



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



# An impossible challenge?

Spatial resolution  
 $\sim 5 \mu m$

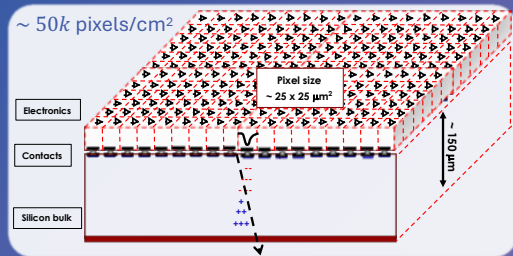
Temporal resolution  
 $\sim 10 ps$

Very low material  
budget

Very low power  
consumption

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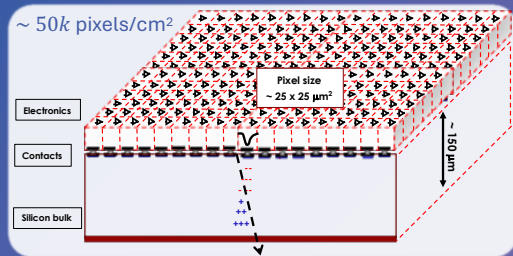
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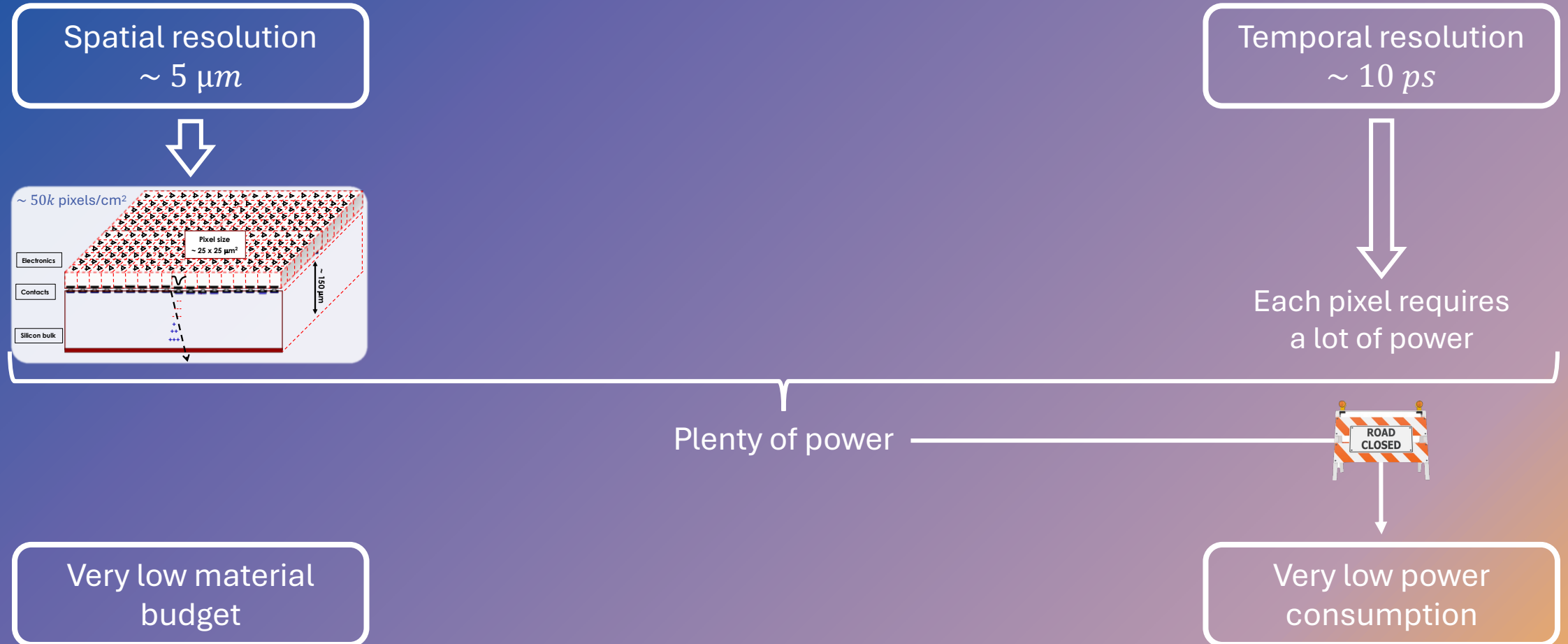
Temporal resolution  
 $\sim 10 ps$



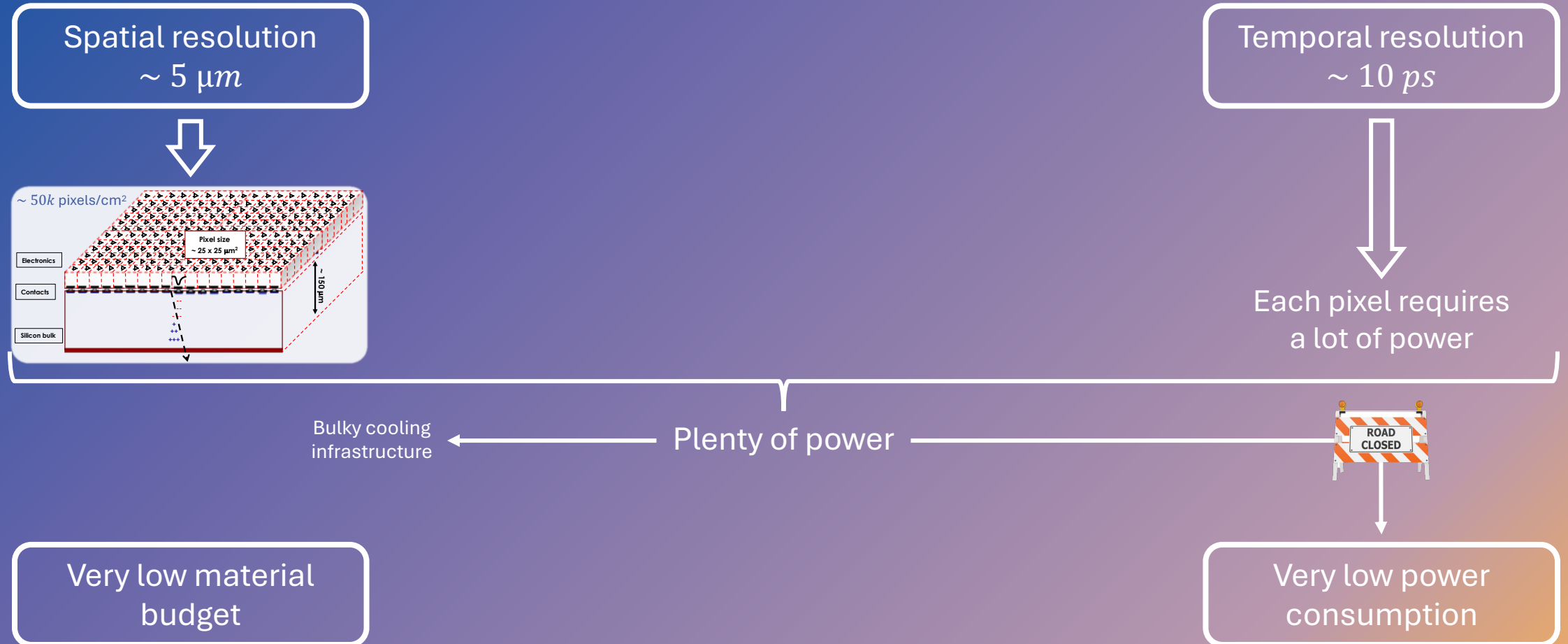
Each pixel requires  
a lot of power

Very low power  
consumption

# An impossible challenge?



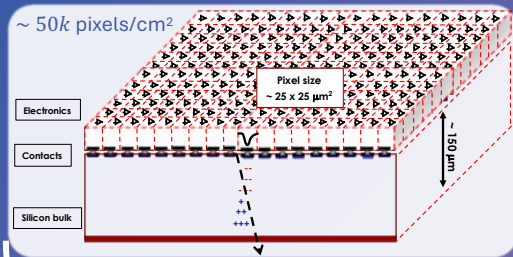
# An impossible challenge?



# An impossible challenge?

Spatial resolution  
 $\sim 5 \mu m$

Temporal resolution  
 $\sim 10 ps$



Each pixel requires  
a lot of power

The signal in thin  
sensors is very small



Bulky cooling  
infrastructure

Plenty of power



Very low material  
budget

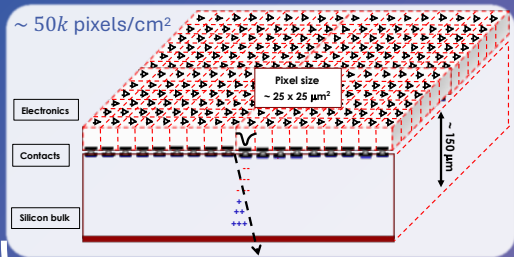
Very low power  
consumption

# An impossible challenge?

Spatial resolution  
 $\sim 5 \mu\text{m}$

Temporal resolution  
 $\sim 10 \text{ ps}$

Is there a way to  
fulfil the four  
specifications  
simultaneously?



Each pixel requires  
a lot of power

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Bulky cooling  
infrastructure

Plenty of power

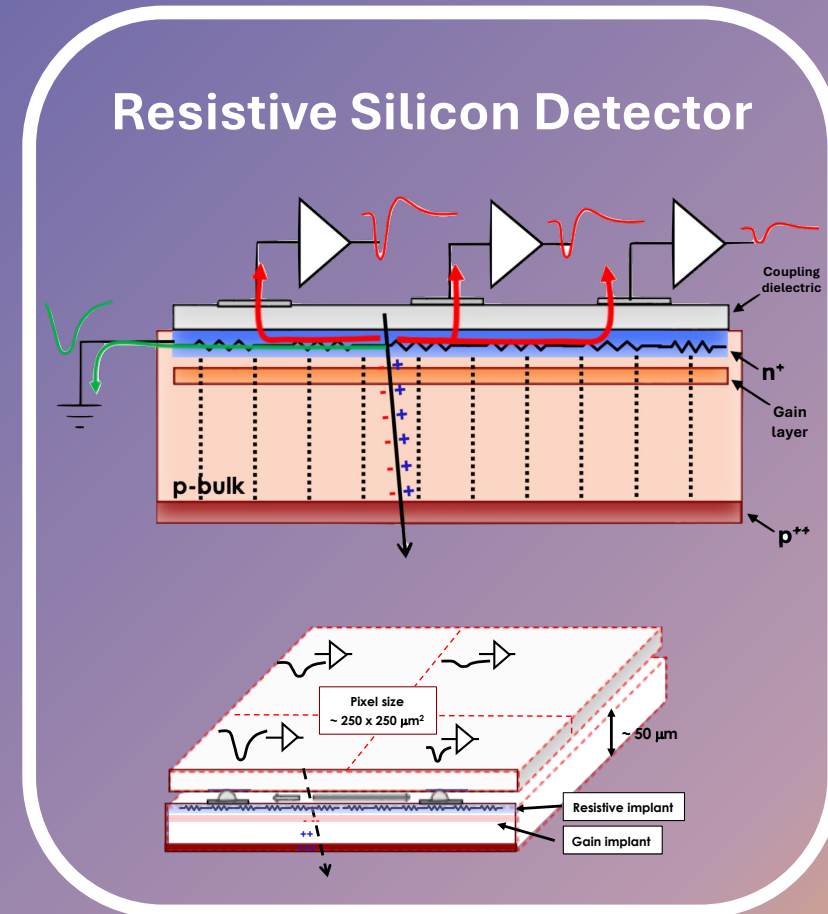
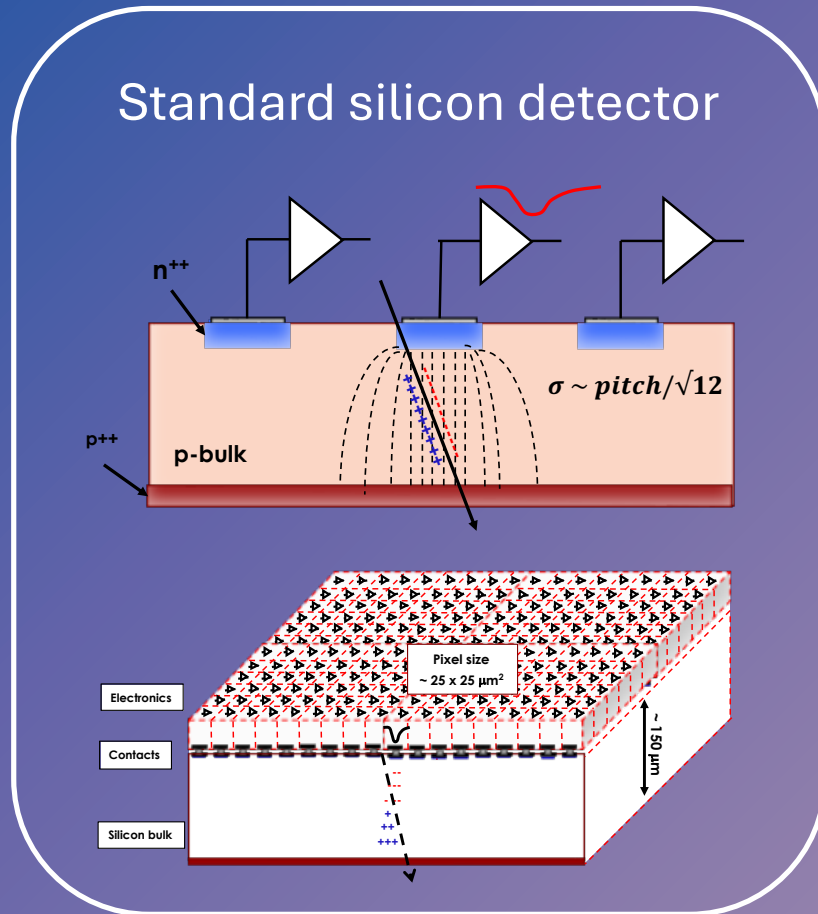


Very low material  
budget

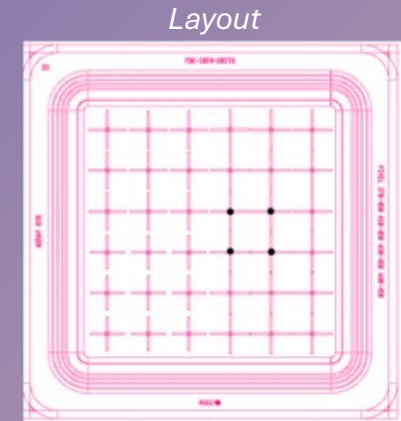
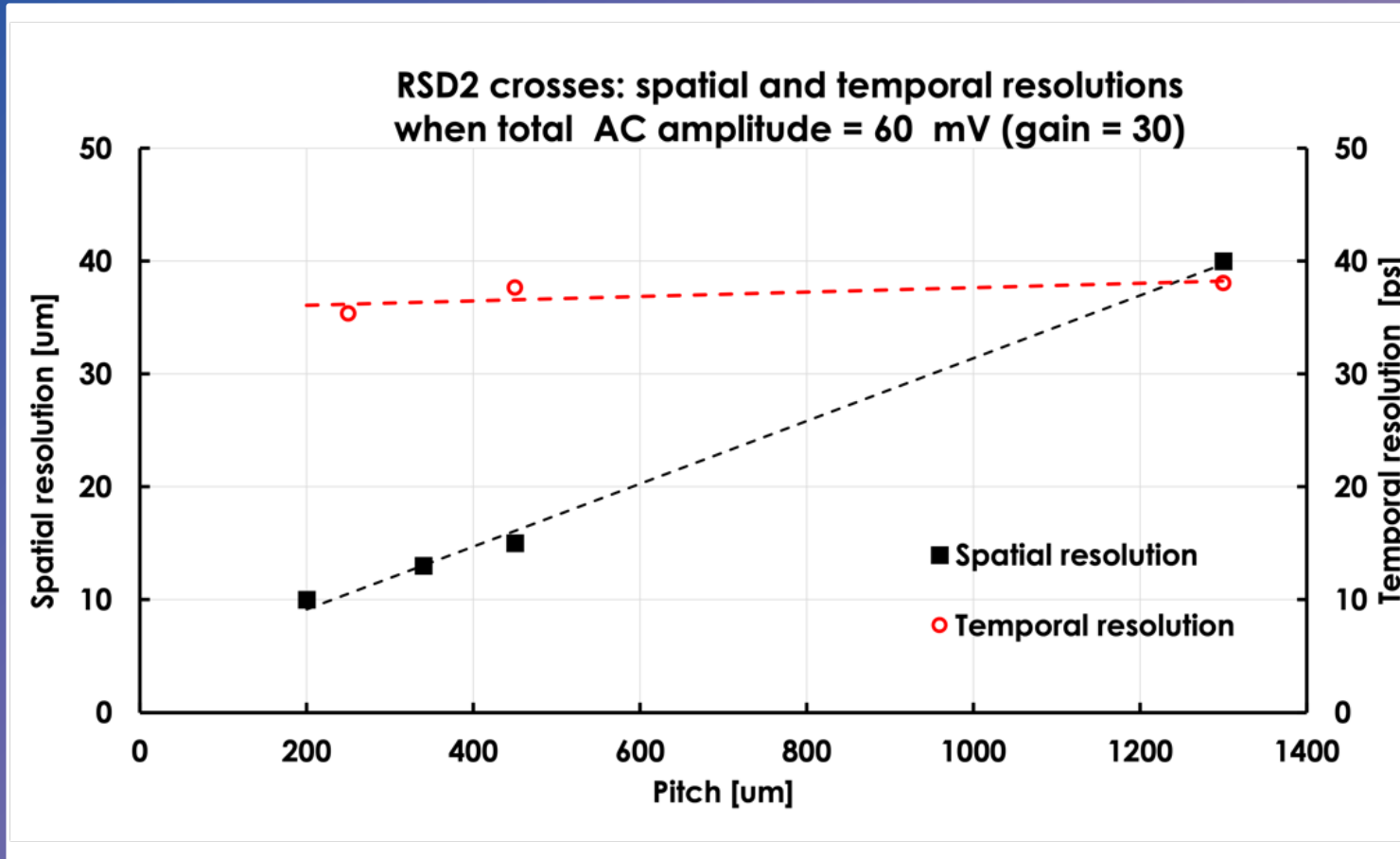
Very low power  
consumption



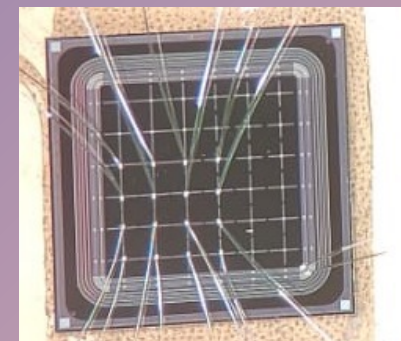
# An intriguing candidate for future colliders



# FBK RSD2 performance summary

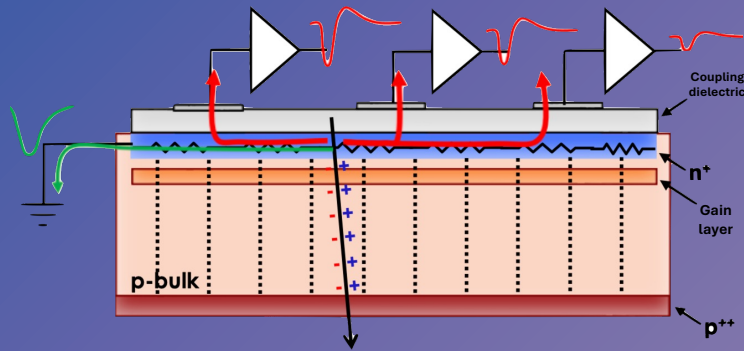


Device made and bonded



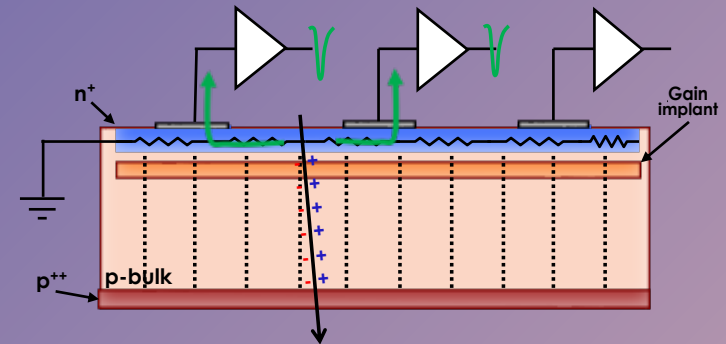
# RSD LGAD: AC or DC coupled electrodes?

## AC-RSD LGAD



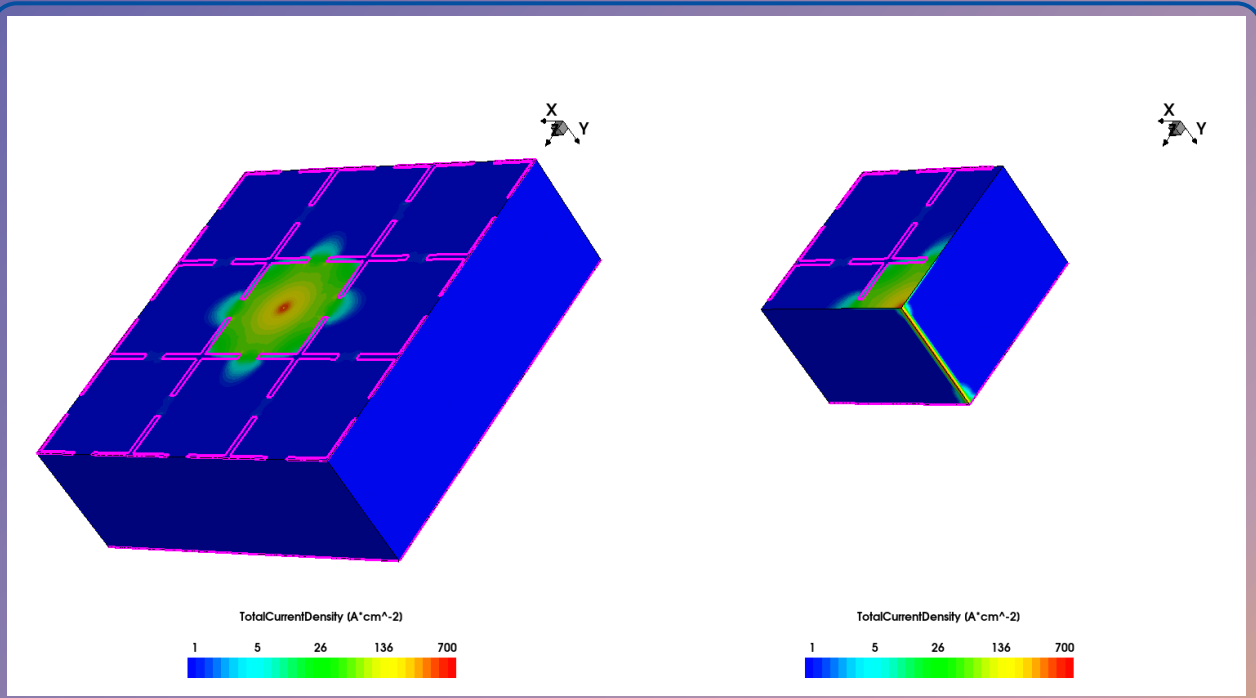
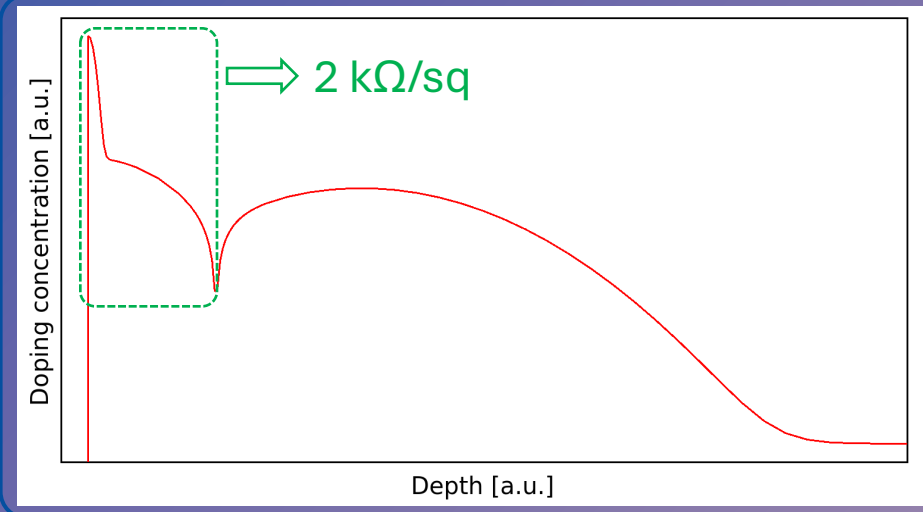
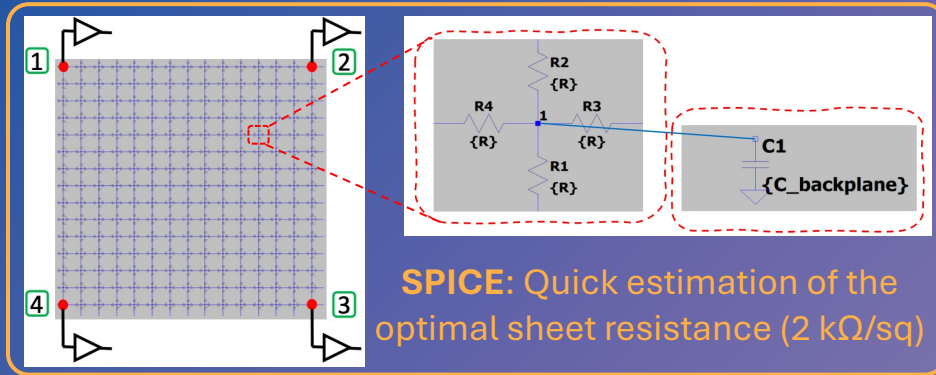
1. Long-tail bipolar signals
2. Baseline fluctuation
3. Uncontrolled signal spreading
4. Not easily scalable to large-area sensors

## DC-RSD LGAD



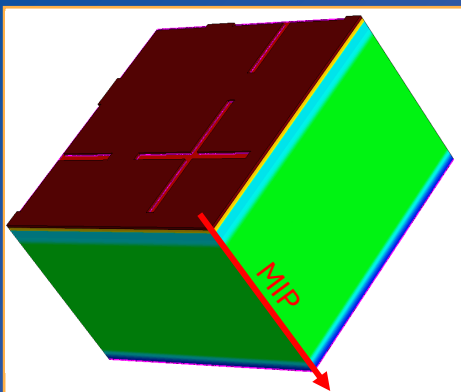
1. Unipolar signals
2. Absence of baseline fluctuation
3. Controlled charge sharing
4. Large sensitive areas (~cm)

# Simulation approach (SPICE & TCAD)

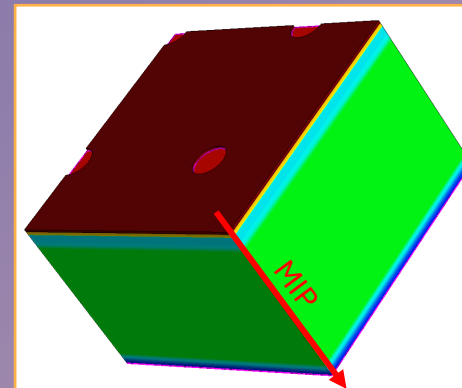
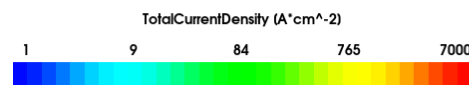
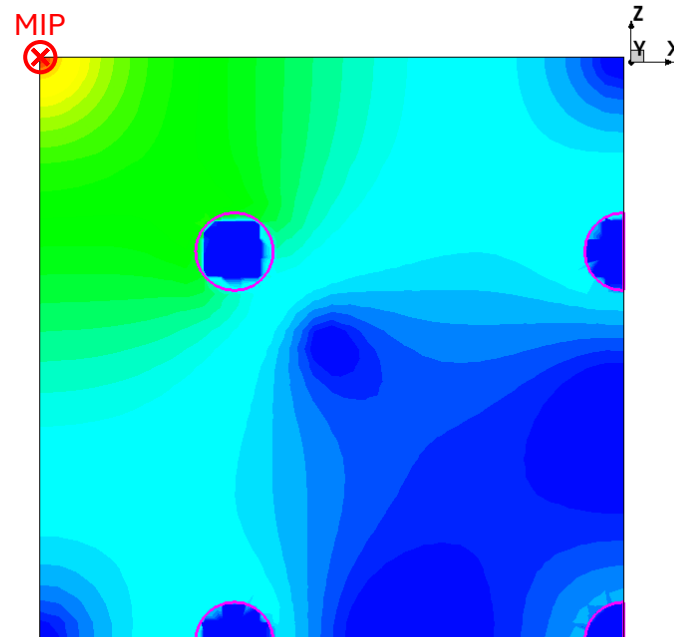
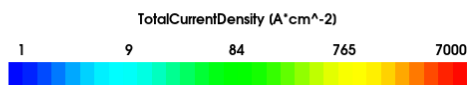
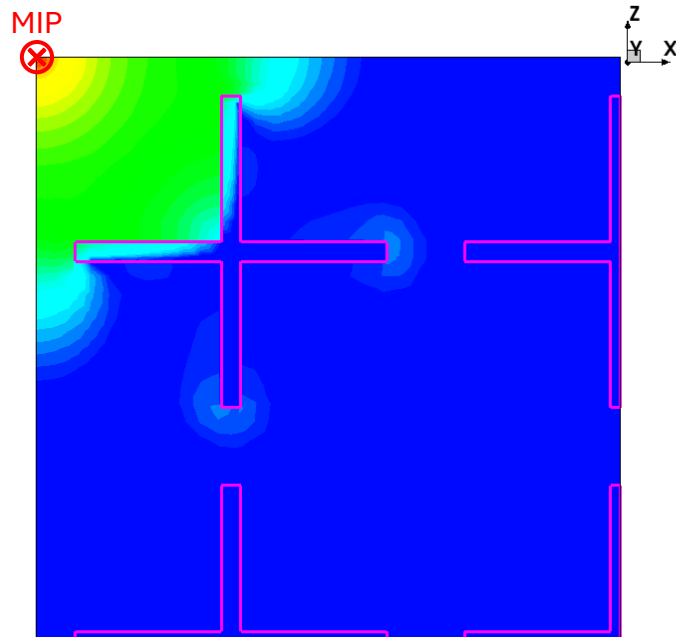
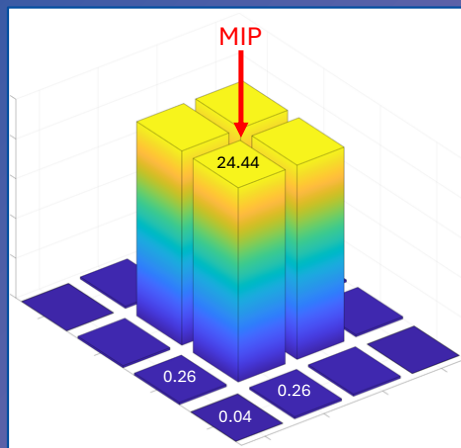


**Full 3D TCAD:** Evaluation of various geometrical layouts (pad and pixel shapes and dimensions) and technological options (resistive strips and silicon oxide trenches) on signal-sharing properties.

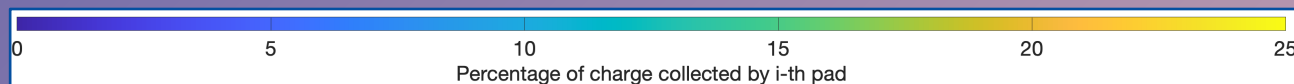
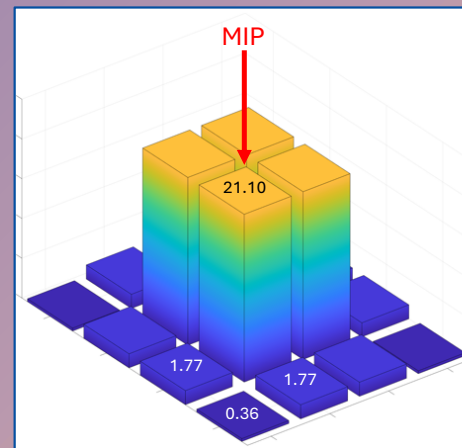
# Playing with pad shape



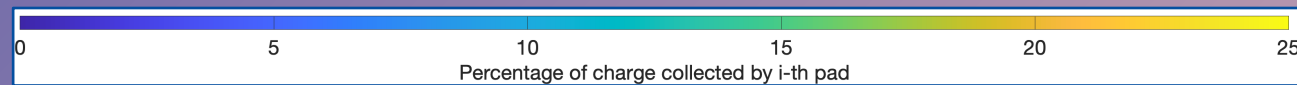
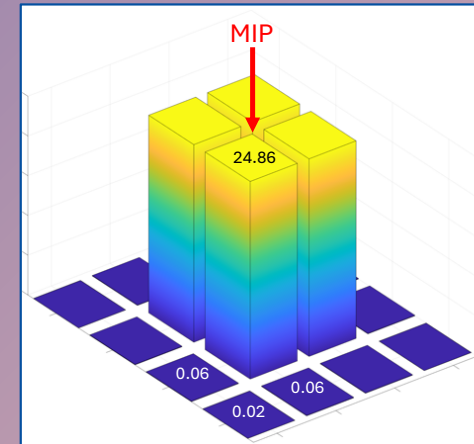
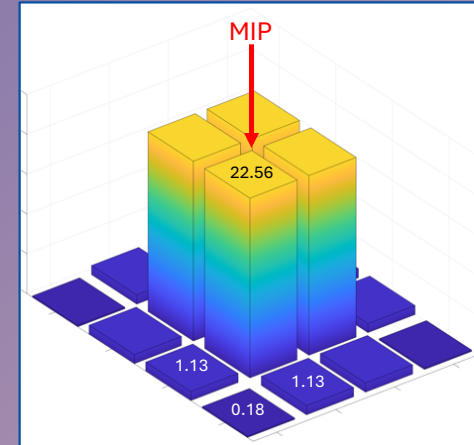
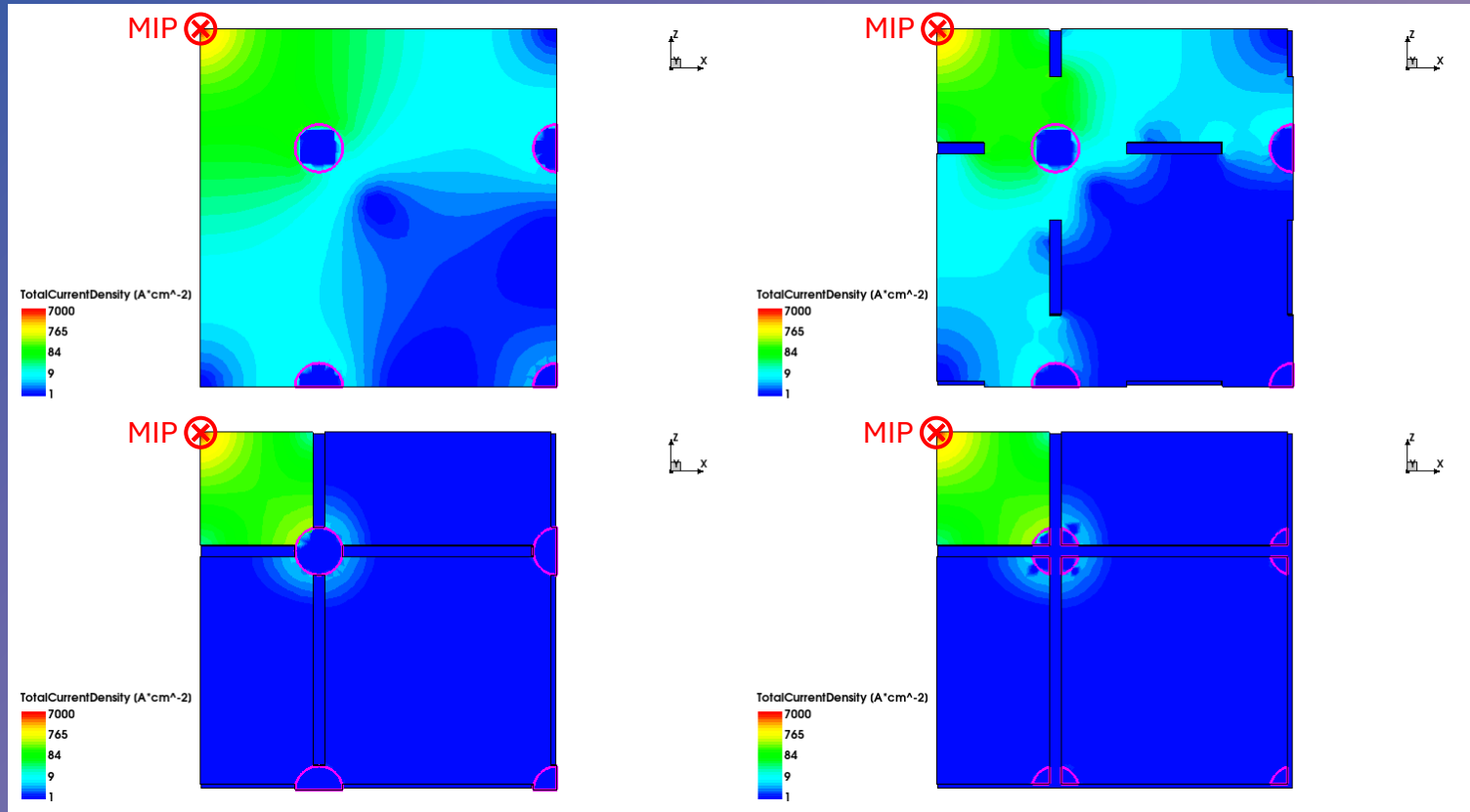
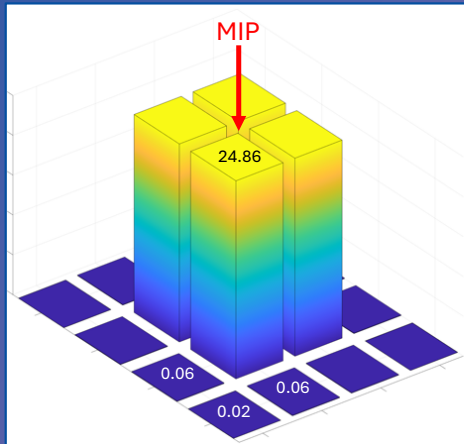
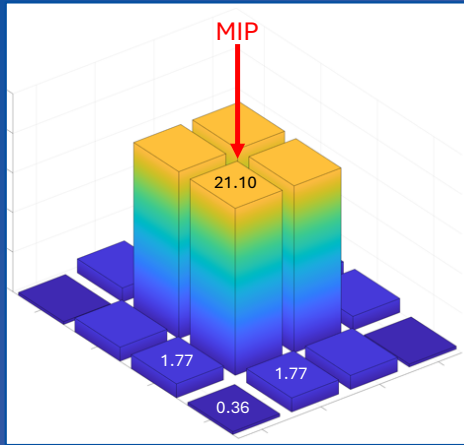
Thickness = 20  $\mu\text{m}$ ;  
 Pitch = 20  $\mu\text{m}$ ;  
 Cross length = 16  $\mu\text{m}$  ;  
 Cross width = 1  $\mu\text{m}$ .



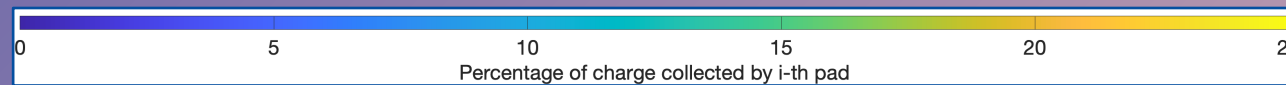
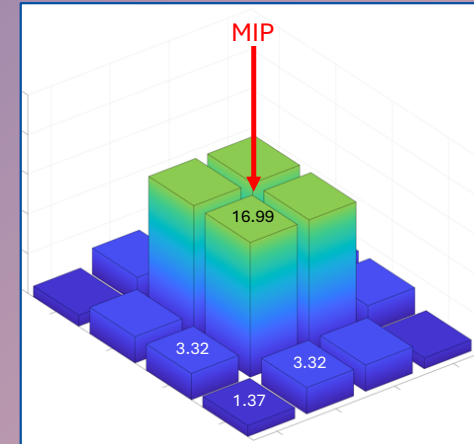
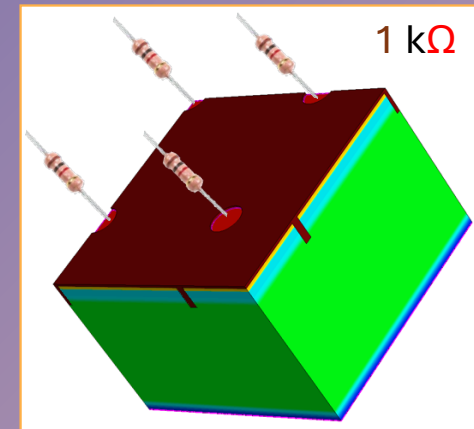
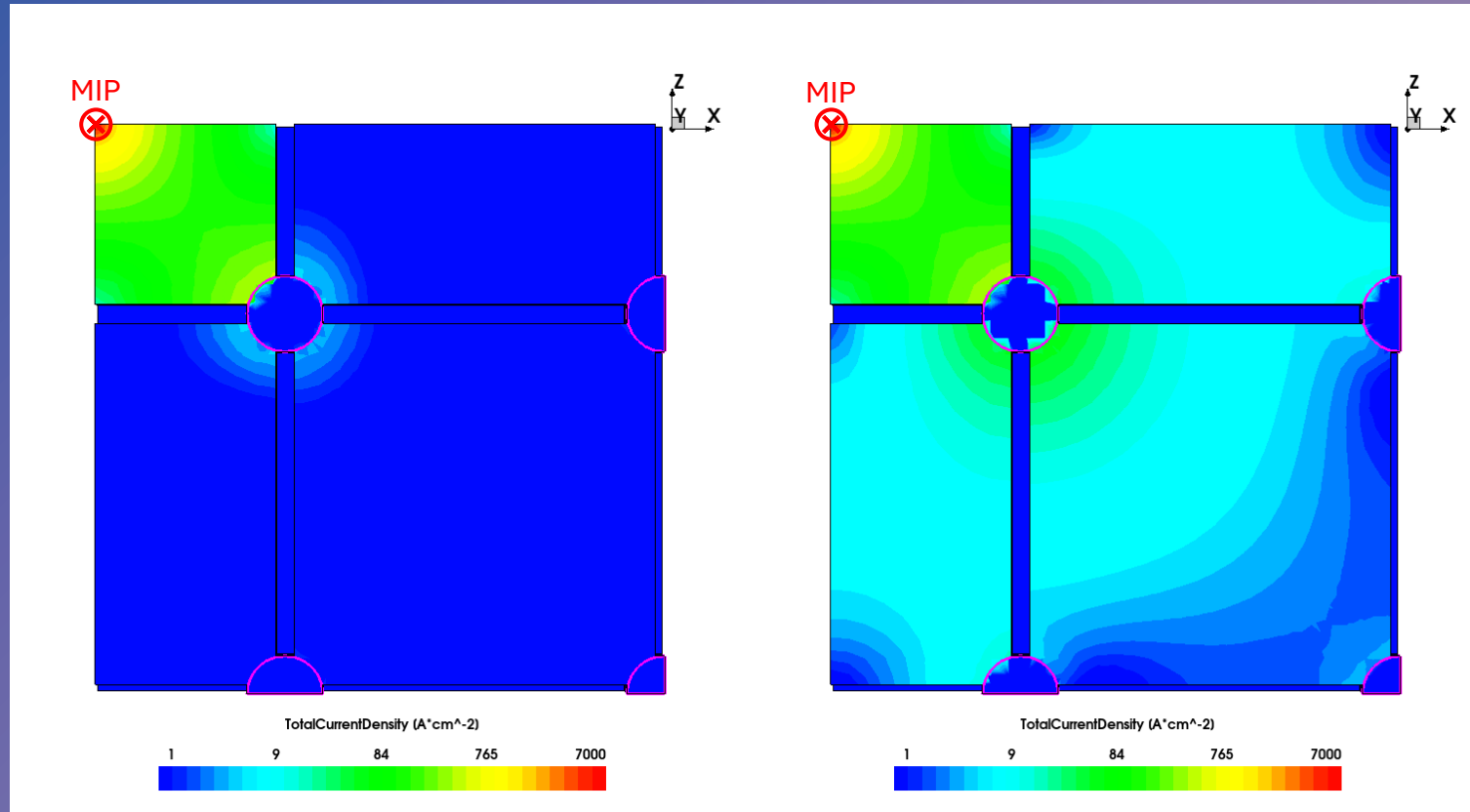
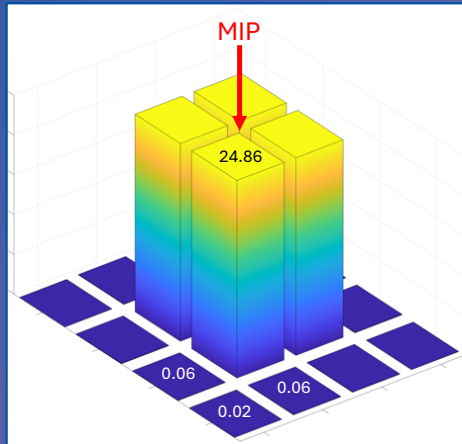
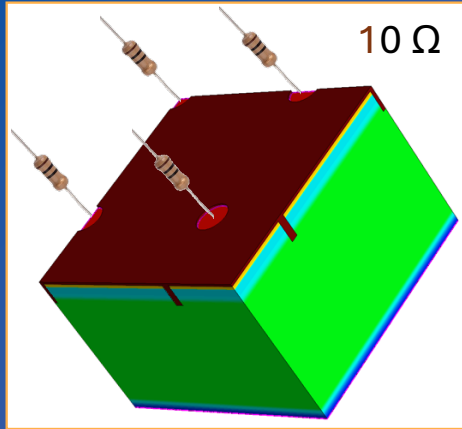
Thickness = 20  $\mu\text{m}$ ;  
 Pitch = 20  $\mu\text{m}$ ;  
 Pad radius = 2  $\mu\text{m}$ .



# Silicon oxide trenches



# Watch out for contact resistance

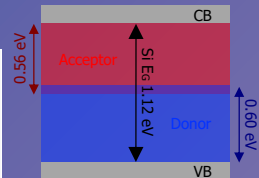


# Radiation damage modelling @ PG

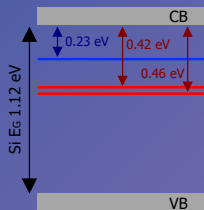
## New University of Perugia Radiation Damage Model

### Surface damage (+Q<sub>ox</sub>)

Type	Energy (eV)	Band width (eV)	Conc. (cm <sup>-2</sup> )
Acceptor	$E_c \leq E_T \leq E_c - 0.56$	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_v \leq E_T \leq E_v + 0.6$	0.60	$D_{IT} = D_{IT}(\Phi)$

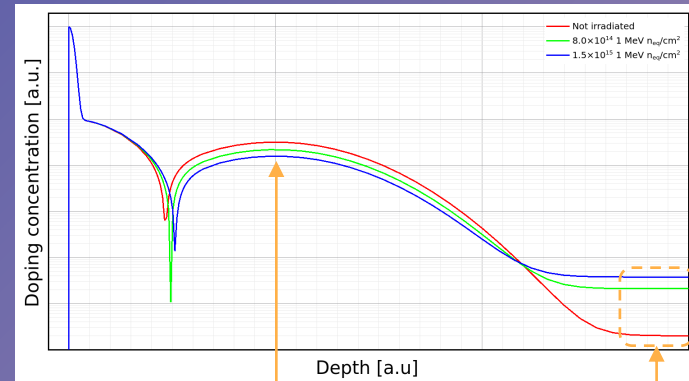


### Bulk damage



Type	Energy (eV)	$\eta$ (cm <sup>-1</sup> )	$\sigma_n$ (cm <sup>2</sup> )	$\sigma_h$ (cm <sup>2</sup> )
Donor	$E_c - 0.23$	0.006	$2.3 \times 10^{-14}$	$2.3 \times 10^{-15}$
Acceptor	$E_c - 0.42$	1.6	$1 \times 10^{-15}$	$1 \times 10^{-14}$
Acceptor	$E_c - 0.46$	0.9	$7 \times 10^{-14}$	$7 \times 10^{-13}$

Physically meaningful  
deep-level radiation-induced traps

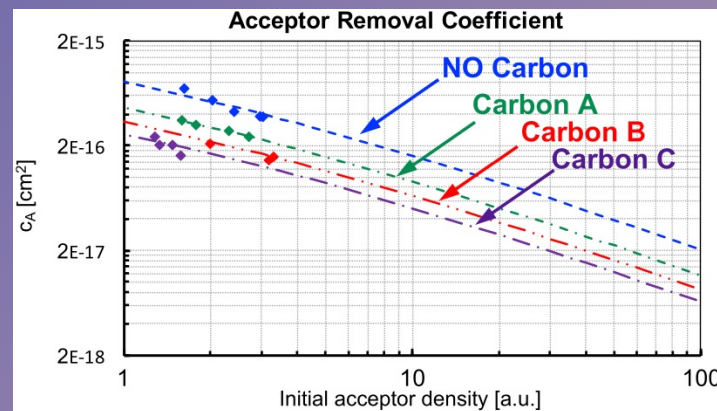


## Acceptor Removal

Transformation of electrically active acceptor atoms into neutral defect complexes.

It can be parameterised as

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



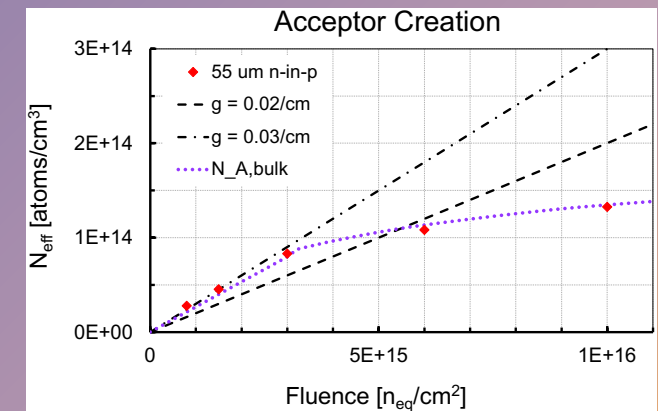
## Acceptor Creation

If  $\phi \leq 3 \cdot 10^{15} \text{ n}_{eq}/\text{cm}^2$

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

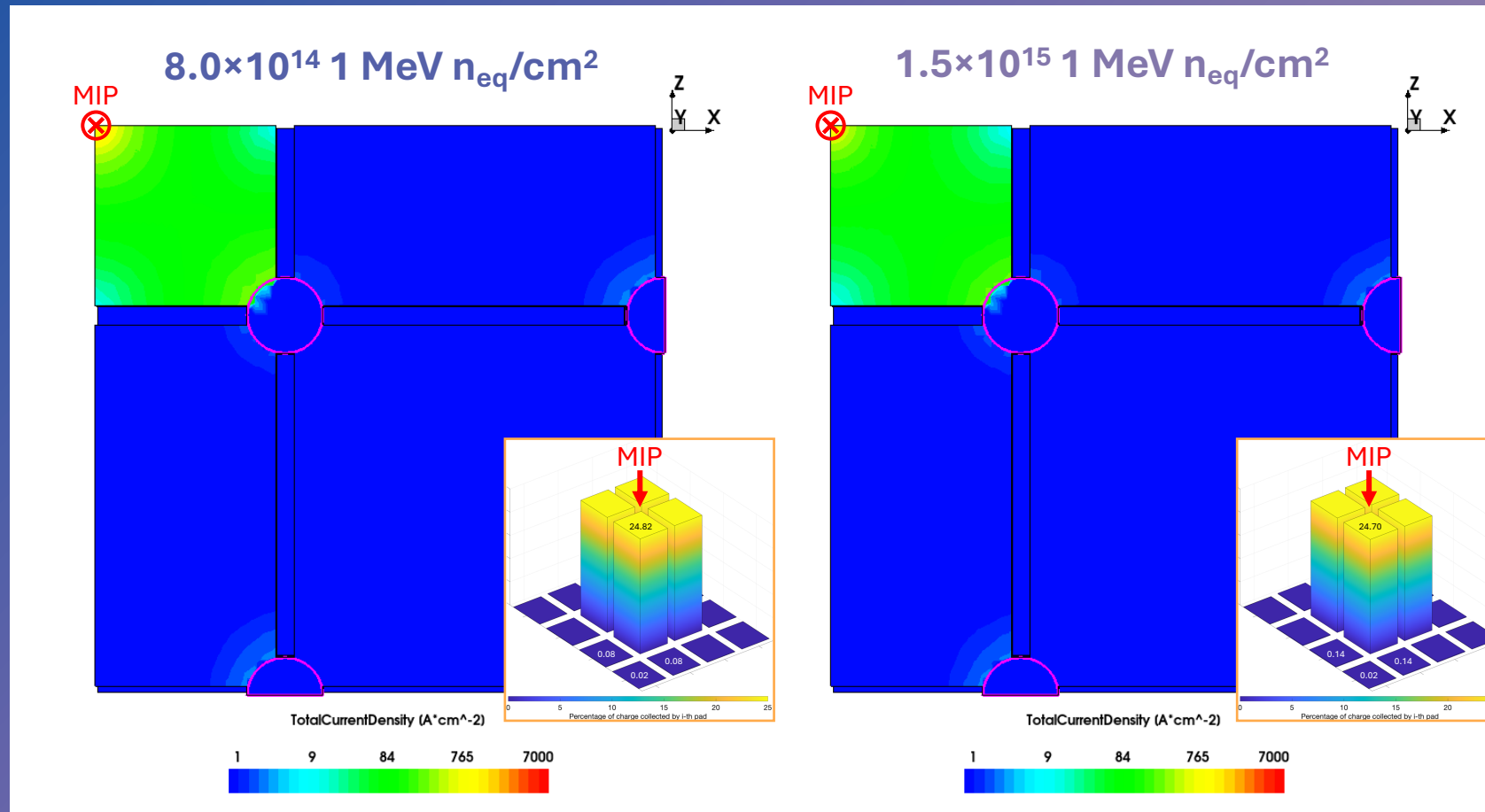
else

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





# 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.



**DC resistive read-out silicon sensors for future 4D tracking**

Roberta Arcidiacono on behalf of the 4DSHARE Project  
 Università del Piemonte Orientale and INFN Torino – Italy, Roberta.Arcidiacono@cern.ch

R. Arcidiacono, N. Cartiglia, M. Bartolini, G. Bardelli, M. Boscardin, A. Casese, R. Ceccarelli, M. Centis Vignali, T. Croci, M. Ferrero, A. Fondacci, O. Hammad Ali, L. Lanteri, L. Menzio, A. Morozzi, F. Moscatelli, D. Passeri, G. Paternoster, G. Sgazzoni, F. Siviero, V. Sola, L. Viliani

MANDO PRIN 2022

EUPH-LABS

PIXEL2024

Goal: development of **high-resolution 4D-tracking detectors** capable of simultaneously measuring the position and time of passage of charged particles within a single sensitive device.

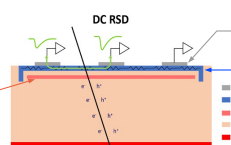
→ **Innovative sensor: thin LGAD with a resistive DC-coupled read-out** (aka DC-RSD)

Moderate internal gain

→ large signals with short rise time and low noise, ideal for timing

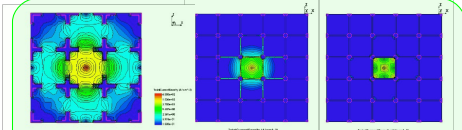
DC-coupled electrodes

→ leakage current removed at every electrode, baseline fluctuation over large devices removed



Resistive layer  
→ intrinsic charge sharing, ideal for high spatial resolution

inter-pad resistors or isolating trenches added to create a "cage" where the signal is confined → achieving signal containment within a pre-determined number of electrodes → better and uniform performance over the pixel surface

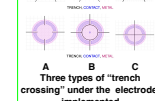


Current density over device surface, generated by a hit in the center of the sensor (3D-TCAD simulation), representing the expected signal confinement in a DC-RSD with cross-hatched metal electrodes (left), and with dot-like electrodes connected with inter-pad resistor (middle) or isolating trenches (right).

More on A. Fondacci's talk "Design and optimisation of radiation resistant AC- and DC-coupled resistive LGADs" (Pixel2024)

The DC-RSD1 production includes **test structures, pixel matrices and strips** with **different pitch, different electrodes layout**, with or without **charge containment** (using isolating trenches)

Most performing electrodes shape/patterns, identified with extensive TCAD simulations



A, B, C  
Three types of "trench crossing" under the electrode implemented

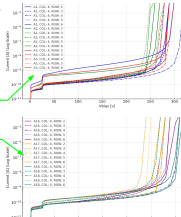
From DC-RSD1 reticle: series of **trenched pixel matrices** with a **squared or exagonal electrode pattern**. Pitch: 500, 300, 200  $\mu\text{m}$

**IV characteristics** for 5 shots on wafer W3

Comparison between the three types of "trench crossing" for:

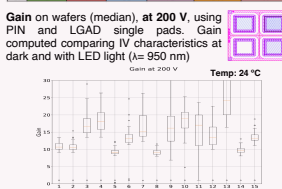
- pixel matrix 3x3 squared 500  $\mu\text{m}$
- exagonal matrix, 15 pixels, 500  $\mu\text{m}$

A1, A16 = type A  
A2, A17 = type B  
A3, A18 = type C



\*Type B\* devices show a slight early BD, either due to the design or to the testing method (single needle measurement).

**Gain on wafers (median), at 200 V, using PIN and LGAD single pads.** Gain computed comparing IV characteristics at dark and with LED light ( $\lambda = 950 \text{ nm}$ )



Temp: 24 °C

**Gain mean value and spread is as expected** in most of the wafers, for the two gain doses.

From IVs: **leakage current in range of operation in reverse bias condition is low** (5 wafers substrate have very high leakage current → discarded!)

Average breakdown: 280-300 V (high gain) and 330-350 V (low gain)

**Testing plans for first 4DSHARE production:**

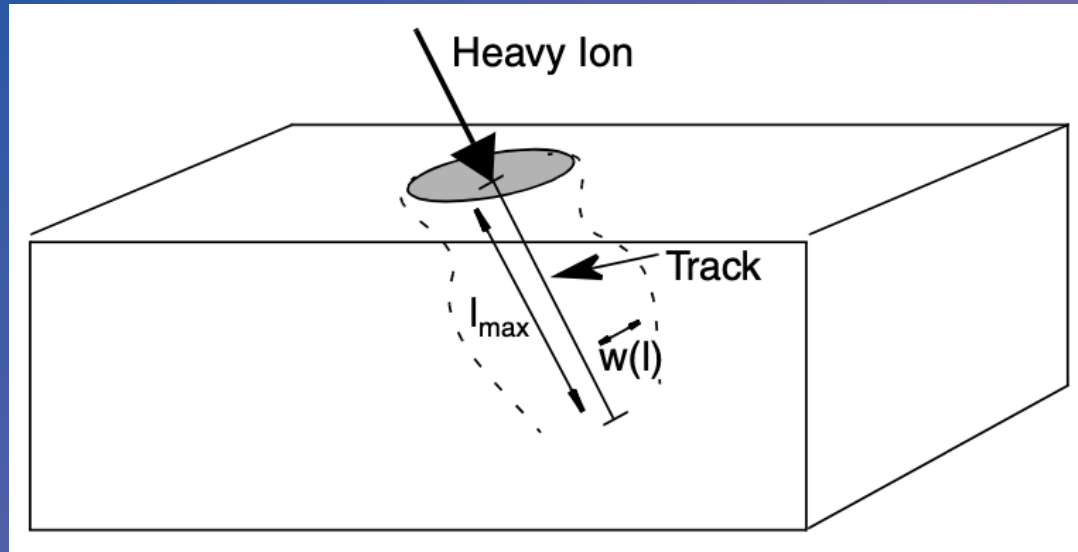
- systematic study of signal propagation and signal sharing/containment as a function of sensor type (in the lab)
- **position and time resolution** measurements with **laser signals (TCT-setup)**
- in parallel, preliminary **performance** studies with 5-GeV **electron beam** in DESY of 3 sensor types (December 2024)

**Acknowledgements:**  
 This work has received funding from: INFN CSNS through the 4DSHARE research project; PRIN MIUR projects 2017L2XKKT "4DiSiDA" and 2022KL94LB "4DSHARE"; Compagnia San Paolo (TRAPEZIO grant); European Union's Horizon Europe research and innovation program under grant agreement no. 101059511. We acknowledge the RPSO and DRPS collaborations, CERN.

The Eleventh International Workshop on Semiconductor Pixel Detectors for Particles and Imaging PIXEL24 – Strasbourg (Fr)

*Backup*

# Heavy Ion Model



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

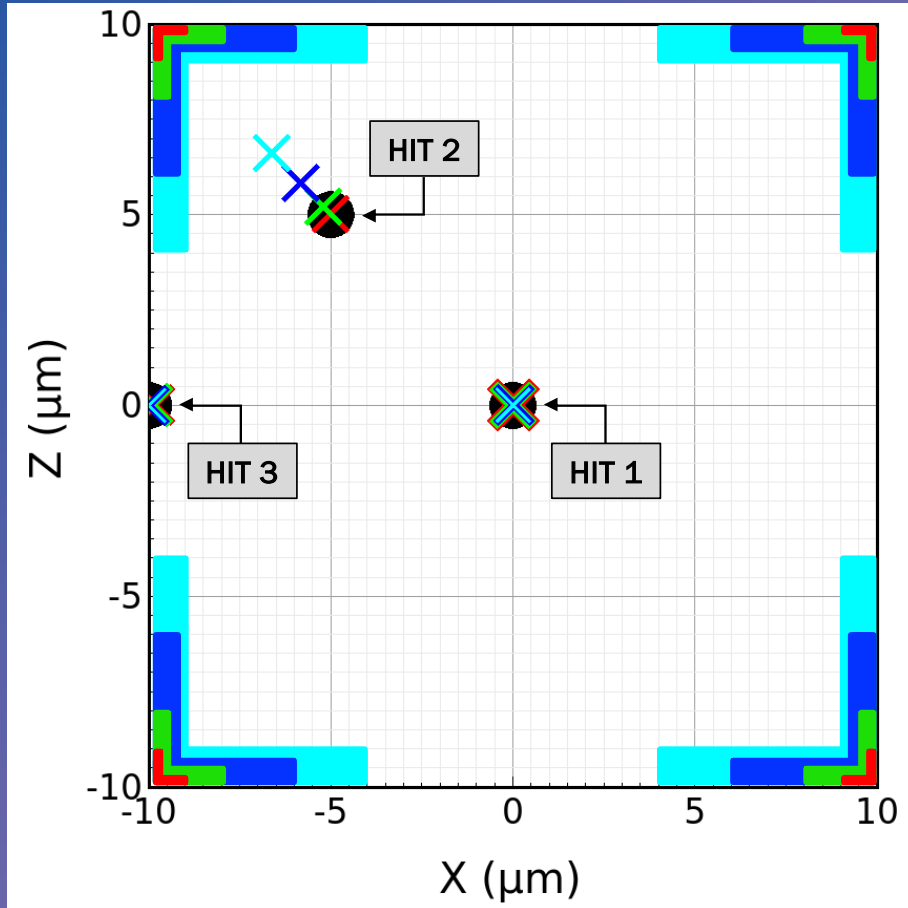
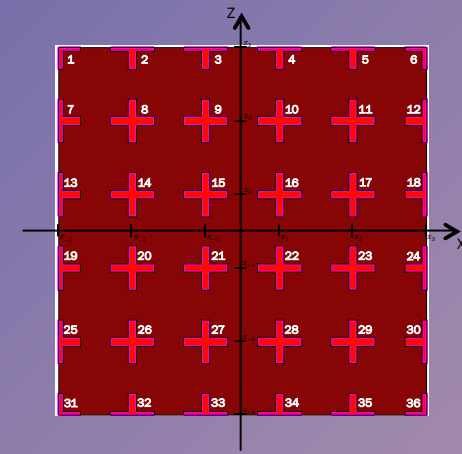
$$G(l, w, t) = \begin{cases} G_{LET}(l)R(w, l)T(t) & \text{if } l < l_{max} \\ 0 & \text{if } l \geq l_{max} \end{cases}$$

- $T(t)$  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  $\text{cm}^3$  by default .

## How many e/h pairs are generated by the MIP for each $\mu\text{m}$ crossed?

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

# Charge imbalance algorithm



## X-coordinate

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

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

## Z-coordinate

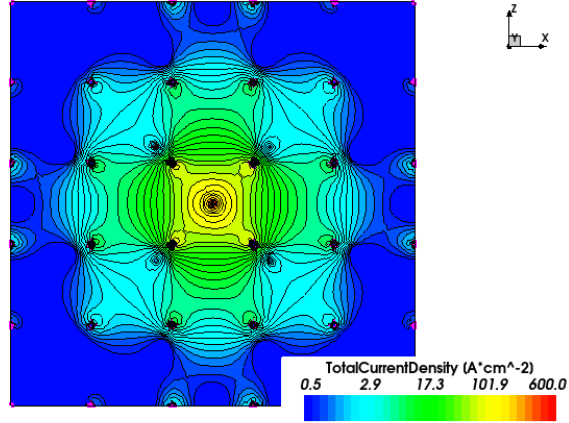
- $Q_{z_{-3}} = Q_{31} + Q_{32} + Q_{33} + Q_{34} + Q_{35} + Q_{36}$
- $Q_{z_{-2}} = Q_{25} + Q_{26} + Q_{27} + Q_{28} + Q_{29} + Q_{30}$
- $Q_{z_{-1}} = Q_{19} + Q_{20} + Q_{21} + Q_{22} + Q_{23} + Q_{24}$
- $Q_{z_1} = Q_{13} + Q_{14} + Q_{15} + Q_{16} + Q_{17} + Q_{18}$
- $Q_{z_2} = Q_7 + Q_8 + Q_9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

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

# Crosses of various sizes

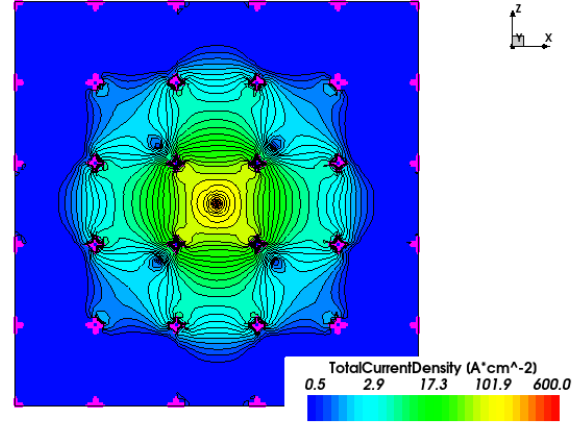
$L_{arm} = 2 \mu m$

$W_{arm} = 0.375 \mu m$



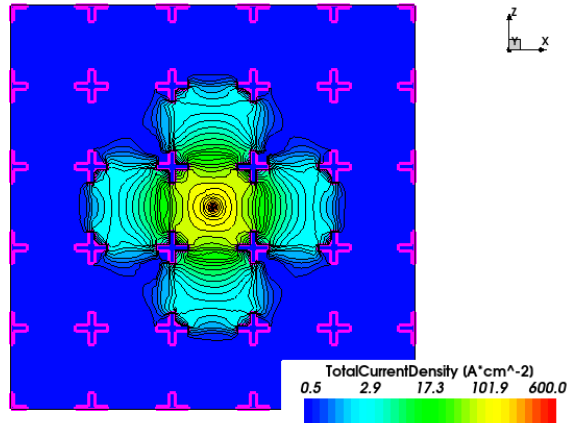
$L_{arm} = 4 \mu m$

$W_{arm} = 0.75 \mu m$



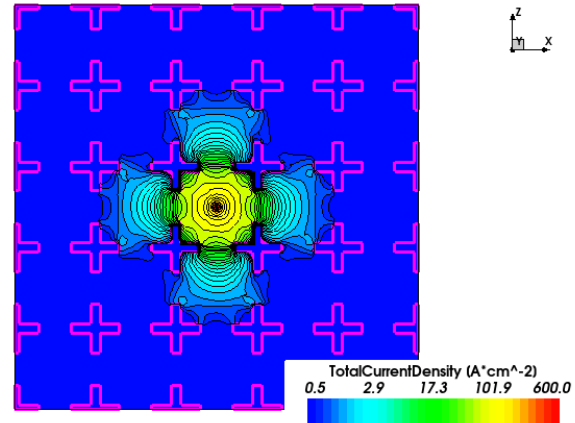
$L_{arm} = 8 \mu m$

$W_{arm} = 1.5 \mu m$



$L_{arm} = 12 \mu m$

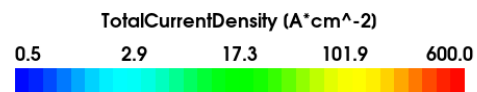
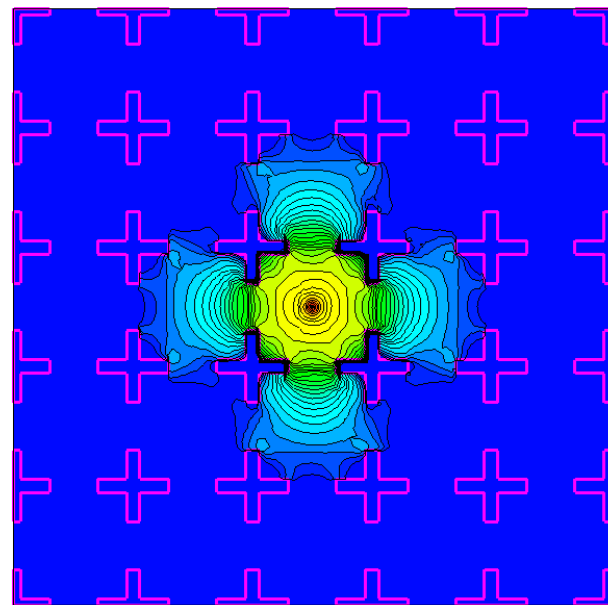
$W_{arm} = 2.25 \mu m$



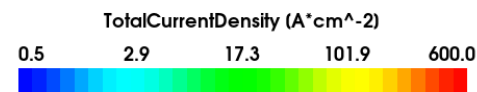
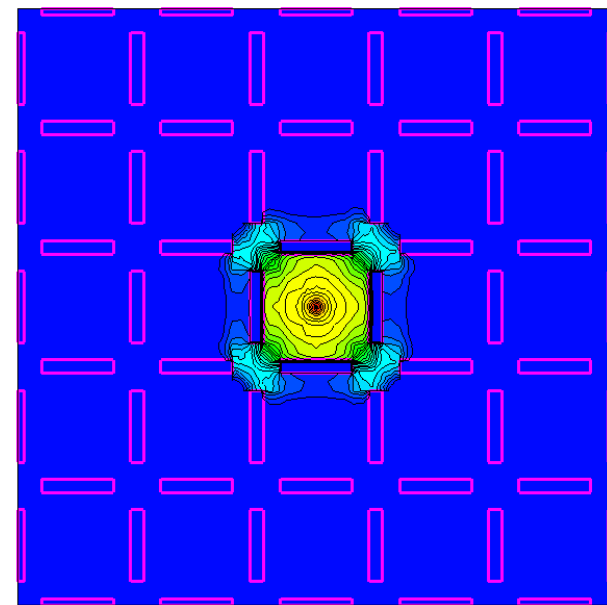
# Crosses 🏆 bars

36 electrodes

Four pads of hit pixel  
collect 96% of the charge



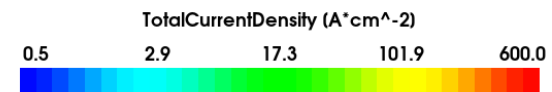
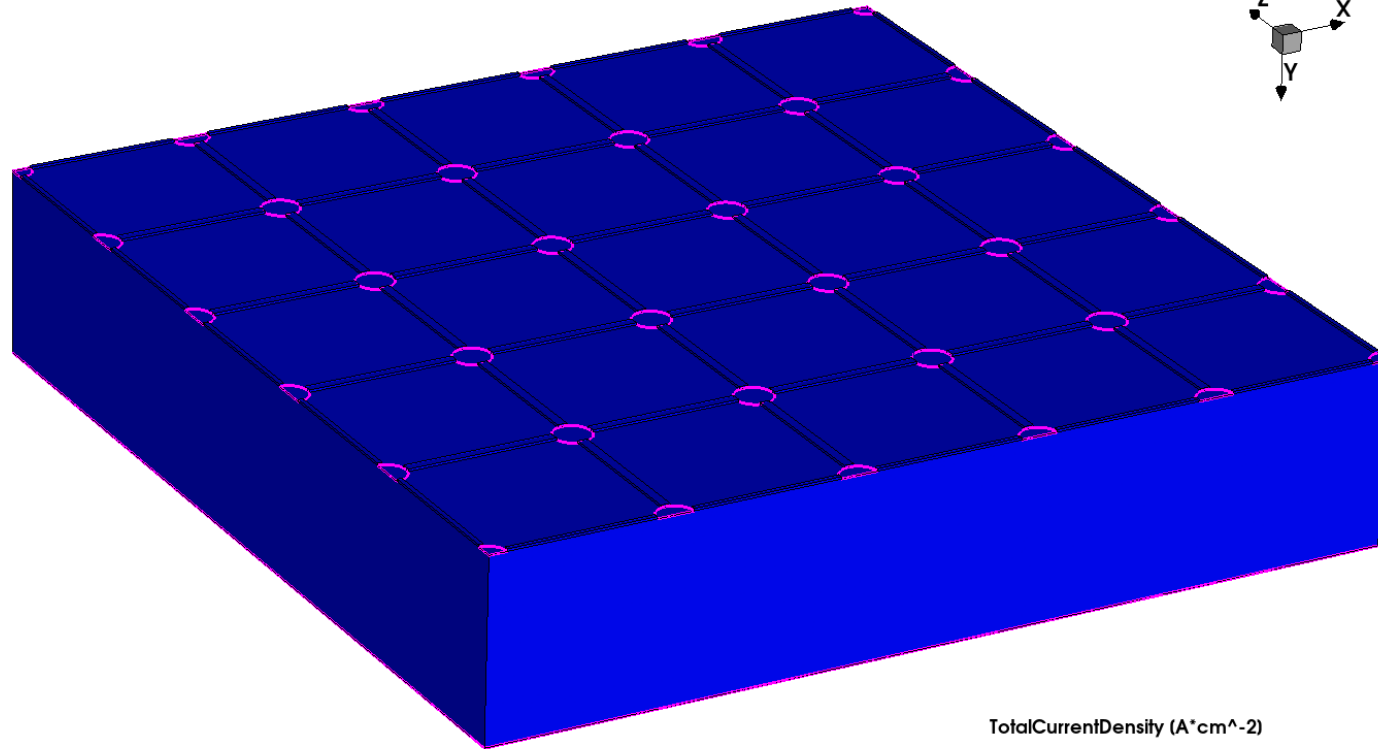
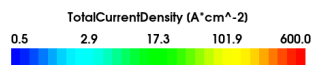
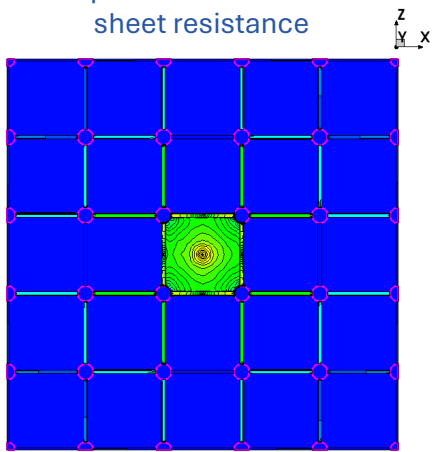
Four pads of hit pixel  
collect 97% of the charge



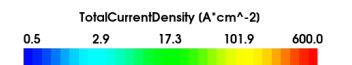
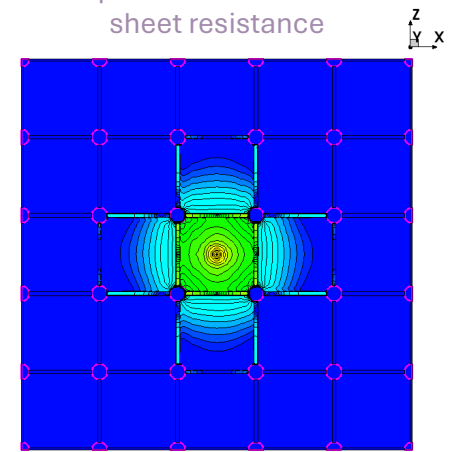
60 electrodes

# Resistive strips

Strip resistance is 2% of sheet resistance



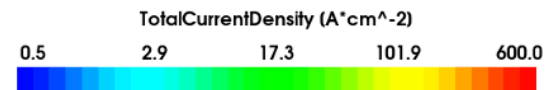
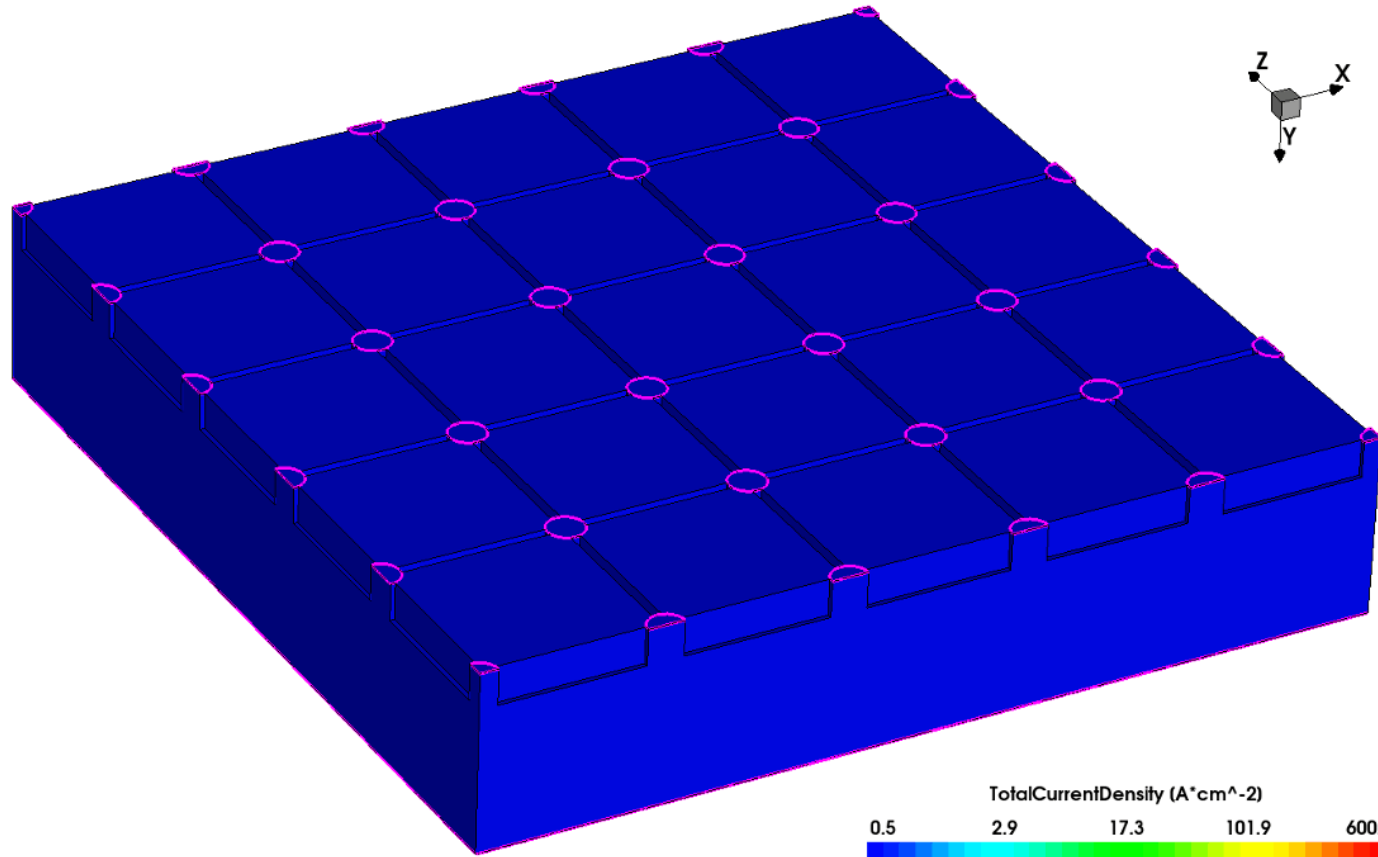
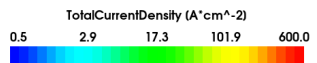
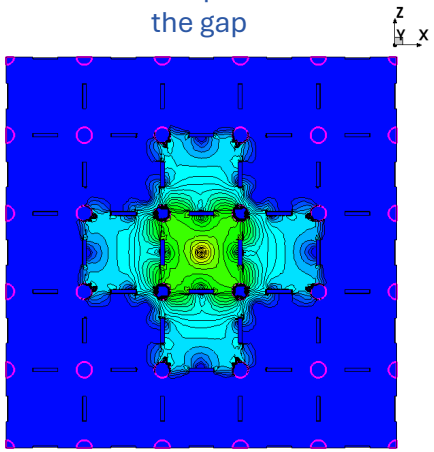
Strip resistance is 40% of sheet resistance



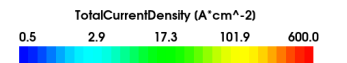
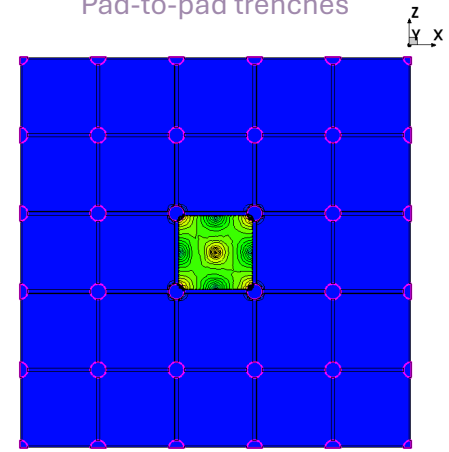


# Silicon oxide trenches

Trenches equal 40% of the gap

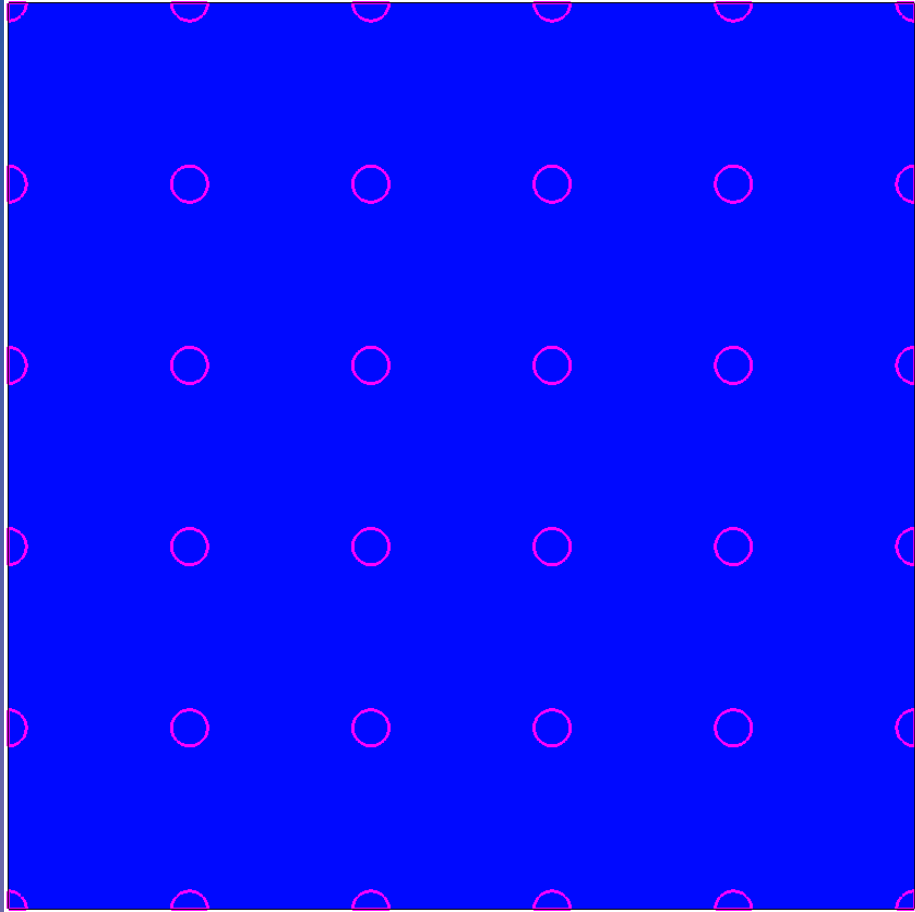


Pad-to-pad trenches

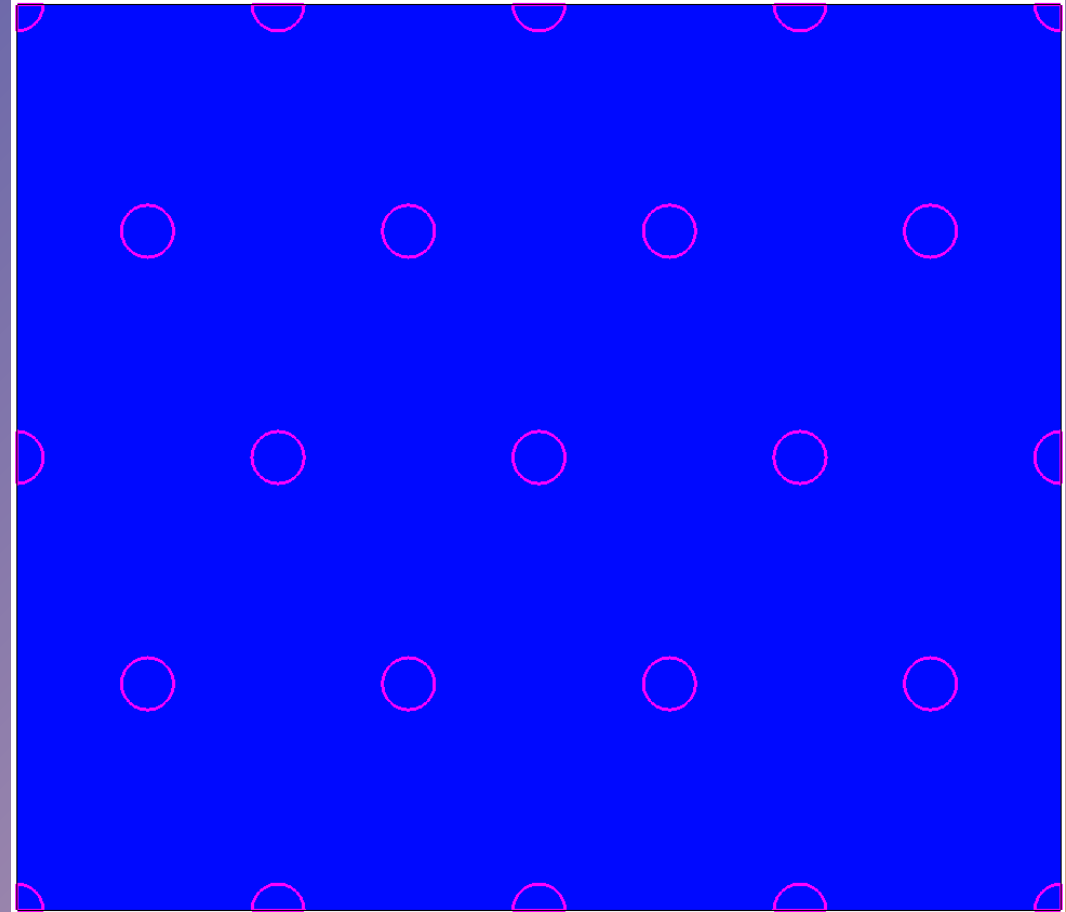


# Different pad arrangements

Matrices of squares

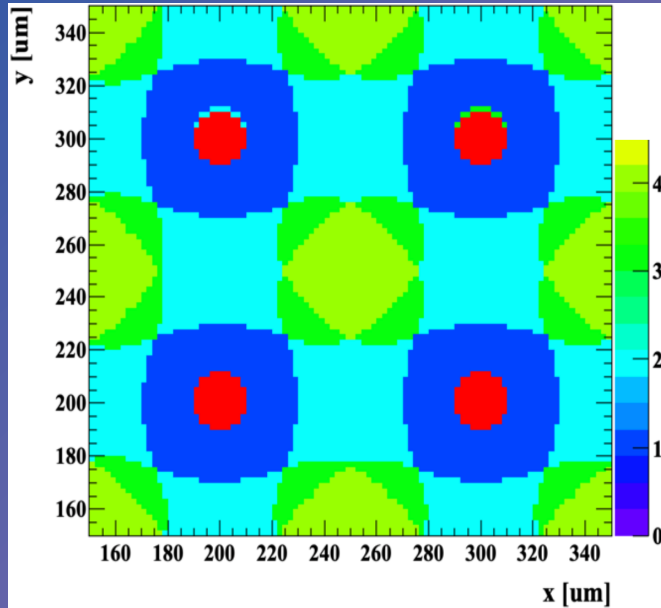


Matrices of hexagons



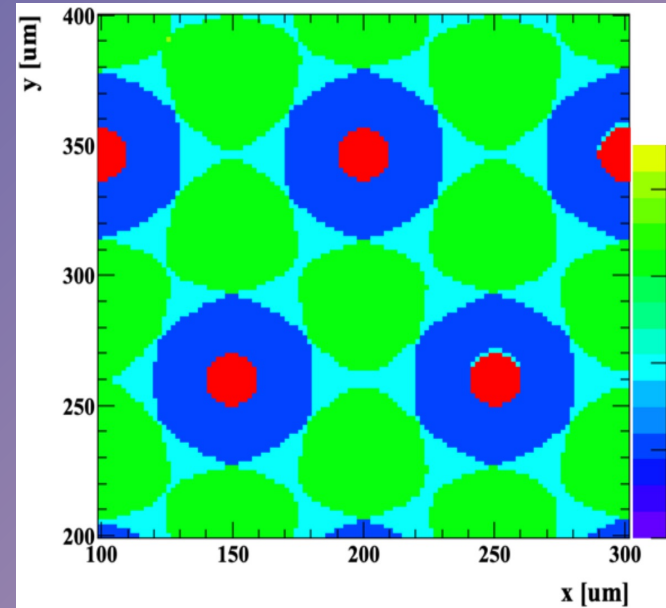
# Different pad arrangements

Matrices of squares



Percentages by event type:

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



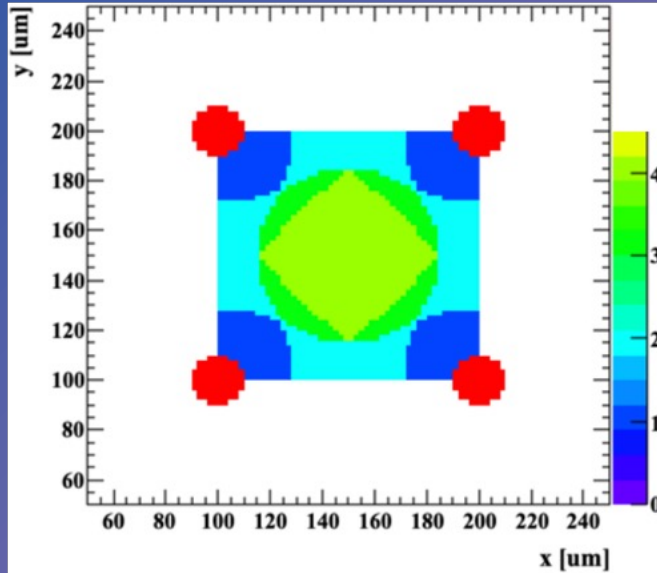
Percentages by event type:

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

Matrices of hexagons

# Different pad arrangements

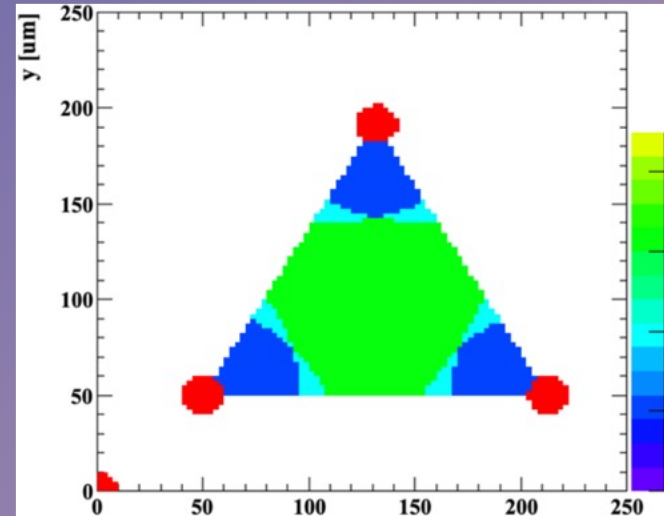
Matrices of squares



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*



Percentages by event type:

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

Matrices of hexagons