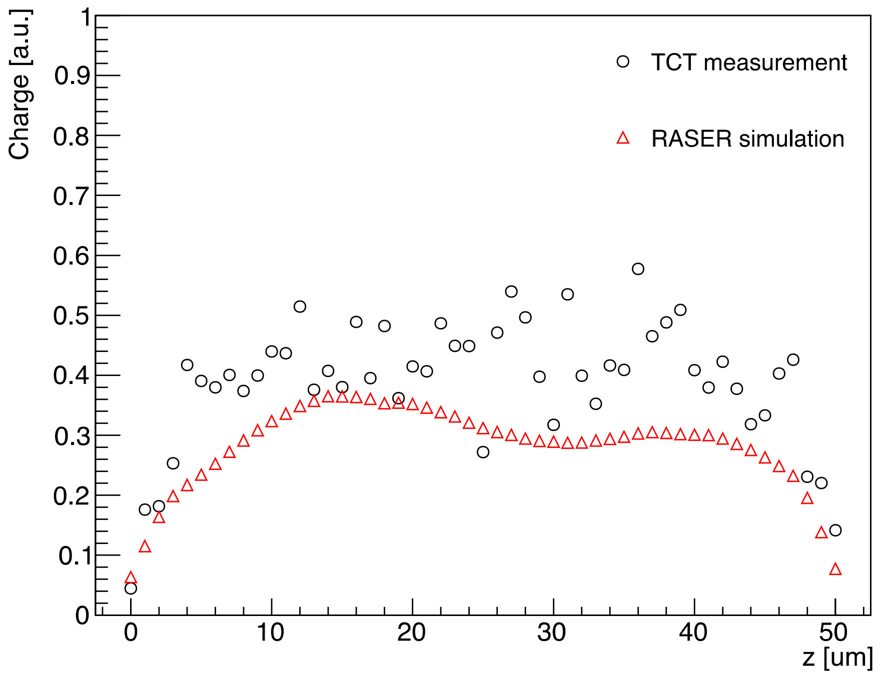

Rise Time-Depth Relation of LGAD



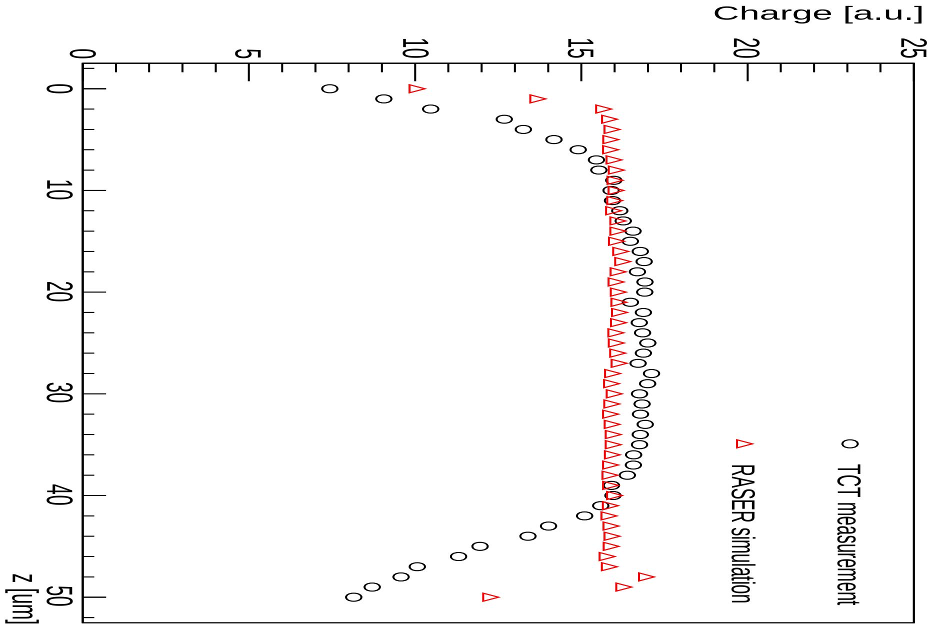

PIN: Underestimated. From ignorance of carrier acceleration.
LGAD: Stable along the z axis. Fit well for high S/N device.

# Charge Collection Comparison

Charge-Depth relation of PIN




Charge-Depth relation of LGAD



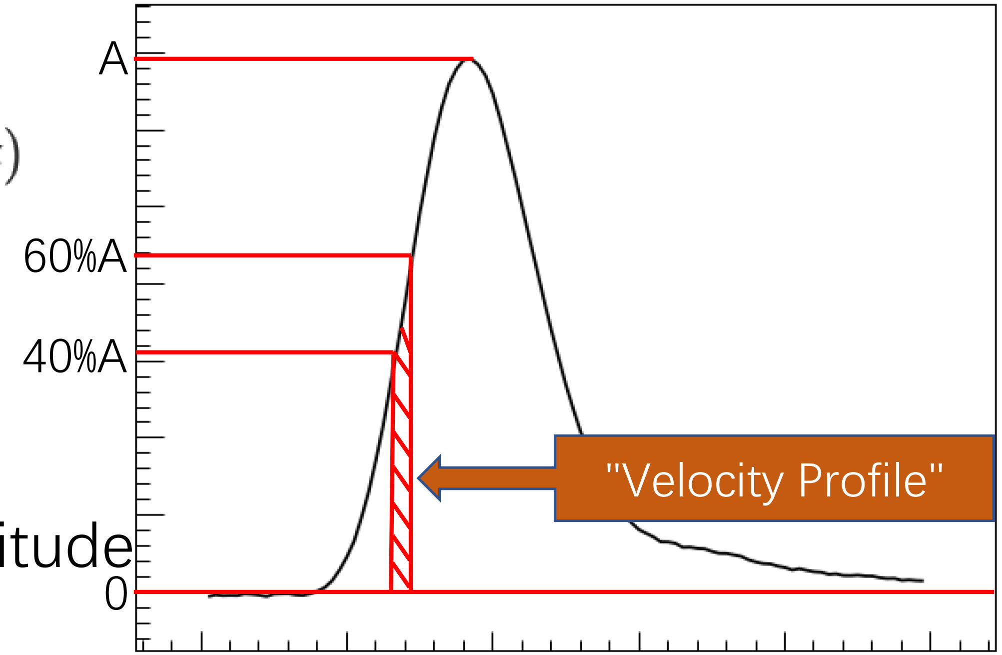

PIN: Fit well as a lower limit. Noise or Landau tail from Compton scattering.
LGAD: Fit well in the center of the bulk. Acts like a thinner laser beam. (P12)

# Methodology of Electric Field Measurement

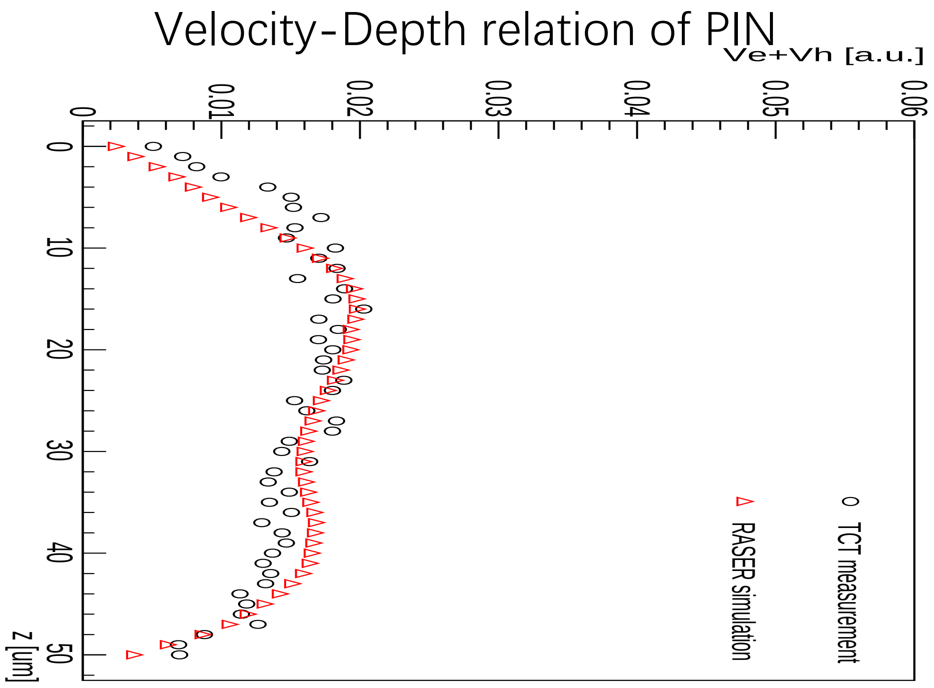
- Principle: for a pair of carriers generated, the sum of their initial velocity $v_e + v_h = (\mu_e + \mu_h)E$ is a function of electric intensity
- Approximation: all carriers generated at a small area in a small time period

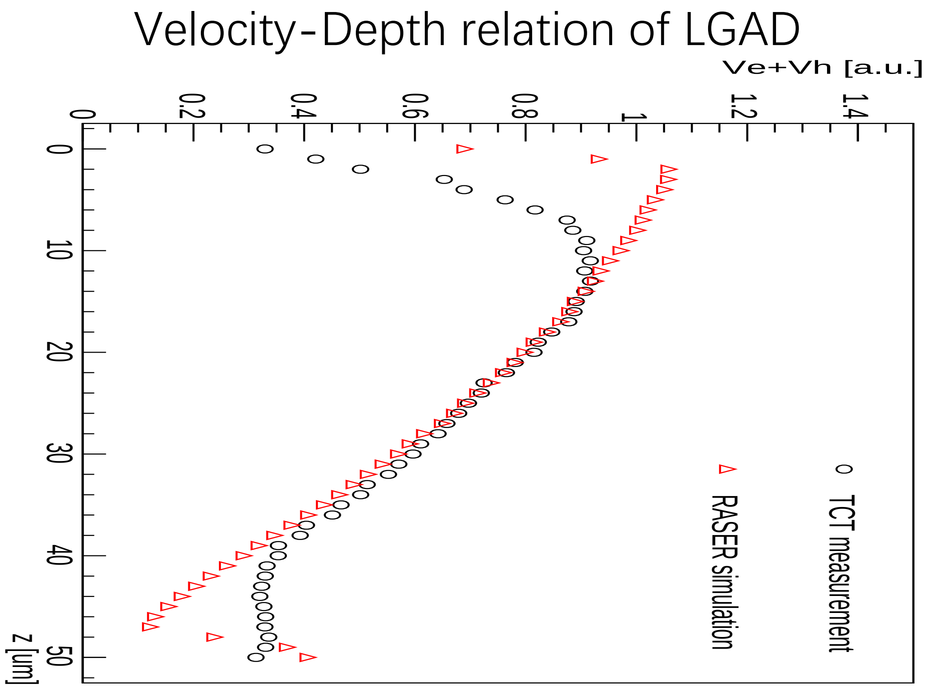
$$I(z; t \to 0) = \sum_q q\vec{v}_q \nabla U_w \approx \frac{ne}{d}(\mu_e + \mu_h)E(z)$$

- Velocity profile calculation
  - After amplification and rectification
  - Get contribution from central carriers
  - Integrate in [40%A, 60%A] average amplitude



# Velocity Profile Comparison




PIN: Fits good. LGAD: Share the same pattern, very close in the central area.
Substrate and gain layer-laser interaction not considered.

# Summary

- Come up with a new method to achieve gain
- RASER simulation fits good in edge-TCT on Si PIN and LGAD
- Laser model need to be optimized
- Plan:
  - Irradiated detectors
  - SiC PIN & LGAD

Thank you for listening!