Improving Spatial and Timing Resolution of 3D Diamond Detectors

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Semiconductor 3D, VCI2025, Vienna, 20 Feb 2025

Diamond detector

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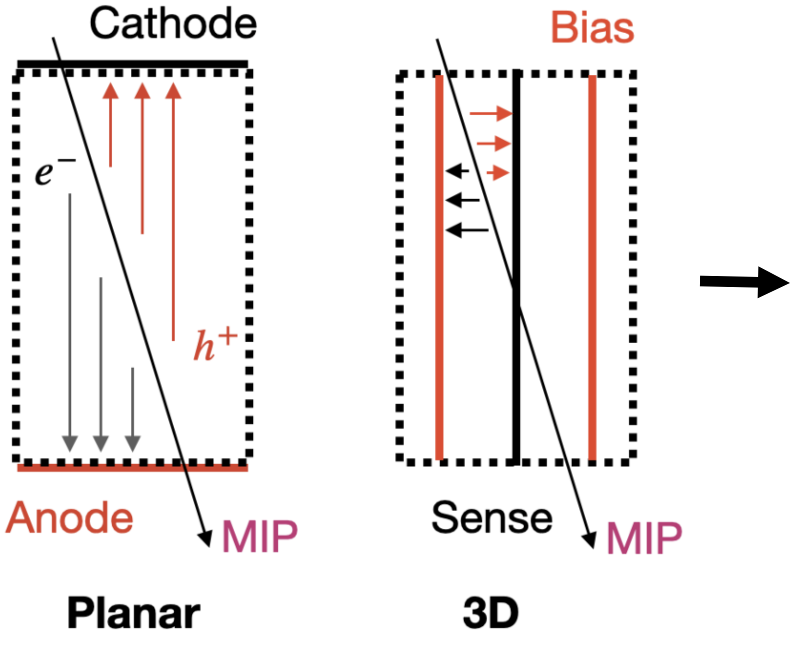
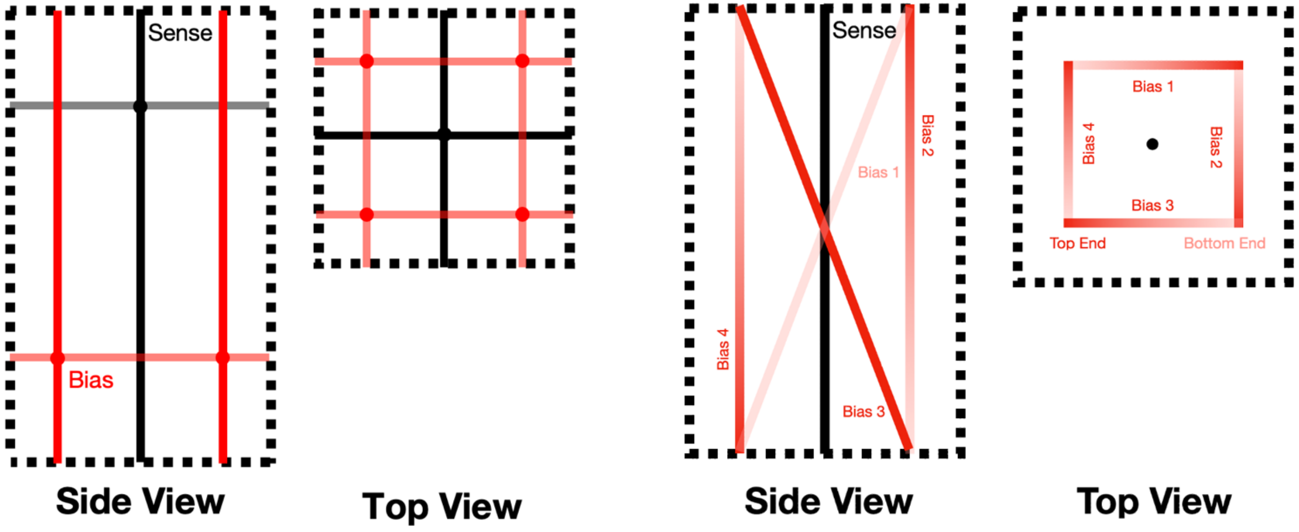
- High radiation hardness ➡ Future HEP experiments
- High thermal conductivity ➡ No cooling needed
- High carrier mobility ➡ Faster signal
- Cost? ➡ Material cost ↑ Processing cost ↓



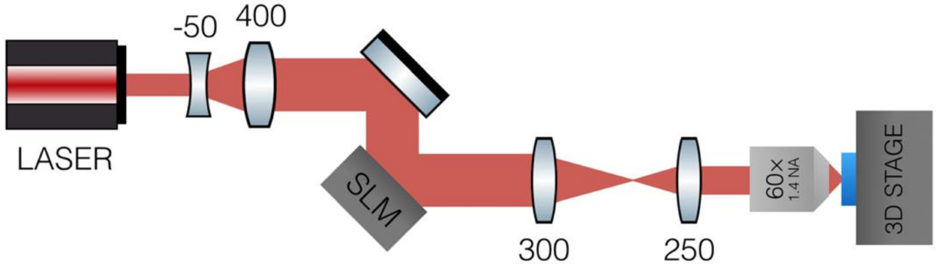
- **Novel 3D Structures:**



Caged Structure **Twisted Structure**

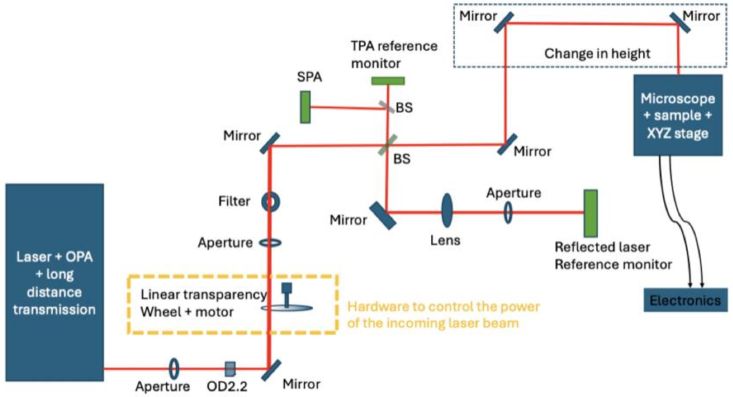
Detector R&D procedures

Fabrication

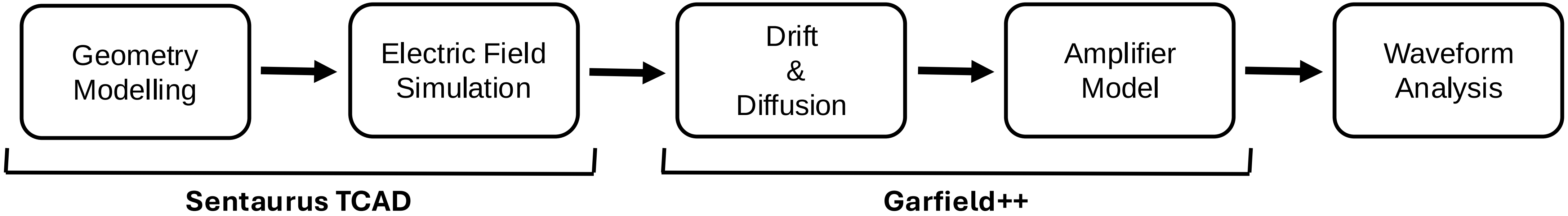


Arnaud Courvoisier, Martin J. Booth, Patrick S. Salter; Inscription of 3D waveguides in diamond using an ultrafast laser. *Appl. Phys. Lett.* 18 July 2016; 109 (3): 031109.

Characterisation (TPA)



FEM & MC simulation Pipeline



Manchester TPA setup (PSI, UoM)

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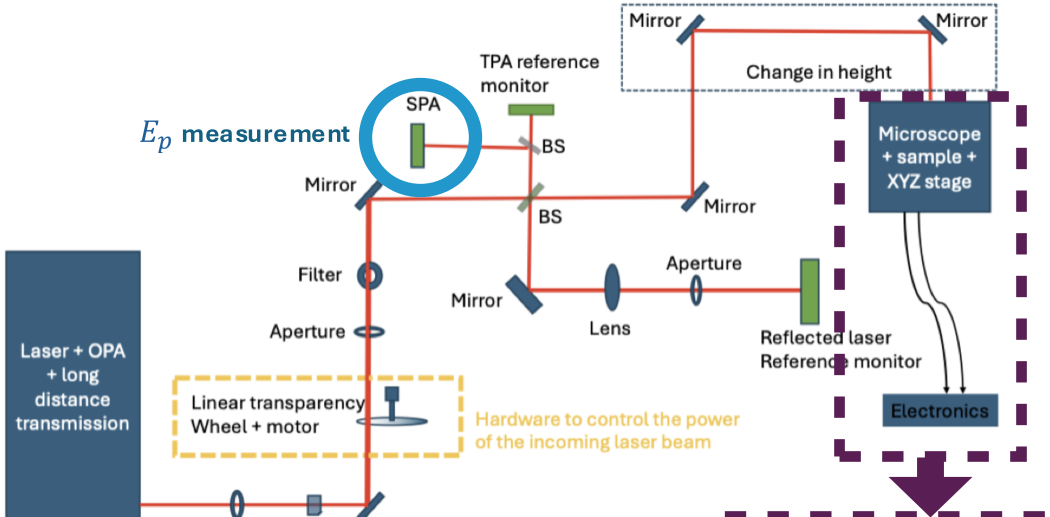
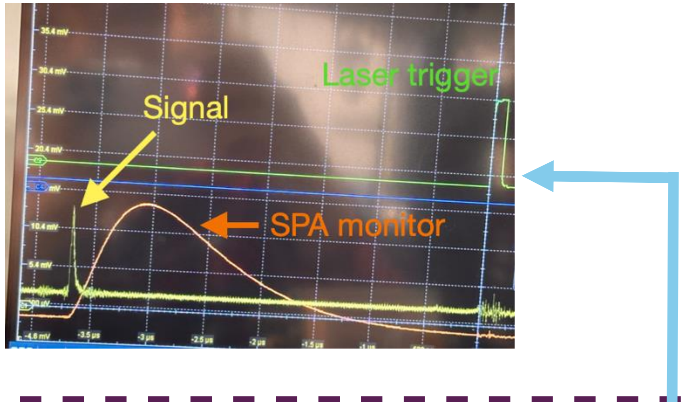
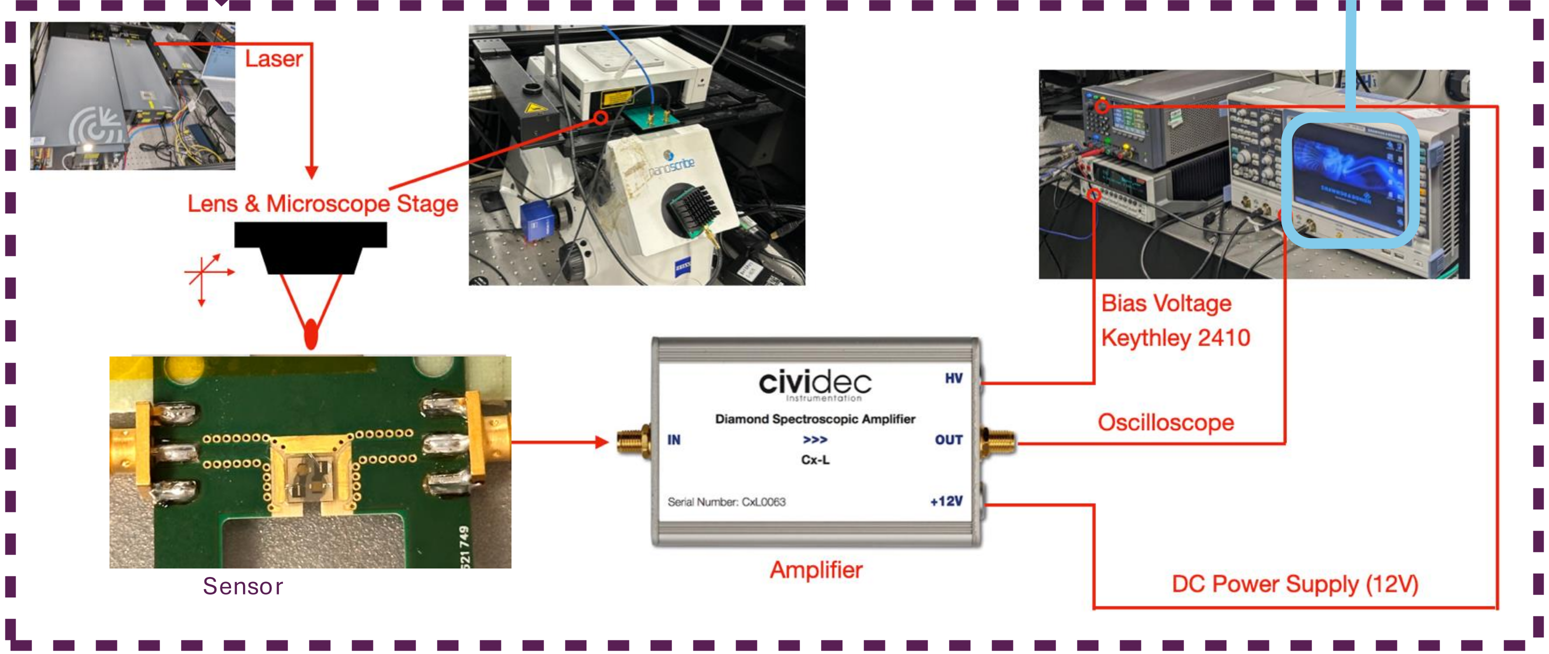


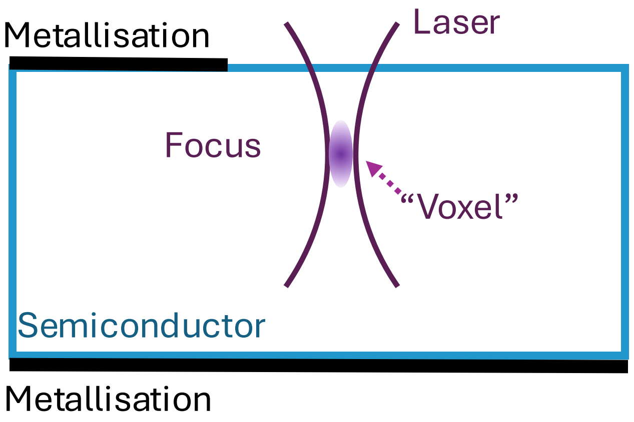
Enoch’s DRD3 week talk : https://indi.to/8jWMZ

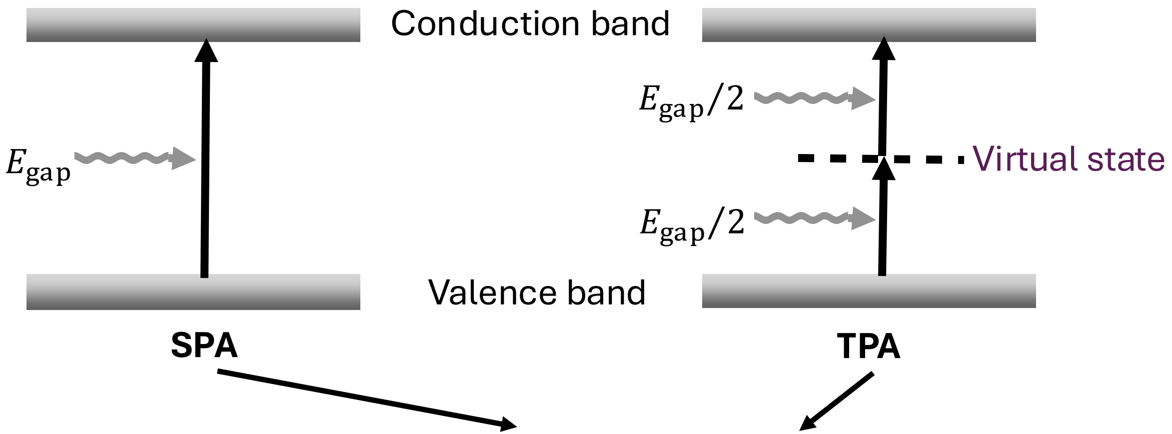




- PHARUS Yb:YAG56 pump laser with OPA.
- **100 kHz** pulse rate.
- λ: 300 ~ 16000 nm tunable.
- SPA monitor calibrated with power-meter **Thorlabs PM100USB.**
- Pulse energy: 0 ~ several μJ .
- **ND filters** used to control energy.

TPA effect in semiconductors





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

- **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"**)

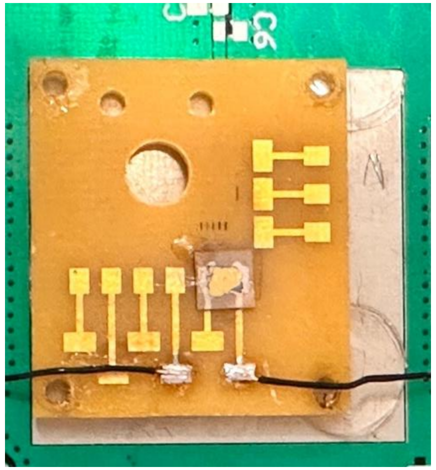
→ High spatial/temporal resolution

TPA induced charge density:

$$n_{\text{TPA}}(z,r) = \frac{\beta_2}{2\hbar\omega}\int_{-\infty}^{+\infty} I^2(r,z,t)\mathrm{d}t$$

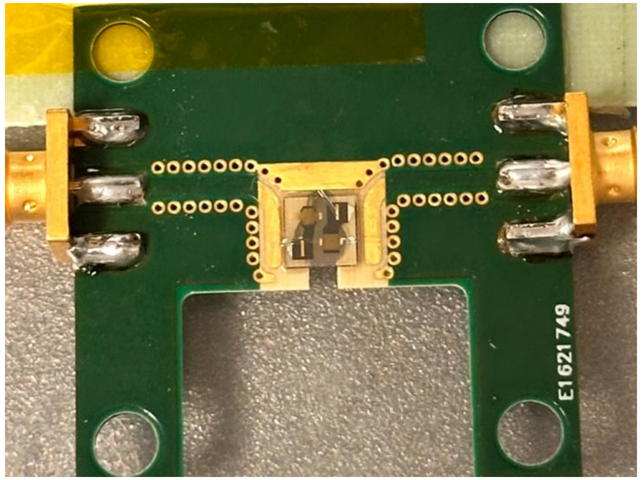
$$= \frac{\boxed{E_p^2}\,\beta_2\, 4\ln 2}{\tau\,\hbar\omega\,\pi^{\frac{5}{2}} w^4(z)\,\sqrt{\ln 4}} \exp\left[-\frac{4r^2}{w^2(z)}\right]$$

Diamond sensors



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

See DRD3 for details: https://indi.to/LHD28

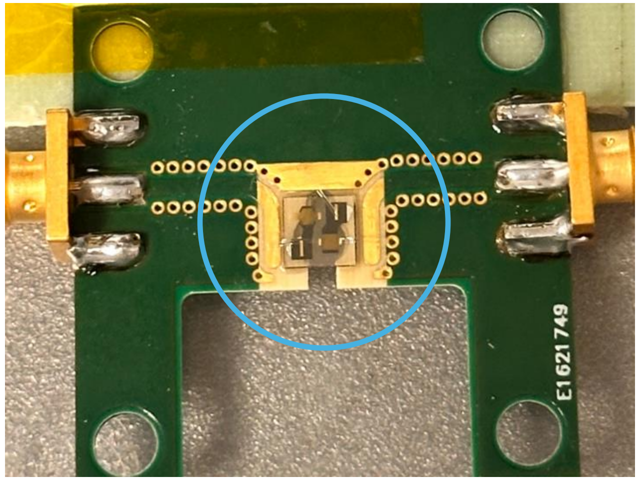


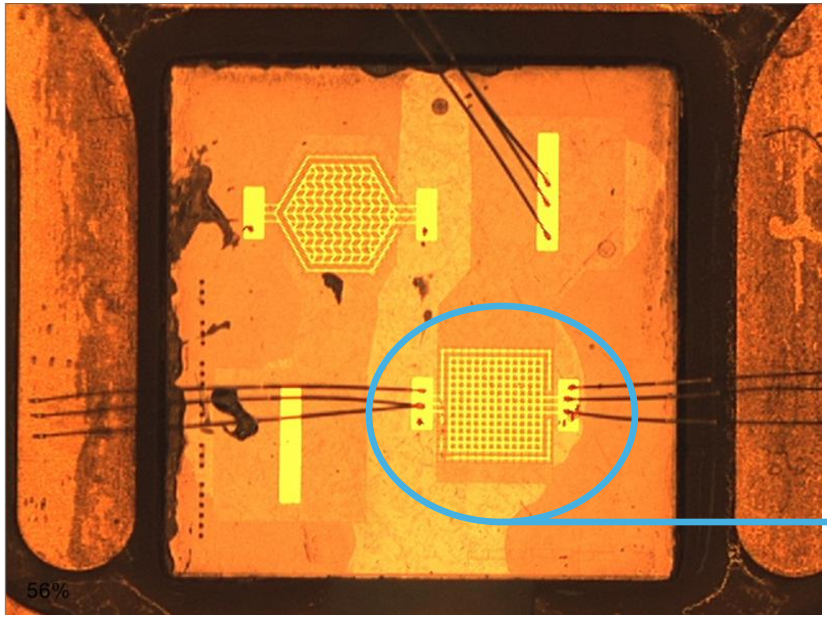
- 3D Diamond sensor from **RD42**
- Caged structure
- pCVD diamond 4mm*4mm*0.5mm
- **TPA wavelength: 405 nm**

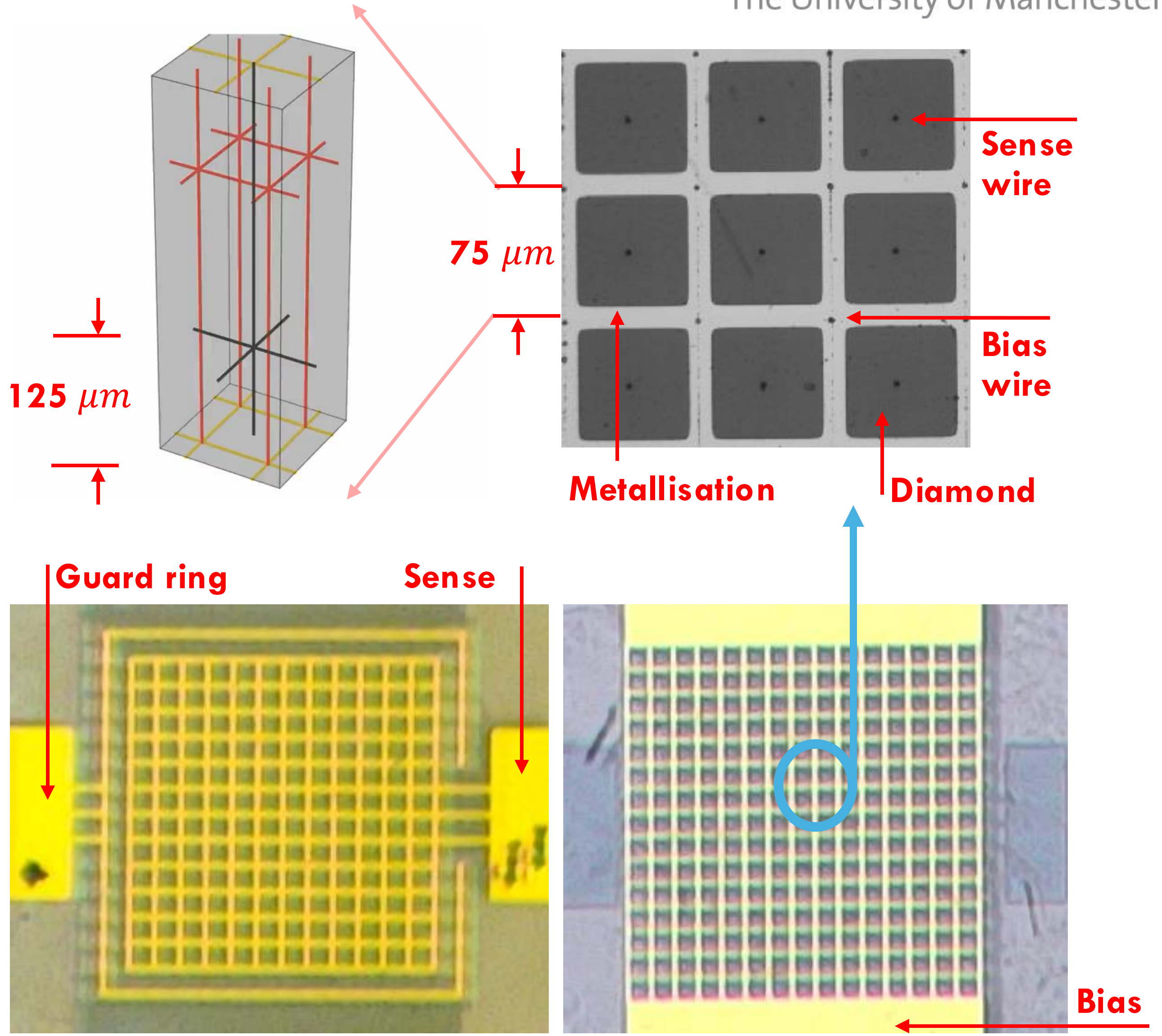
New sample

•••

3D caged diamond sensor

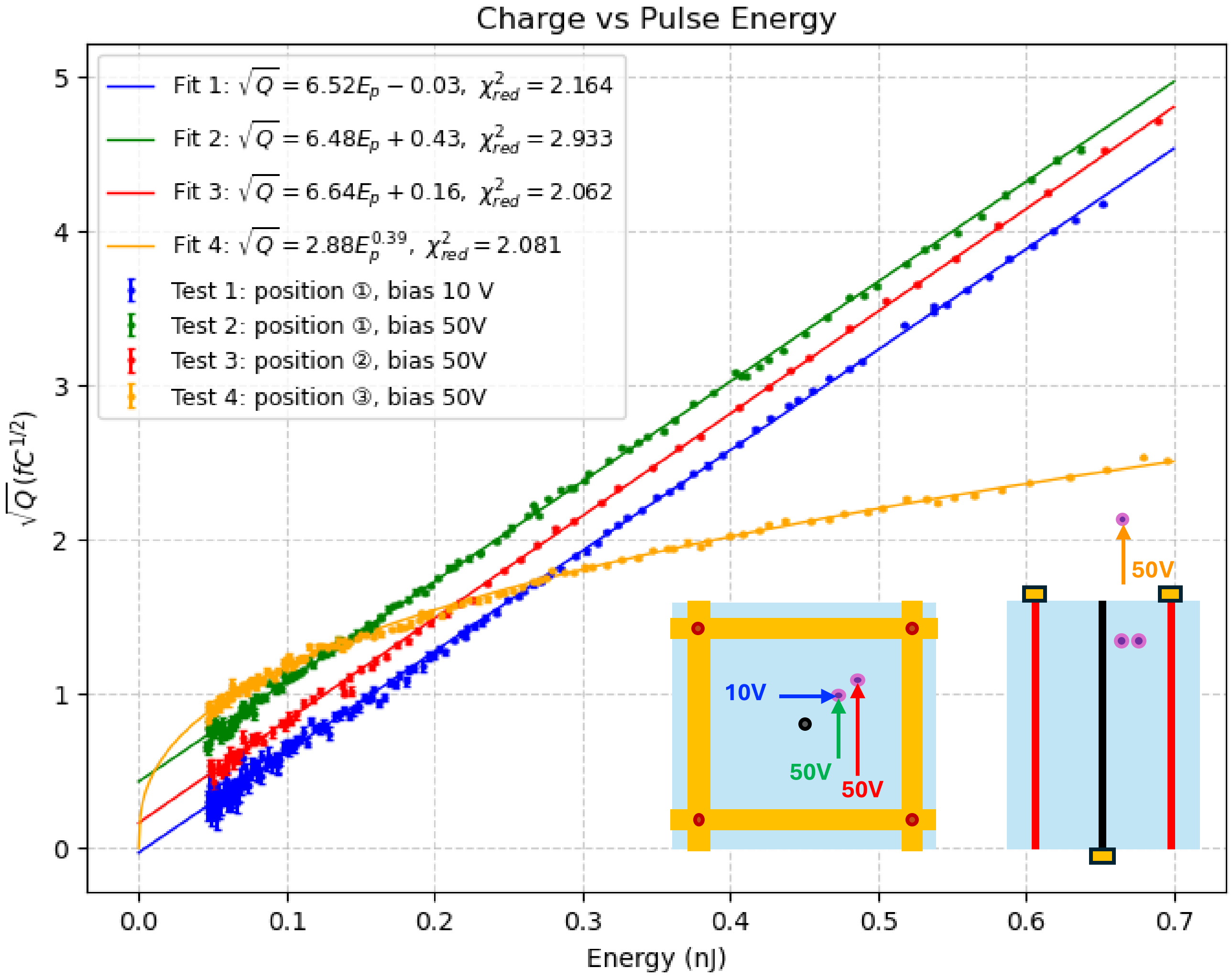






Energy scan

- **Scan results:**



2. $\alpha/\beta_2 = 0.132$

3. $\alpha/\beta_2 = 0.048$

1. $\alpha/\beta_2 < 0.01$

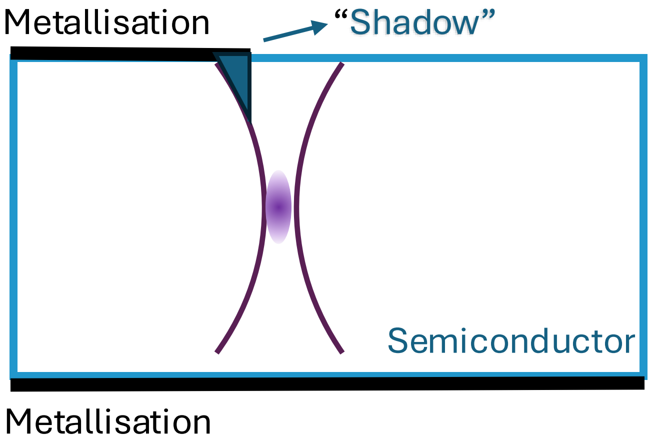
4. $Q = 8.28E_p^{0.77}$ ⟶ **Closer to SPA**

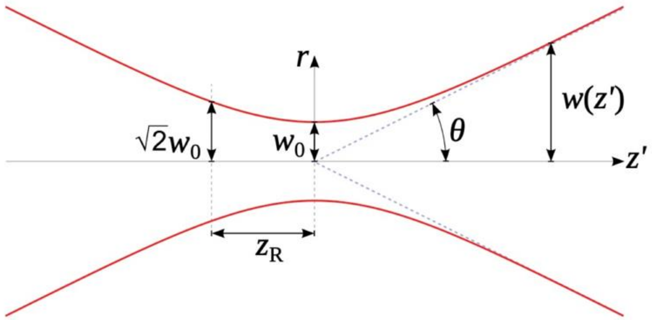
- **SPA-like component increases as:**
  - Bias voltage increases
  - Laser getting closer to graphitised wires
  - Laser intensity reduces / spot expands

- **Generated by graphitized area?**

Depth scan

- **A good method to test device performance, but…**





- **Usually needs a large opening**

  Or laser spot will be shadowed by metallisation

  ⟶ Energy reduction

- **For diamond:**

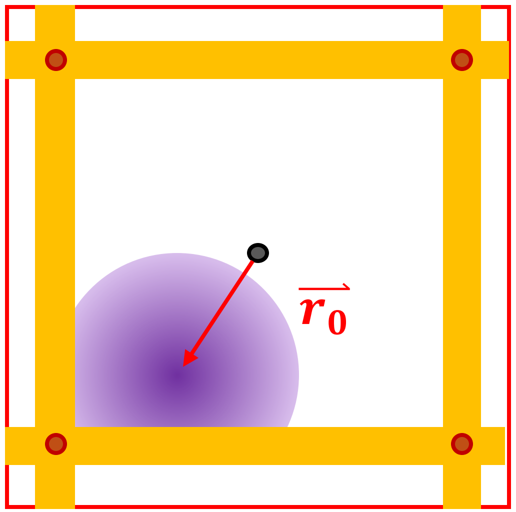
  To reach 500 μm deep without shadowing:

$$w(z) = \sqrt{\frac{\lambda^2}{\pi^2 NA^2} + \frac{NA^2 z^2}{n^2}},$$

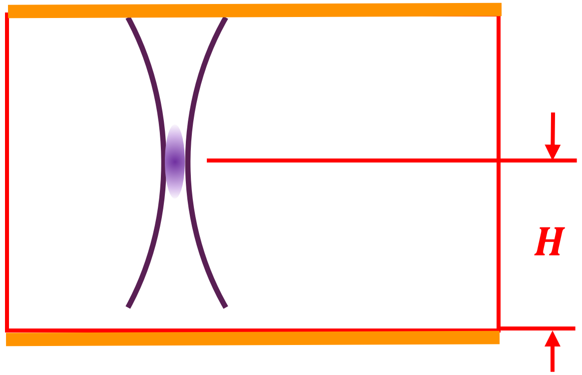
$w(500\ \mu m) \approx 101.7\ \mu m$, while pitch size = $75\ \mu m$

Depth scan

- **Good news: the shadowing effect is predictable**



Top view



Side view

- **Define shadowing correction factor:**

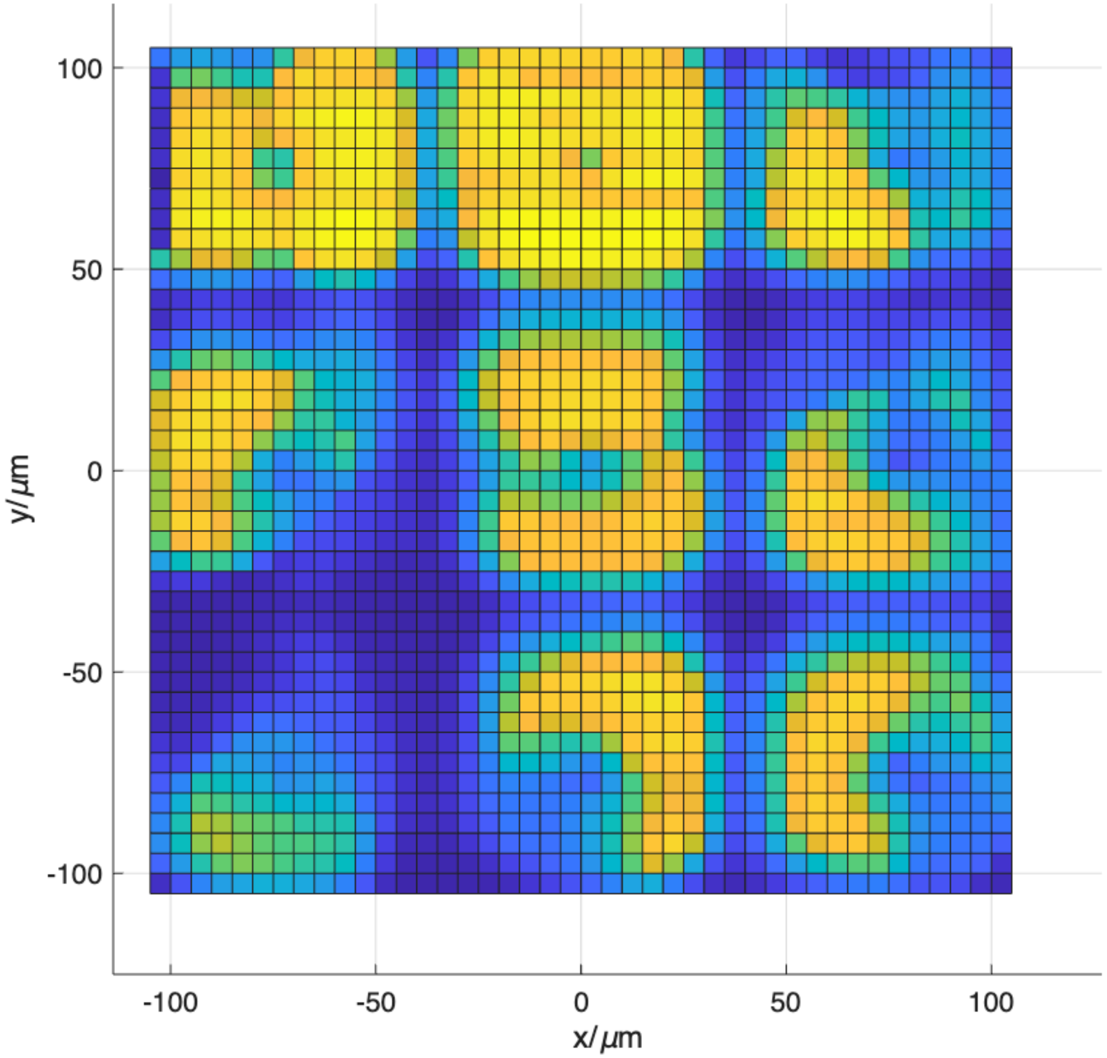
$$Cr = \left(1 - \int_{\text{metal}} \mathrm{dA}\, I_0(|\vec{r} - \vec{r_0}|, z_{\max} - H) \Big/ \int_{\infty} \mathrm{dA}\, I_0(r, z_{\max} - H)\right)^2$$

$$Q_{\text{correct}} = Q_0 Cr$$

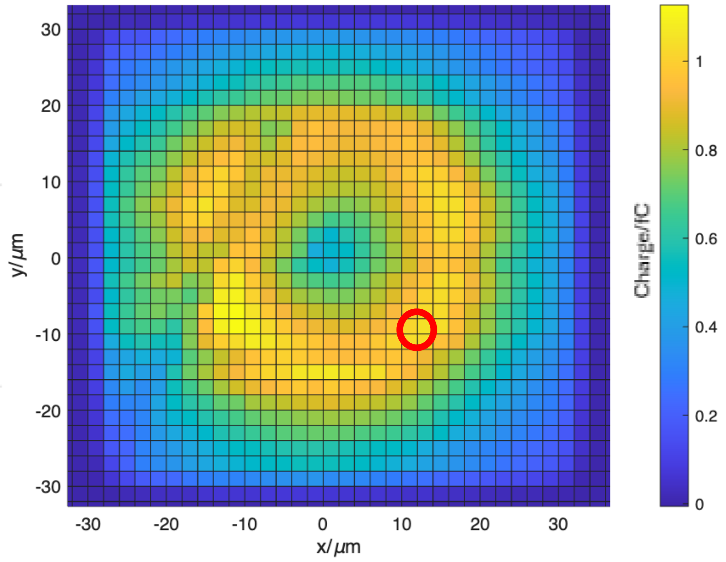
- **Analysing procedures**
  1. Perform TPA depth scans at different XY positions (using CIVIDEC CxL charge amplifier)
  2. Select good XY positions, fit with shadow corrected charge: Q_{correct}, get NA_{eff}
  3. Obtain global correction factor
  4. Get corrected XYZ scan result $Q_0(x, y, z)$

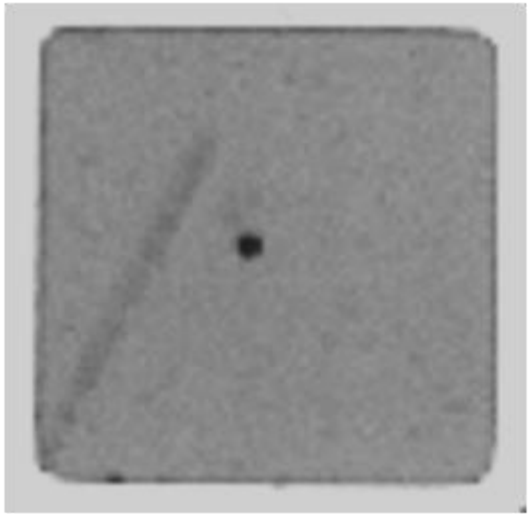
Depth scan

- **Coarse XY scan near surface & single pixel XYZ scan**



(Bias: 10V)

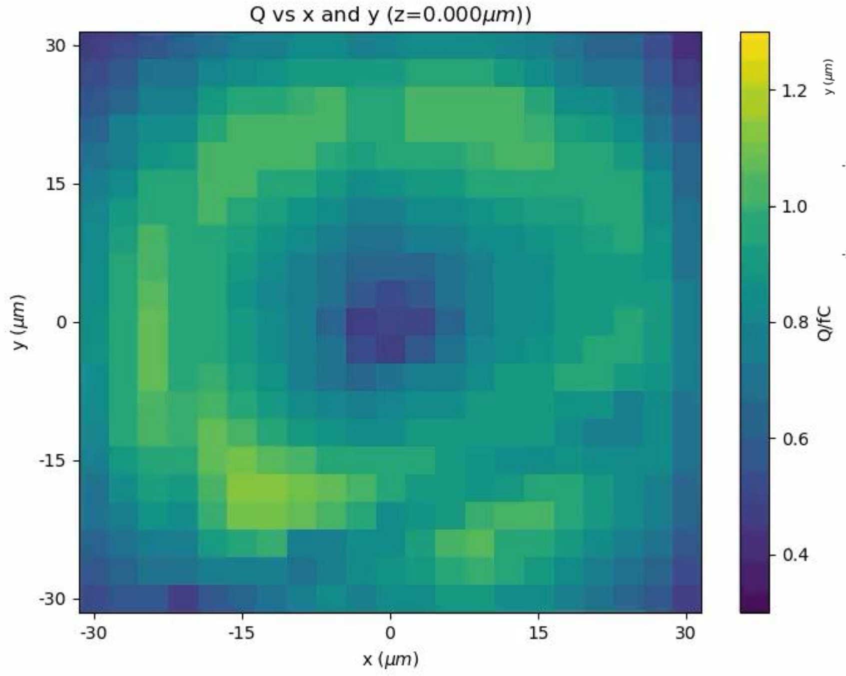


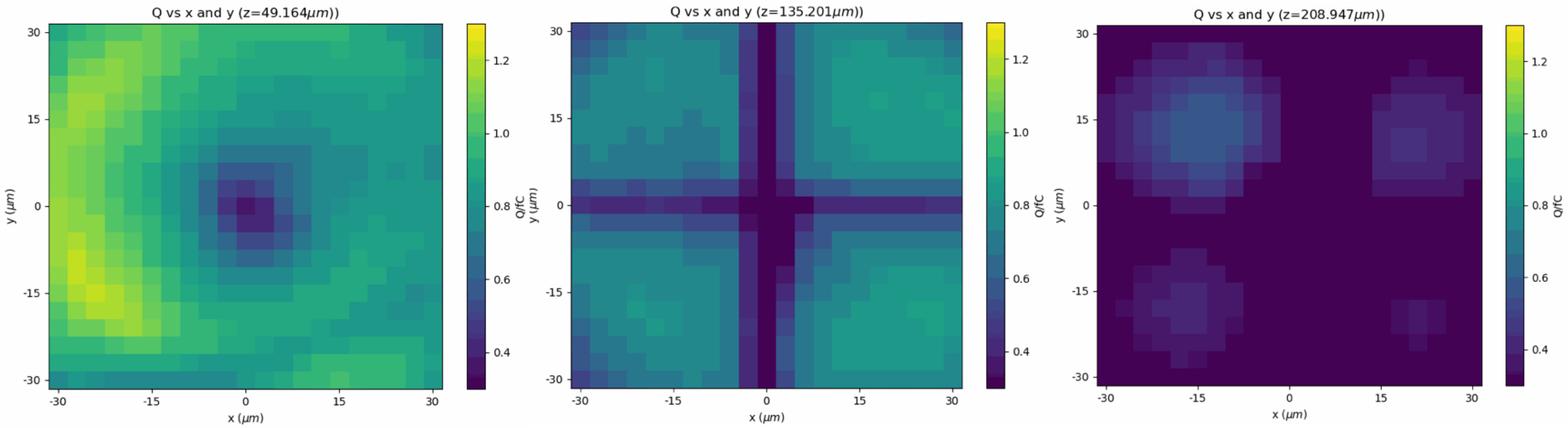


- **Pixel with high uniformity is selected**
- **Then XY positions with relatively higher charge is selected**

Depth scan

- **Charge vs XYZ before shadowing correction**



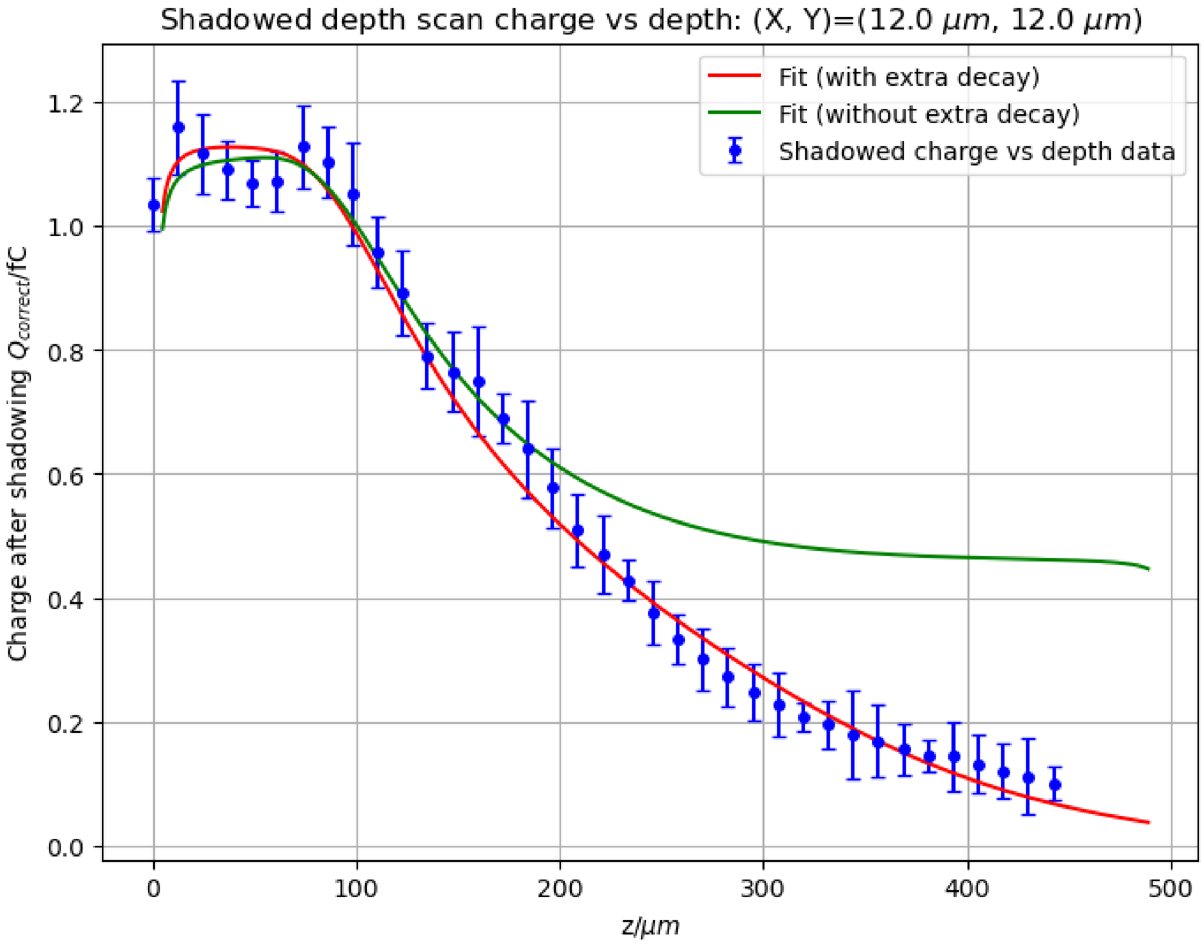


$z = 49.2\ \mu m$ $z = 135.2\ \mu m$ $z = 208.9\ \mu m$

- **As focal point moving into diamond, patterns appear:**
  - **Overall charge reduces (shadowing effect)**
  - **Patterns caused by interconnects**
  - **Patterns caused by pCVD grains**

Depth scan

- **Charge after cropping vs depth**



- Shadowing can not explain the continuous dropping trend
- An extra sigmoid decay factor introduced
- **Fitting results:**

$$NA_{\mathrm{eff}} = NA * \varepsilon = \mathbf{0.464}$$

$$\varepsilon = 92.8\% \ (NA = 0.5)$$

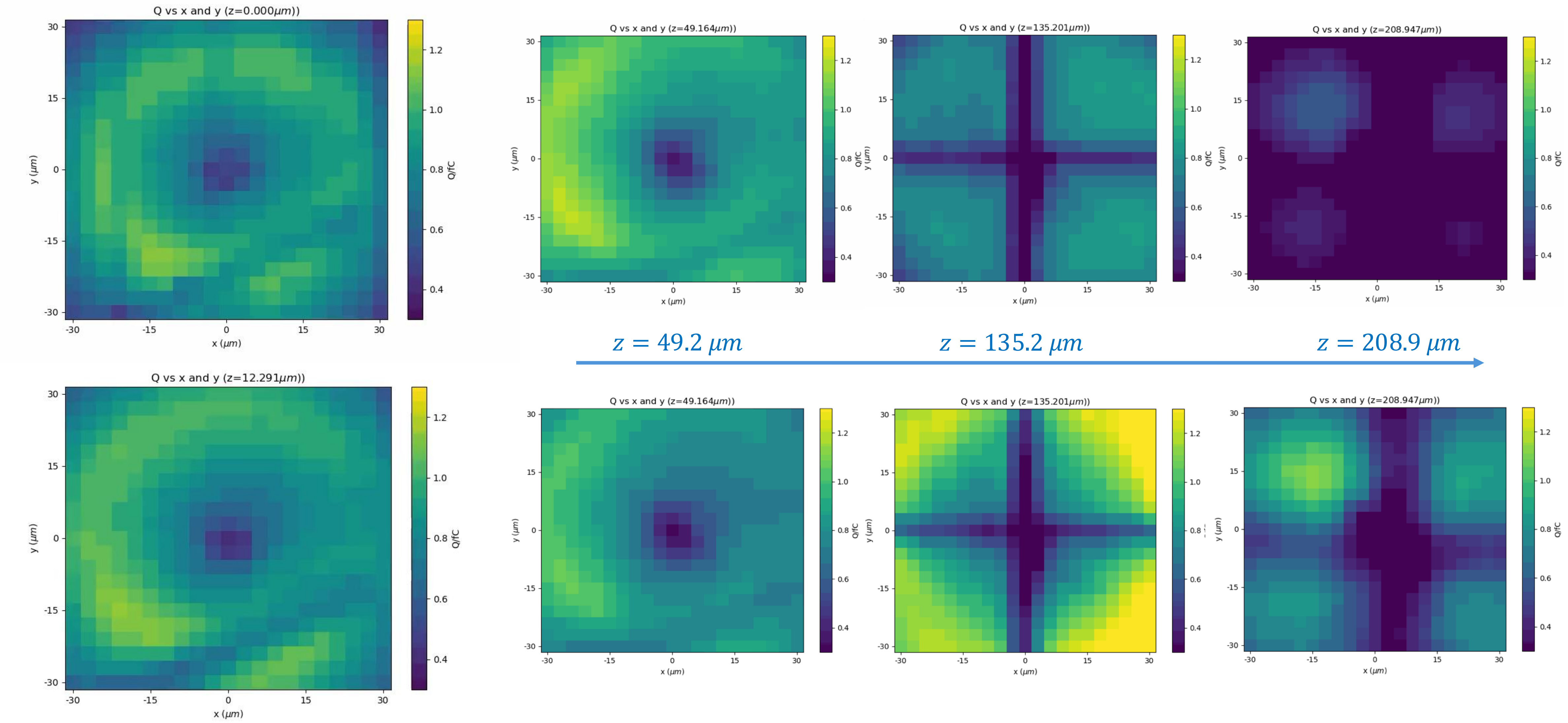
Other free parameters: $Q, \Delta z$

Shadowing correction function:

$Cr(H, \overrightarrow{r_0}, NA_{\mathrm{eff}})$ **obtained.**

Depth scan

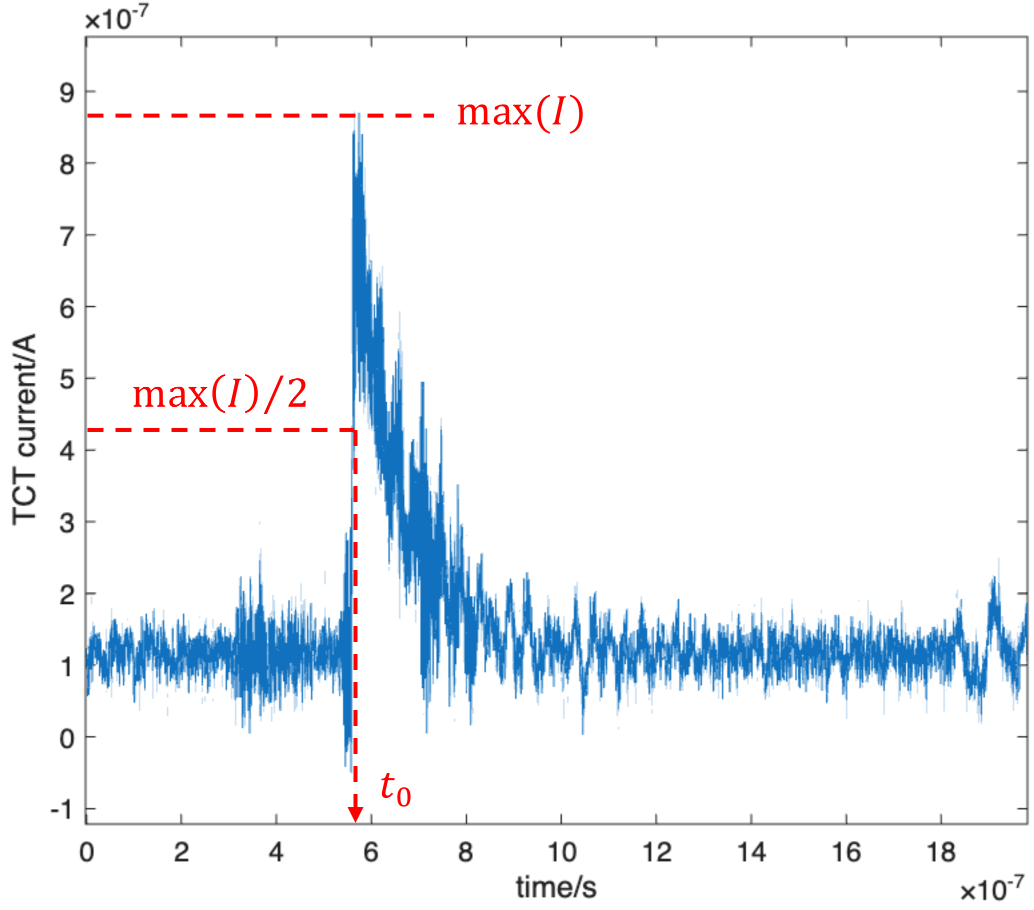
- Charge vs XYZ before/after shadowing correction



Transient Current Technique (TPA-TCT)

The University of Manchester

- t_0 and normalised $\max(I)$

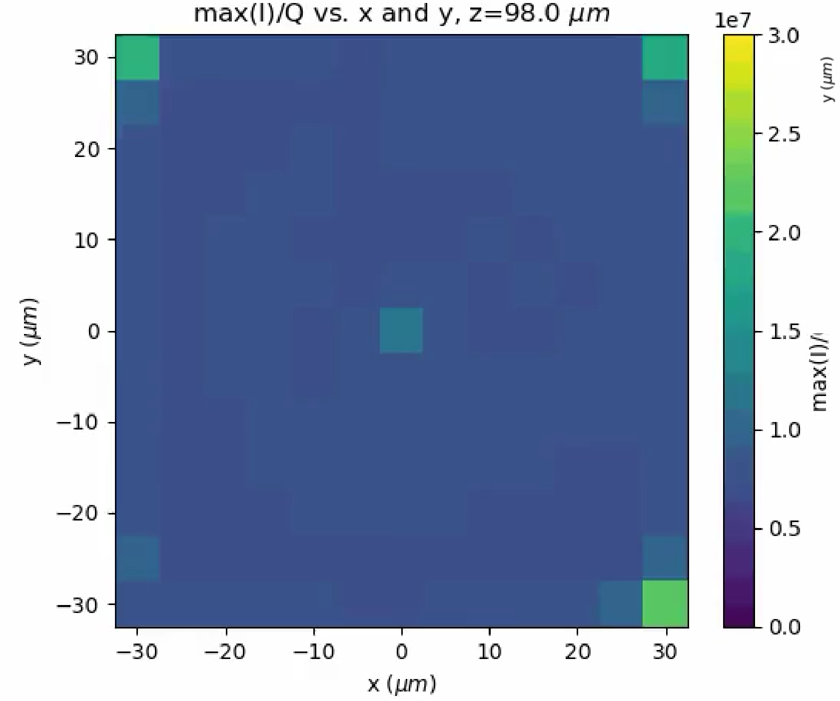


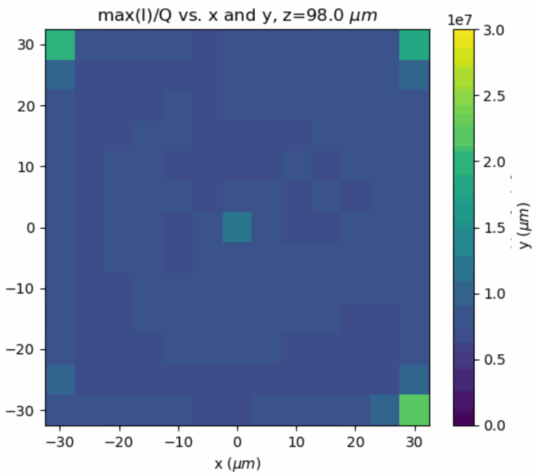
Two parameters:

- t_0: half maximum time
- $\max(I)$: maximum value
  - Affected by laser cropping
  - Normalised $\max(I)$: $\max(I)/Q$

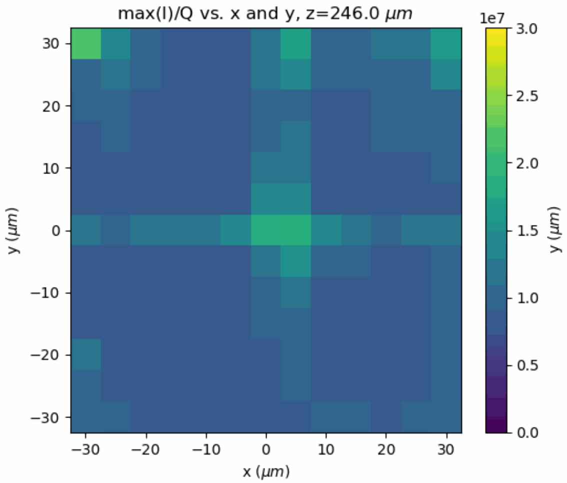
Transient Current Technique (TPA-TCT)

- $\max(I)/Q$ vs. XYZ

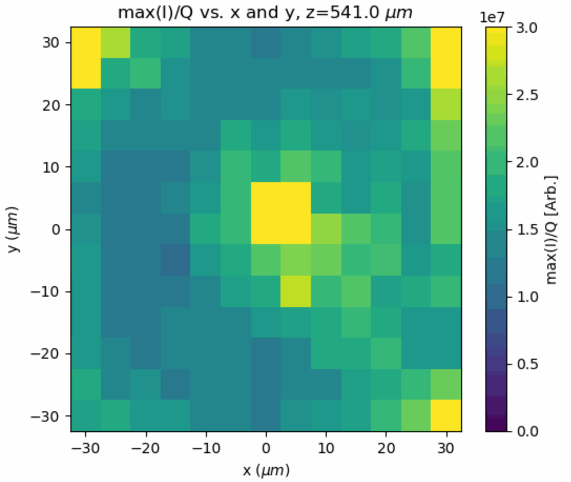




$z = 98.0\ \mu m$



$z = 246.0\ \mu m$

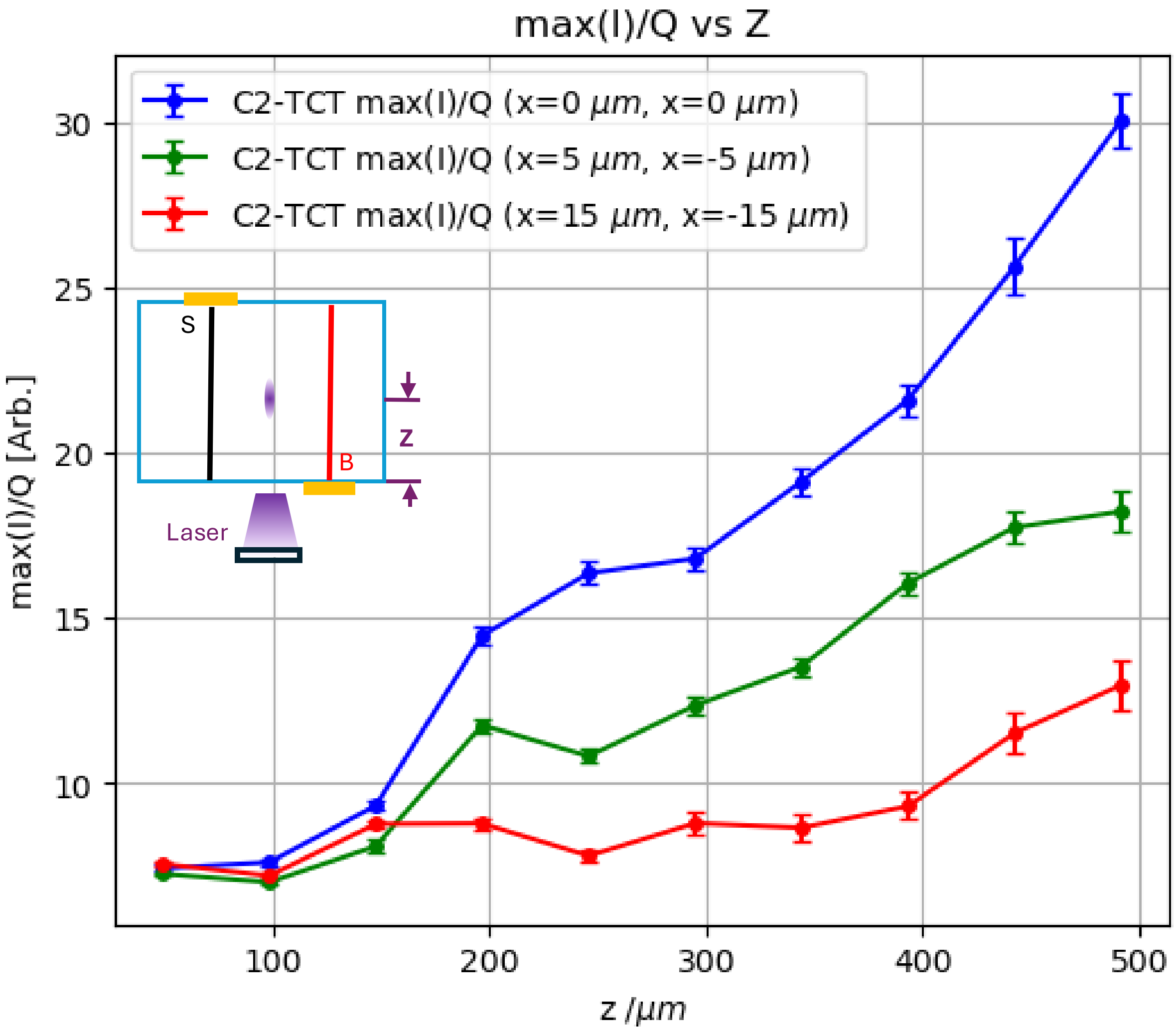


$z = 541.0\ \mu m$

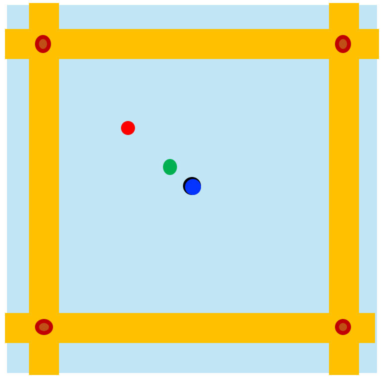
- **As focal point moving into diamond:**
  - $\max(I)/Q$ increases
  - Patterns observed on XY plane

Transient Current Technique (TPA-TCT)

- $\max(I)/Q$ vs. Z position of voxel



- 3 TCT depth scan is taken at different x-y positions:



$(0\mu m, 0\mu m)$

$(5\mu m, -5\mu m)$

$(15\mu m, -15\mu m)$

- Correlation between $\max(I)/Q$ and (x, y, z) is observed
  - Distance to metallisation ↓, $\max(I)\ /Q$ ↑
  - Distance to pixel center ↑, $\max(I)\ /Q$ ↑

3D Diamond sensor simulation

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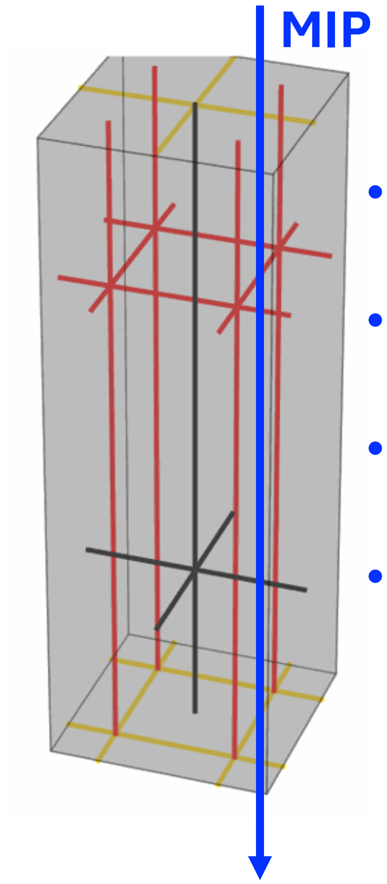
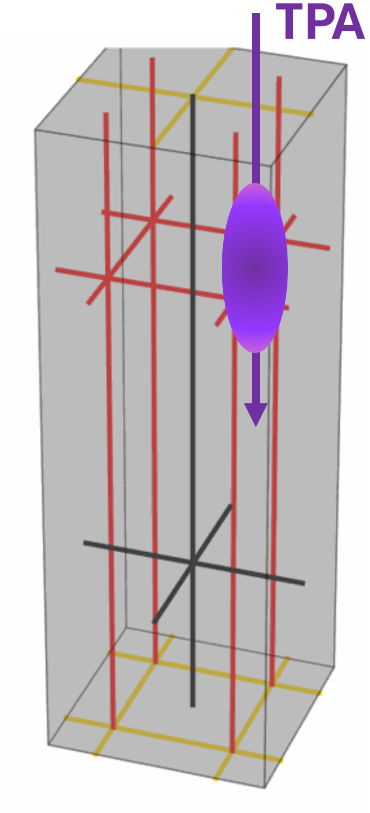


- Uniform e/h generation
- Easy to simulate
- No z-position information
- Currently no experimental data yet…



- Point-like e/h generation

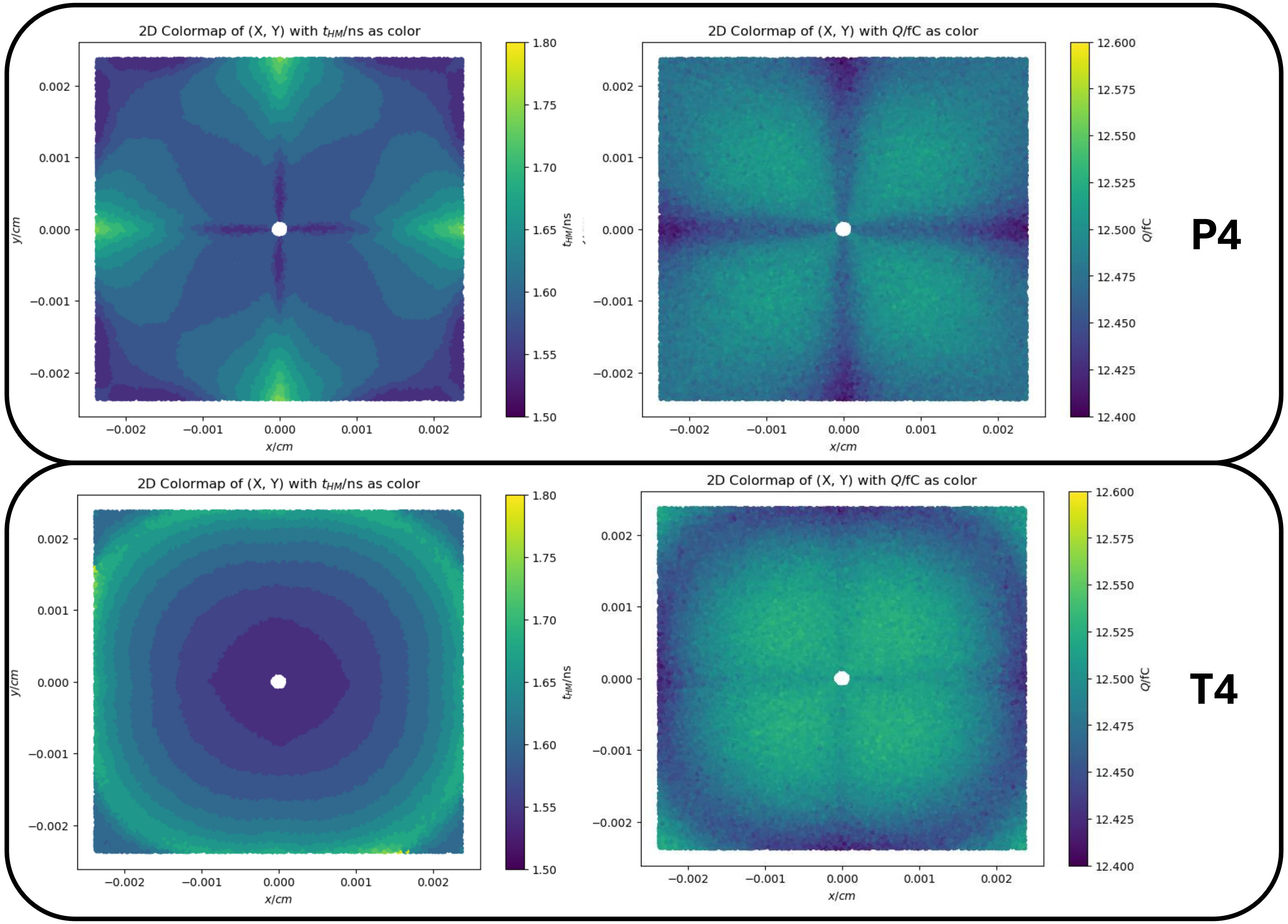
$$n_{\mathrm{TPA}}(z,r) = \frac{\beta_2}{2\hbar\omega}\int_{-\infty}^{+\infty} I^2(r,z,t)\mathrm{d}t$$

⟶ Empirical parameter Needs TPA data!

- TPA data is more accessible.

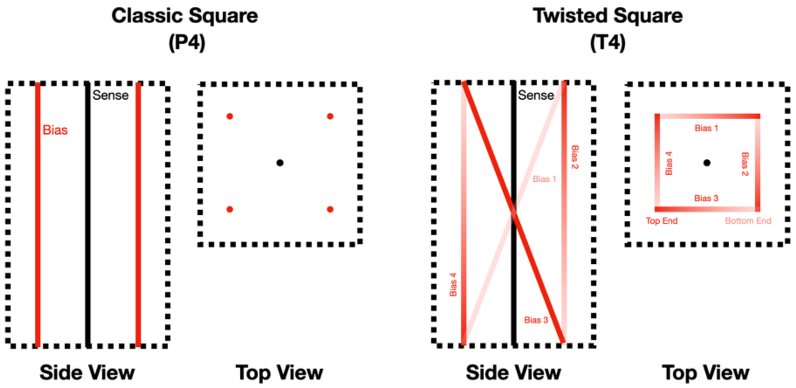
- For now, use MIP simulation
- Next step: use TPA empirical parameters to refine simulation

3D Diamond sensor simulation



t_{HM} Q

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



- Quantities compared:

  t_{HM} :Half-max time

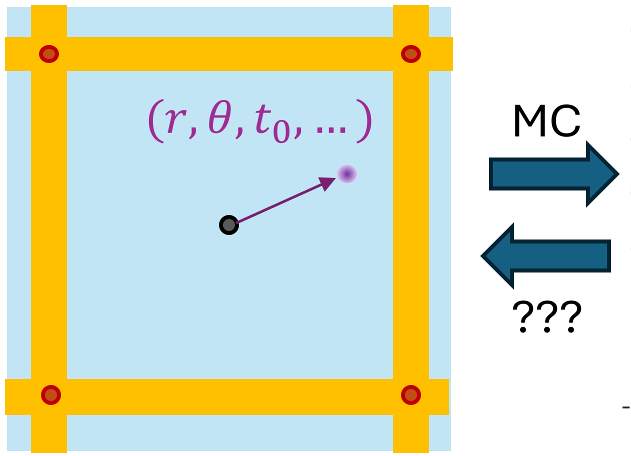
  Q: Collected charge

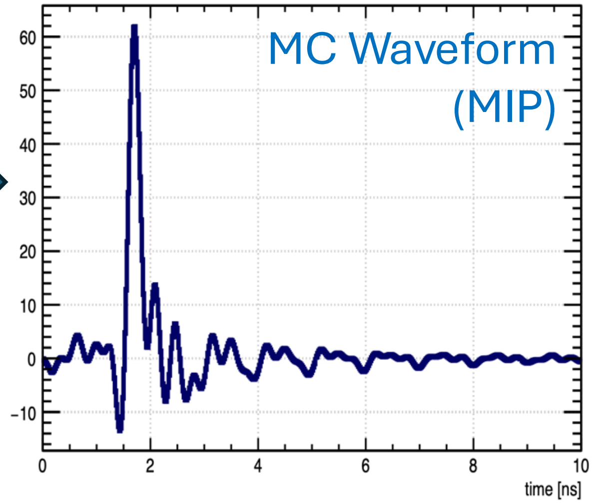
  (Integration from 0 to 10ns)

- **Conclusion**

- **T4 structured sensor shows a more radial symmetric t_{HM} and Q response**

DNN based reconstruction

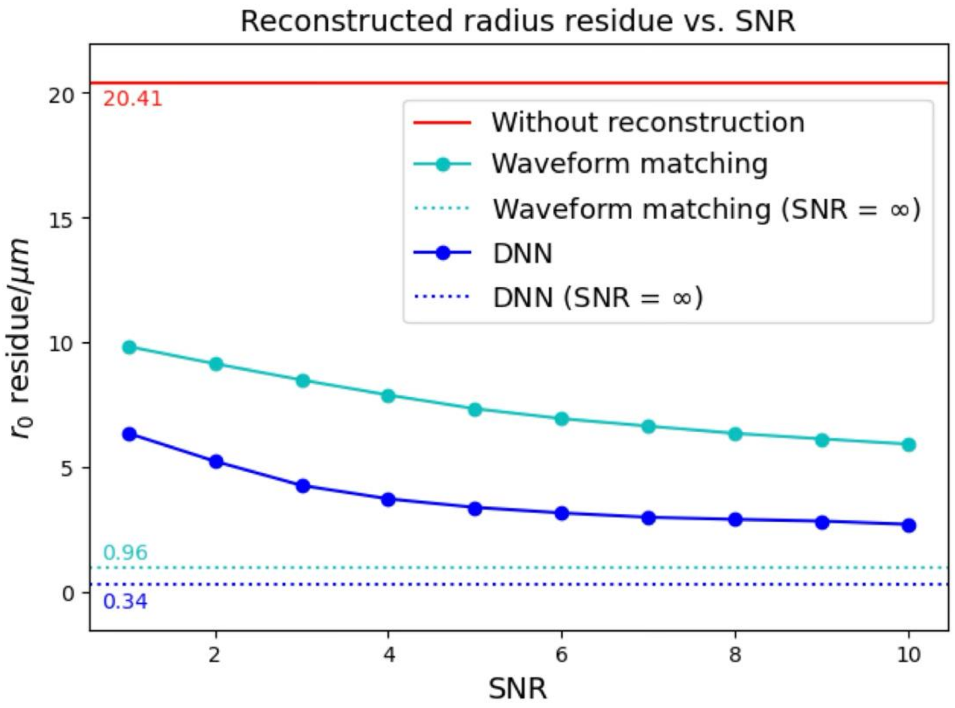




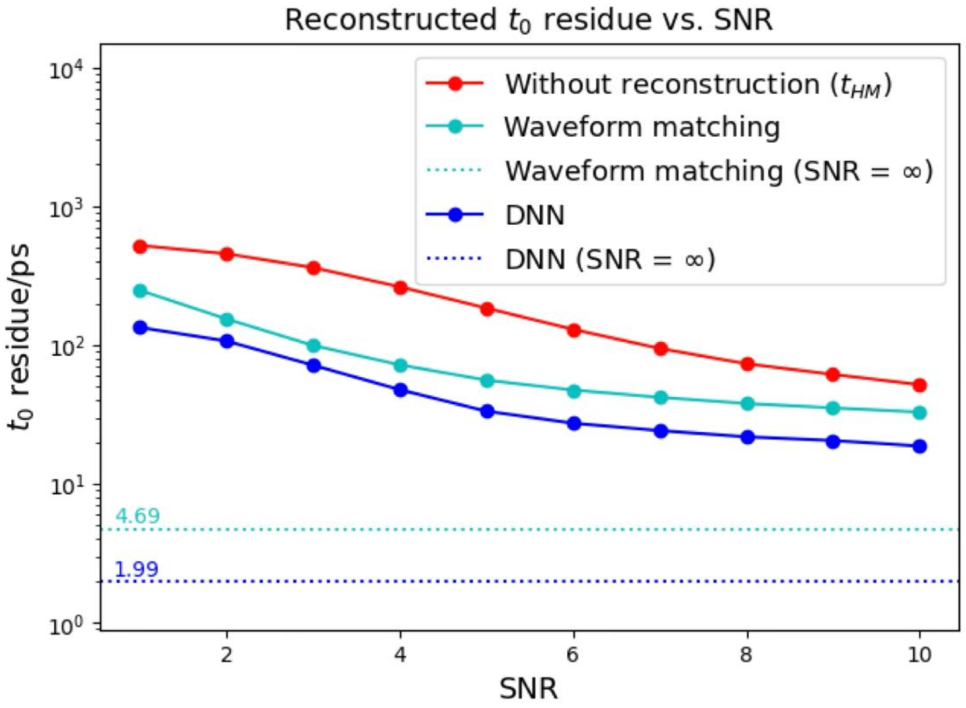
- Current waveform has complicated relationship with physical properties.
- **NN** based algorithm can be used to extract these properties from analog waveform?
- We can use MC simulation to test its ability & stability first.

DNN based reconstruction

- **Tolerance to electric noise**



Reconstructed radius residue vs. SNR



Reconstructed t_0 residue vs. SNR

- As SNR decreasing, spatial and temporal residues of different reconstruction methods are all increasing.
- In all experimental sets, DNN reconstruction method has smaller residue than others.

Work in progress…

Summary and to do list

- **Summary**

TPA energy scan → TPA effect valid, and SPA effect observed

XYZ scan using Cx-L → Correction obtained to remove shadowing effect

XYZ scan using C2-TCT → Correlation between hit position and $\max(I)\ /Q$

MC simulation and DNN → Possibility of new reconstruction method explored

- **To do list**

Reconstructing hit position/time using TPA-TCT and DNN

RC constant: matching MC with TPA data

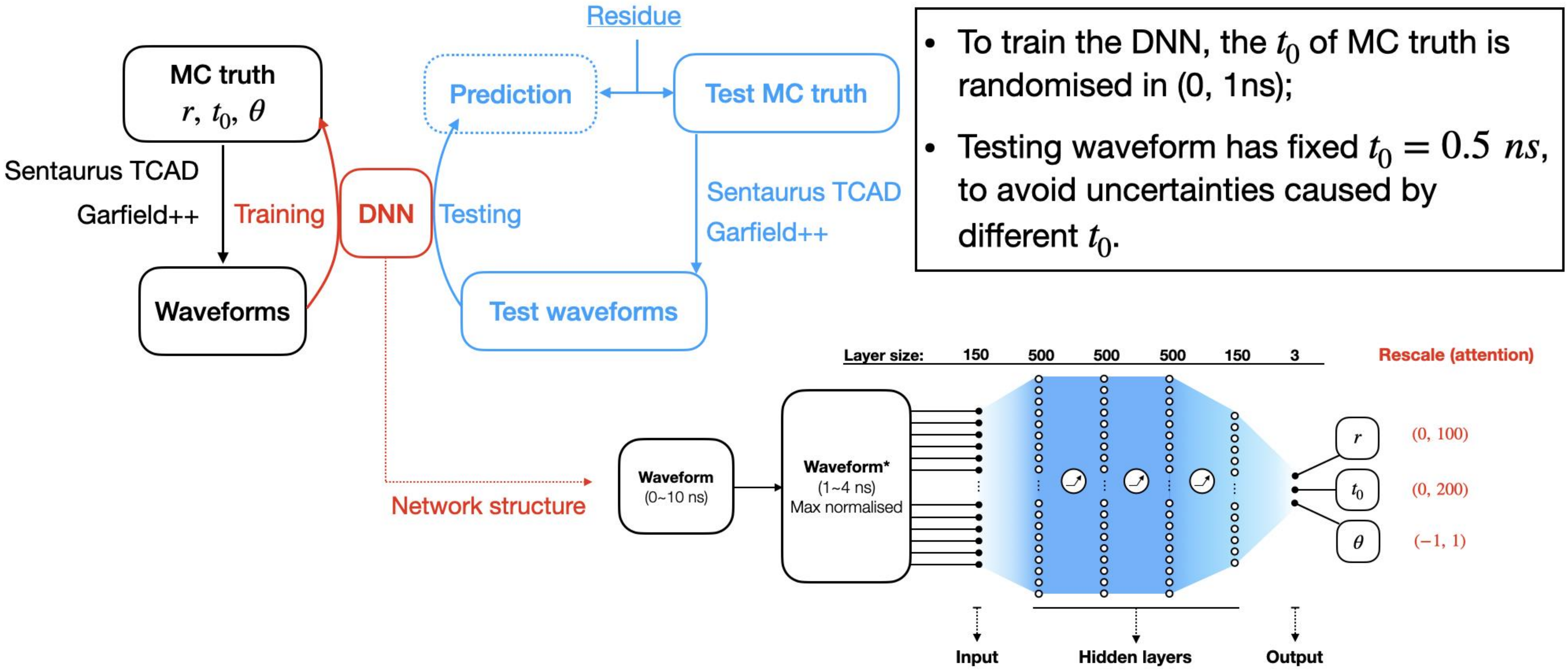
New structured 3D sensors…

Thanks for your attention

Appendix

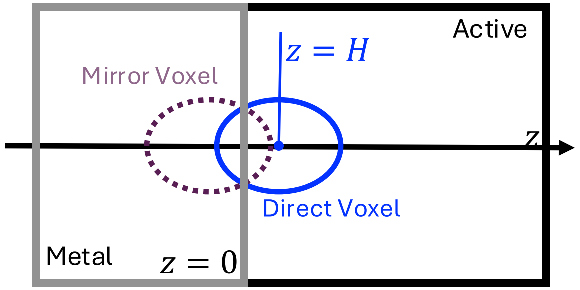
- **DNN based reconstruction: NN structure**

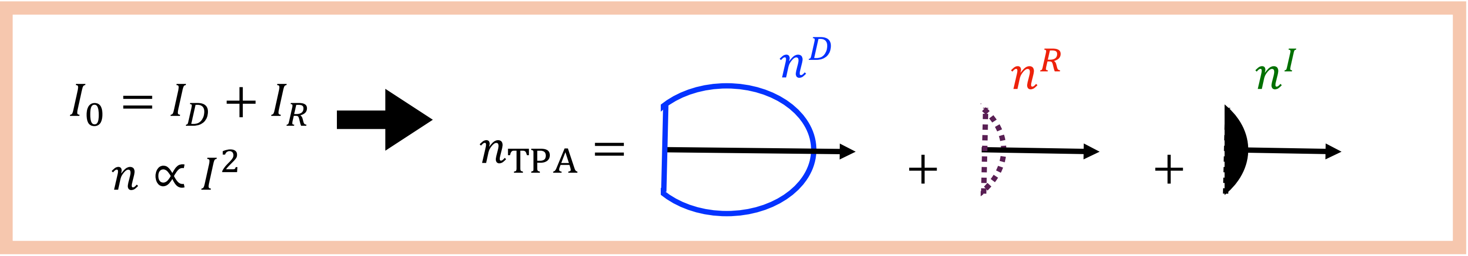
- To train the DNN, the t_0 of MC truth is randomised in (0, 1ns);
- Testing waveform has fixed $t_0 = 0.5\ ns$, to avoid uncertainties caused by different t_0.



Appendix

- **TPA charge deposition**





$I_0 = I_D + I_R$

$n \propto I^2$

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

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

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

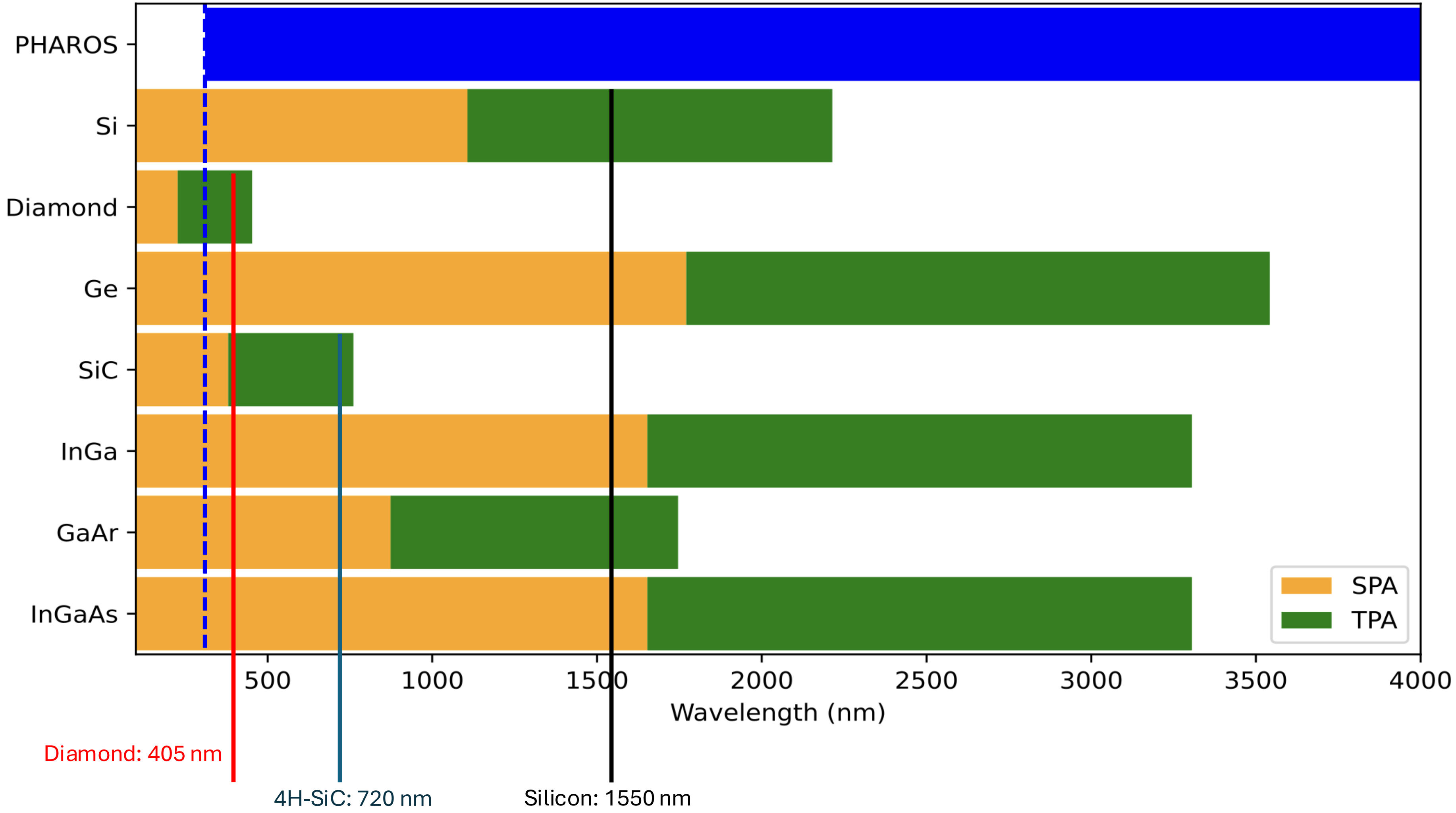
$n^R = R^2 n^D(z+H,r)$

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

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

Appendix

- **TPA wavelength selection**



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