Characterisation of **Diamond** and **SiC** sensors with **TPA** and modelling of response

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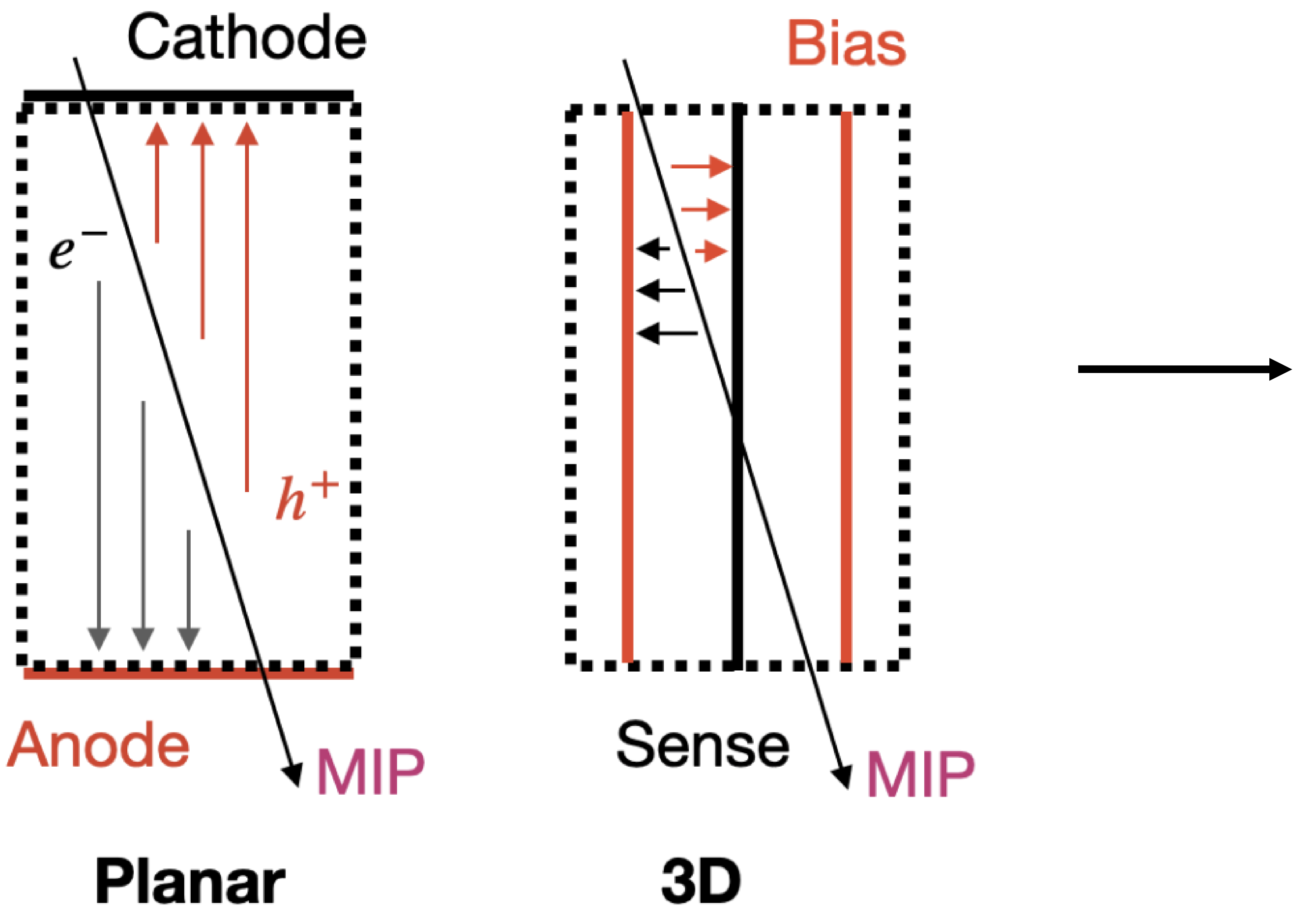
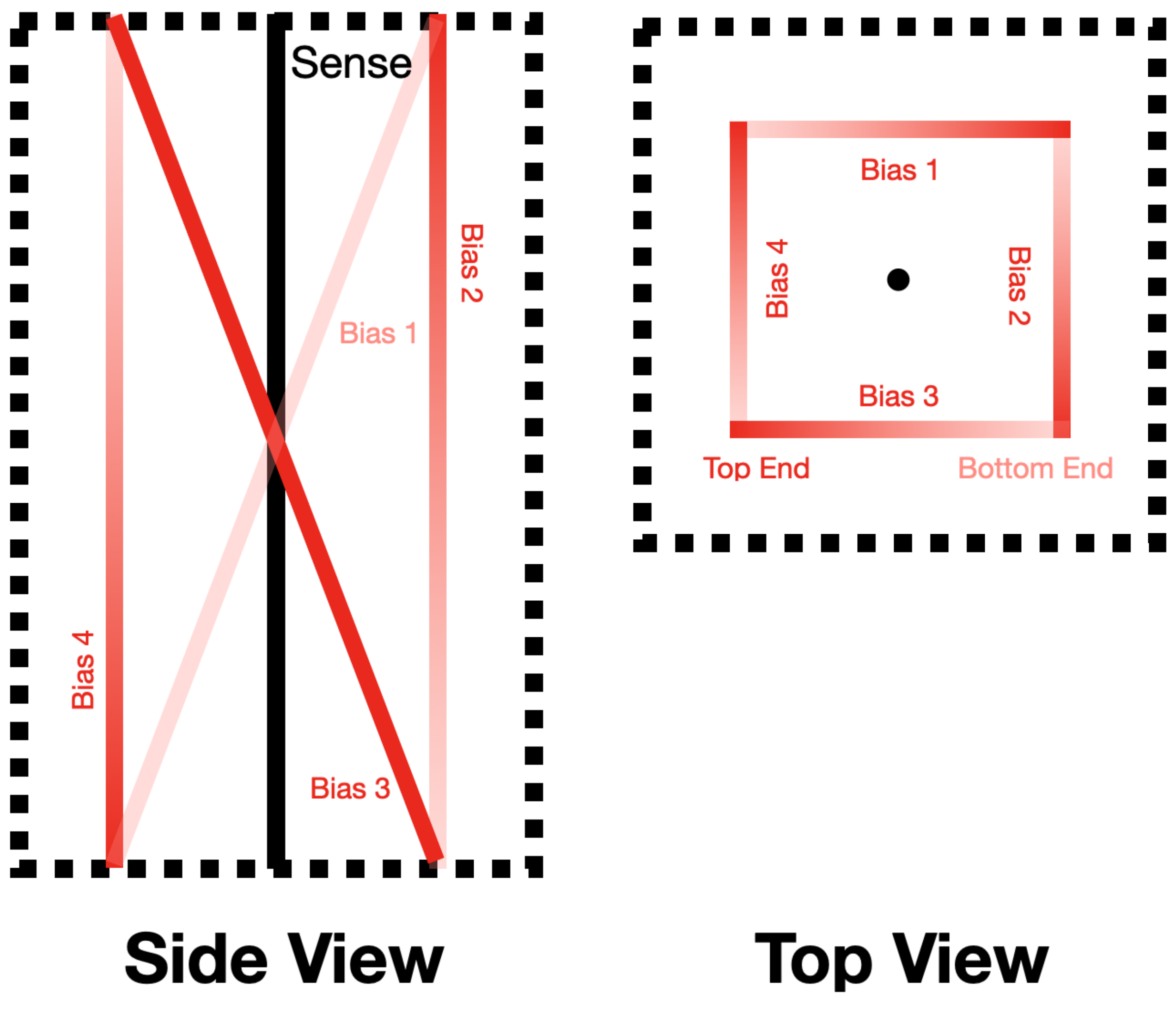
Diamond detector

- High radiation hardness ➡ Future HEP experiments
- High thermal conductivity ➡ No cooling needed
- High carrier mobility ➡ Faster signal
- Cost? ➡ Material cost ↑ Processing cost ↓



- **Novel 3D Structures:**



Twisted Structure

Detector R&D procedures

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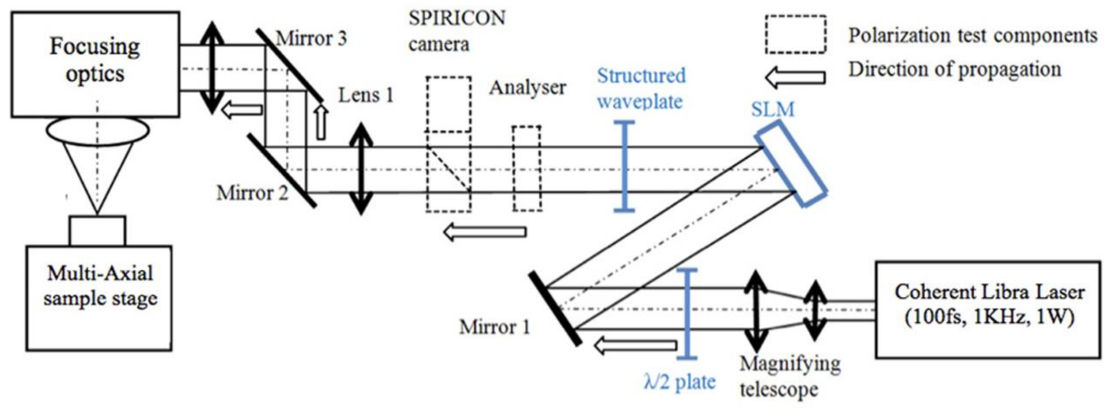
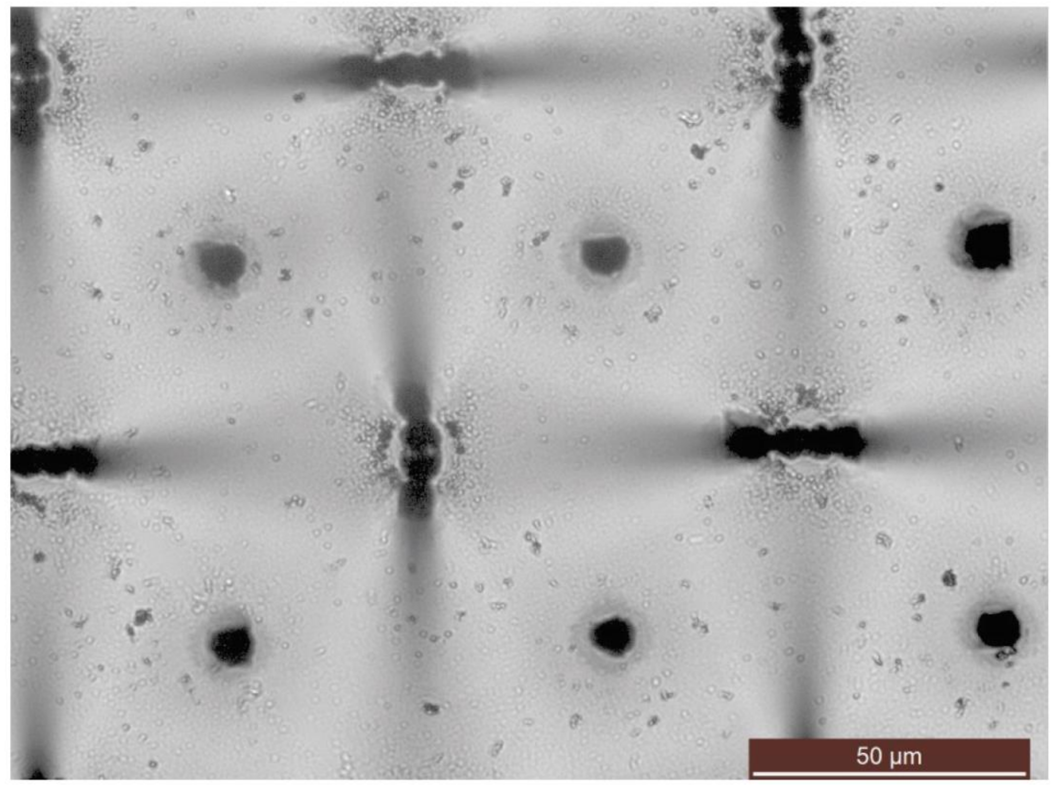
Fabrication

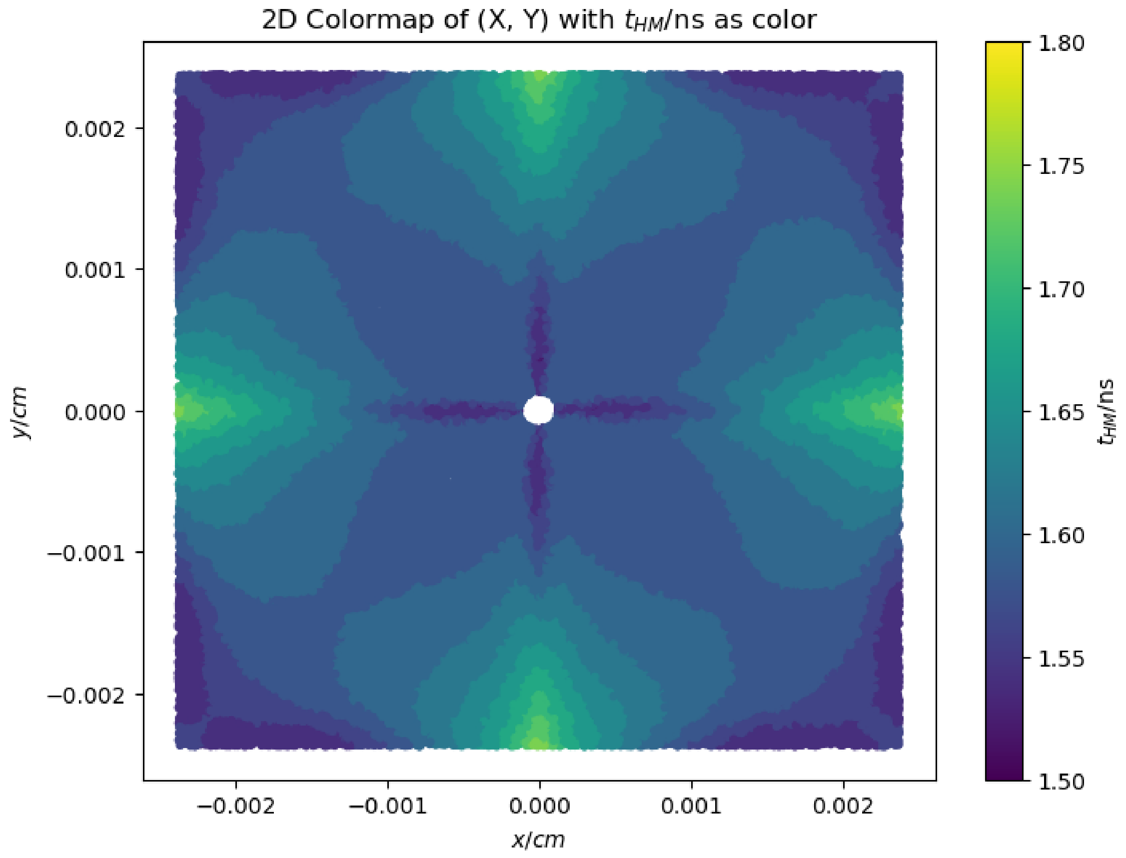




Laser writing, Metallisation

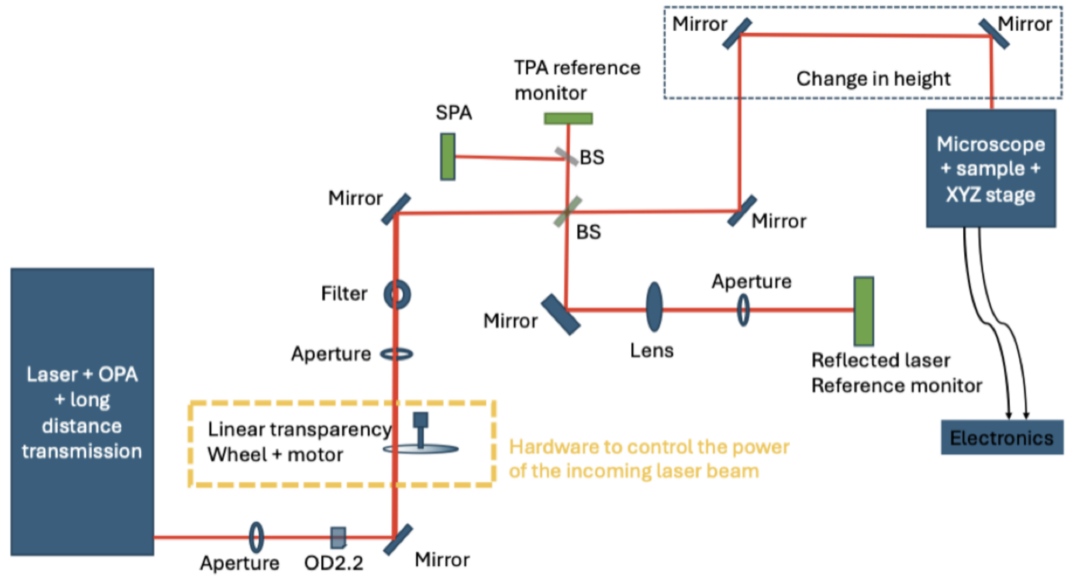
Simulation

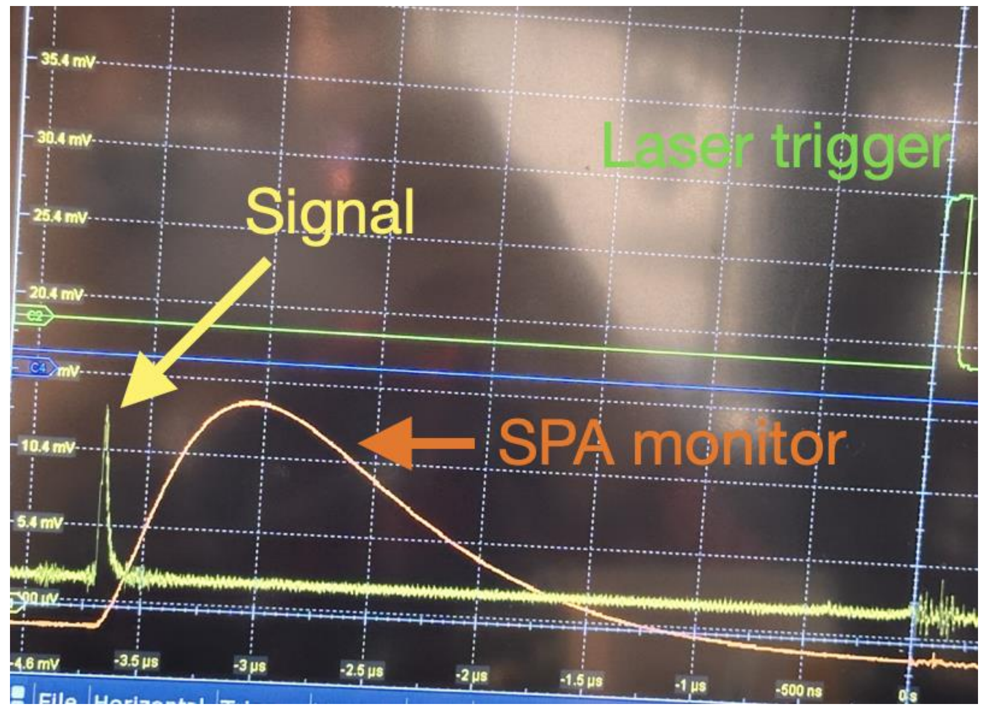
SYNOPSYS
Sentaurus TCAD



FEM & MC simulation

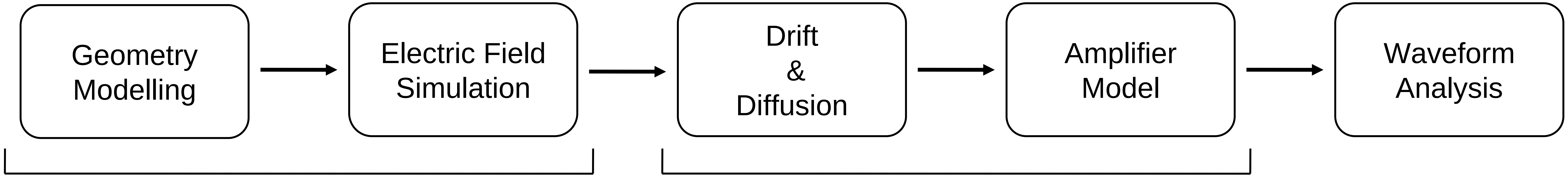
Characterisation





TPA Characterisation

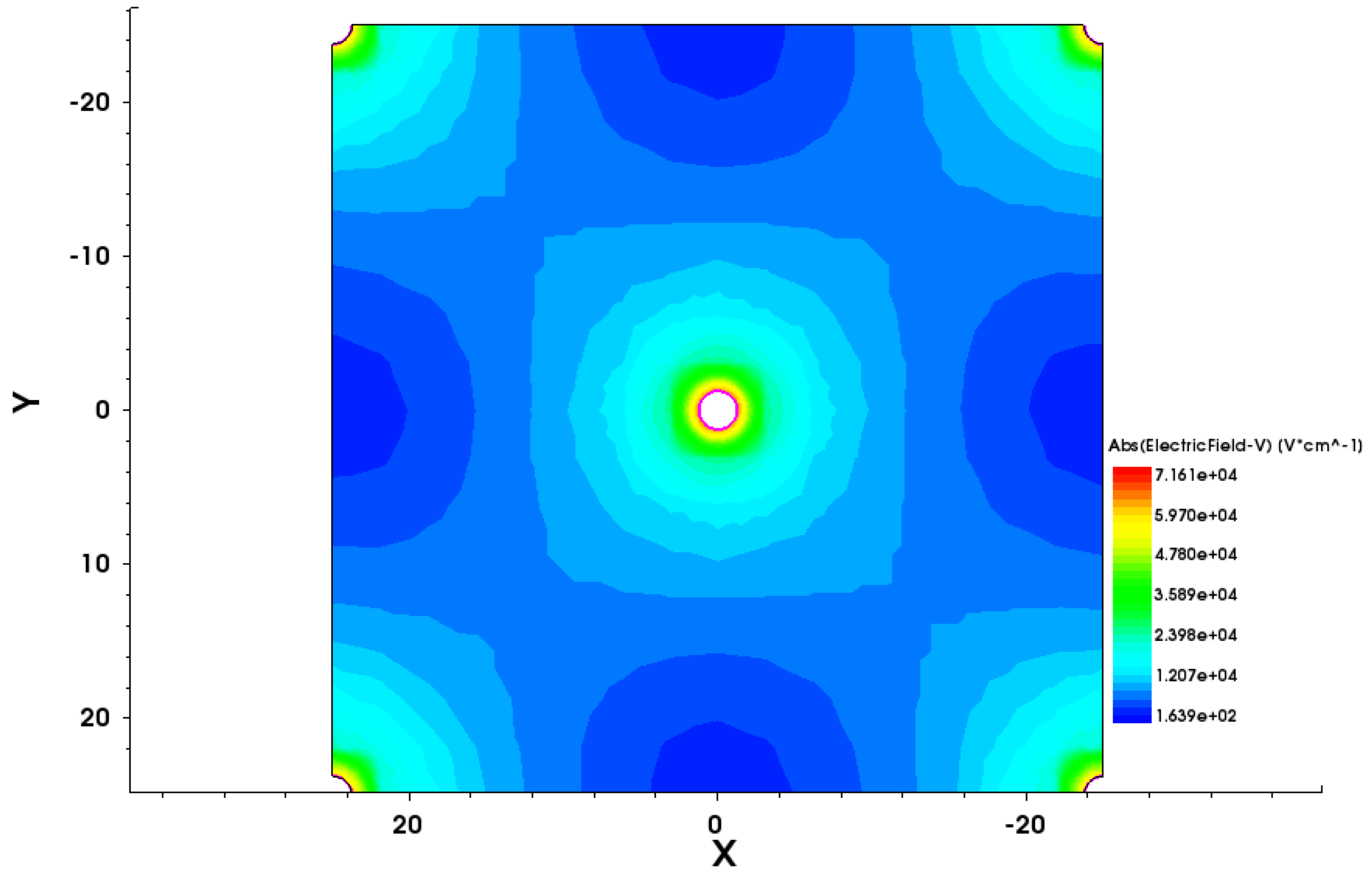
Detector simulation workflow



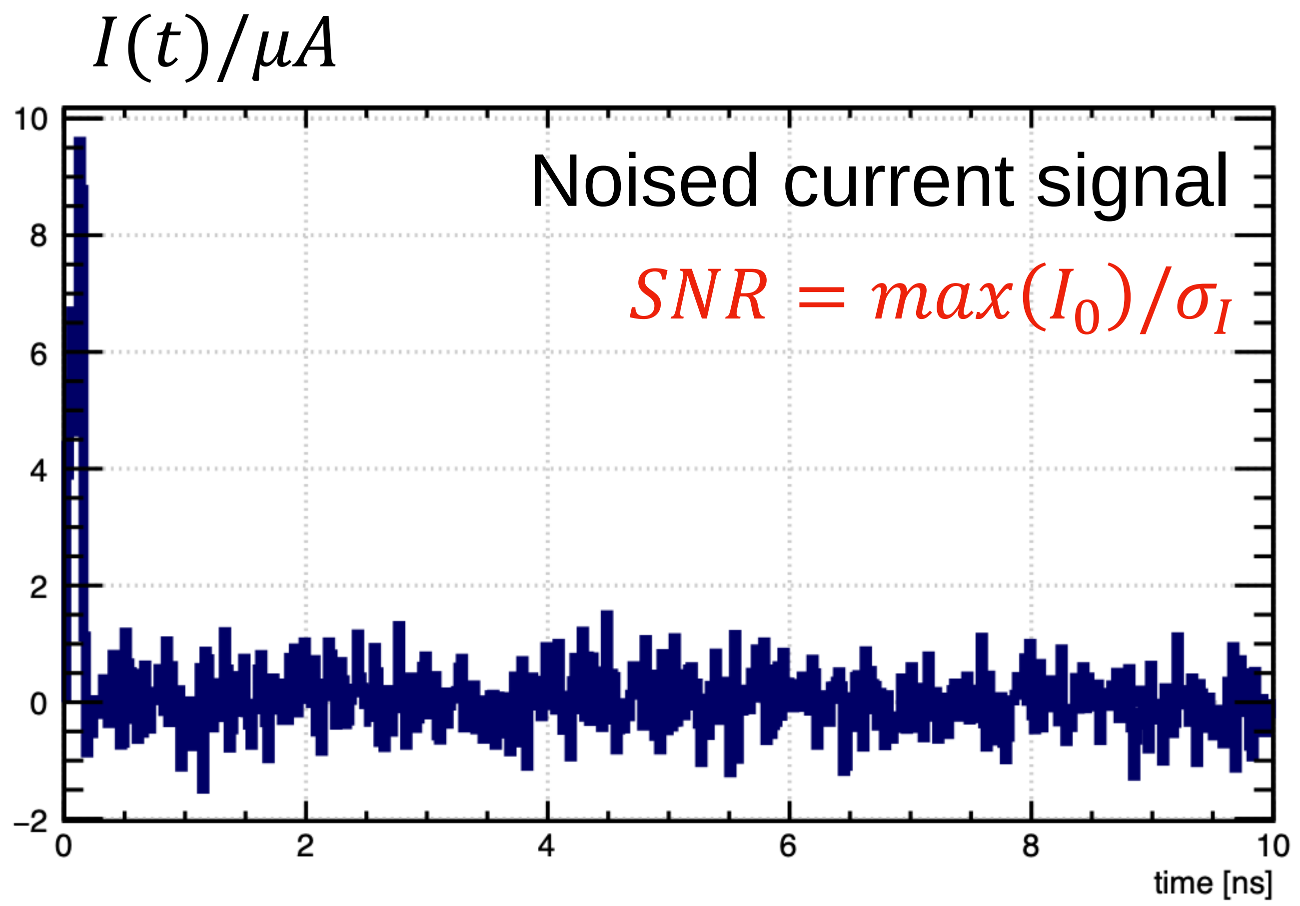
Geometry Modelling → Electric Field Simulation → Drift & Diffusion → Amplifier Model → Waveform Analysis

Sentaurus TCAD

Garfield++

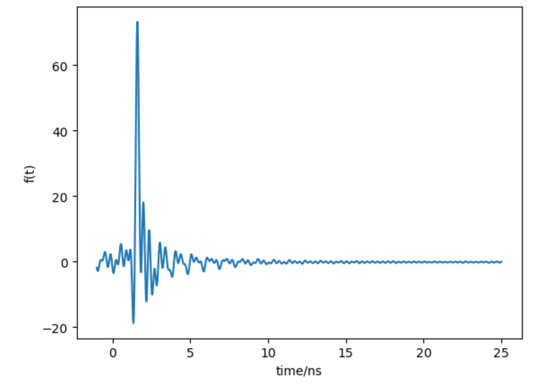


Electric field in a classic 3D Diamond sensor pixel (Simulated by TCAD)

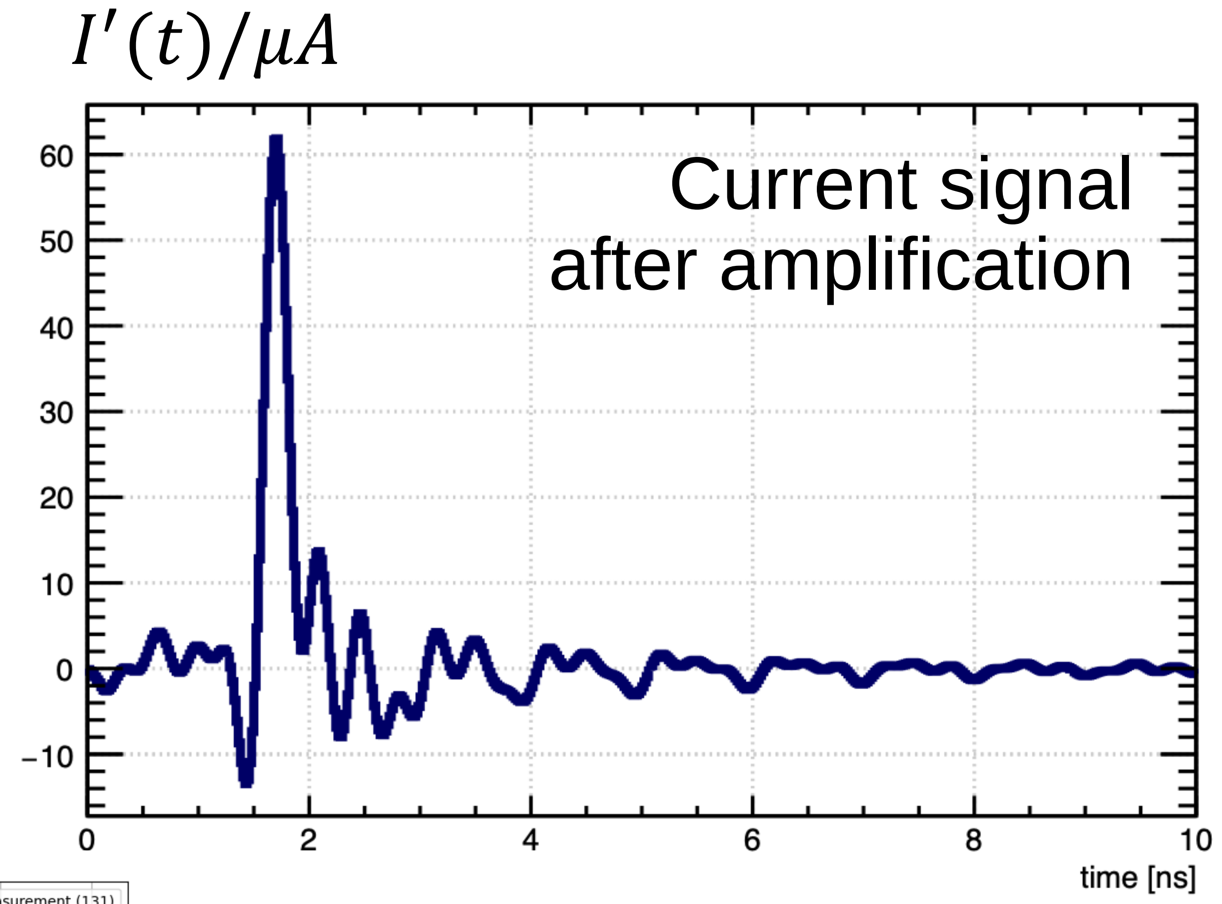


Noised current signal

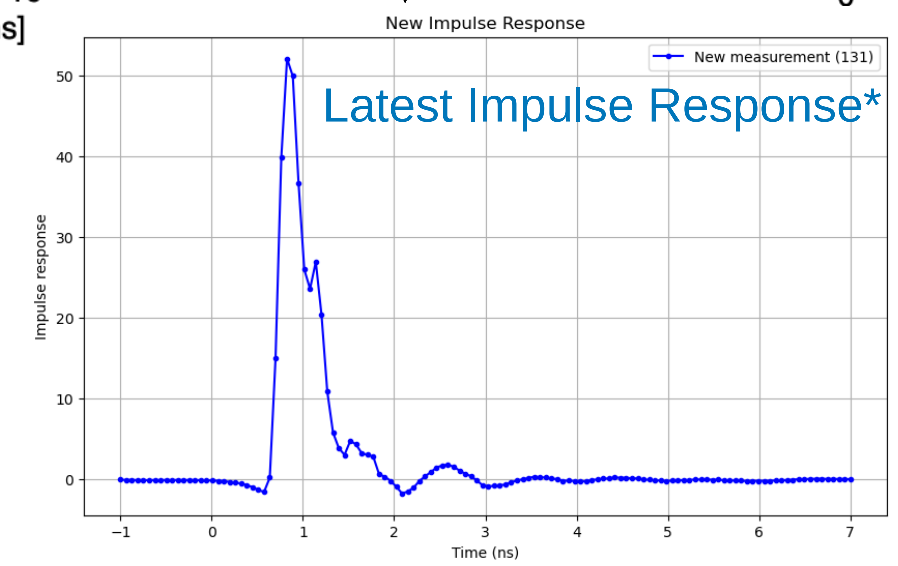
$SNR = max(I_0)/\sigma_I$



Amp impulse response*



Current signal after amplification



Latest Impulse Response*

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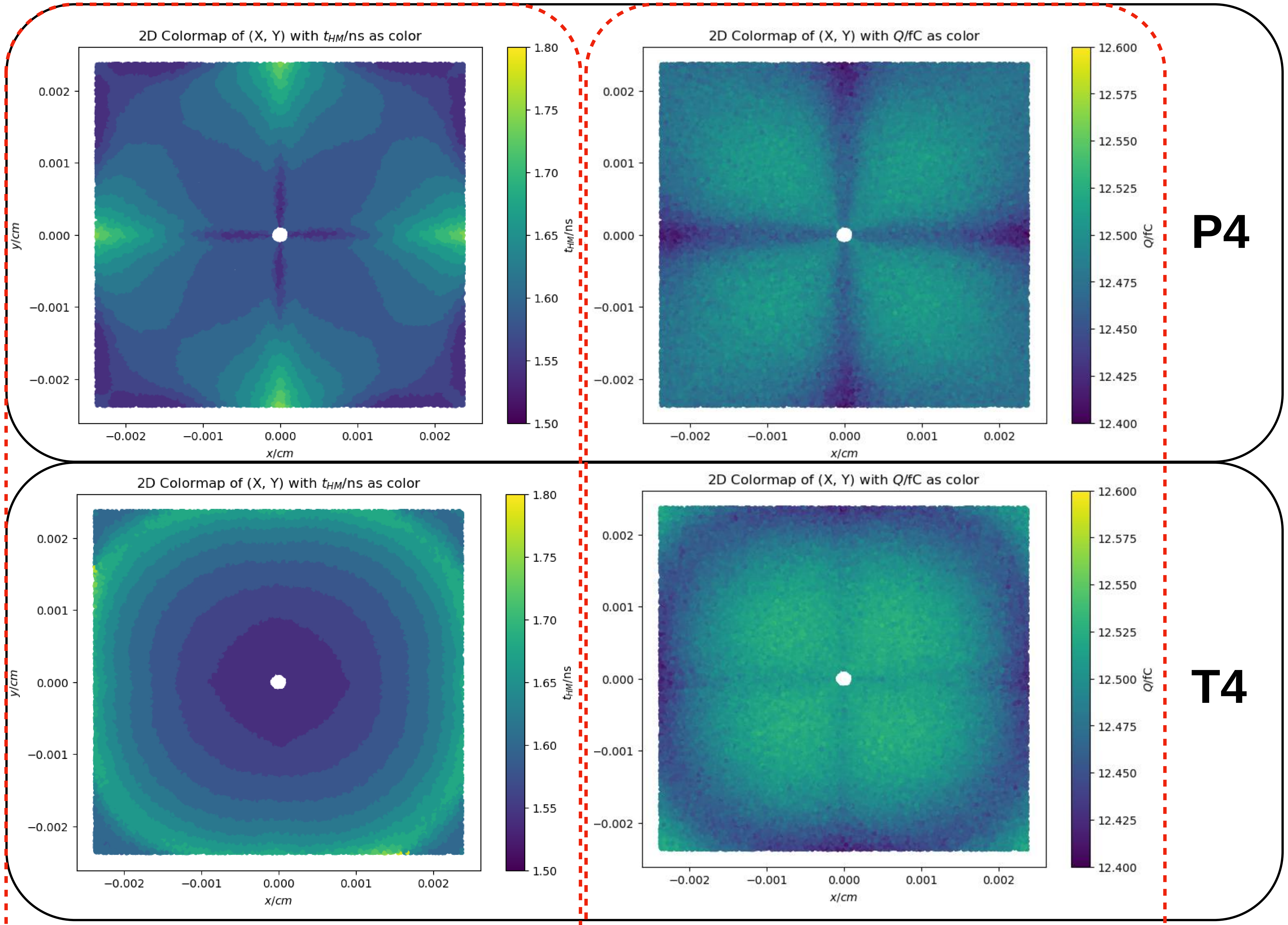
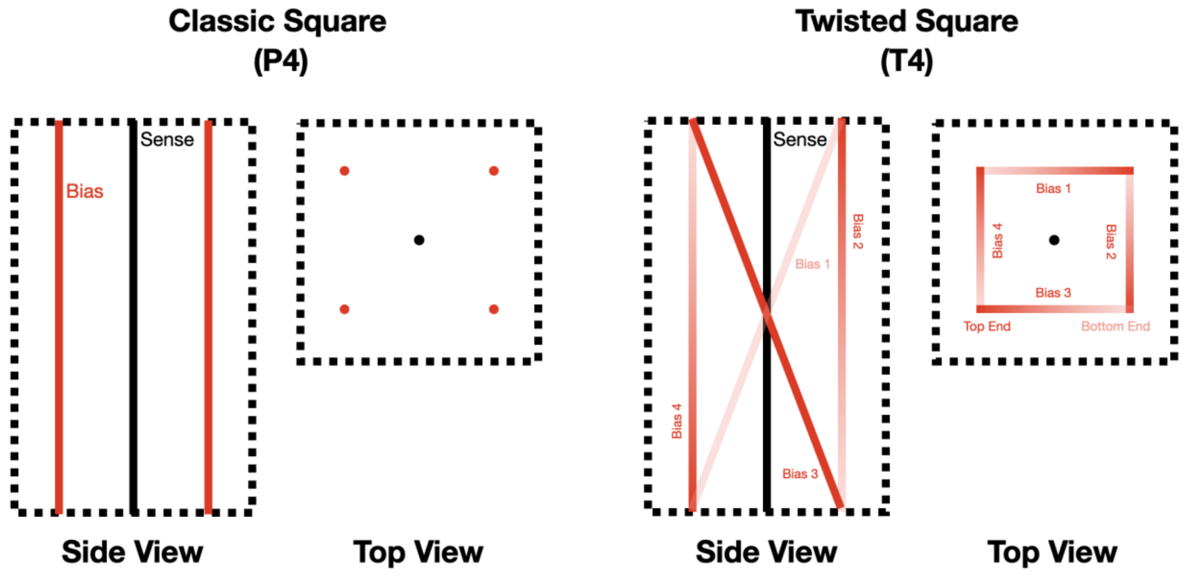
*Work in progress, see Enoch’s 1st DRD3 week talk : https://indi.to/8jWMZ

E.g. 3D Diamond sensor simulation



t_{HM} $(1.5 \sim 1.8\ ns)$ Q $(12.4 \sim 12.6\ fC)$

- Incident particle type: **MIP**
- Structure simulated:



- Quantities compared:

  t_{HM}: Half-max time

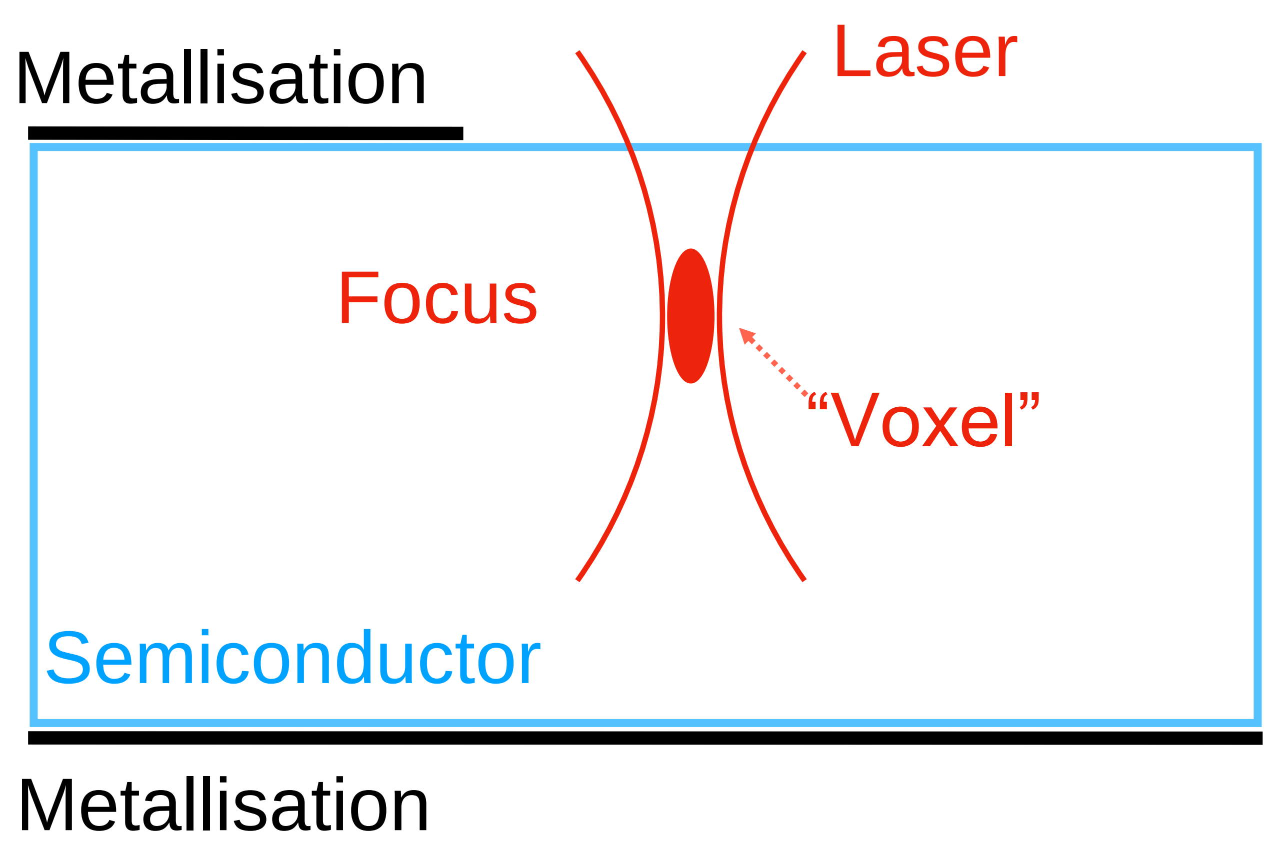
  Q: Collected charge

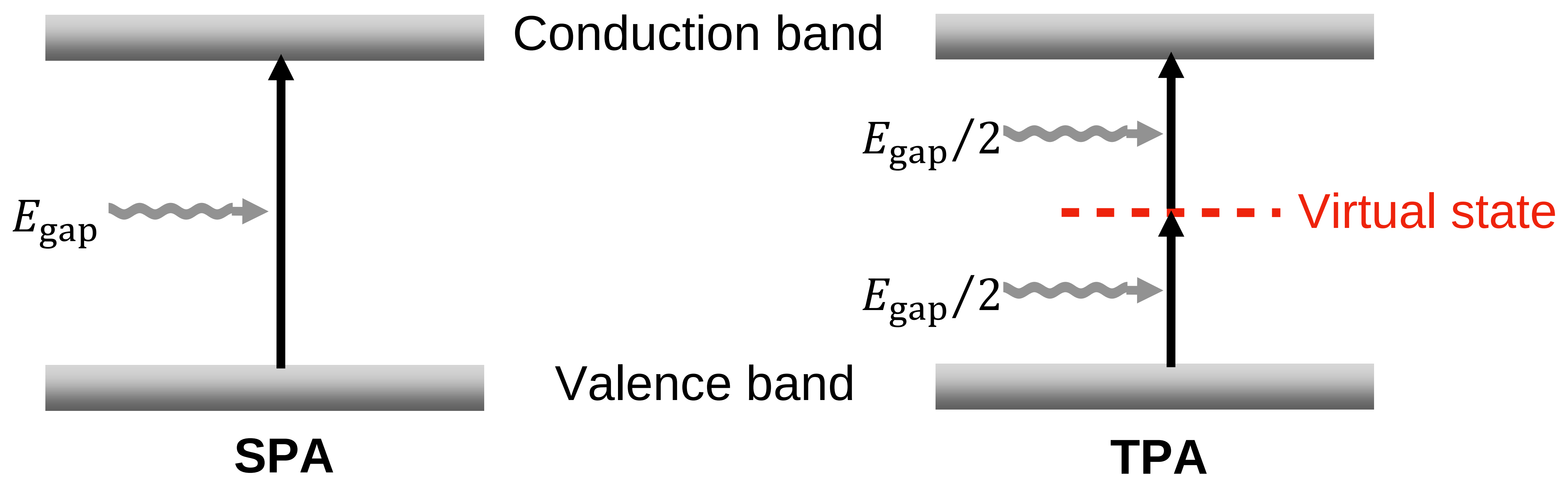
  (Integration from 0 to 10ns)

- **Conclusion**

  Uniformity: **T4 > P4**

TPA effect in semiconductors





- **T**wo **P**hoton **A**bsorption (TPA):

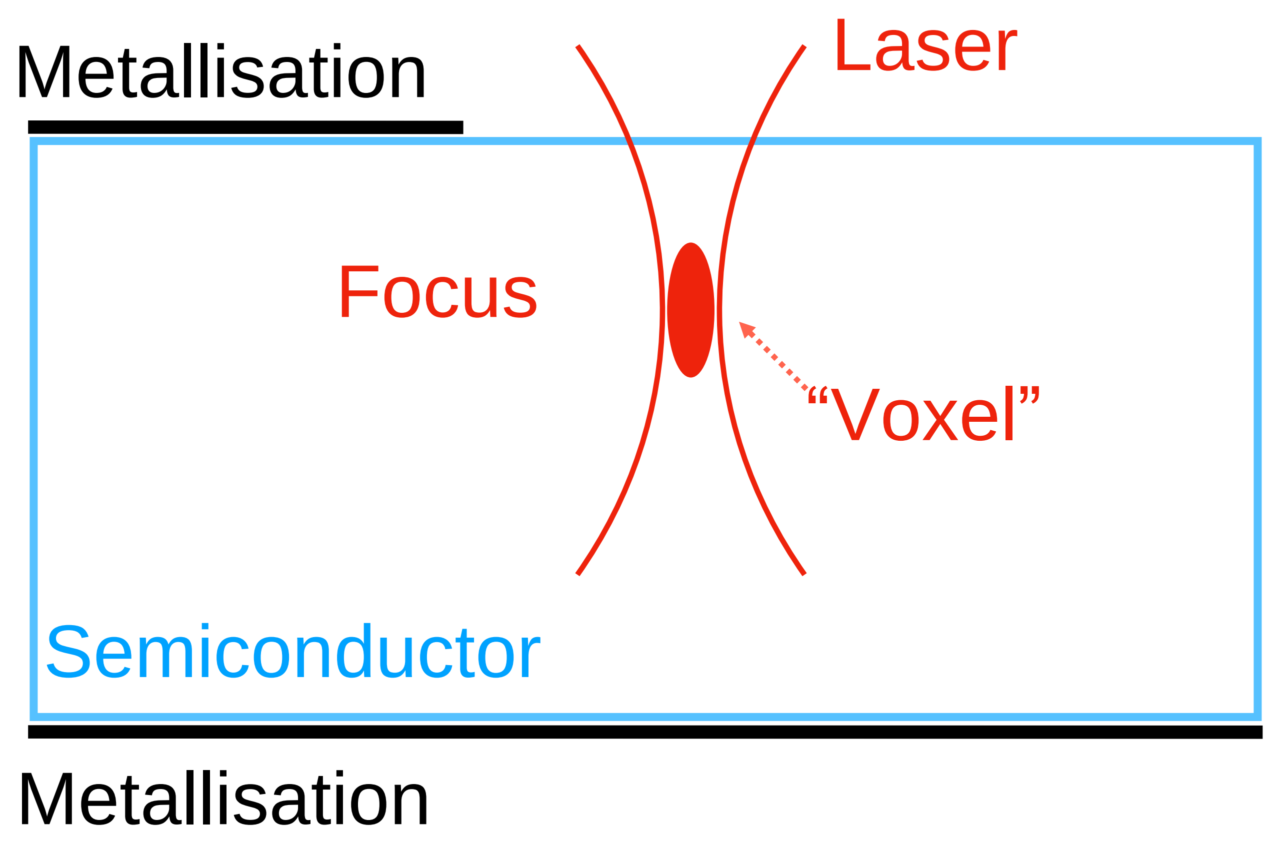
  Electrons simultaneously absorb **2** photons when transitioning.

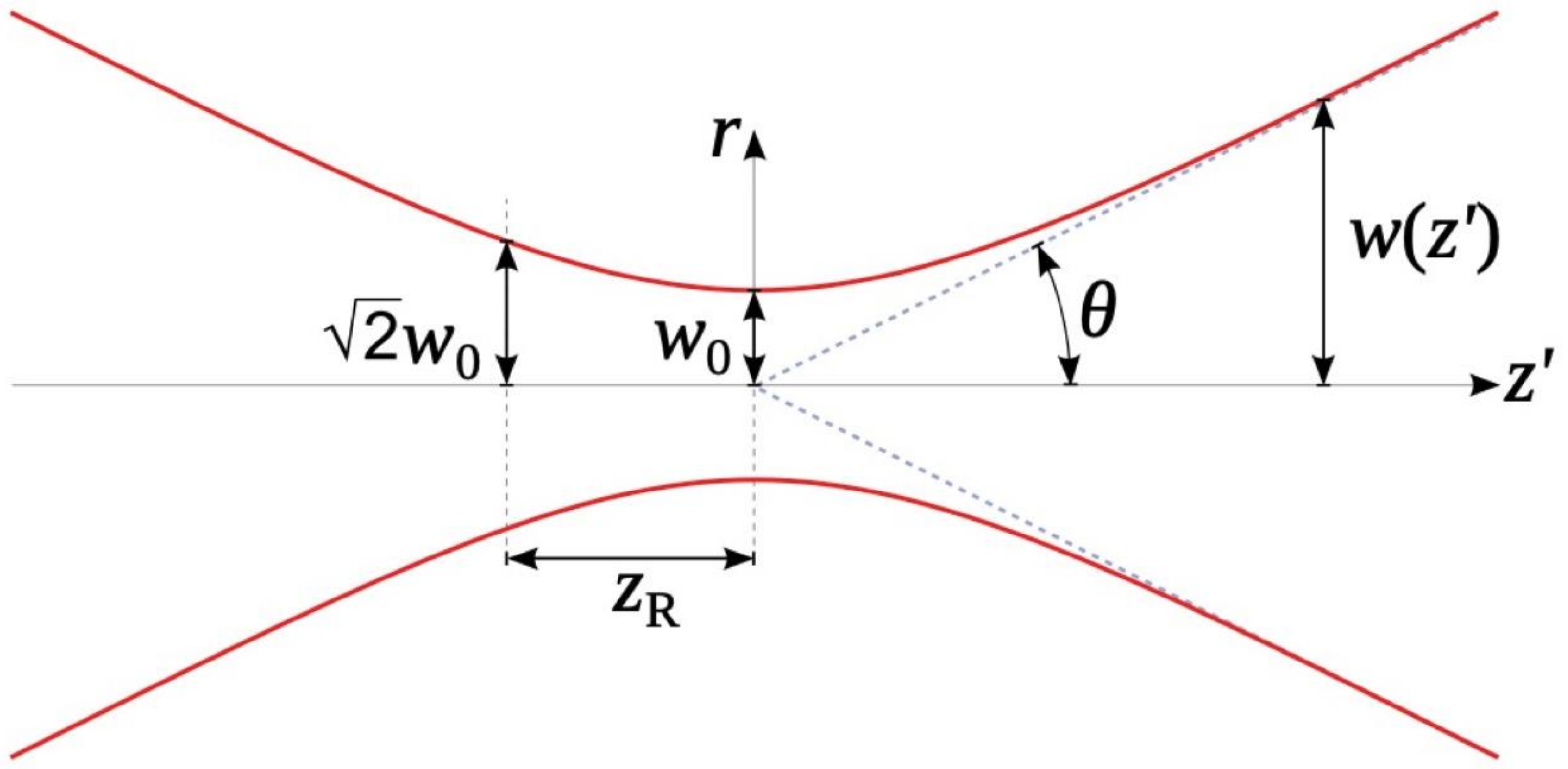
- Charge generation only happens in a small region near focal point (**"voxel"**)

$$\frac{dn(r,z,t)}{dt} = \overline{\frac{\alpha I(r,z,t)}{\hbar\omega}} + \overline{\frac{\beta_2 I^2(r,z,t)}{2\hbar\omega}}$$

→ High spatial/temporal resolution

TPA effect in semiconductors





TPA induced charge density: $n_{\mathrm{TPA}}(z,r) = \frac{\beta_2}{2\hbar\omega}\int_{-\infty}^{+\infty} I^2(r,z,t)\mathrm{d}t = \frac{\boxed{E_p^2}\beta_2\, 4\ln 2}{\tau\,\hbar\omega\,\pi^{\frac{5}{2}} w^4(z)\,\sqrt{\ln 4}} \exp\left[-\frac{4r^2}{w^2(z)}\right]$

➡ Total collected charge: $Q \propto E_p^2$ ⟶ TPA Characteristic

➡ $Q_{\mathrm{TPA}}(NA, Z_{\max}, n, E_p)$

If reflection considered, need to add D and R. (see Appendix.)

Manchester TPA setup (PSI, UoM)

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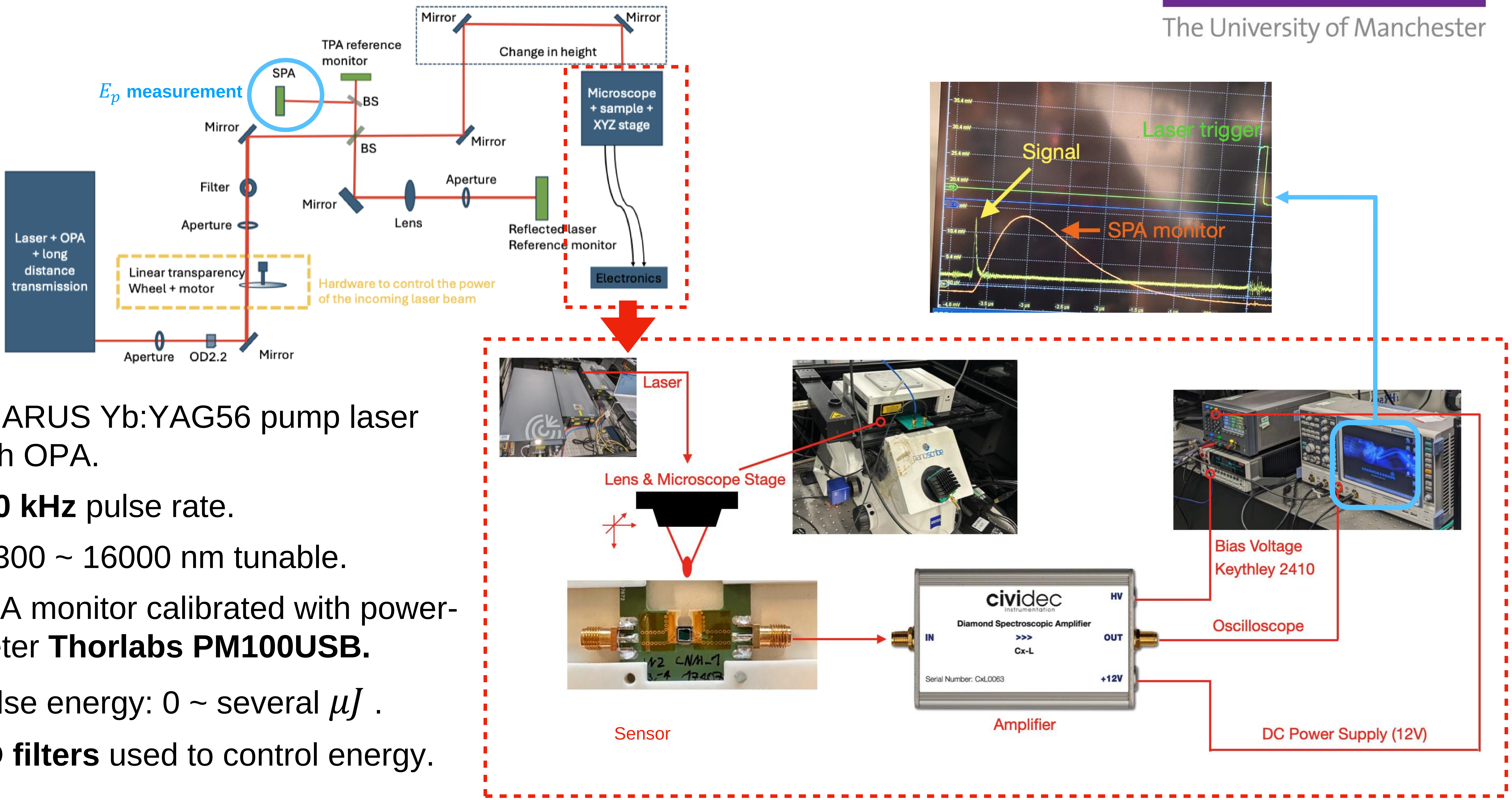
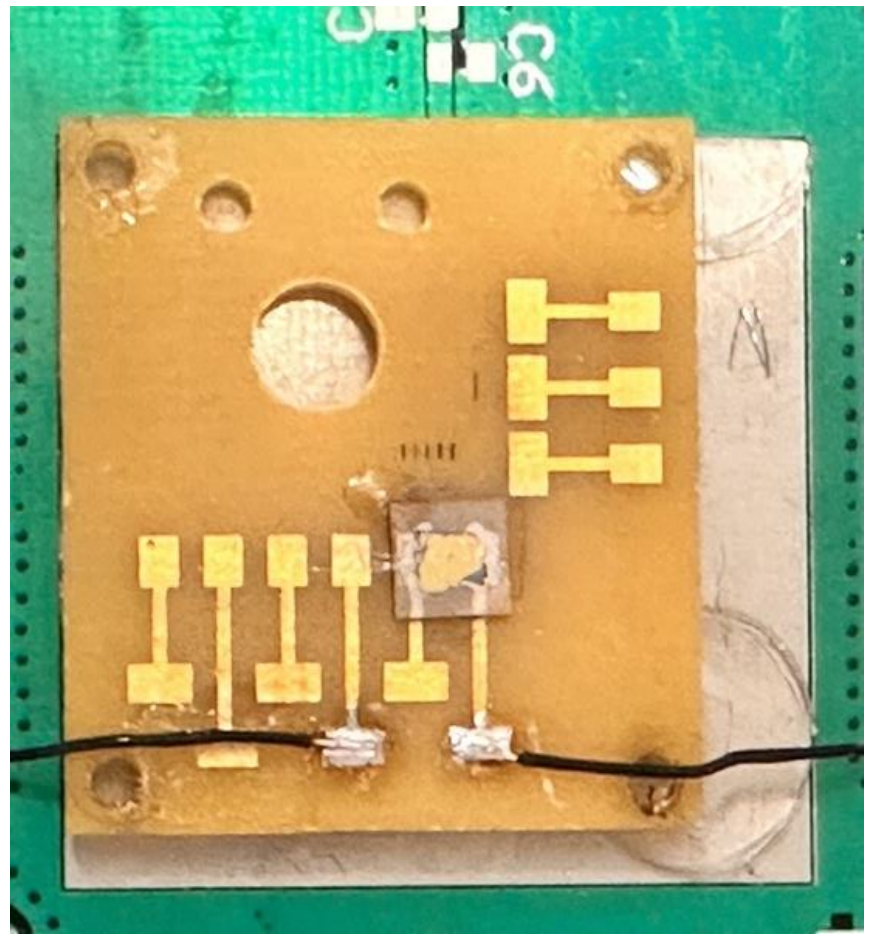
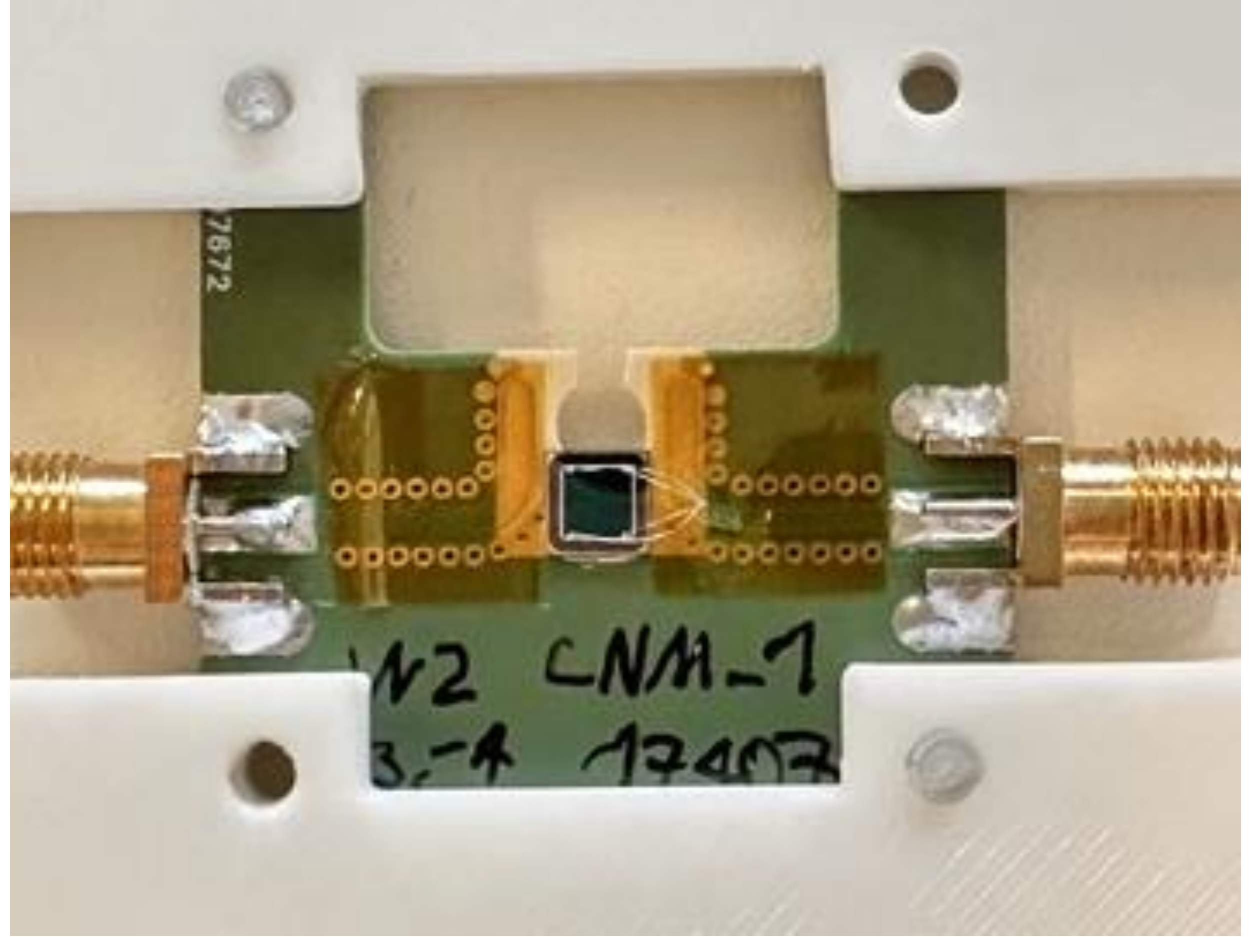


- PHARUS Yb:YAG56 pump laser with OPA.
- **100 kHz** pulse rate.
- λ: 300 ~ 16000 nm tunable.
- SPA monitor calibrated with power-meter **Thorlabs PM100USB.**
- Pulse energy: 0 ~ several μJ .
- **ND filters** used to control energy.

Sensors





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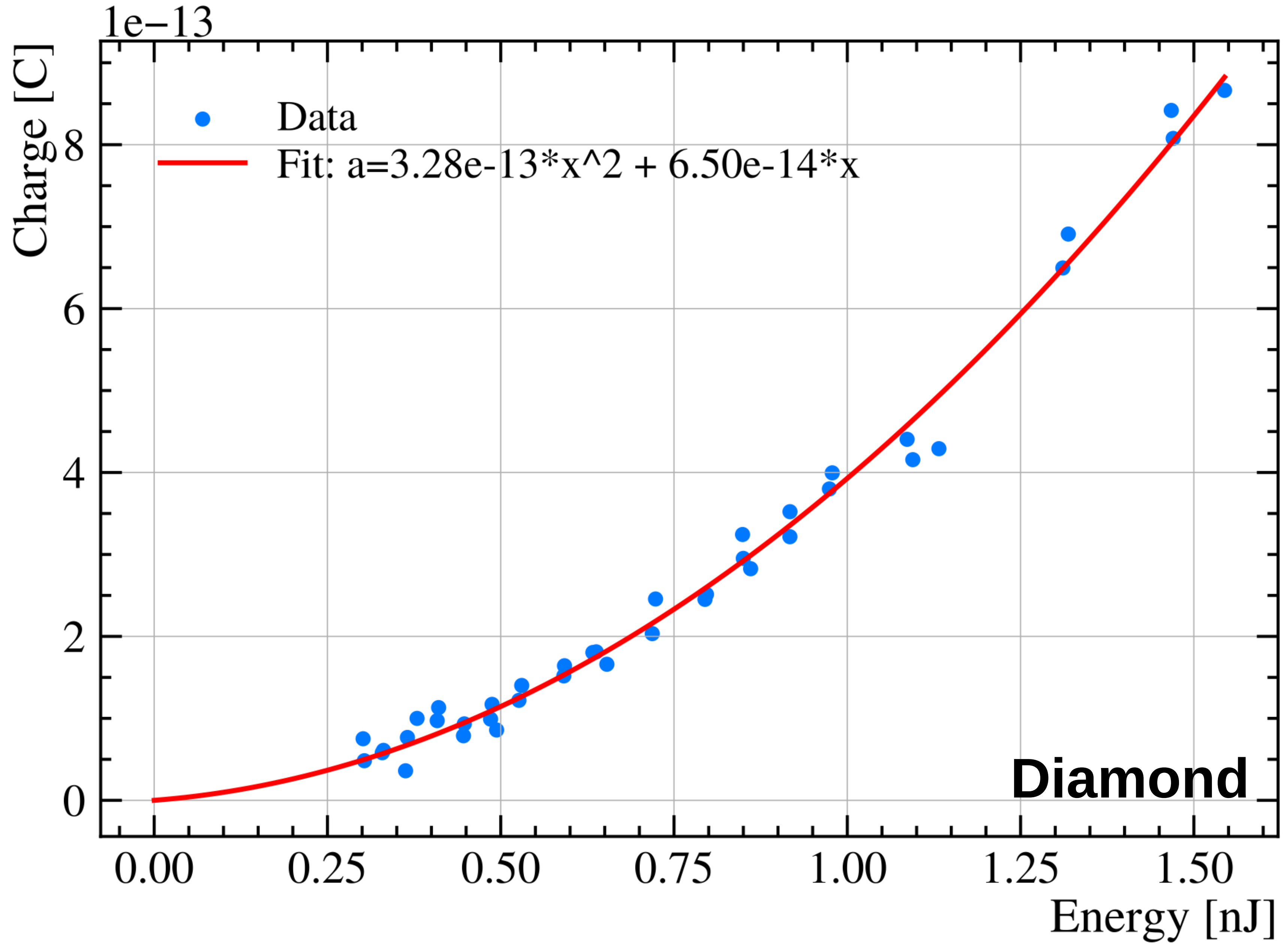
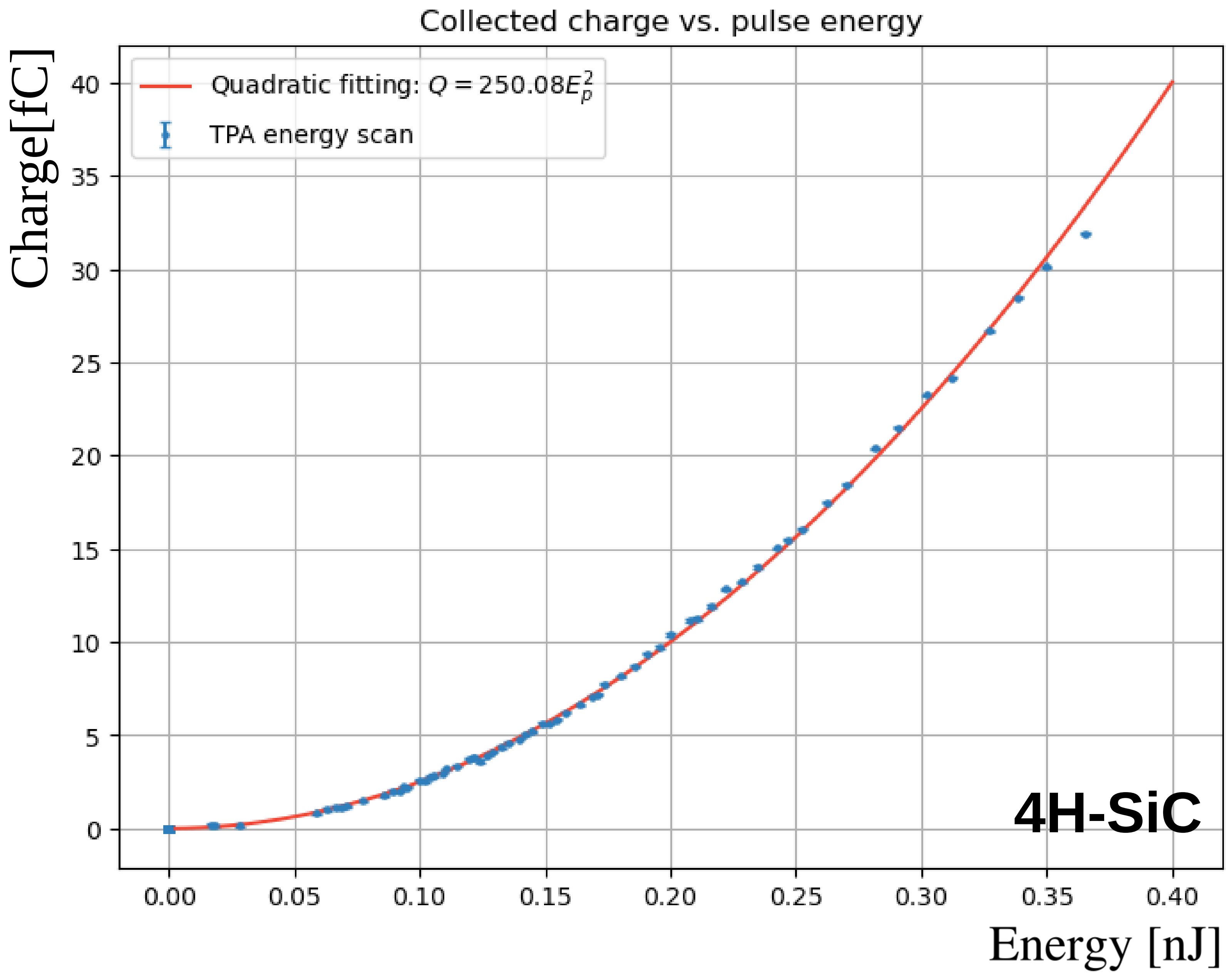
- Planar Diamond sensor
- sCVD diamond 4mm*4mm*0.5mm
- Irregular surface metallisation shape
- **TPA wavelength: 405 nm**

- 4H-SiC sensor from HEPHY
- 3mm*3mm*50μm epitaxy
- 4 Contact pads in the corners on top surface
- **TPA wavelength: 720 nm**

TPA energy scan

- Amplifier: **CIVIDEC Cx-L.** Pulse energy obtained by SPA monitor (calibrated by power meter)





- **Quadratic** $Q - E_p$ **relationship** shown in both diamond and 4H-SiC samples; ⟶ TPA valid
- Quadratic fitting results:

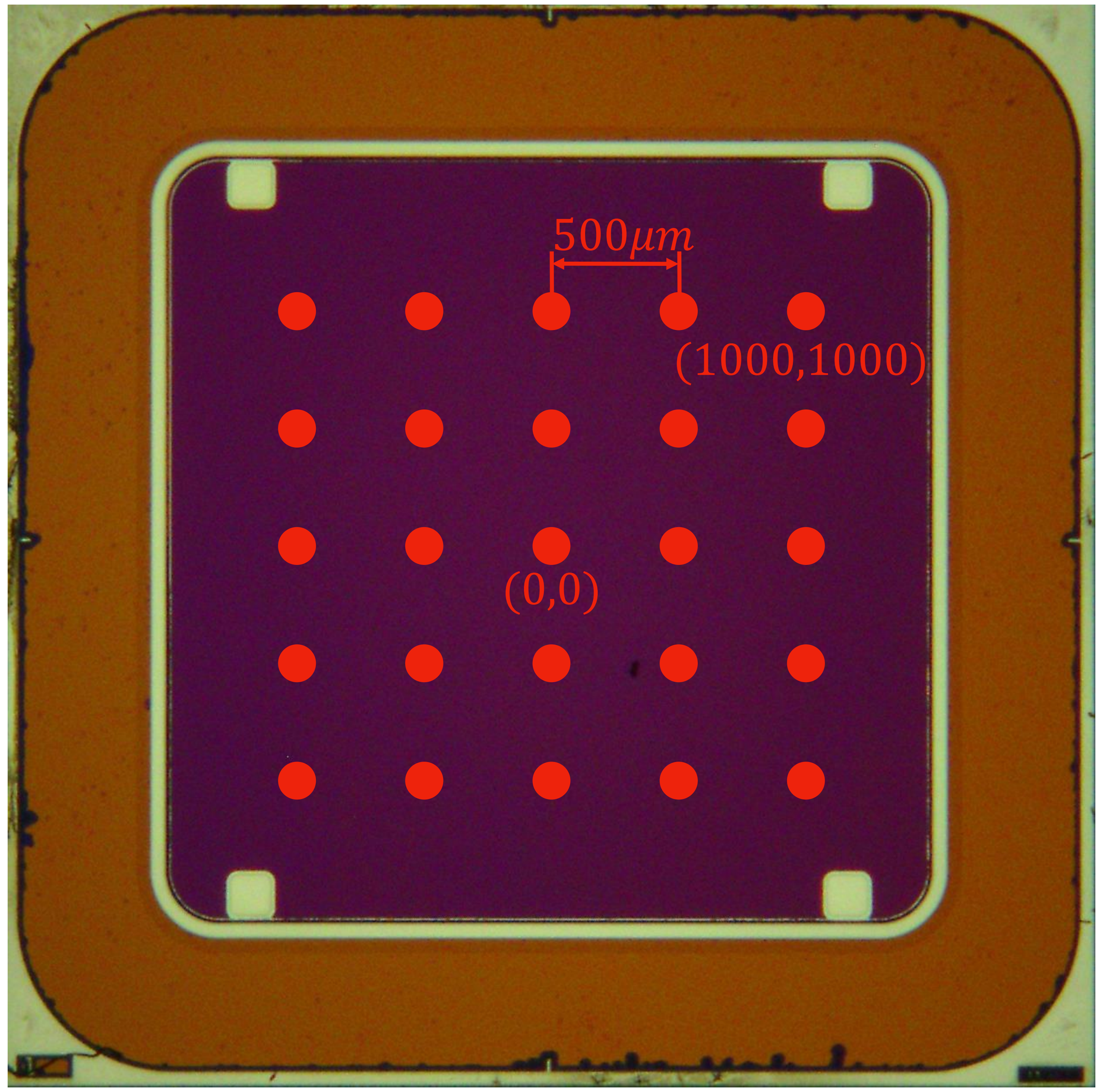
Diamond: $Q(\text{fC}) = 328E_p^2 + 65E_p$

4H-SiC: $Q(\text{fC}) = 250E_p^2$

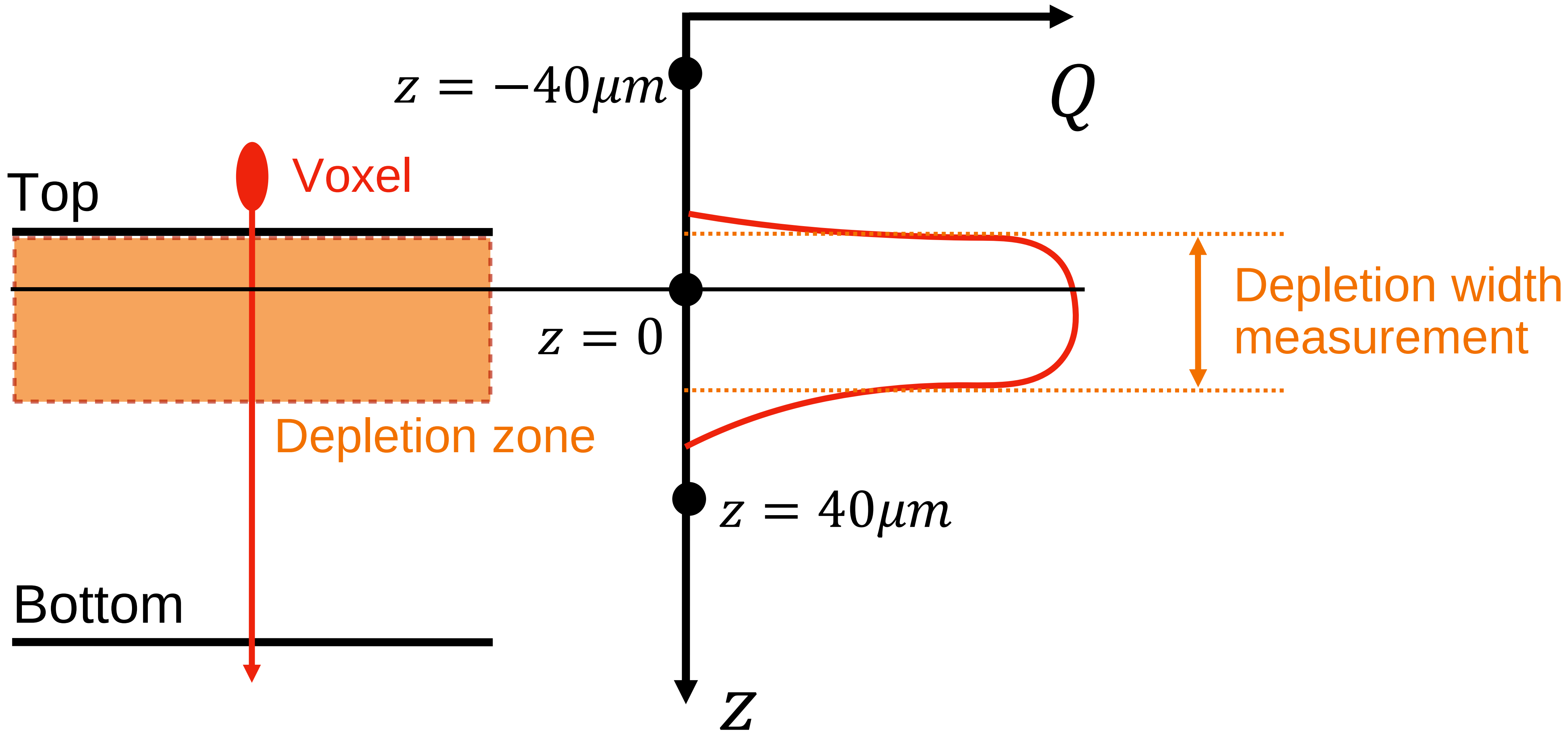
Si factor: 35400

TPA voltage-depth-XY scan (4H-SiC)

- **On XY plane:**

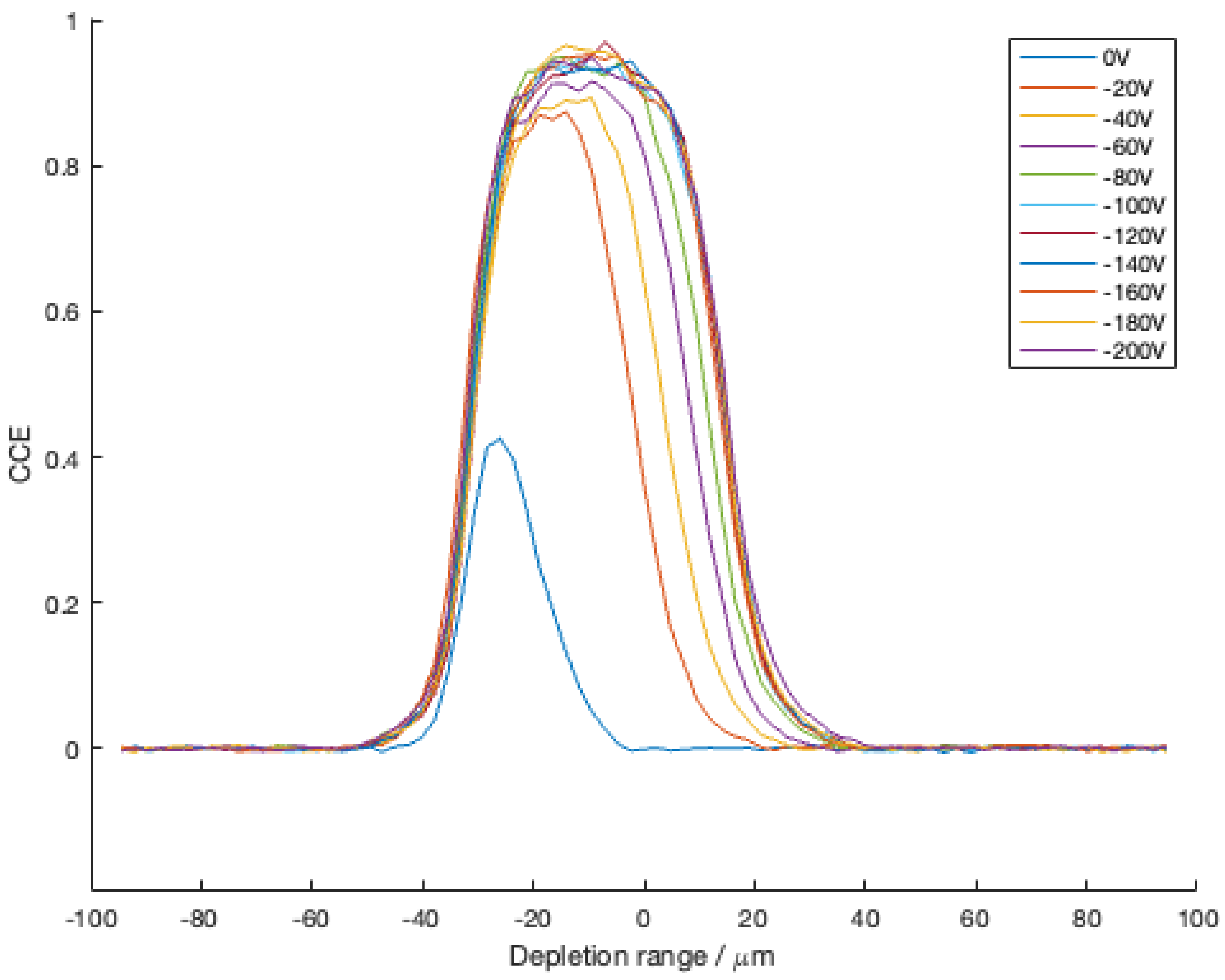


- At each point on XY plane, bias voltage changes from **0V ~ 200V** (reversed bias);
- For each bias voltage, laser focus moves from **Z = -40 μm ~ 40 μm**.
- At each Z, measure the collected charge Q.



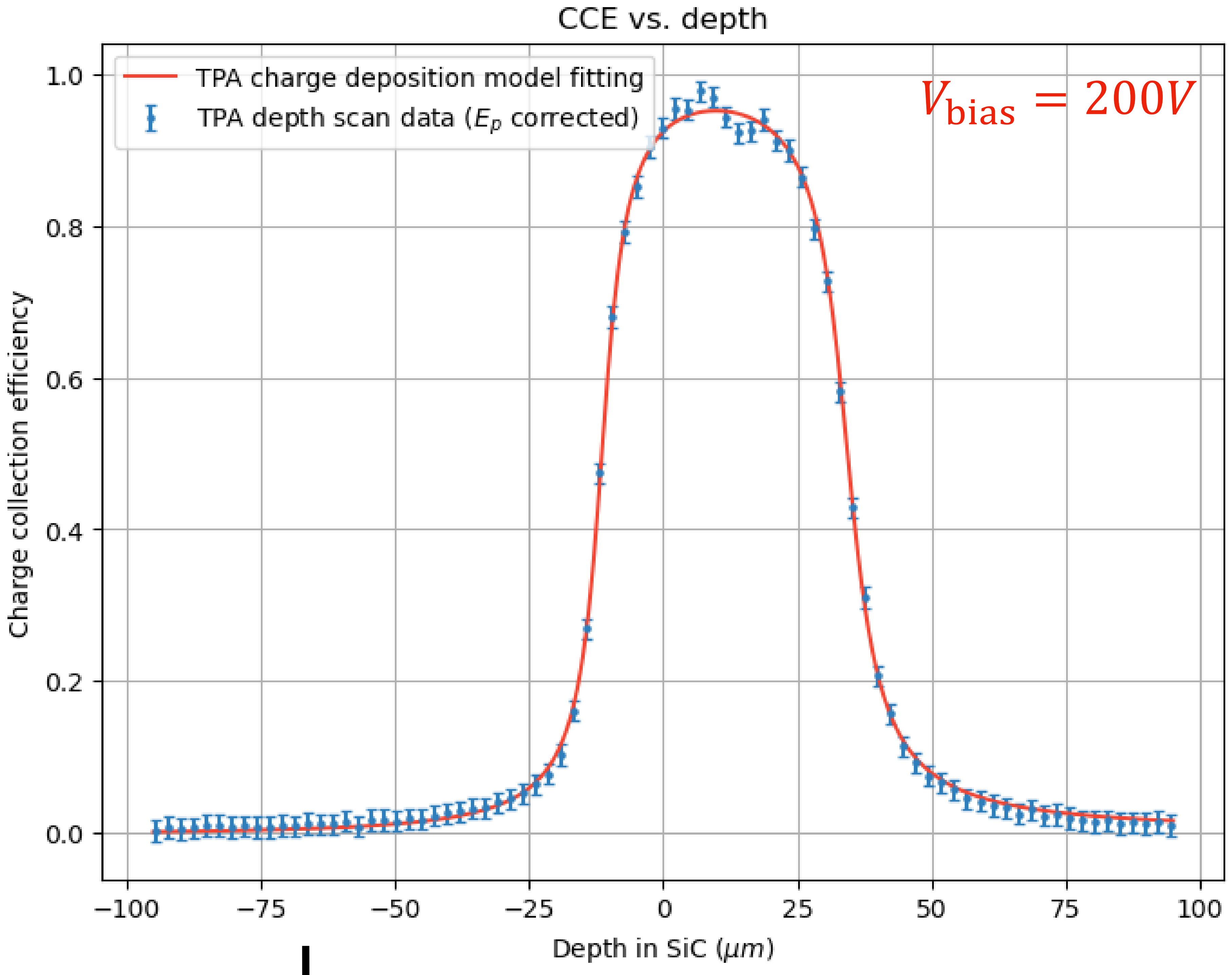
TPA voltage-depth-XY scan (4H-SiC)

- **Center point (X=0, Y=0) Voltage-depth scan:**



Fitting:

$Q_{\text{TPA}}(z, r, NA, Z_f, n, E_p)$



Q corrected using E_p.

Charge collection efficiency:

$$\text{CCE} = Qf/250.08E_p^2$$

Efficiency factor
Assumption: f=1

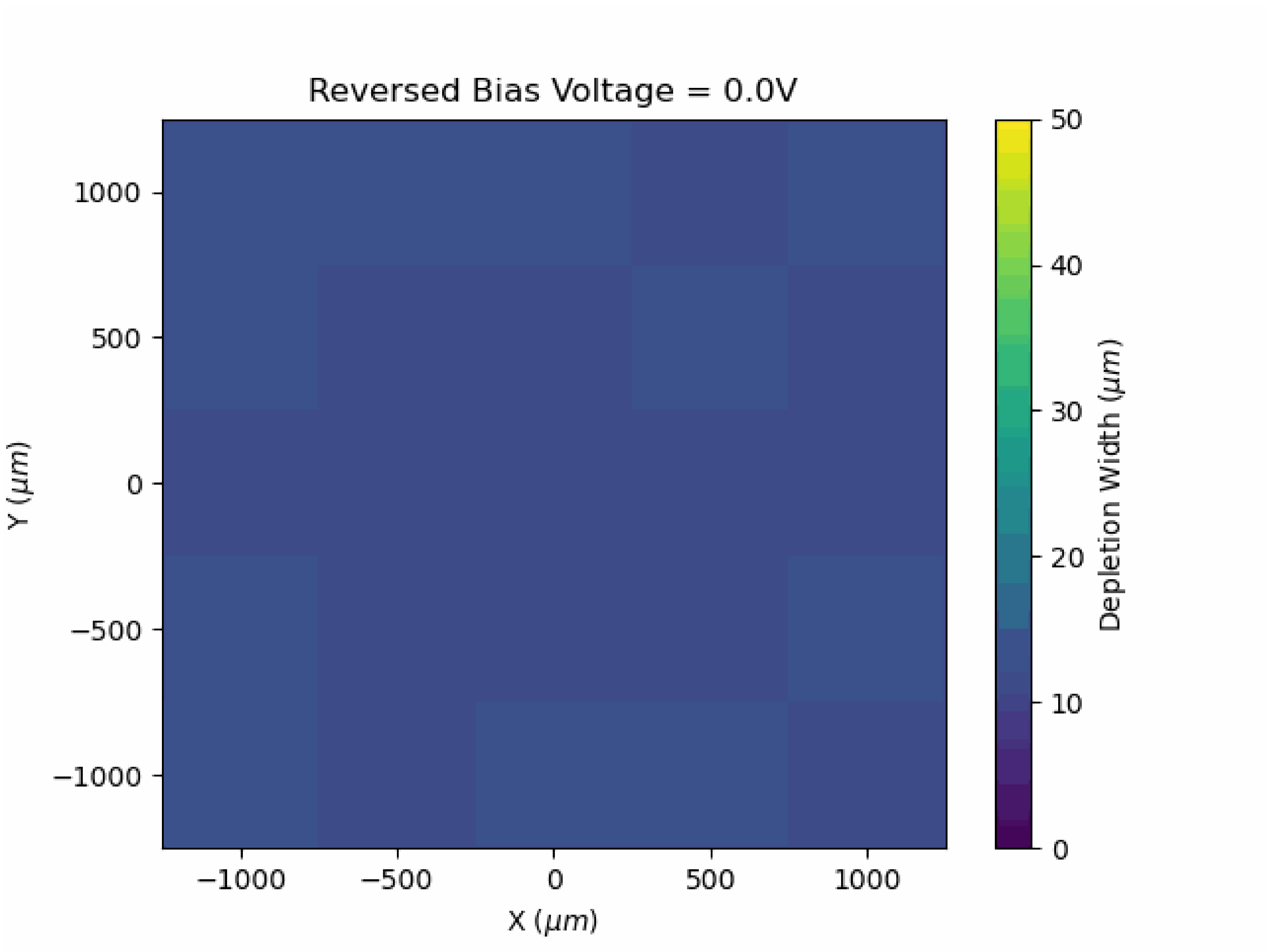
Free parameters: NA_{eff} , $Z_{\max}$ → Depletion width

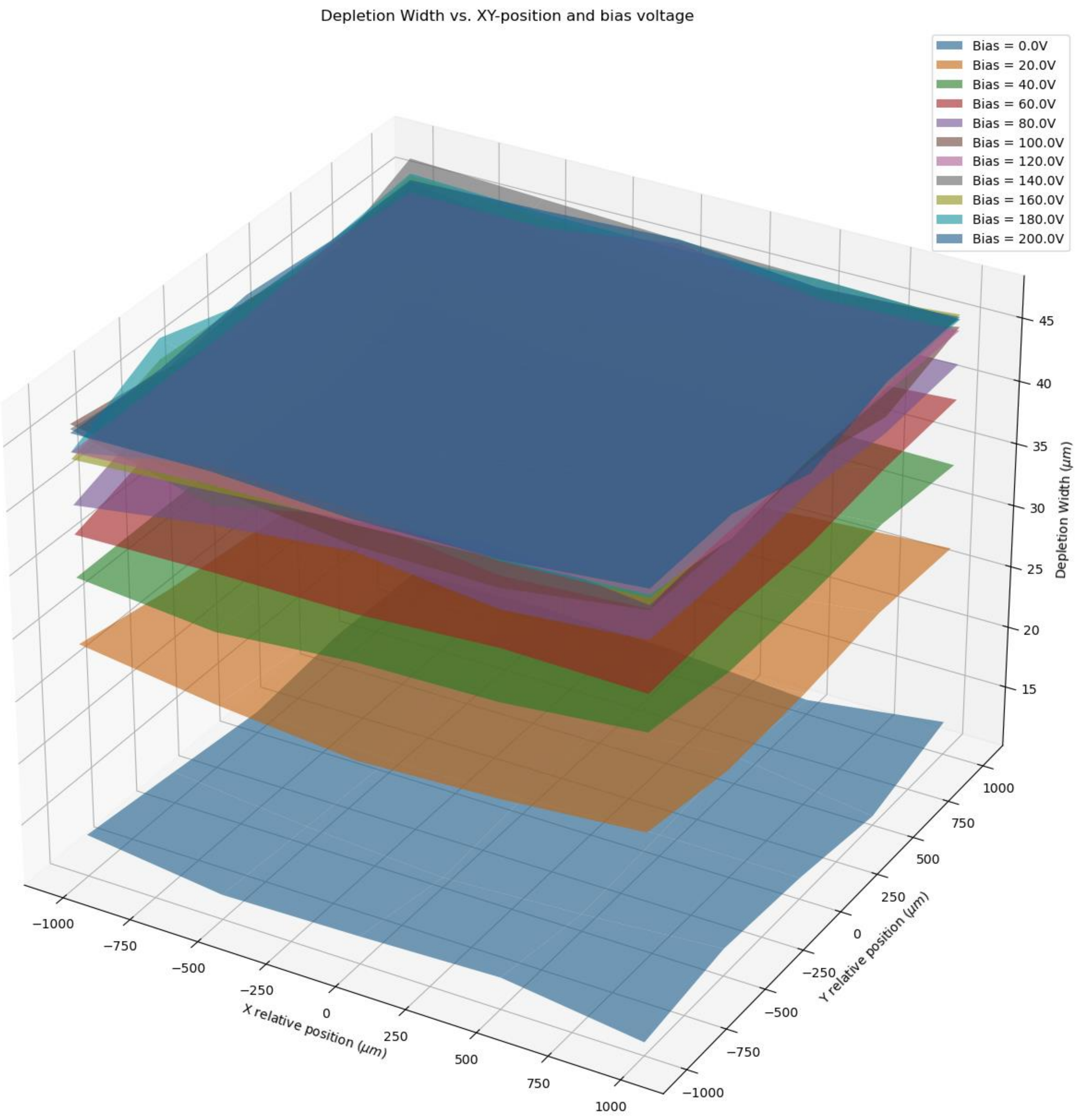
Effective numerical aperture (taking voxel aberration into account)

TPA voltage-depth-XY scan (4H-SiC)

- **For different bias voltages, fitted $Z_{\max}$ vs XY:**

Depletion width is constant with respect to **X** and **Y** under different V_{bias}





TPA voltage-depth-XY scan (4H-SiC)

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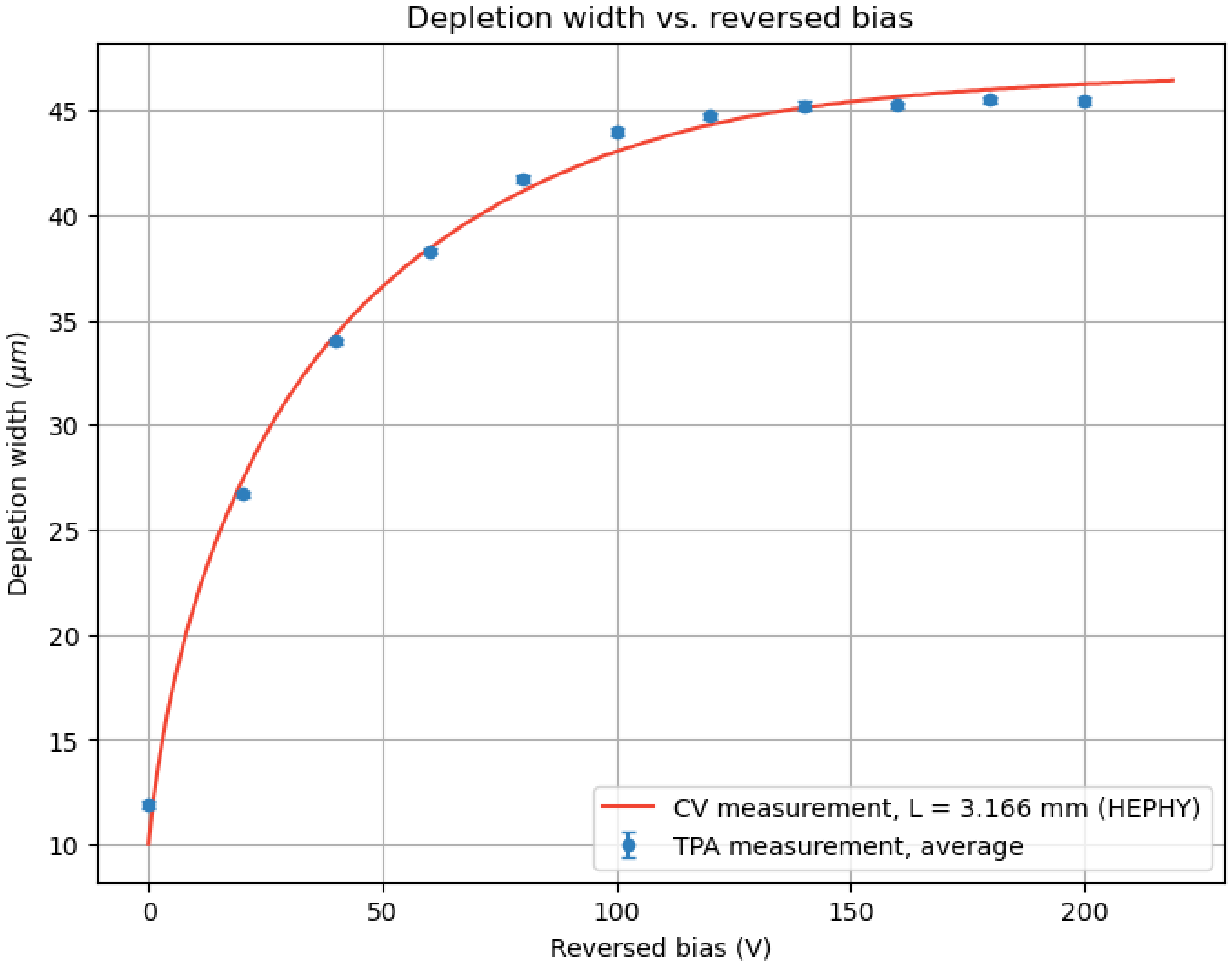
- **Fitted $Z_{\max}$ vs V_{bias}:**



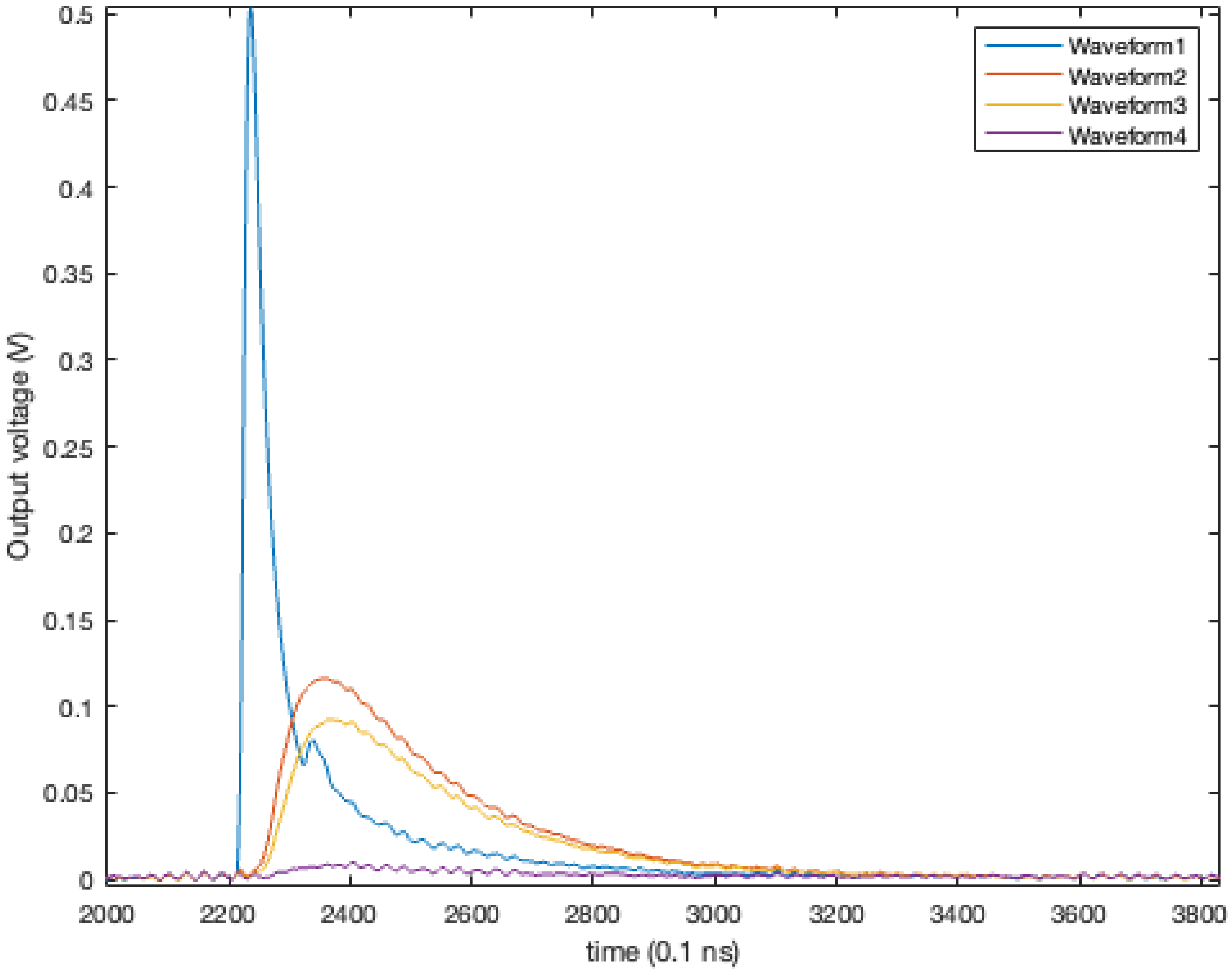
- Depletion width obtained from C-V measurement from HEPHY :

$$Z_{\max}(V_{\text{bias}}) = \varepsilon_r \varepsilon_0 A / C(V_{\text{bias}})$$

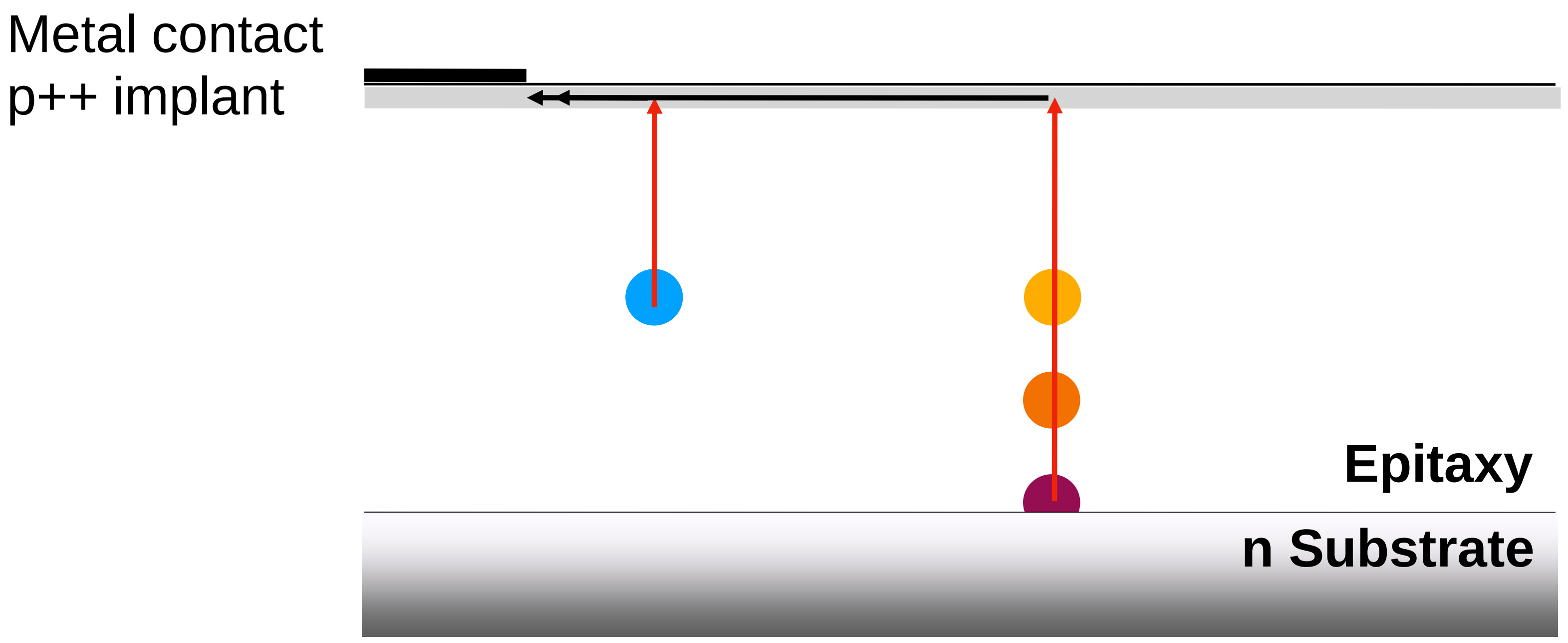
- TPA measurements are in keeping with C-V measurements. Small deviation between TPA and C-V measurements observed.

TPA current waveform (4H-SiC)

- **Using TCT amplifier: CIVIDEC C2-TCT**

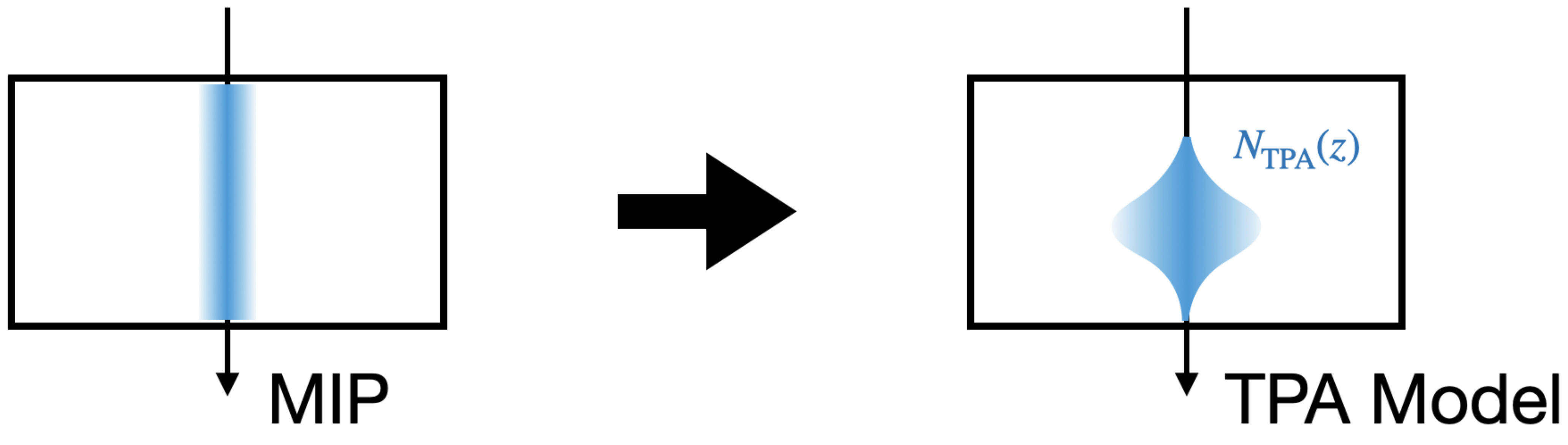


- Different positions used for TPA-TCT test
- **Long tails observed, and signals at different positions vary a lot.**
- **Can be explained by resistance of p implant**



- **Time resolution measurement using 2-pulse method not possible for this sensor**

TPA simulation



- Change uniform charge generation (MIP) to manually controlled charge density.
- Parameters need to be obtained from **TPA experiments!**

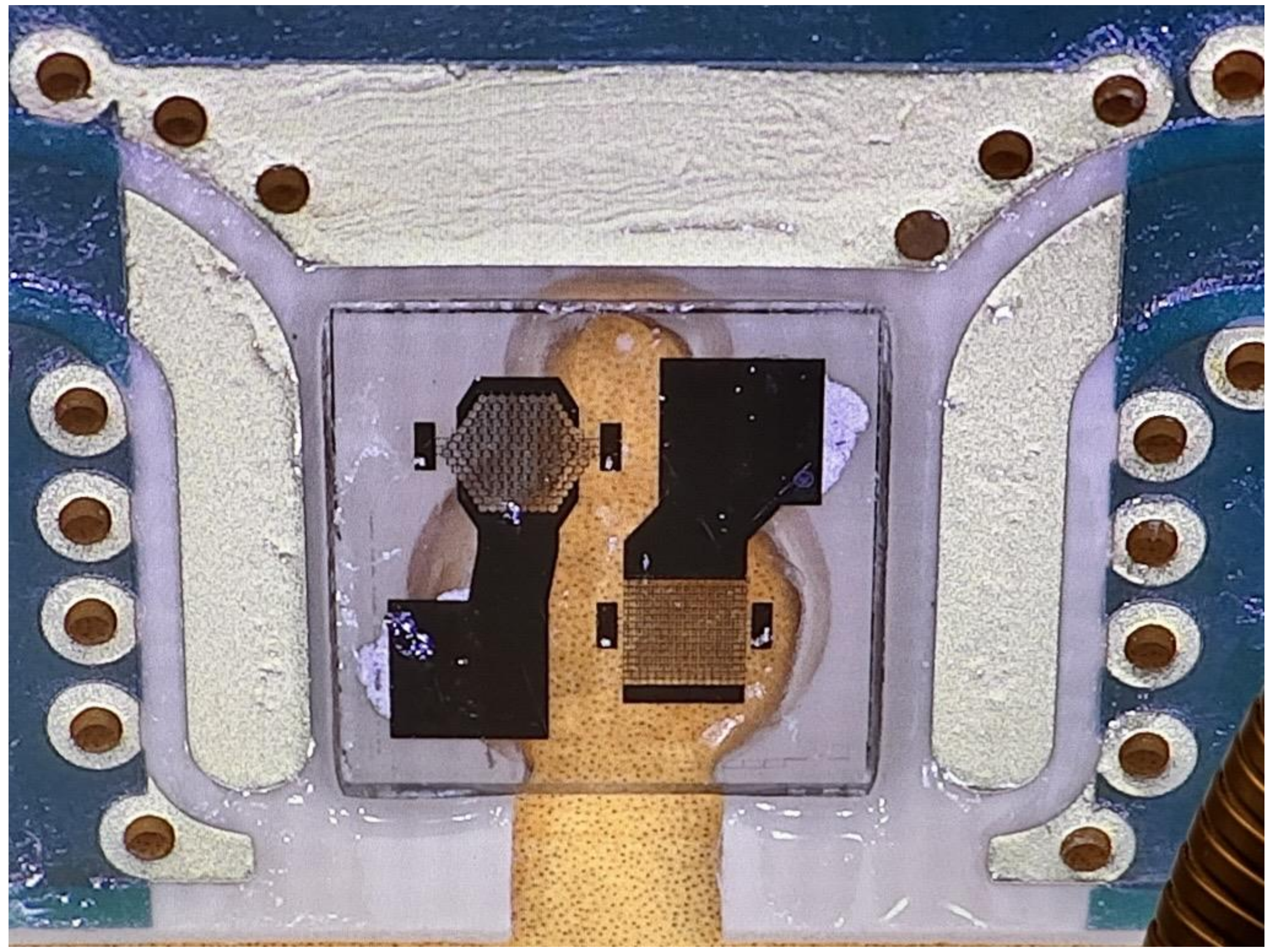
TPA Testing → Parameters $NA_{\mathrm{eff}}, Z_{\max}, \ldots$ → Simulation → Analysis

Conclusions

- **TPA characterisation performed on Diamond sensor & 4H-SiC sensor from HEPHY. Energy scan results indicate valid TPA charge generation in both sensors;**
- **Voltage-depth-X-Y scan performed on the 4H-SiC sensor. The depletion width vs. XY & bias voltage relationship is measured, which is in keeping with C-V measurements;**

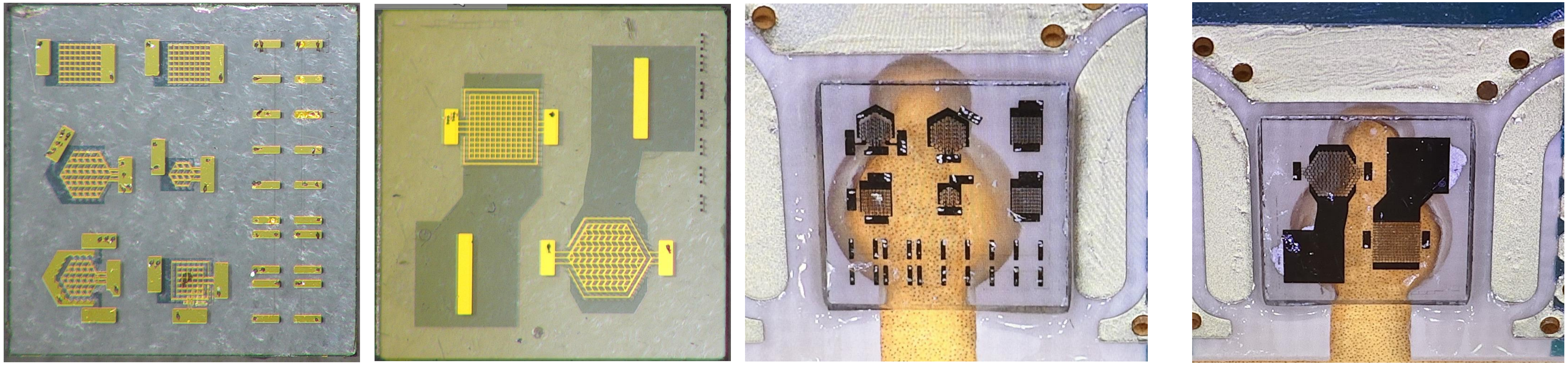
- **On going:**

  A. **Optimisation of TPA simulation using Sentaurus TCAD + Garfield**
  B. **Preparing more 3D diamond samples for TPA**
  C. **Optimisation of reconstruction to improve detector's time/space resolution**

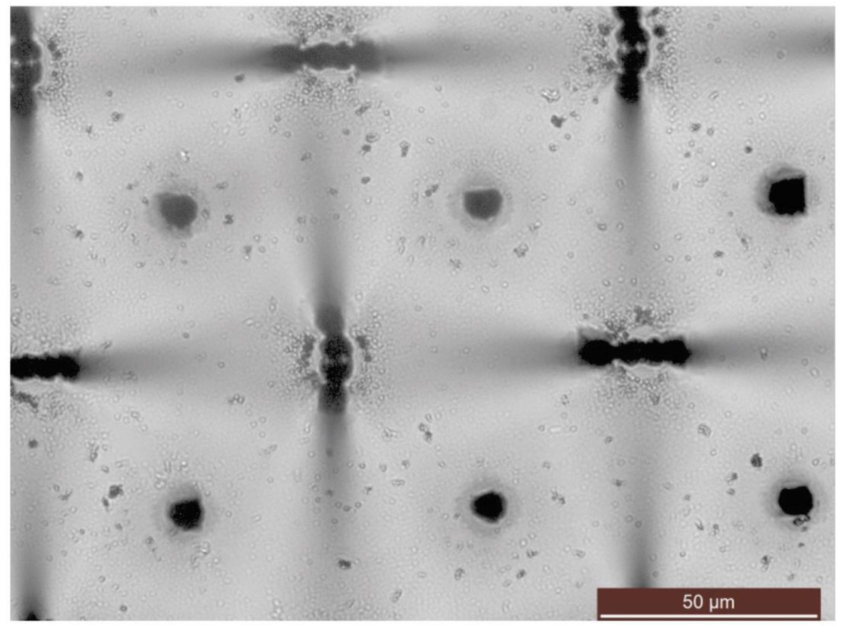


Future steps

- **New 3D diamond sensors ready for assembly:**



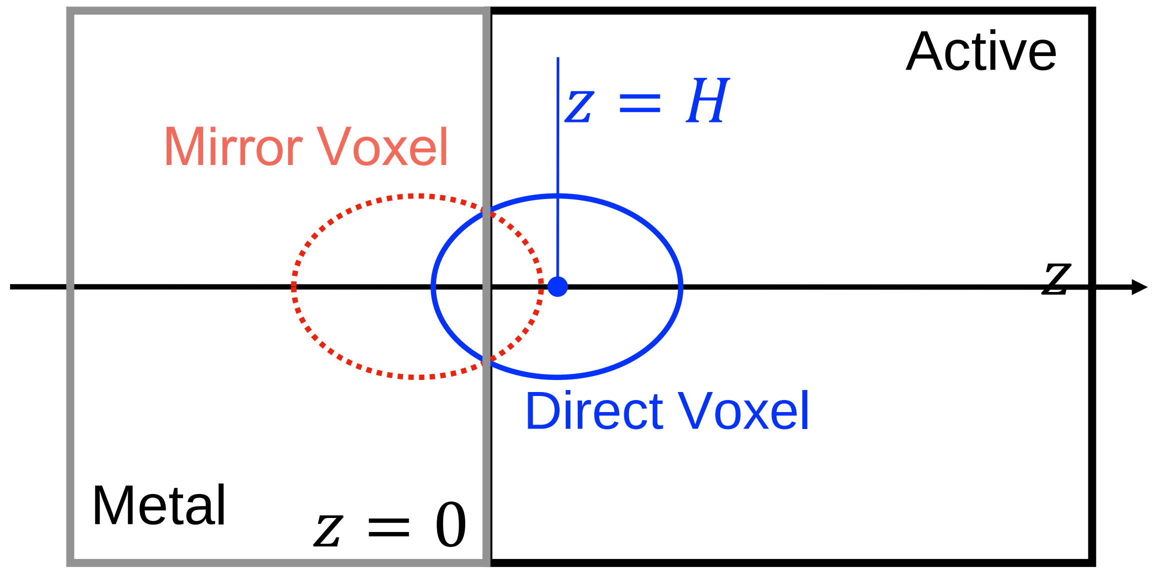
- **Twisted structure sample waiting for metallisation, will be ready soon.**



Thank you for your Attention!

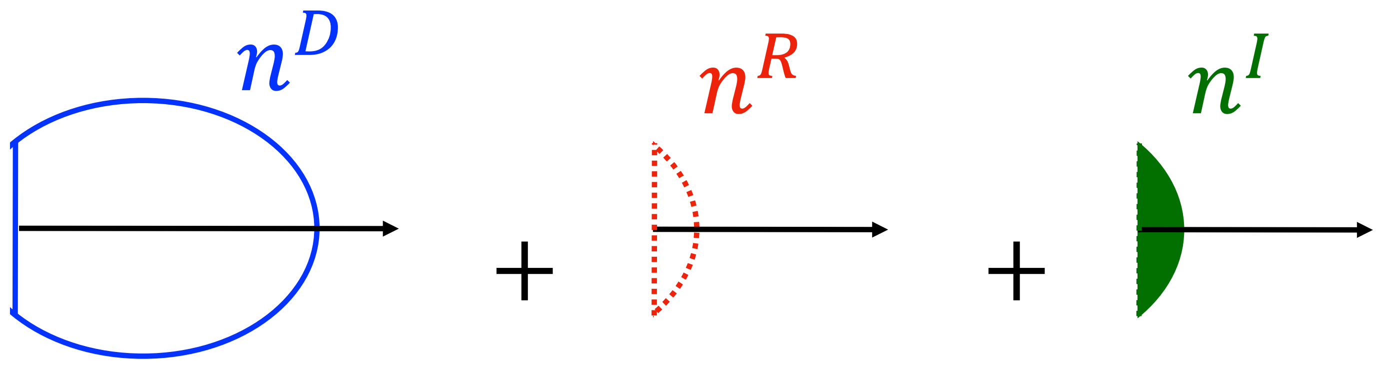
Backups

- **Reflection model**



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

$n_{\text{TPA}} =$



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

$$= \boxed{\frac{\beta_2\tau}{4\hbar\omega}\sqrt{\frac{\pi}{2\ln 2}}I_D^2(z-H,r)} + \boxed{\frac{\beta_2 R^2\tau}{4\hbar\omega}\sqrt{\frac{\pi}{2\ln 2}}I_D^2(z+H,r)}$$

$n^D(z-H,r)$

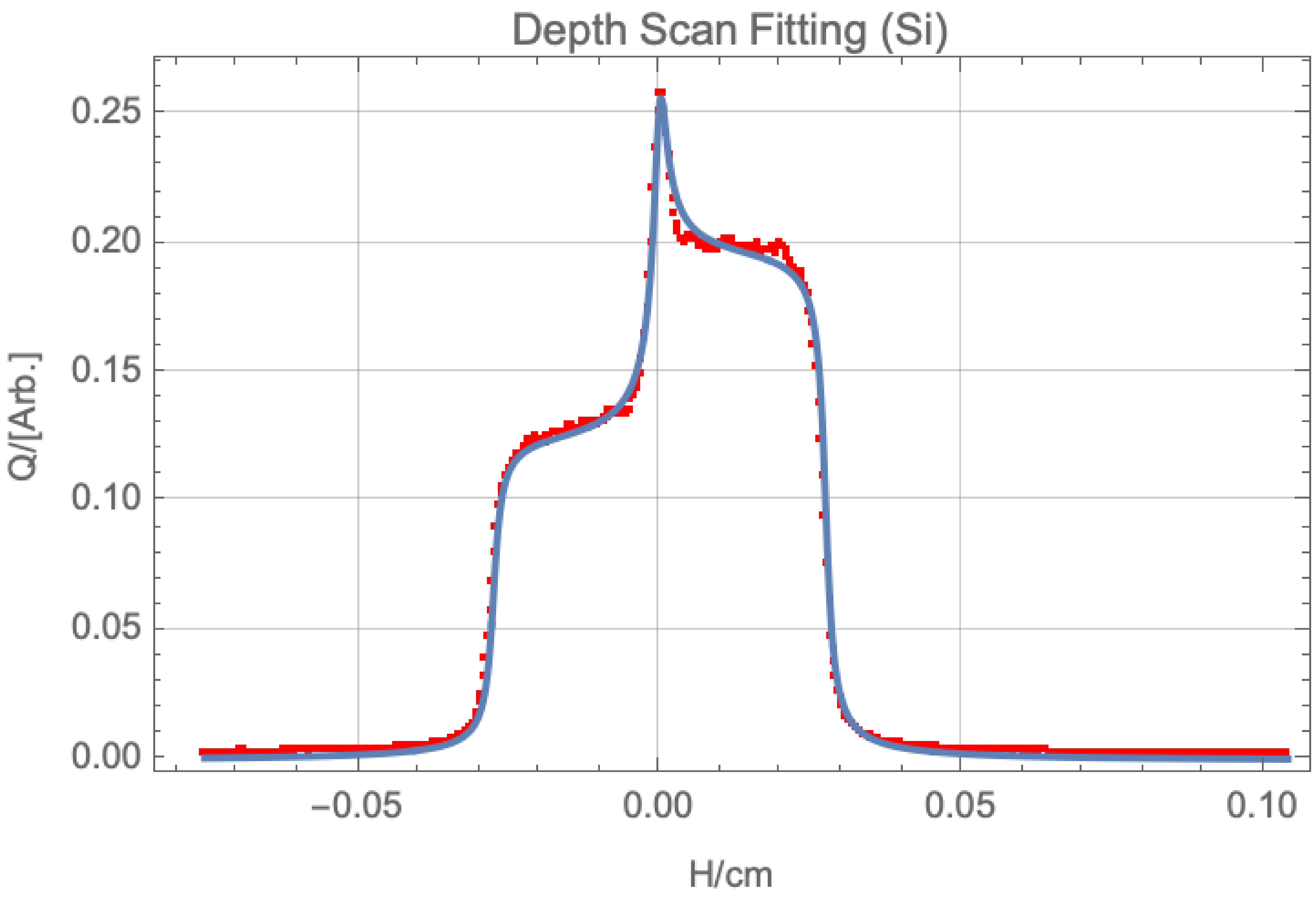
$n^R = R^2 n^D(z+H,r)$

$$+ \boxed{\frac{\beta_2 R\tau}{2\hbar\omega}\sqrt{\frac{\pi}{2\ln 2}}I_D(z+H,r)I_D(z-H,r)e^{-\frac{2\ln 2(\Delta t)^2}{\tau^2}}}$$

$$n^I = 2R\sqrt{n^D(z-H,r)n^D(z+H,r)}e^{-\frac{2\ln 2(\Delta t)^2}{\tau^2}}$$

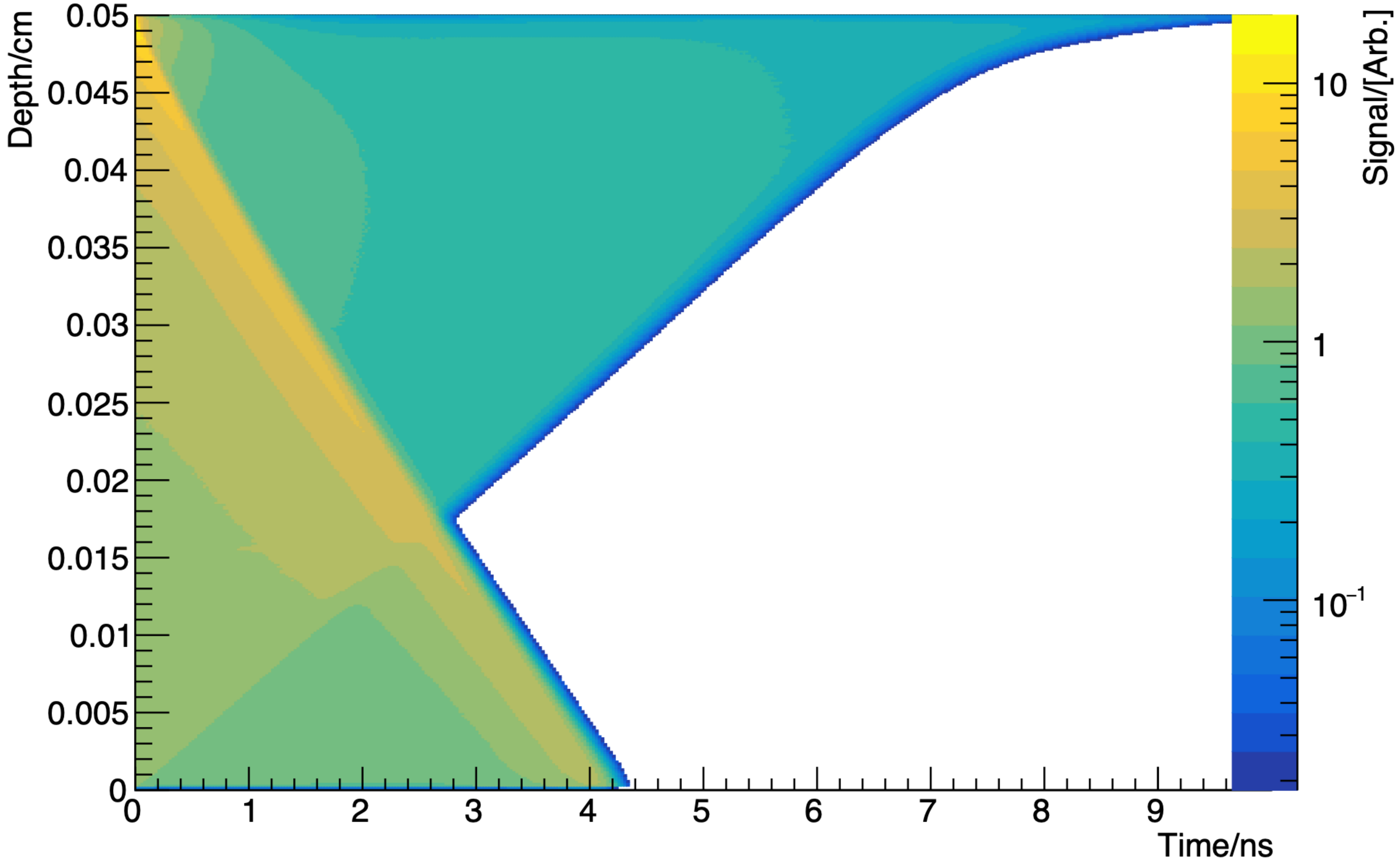
Backups

- **Reflection model: fitting (CNM Silicon sensor)**

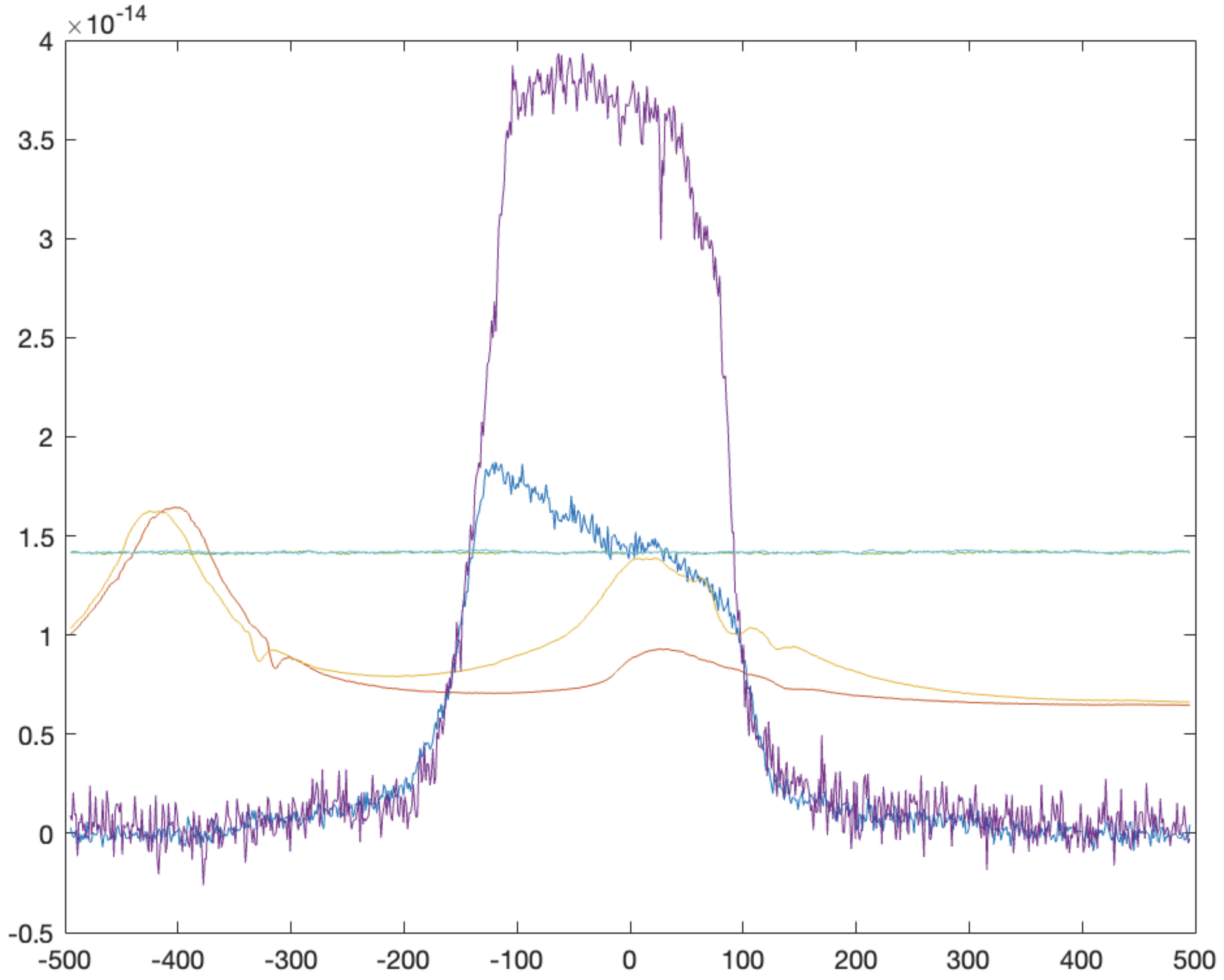


Backups

- **TPA simulation: Diamond waveform using fitting parameters from CNM silicon diode depth scan**

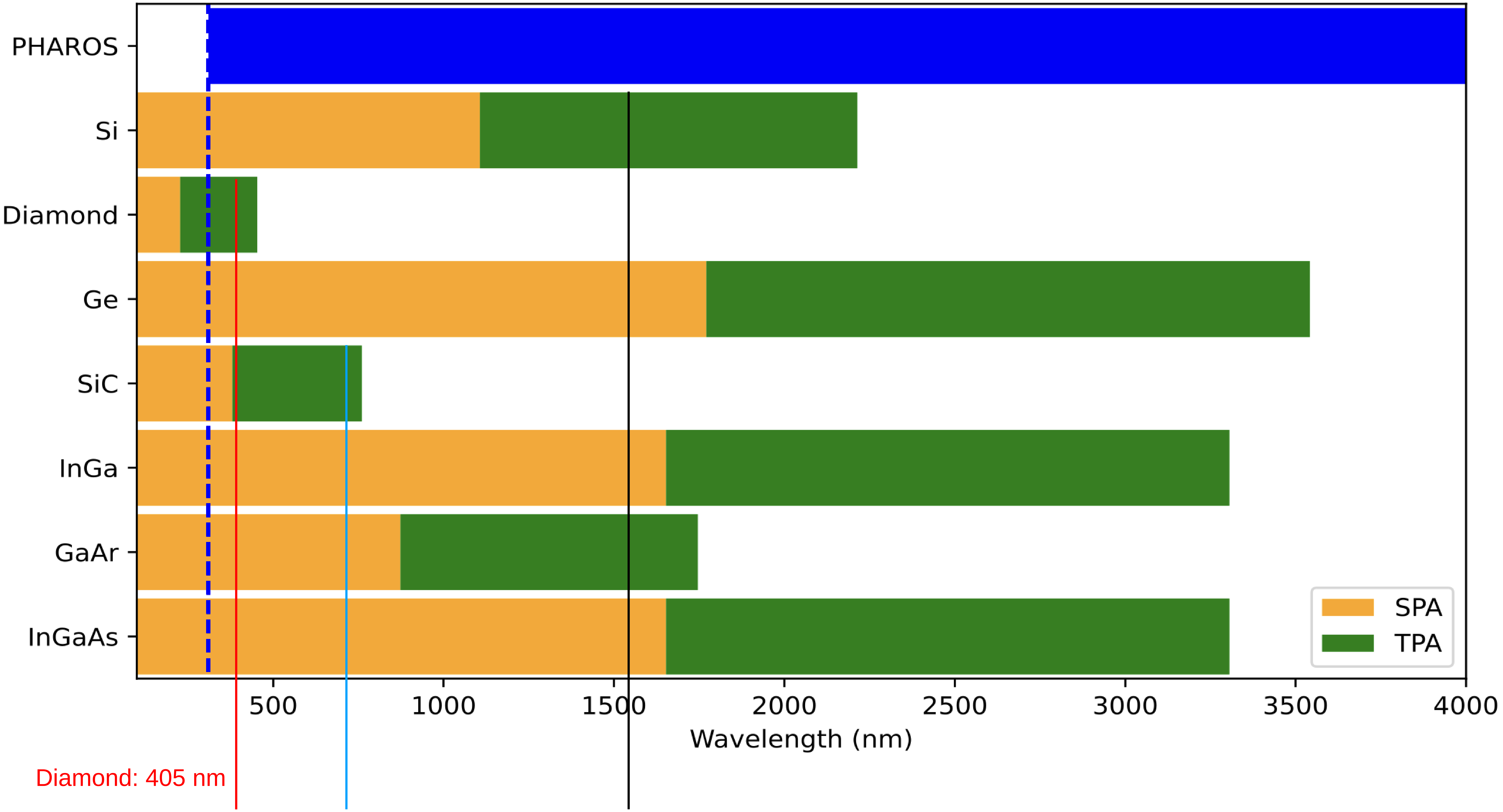


- **TPA depth scan: planar device**



Backups

- **TPA wavelength range**



Diamond: 405 nm

4H-SiC: 720 nm

Silicon: 1550 nm

*See Enoch’s 1st DRD3 week talk : https://indi.to/8jWMZ

Backups

- **Deviation observed between TCAD and Garfield++ MC simulation**