TPA-Based Characterisation of Solid-State Sensors Using a Tunable Femtosecond Pulsed Laser

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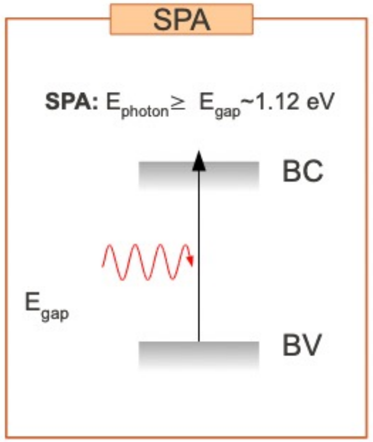
Outline

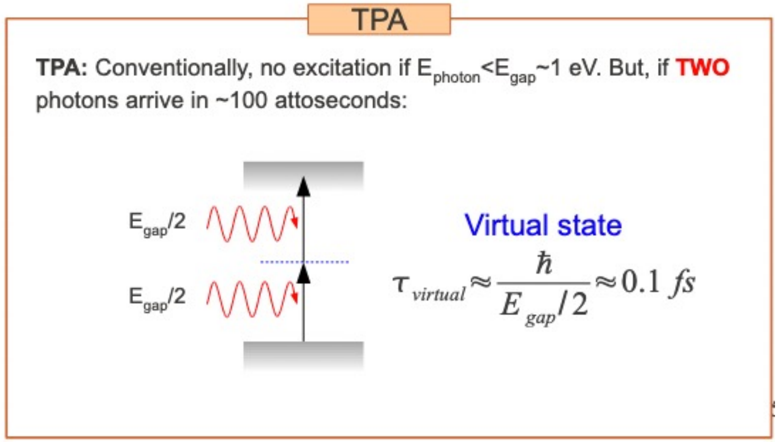
- **Introduction**
- **Set-up**
- **Measurements**
- **Summary**

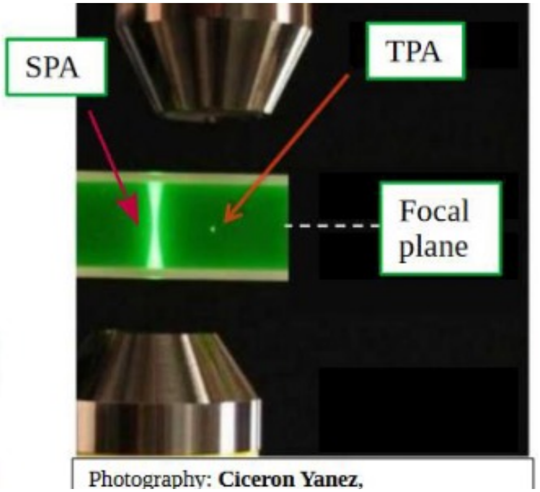
Marcos Fernandez

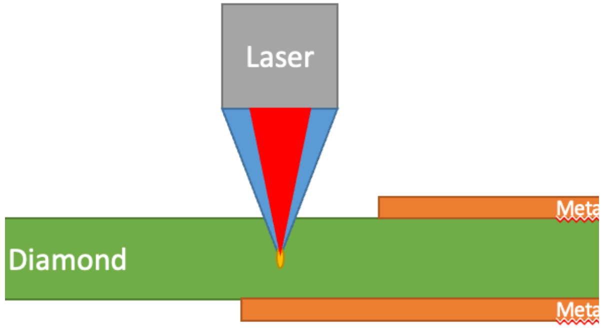
Introduction

- Two-Photon Absorption (TPA) involves simultaneous absorption of two photons.
- Relies on photon density achieved by laser focus called "voxel" .
- No photons are absorbed out of the focus.
- Single beam is focused by a lens.



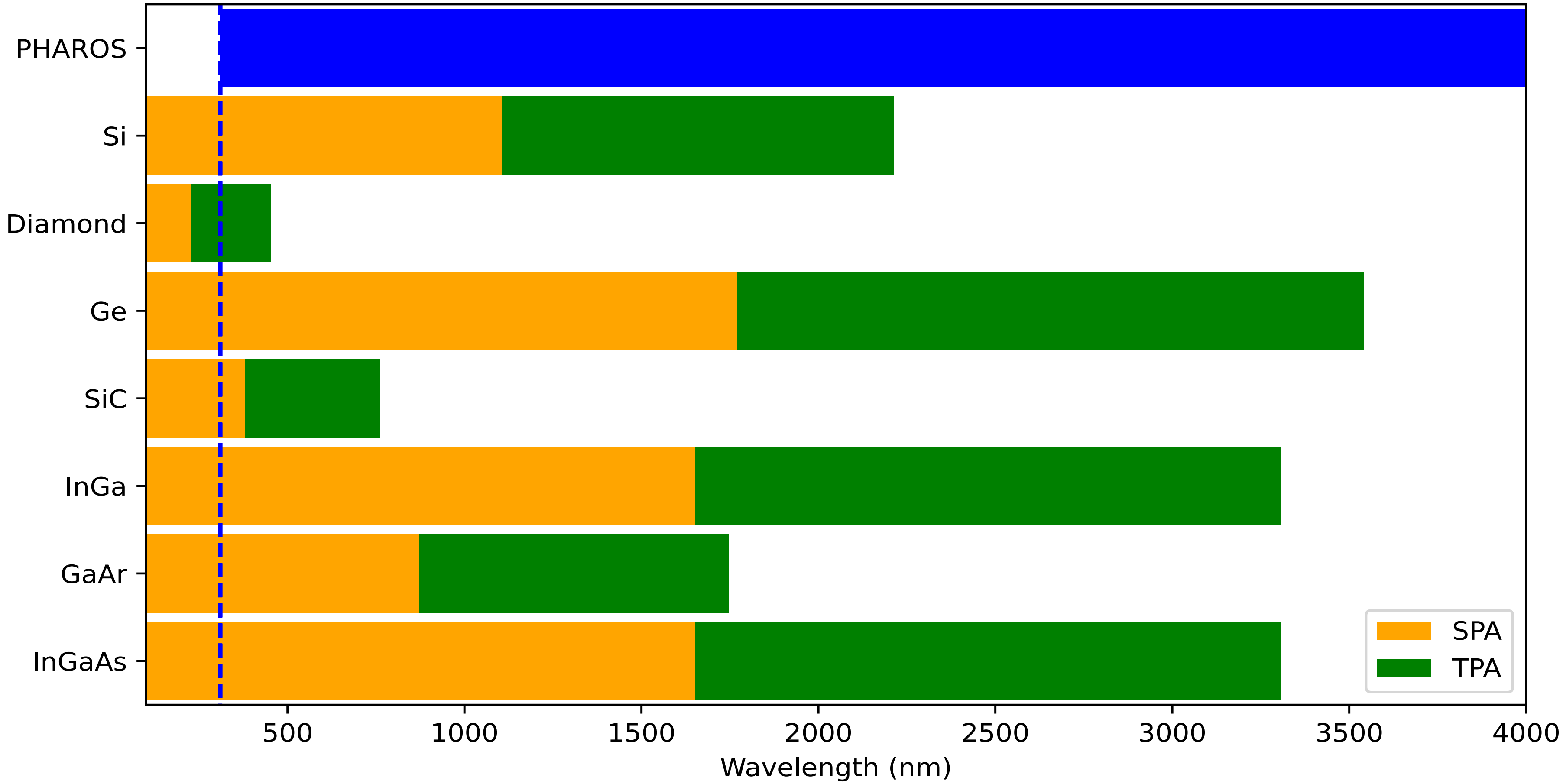


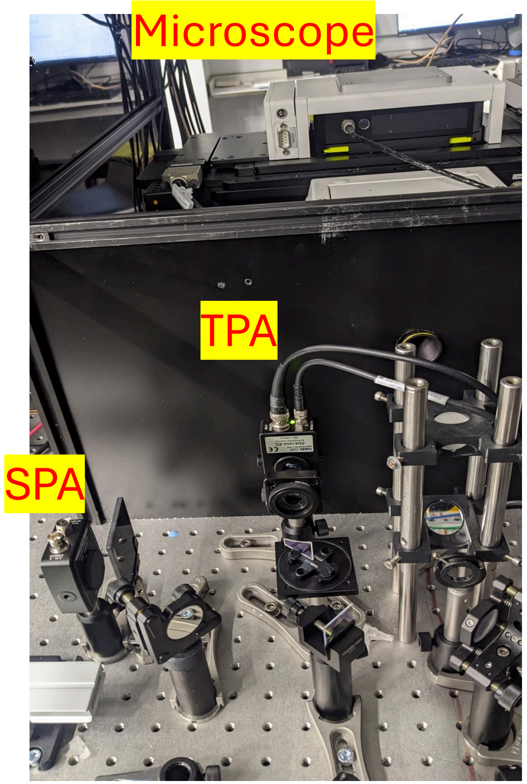


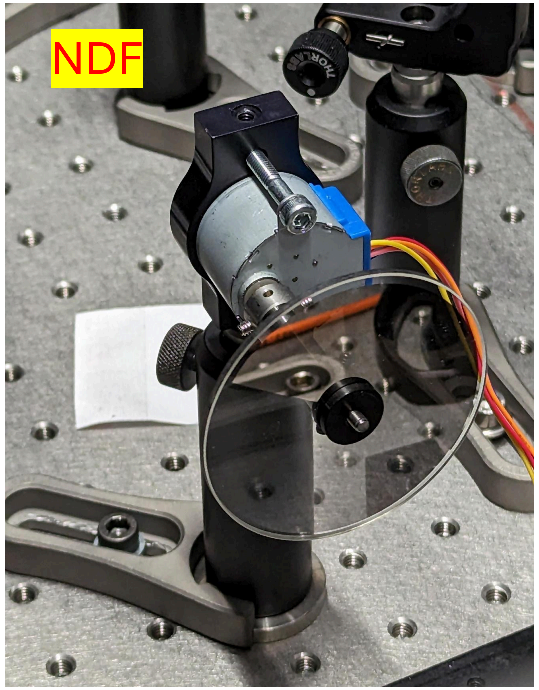


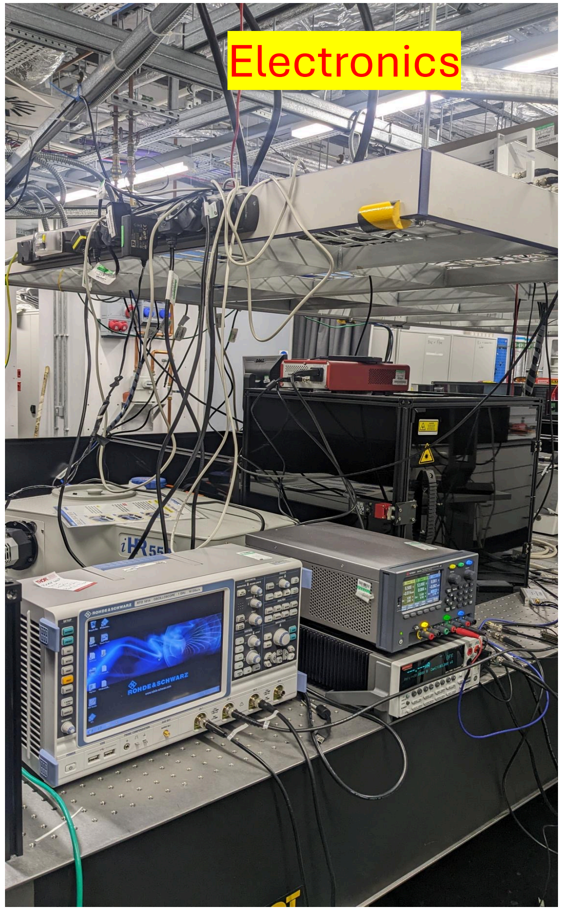
Laser Capability

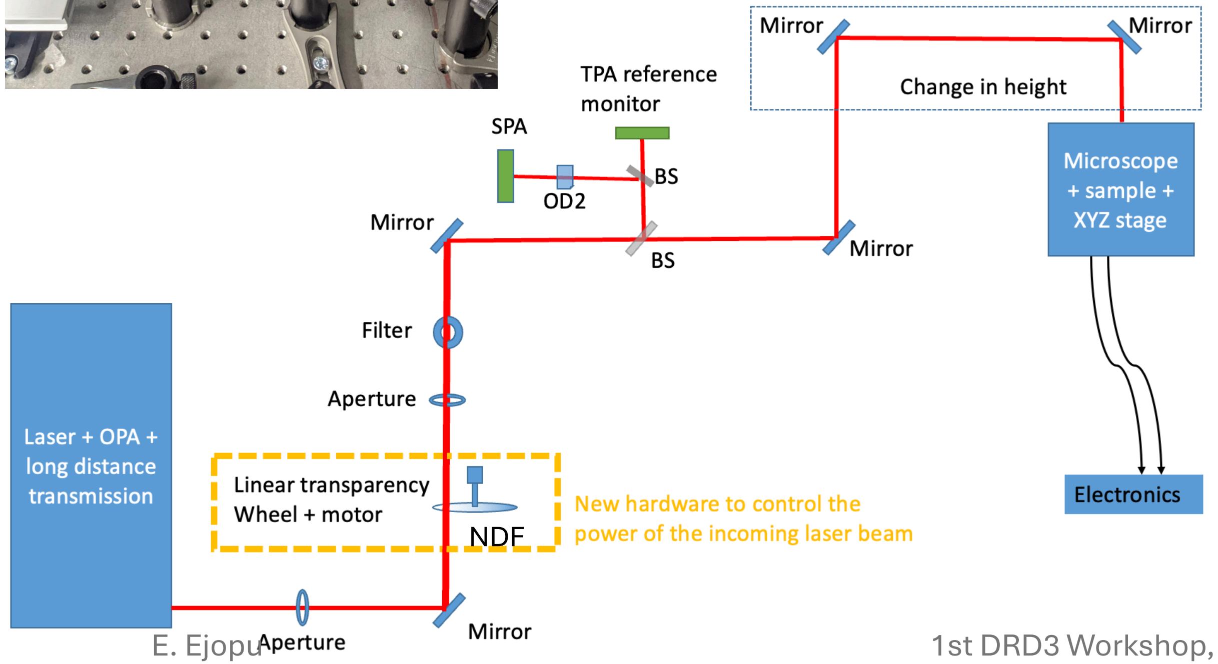
- Pharos wavelength range is from 330 nm to 16000 nm.
- Tuned by the Optical Linear Parametric Amplifier (OPA).









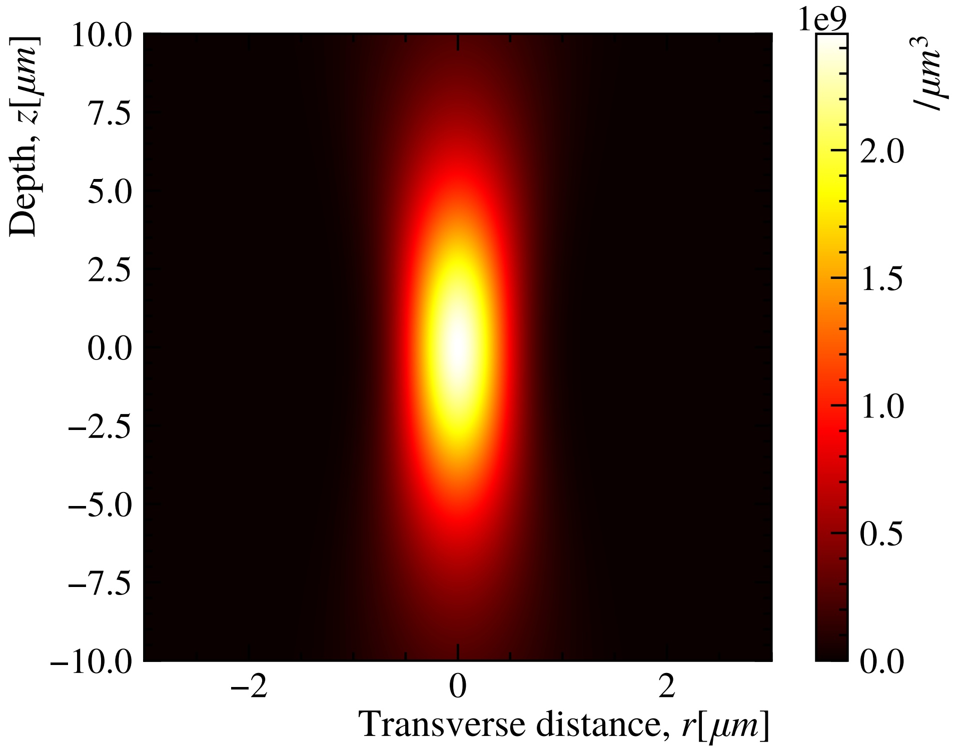


- PHAROS Femtosecond laser:
- Laser system: PHAROS Yb:Yag laser.
- Pulse duration (160 fs).
- Wavelength range from 330 nm to 16000 nm (3.757 eV to 0.077 eV).
- For Si as the DUT;
- Silicon sensor as reference monitor for TPA.
- And Ge sensor –SPA.
- Using an CIVIDEC C2 amplifier of 2 GHz.

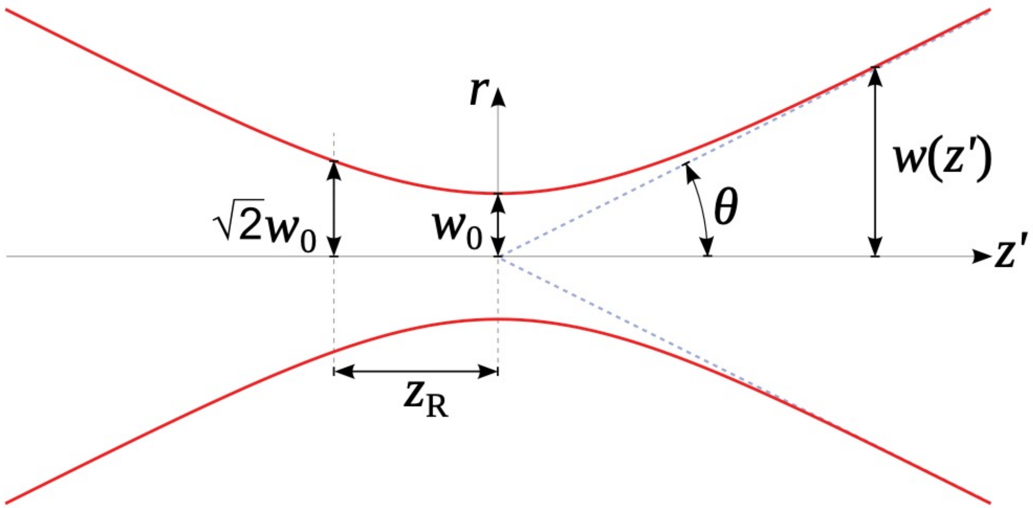
Expected charge carrier density

- Determination of expected amount of charge carrier density.
- Based on the properties of the lens (NA 0.5, 20X) we expect the following voxel shape.
- Parameters: $\lambda = 1550$ nm, $\tau = 160 \times 10^{-15}$ s,

$\beta_2 = 1.5$ cm/GW, f = 10 kHz, E_p=350 pJ.

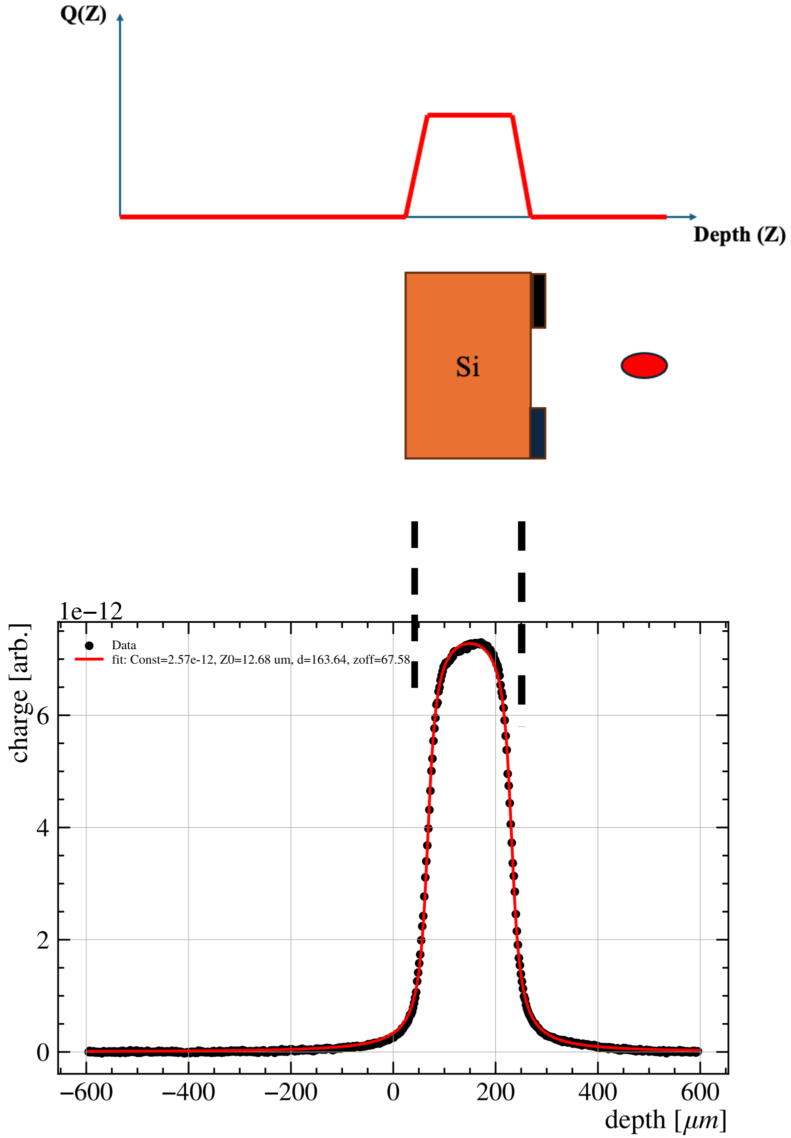


$$n_{tpa}(r,z) = \frac{E_p^2 \beta_2 4 \ln 2}{\tau \hbar\omega \pi^{\frac{5}{2}} w^4(z) \sqrt{\ln 4}} \exp\left[-\frac{4r^2}{w^2(z)}\right].$$



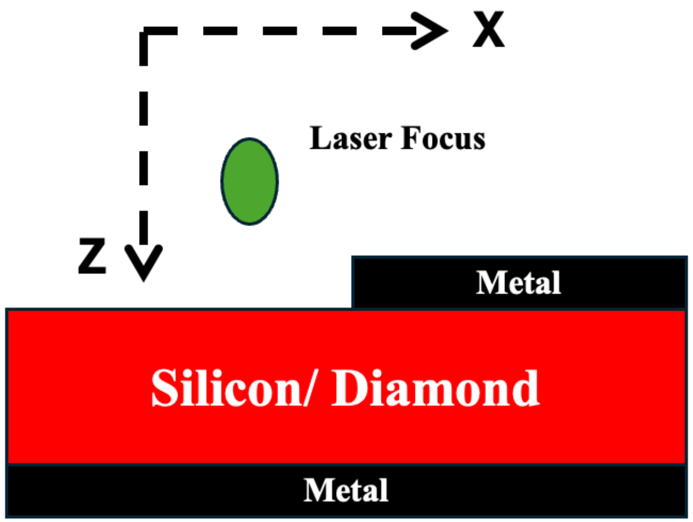
Silicon Diode Measurements

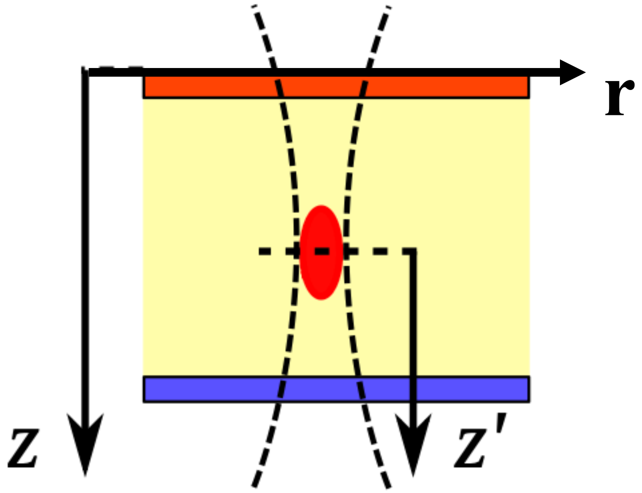
- Signal shape throughout the device depth.
- Charge distribution vs Depth well described by model.

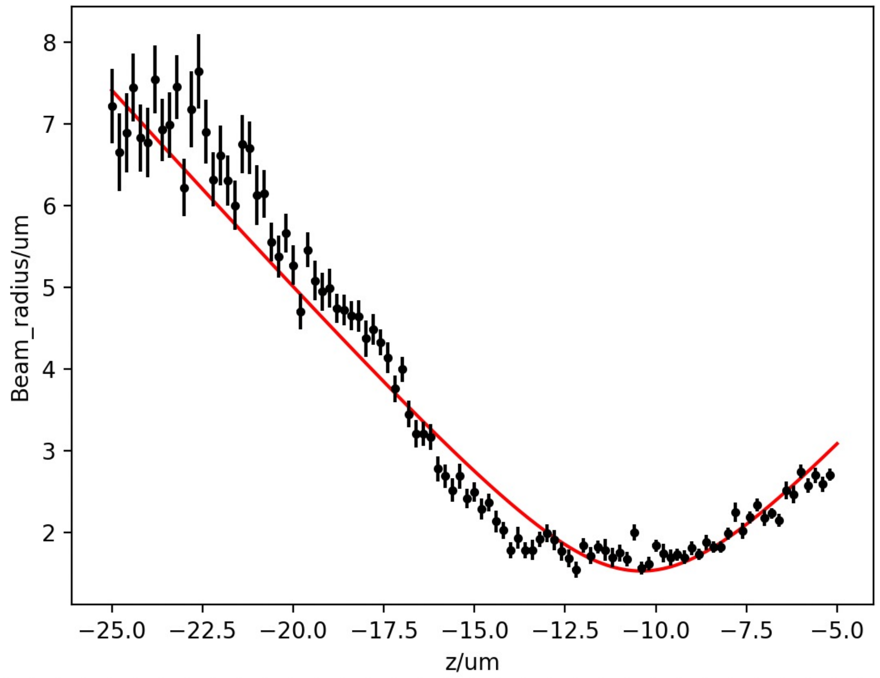


Silicon Diode Measurements

- Spatial resolution defined by the voxel.
- Knife edge scan.
- Voxel was found to be **10.4 um** by **1.5 um**.



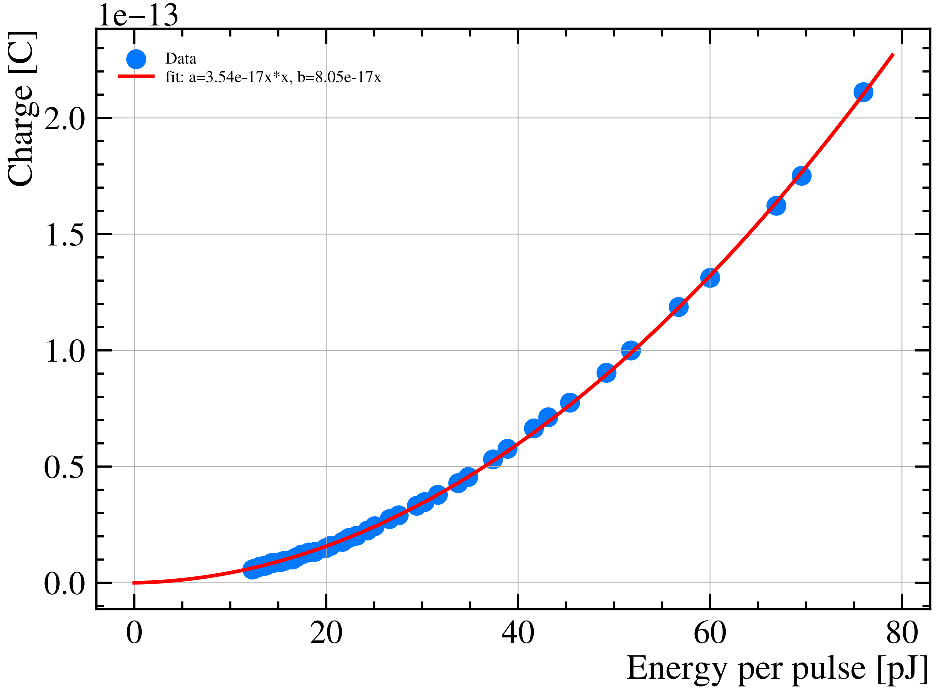




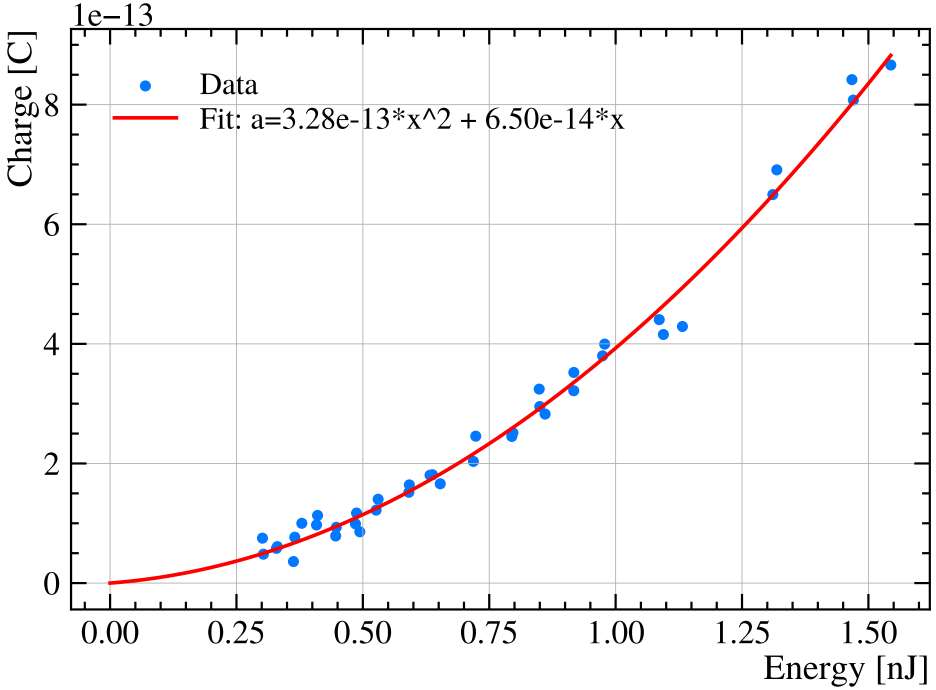
Measurements

- TPA confirmed in silicon (left) and diamond (right) as seen from the quadratic dependence and depth scan.
- Ionization density is proportional to the photon intensity squared.

Silicon, Wavelength = 1550 nm

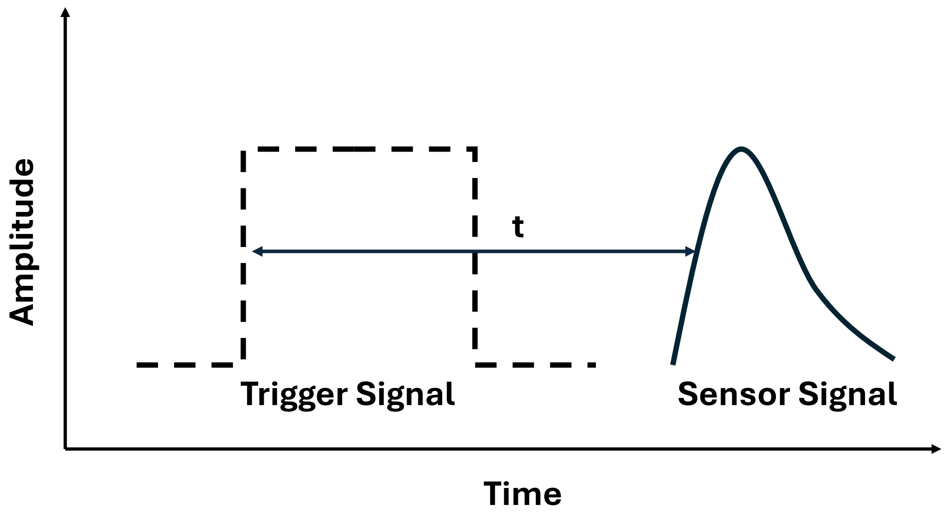


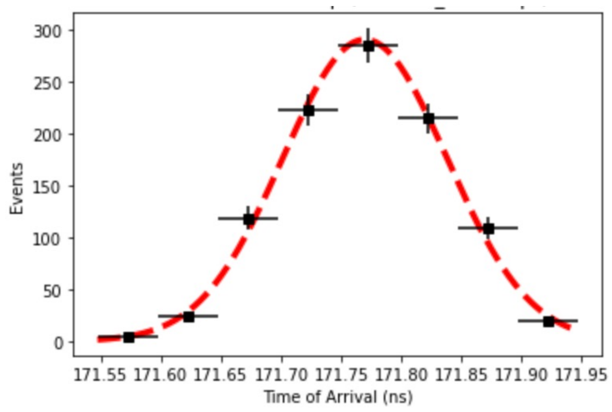
Diamond, Wavelength = 405 nm



Time Resolution Measurement

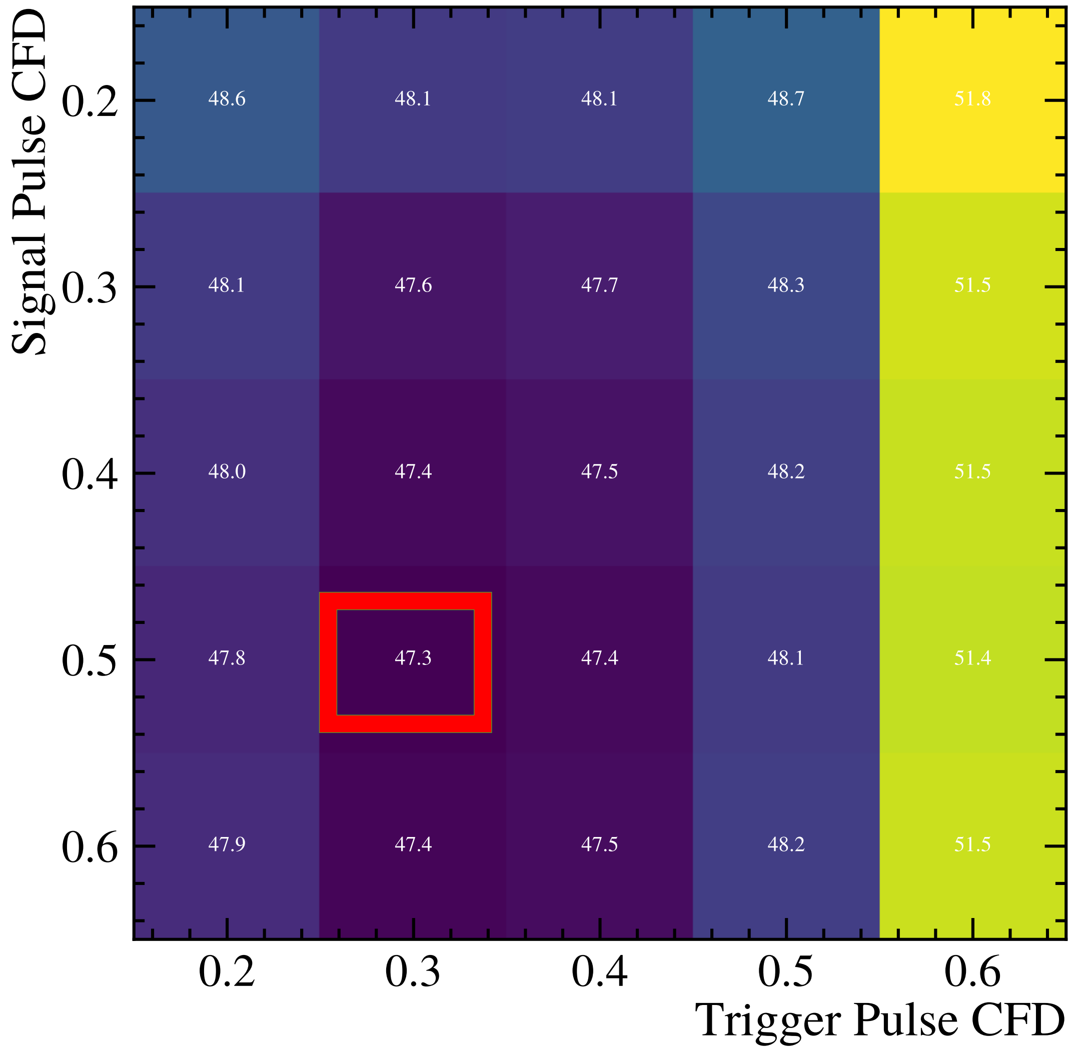
- Obtaining multiple waveforms (1000) with no averaging.
- Constant Fraction Discriminator (CFD).
- Two methods used:
- Method 1: **Laser Trigger.**
  - The arrival time difference with respect to the trigger are determined at a fixed CFD.
  - The standard deviation of the difference gives the time resolution.





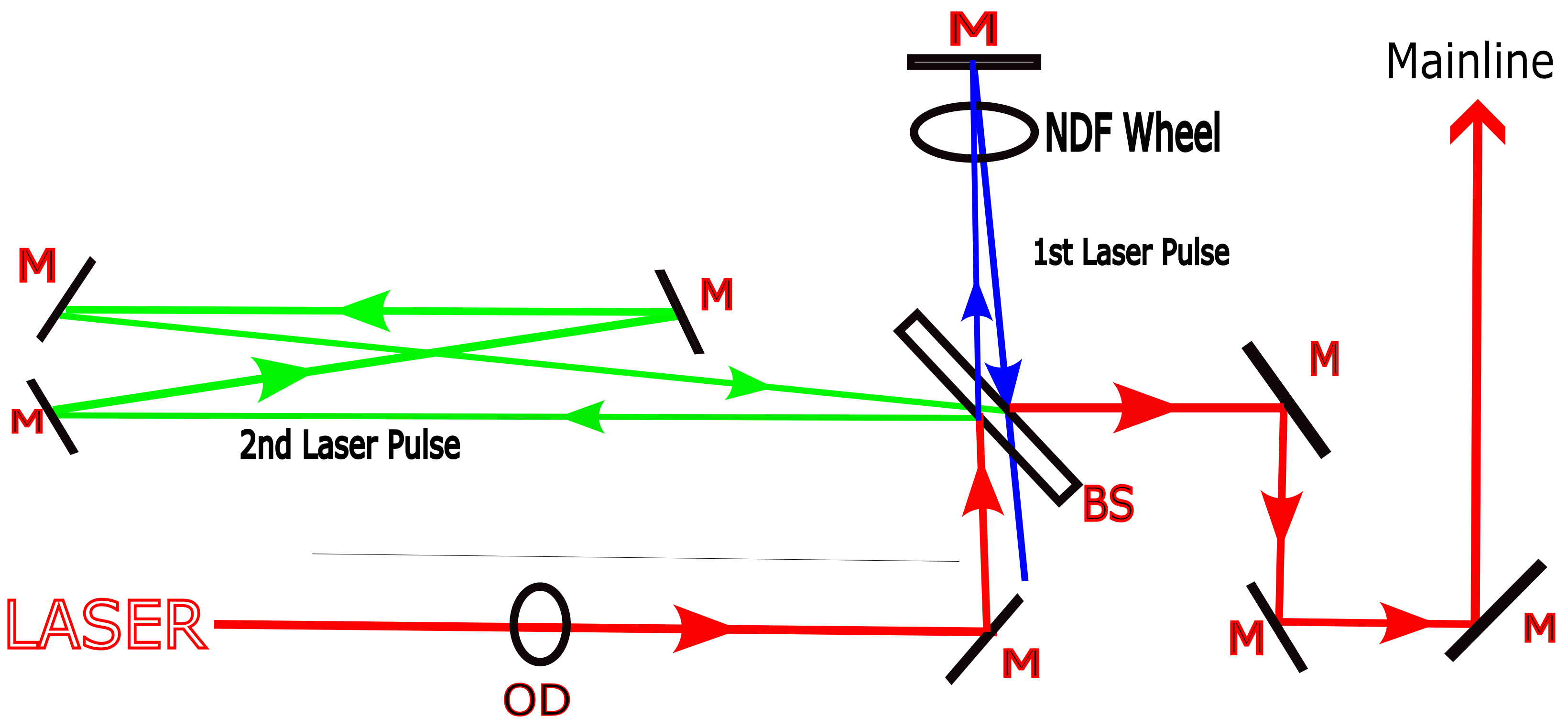
Timing...

- Time resolution for each combination of the trigger and signal thresholds were calculated.
- For LGADs, constant fraction discriminator + linear interpolation algorithm: **47.3 ps**.
- Pharos trigger time resolution is 20 ps with room for improvement.



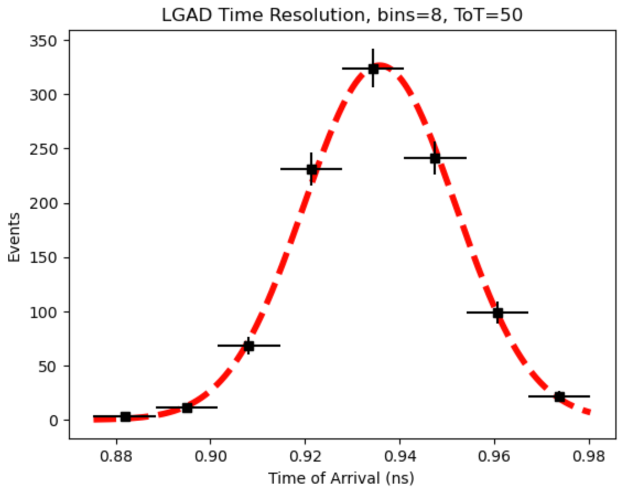
Double Pulse Method

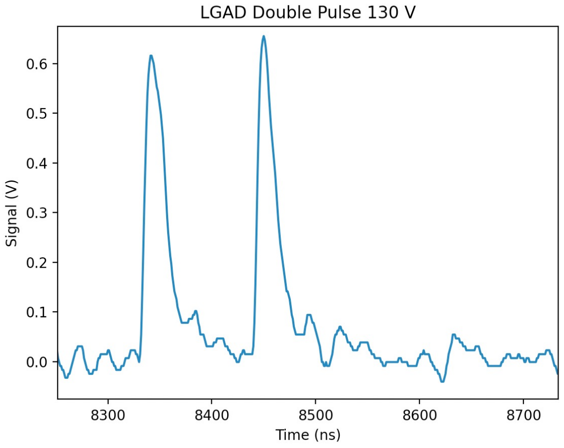
By splitting the laser beam using the set-up shown.

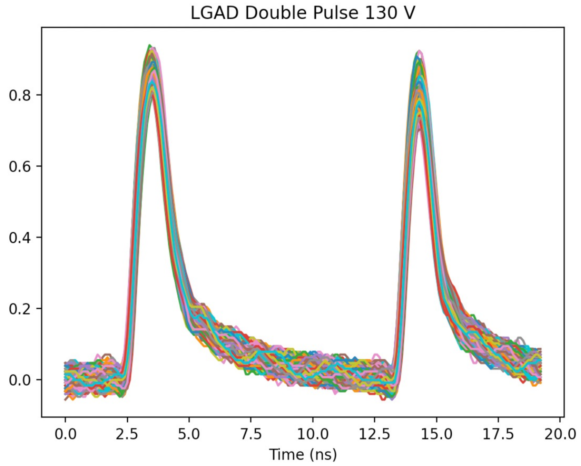


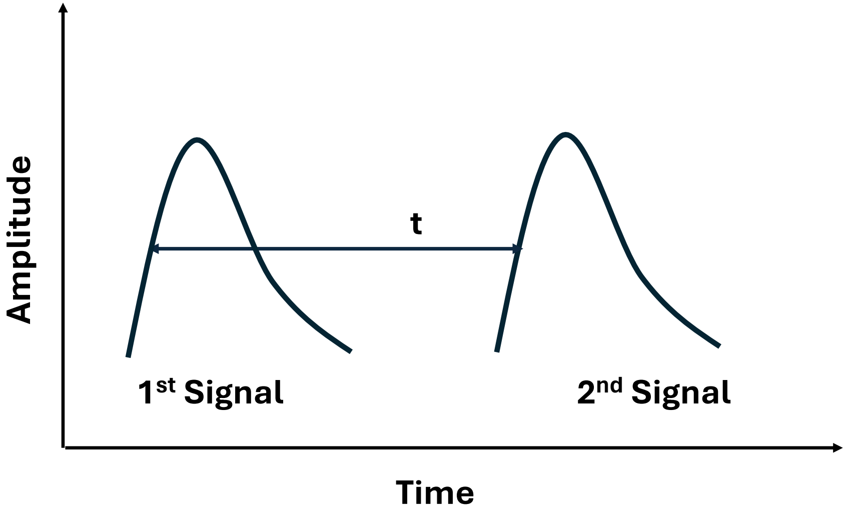
Timing…

- The arrival time difference between the 1st and 2nd pulse are determined.
- The standard deviation of the difference gives the time resolution.



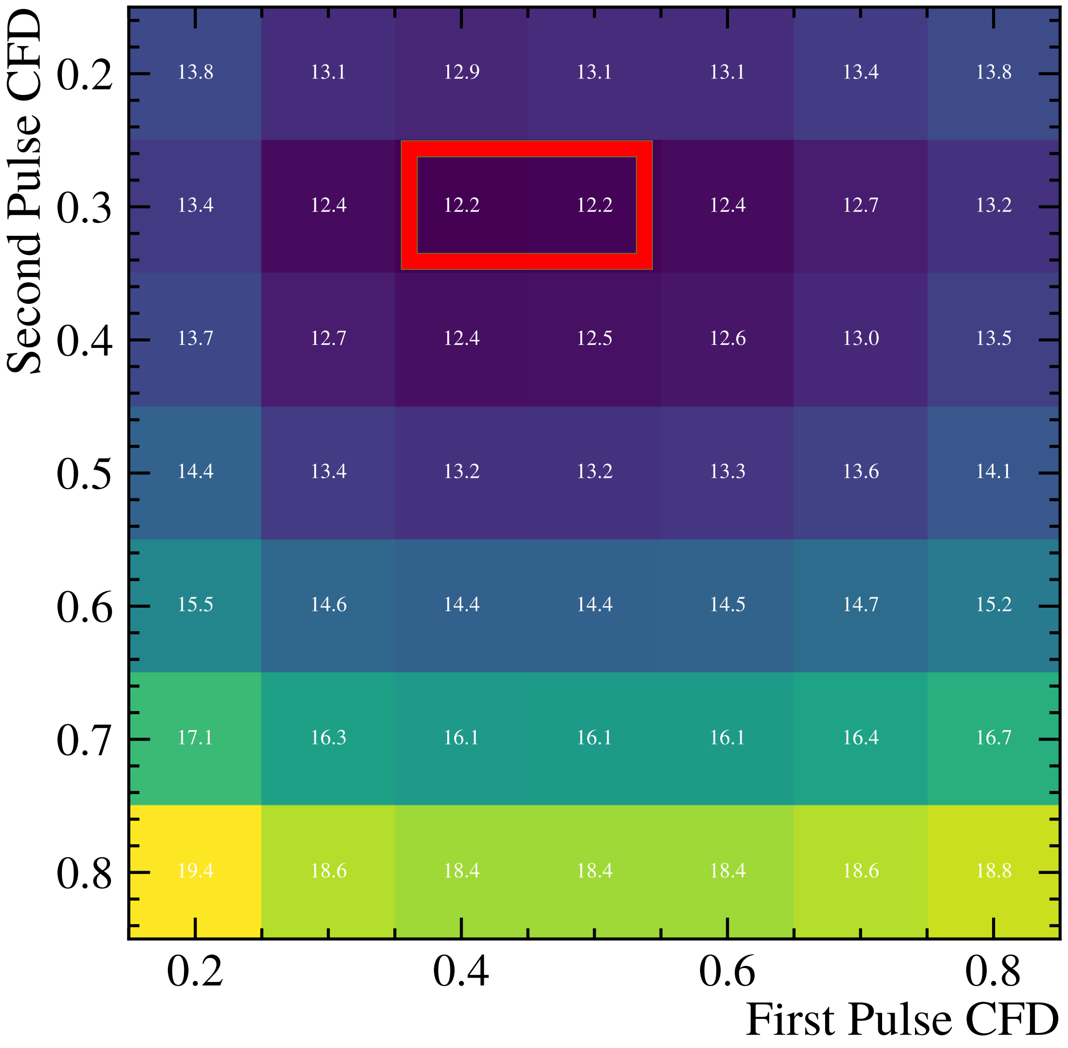






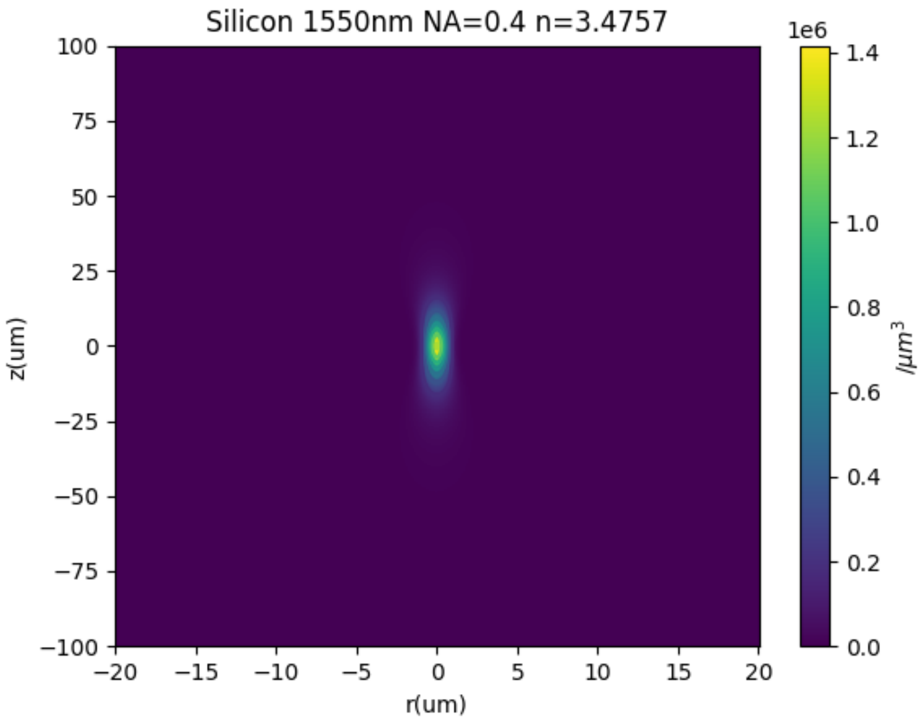
Time Resolution Mapping for different CFDs

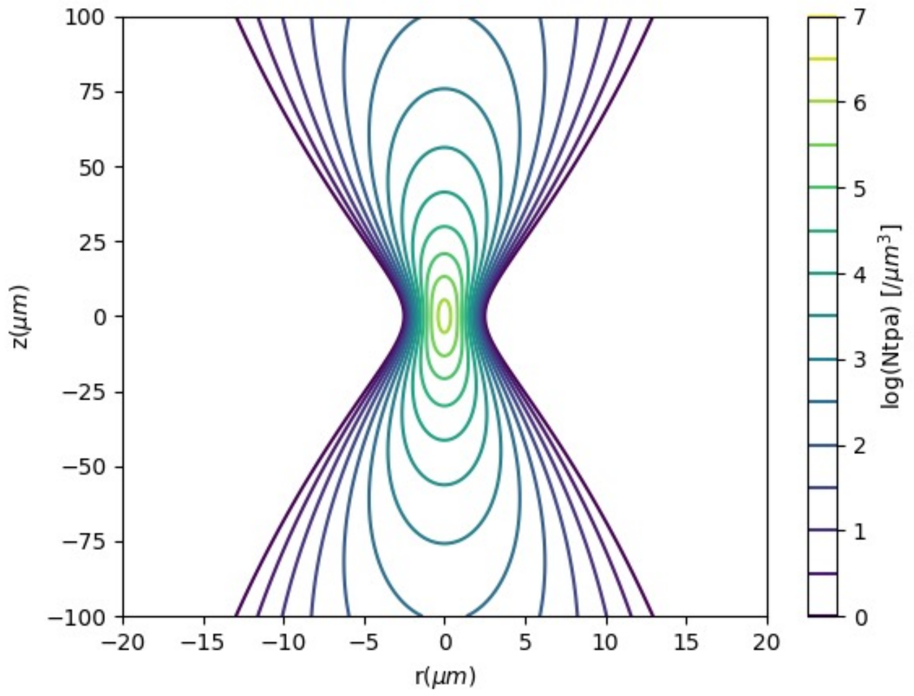
- Bias voltage = 130 V
- LGAD: 3331_13 #5
- CFD method.
- 0.1 is 10%, 0.2 = 20% etc of signal.
- Horizonal- 1st pulse CFD and Vertical- 2nd pulse CFD.
- Best time resolution of **12.2 ps** at a CFD of (40%, 30%) & (50%, 30%) for 1st pulse and 2nd pulse respectively.
- **8.6 ps** intrinsic time resolution.



KDetSim Simulation

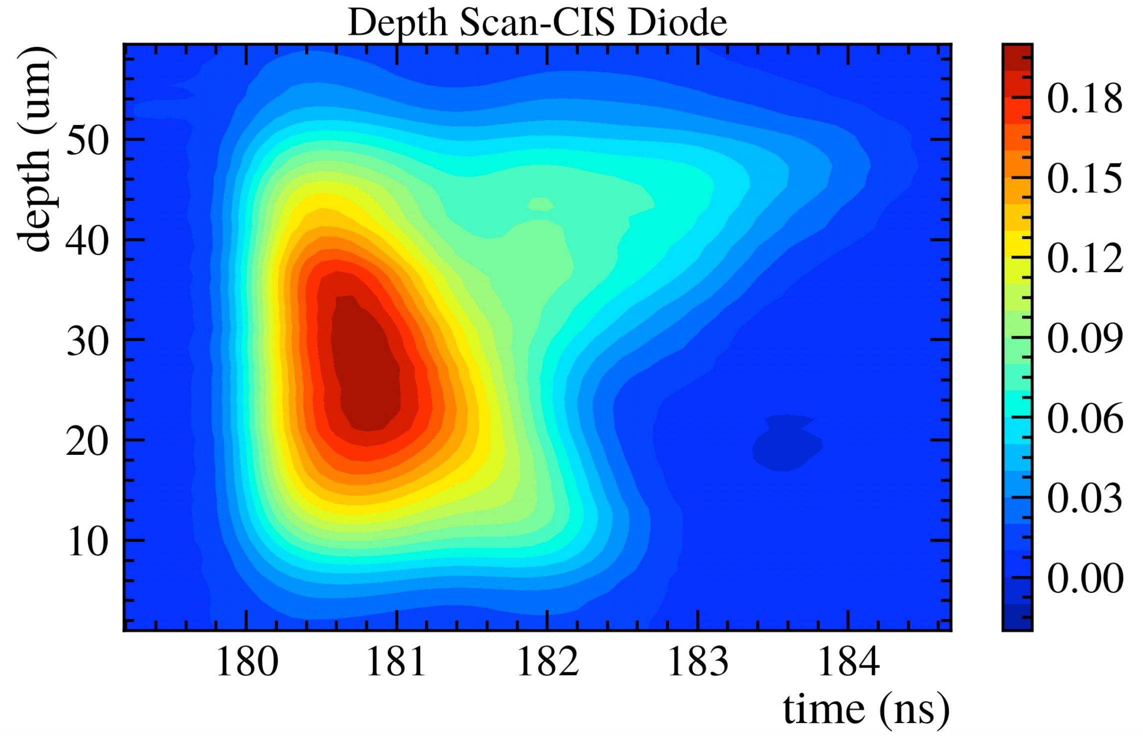
- The expected induced charge in a silicon device and the corresponding curve levels in logarithmic scale.
- Simulation parameters: wavelength =1550nm, Ep = 0.1nJ, NA=0.37 and τ = 160fs.

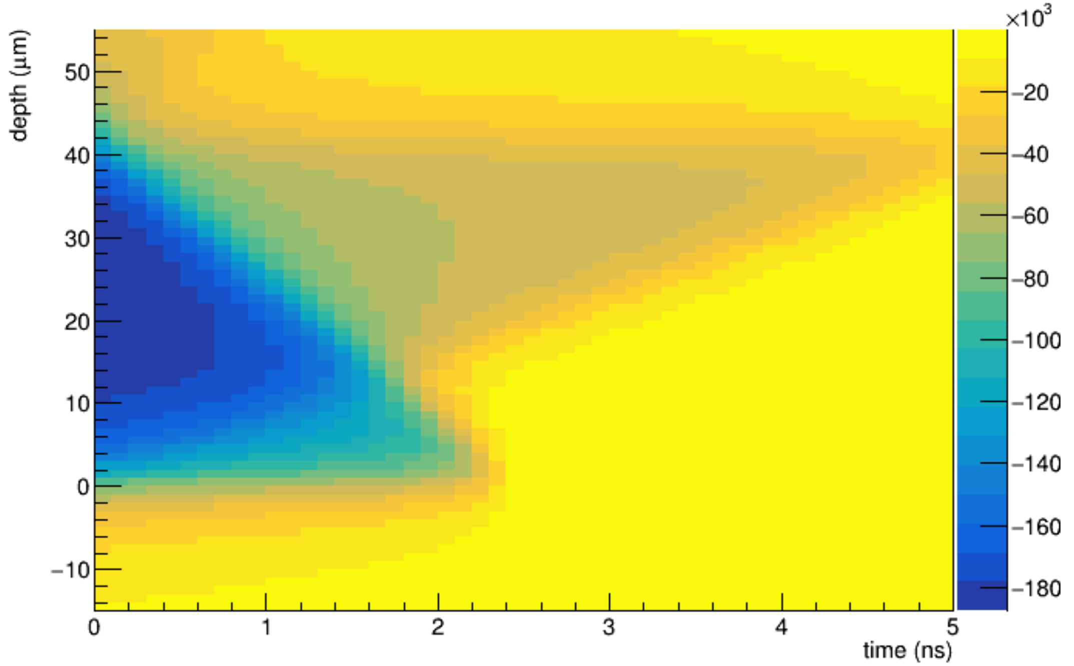




KDetSim

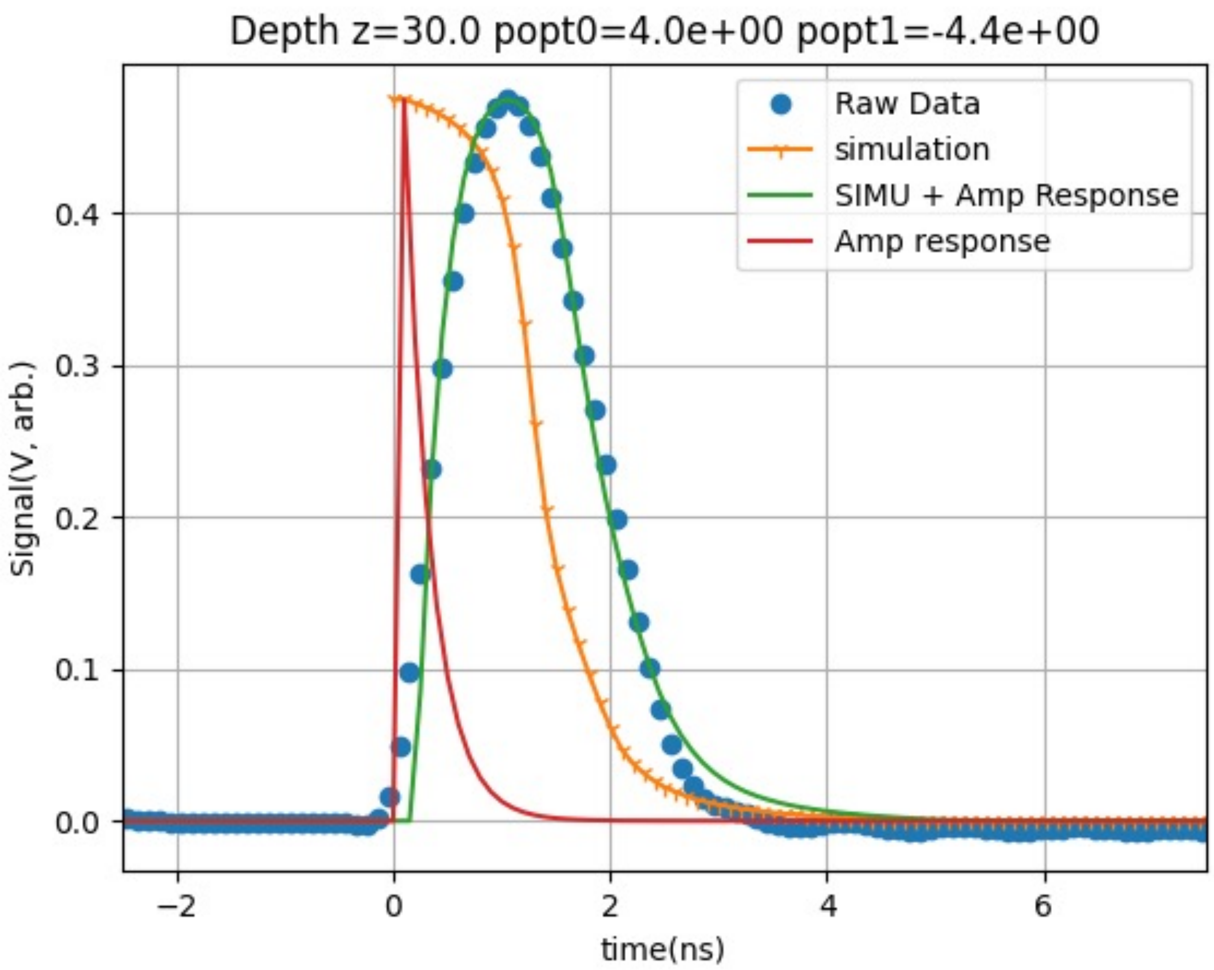
Comparison between experimental (left) and simulation (right) Depth-time scan of TPA signal using a diode.





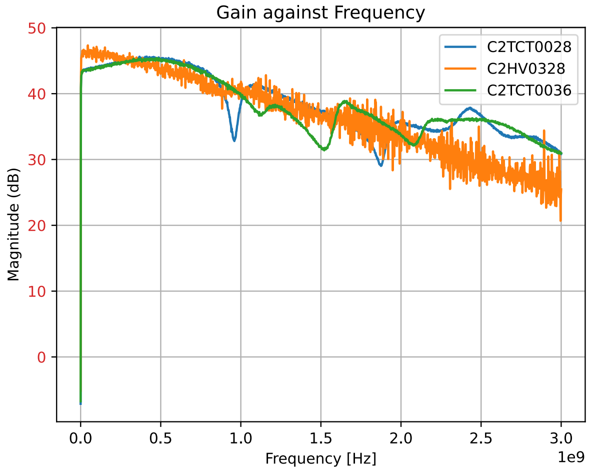
KDetSim

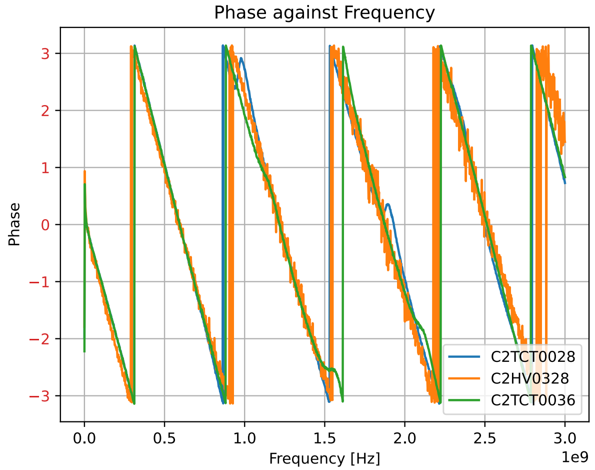
- Voxel is projected in 1D and used as input on KDetSim.
- KDetSim predictions as a function of depth at different depths at the device at the middle of the device (z = 30μm).

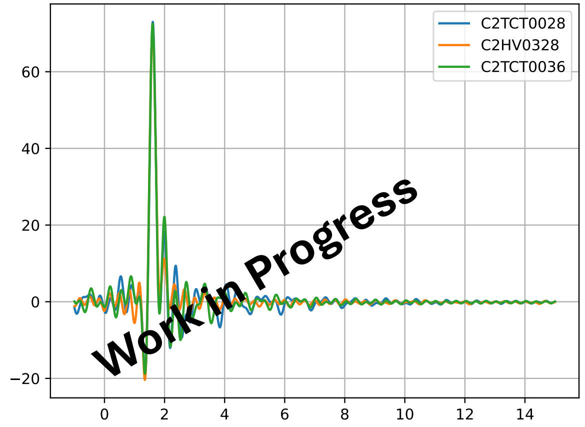


Simulation & Amplifier Modeling

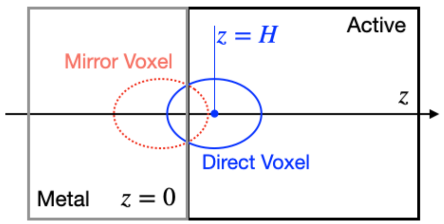
- Amplifier response (below) is determined using a Network Analyzer (KEYSIGHT E5061B ENA Series, 5Hz – 3 GHz).
- Results used for simulation studies.



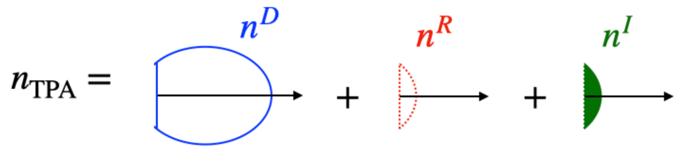




Reflection Model

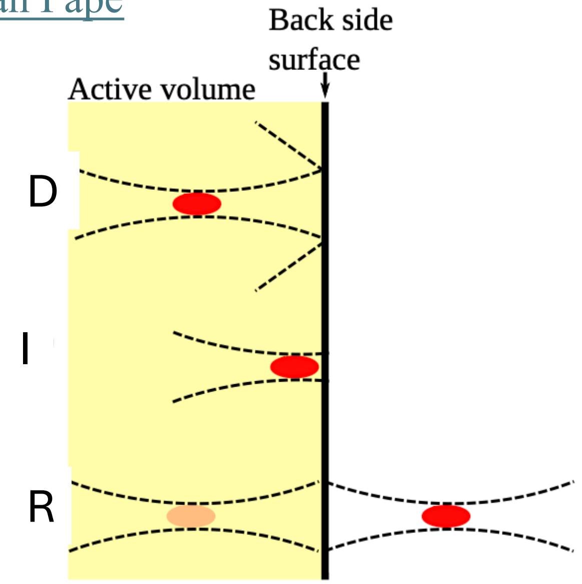


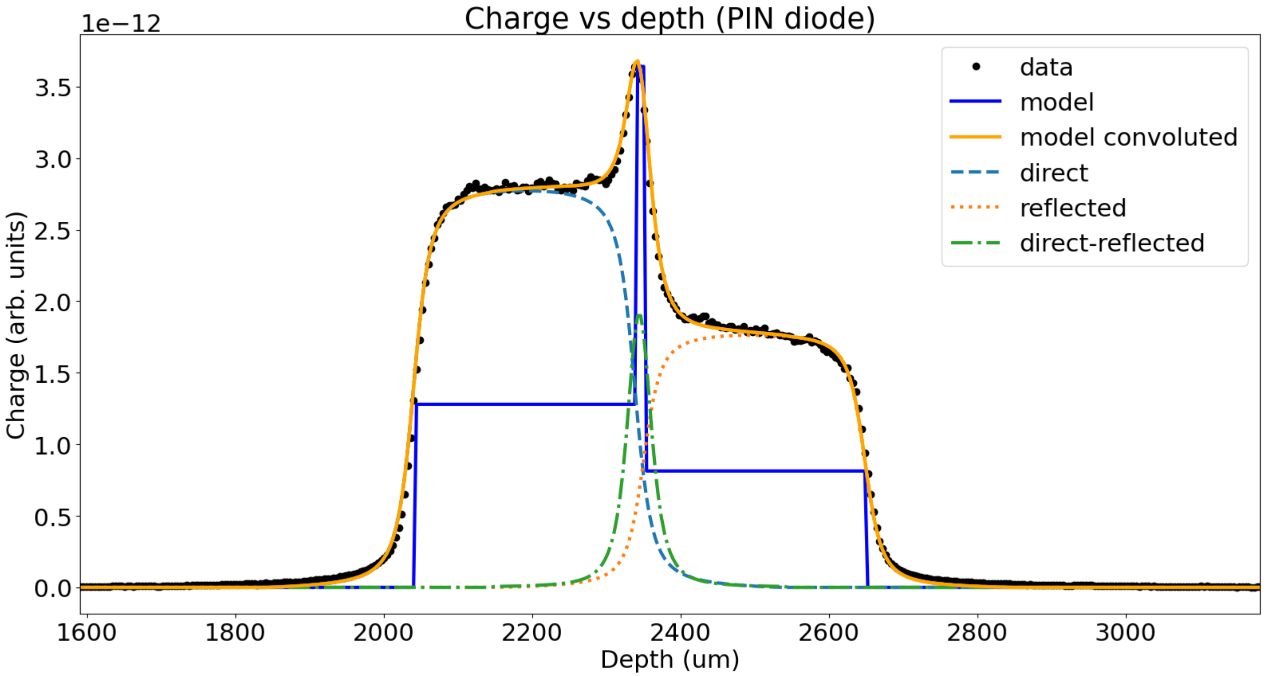
$$I_0 = I_D + I_R$$
$$n \propto I^2$$



- To understand the voxel reflection.
- Convolute the reflected charge over z-axis.

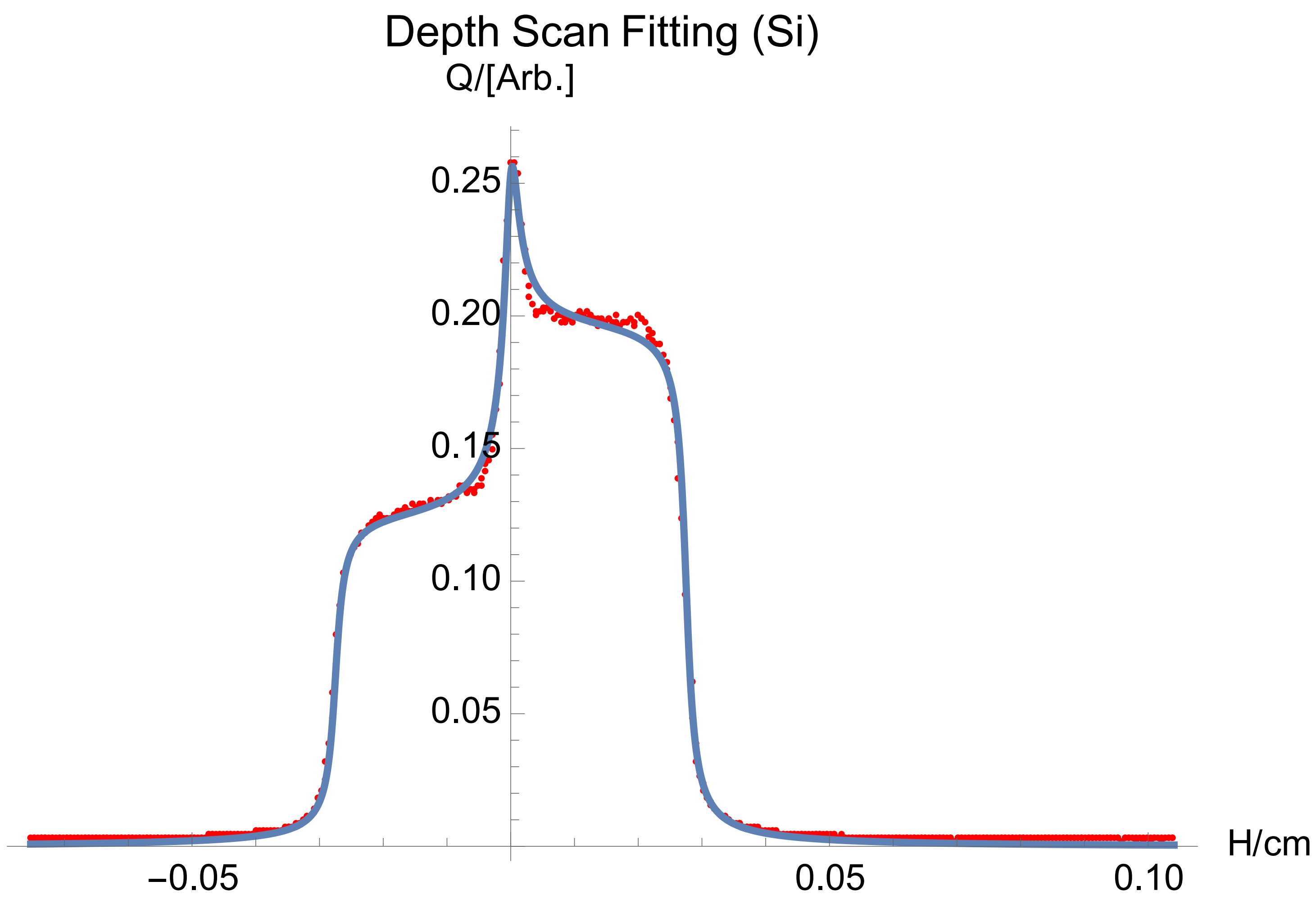
Sebastian Pape





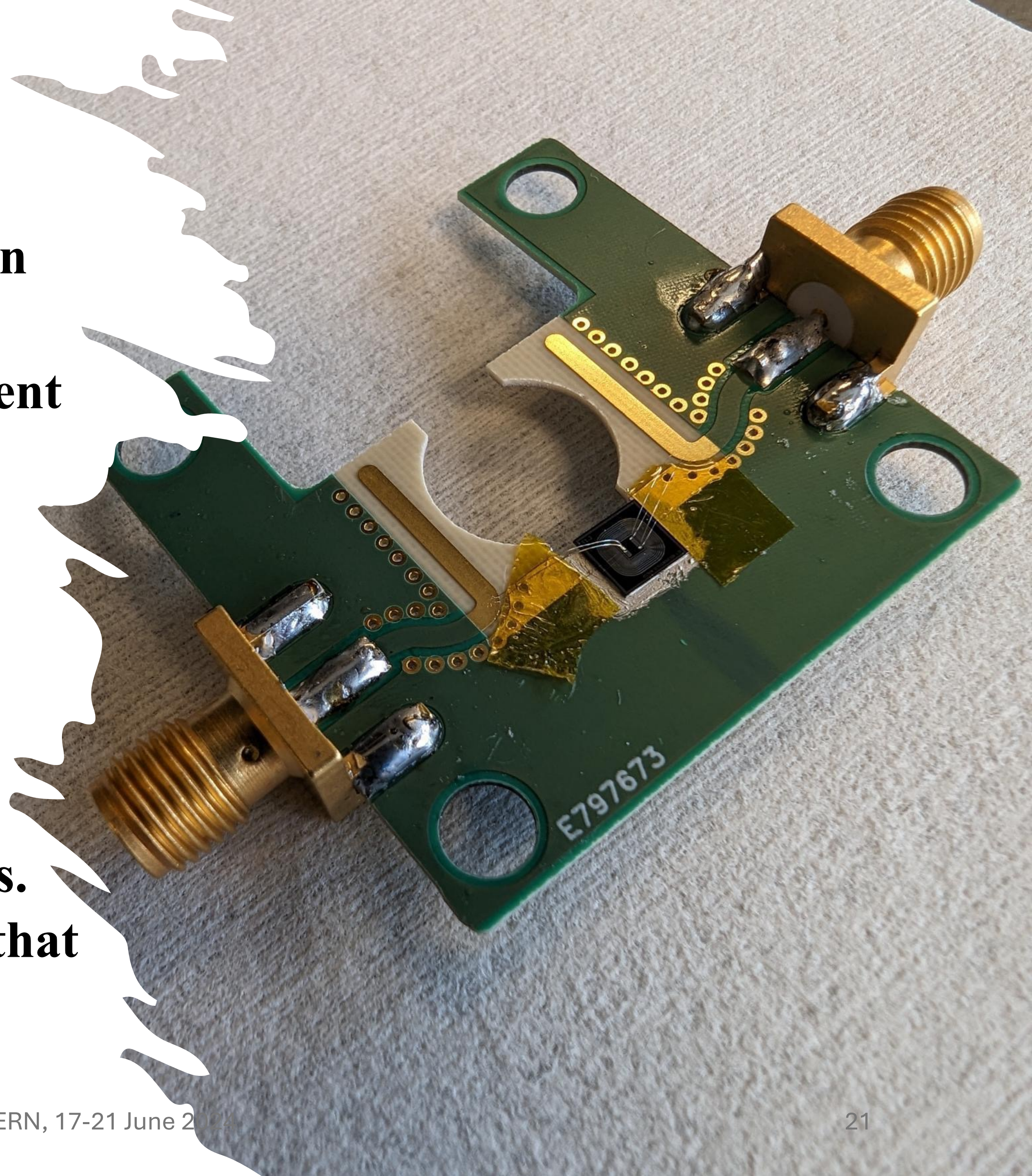
Reflection Model

- Comparison between fitted model and depth scan data for CNM Silicon sample (275 μm thickness).



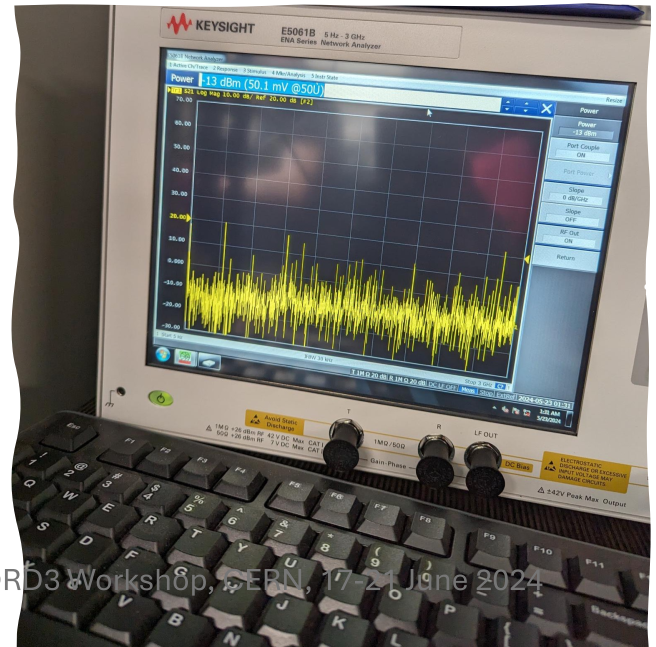
Summary

- **Performed TPA characterisation for Silicon diodes, LGADs and Diamond.**
- **Measured time resolution using two different techniques.**
- **On going:**
  - **3D diamond characterisation.**
  - **Trench LGADs.**
  - **Optimization of simulation.**
- **Potential Improvements:**
  - **A cooling system for irradiated samples.**
  - **Additional sensor to measure photons that go through the sample.**



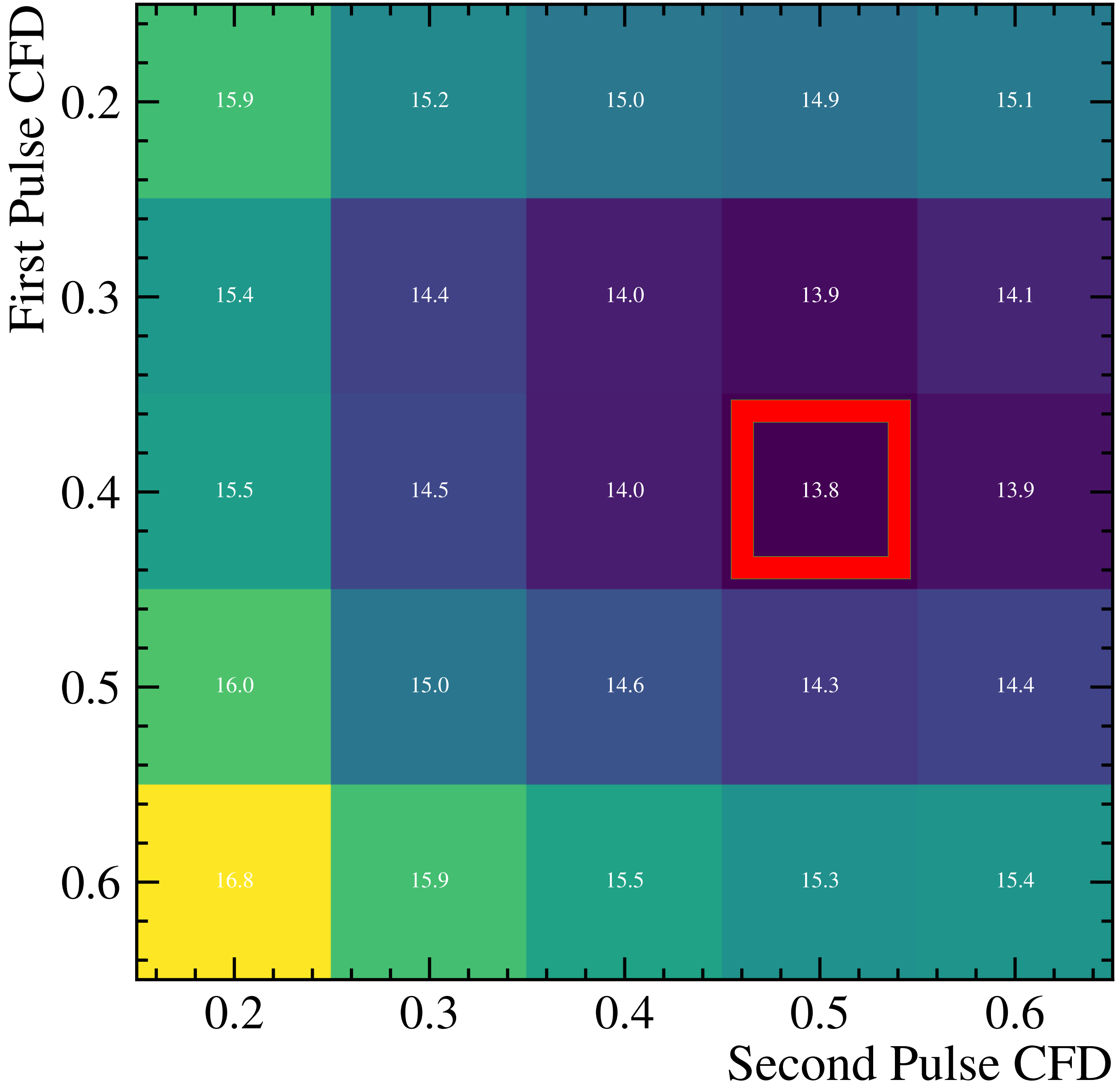
Back Up

- Amp modelling set-up.



Time Resolution Mapping for different CFDs

- Bias voltage = 100 V
- LGAD: 3331_13 #5
- CFD method.
- Horizonal- 1st pulse CFD and Vertical- 2nd pulse CFD.
- Best time resolution of **13.8 ps** at a CFD of (40%, 50%) for 1st pulse and 2nd pulse respectively.



Reflection Model

$$
\begin{aligned}
n_{\mathrm{TPA}}(z,H,r) &= \frac{\beta_2}{2\hbar\omega}\int_{-\infty}^{\infty}\mathrm{d}t\, I^2(z,r,t)\\
&= \frac{\beta_2}{2\hbar\omega}\int_{-\infty}^{\infty}\mathrm{d}t\left[I_D(z-H,r)e^{-\frac{4\ln 2 t^2}{\tau^2}} + RI_D(-z-H,r)e^{-\frac{4\ln 2 (t+\Delta t)^2}{\tau^2}}\right]^2\\
&= \frac{\beta_2\tau}{4\hbar\omega}\sqrt{\frac{\pi}{2\ln 2}}I_D^2(z-H,r) + \frac{\beta_2R^2\tau}{4\hbar\omega}\sqrt{\frac{\pi}{2\ln 2}}I_D^2(z+H,r)\\
&+ \frac{\beta_2R\tau}{2\hbar\omega}\sqrt{\frac{\pi}{2\ln 2}}I_D(z+H,r)I_D(z-H,r)e^{-\frac{2\ln 2(\Delta t)^2}{\tau^2}},
\end{aligned}
$$

Figure 14: Schematic plot of two-voxel model. Any direct voxel centered at $z = H$ must have a corresponding mirror voxel at $z = -H$. Plane $z = 0$ is defined as the bottom plane of the sample.