Design and optimisation of radiation resistant AC- and DC-coupled resistive LGADs

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An impossible challenge?

Spatial resolution
$\sim 5\ \mu m$

Temporal resolution
$\sim 10\ ps$

Very low material budget

Very low power consumption

alessandro.fondacci@pg.infn.it

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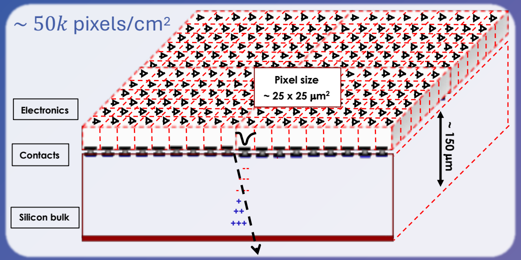

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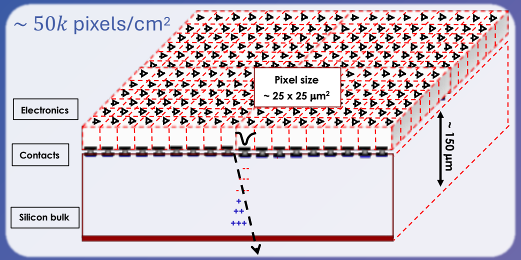

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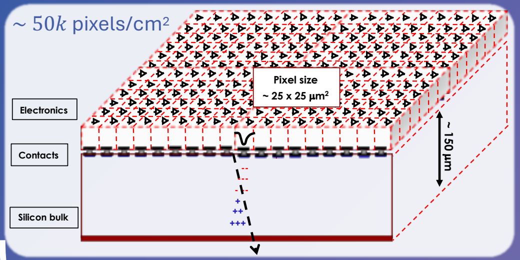

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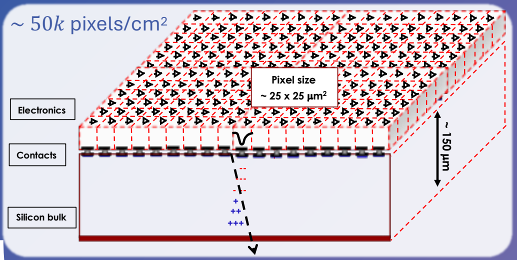

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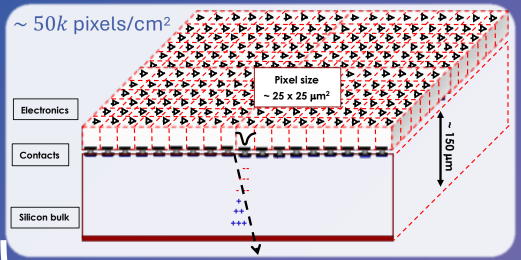

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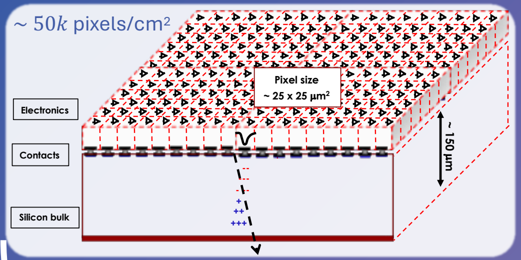

Is there a way to fulfil the four specifications <u>simultaneously</u>?

Temporal resolution
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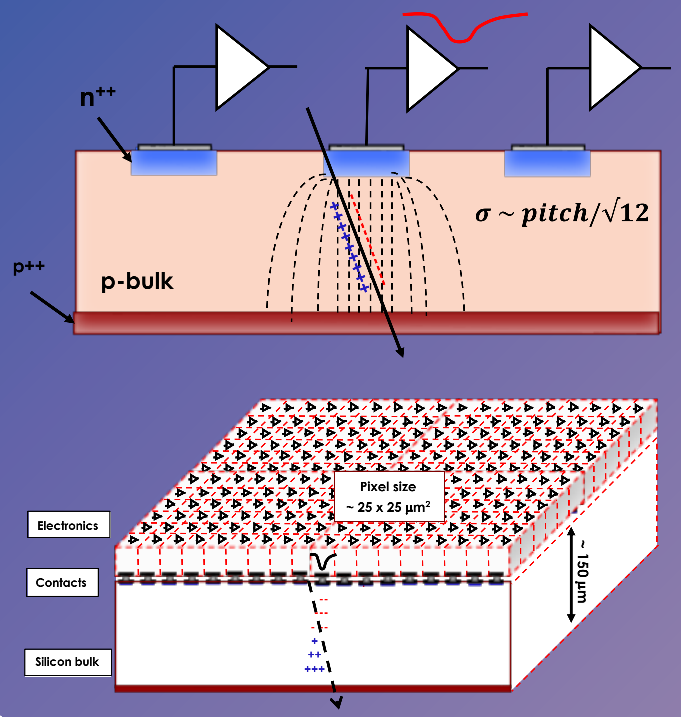
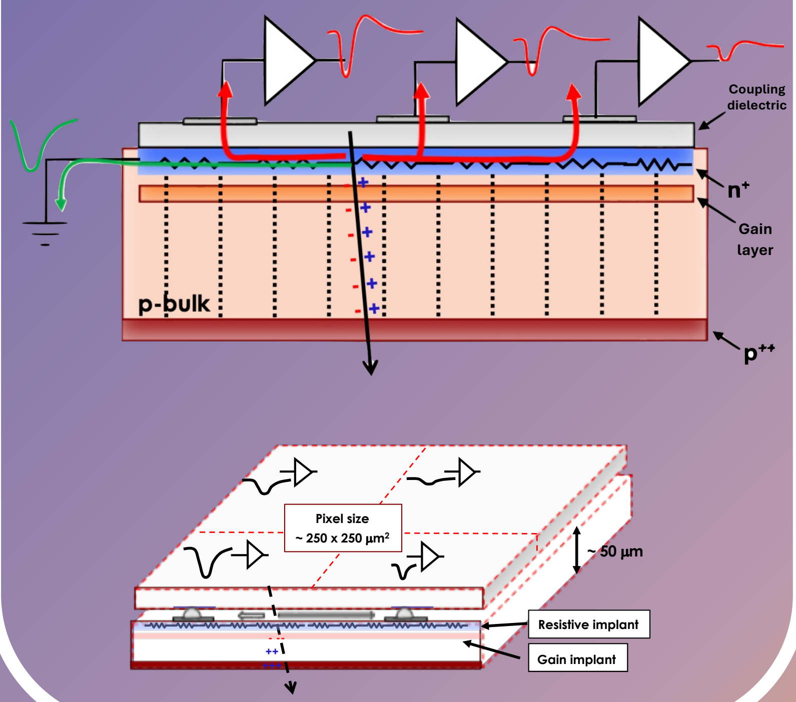
An intriguing candidate for future colliders

Standard silicon detector



Resistive Silicon Detector



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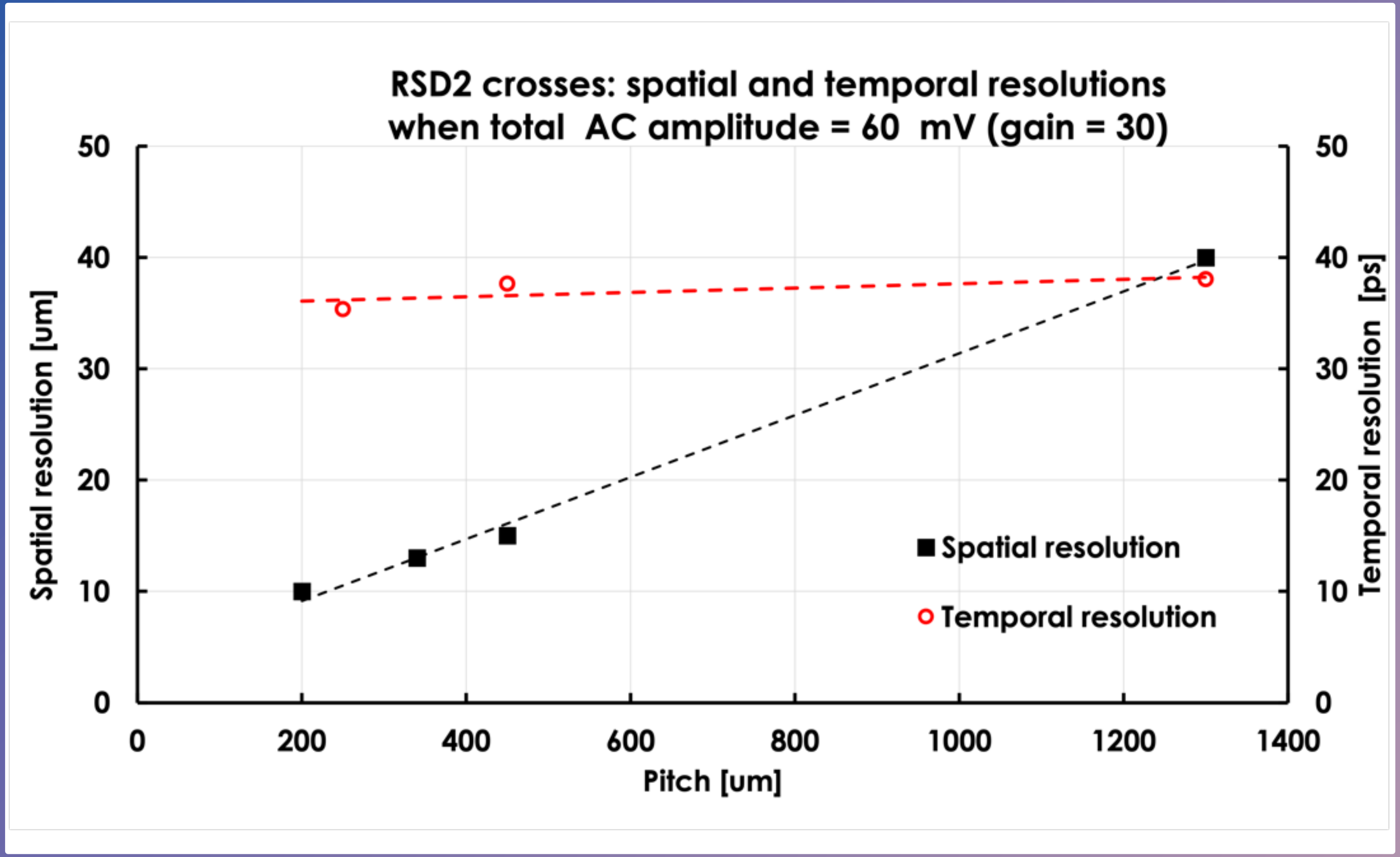
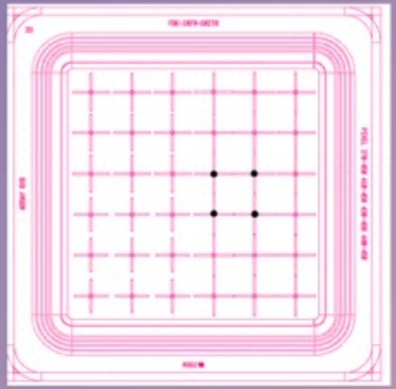
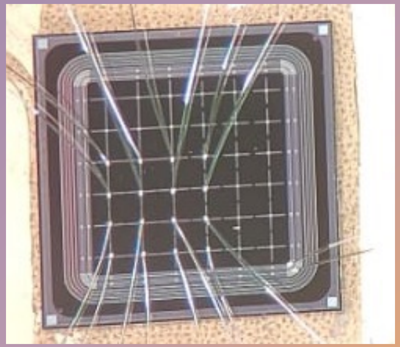
FBK RSD2 performance summary



Layout

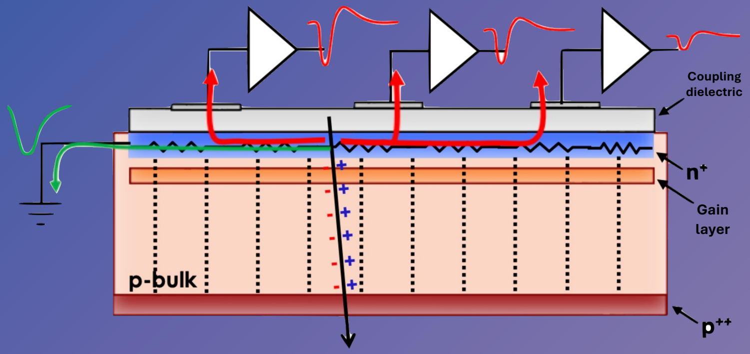


Device made and bonded



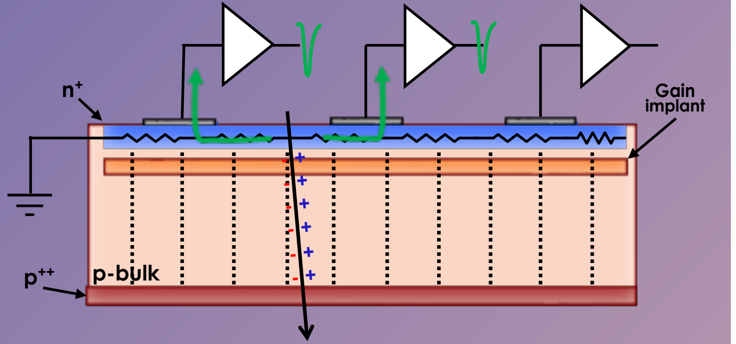
RSD LGAD: AC or DC coupled electrodes?

AC-RSD LGAD



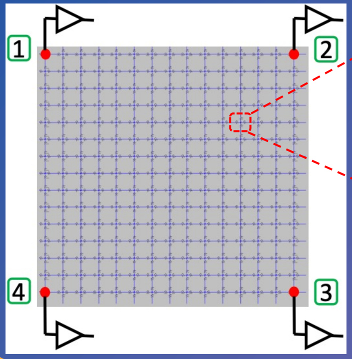
1. Long-tail bipolar signals
2. Baseline fluctuation
3. Uncontrolled signal spreading
4. Not easily scalable to large-area sensors

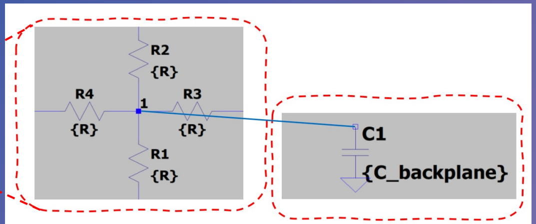
DC-RSD LGAD



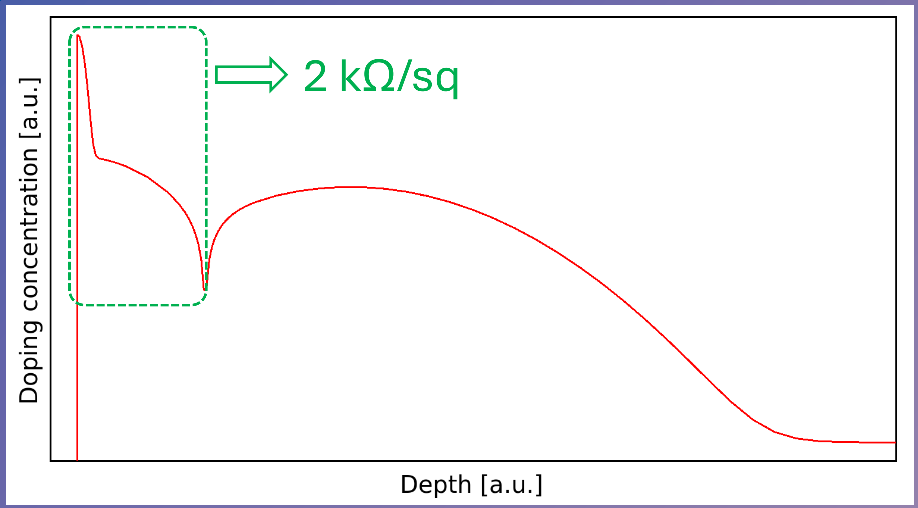
1. Unipolar signals
2. Absence of baseline fluctuation
3. Controlled charge sharing
4. Large sensitive areas (~cm)

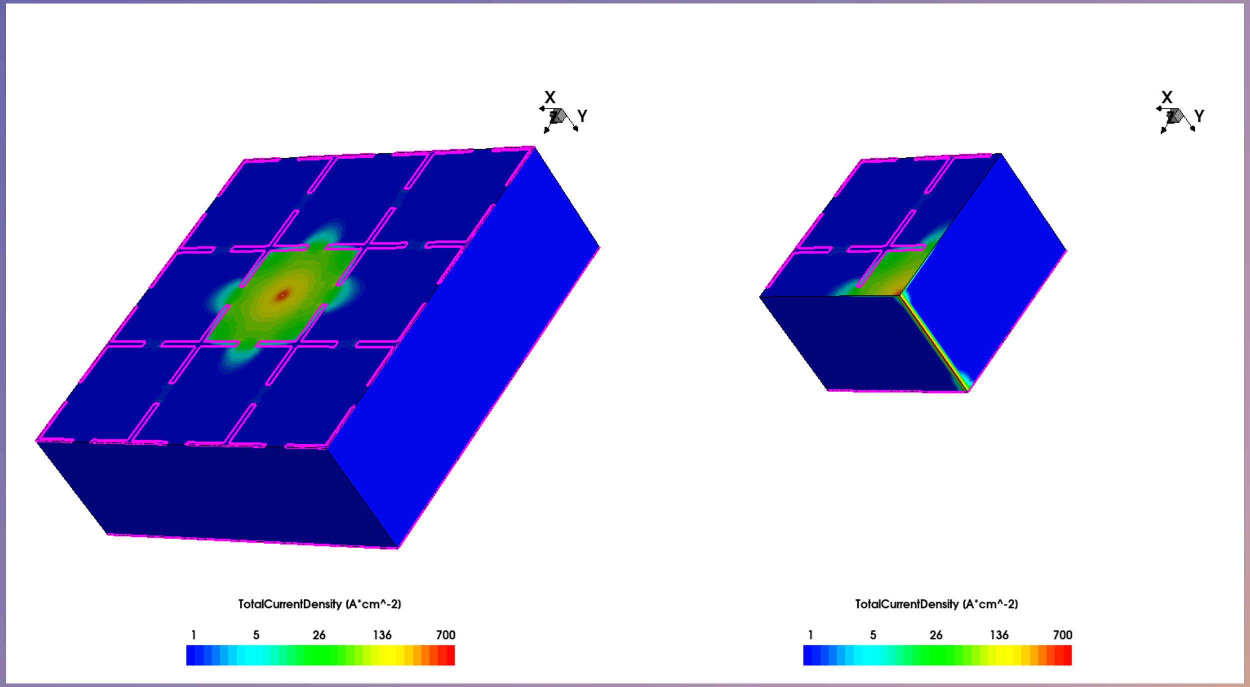
Simulation approach (SPICE & TCAD)





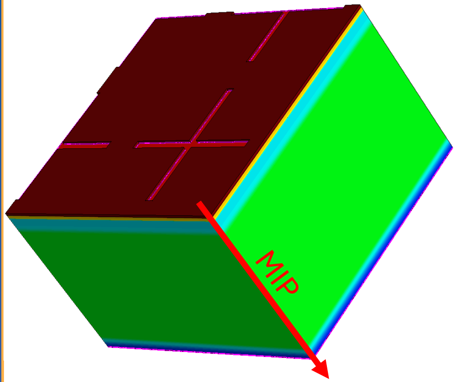
SPICE: Quick estimation of the optimal sheet resistance (2 kΩ/sq)



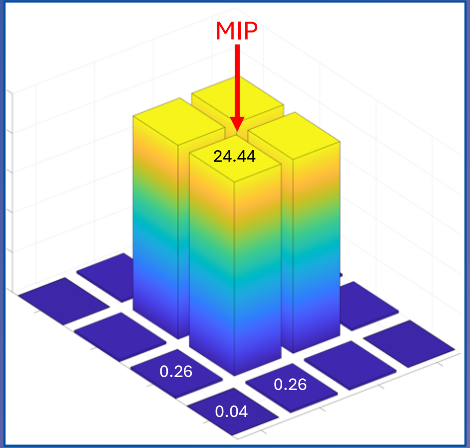


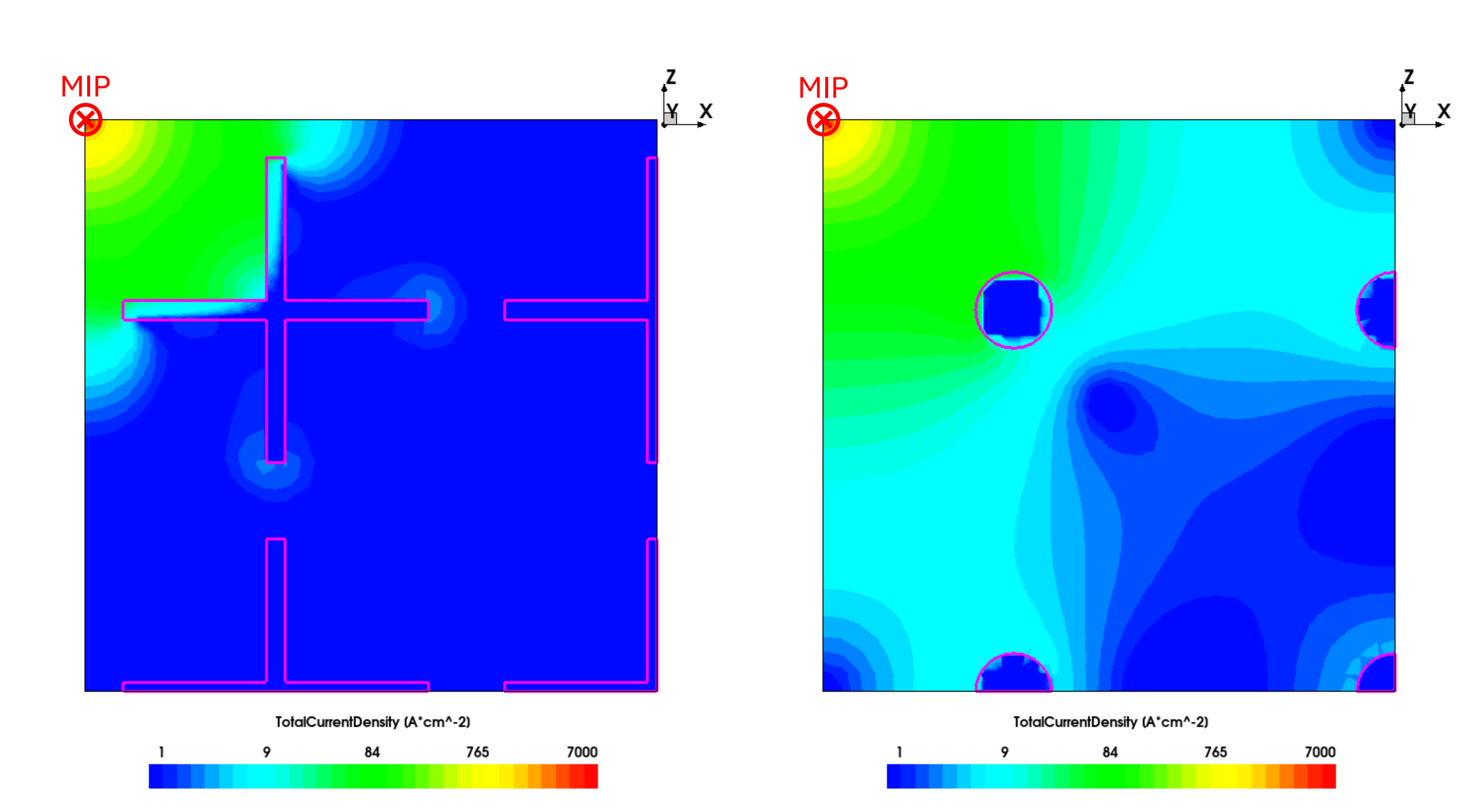
Full 3D TCAD: Evaluation of various geometrical layouts (pad and pixel shapes and dimensions) and technological options (resistive strips and silicon oxide trenches) on signal-sharing properties.

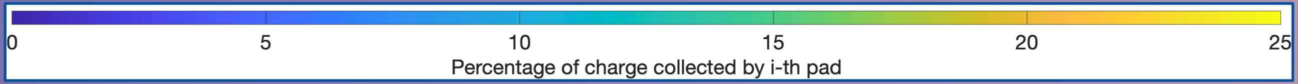
Playing with pad shape

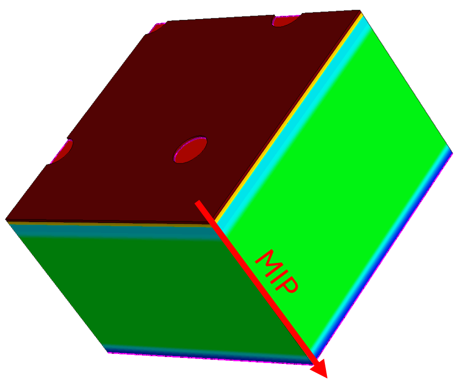


Thickness = 20 μm;
Pitch = 20 μm;
Cross length = 16 μm ;
Cross width = 1 μm.

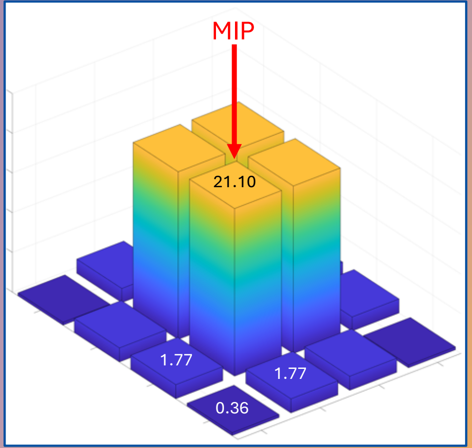




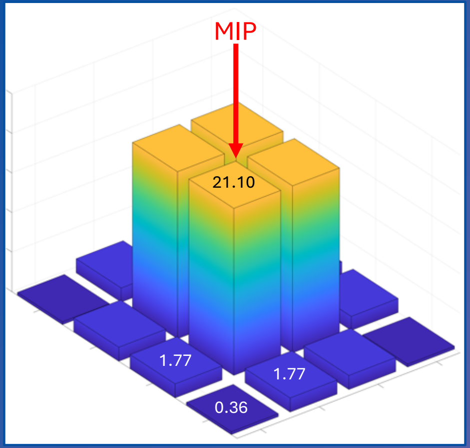


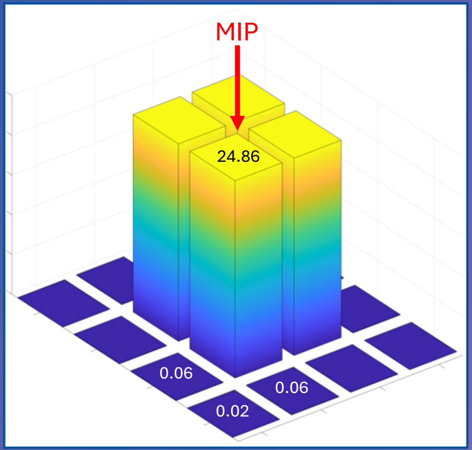


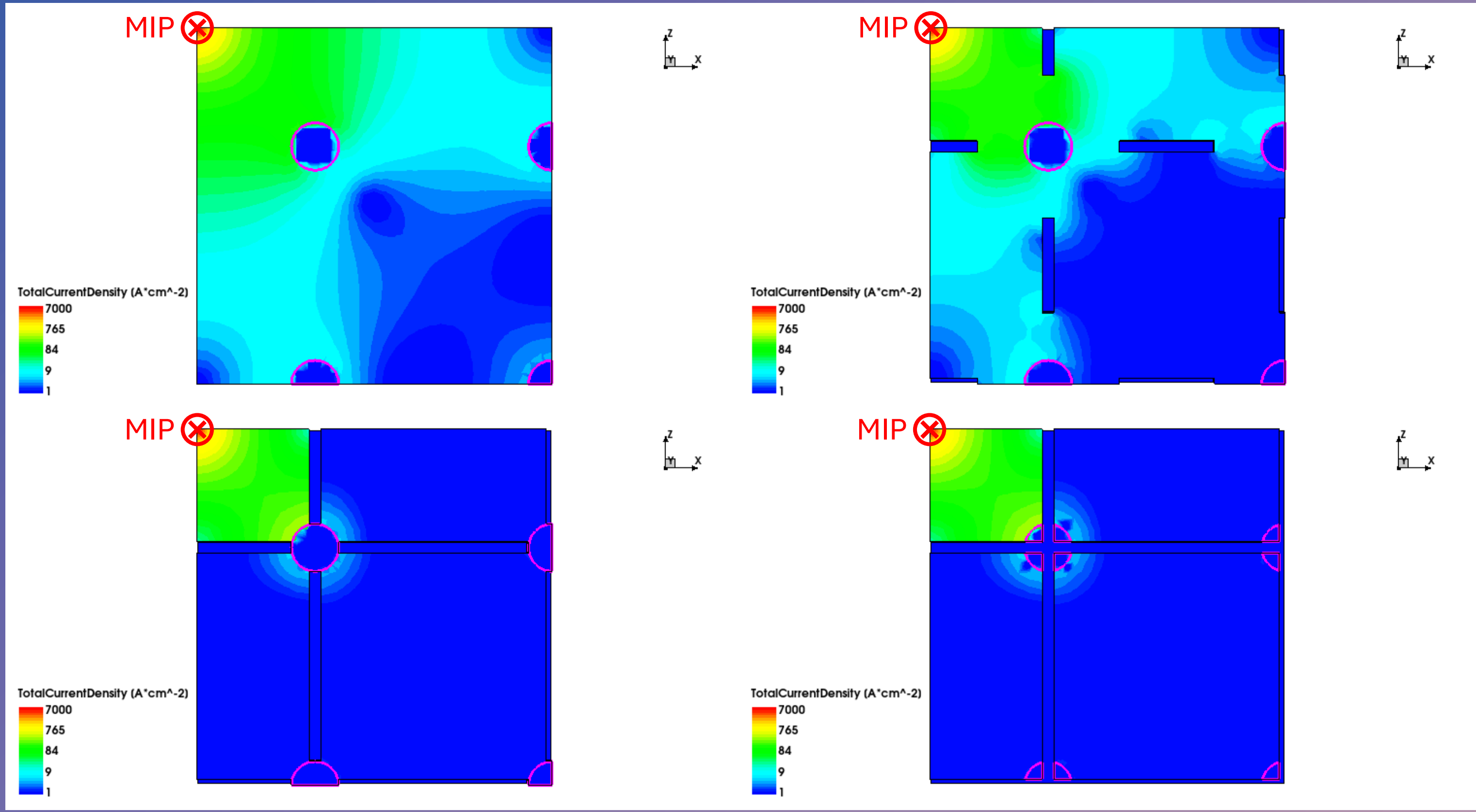
Thickness = 20 μm;
Pitch = 20 μm;
Pad radius = 2 μm.

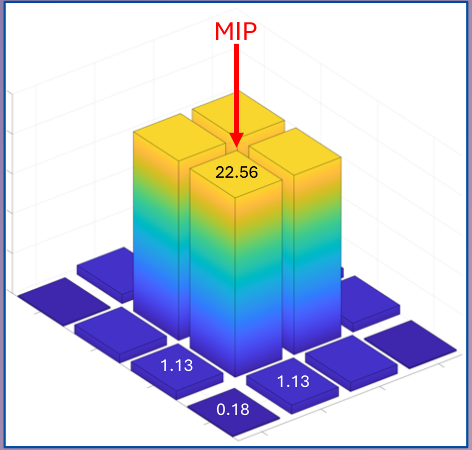


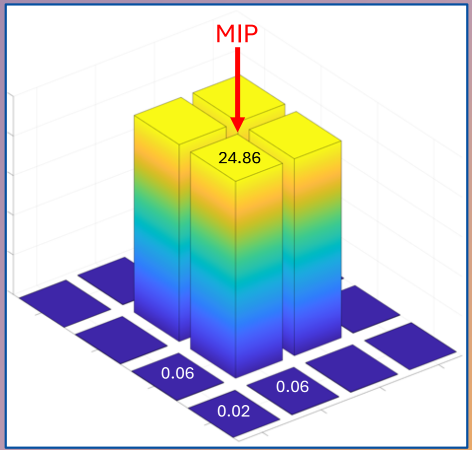
Silicon oxide trenches

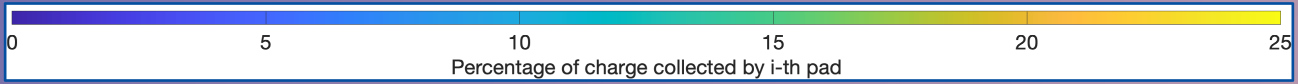




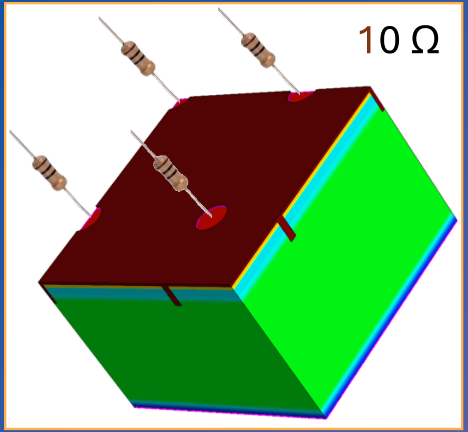


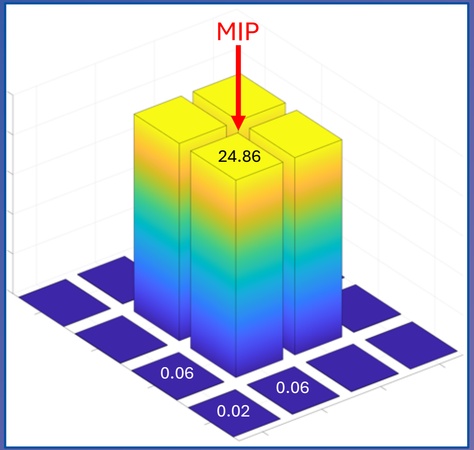


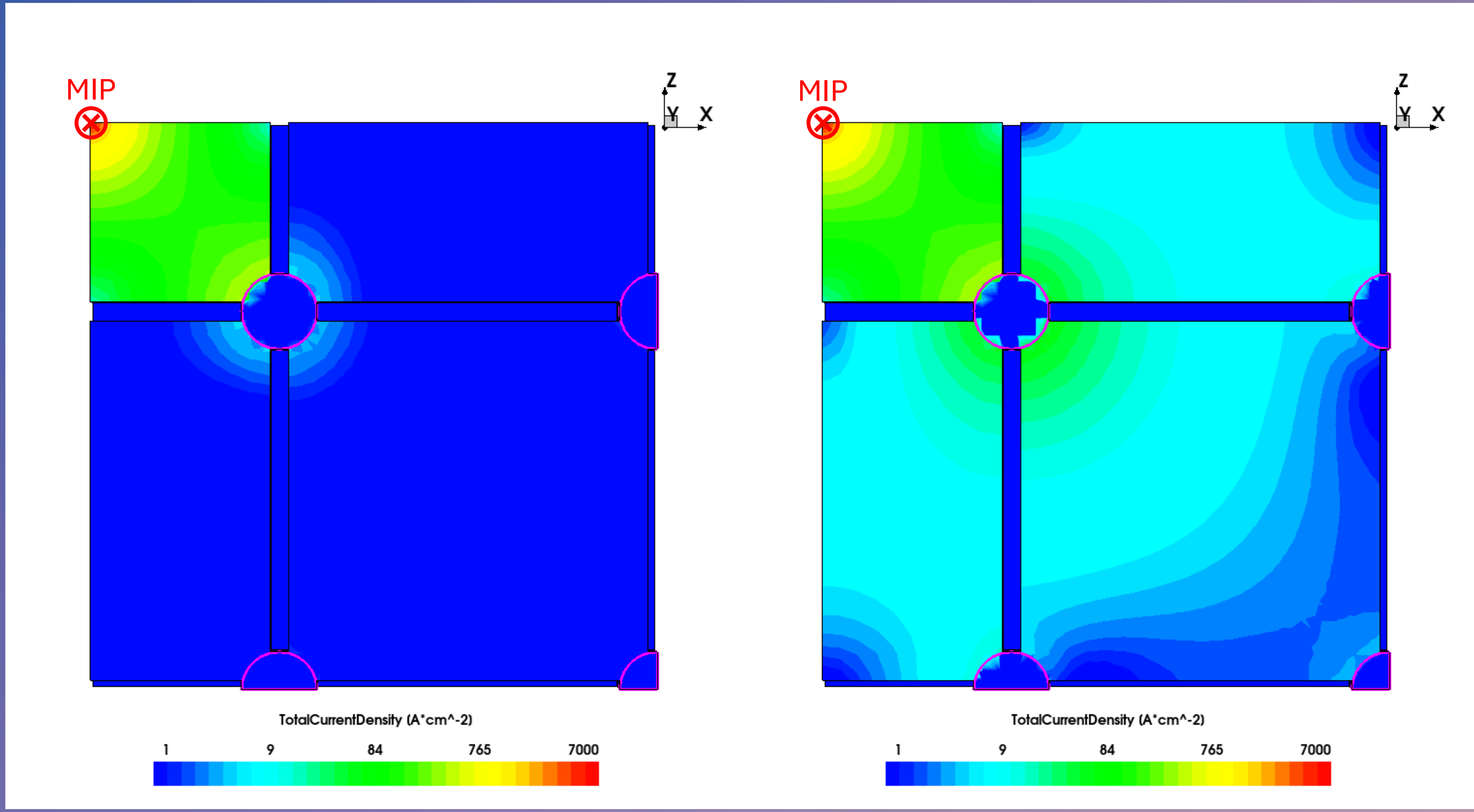


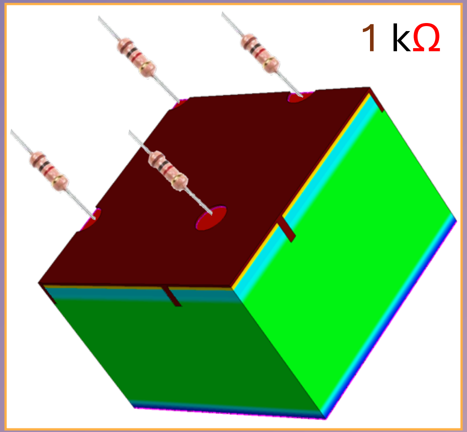


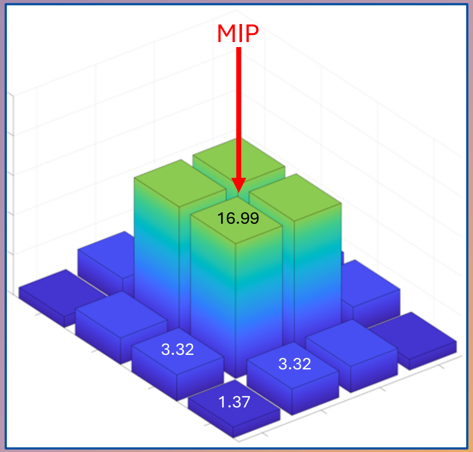
Watch out for contact resistance

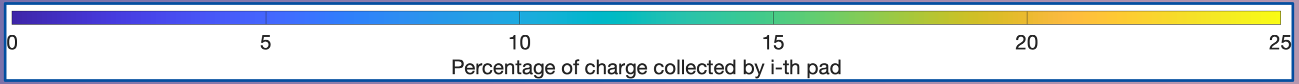




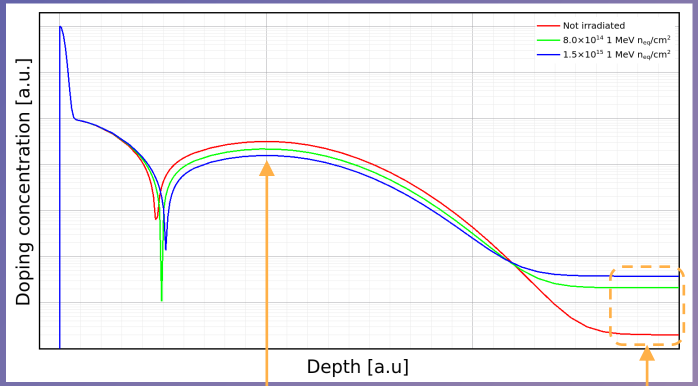








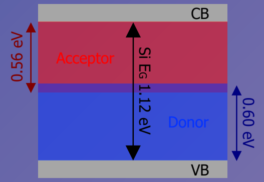
Radiation damage modelling @ PG



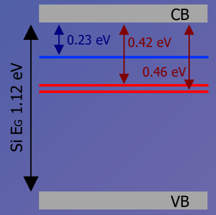
New University of Perugia Radiation Damage Model

Surface damage (+Q_{OX})

Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C$-0.56	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \le E_T \le E_V$+0.6	0.60	$D_{IT} = D_{IT}(\Phi)$



Bulk damage



Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	E_C - 0.23	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

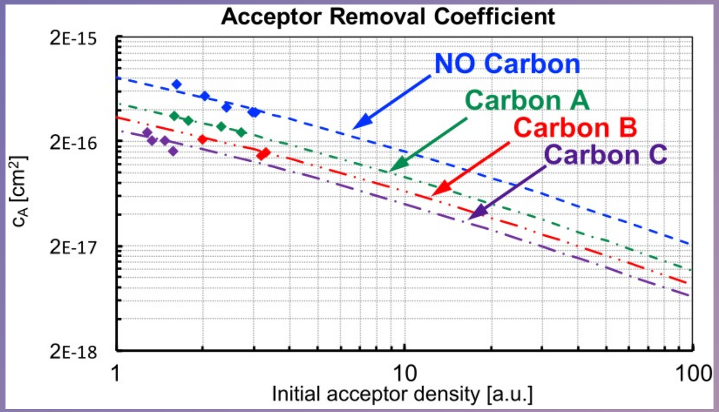
Physically meaningful
deep-level radiation-induced traps

Acceptor Removal

Transformation of electrically active acceptor atoms into neutral defect complexes.

It can be parameterised as

$$N_{A,GL}(\Phi) = N_{A,GL}(0) \cdot e^{-c_A \cdot \phi}$$



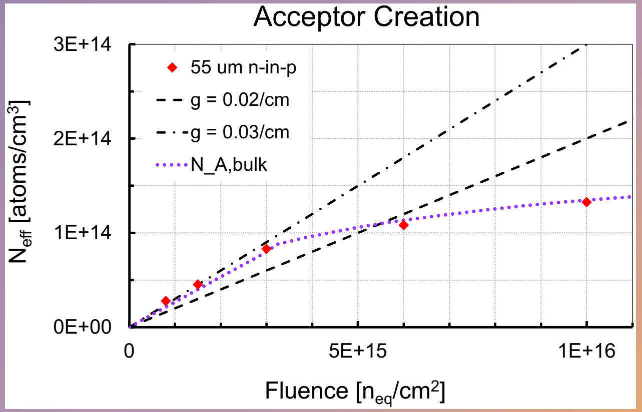
Acceptor Creation

If $\phi \le 3 \cdot 10^{15}\ n_{eq}/cm^2$

$$N_{A,Bulk}(\Phi) = N_{A,Bulk}(0) + g_c \cdot \Phi$$

else

$$N_{A,Bulk}(\Phi) = 4.17 \cdot 10^{13} \cdot \ln\Phi - 1.41 \cdot 10^{15}$$



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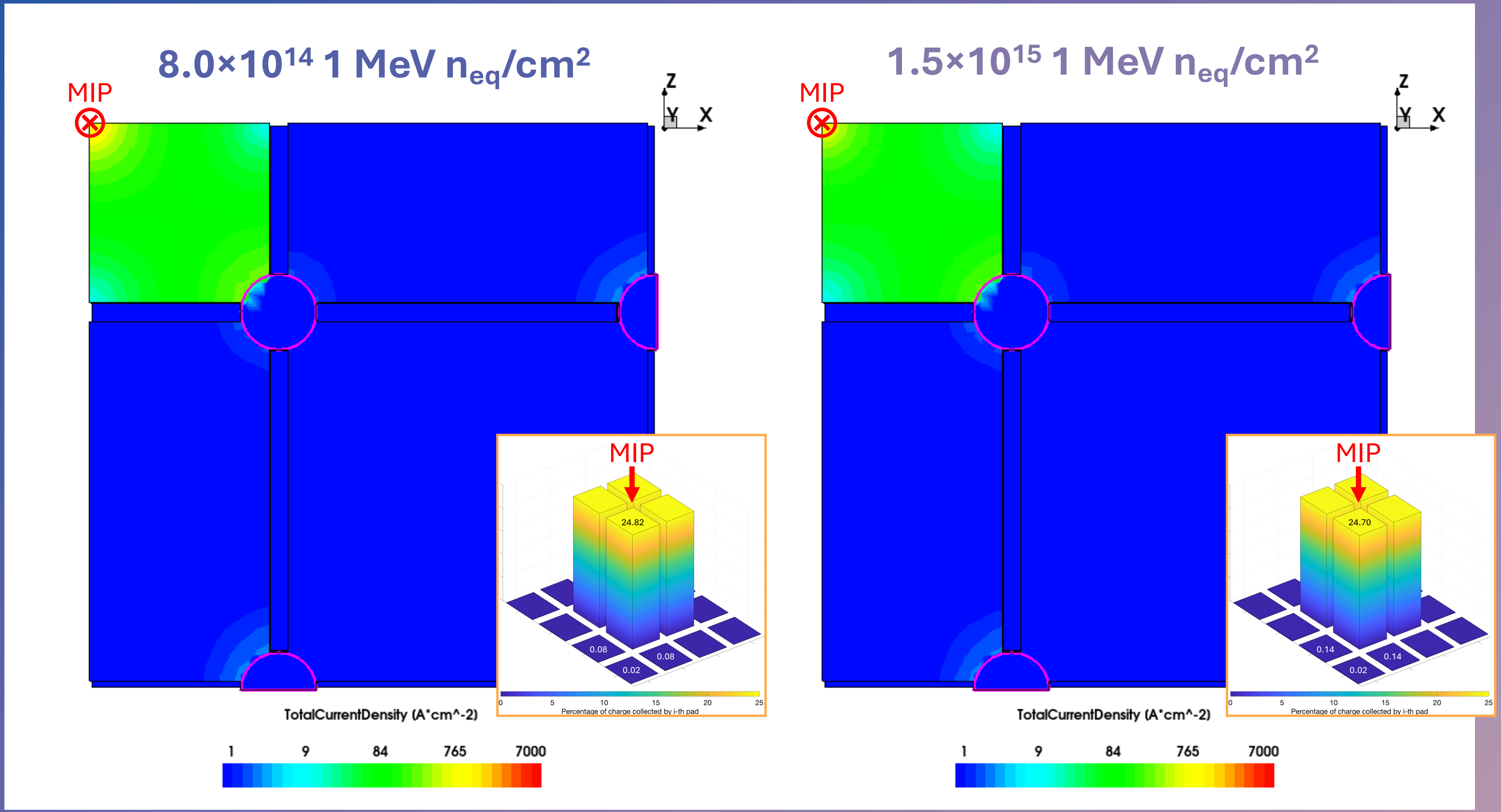
After irradiation performances

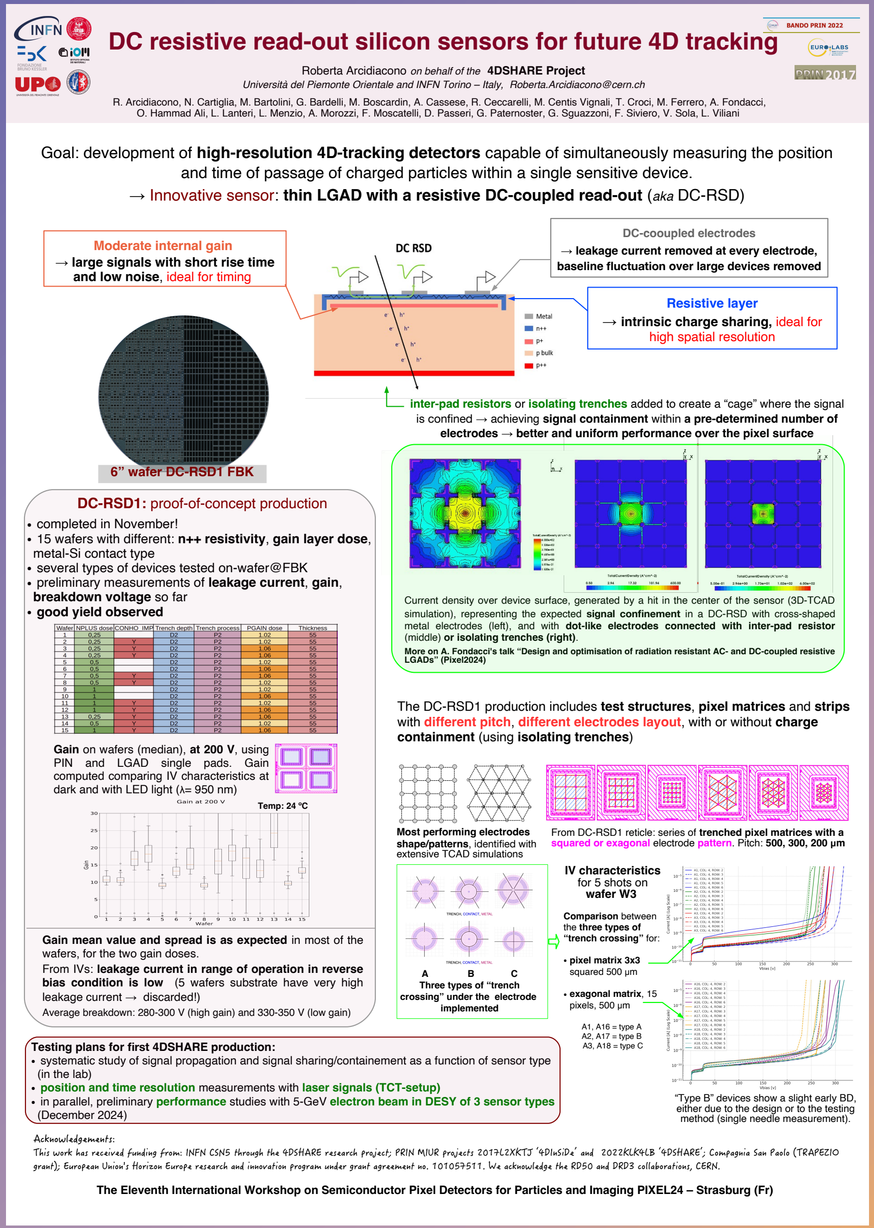


As the fluence increases, the total collected charge decreases due to charge trapping.

However, the total collected charge is always divided in the same way by the resistive plane.

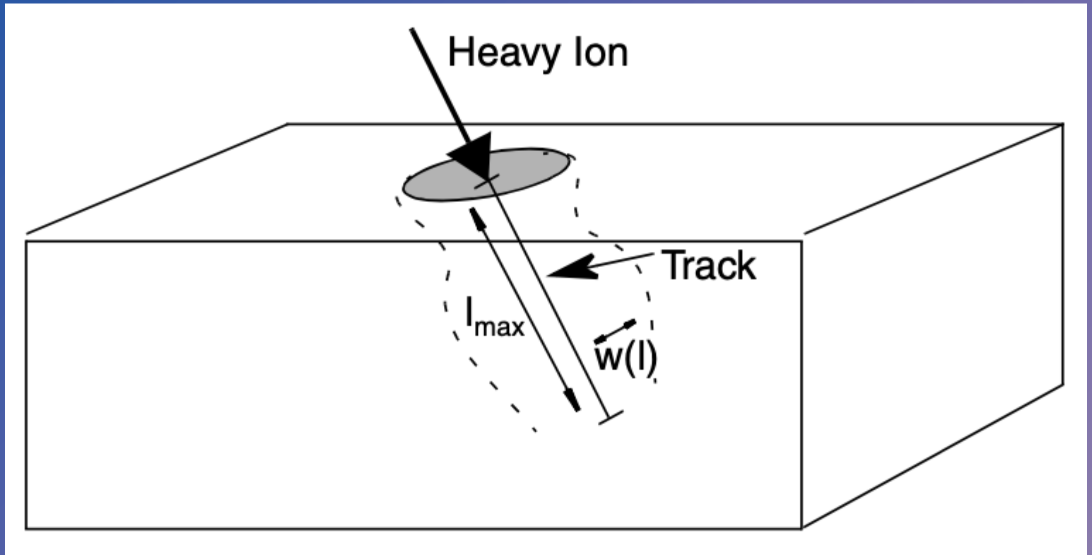
Conclusions

- DC-RSDs are promising candidates for future colliders (e.g. FCC);
- Their first production was guided by comprehensive 3D TCAD simulations:
  - The pads should be small to avoid introducing significant distortion into the impact point reconstruction;
  - Pad-to-pad trenching effectively confines the signal when utilising small circular pads.
- The wafers left the clean room a fortnight ago, and the first experimental measurements were carried out.



Backup

Heavy Ion Model



- A **MIP** can be modelled through the Heavy Ion Model, whose generation rate is given by the following expression:

$$G(l,w,t) = \begin{cases} G_{LET}(l)R(w,l)T(t) & if\ l < l_{max} \\ 0 & if\ l \geq l_{max} \end{cases}$$

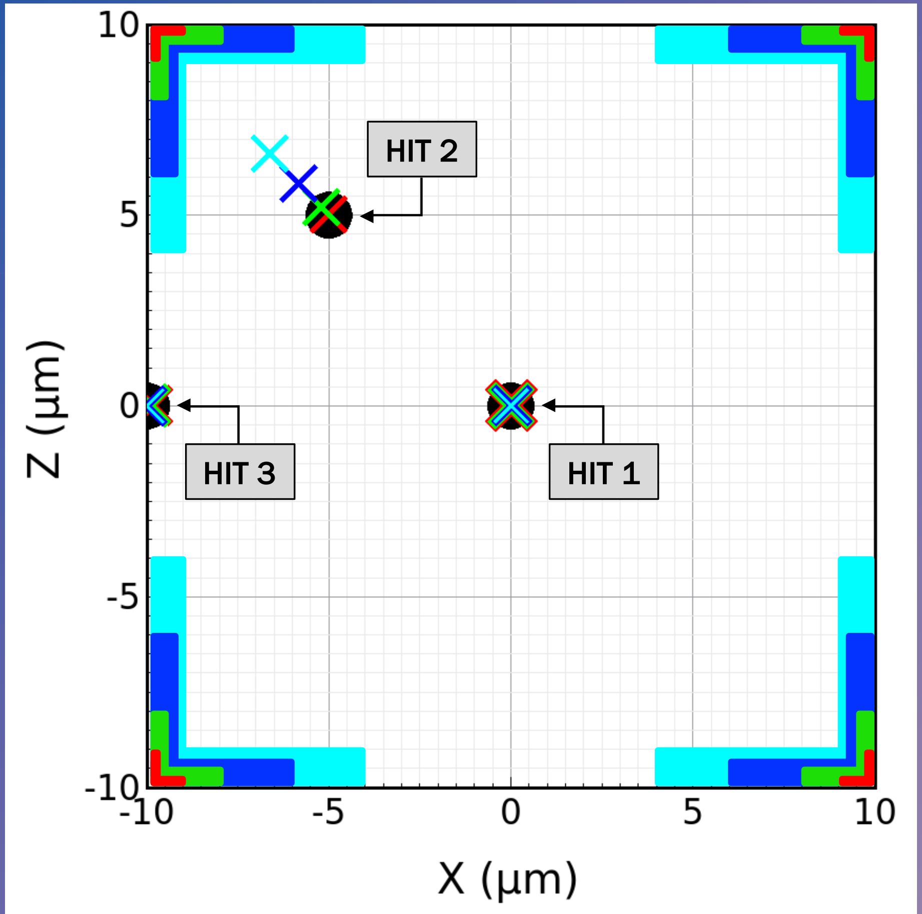
- $T(t)$ is a function describing the temporal variation of the generation rate;
  - *In particular, it's a Gaussian function whose mean value represents the moment of the heavy ion penetration.*
- $R(w,l)$ is a function describing the spatial variation of the generation rate;
  - *It too is a Gaussian and $w(l)$ represents its standard deviation.*
- $G_{LET}(l)$ represents the linear energy transfer generation density, expressed in e/h pairs per cm^3 by default .

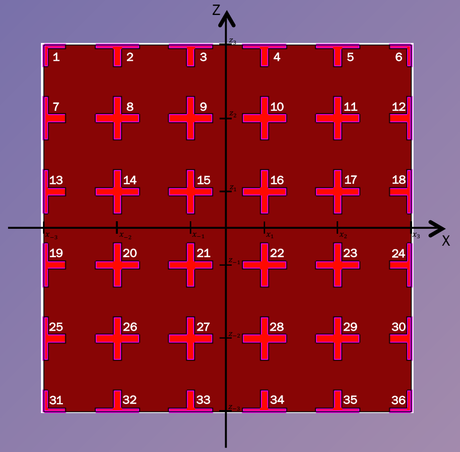
How many e/h pairs are generated by the MIP for each µm crossed?

- $\frac{Energy\ Loss\ [eV/\mu m]}{3.68\ eV}$
- $Energy\ Loss[keV/\mu m] = 0.027\ln(depth) + 0.126$

S. Meroli et al., *Energy loss measurement for charged particles in very thin silicon layers,* Journal of Instrumentation, vol. 06, P06013, Jun. 2011

Charge imbalance algorithm





X-coordinate

- $Q_{x_{-3}} = Q_1 + Q_7 + Q_{13} + Q_{19} + Q_{25} + Q_{31}$
- $Q_{x_{-2}} = Q_2 + Q_8 + Q_{14} + Q_{20} + Q_{26} + Q_{32}$
- $Q_{x_{-1}} = Q_3 + Q_9 + Q_{15} + Q_{21} + Q_{27} + Q_{33}$
- $Q_{x_1} = Q_4 + Q_{10} + Q_{16} + Q_{22} + Q_{28} + Q_{34}$
- $Q_{x_2} = Q_5 + Q_{11} + Q_{17} + Q_{23} + Q_{29} + Q_{35}$
- $Q_{x_3} = Q_6 + Q_{12} + Q_{18} + Q_{24} + Q_{30} + Q_{36}$

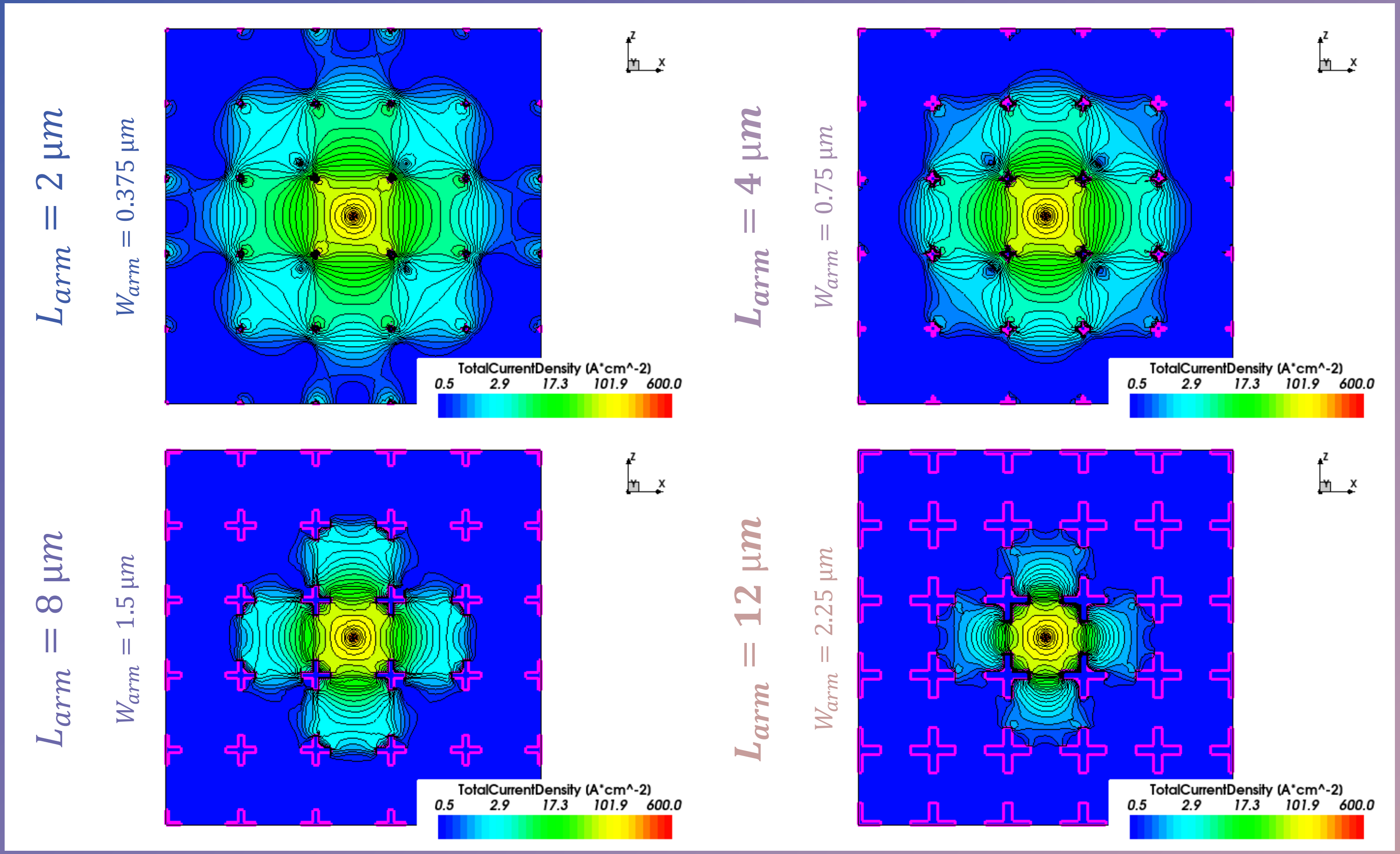
$$X_R = \frac{\sum_{\substack{i=-3 \\ i\neq 0}}^{3} Q_{x_i} \cdot x_i}{\sum_{i=1}^{36} Q_i}$$

Z-coordinate

- $Q_{z_{-3}} = Q_{31} + Q_{32} + Q_{33} + Q_{34} + Q_{35} + Q_{36}$
- $Q_{z_{-2}} = Q_{25} + Q_{26} + Q_{27} + Q_{28} + Q_{29} + Q_{30}$
- $Q_{z_{-1}} = Q_{19} + Q_{20} + Q_{21} + Q_{22} + Q_{23} + Q_{24}$
- $Q_{z_1} = Q_{13} + Q_{14} + Q_{15} + Q_{16} + Q_{17} + Q_{18}$
- $Q_{z_2} = Q_7 + Q_8 + Q_9 + Q_{10} + Q_{11} + Q_{12}$
- $Q_{z_3} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$

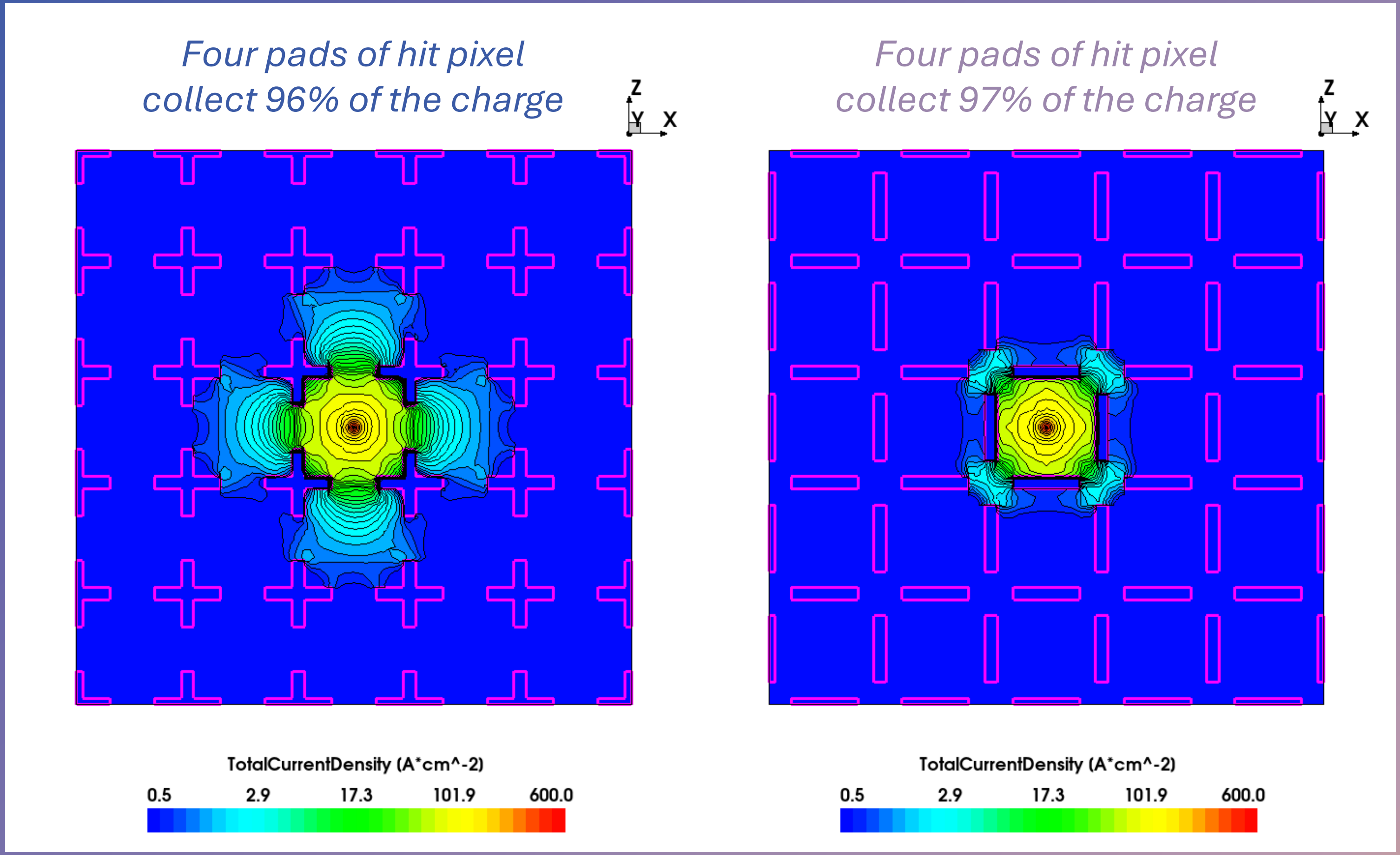
$$Z_R = \frac{\sum_{\substack{i=-3 \\ i\neq 0}}^{3} Q_{z_i} \cdot z_i}{\sum_{i=1}^{36} Q_i}$$

Crosses of various sizes



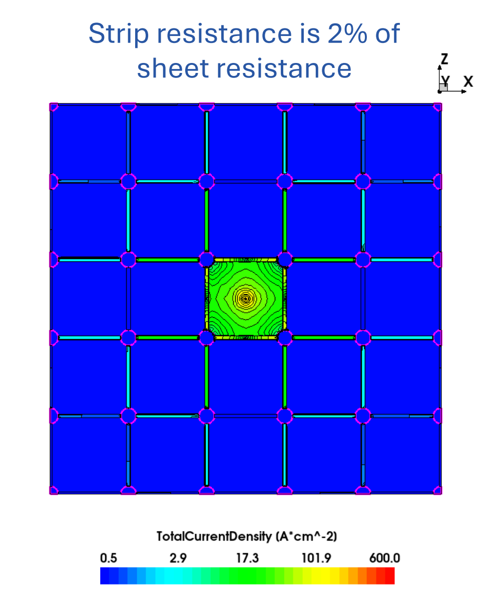
Crosses 🤼 bars

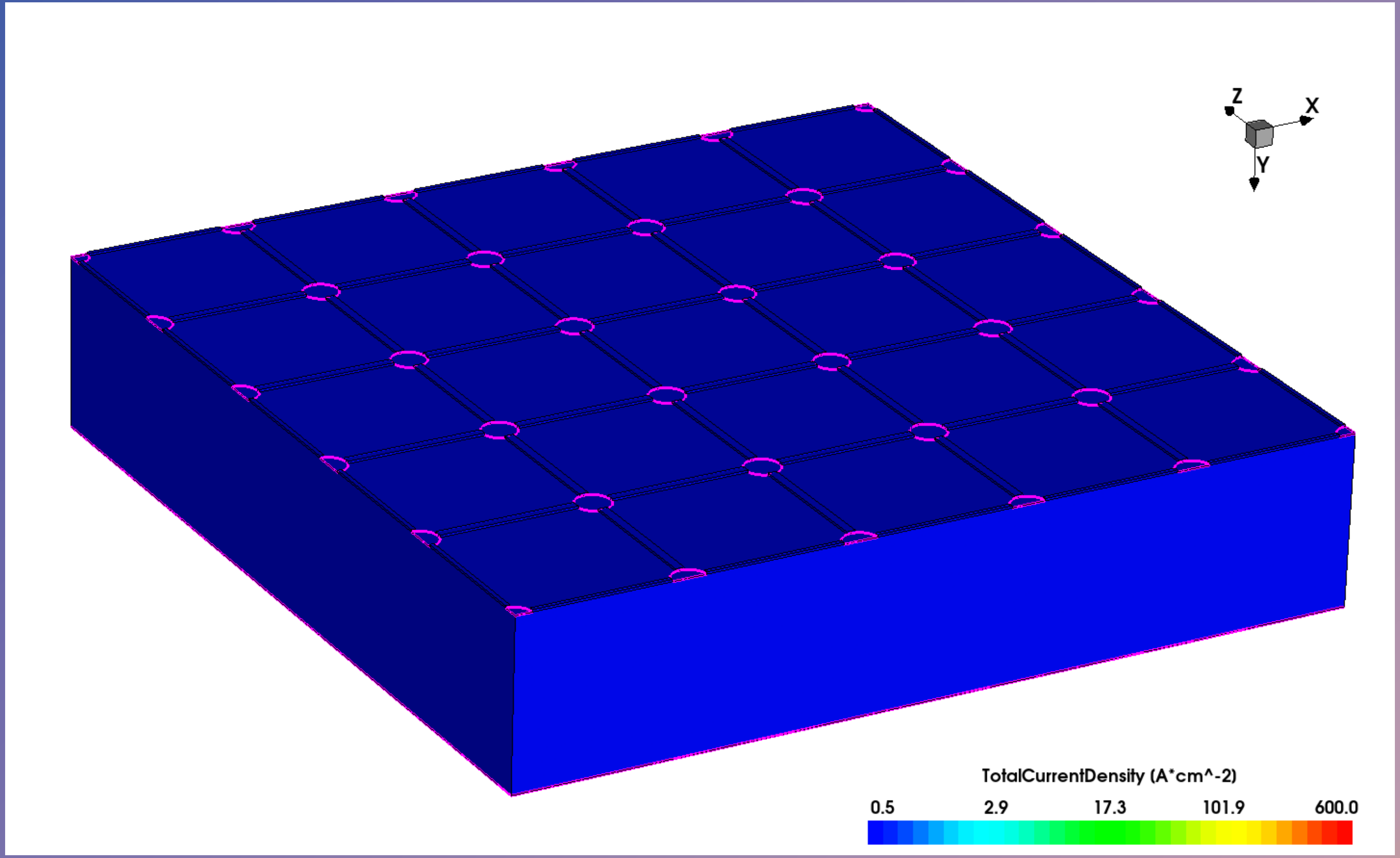
36 electrodes

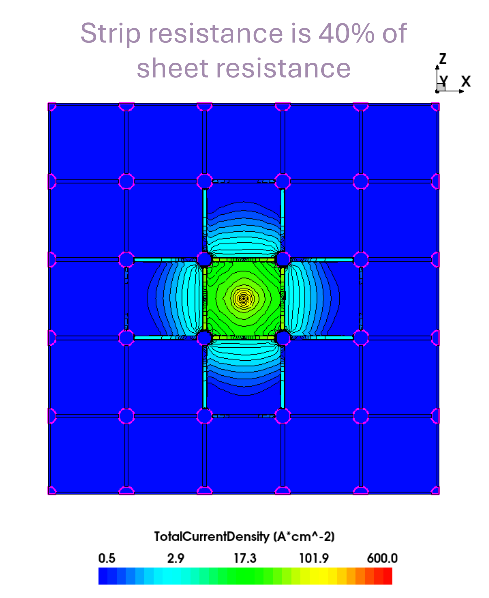


60 electrodes

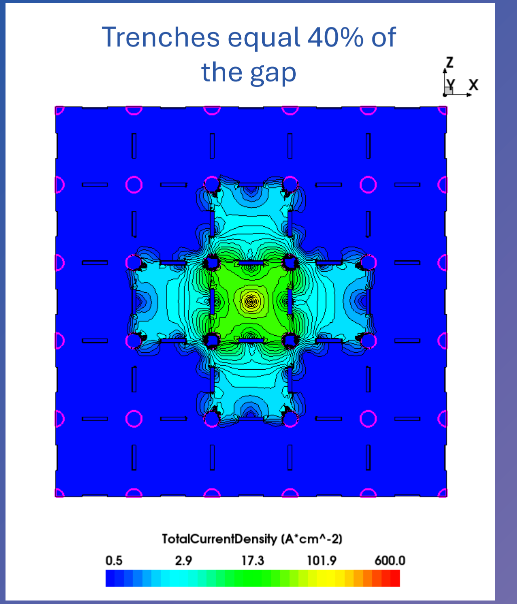
Resistive strips

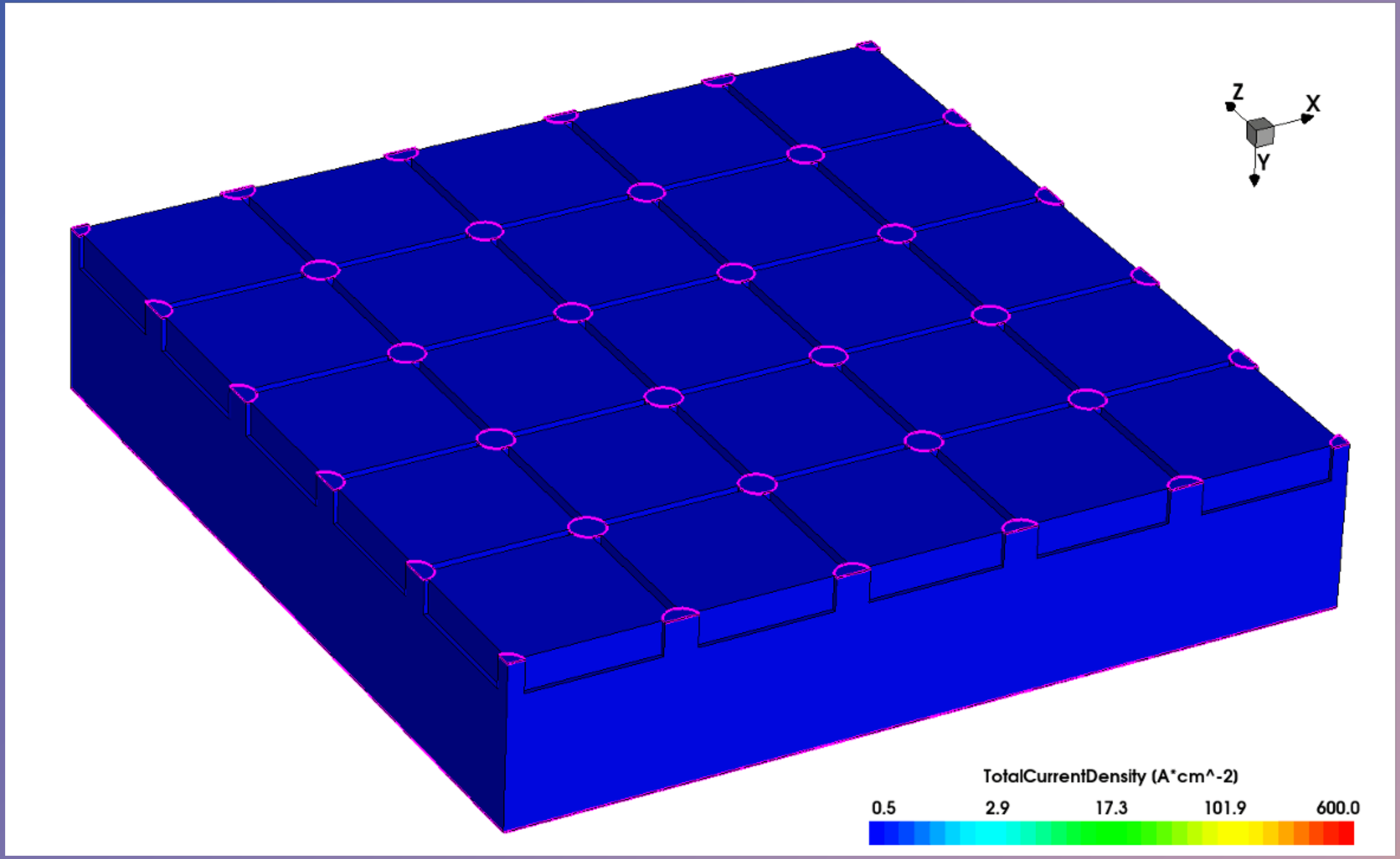


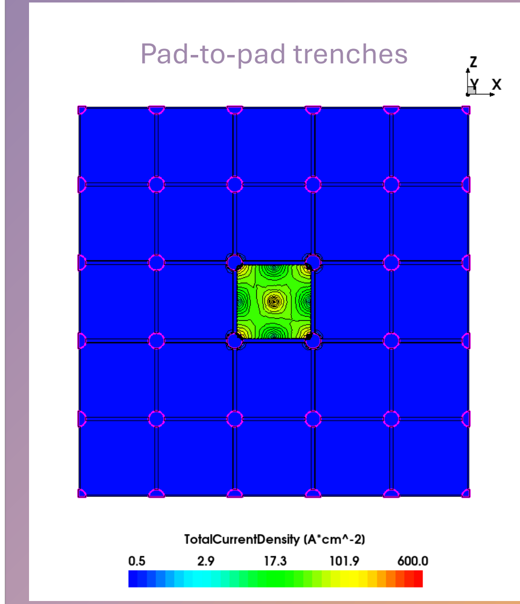




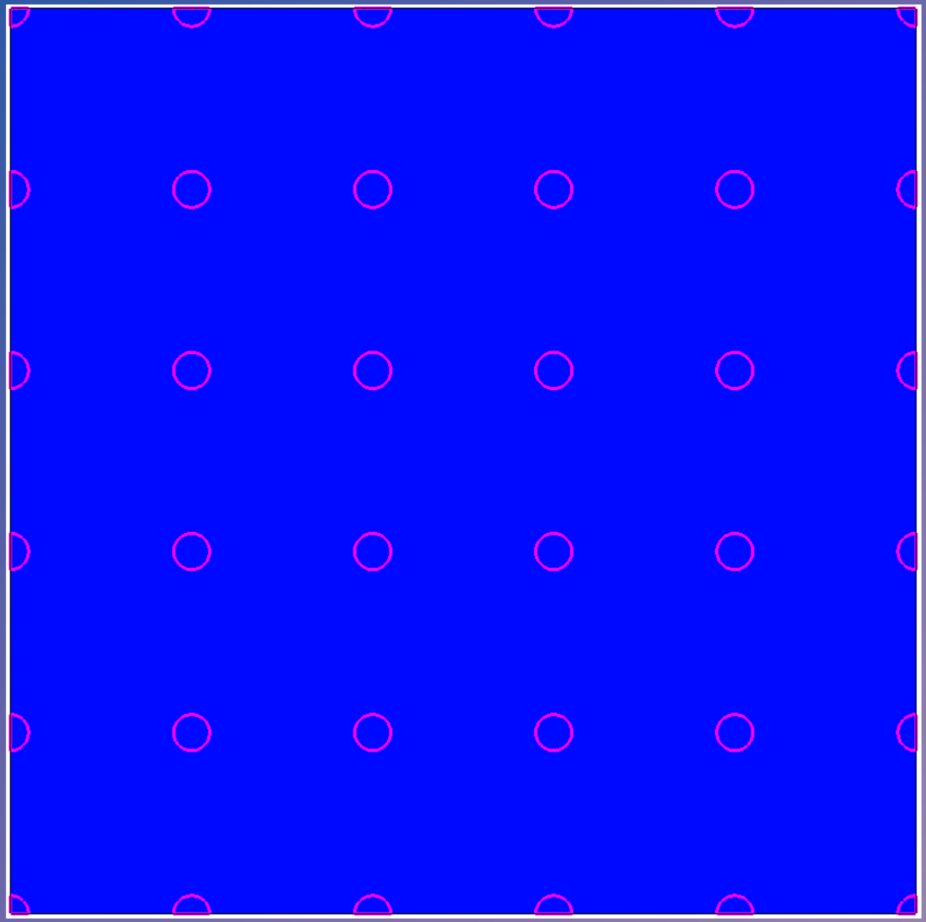
Silicon oxide trenches

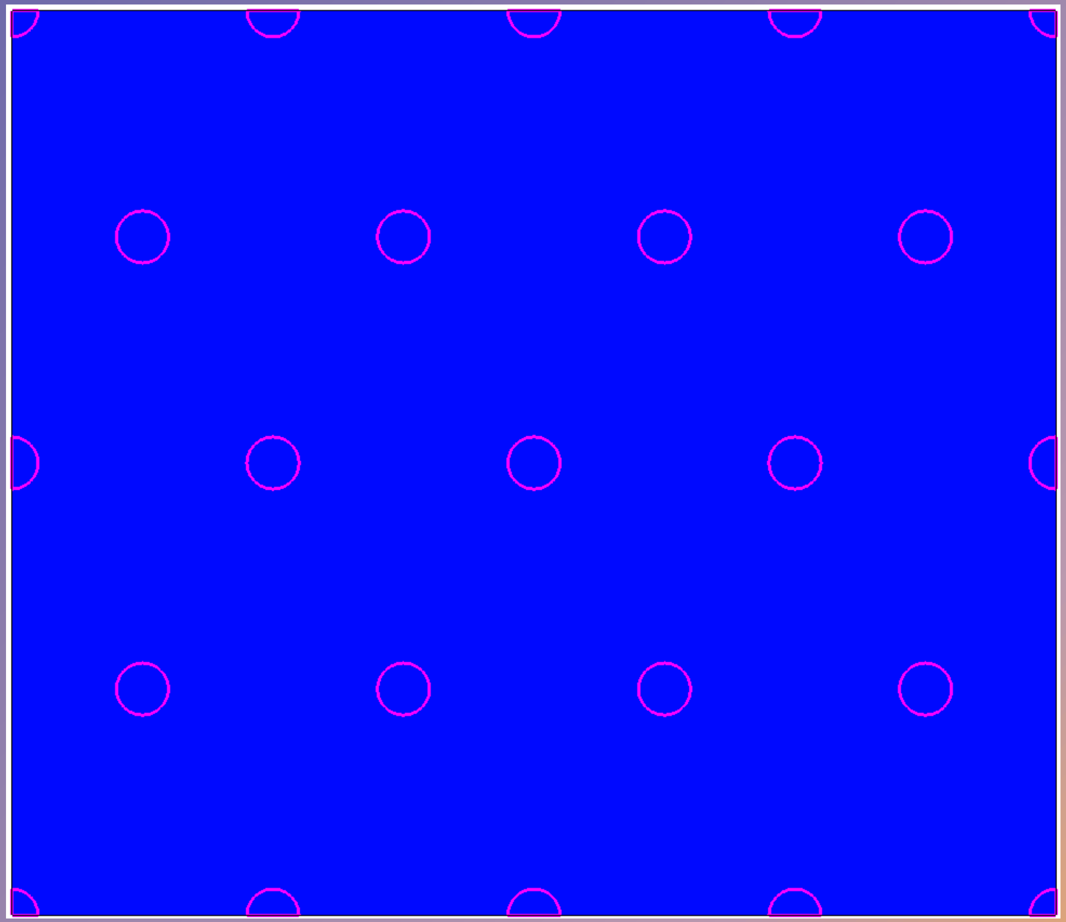






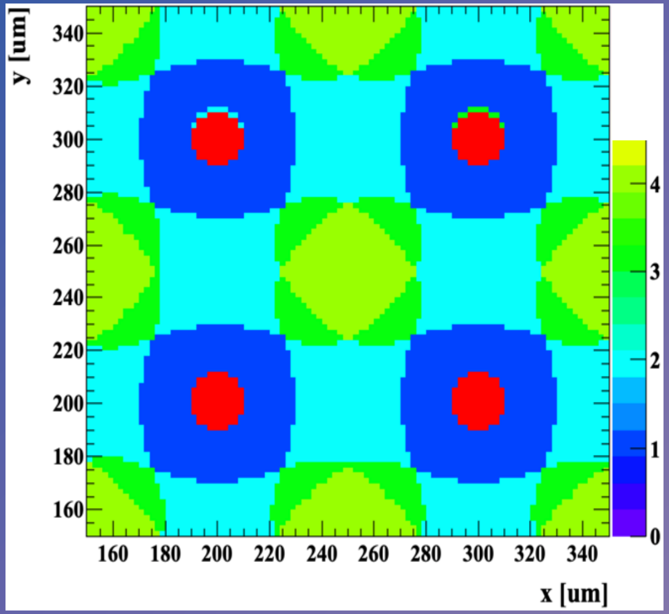
Different pad arrangements





Different pad arrangements

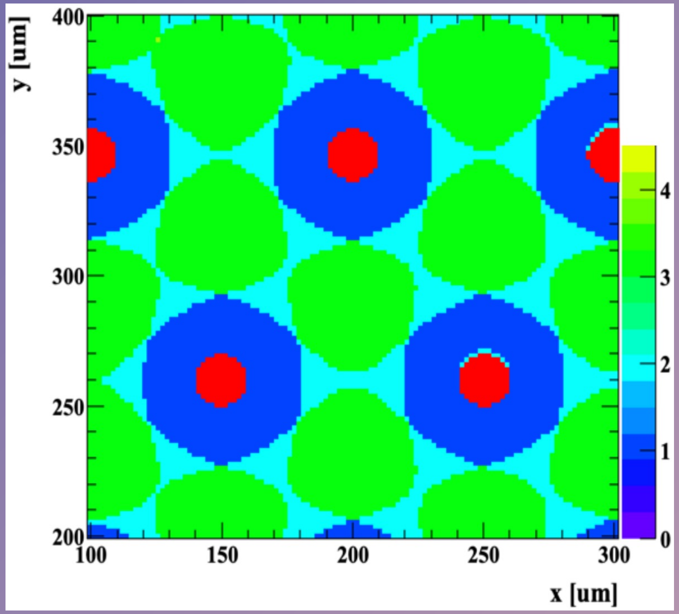
Matrices of squares



Percentages by event type:

- 1-electrode: **30%**
- 2-electrode: 40%
- 3-electrode: 14%
- 4-electrode: **16%**

Matrices of hexagons

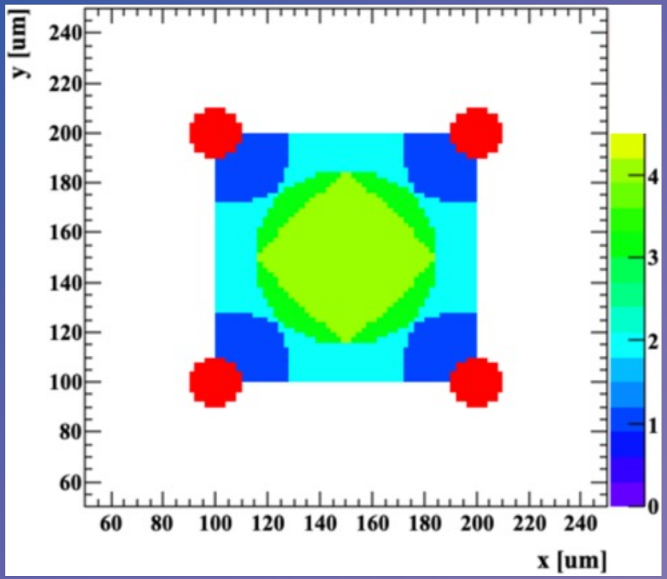


Percentages by event type:

- 1-electrode: **38%**
- 2-electrode: 25%
- 3-electrode: **37%**

Different pad arrangements

Matrices of squares

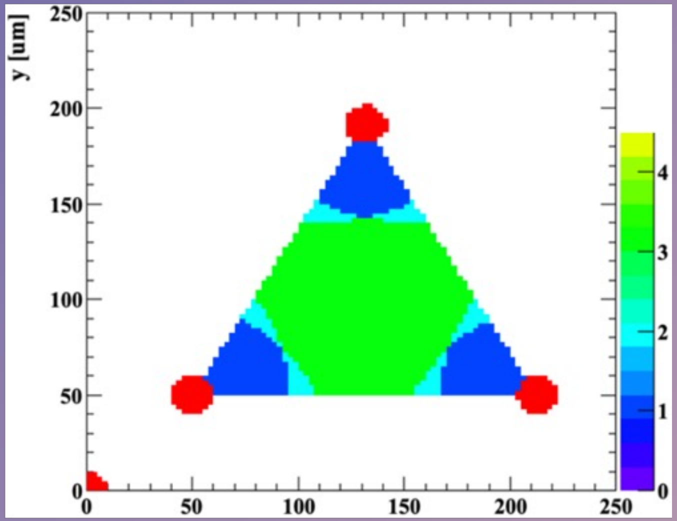


Percentages by event type:

- 1-electrode: **30%** ⟶ **25%**
- 2-electrode: 40% ⟶ 33%
- 3-electrode: 14% ⟶ 12%
- 4-electrode: **16%** ⟶ **30%**

By adding silicon oxide trenches

Matrices of hexagons



Percentages by event type:

- 1-electrode: **38%** ⟶ **28%**
- 2-electrode: 25% ⟶ 12%
- 3-electrode: **37%** ⟶ **60%**