FAST 2023

TCAD simulations of DC-RSD LGAD devices

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May 28 - June 1st 2023 | *Elba Island*

An impossible challenge?

N. Cartiglia, *The power of gaining and sharing: introducing internal gain and built-in charge sharing in silicon sensors*, ULITIMA, 2023

alessandro.fondacci@pg.infn.it

An impossible challenge?

Spatial resolution
$\sim 5\ \mu m$

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Temporal resolution
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Very low material budget

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Temporal resolution
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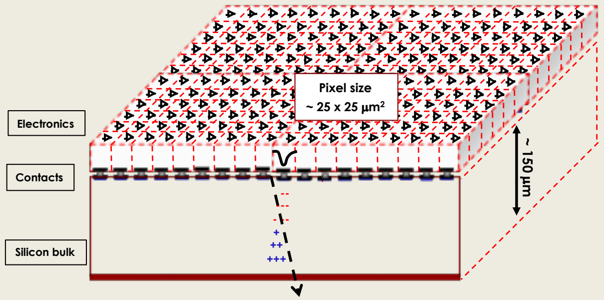
~ $50k$ pixels/cm²



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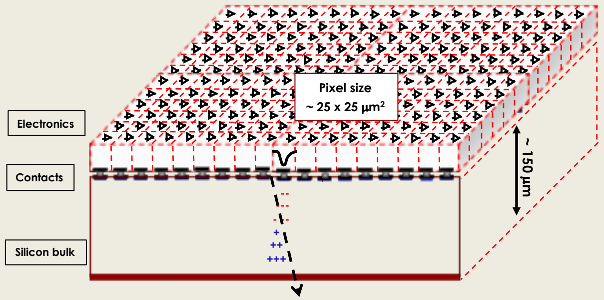

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Each pixel requires a lot of power

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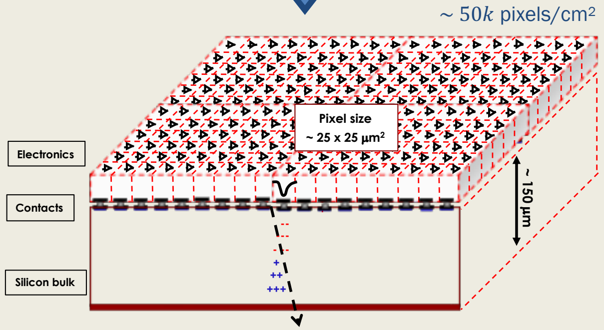

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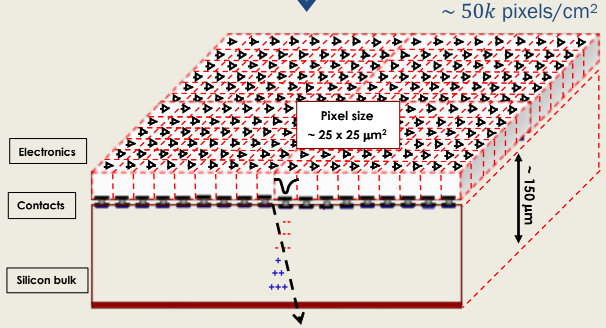

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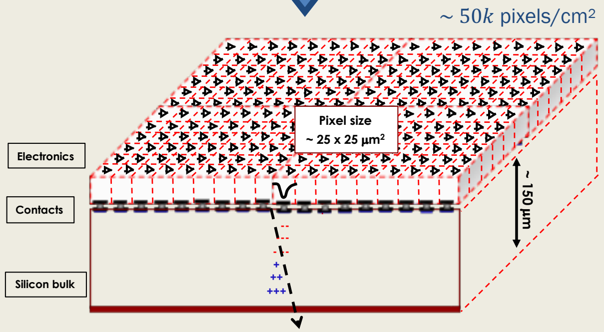

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Bulky cooling
infrastructure

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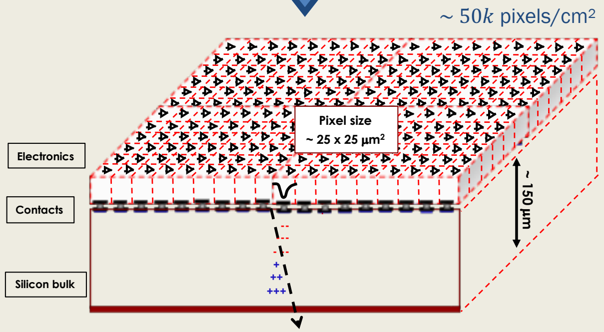

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The signal in thin
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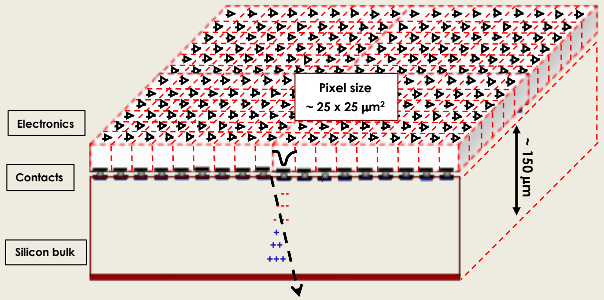

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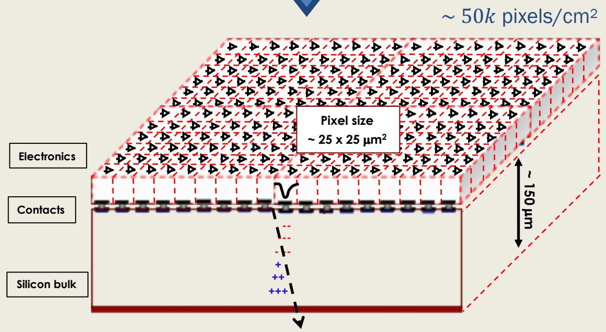

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Each pixel requires
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Is there a way to fulfil the four specifications simultaneously?

Plenty of power

Bulky cooling
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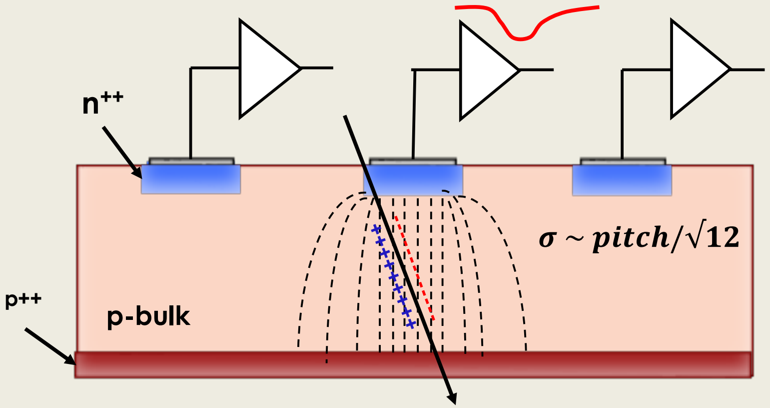
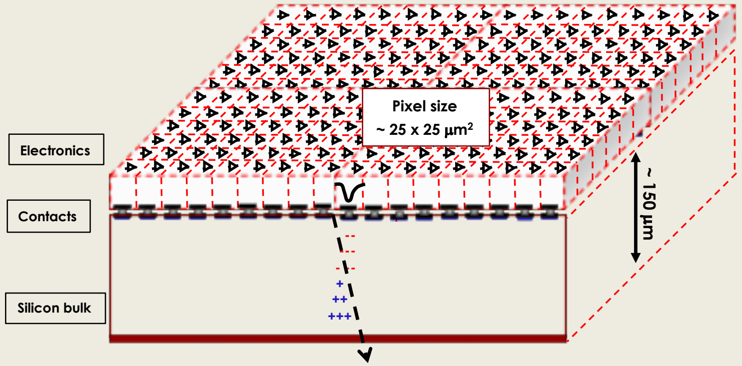
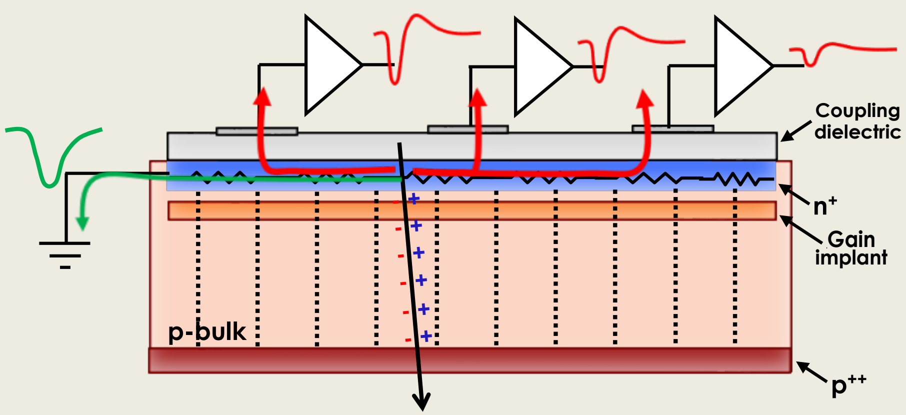
An intriguing candidate for future colliders

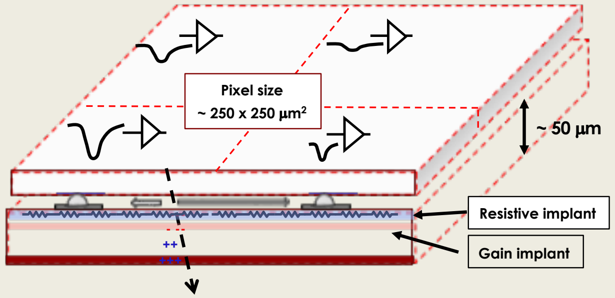
Standard silicon detector





Resistive Silicon Detector





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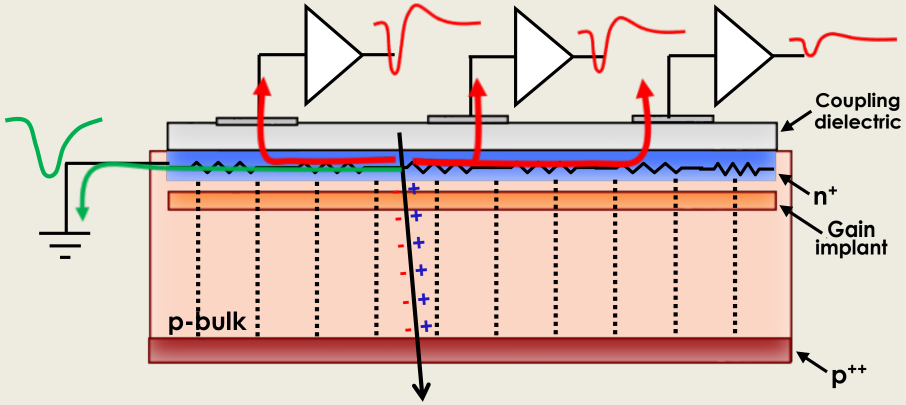
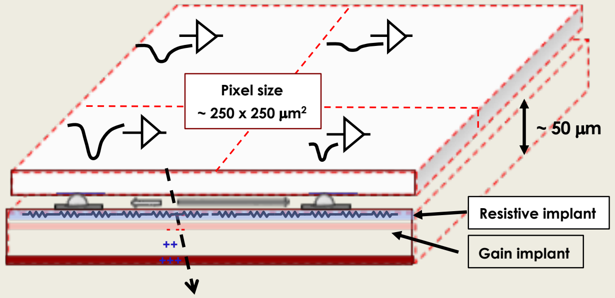
An intriguing candidate for future colliders

Innovation	Sensor property	Experimental feature
Resistive read-out	Continuous gain layer	100% fill factor
	Continuous cathode	Uniform weighting field
		Uniform carriers drift velocity
	Large pixels	Reduced power consumption
		Space for electronics
	Signal sharing	Excellent spatial precision
Internal gain	Thin	Low material budget
	Large signals	100% efficiency
		Excellent temporal precision

Resistive Silicon Detector





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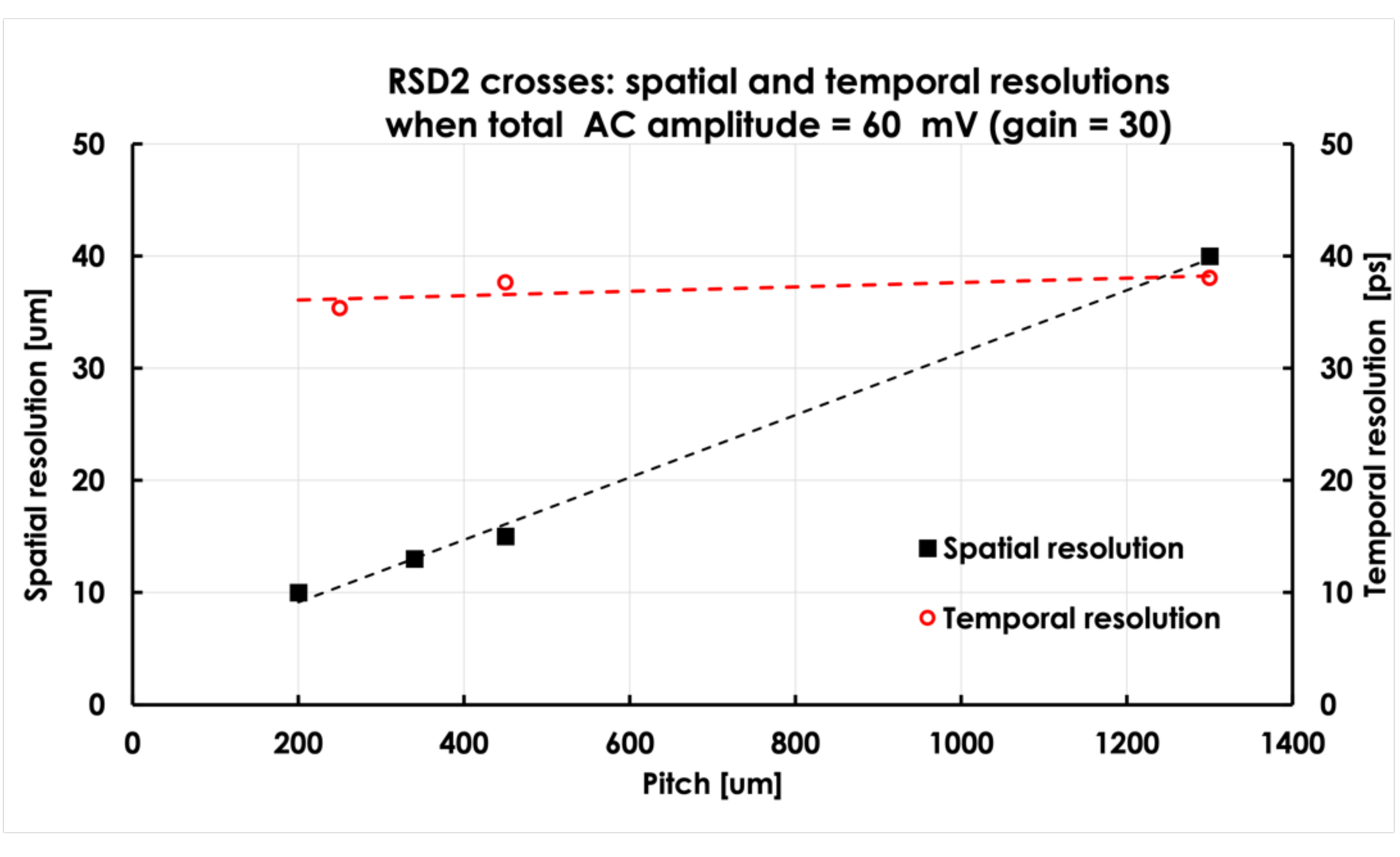
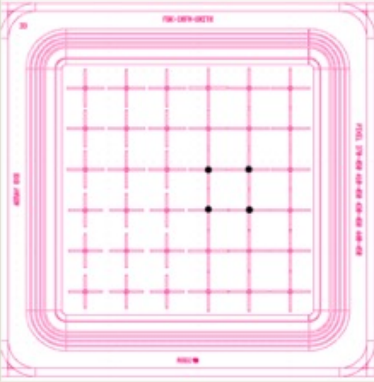
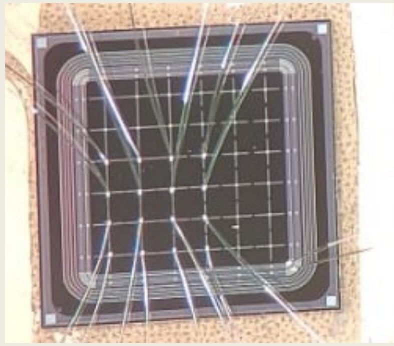
Experimental Results: FBK RSD2 performance summary



Layout



Device made and bonded



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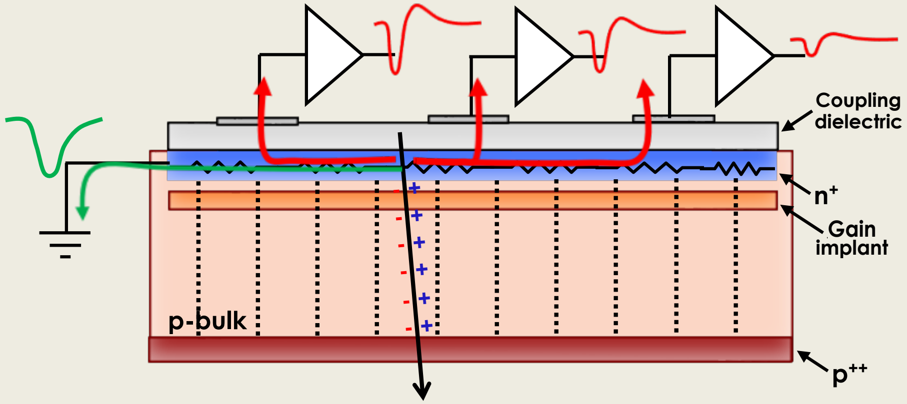
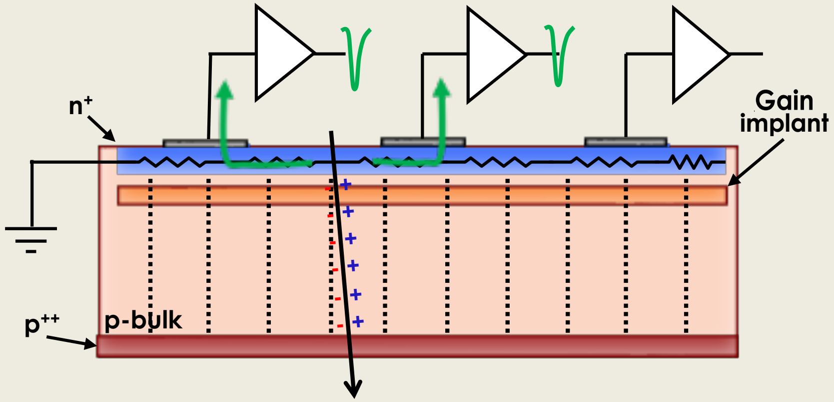
RSD LGAD: AC or DC coupled electrodes?

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)

N. Cartiglia, *The power of gaining and sharing: introducing internal gain and built-in charge sharing in silicon sensors*, ULITIMA, 2023

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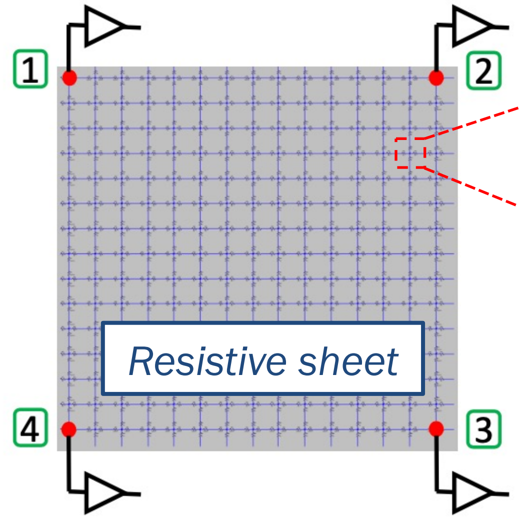
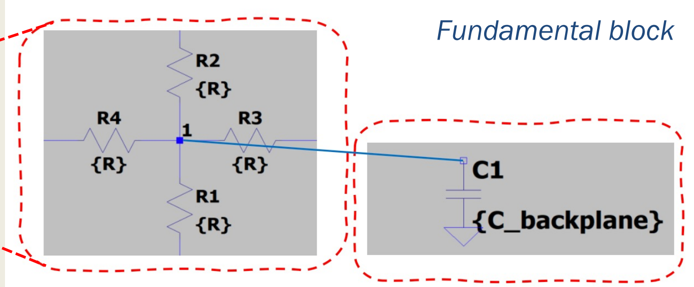
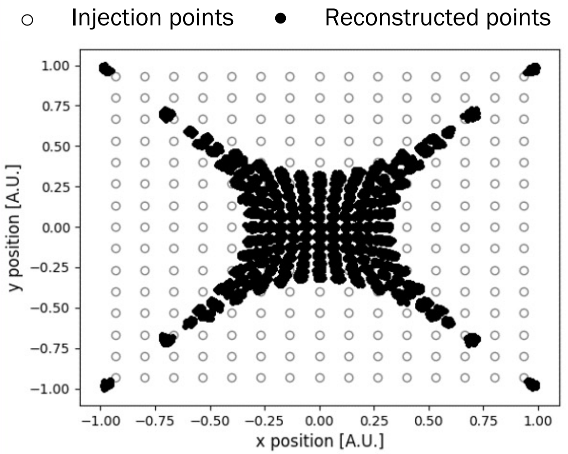
Proof of concept: Spice (circuit-level) simulations







On the dynamic two-dimensional charge diffusion of the interpolating readout structure employed in the MicroCAT detector, Wagner et al., NIM A, (2002)

L. Menzio et al., *DC-coupled resistive silicon detectors for 4D tracking*, Nuclear Instr. Meth. In Phys. Res. A, Vol. 1041, 2022

DC-RSD LGAD

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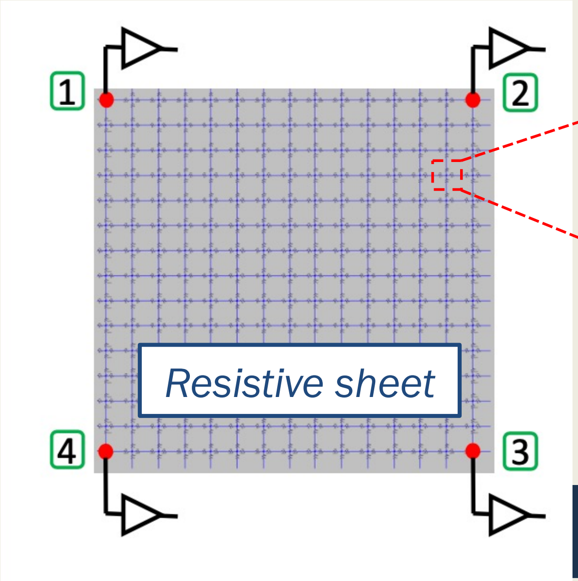

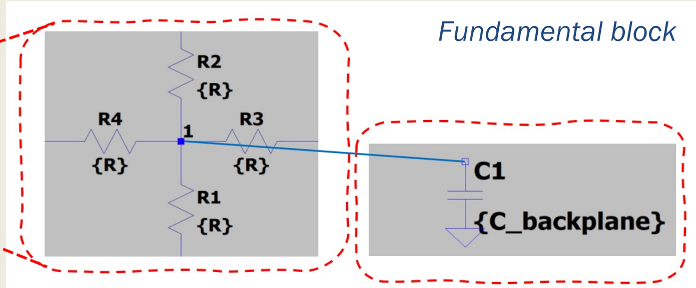

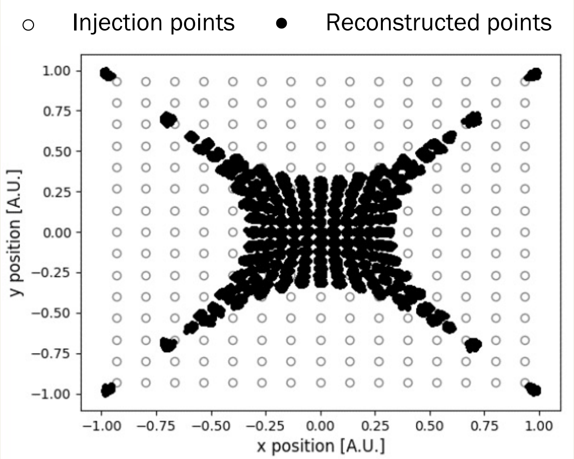

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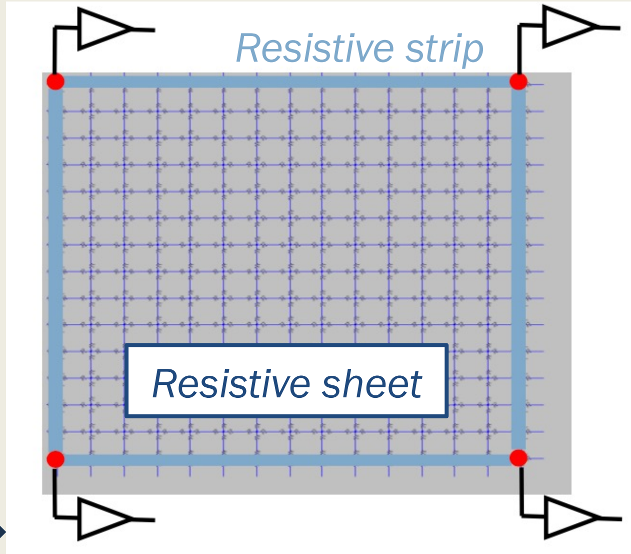

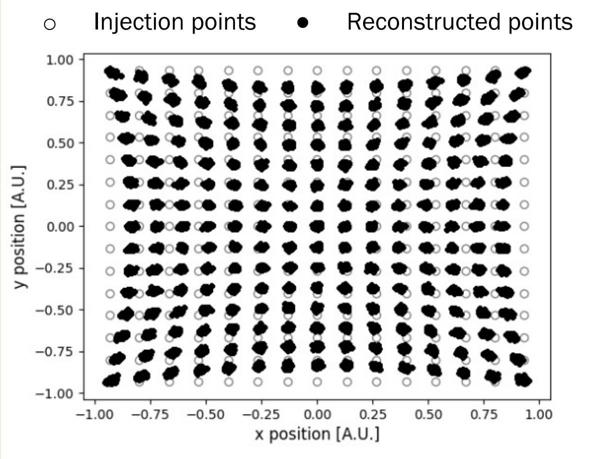

Sheet resistance: $1 \div 3\ k\Omega/sq$

Strip resistance: $2.0 \div 6.5\ \Omega/\mu m$

L. Menzio et al., *DC-coupled resistive silicon detectors for 4D tracking*, Nuclear Instr. Meth. In Phys. Res. A, Vol. 1041, 2022

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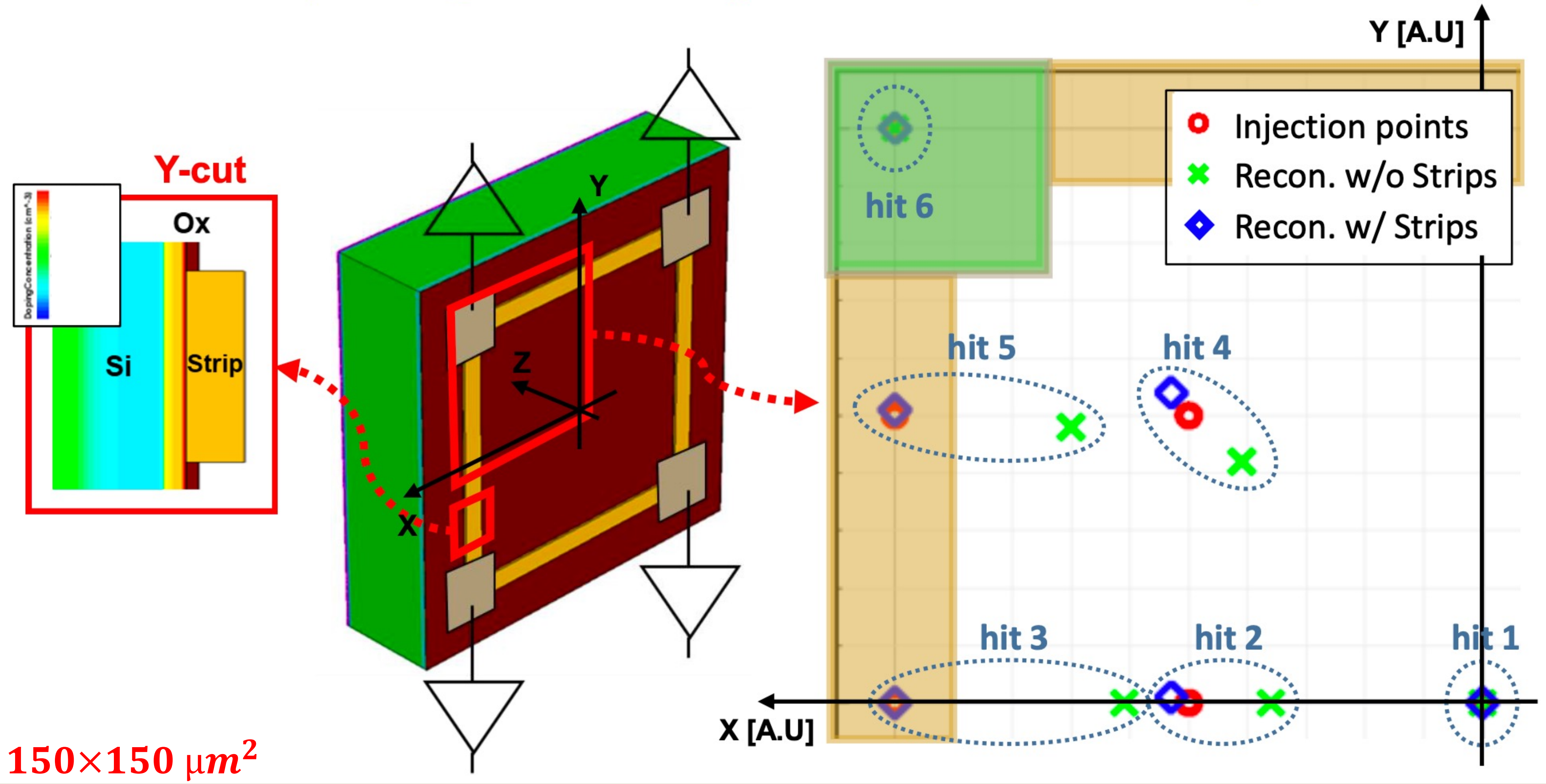
Spice results comparison: TCAD (device-level) simulations



T. Croci et al., *A two-prong Approach to the Simulation of DC-RSD: TCAD and Spice*, 2022 IEEE NSS MIC RTSD

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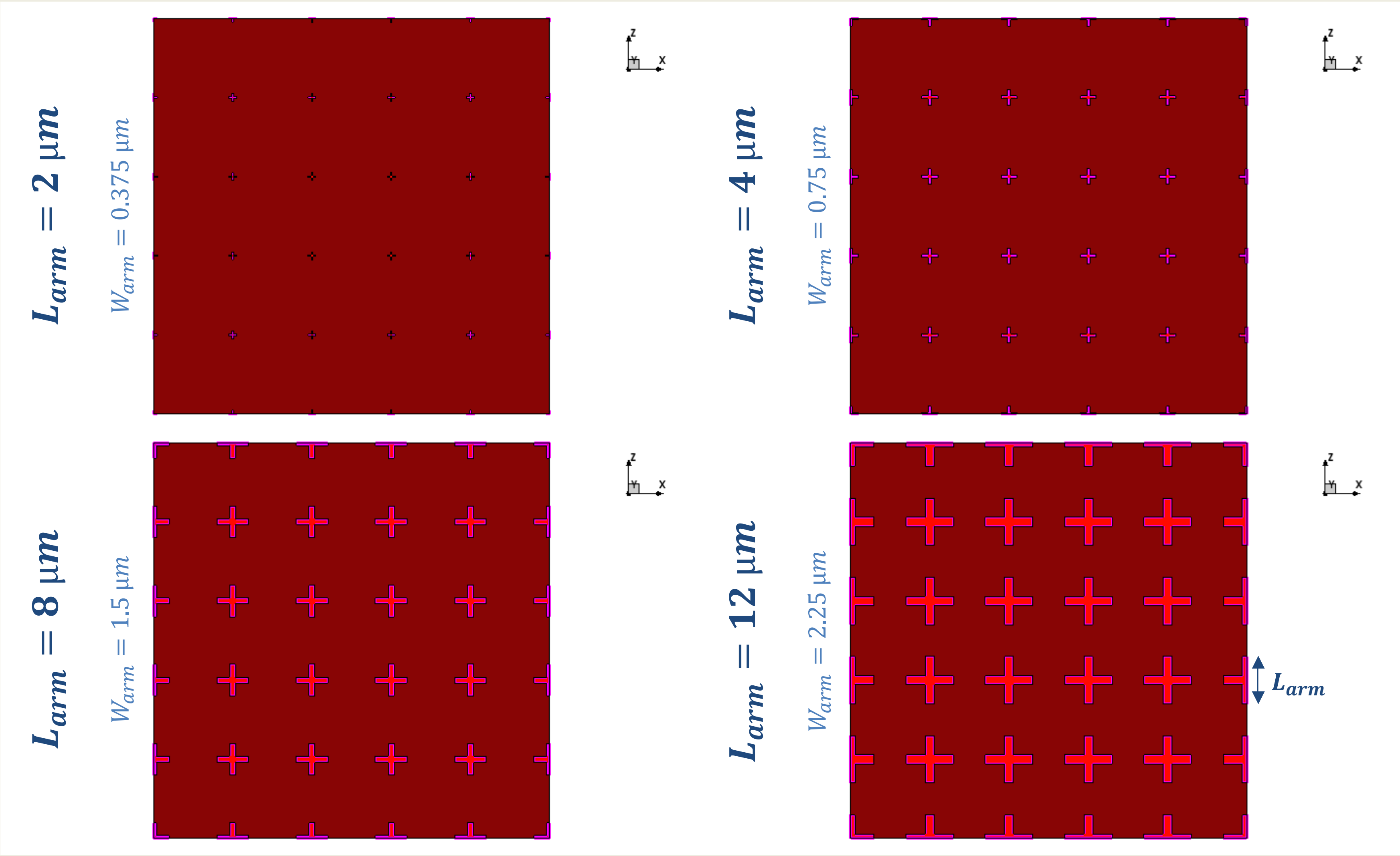
Seeking to limit charge sharing: Cross-shaped pads



Structure with many pixels to study signal confinement

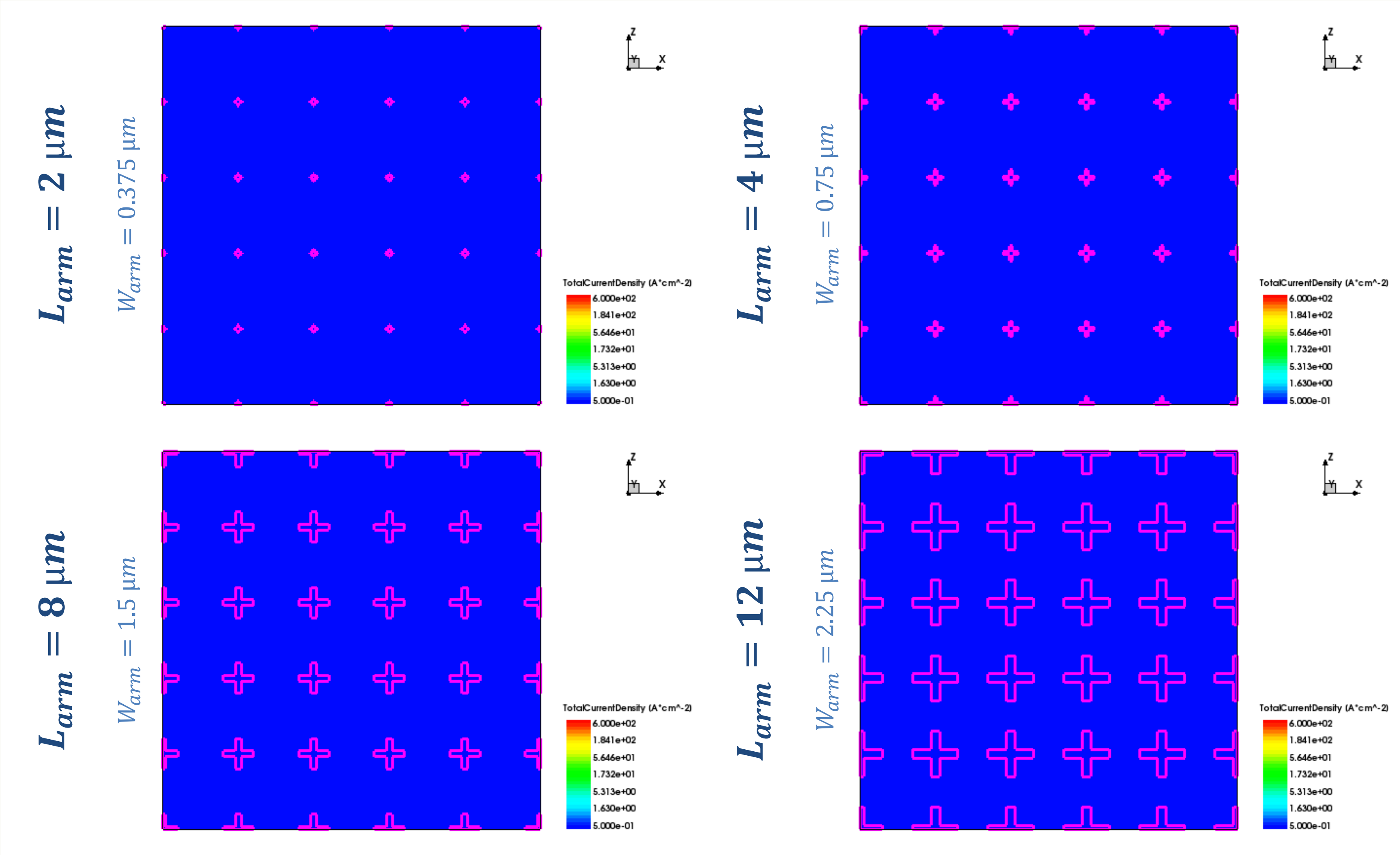
↓

For computationally acceptable 3D simulations each pixel must be small

↓

Footprint of $100\times100\ \mu m^2$

Temporal evolution of current density maps



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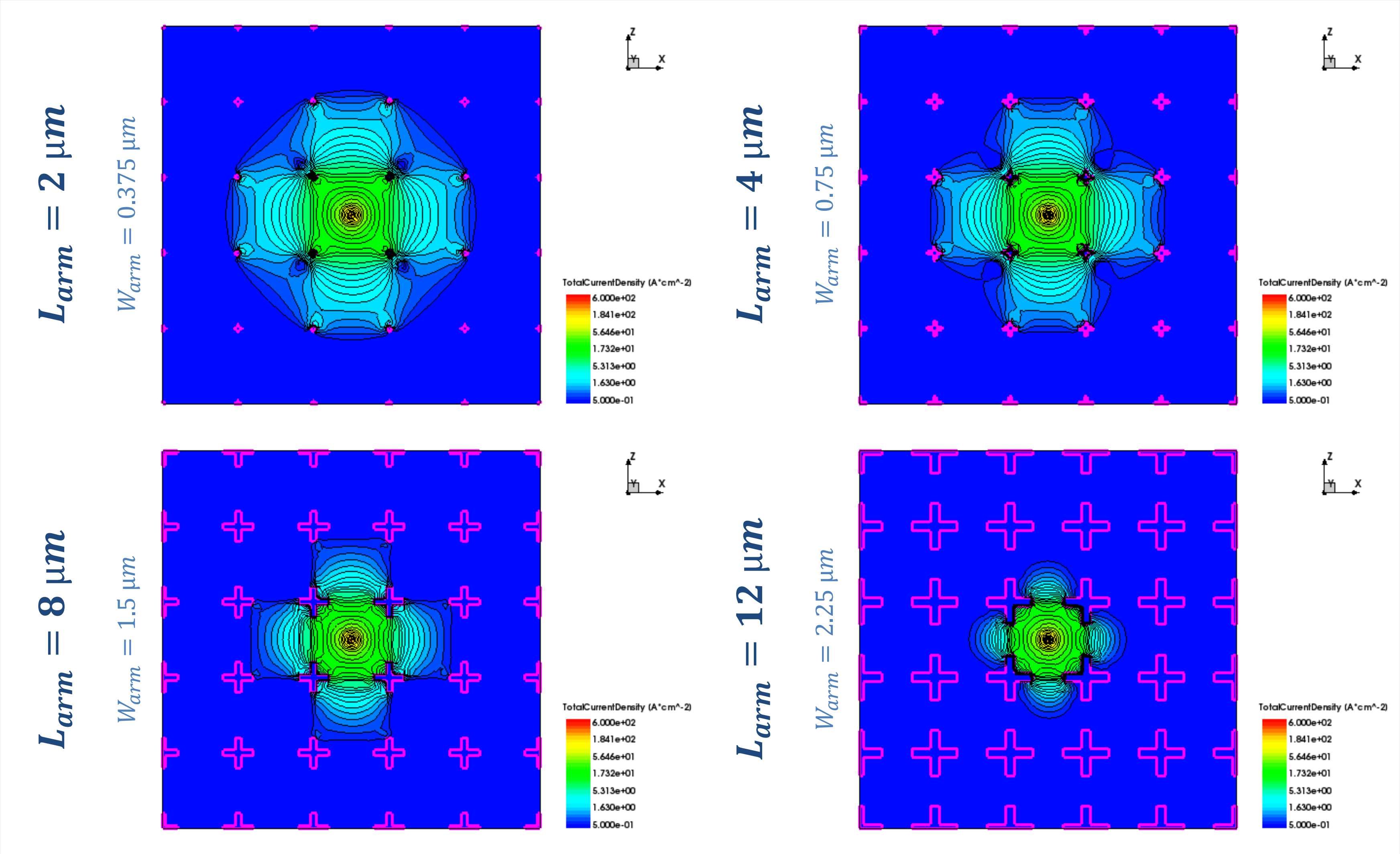
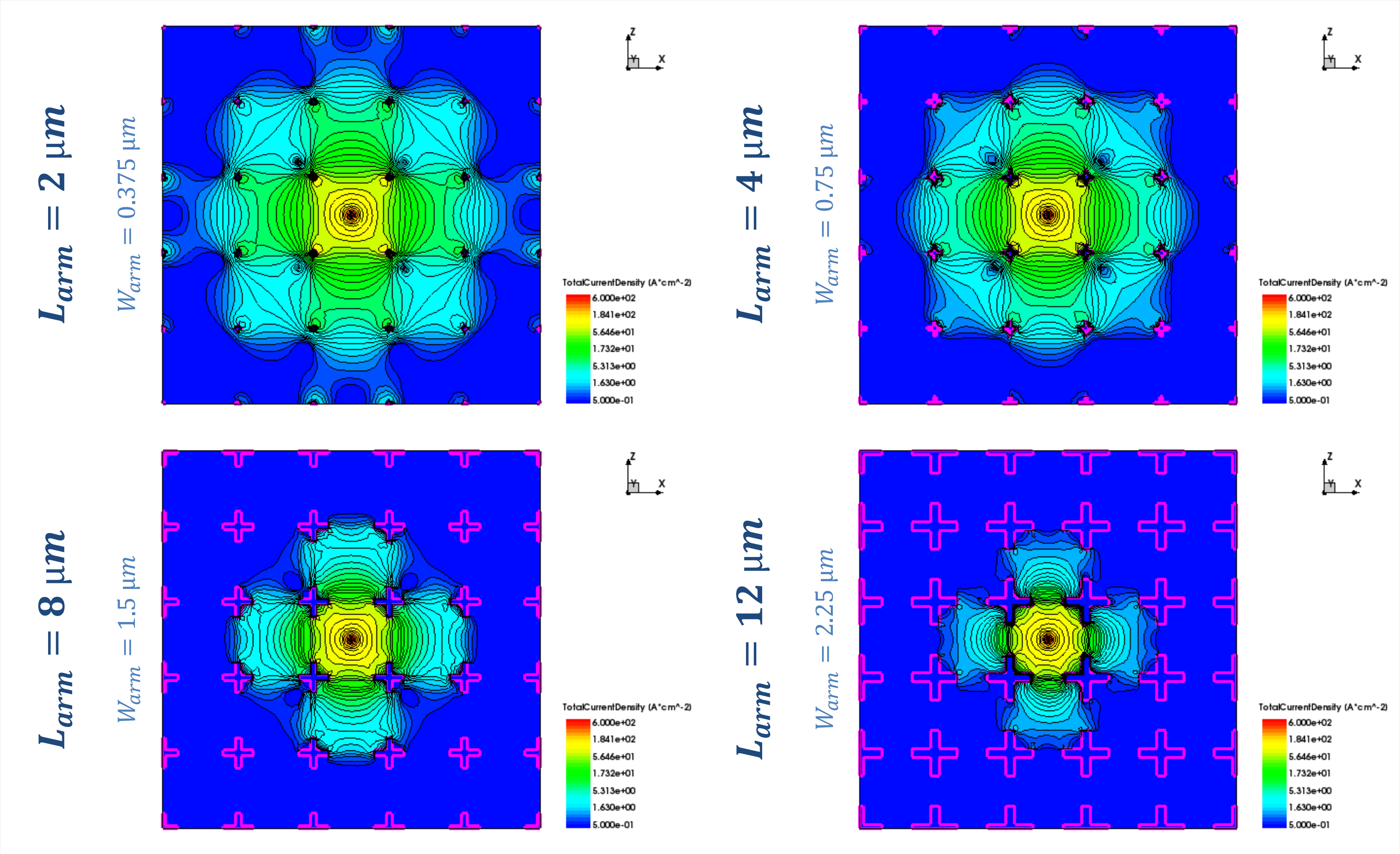


Cross-shaped pads

DC-RSD LGAD

HIT 1

Temporal evolution of current density maps



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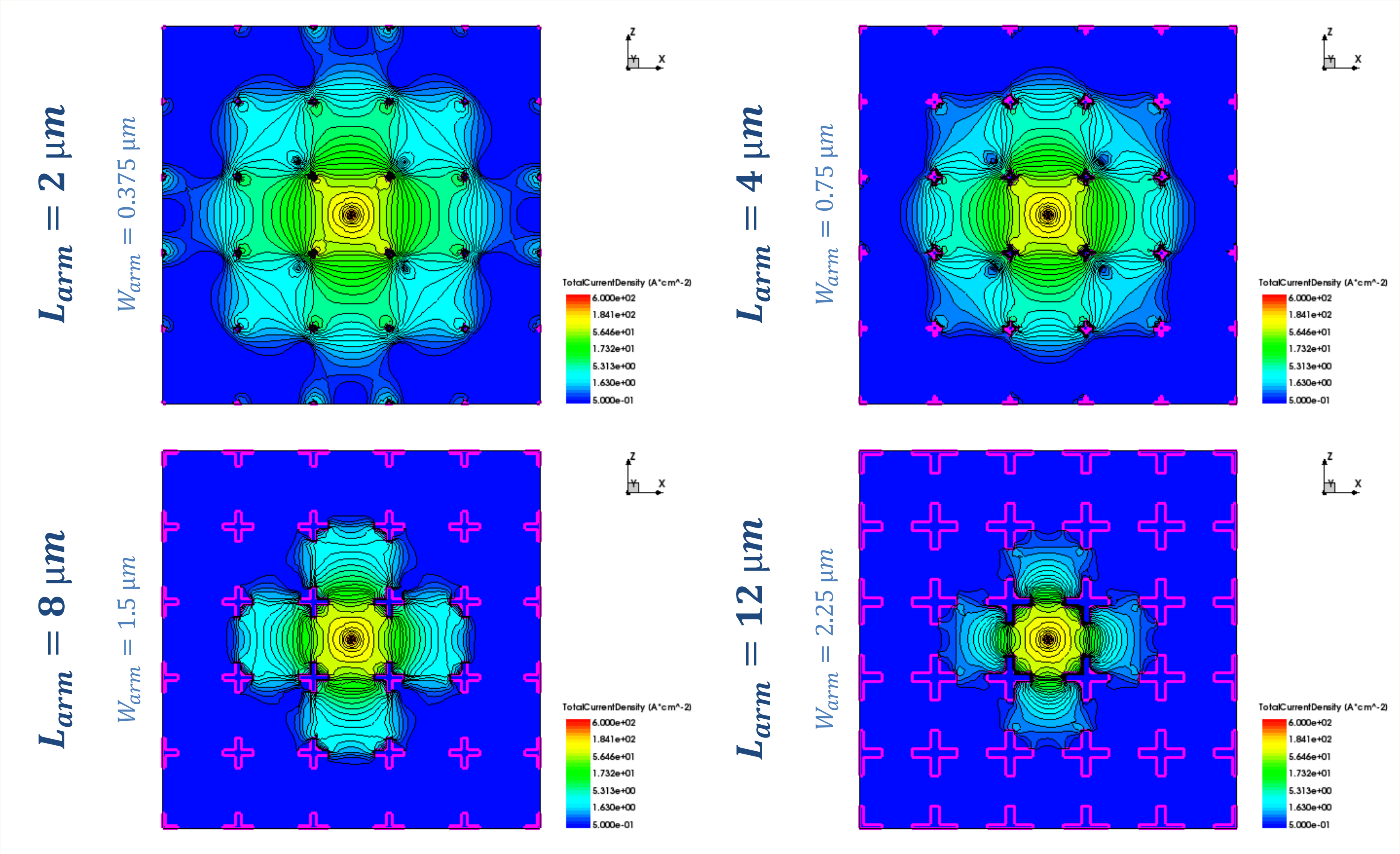

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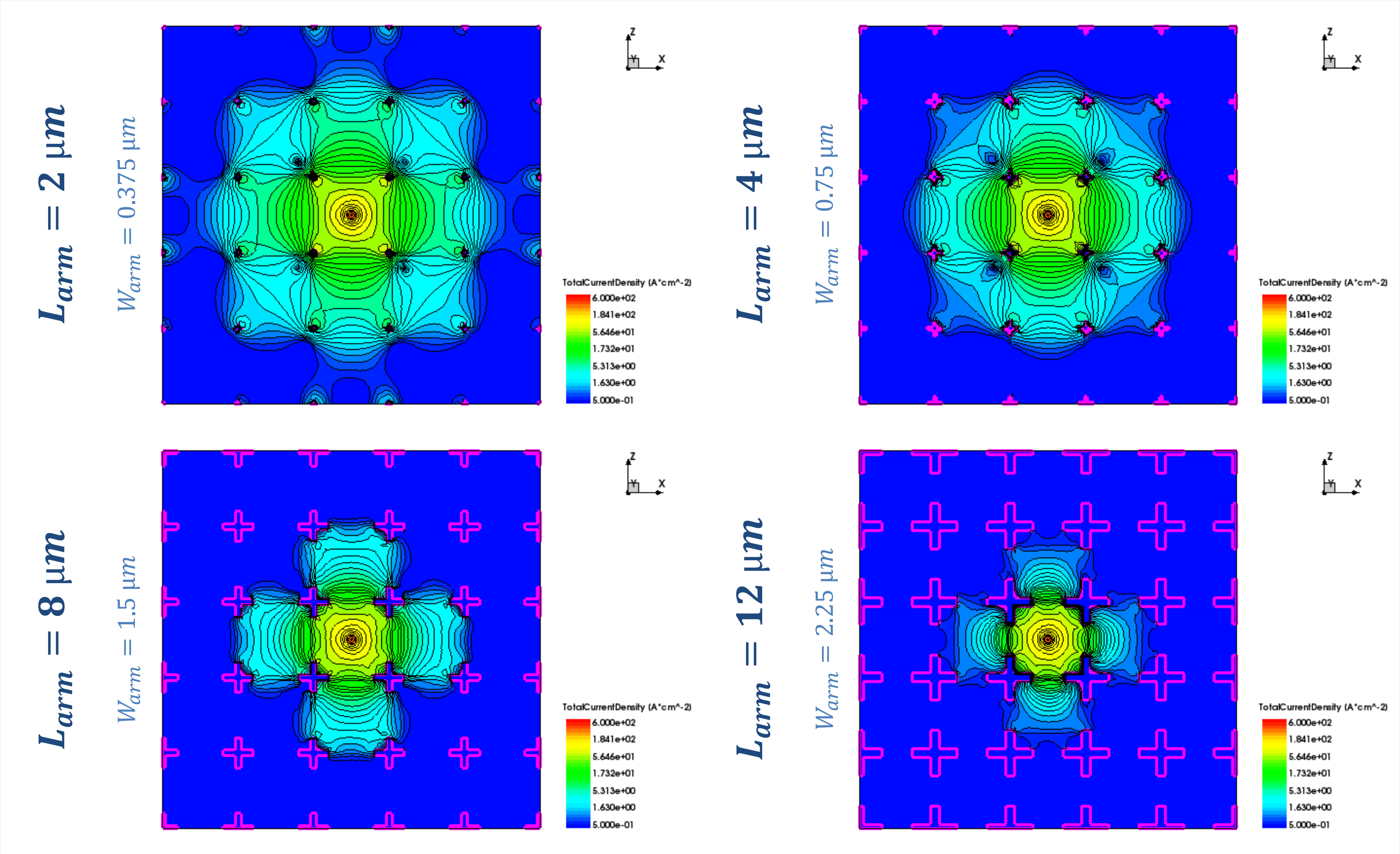

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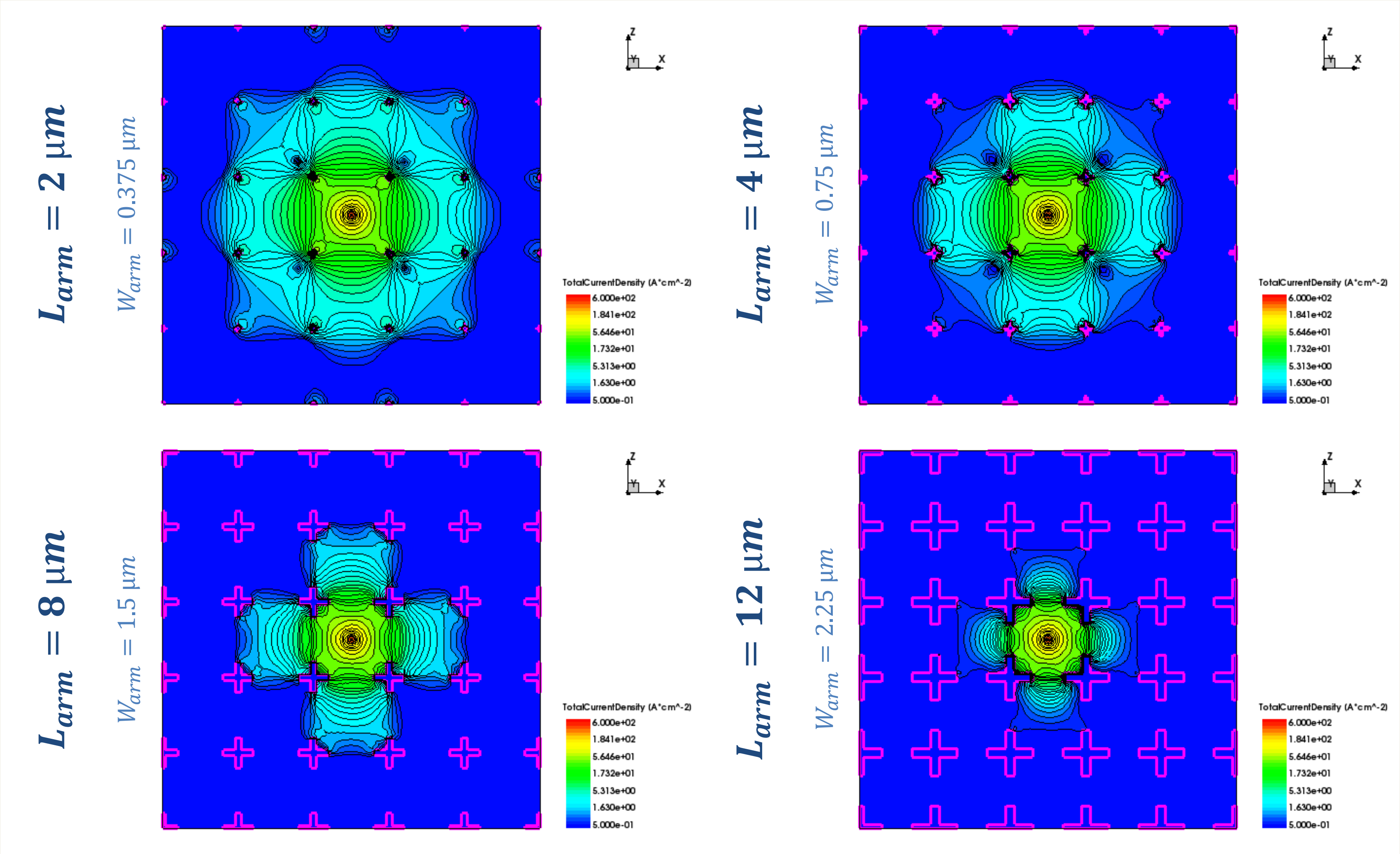

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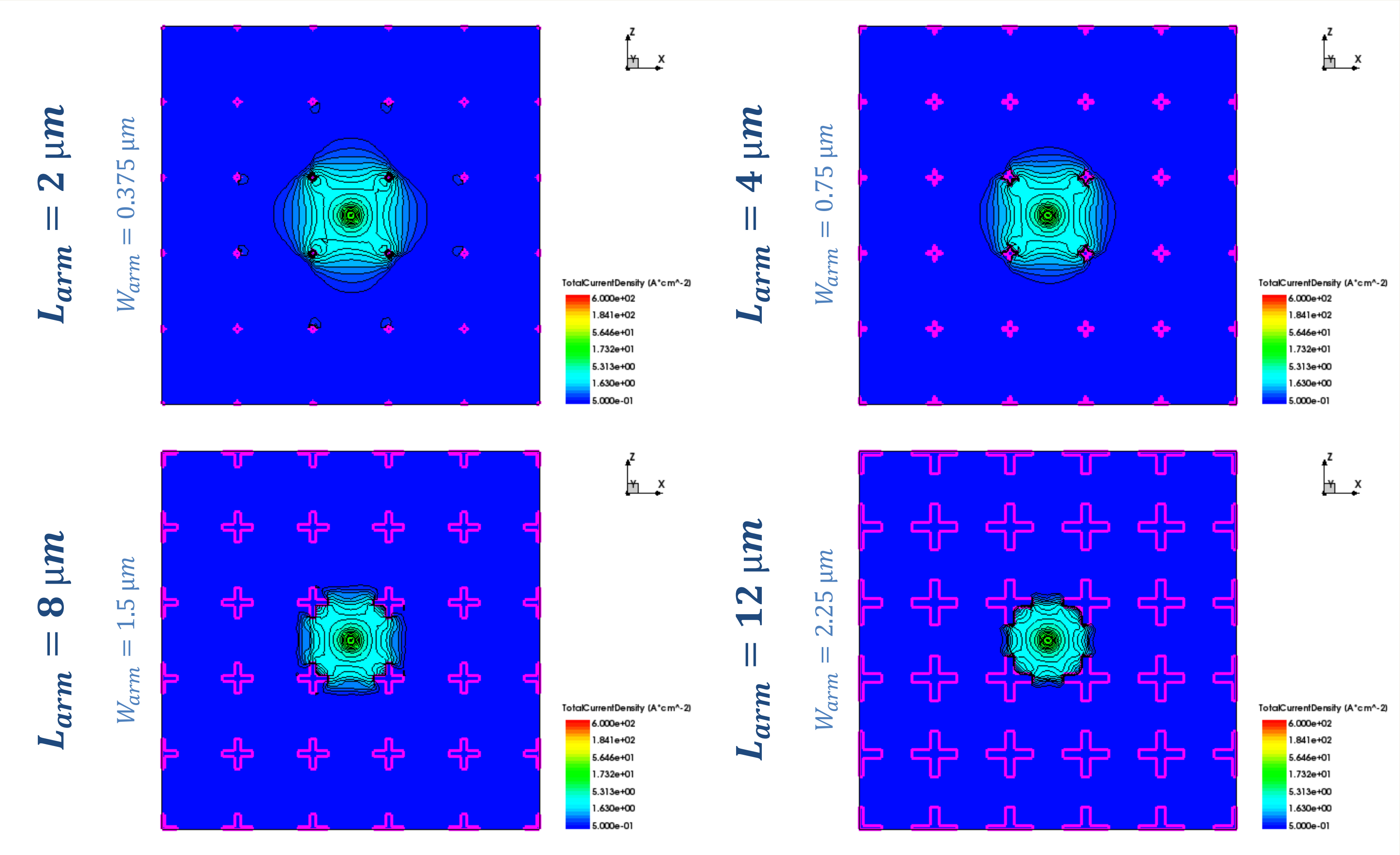

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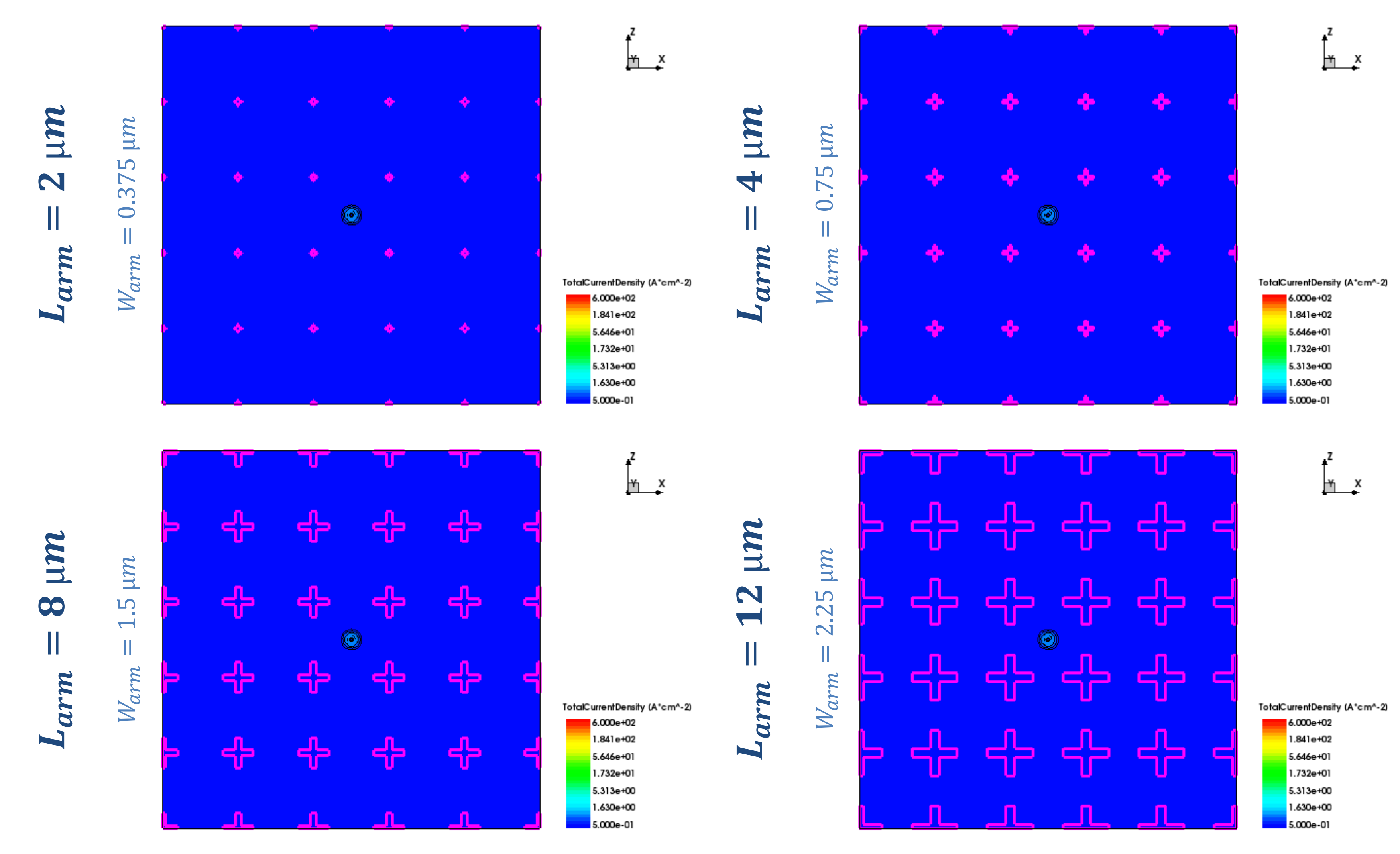

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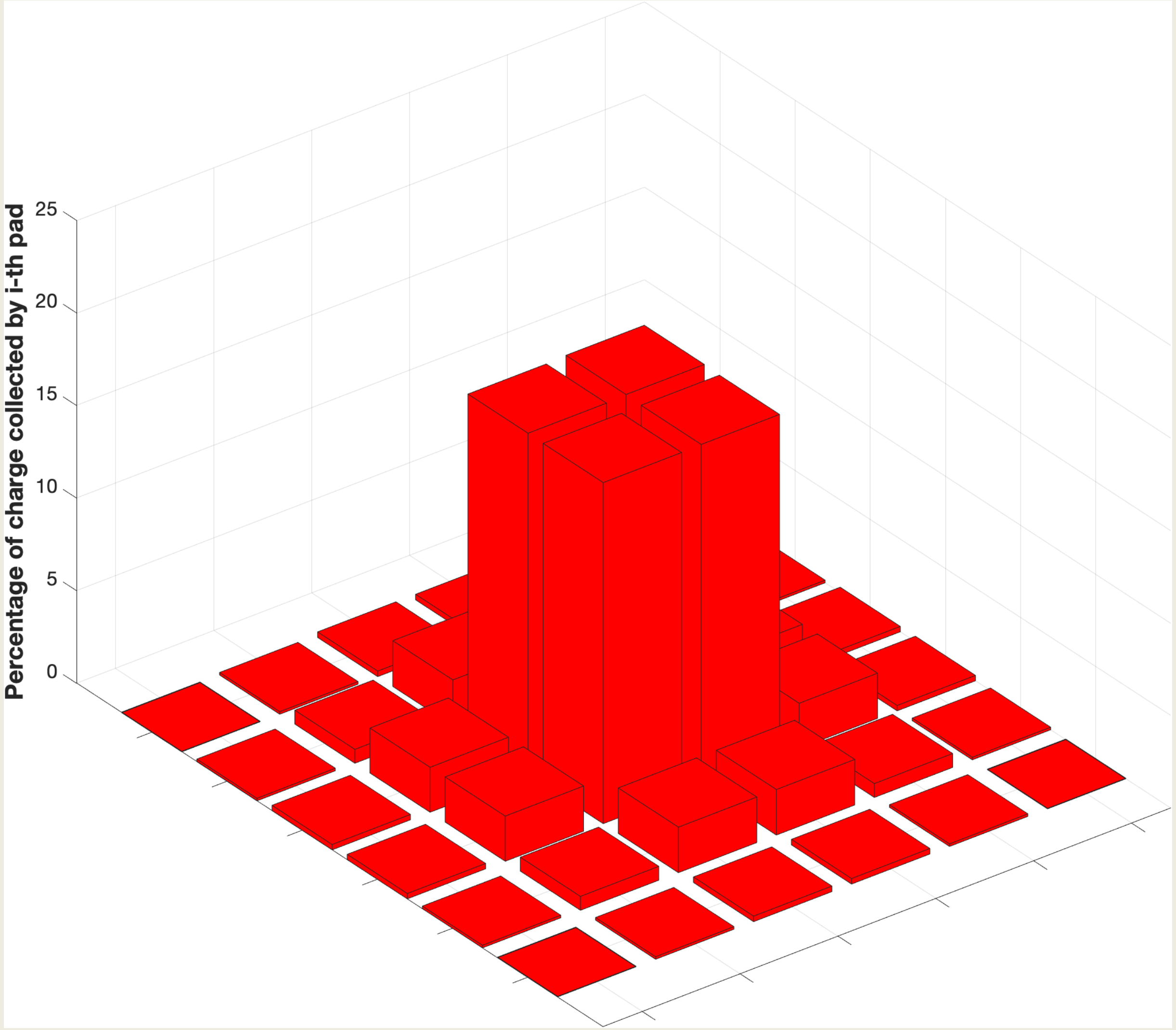
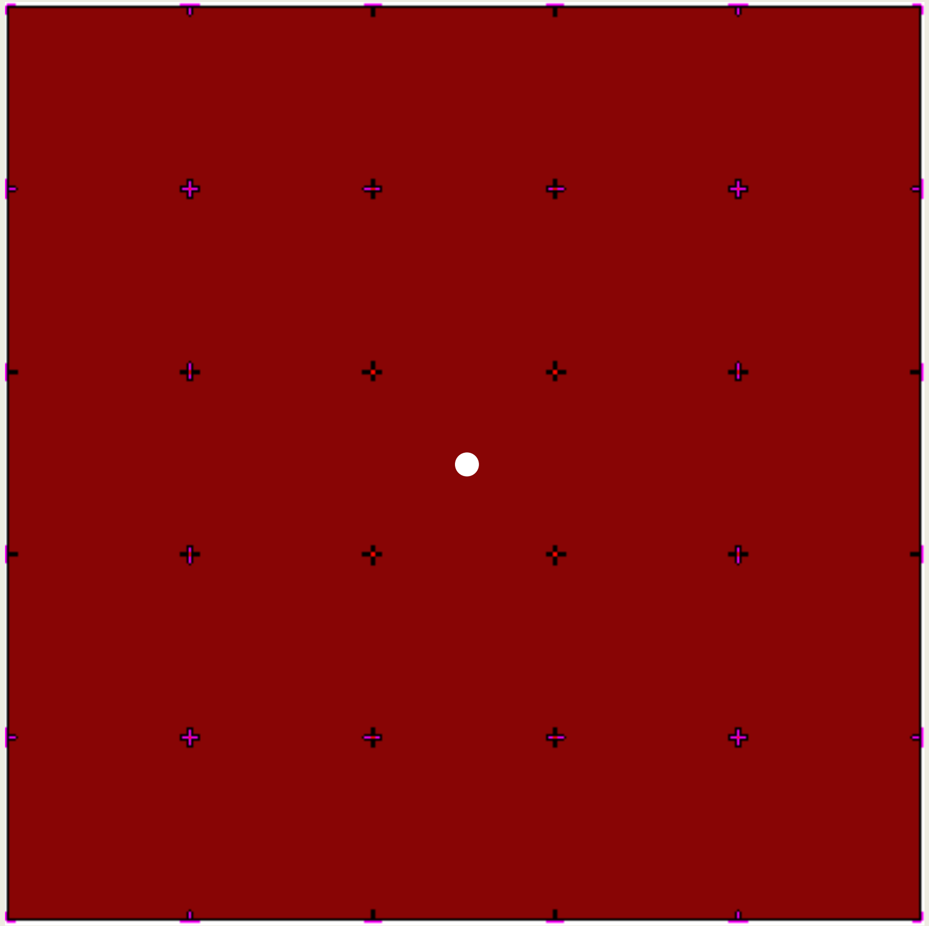
Distribution of collected charge between pads as a function of their size



$L_{arm} = 2\ \mu m$



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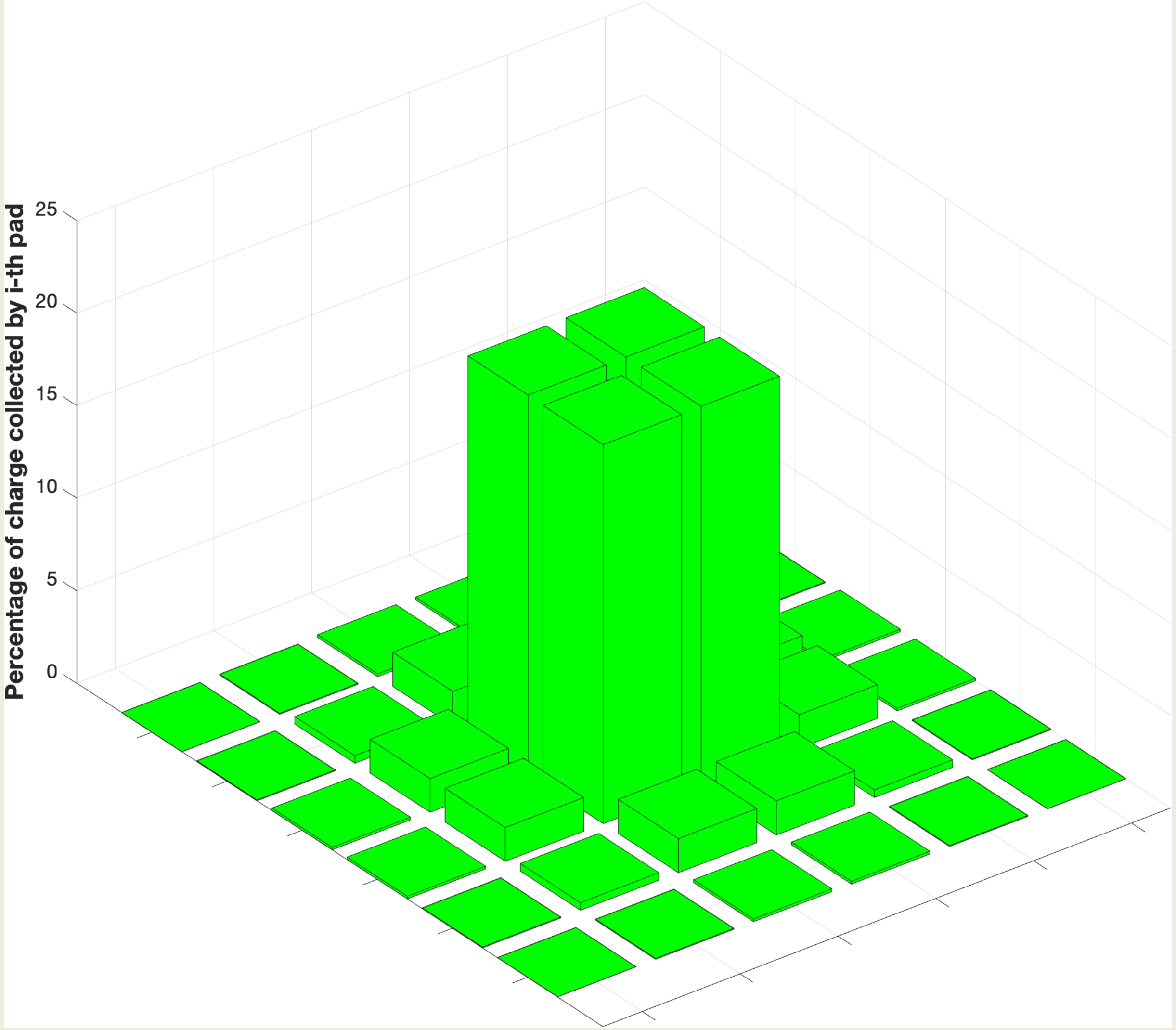
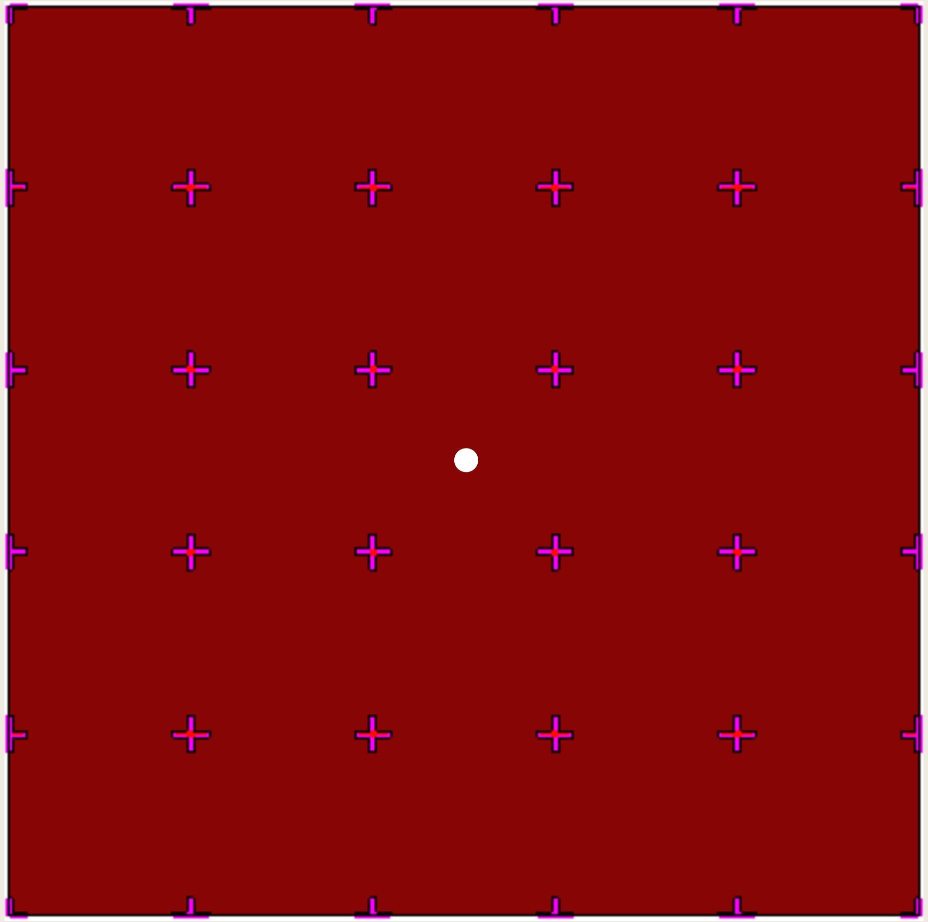


L$_{arm}$ = $4\ \mu m$



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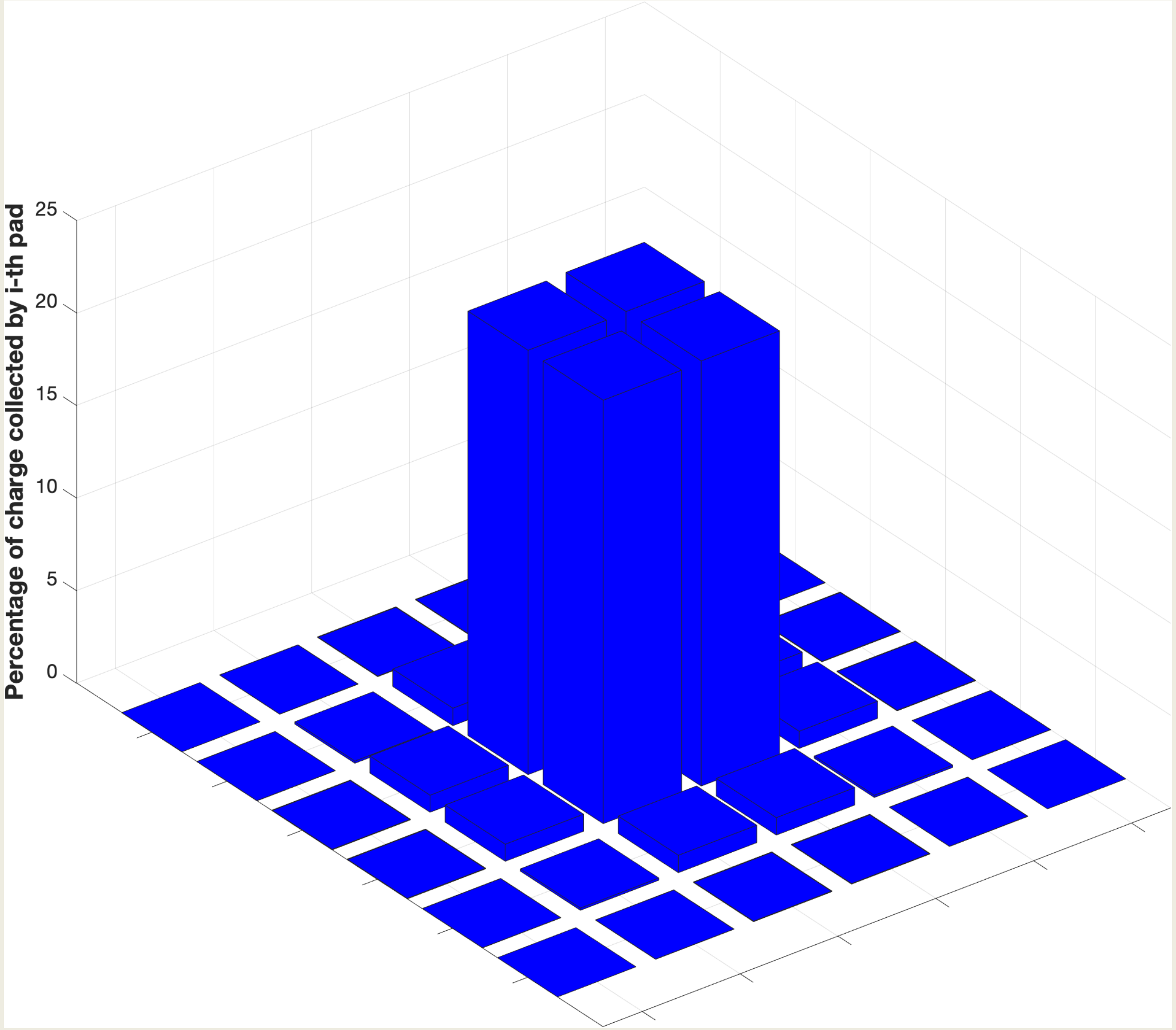
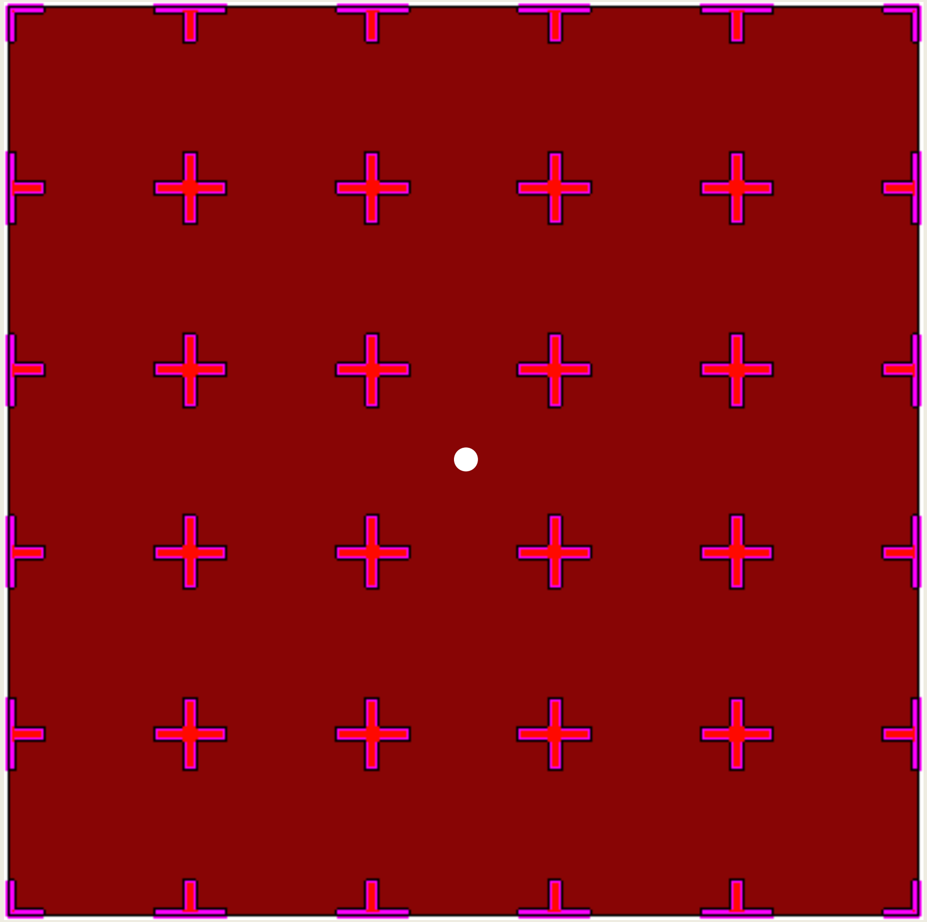


$L_{arm} = 8\ \mu m$



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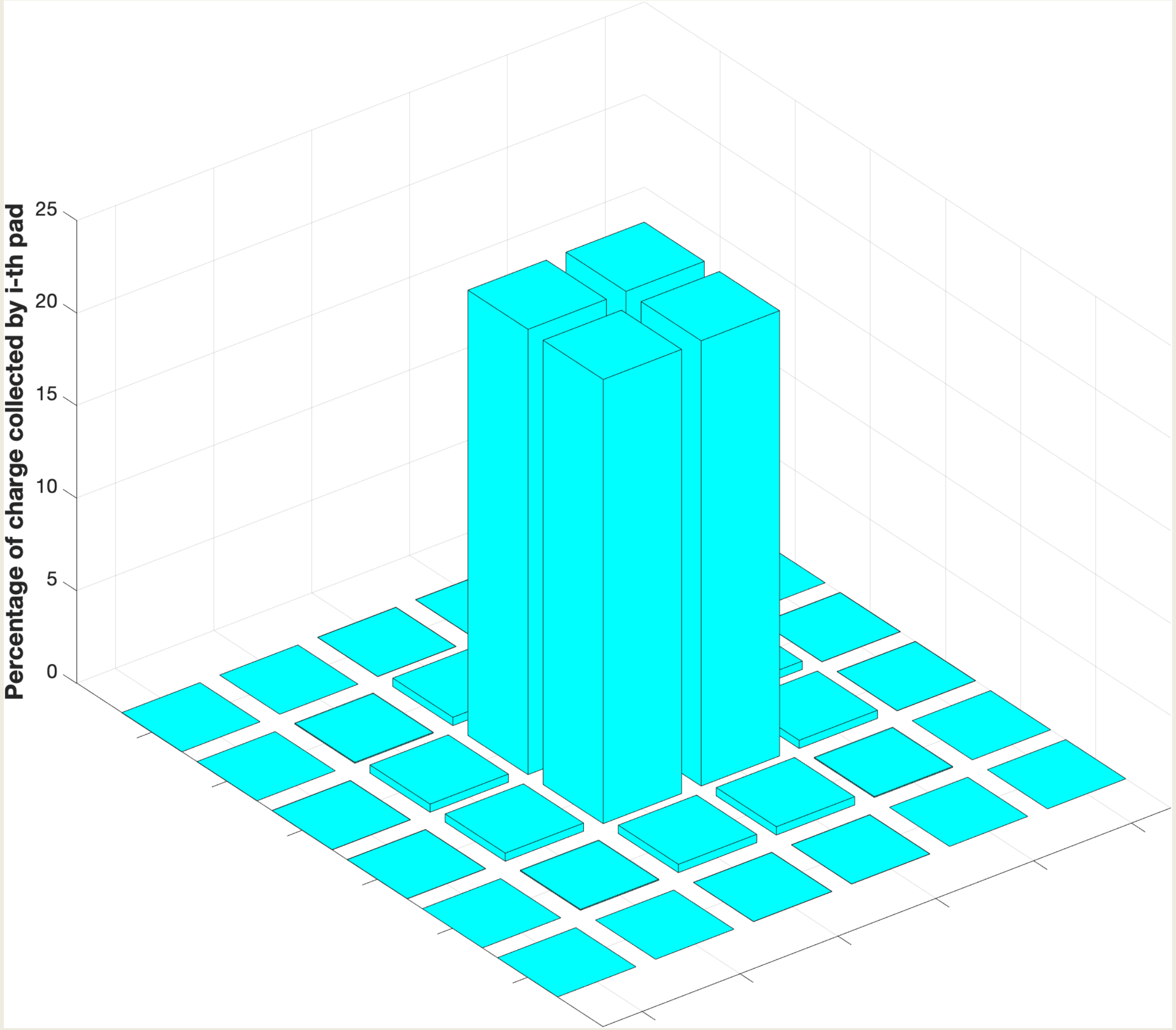
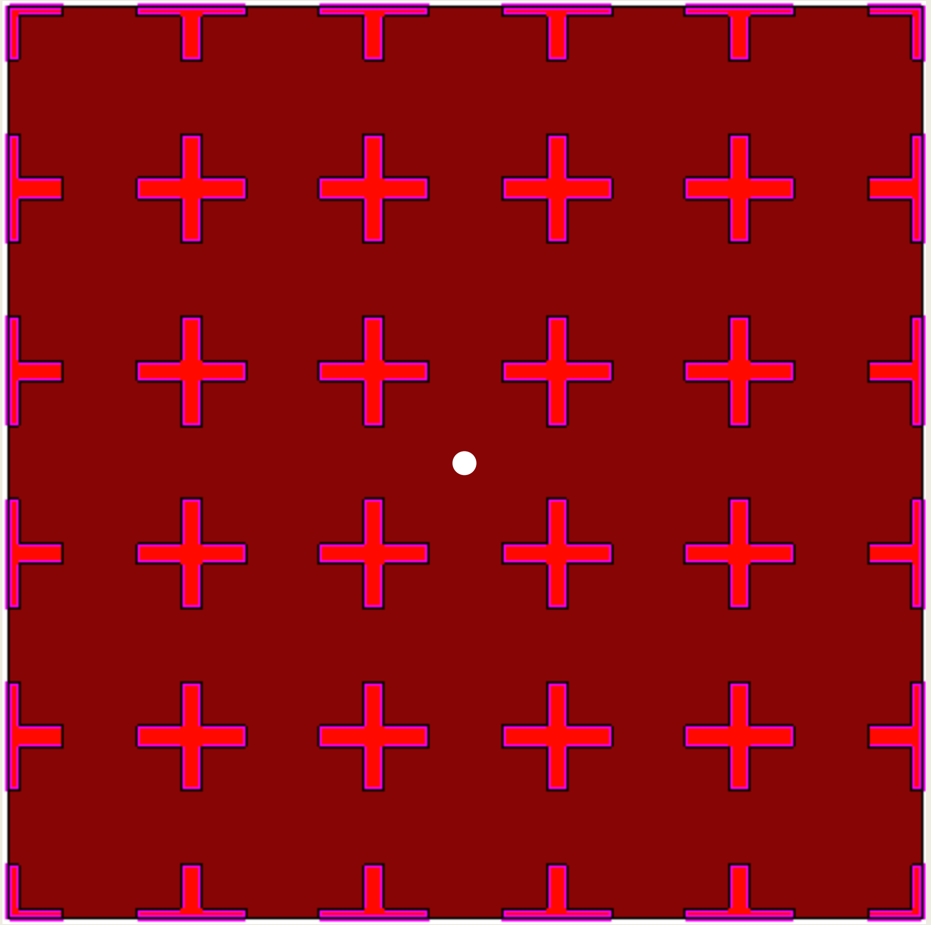


L$_{arm}$ = 12 μm



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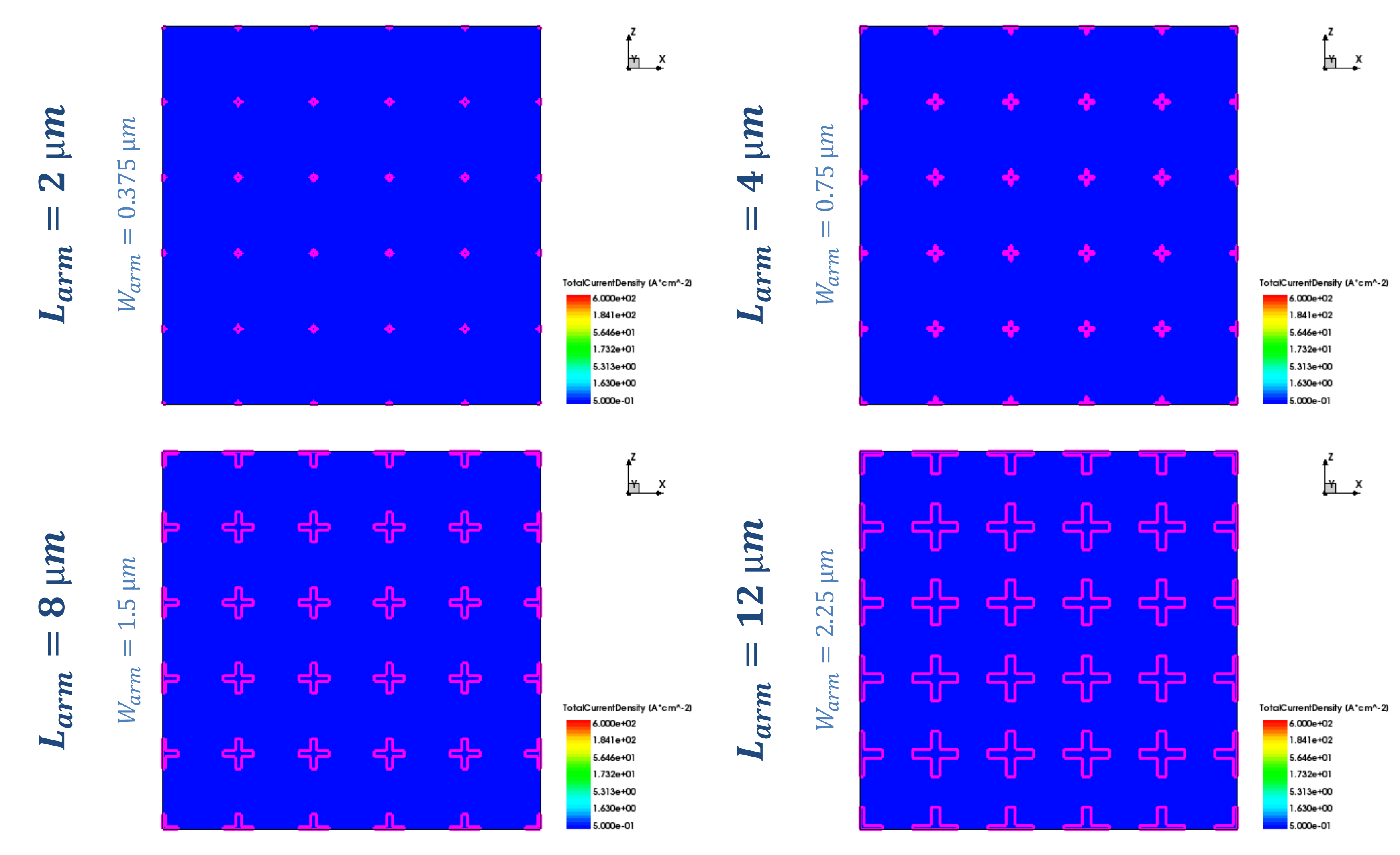
Temporal evolution of current density maps



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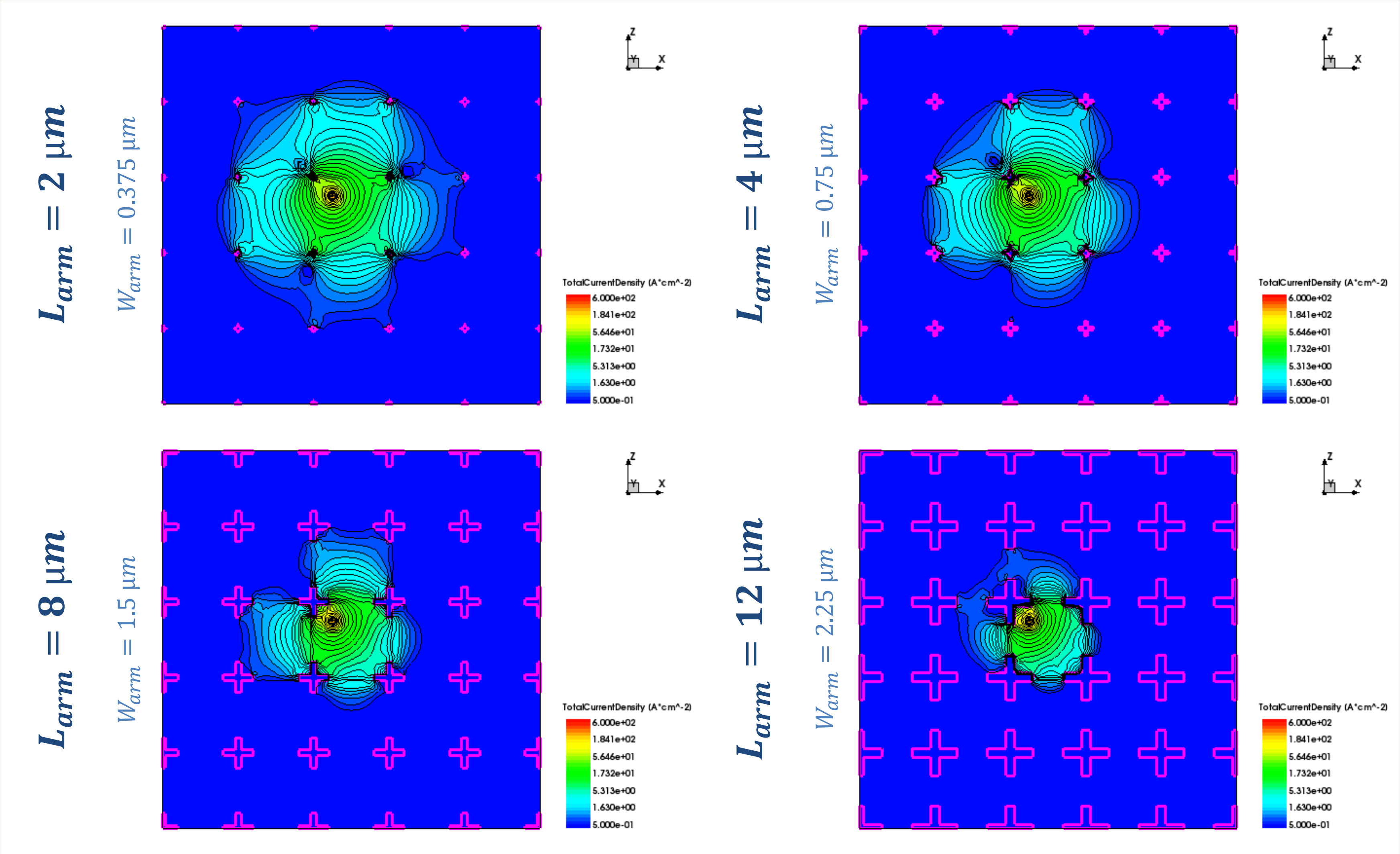
Cross-shaped pads

DC-RSD LGAD

HIT 2

Temporal evolution of current density maps



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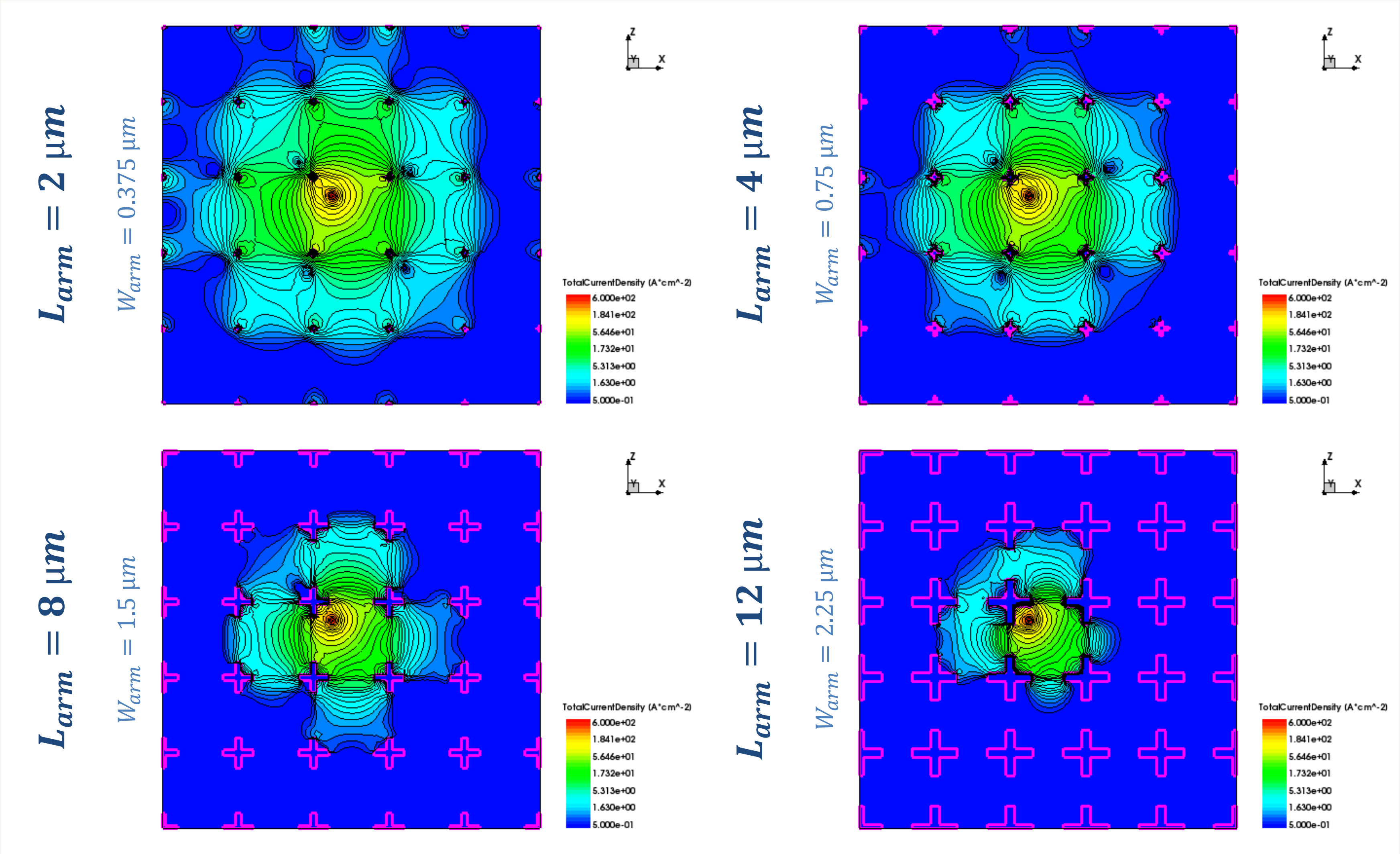

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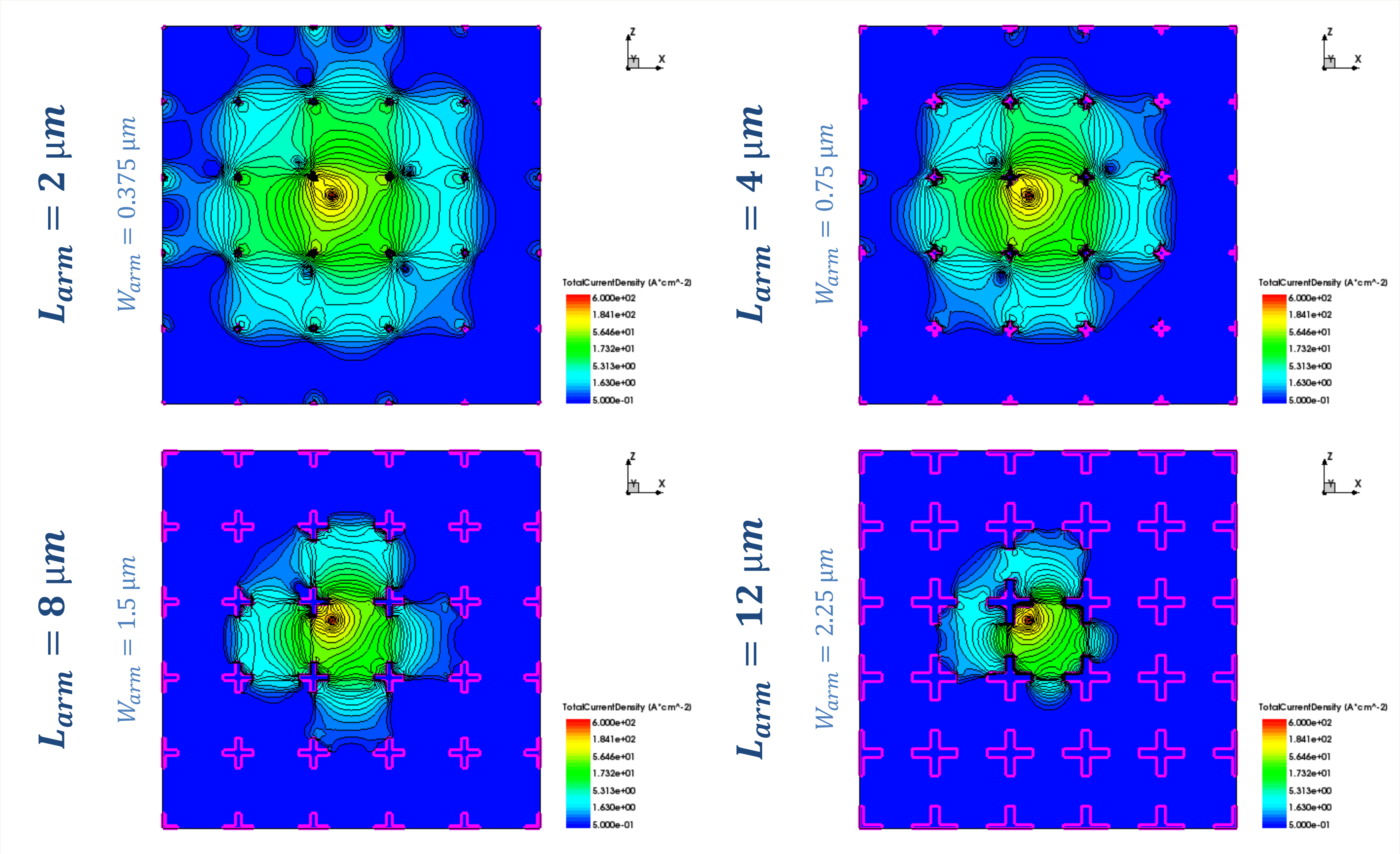
Temporal evolution of current density maps

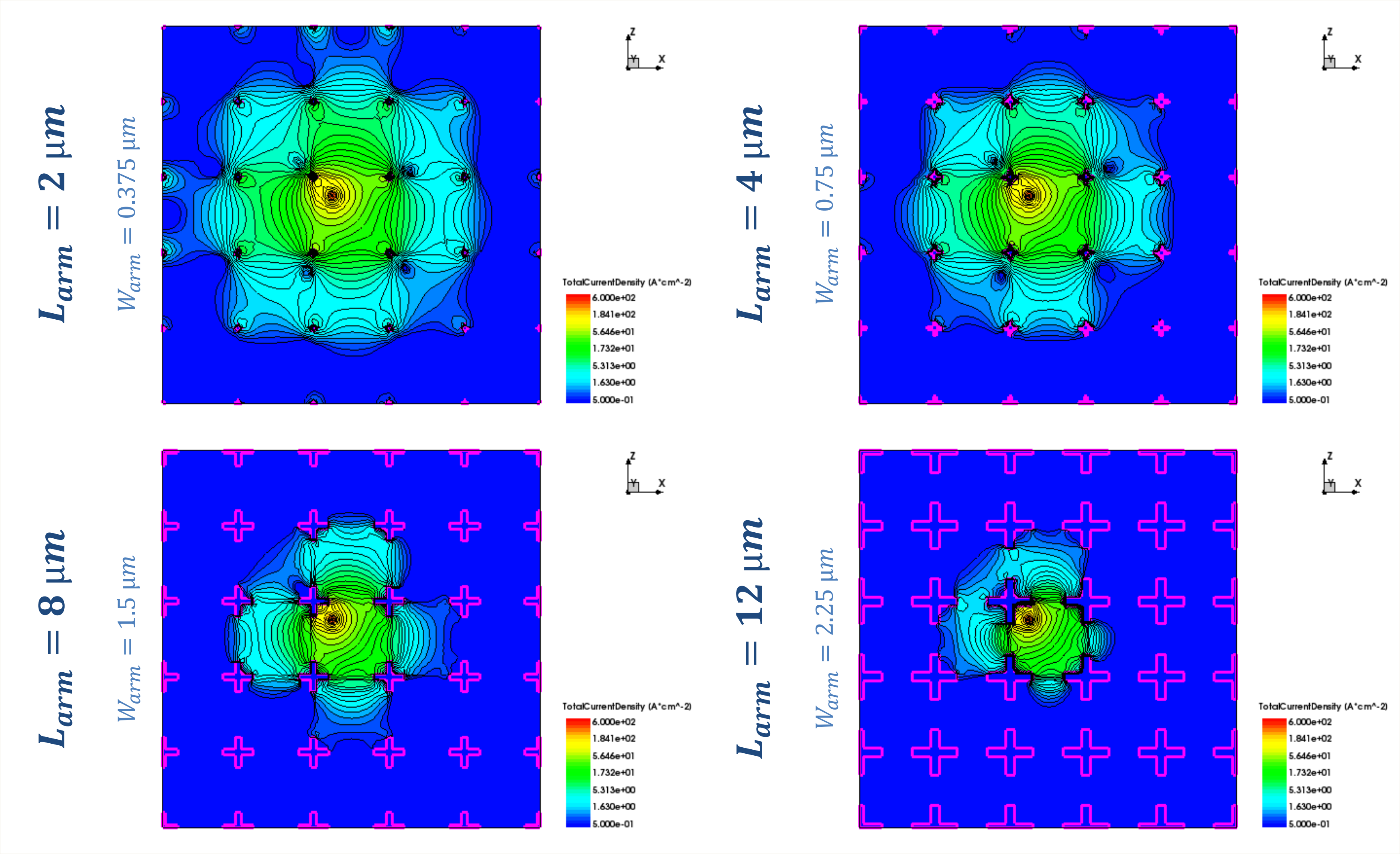


Cross-shaped pads

DC-RSD LGAD

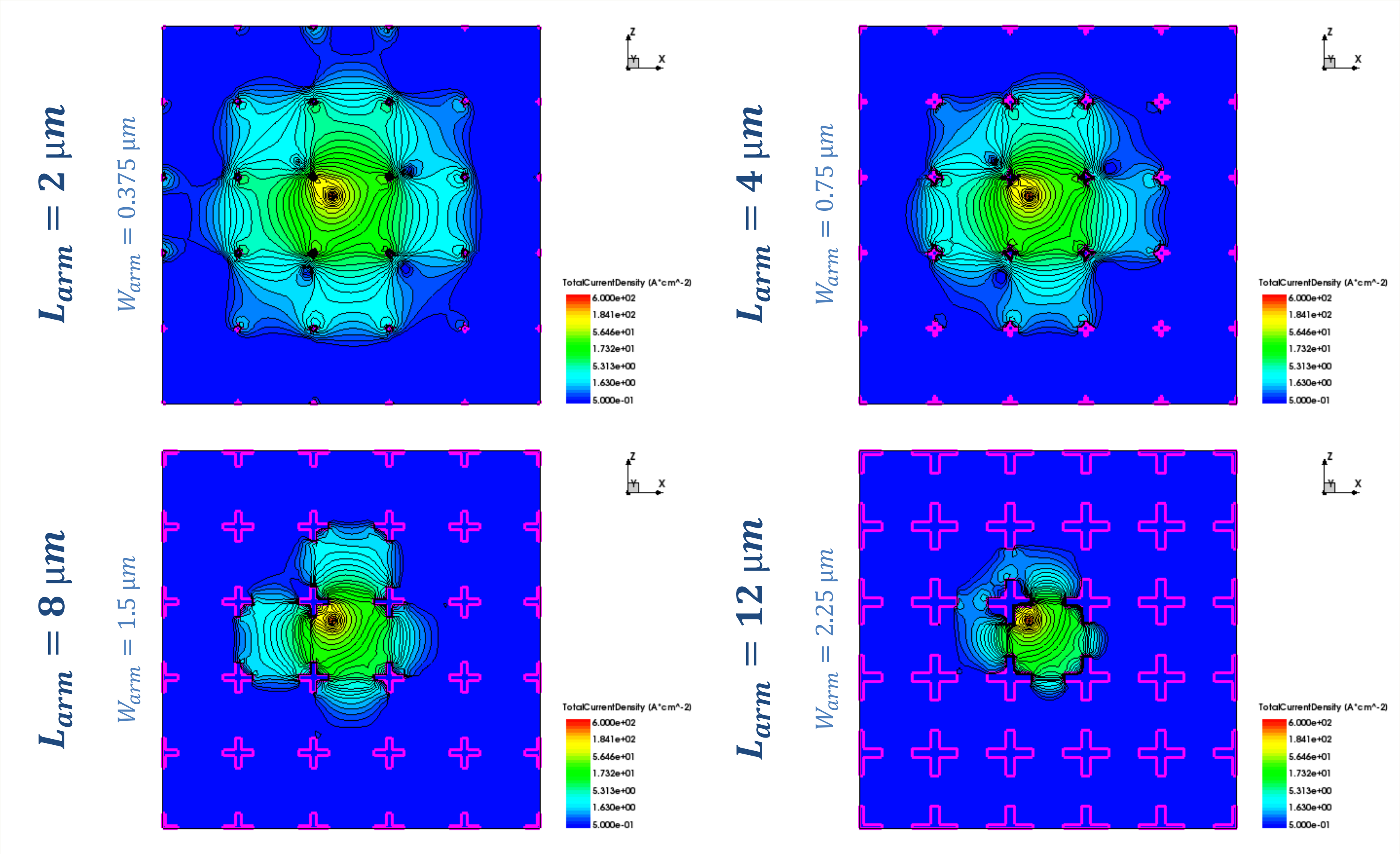
HIT 2

Temporal evolution of current density maps

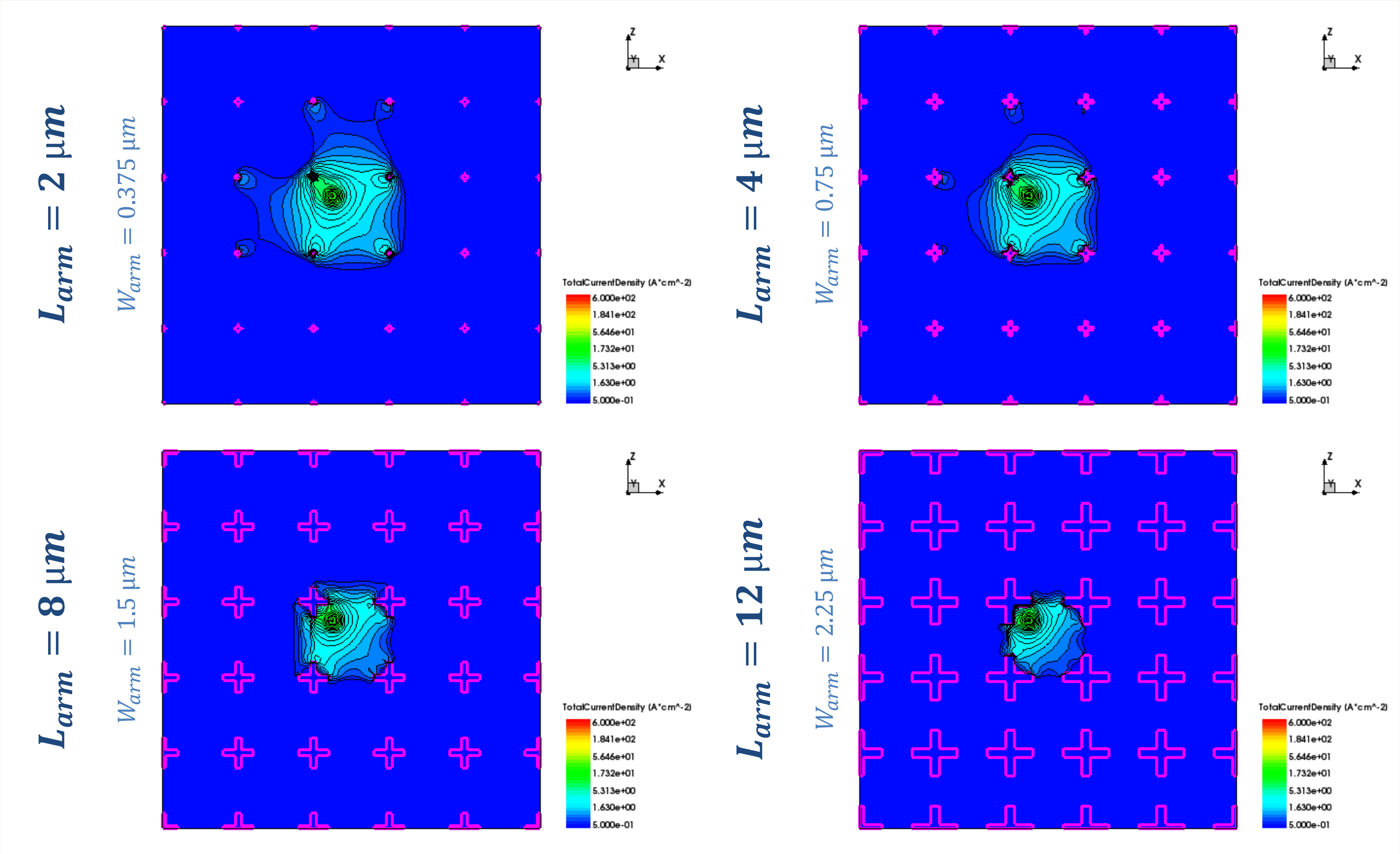


alessandro.fondacci@pg.infn.it

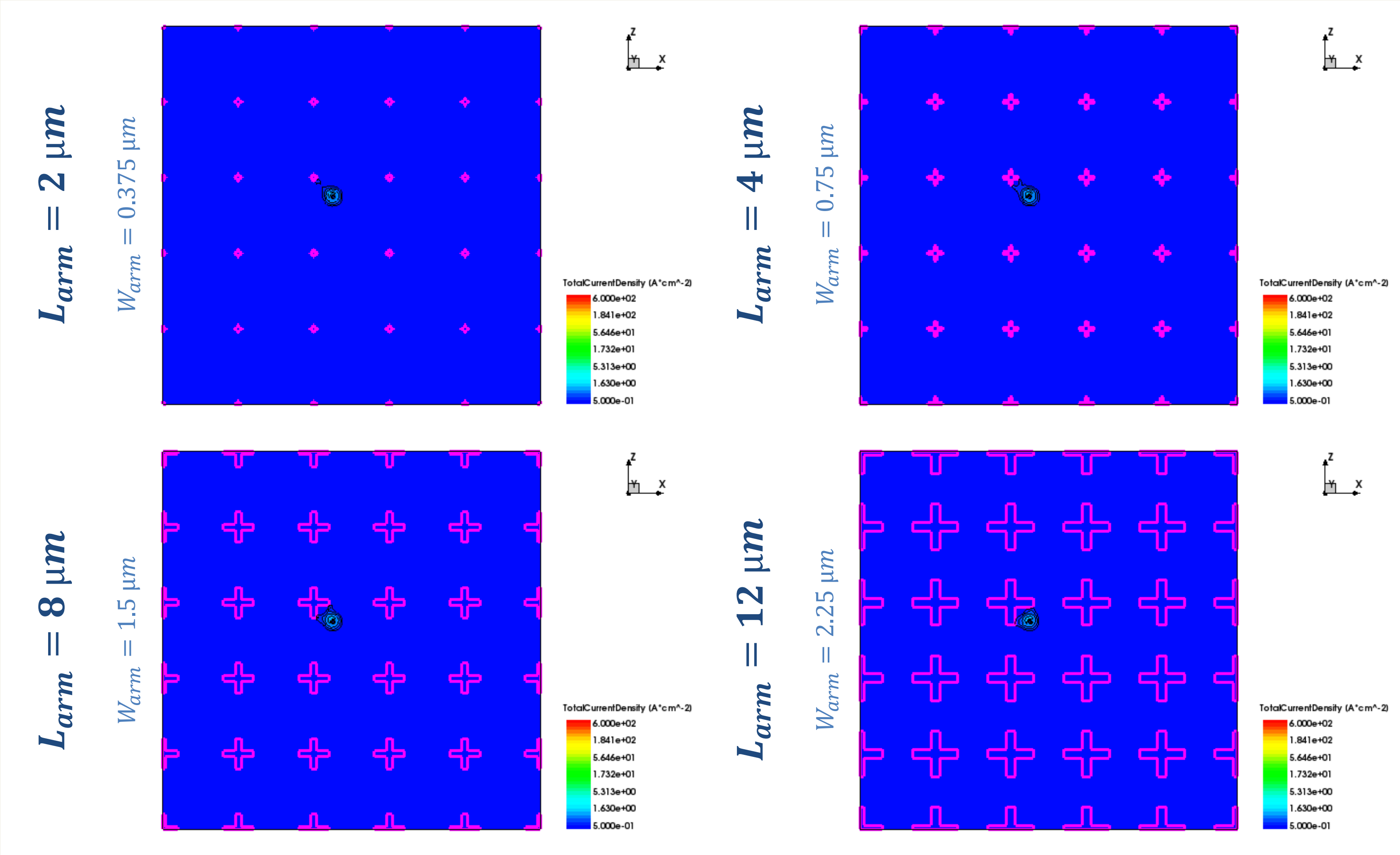
Temporal evolution of current density maps



Temporal evolution of current density maps



Temporal evolution of current density maps



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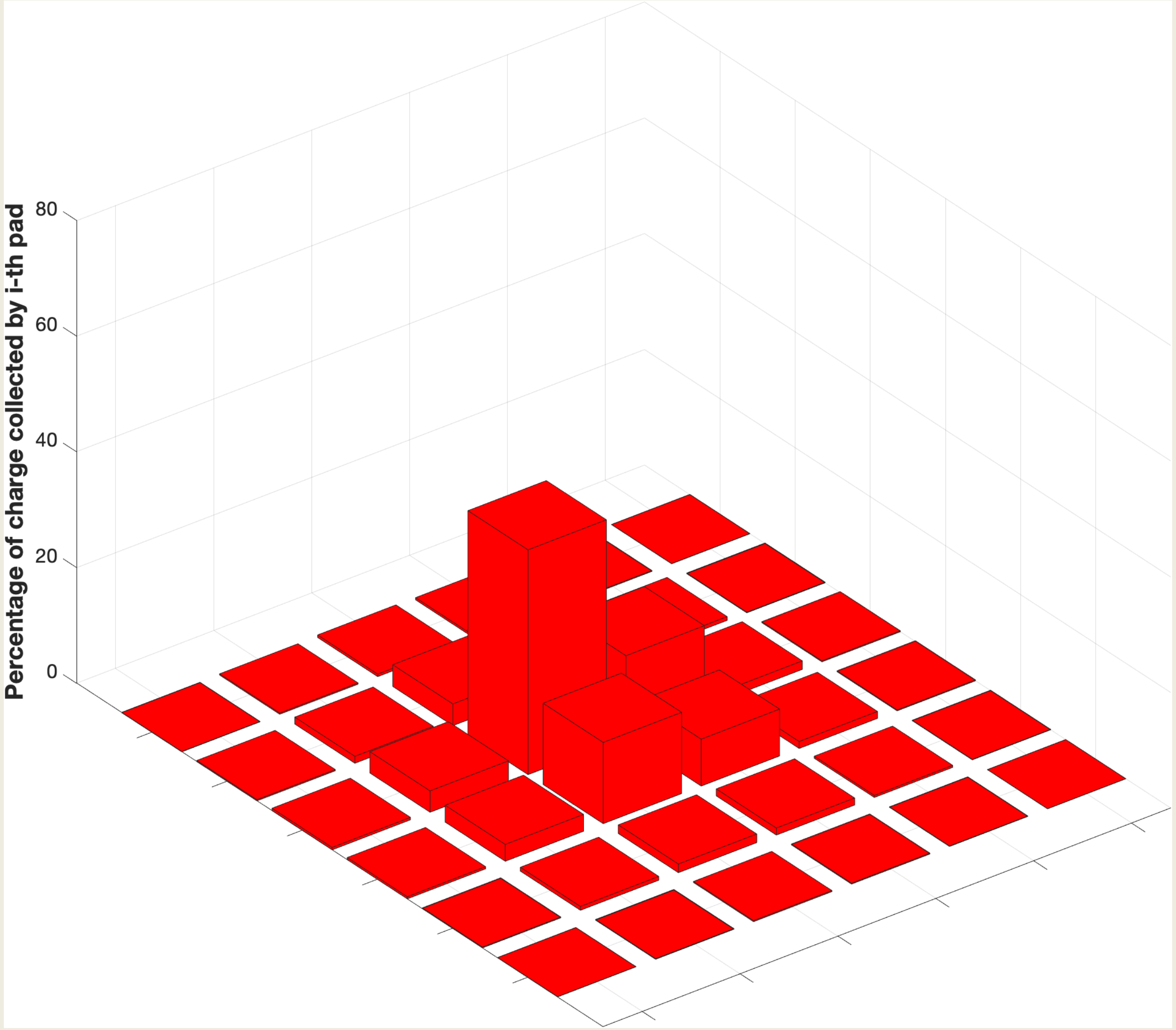
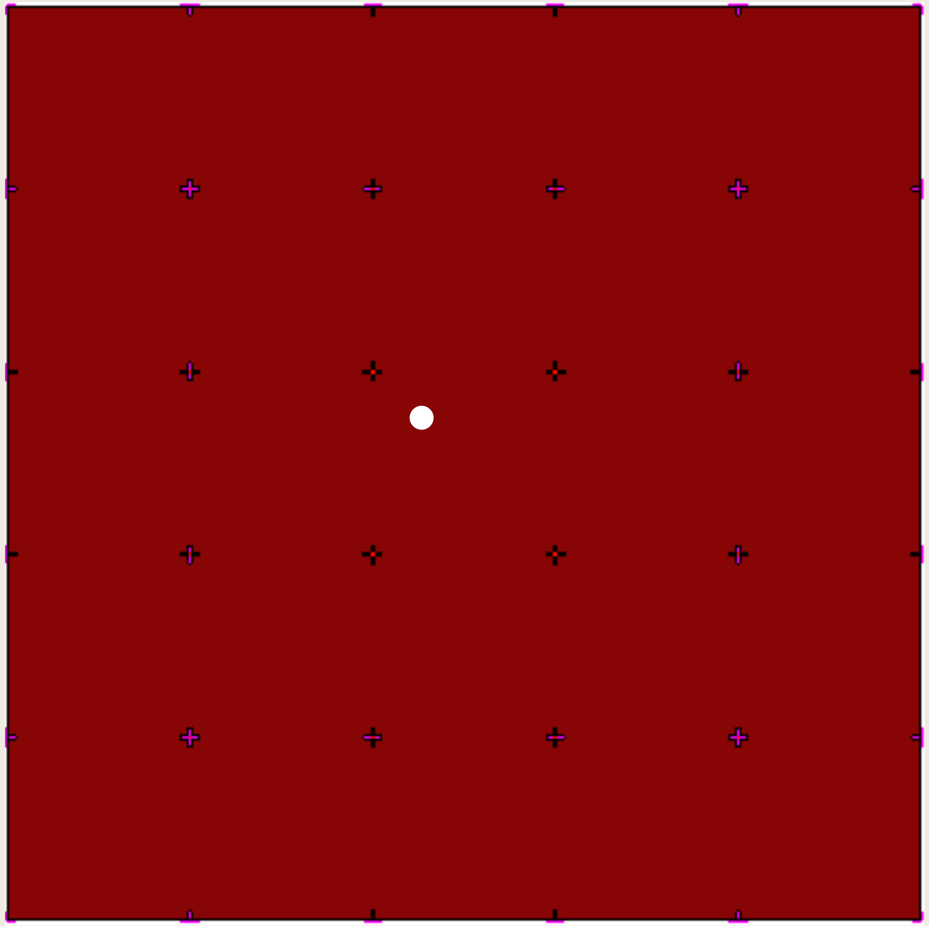
Distribution of collected charge between pads as a function of their size



$L_{arm} = 2\ \mu m$



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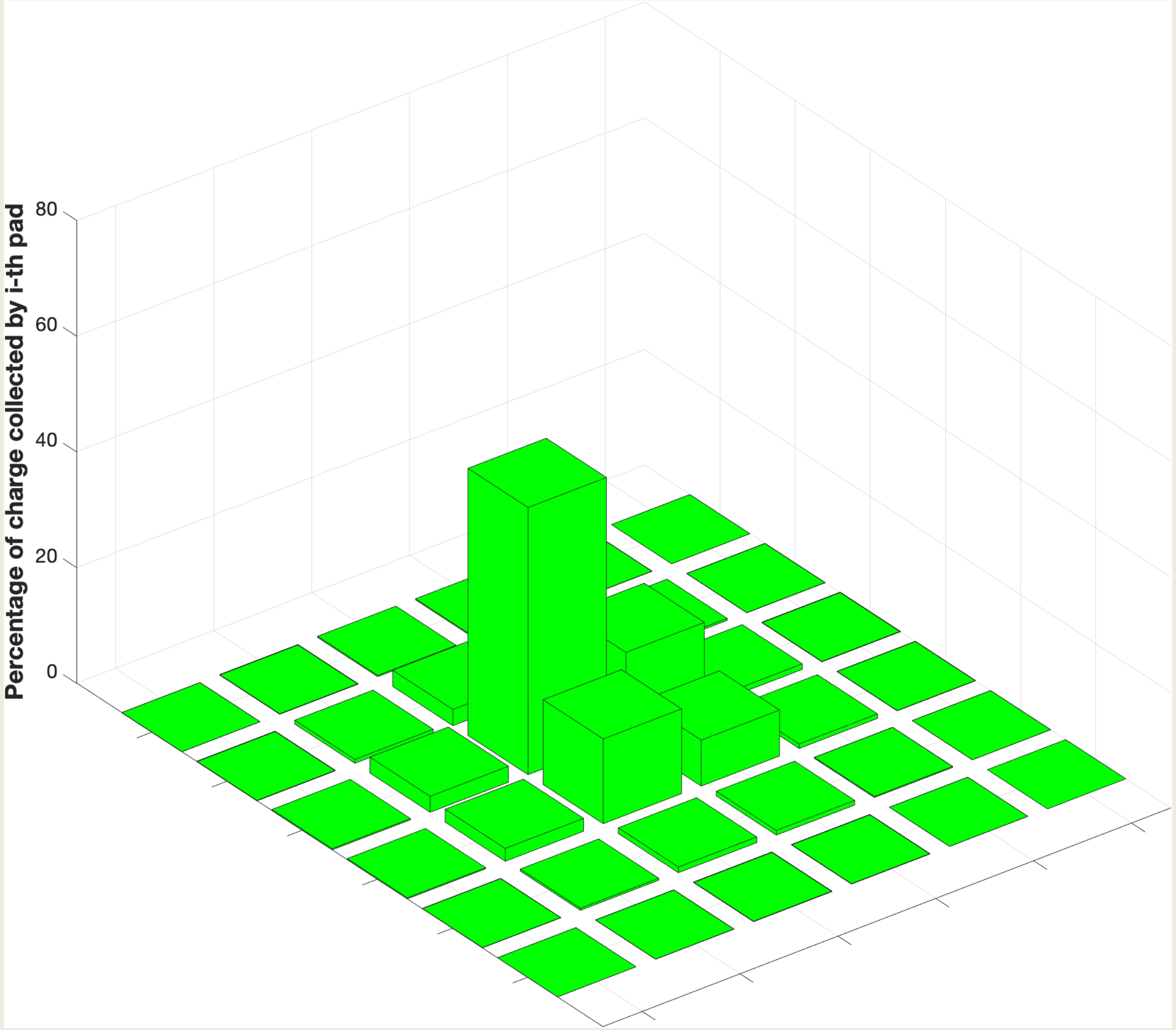
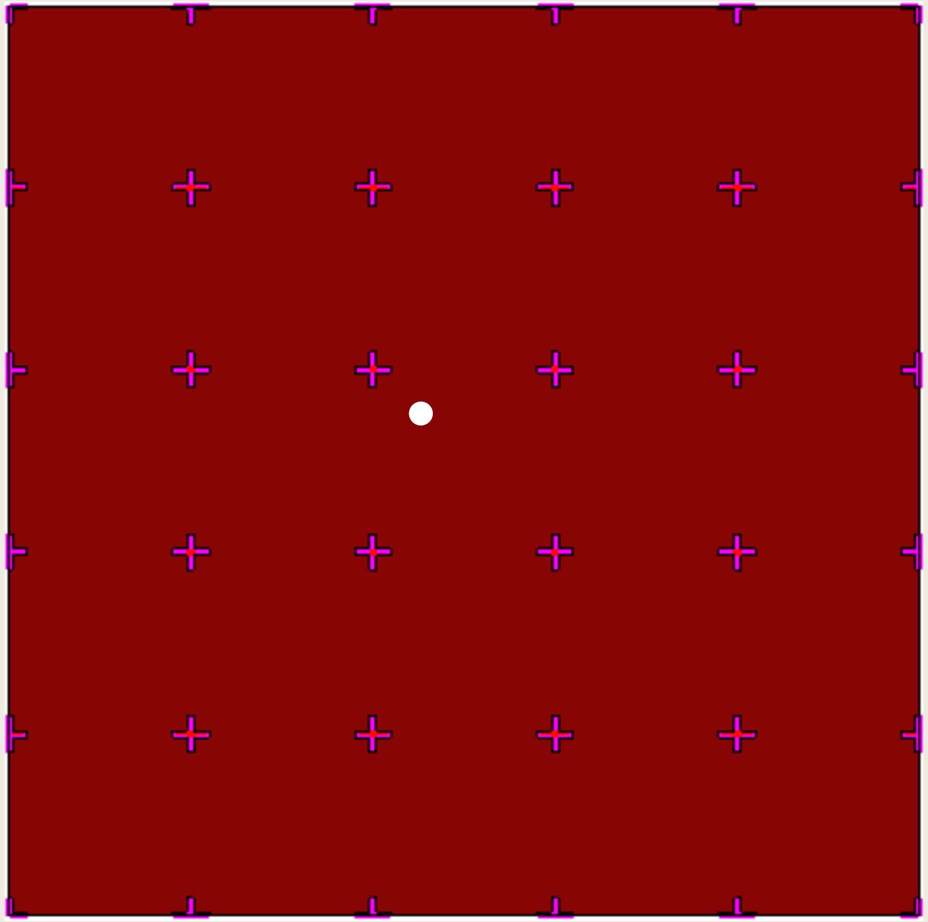
Distribution of collected charge between pads as a function of their size



L_{arm} = 4 μm



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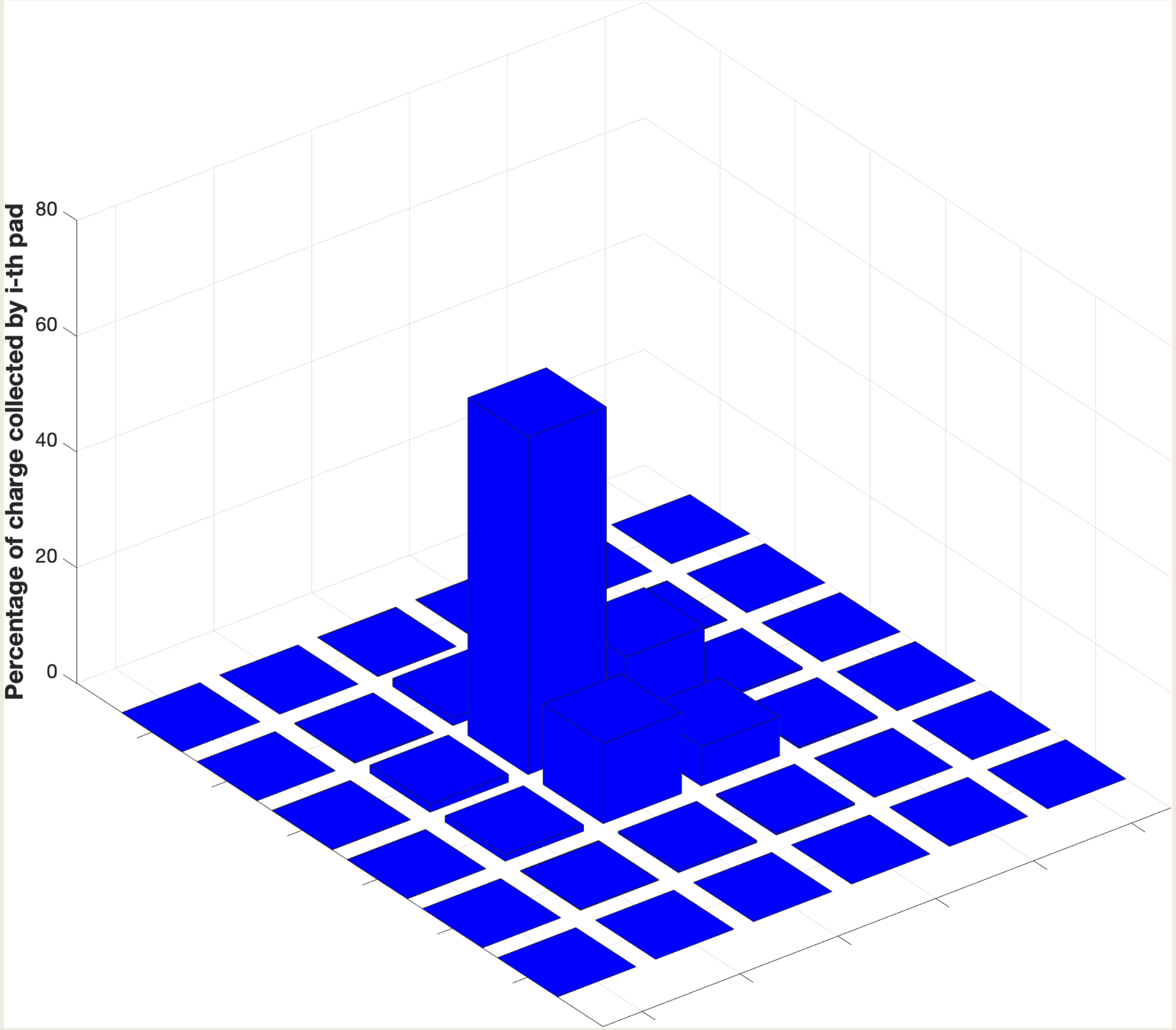
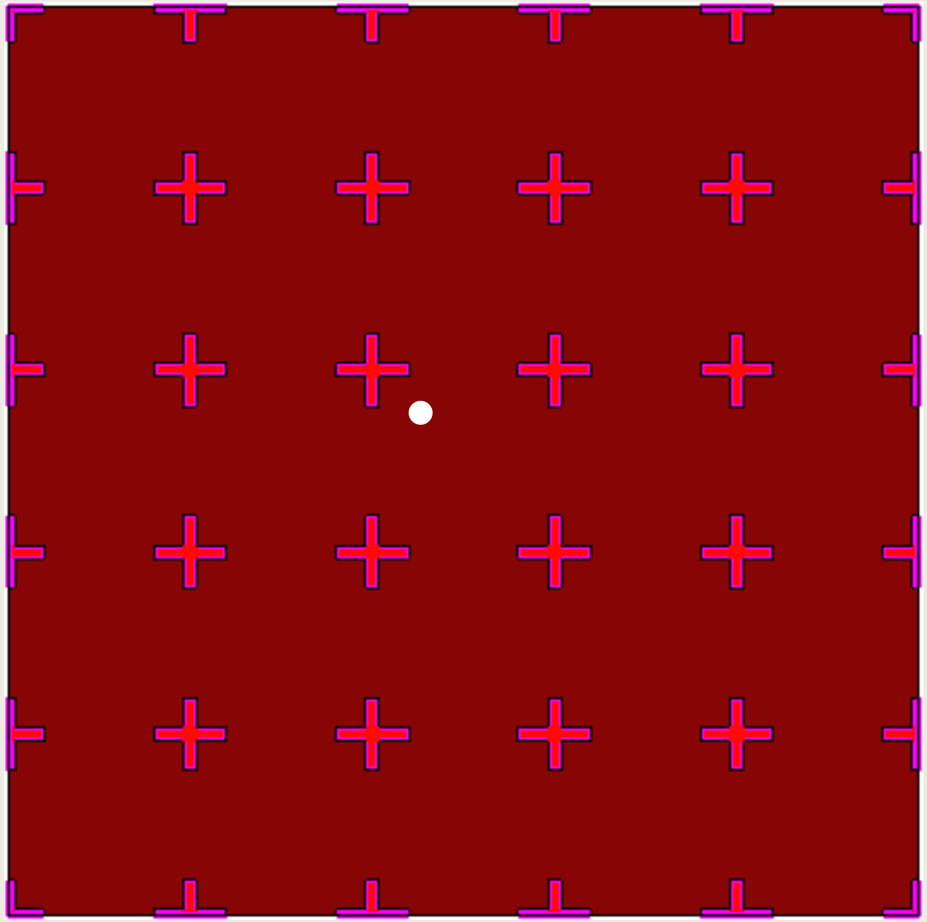
Distribution of collected charge between pads as a function of their size



$L_{arm} = 8\ \mu m$



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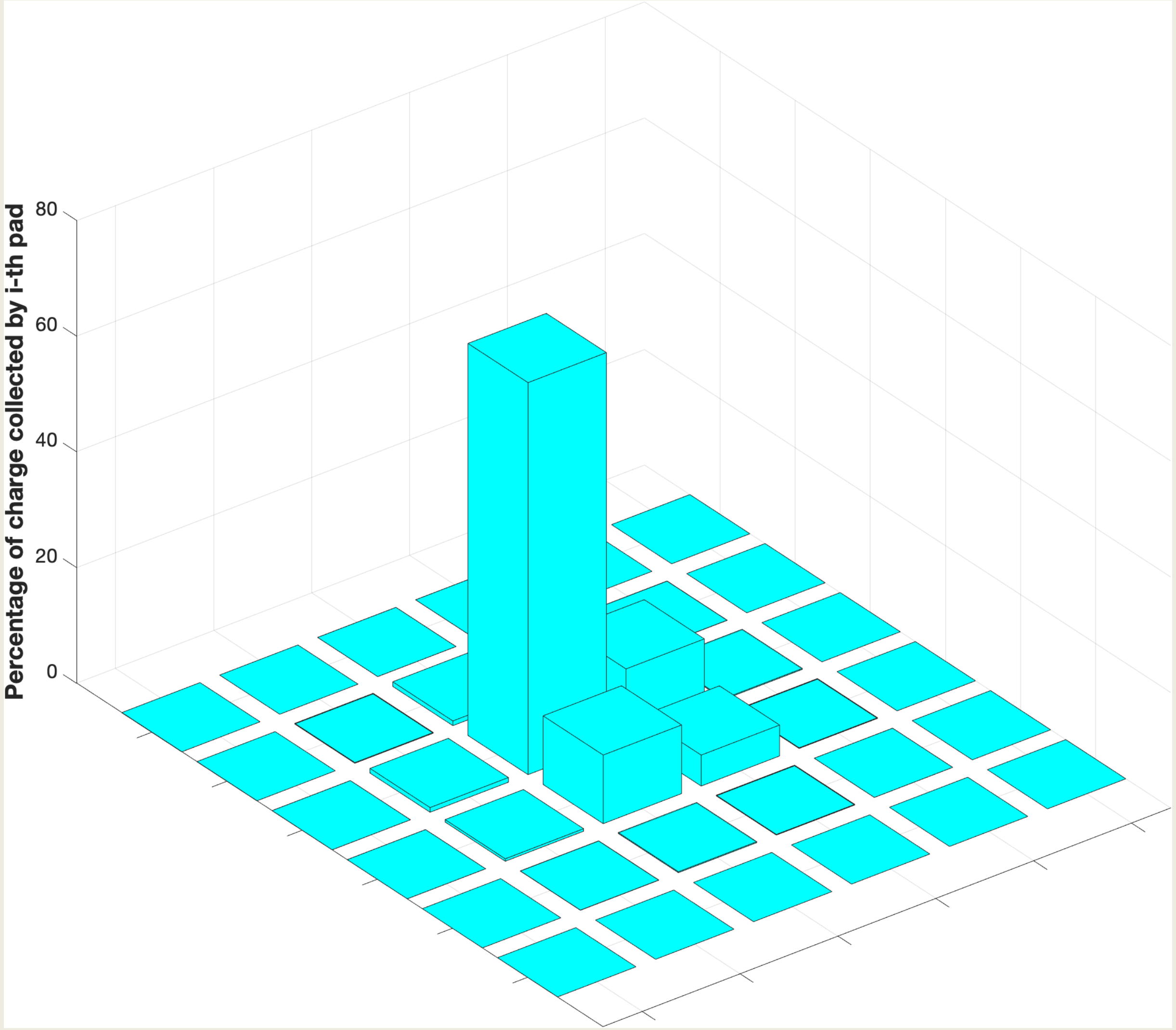
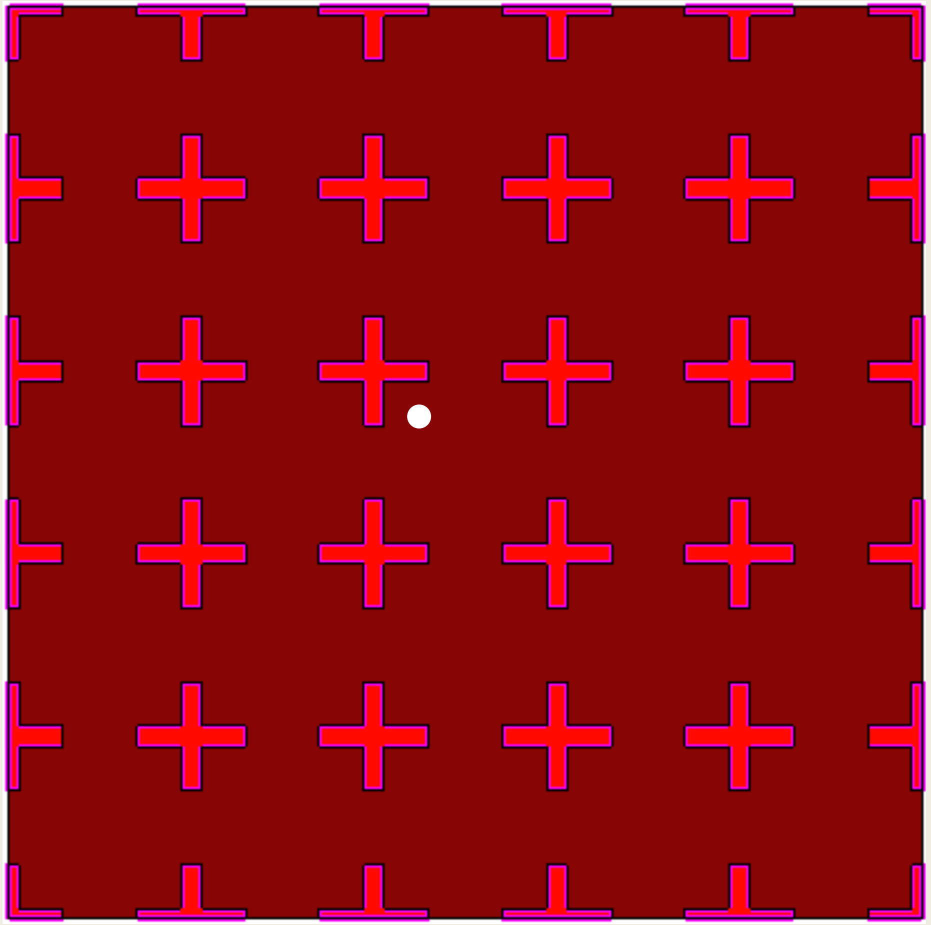
Distribution of collected charge between pads as a function of their size



LL_{arm} = 12 μm



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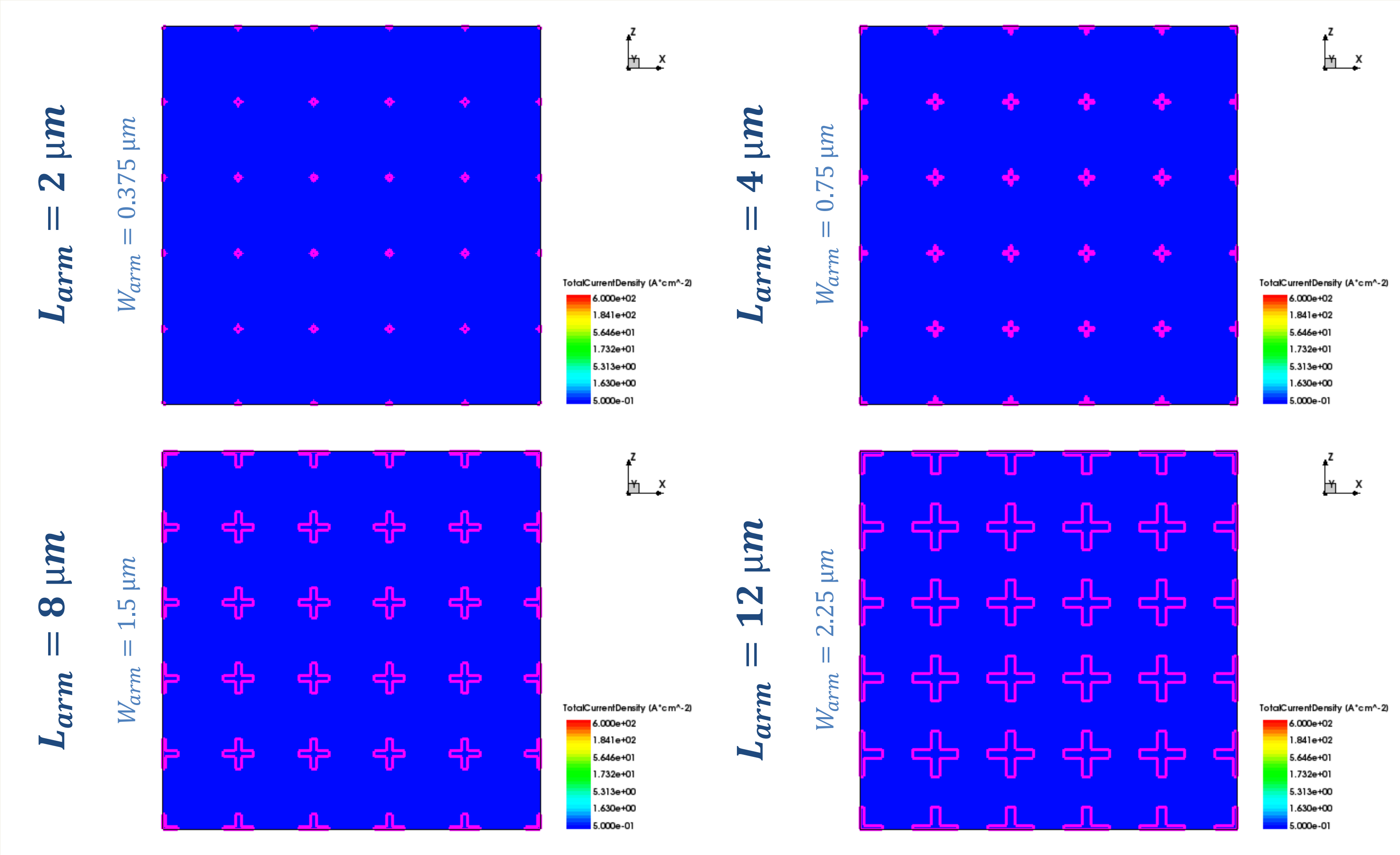
DC-RSD LGAD

Cross-shaped pads

HIT 3

Temporal evolution of current density maps



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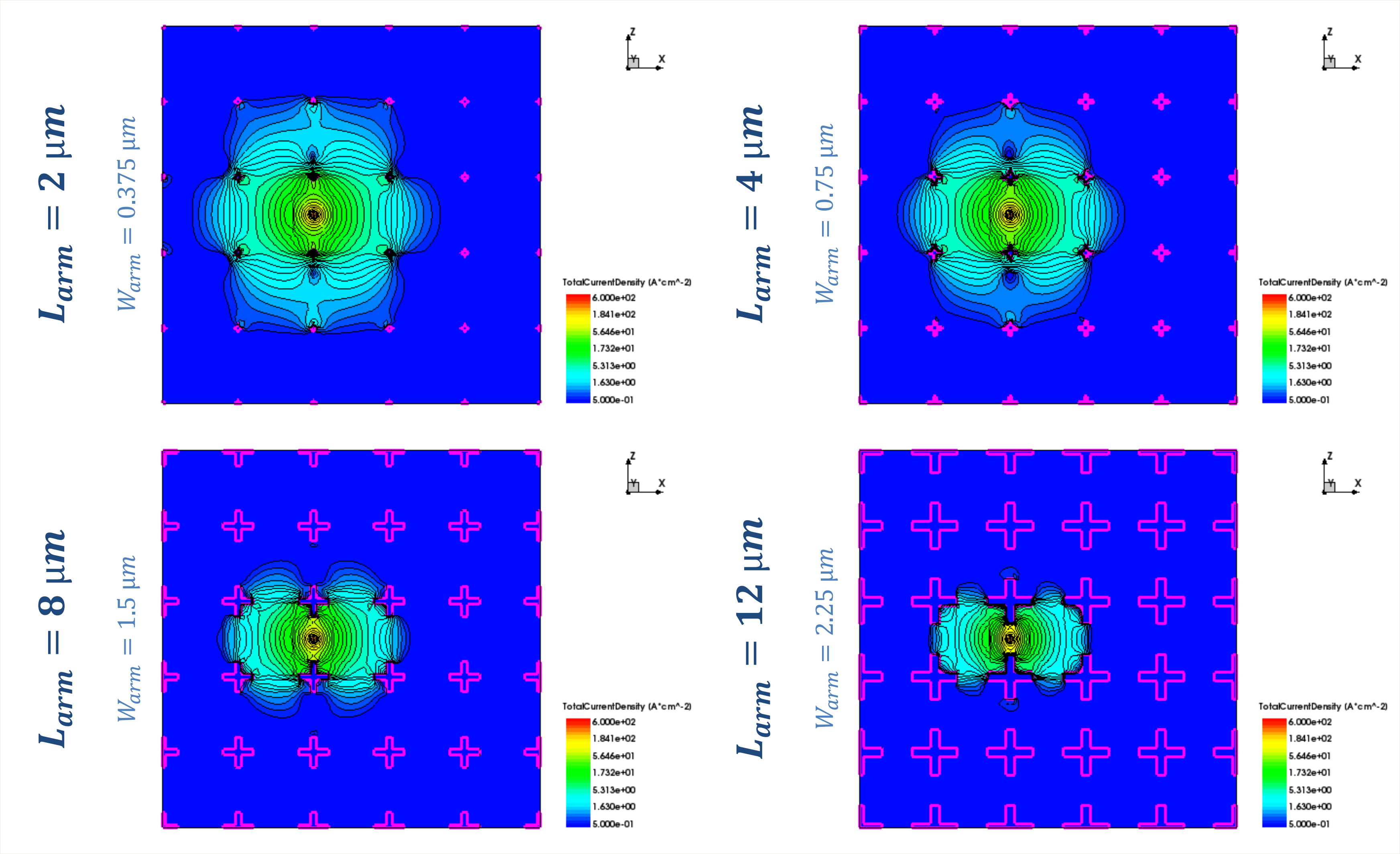
Temporal evolution of current density maps



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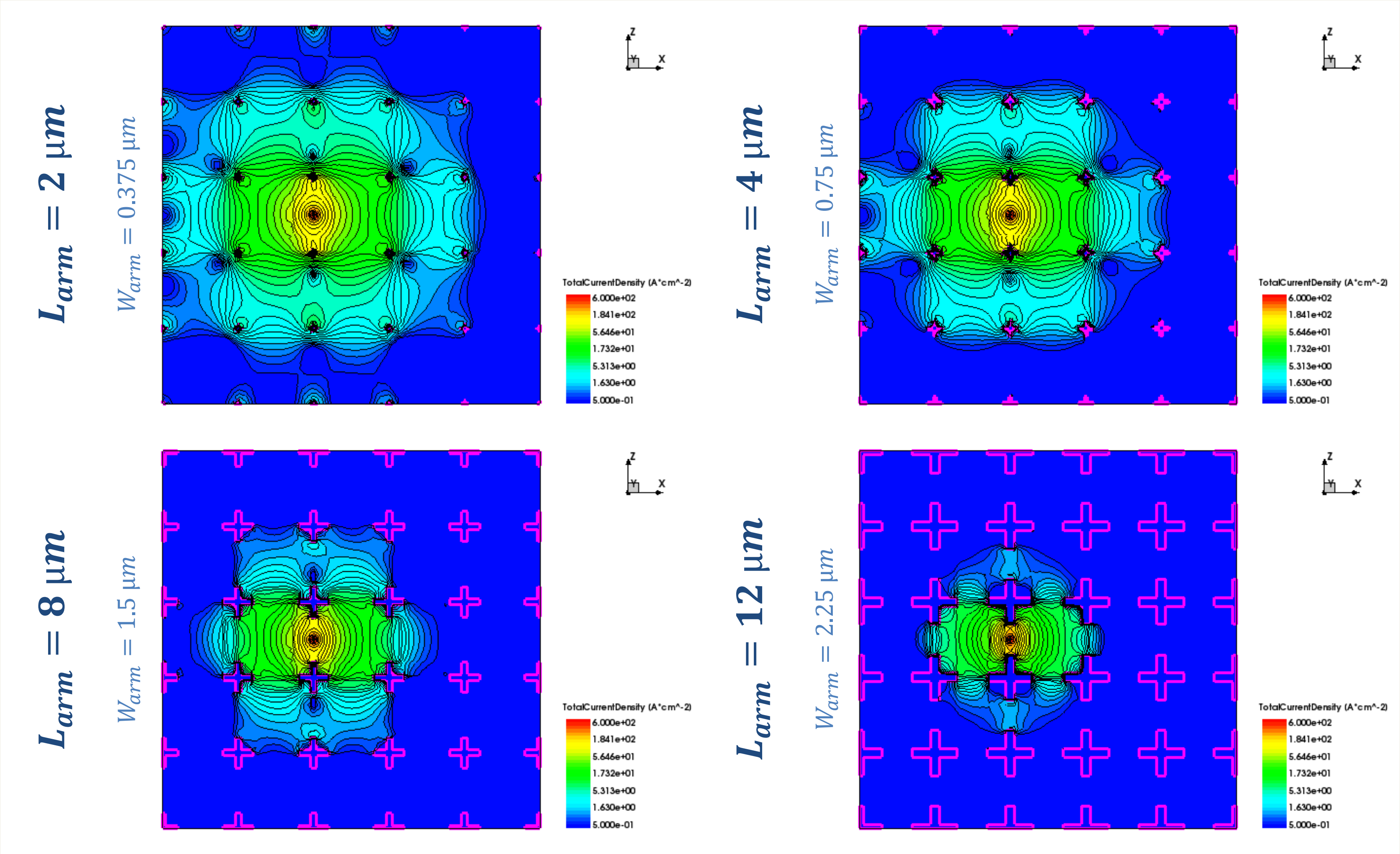
Temporal evolution of current density maps



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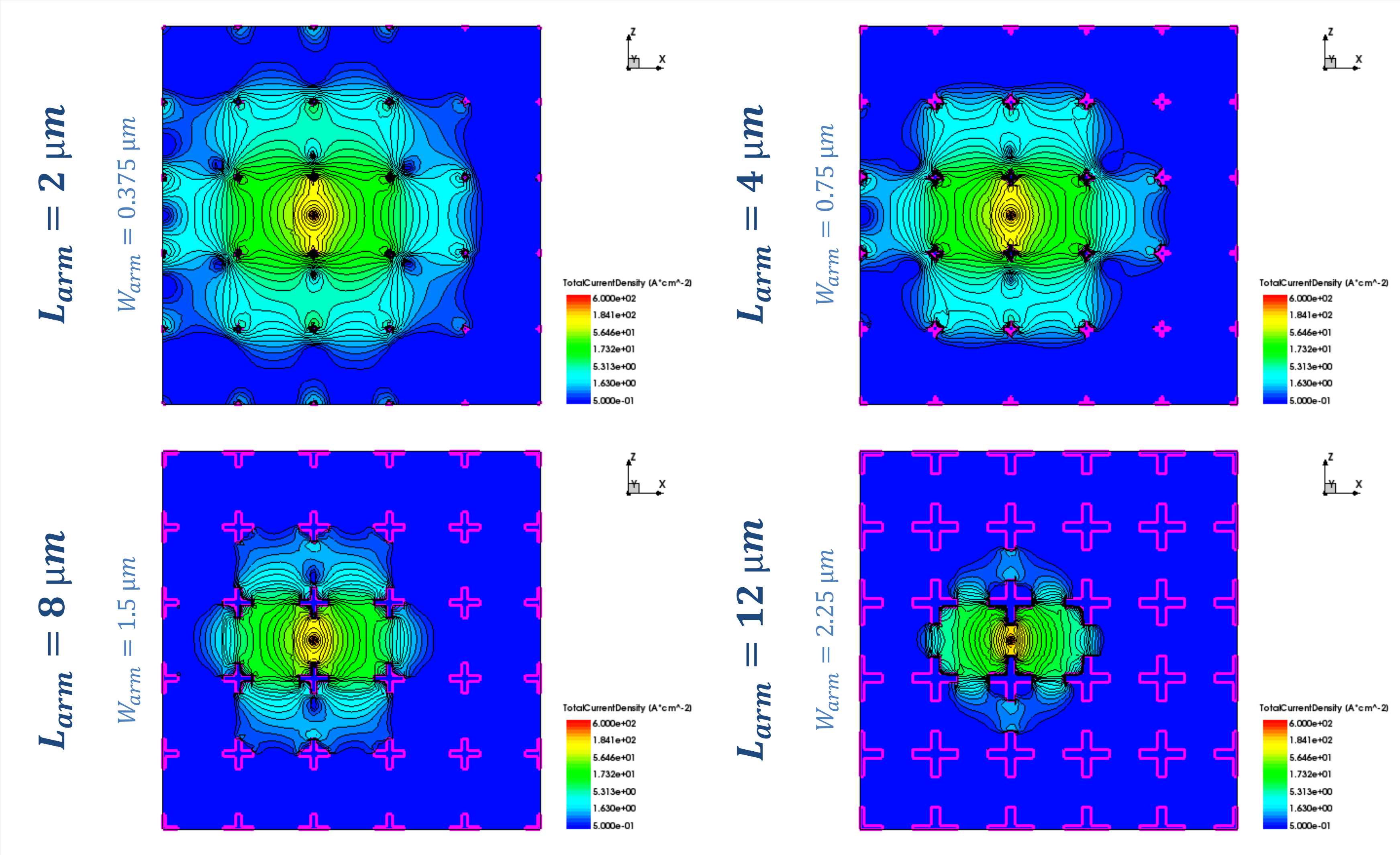
Temporal evolution of current density maps



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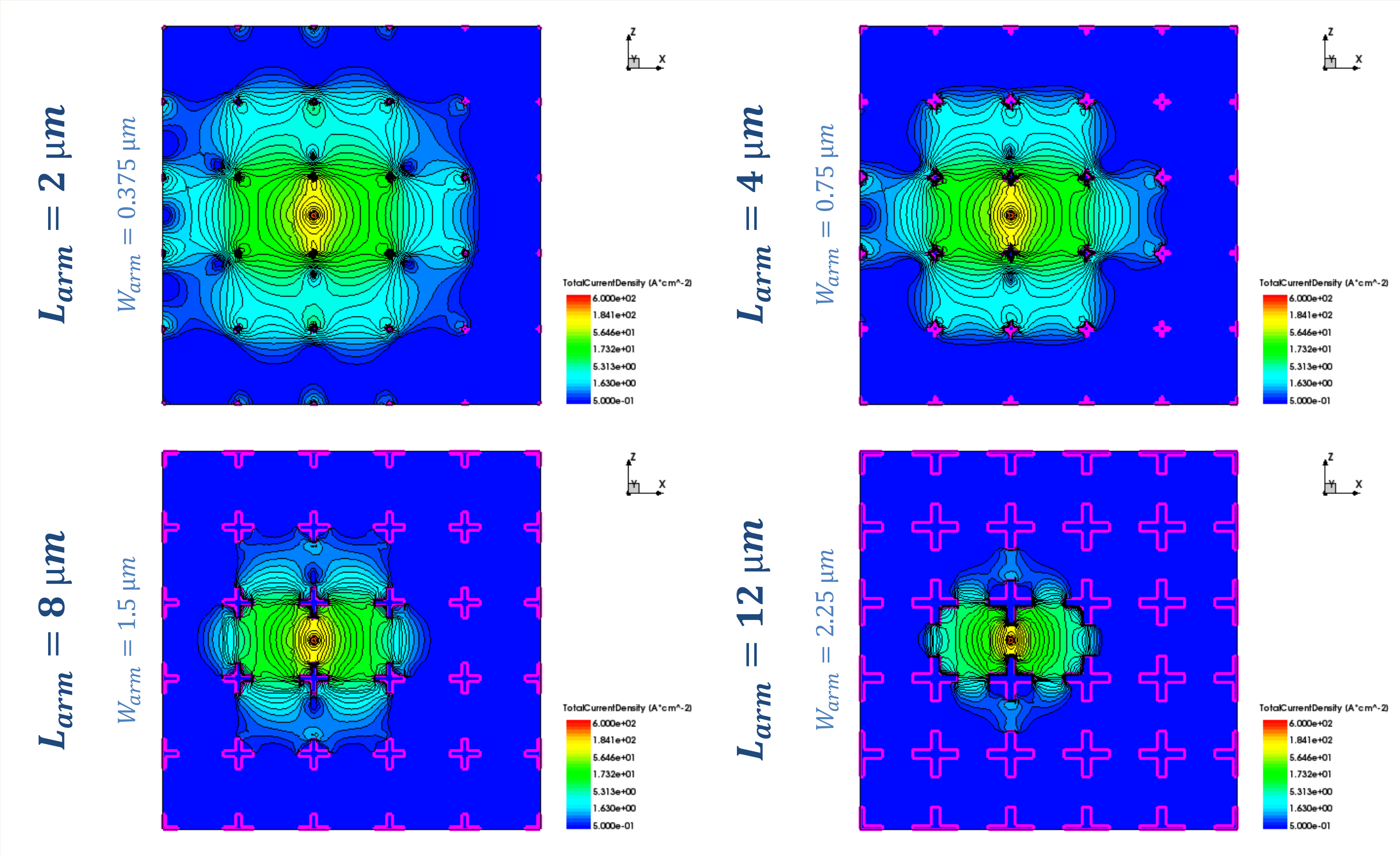
Temporal evolution of current density maps



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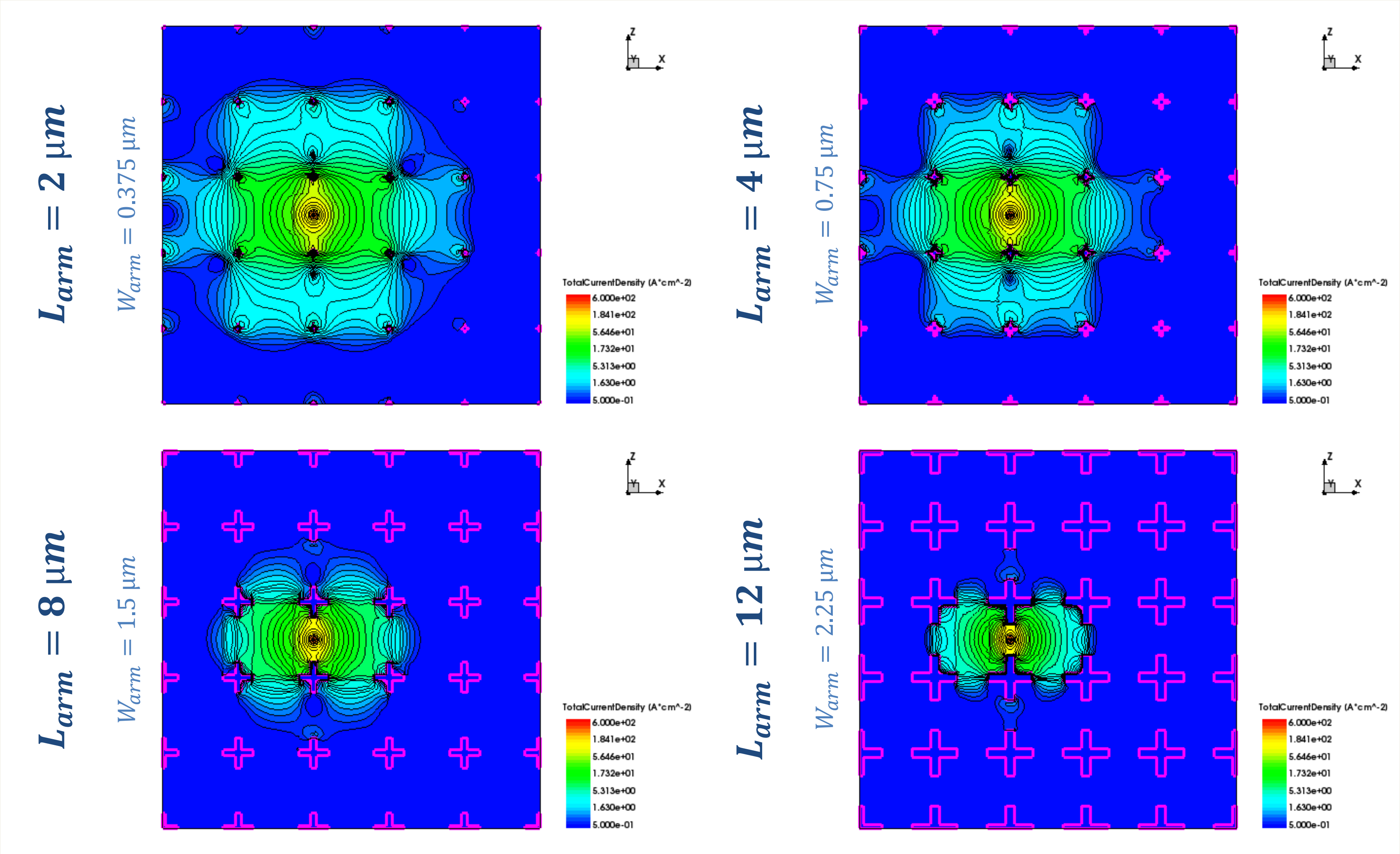
Temporal evolution of current density maps



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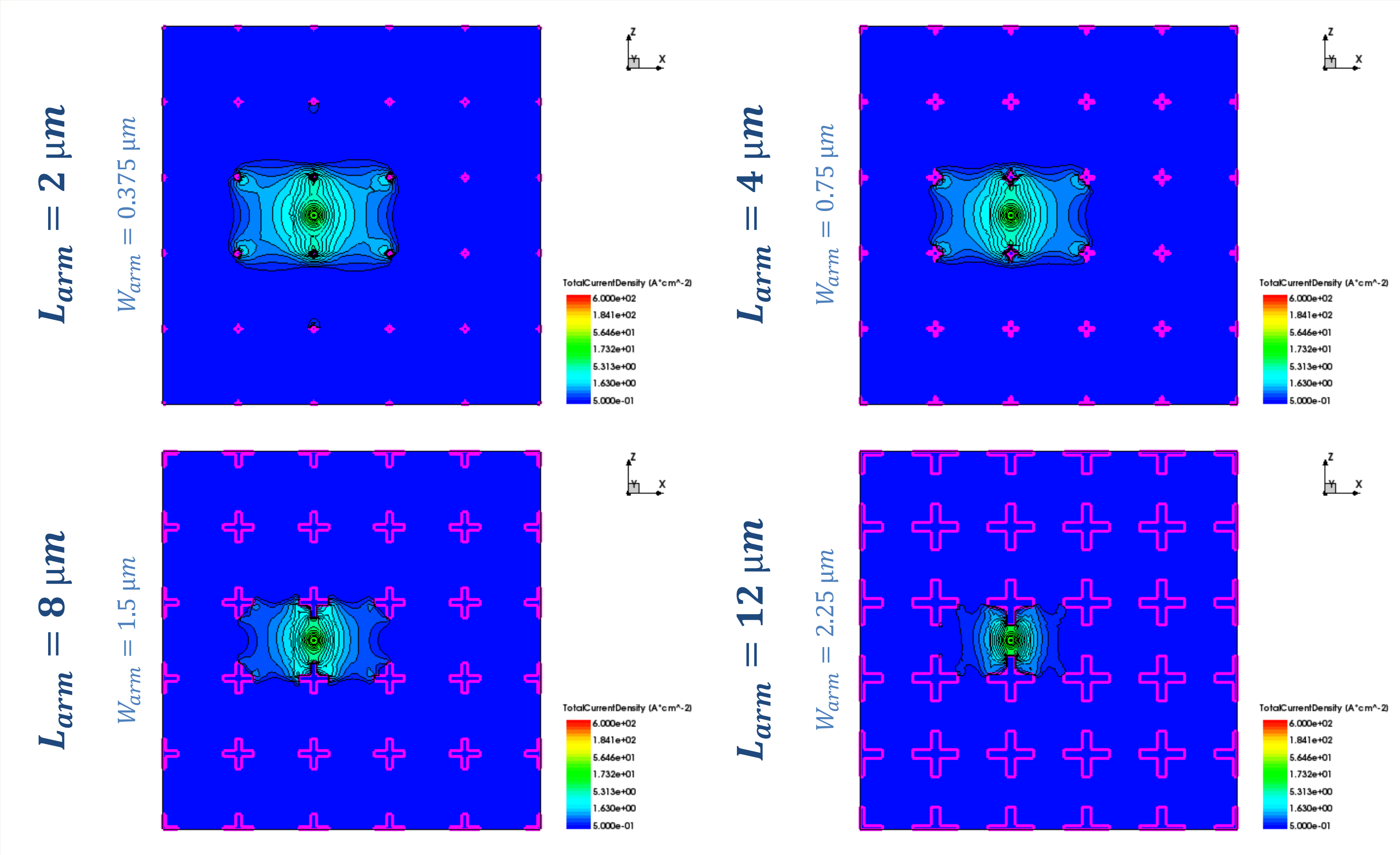
Temporal evolution of current density maps



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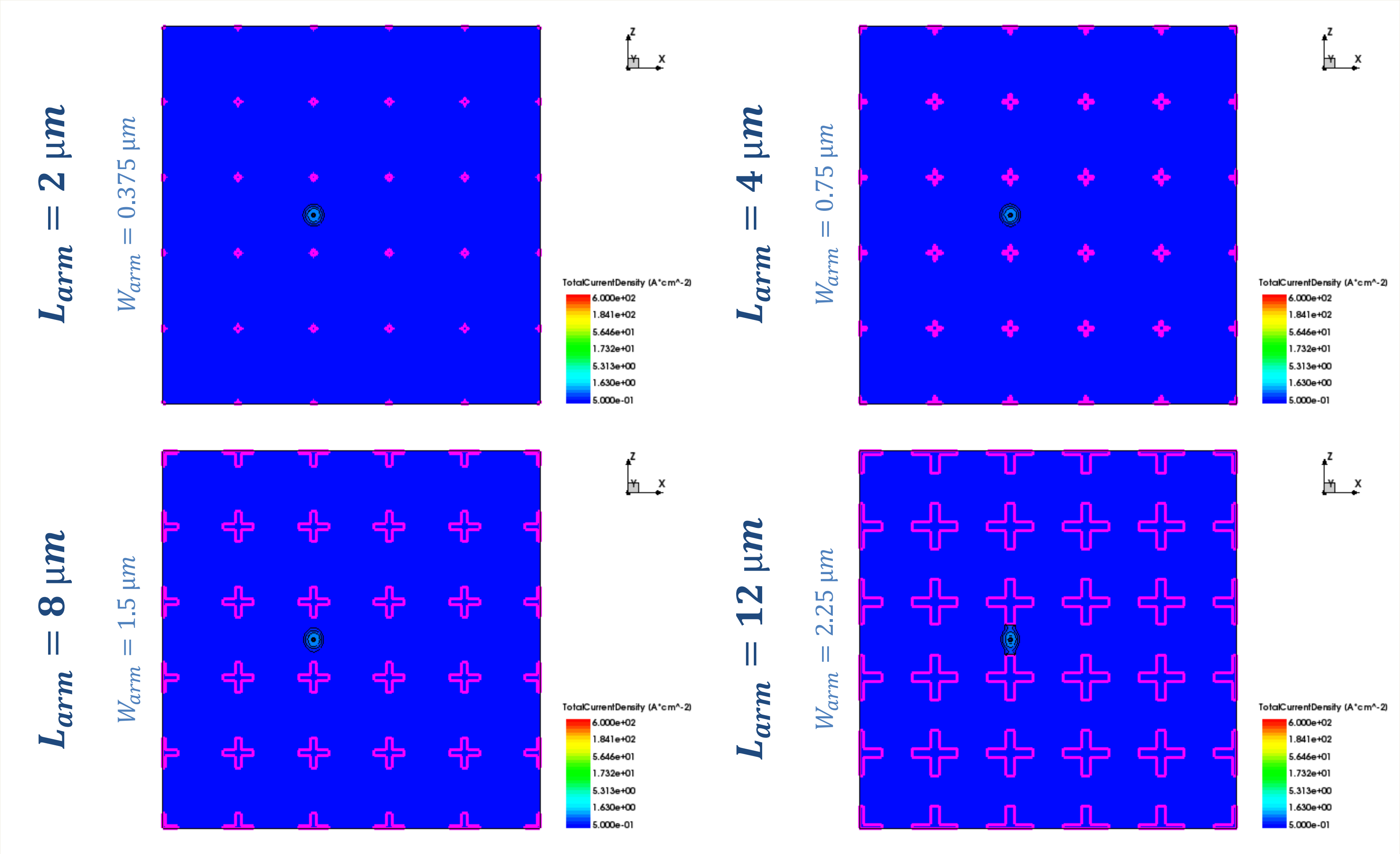
Cross-shaped pads

DC-RSD LGAD

HIT 3

Temporal evolution of current density maps



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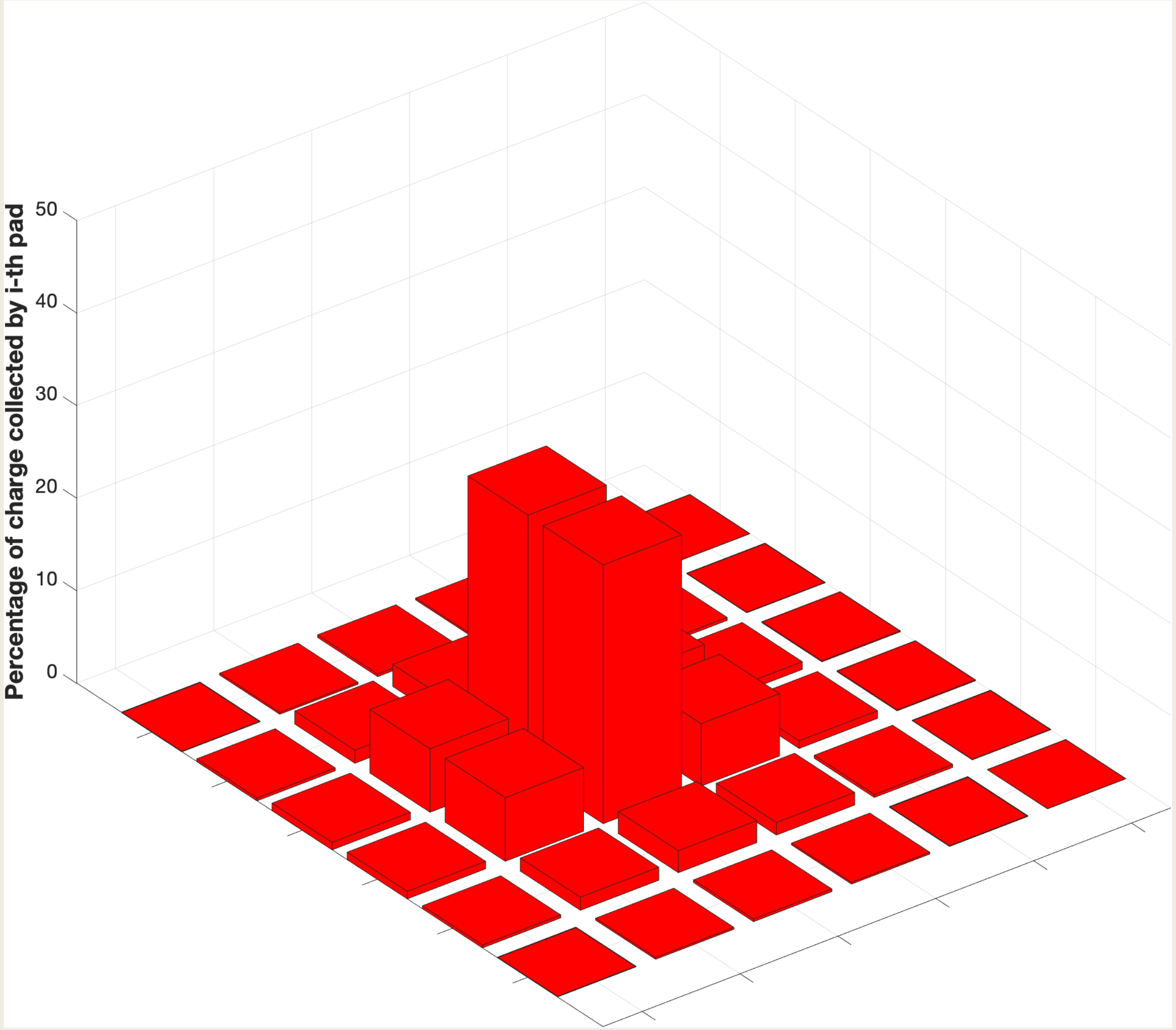
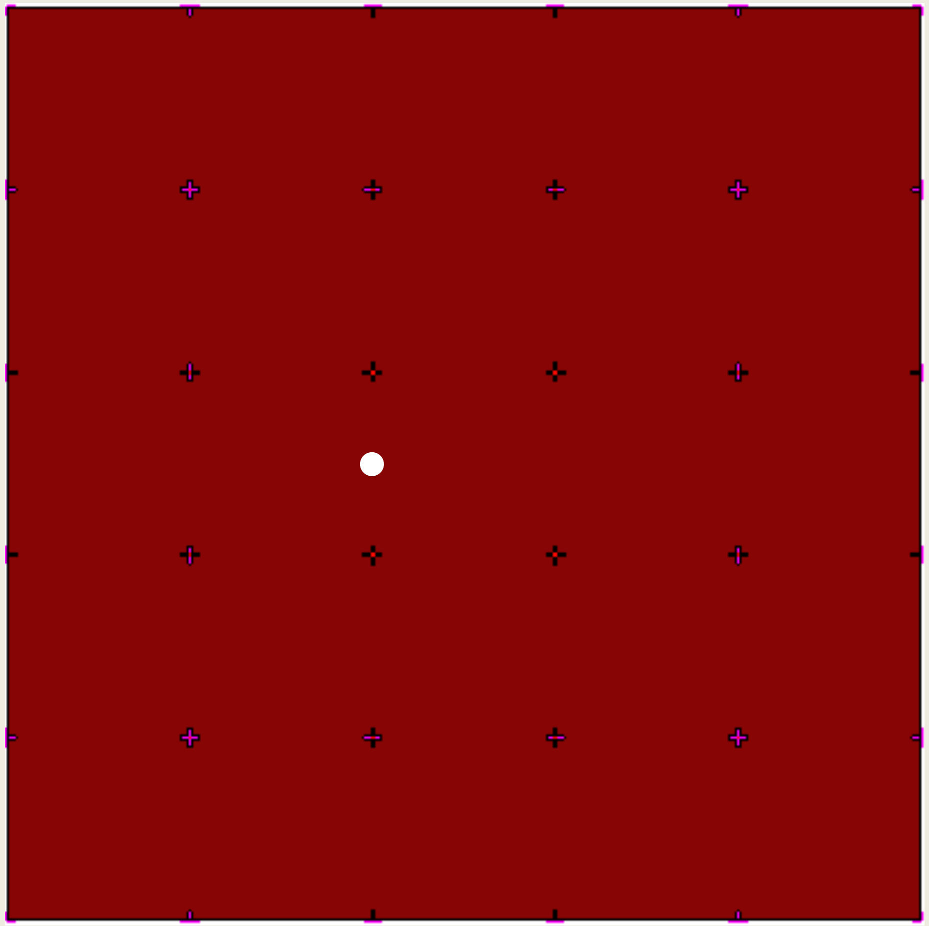
HIT 3

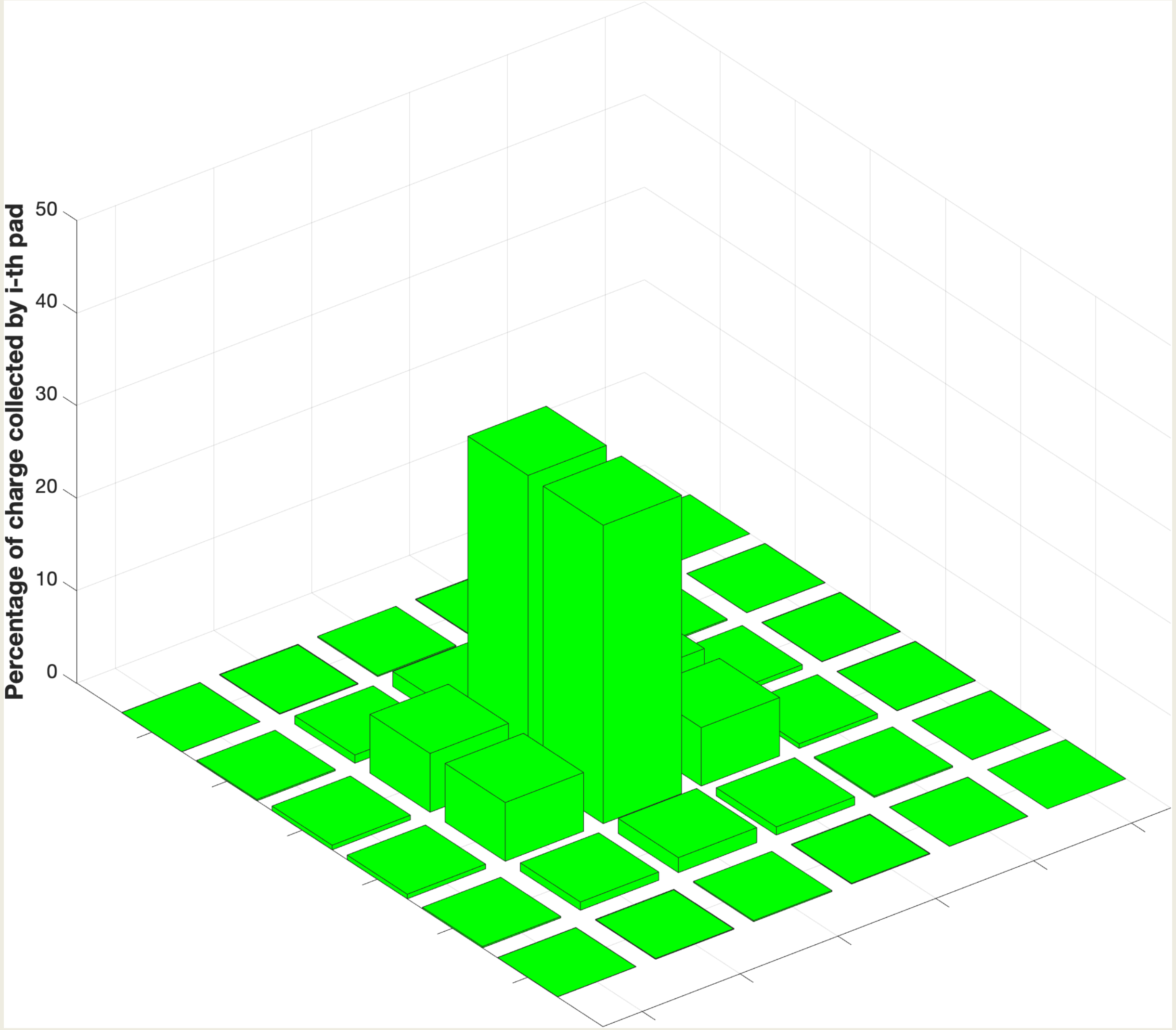
Distribution of collected charge between pads as a function of their size



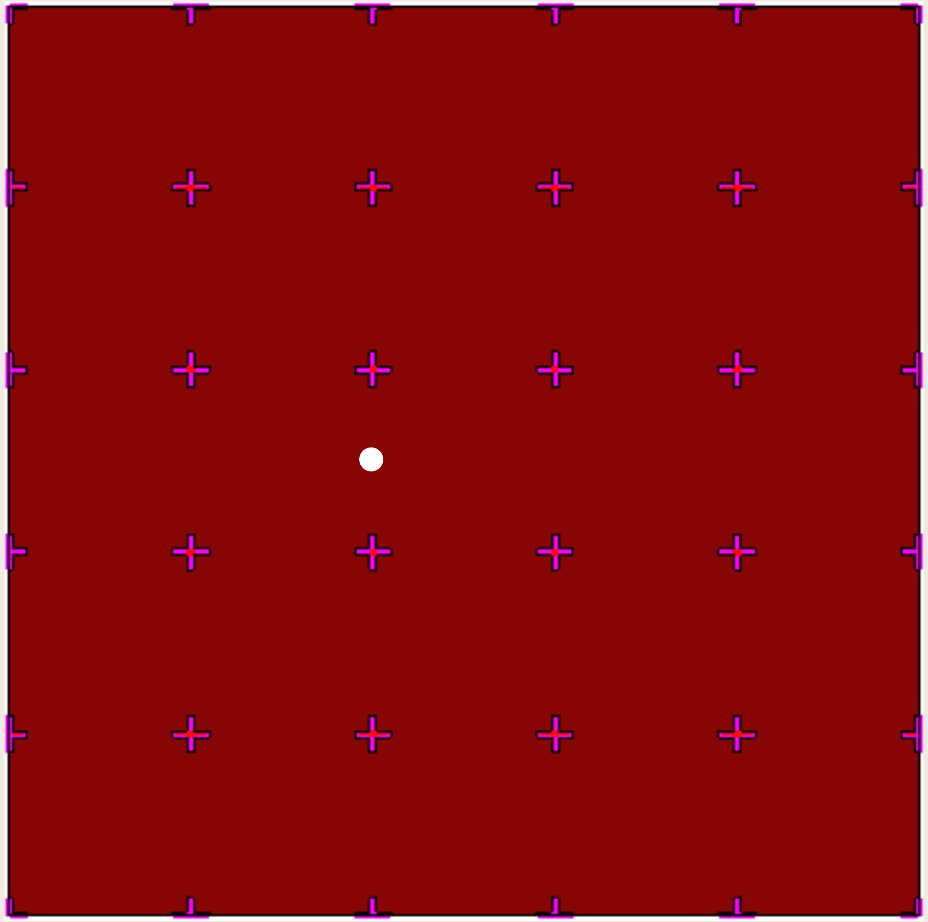
$L_{arm} = 2\ \mu m$



Distribution of collected charge between pads as a function of their size



$L_{arm} = 4\ \mu m$



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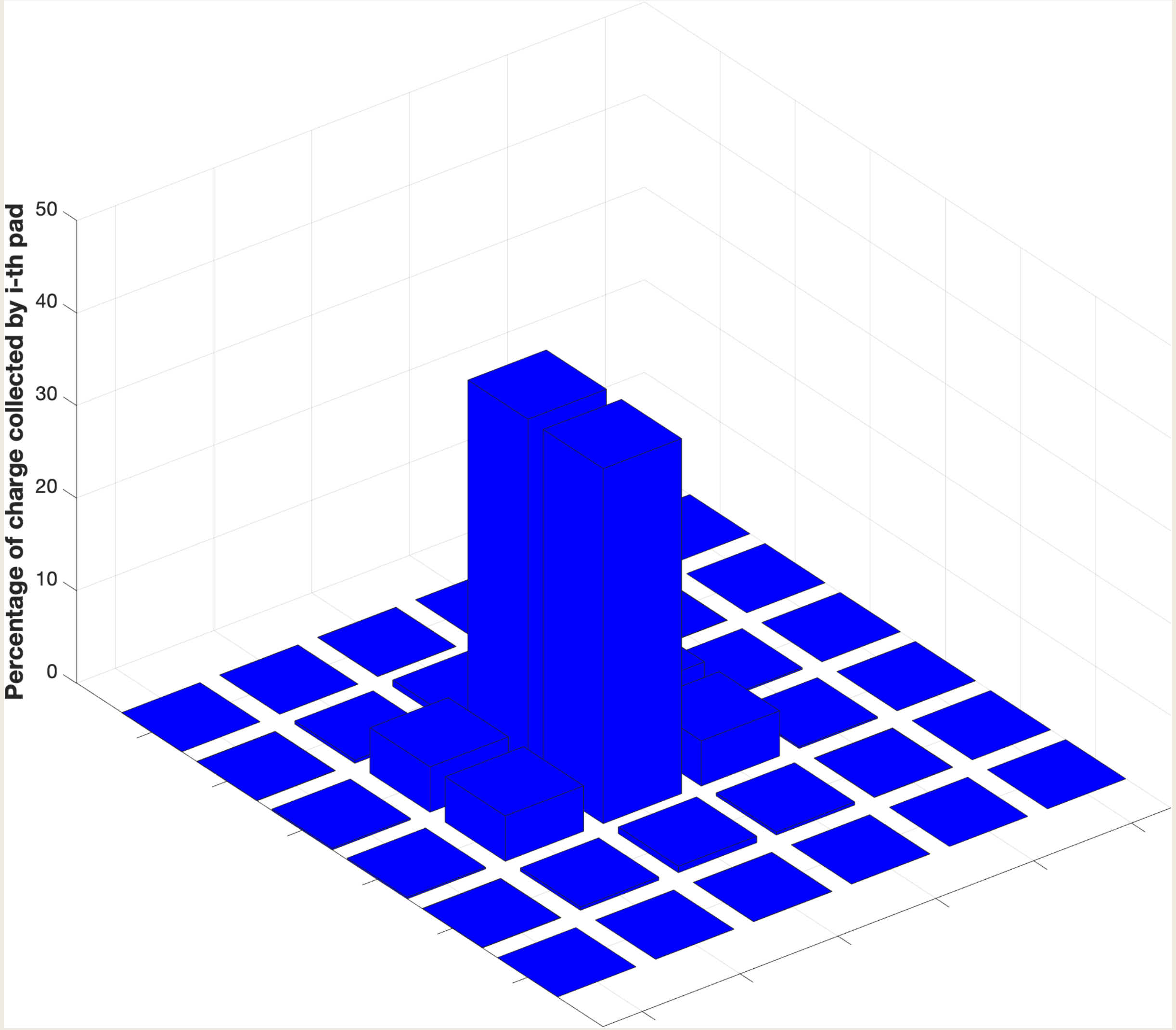
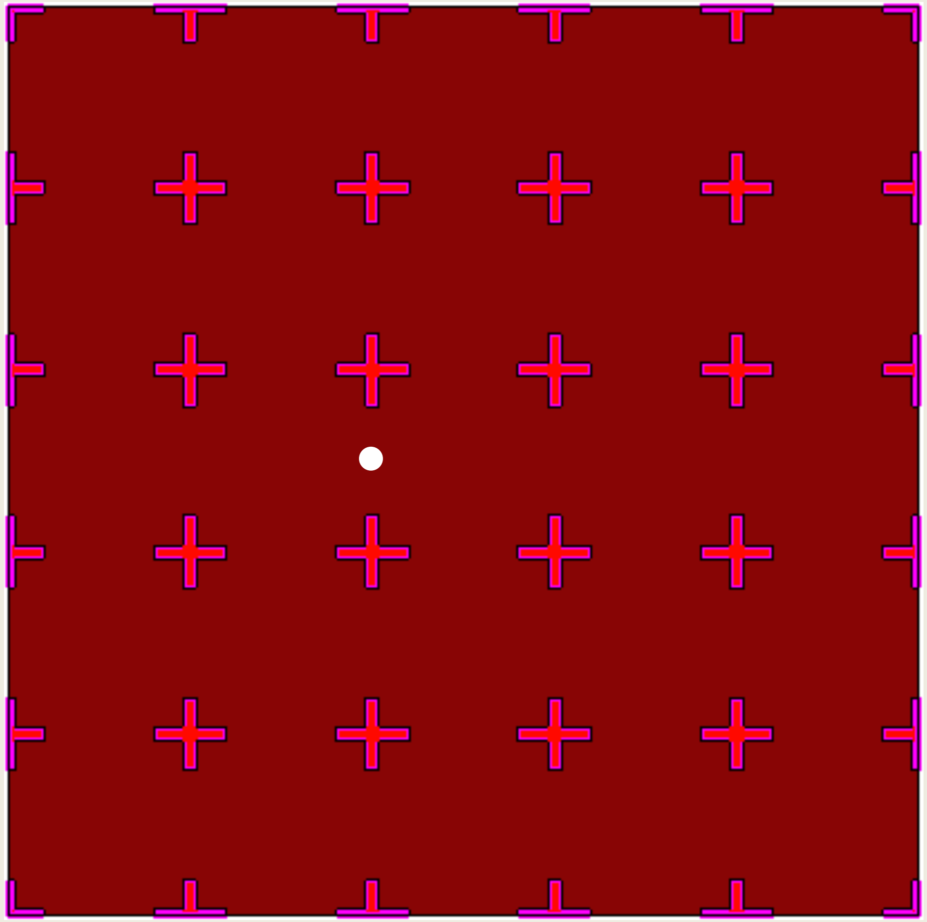
Distribution of collected charge between pads as a function of their size



L$_{arm}$ = $8\ \mu m$



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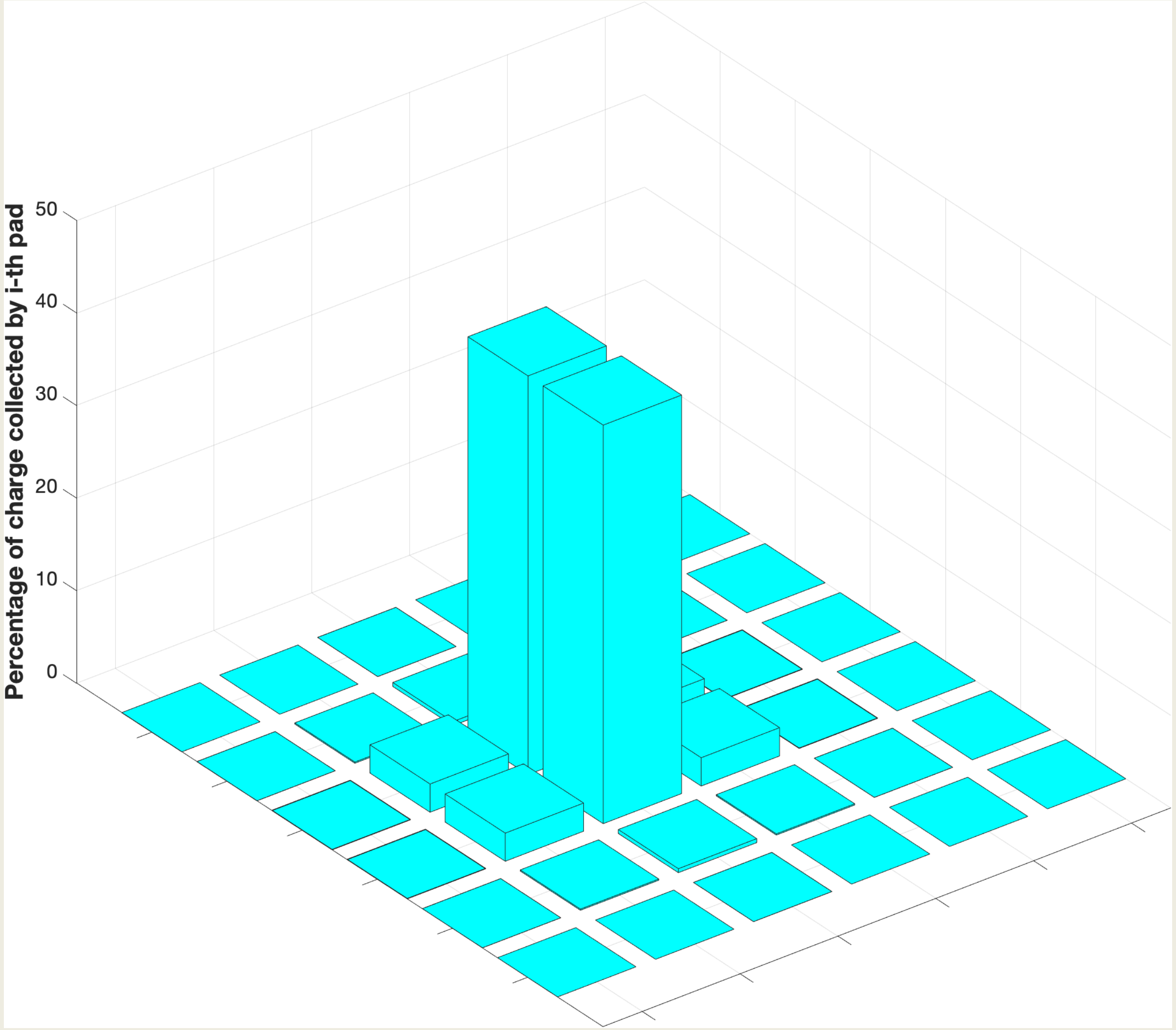
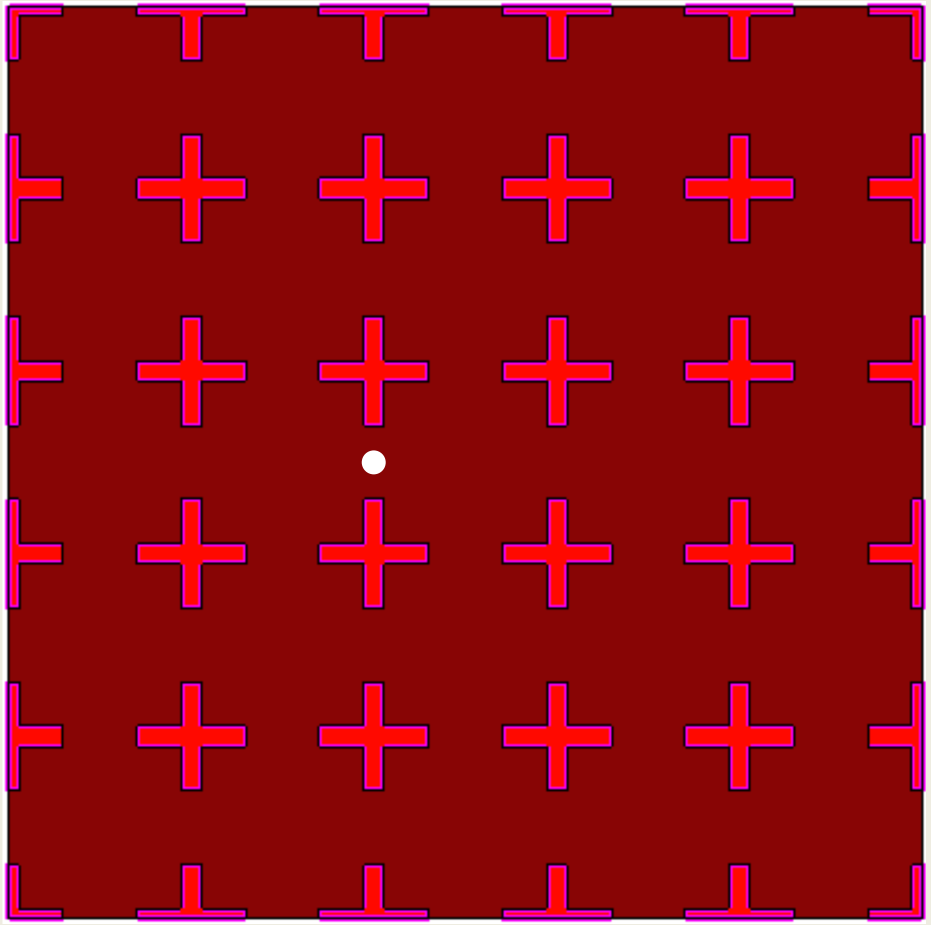
Distribution of collected charge between pads as a function of their size



$L_{arm} = 12\ \mu m$



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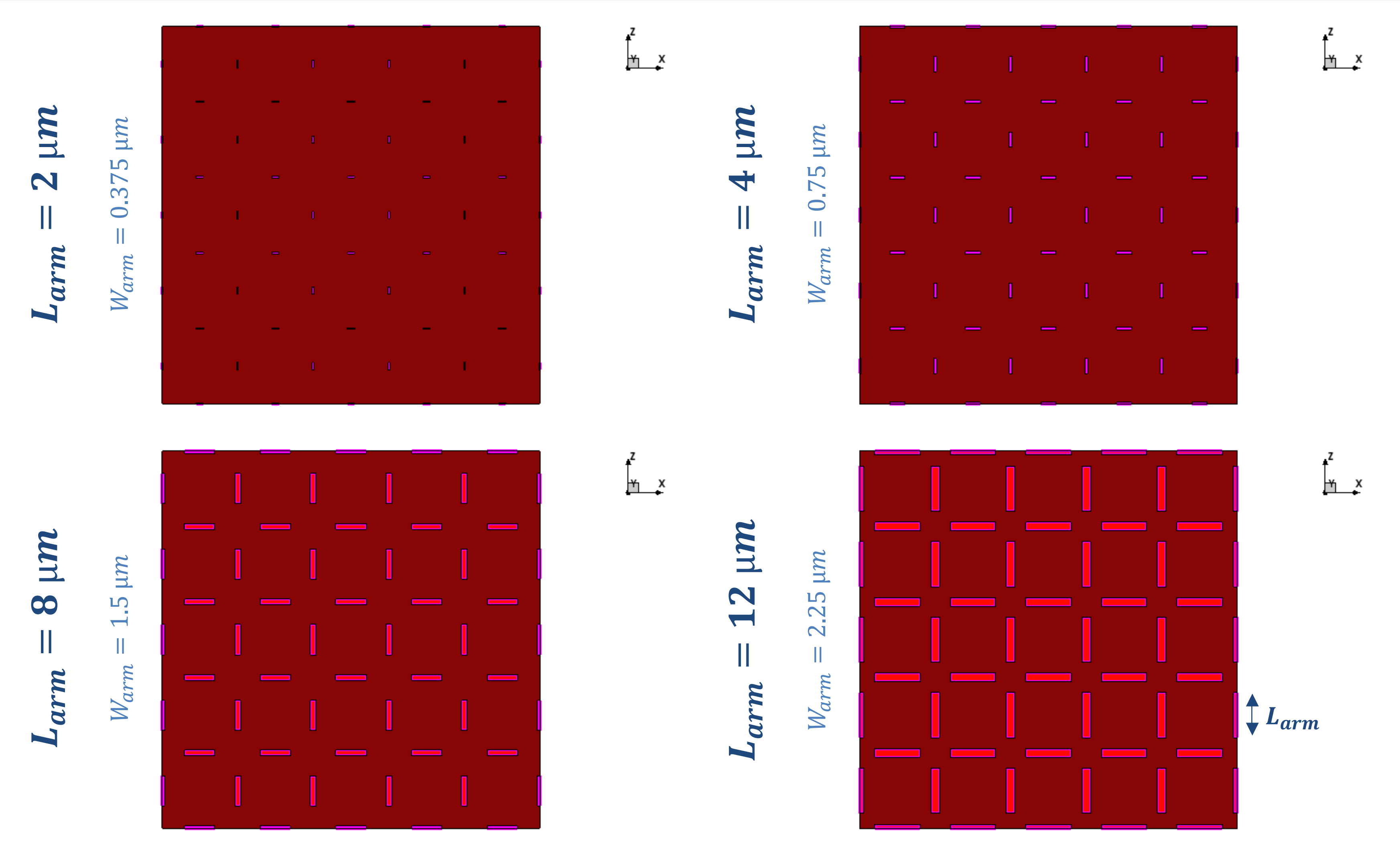
Seeking to limit charge sharing: Bar-shaped pads



Structure with many pixels to study signal confinement

↓

For computationally acceptable 3D simulations each pixel must be small

↓

Footprint of $100\times100\ \mu m^2$

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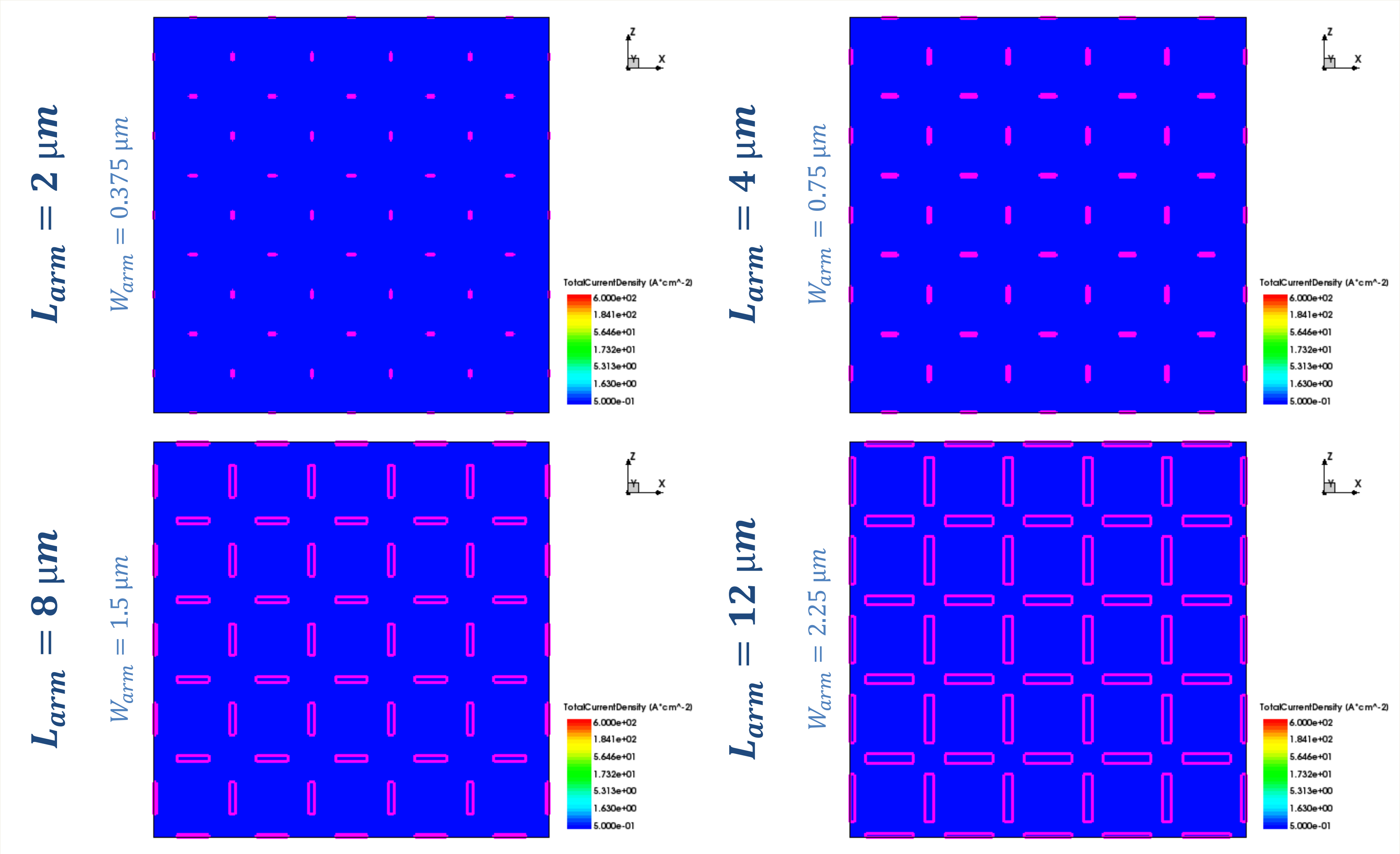
Temporal evolution of current density maps



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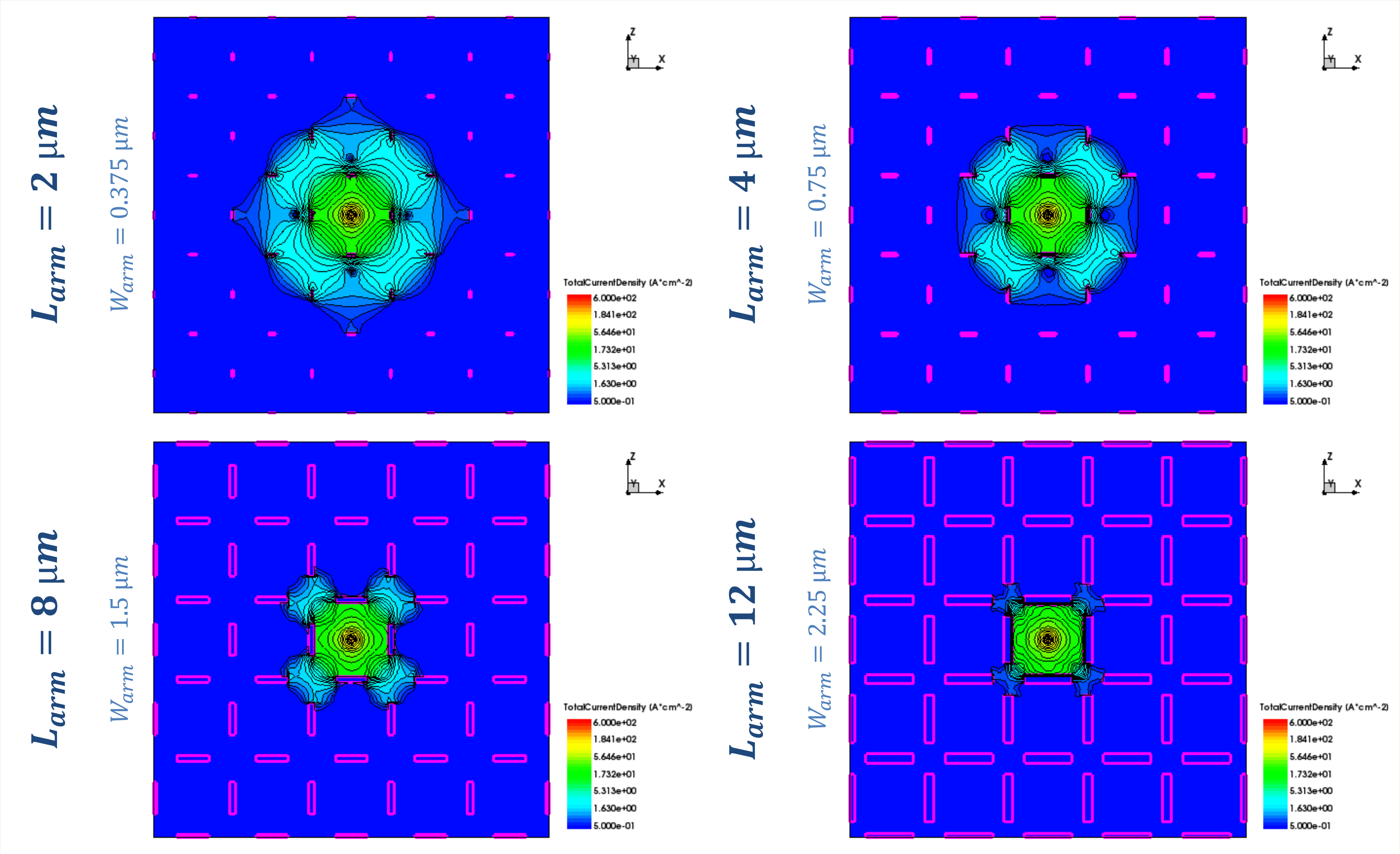
Temporal evolution of current density maps



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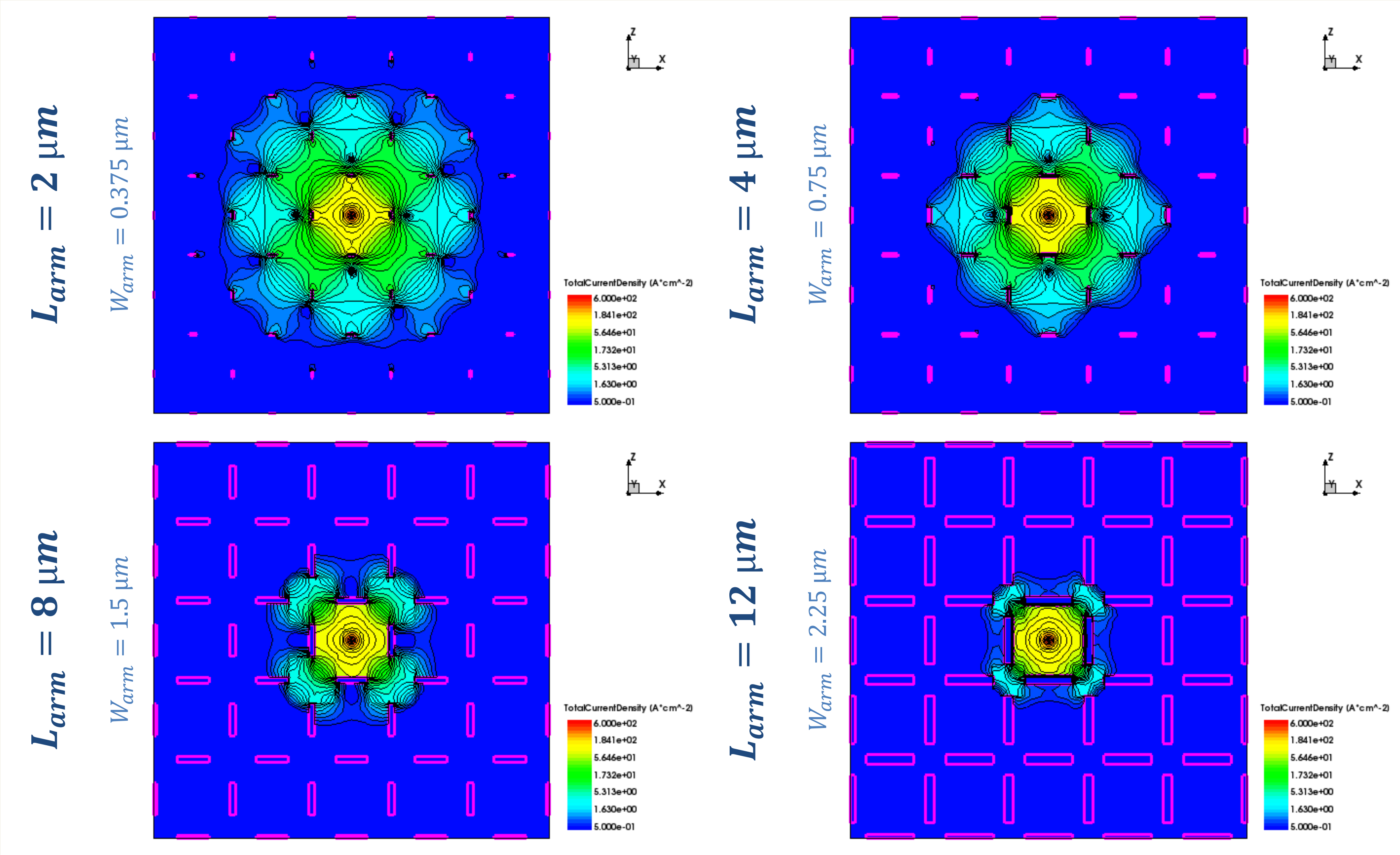
alessandro.fondacci@pg.infn.it

HIT 1

Temporal evolution of current density maps



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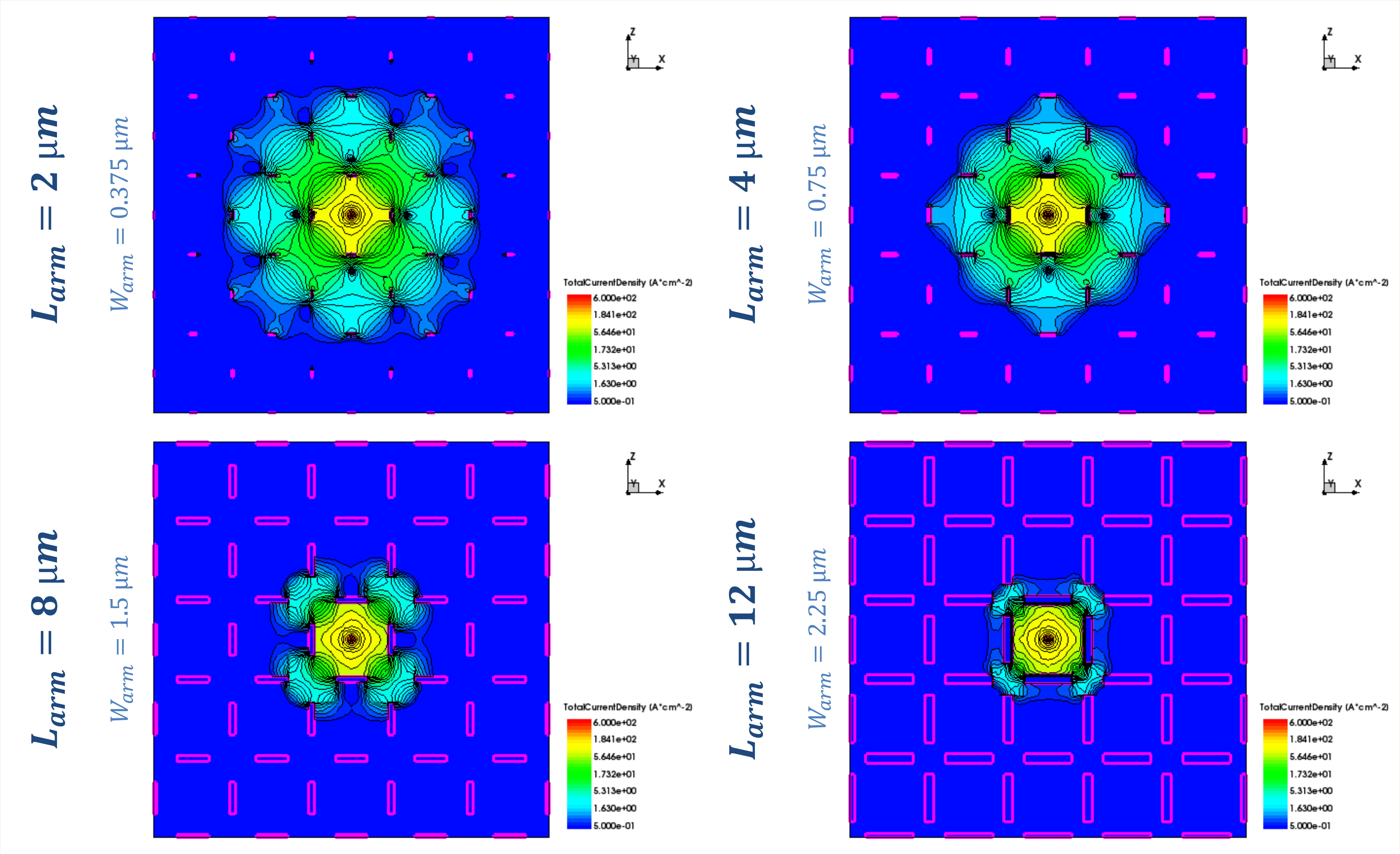

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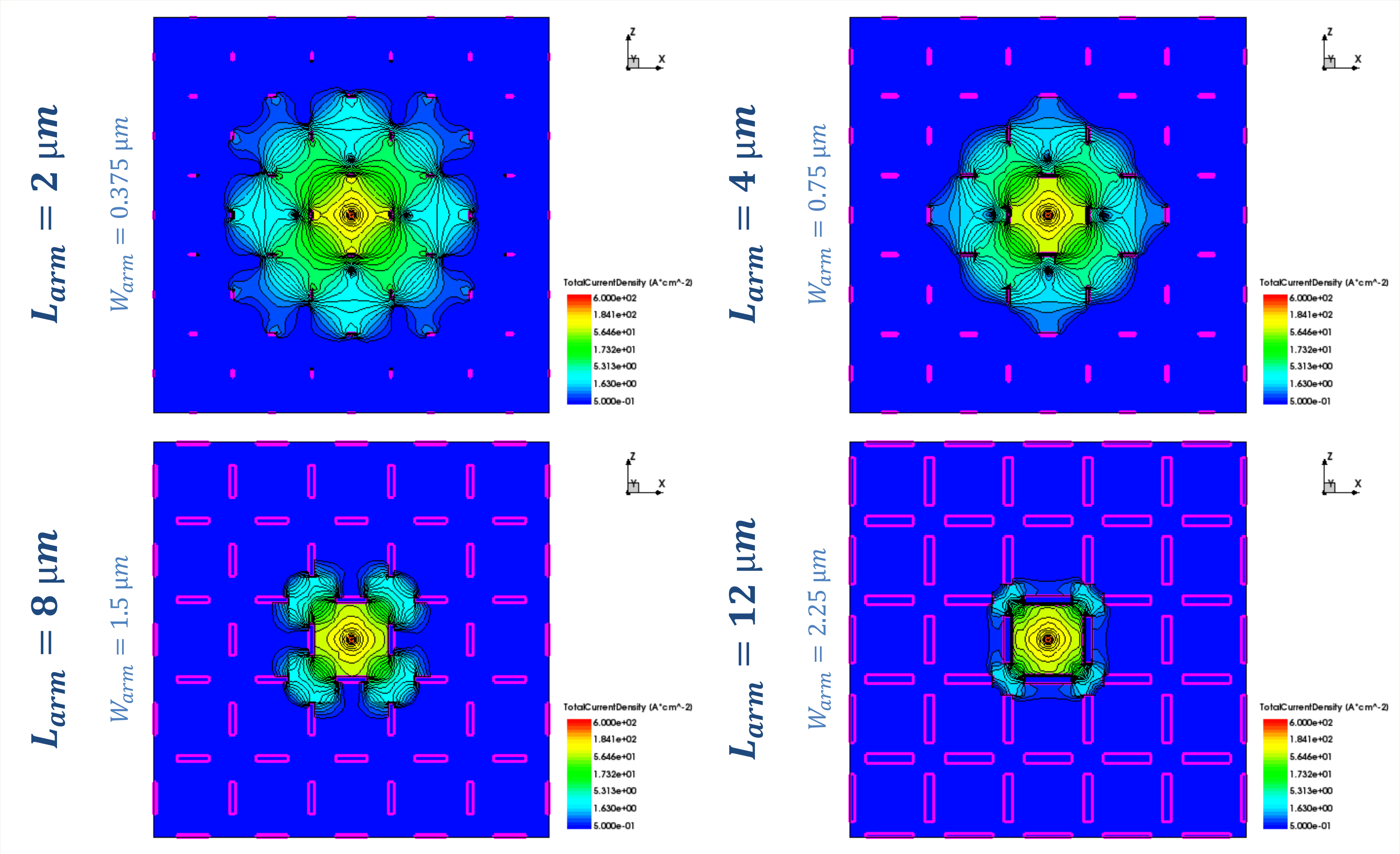
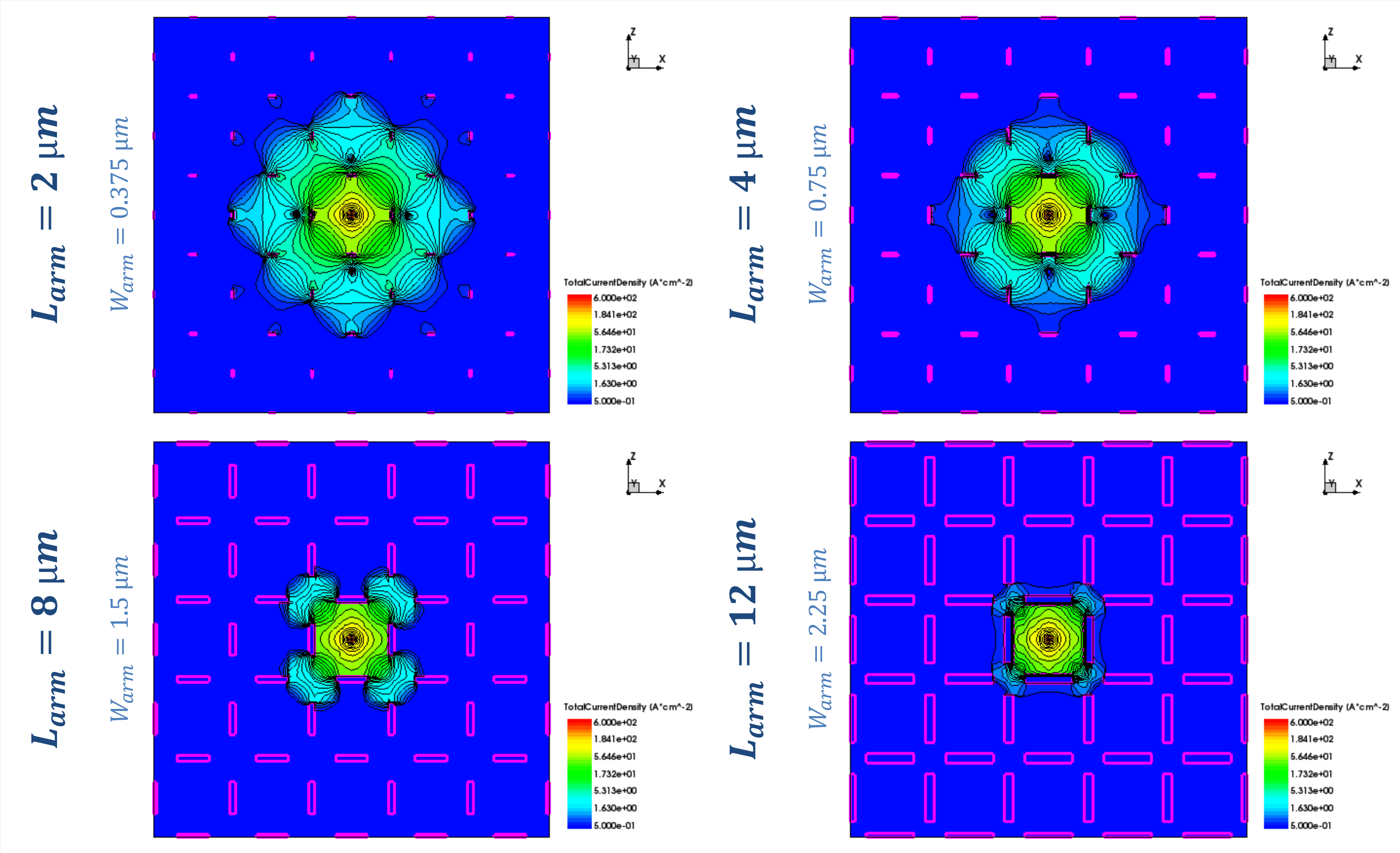


Temporal evolution of current density maps



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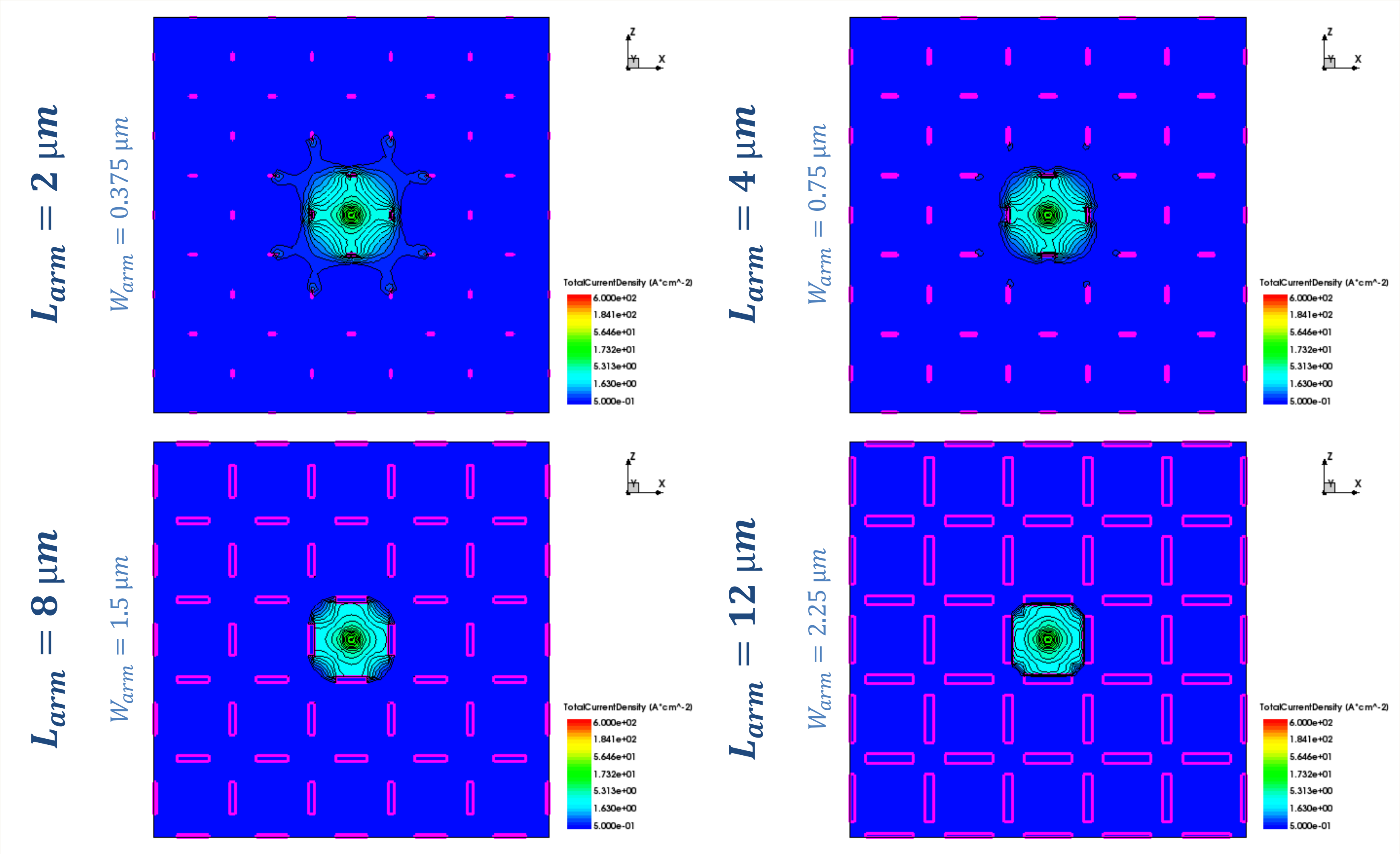

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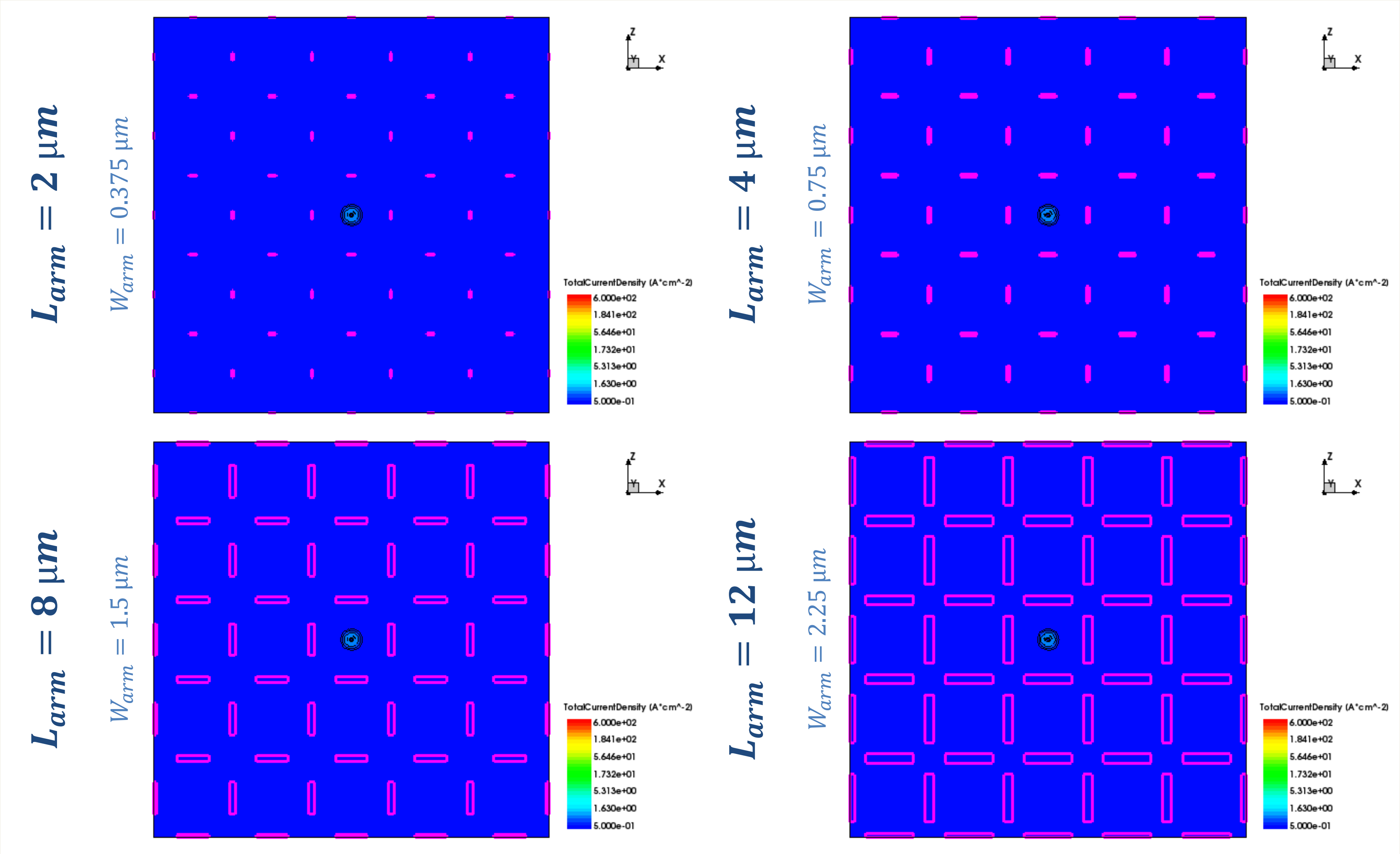
Temporal evolution of current density maps



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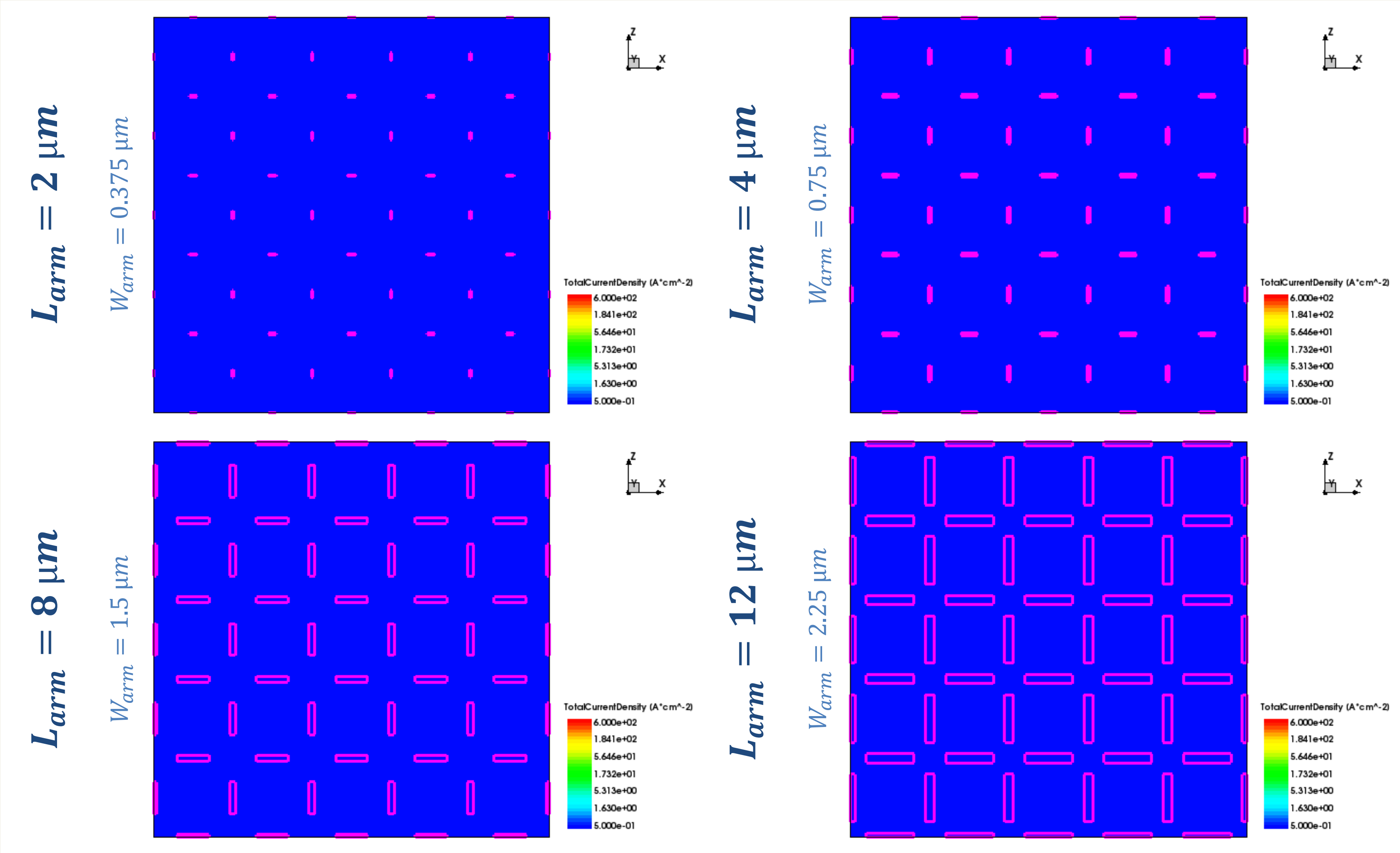

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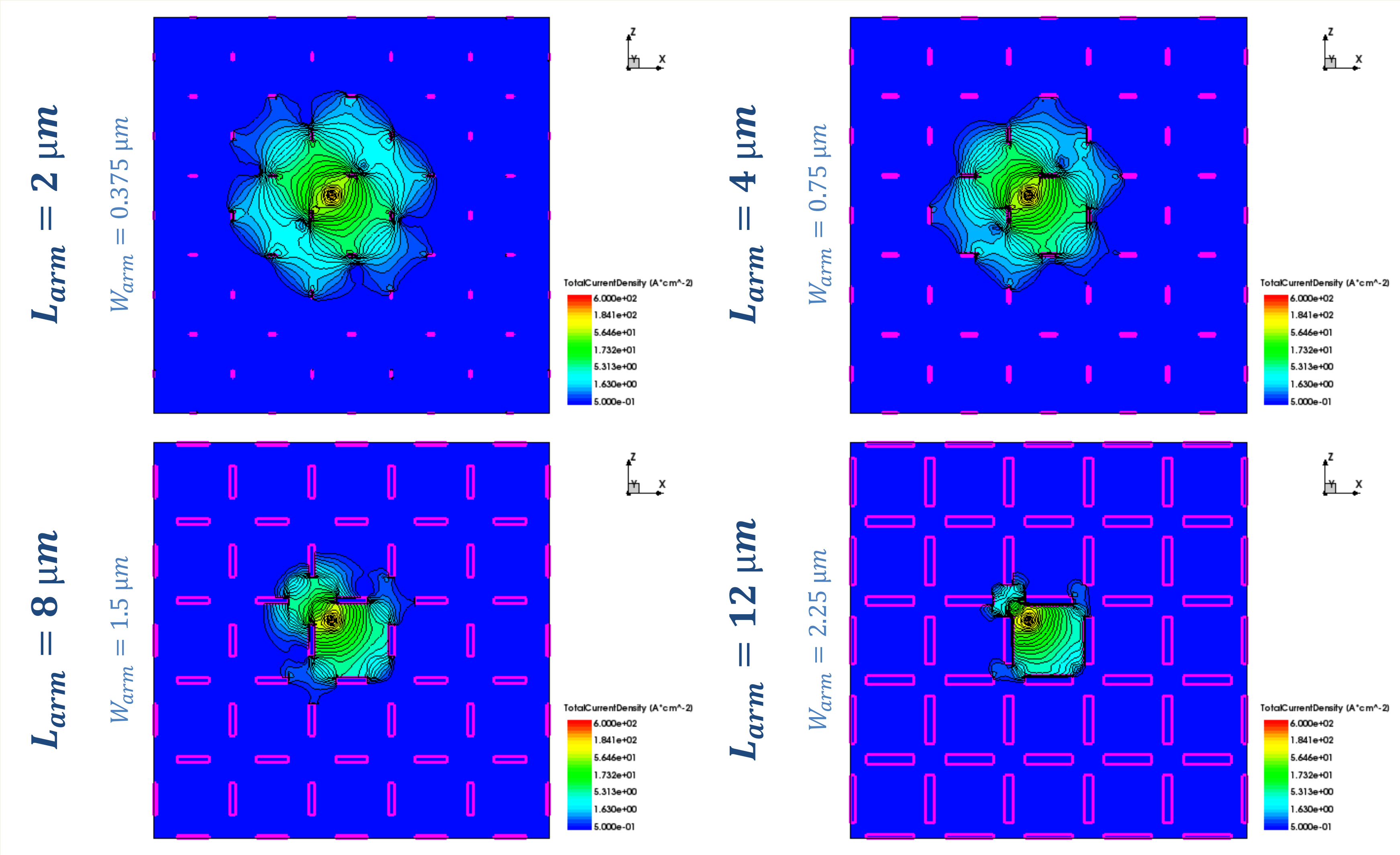

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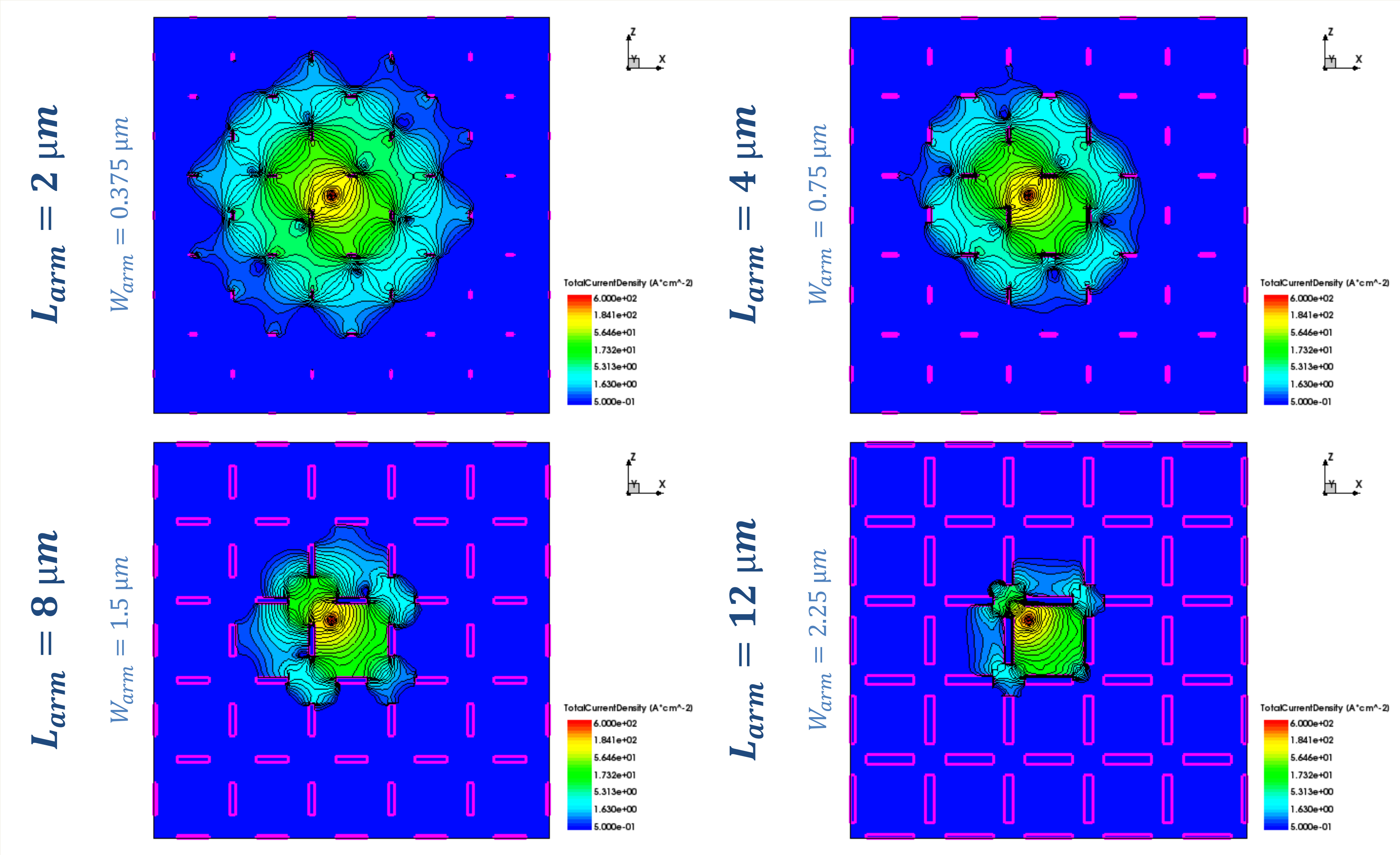
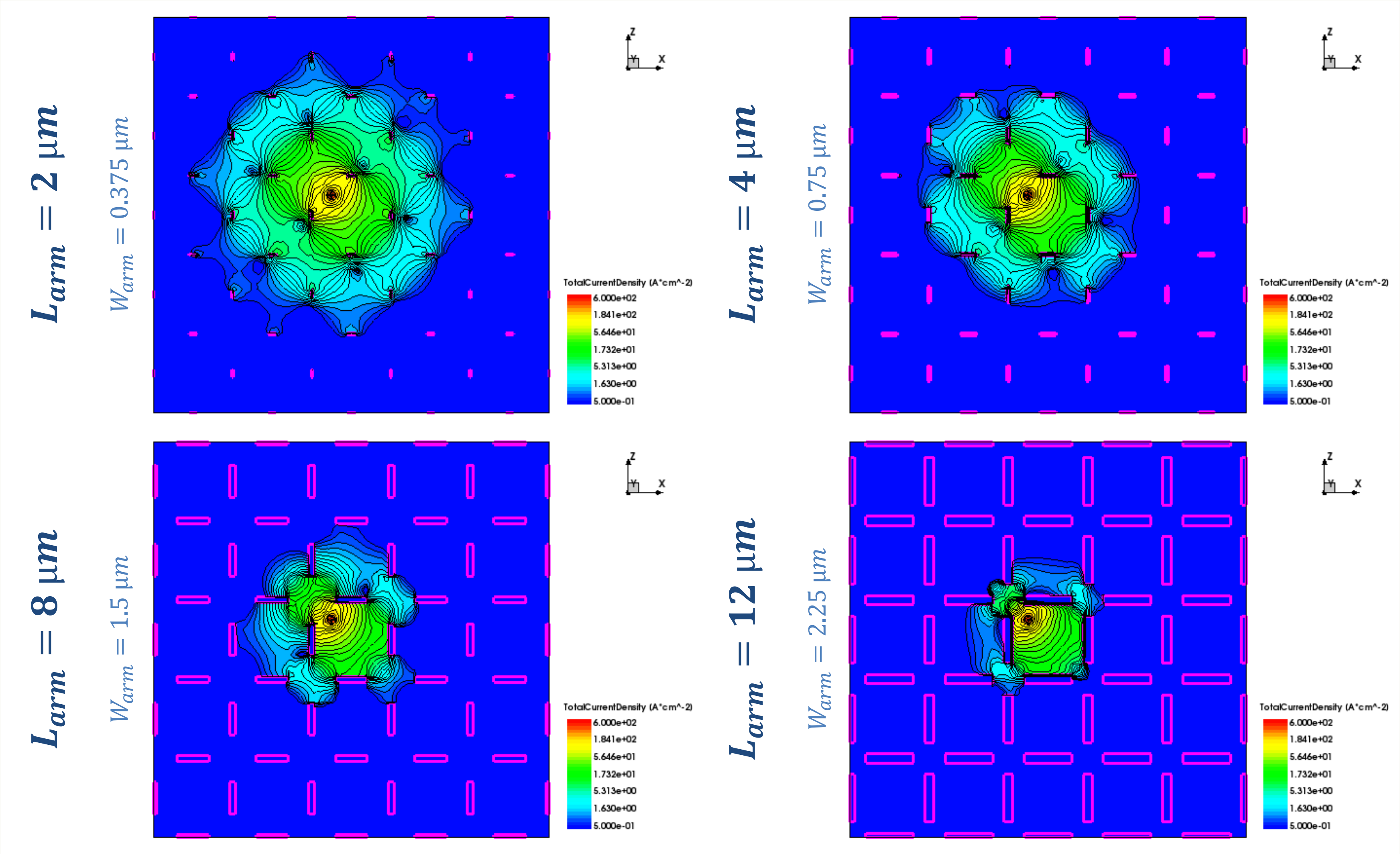
Temporal evolution of current density maps



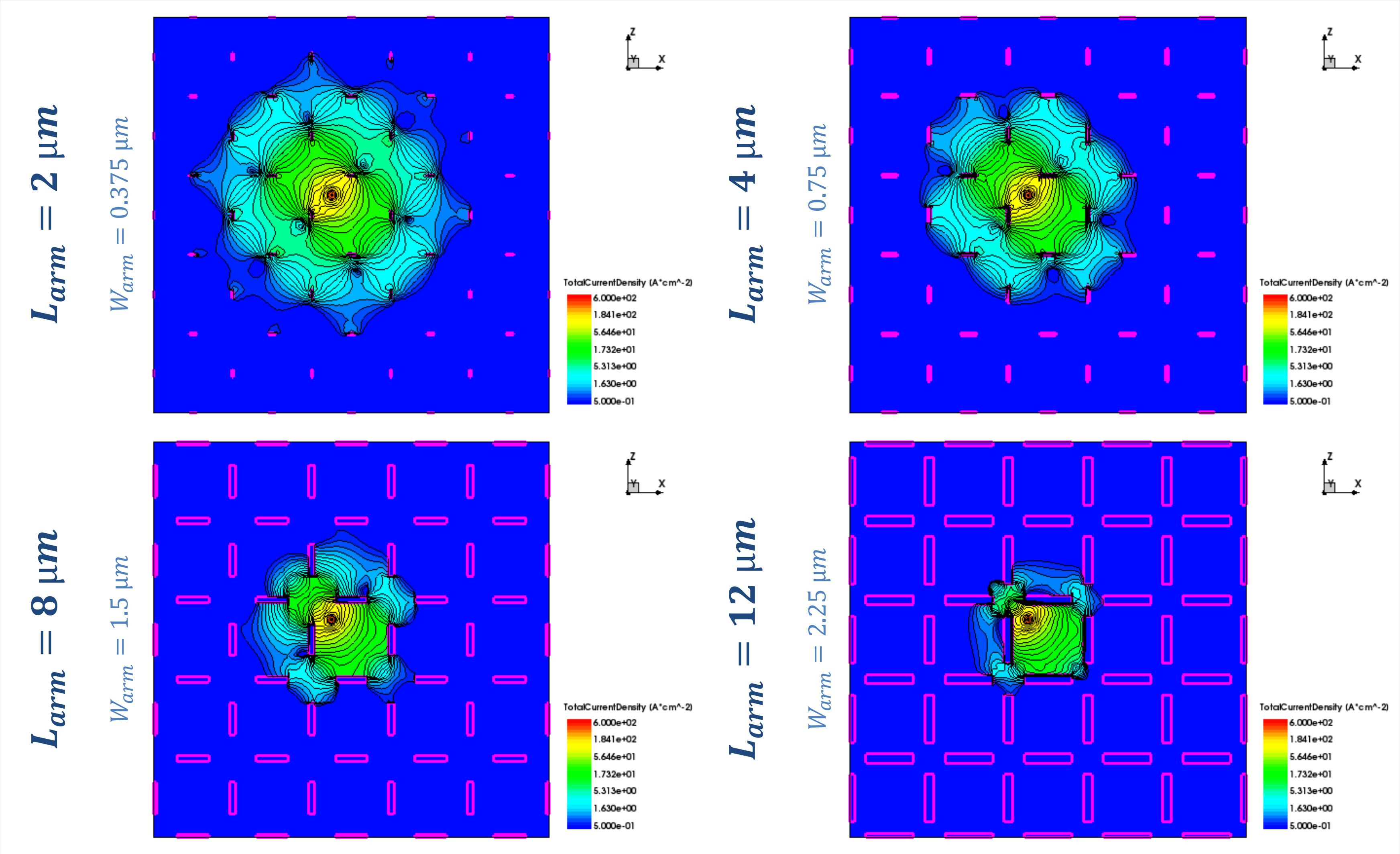
alessandro.fondacci@pg.infn.it

HIT 2

Temporal evolution of current density maps



Temporal evolution of current density maps



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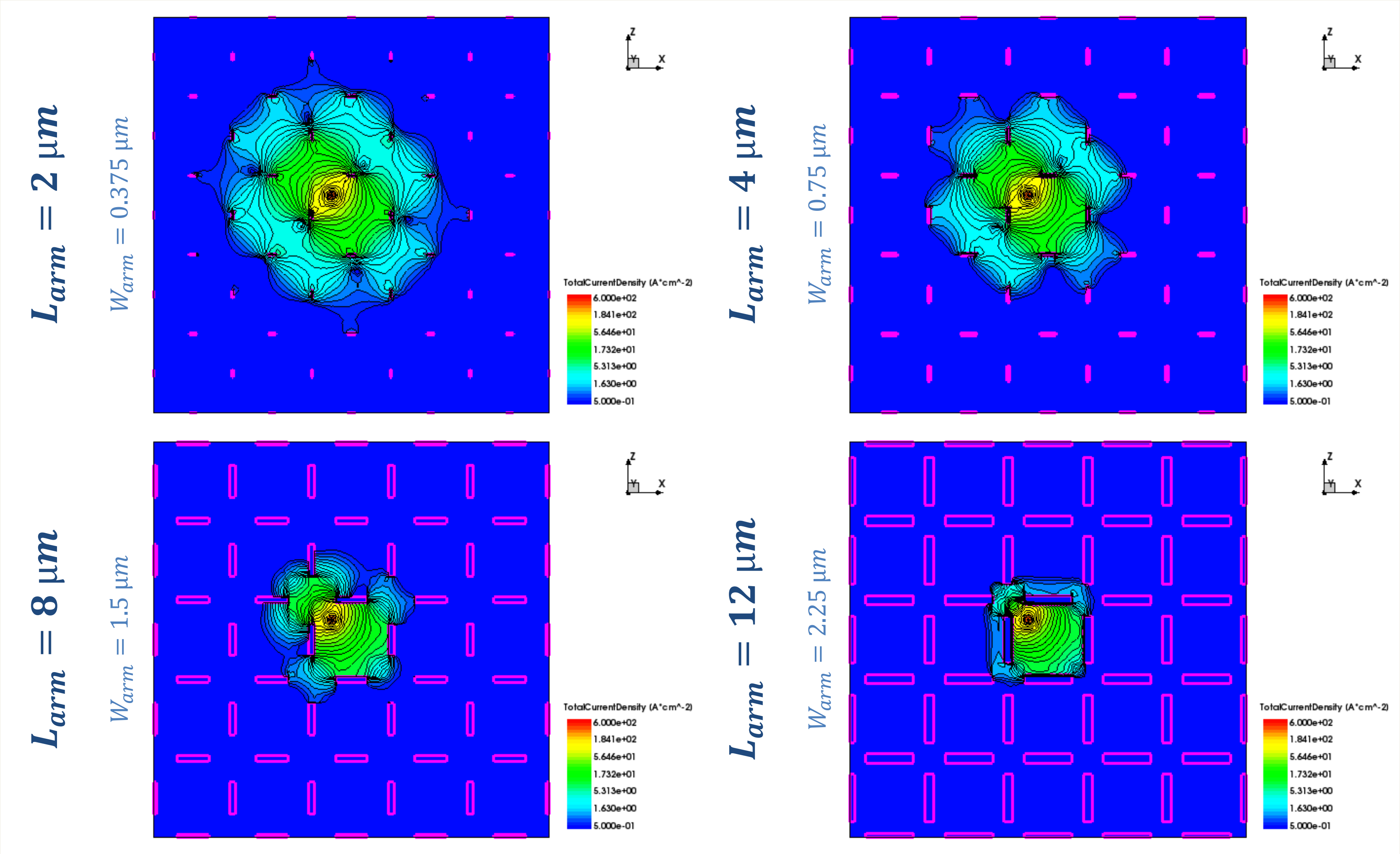
Bar-shaped pads

DC-RSD LGAD

HIT 2

Temporal evolution of current density maps



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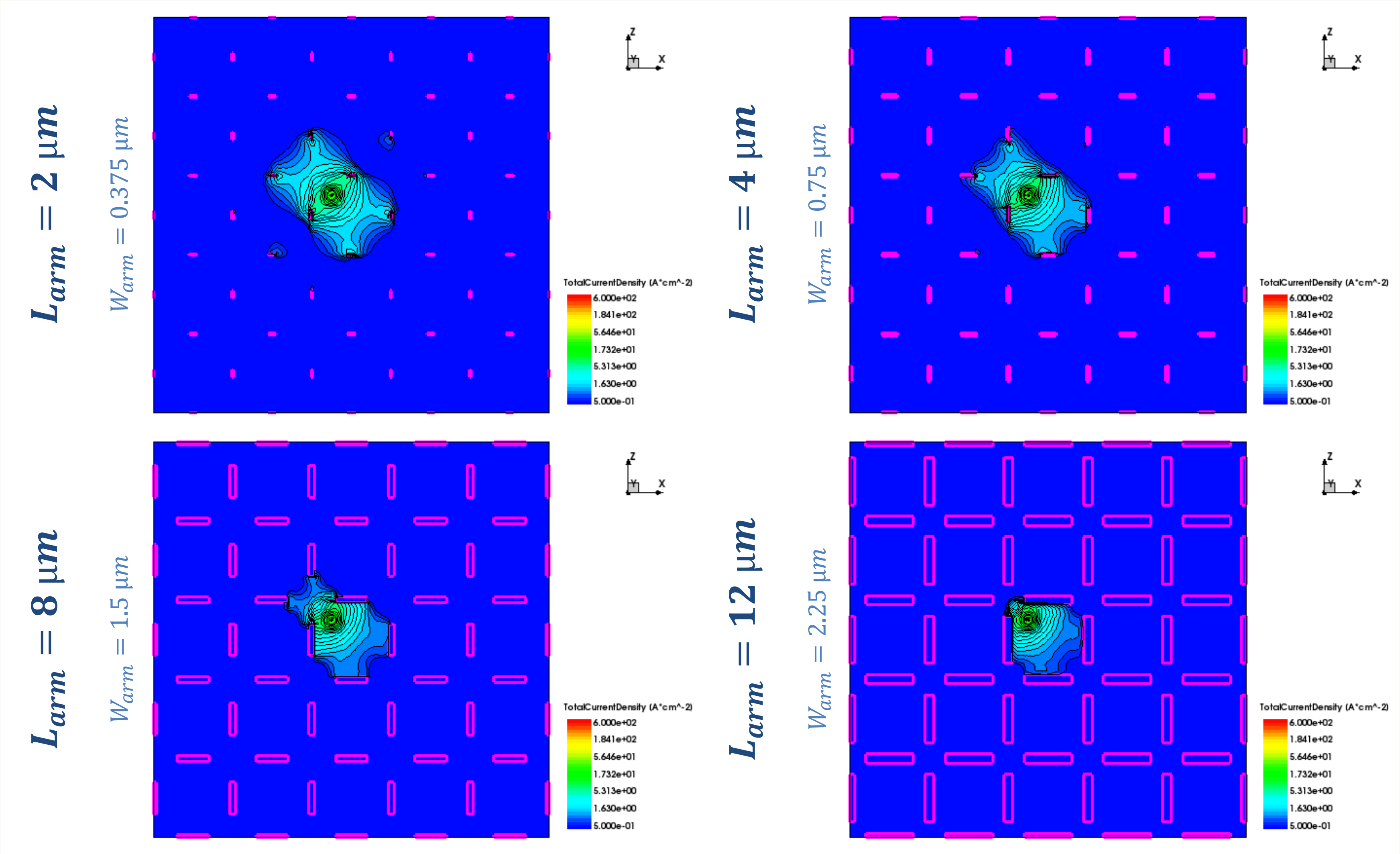
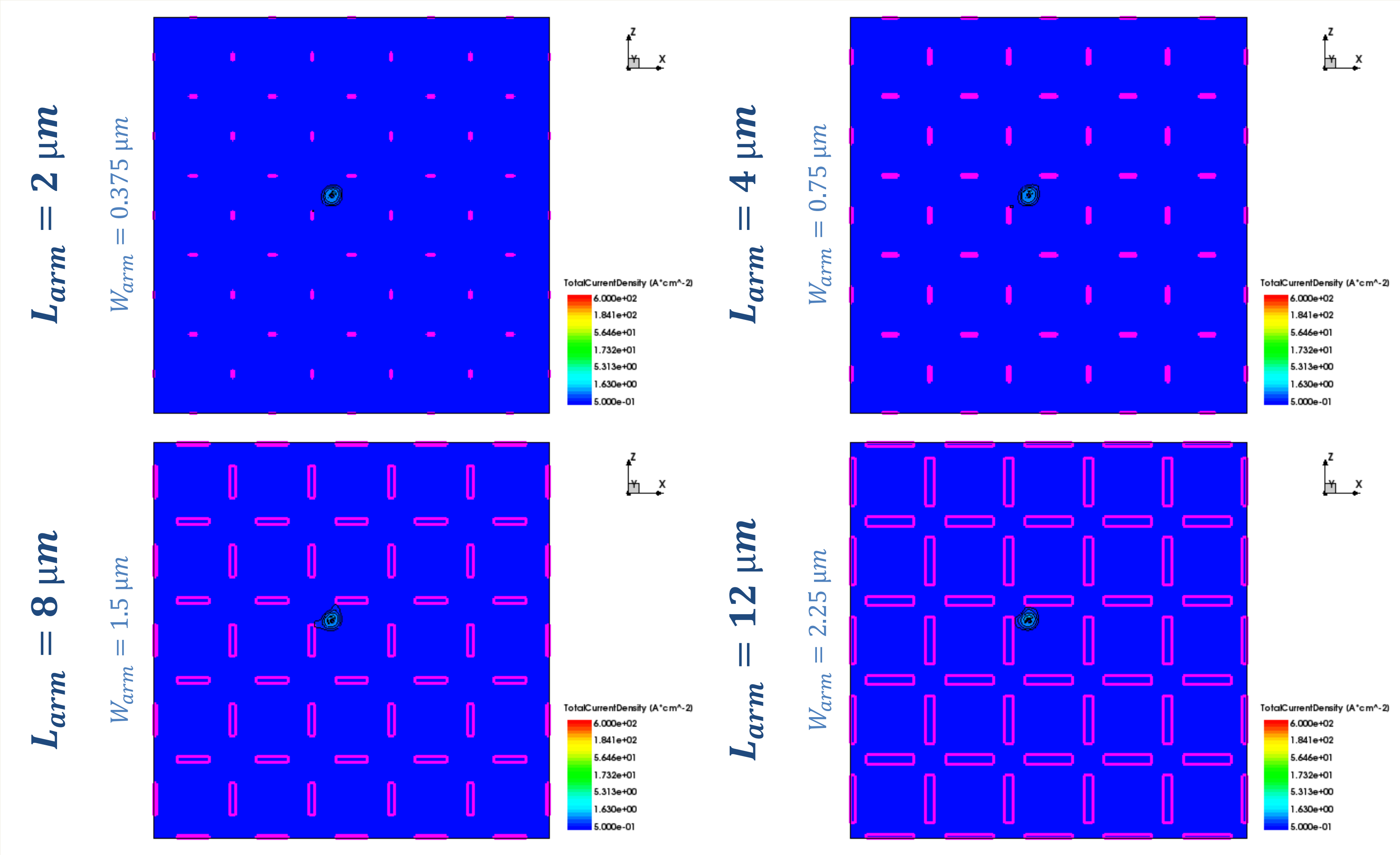
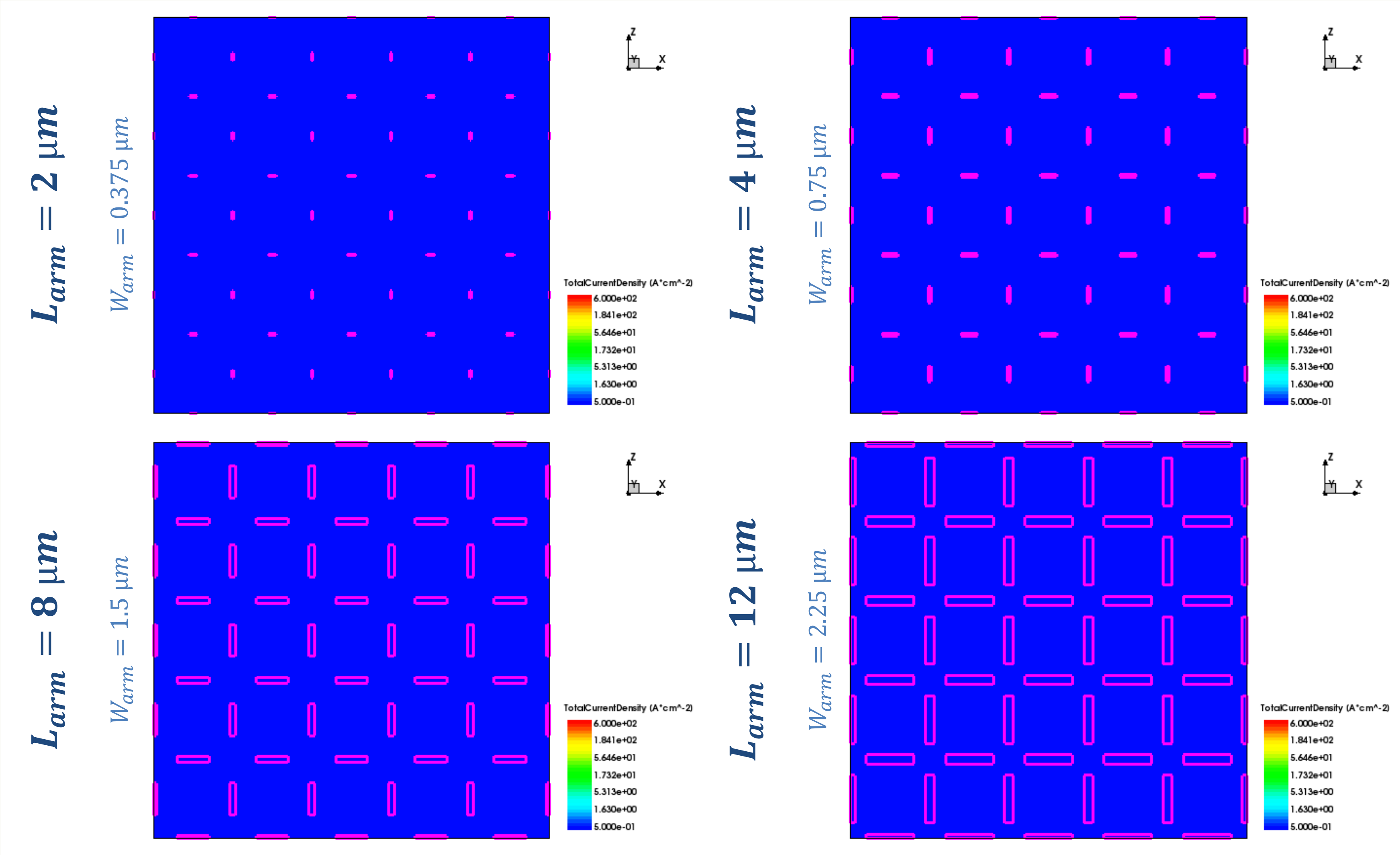


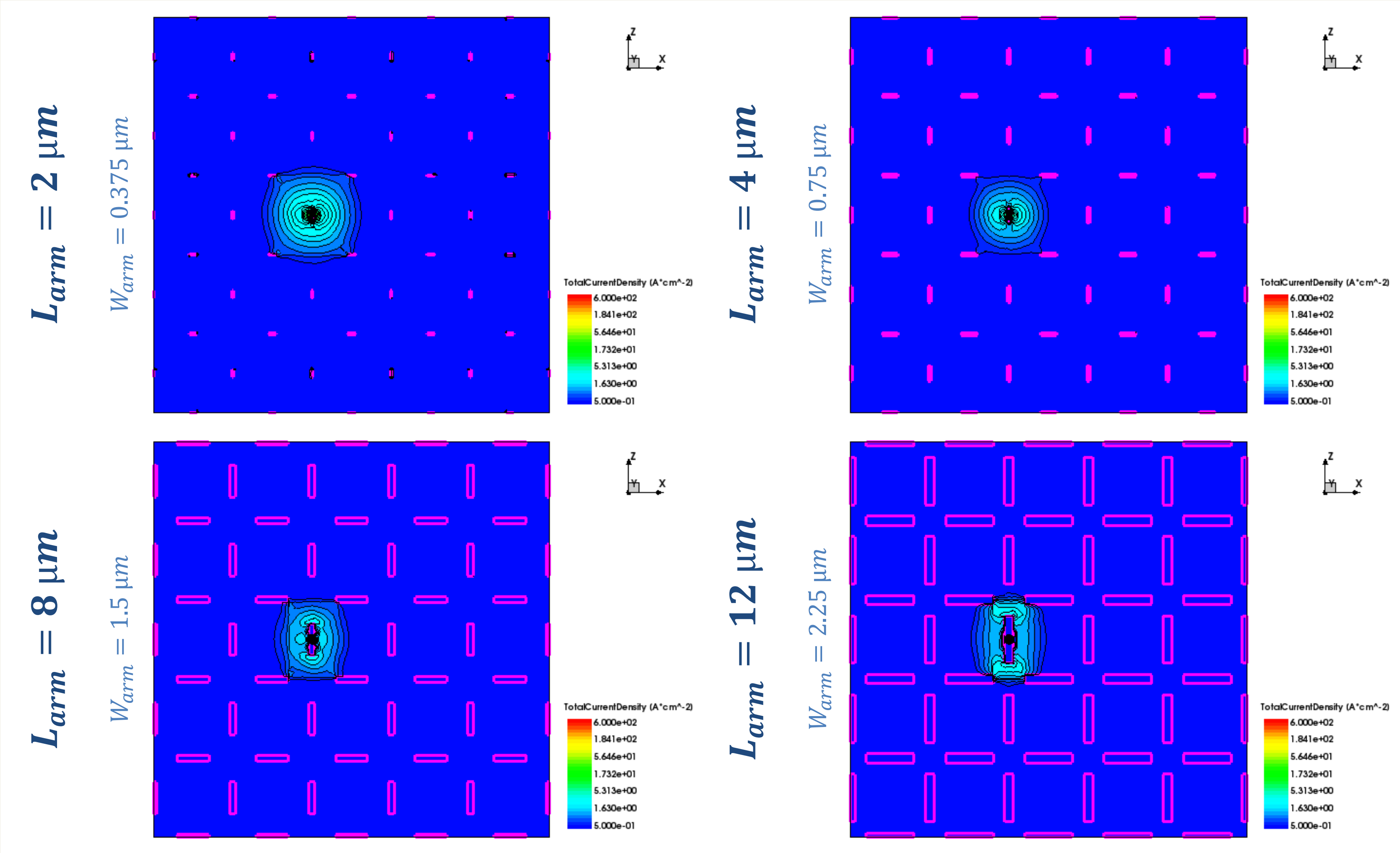
Temporal evolution of current density maps



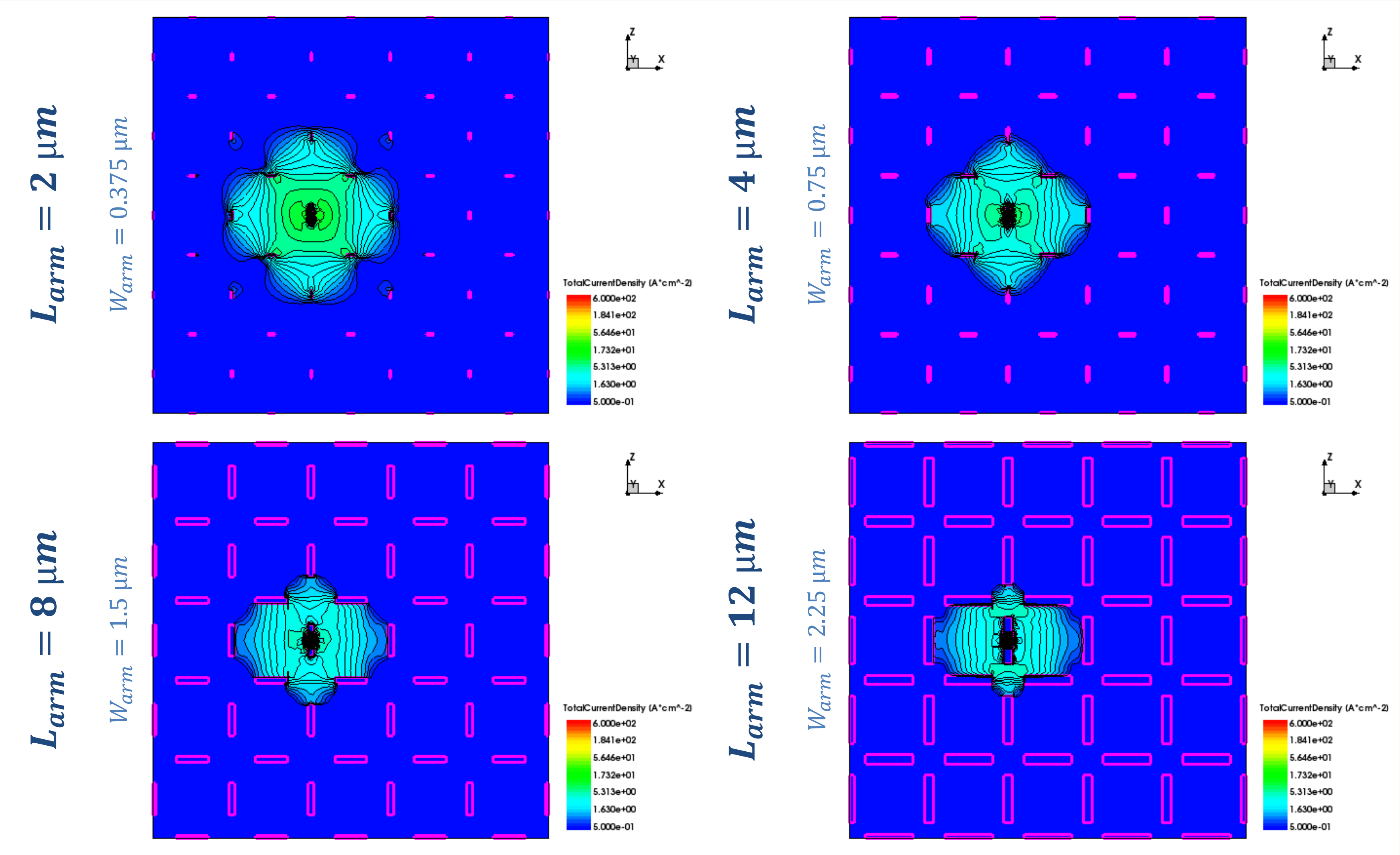
Temporal evolution of current density maps



Temporal evolution of current density maps



Temporal evolution of current density maps



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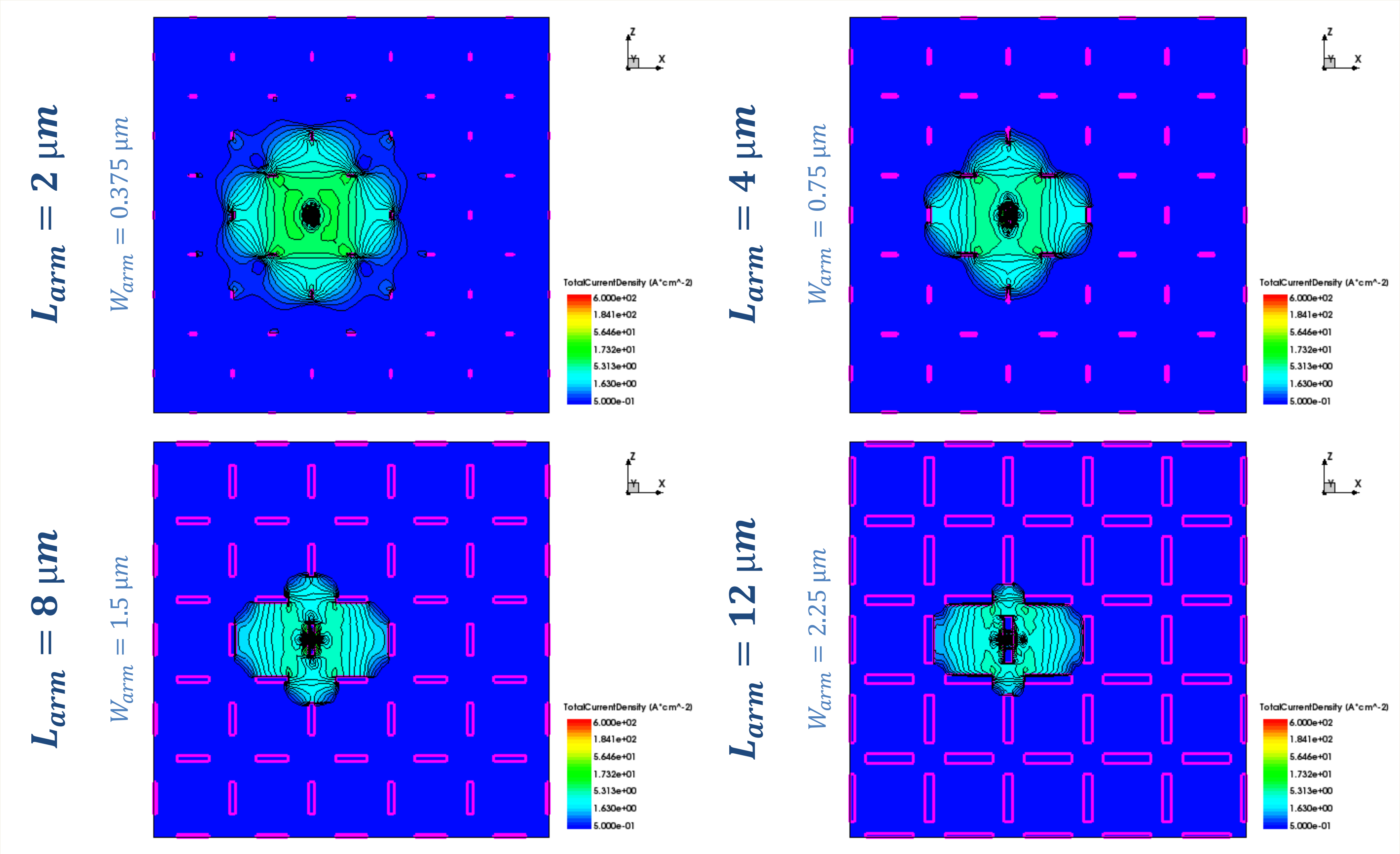
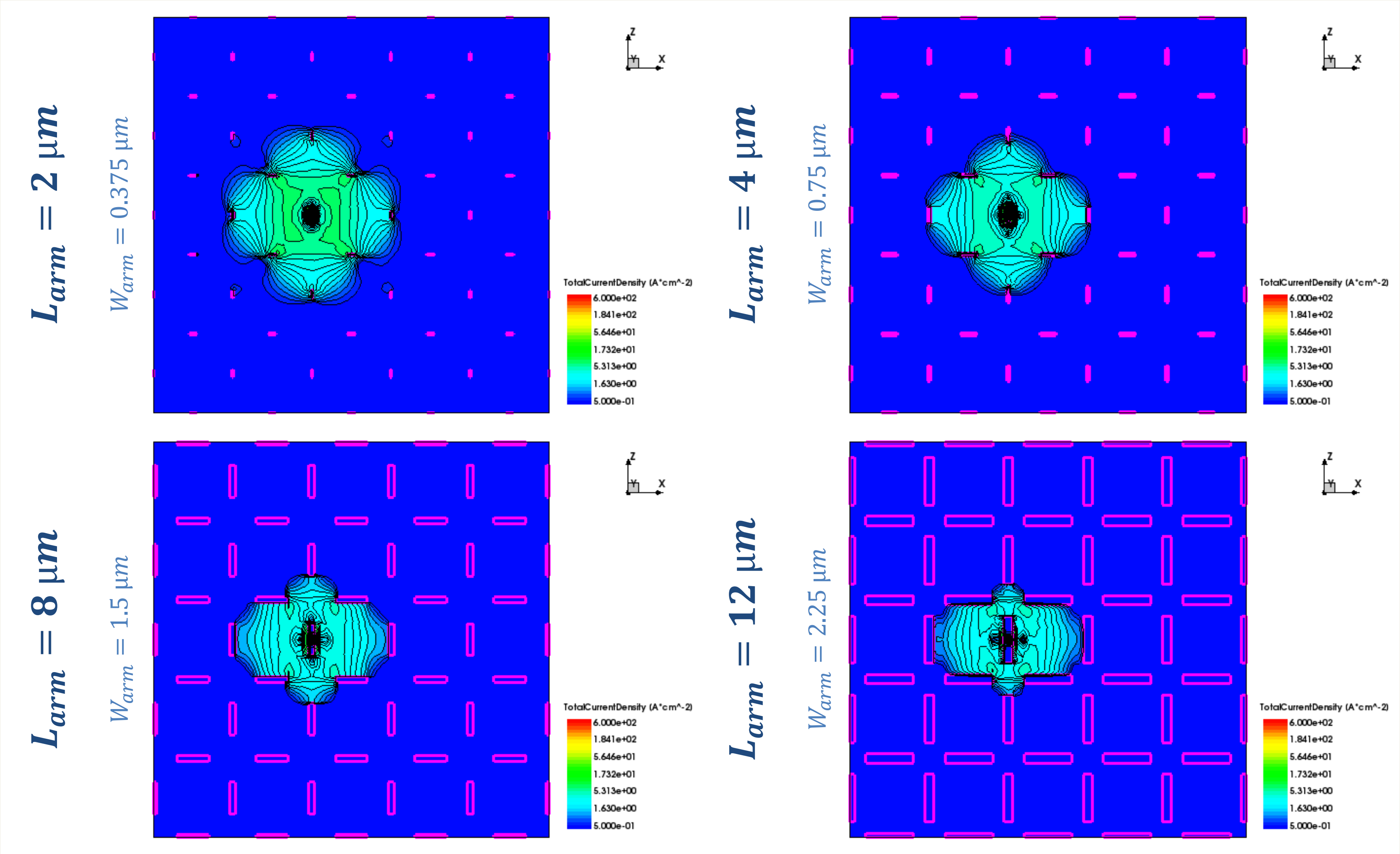
Temporal evolution of current density maps

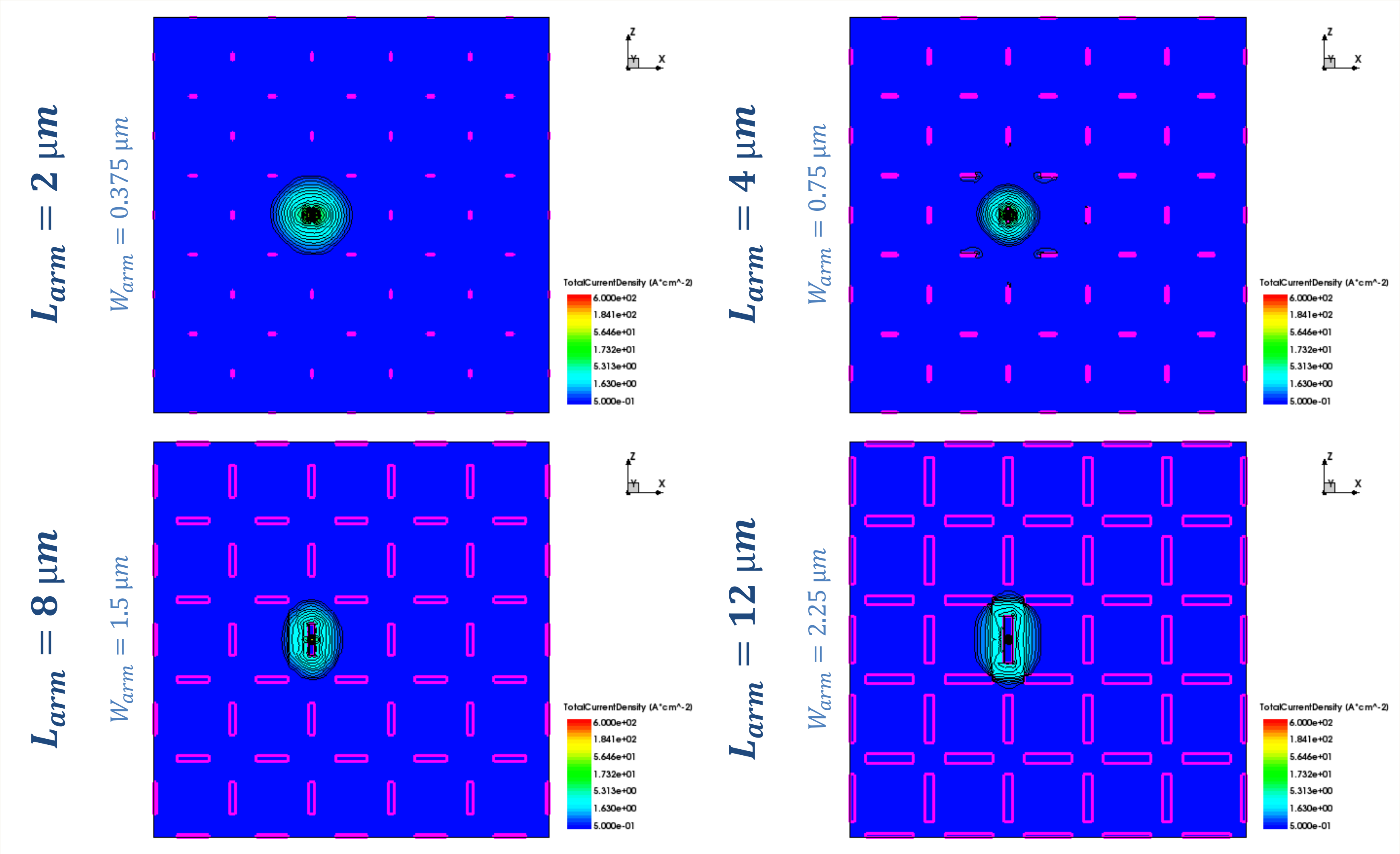


Temporal evolution of current density maps



HIT 3

Temporal evolution of current density maps



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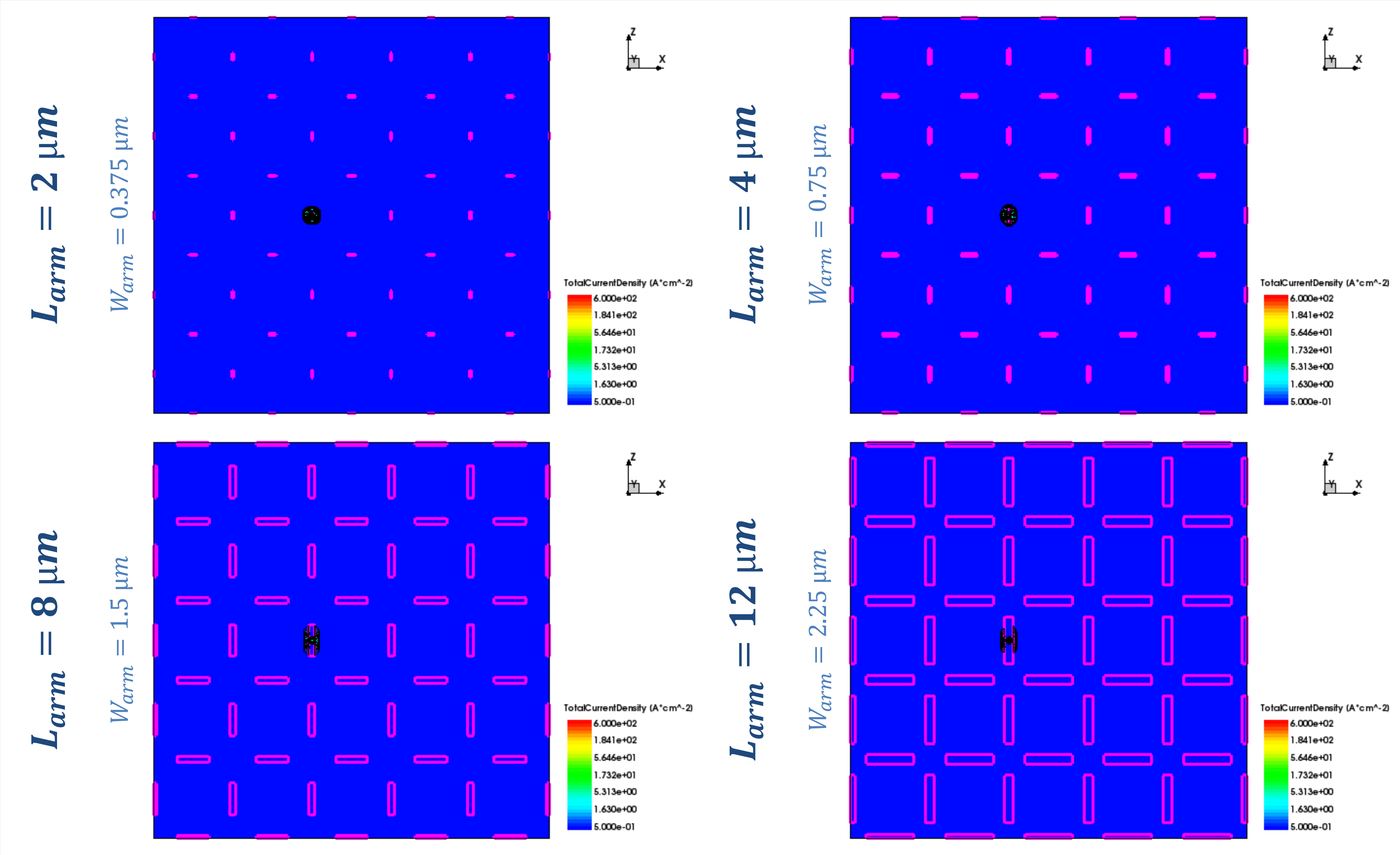
Temporal evolution of current density maps

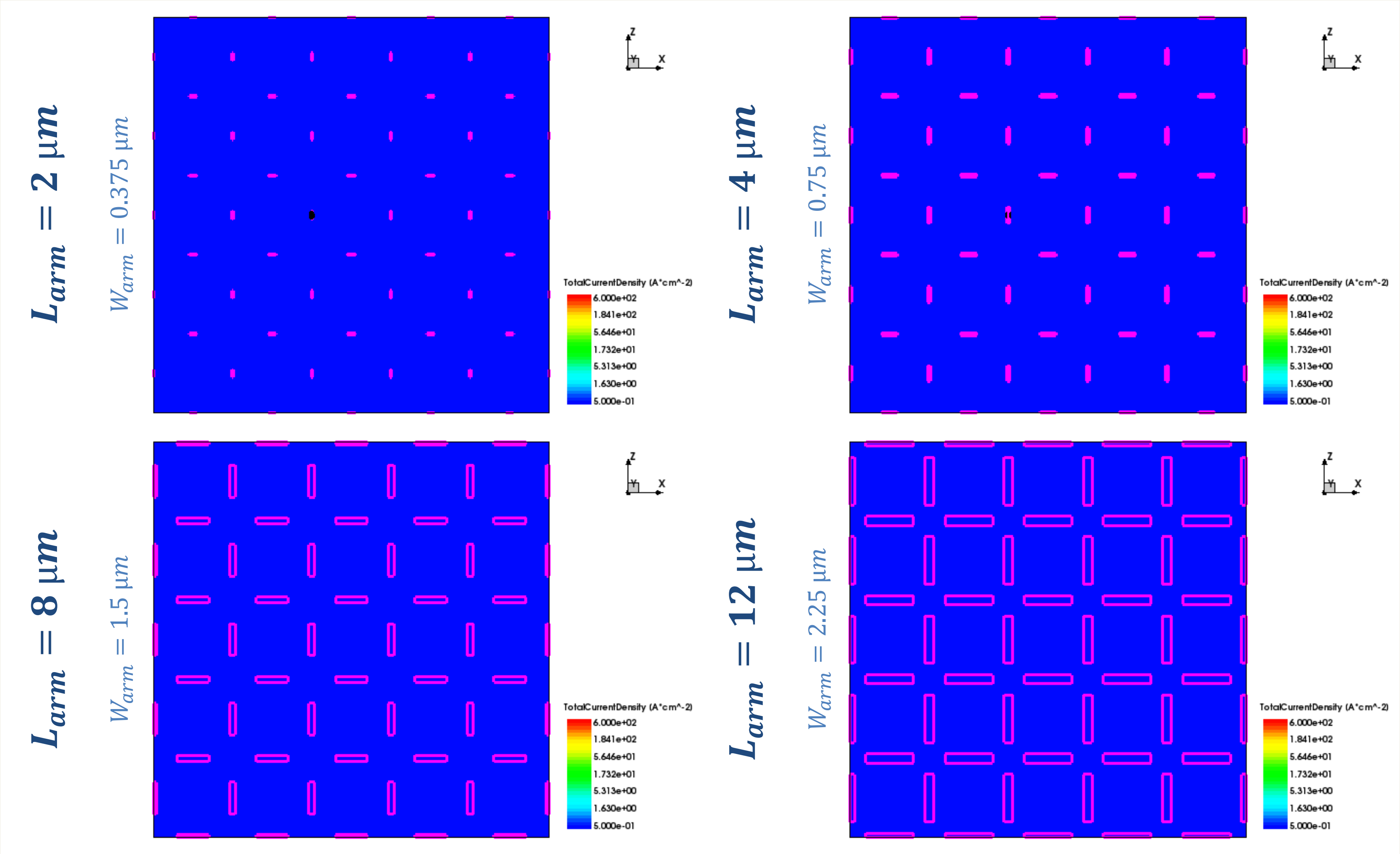


Bar-shaped pads

DC-RSD LGAD

HIT 3

Temporal evolution of current density maps



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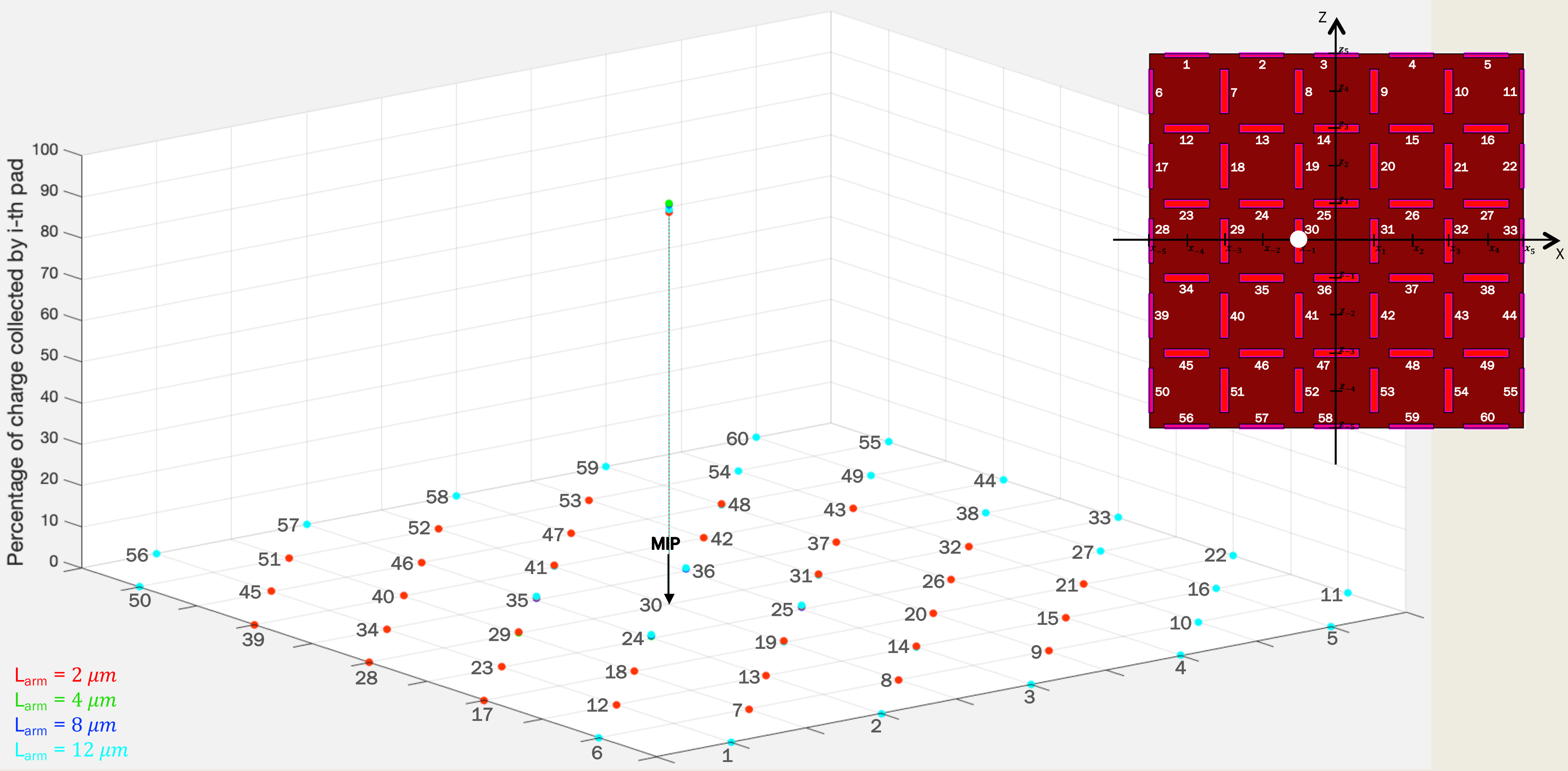
Bar-shaped pads

DC-RSD LGAD

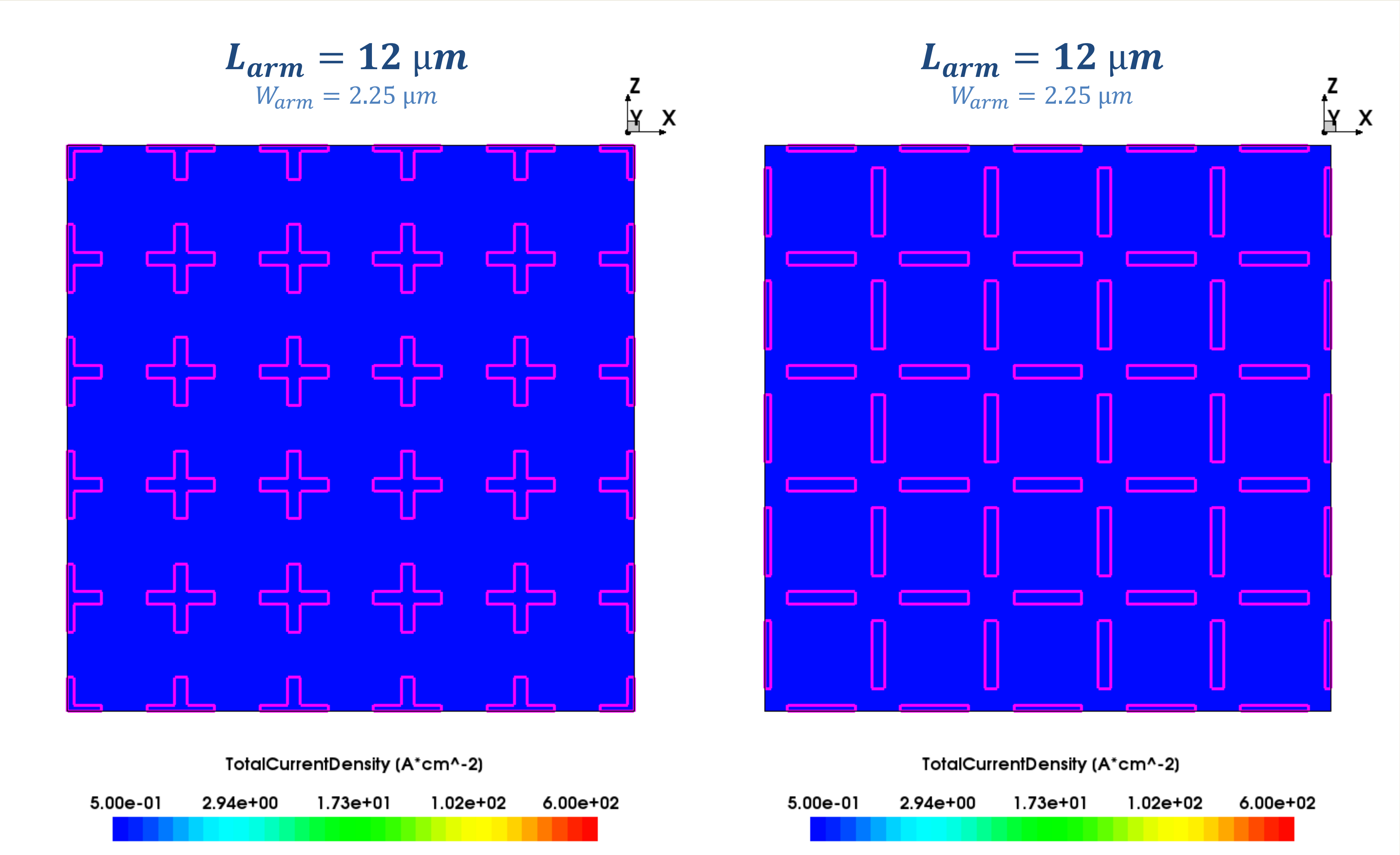
HIT 3

Distribution of collected charge between pads as a function of their size



HIT 1

So cross or bar pads?



$L_{arm} = 12\ \mu m$
$W_{arm} = 2.25\ \mu m$

$L_{arm} = 12\ \mu m$
$W_{arm} = 2.25\ \mu m$

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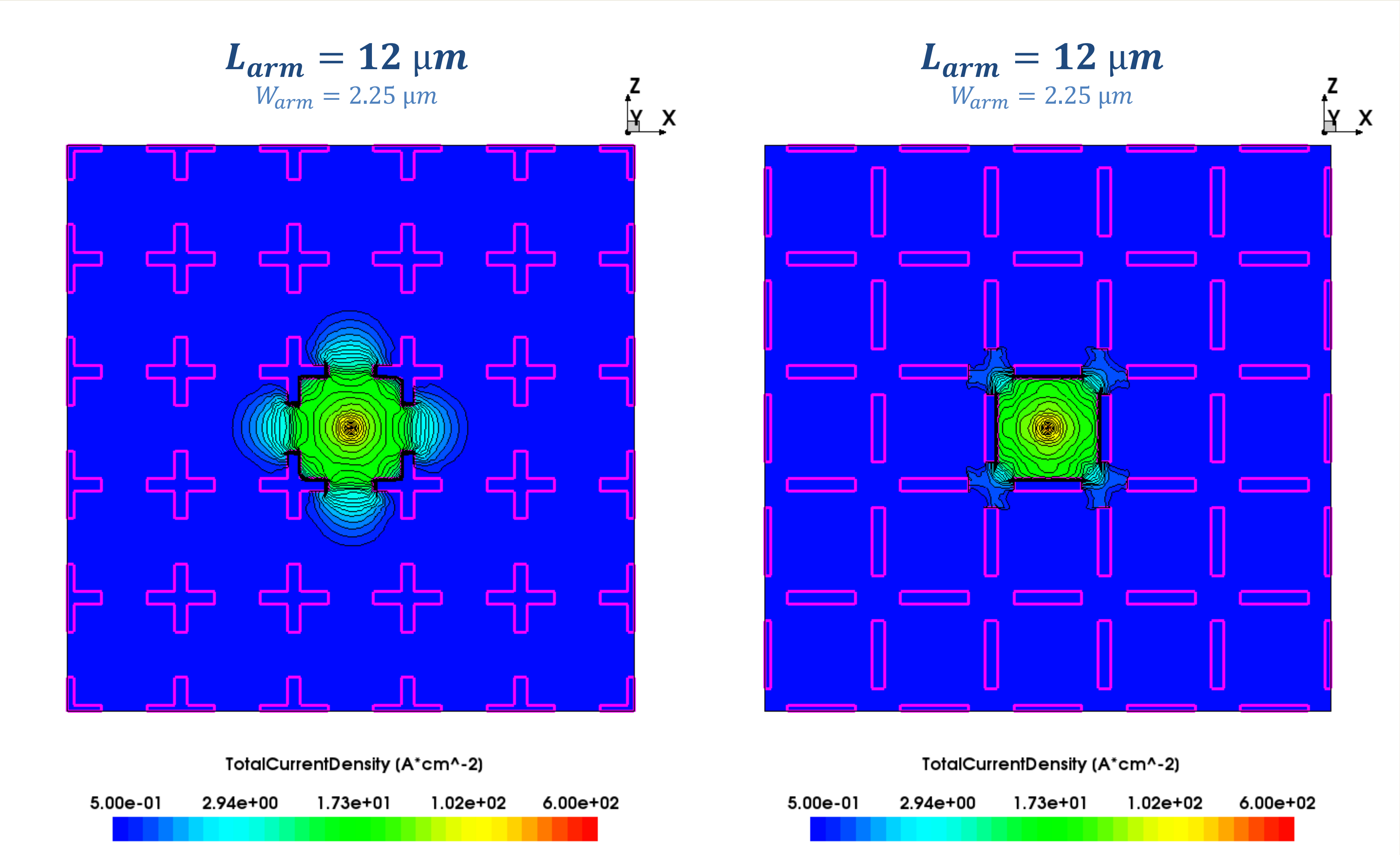

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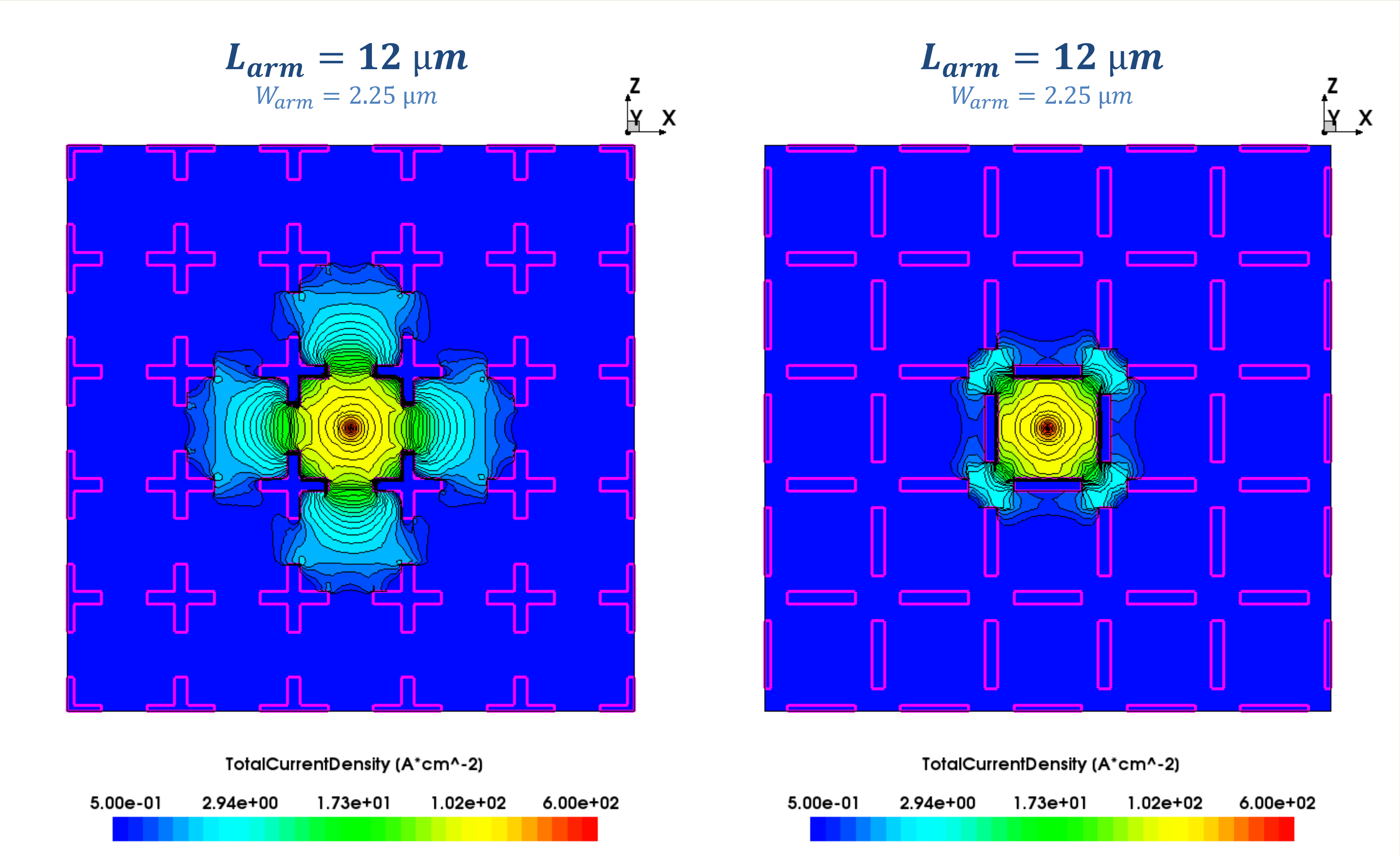
HIT 1

So cross or bar pads?



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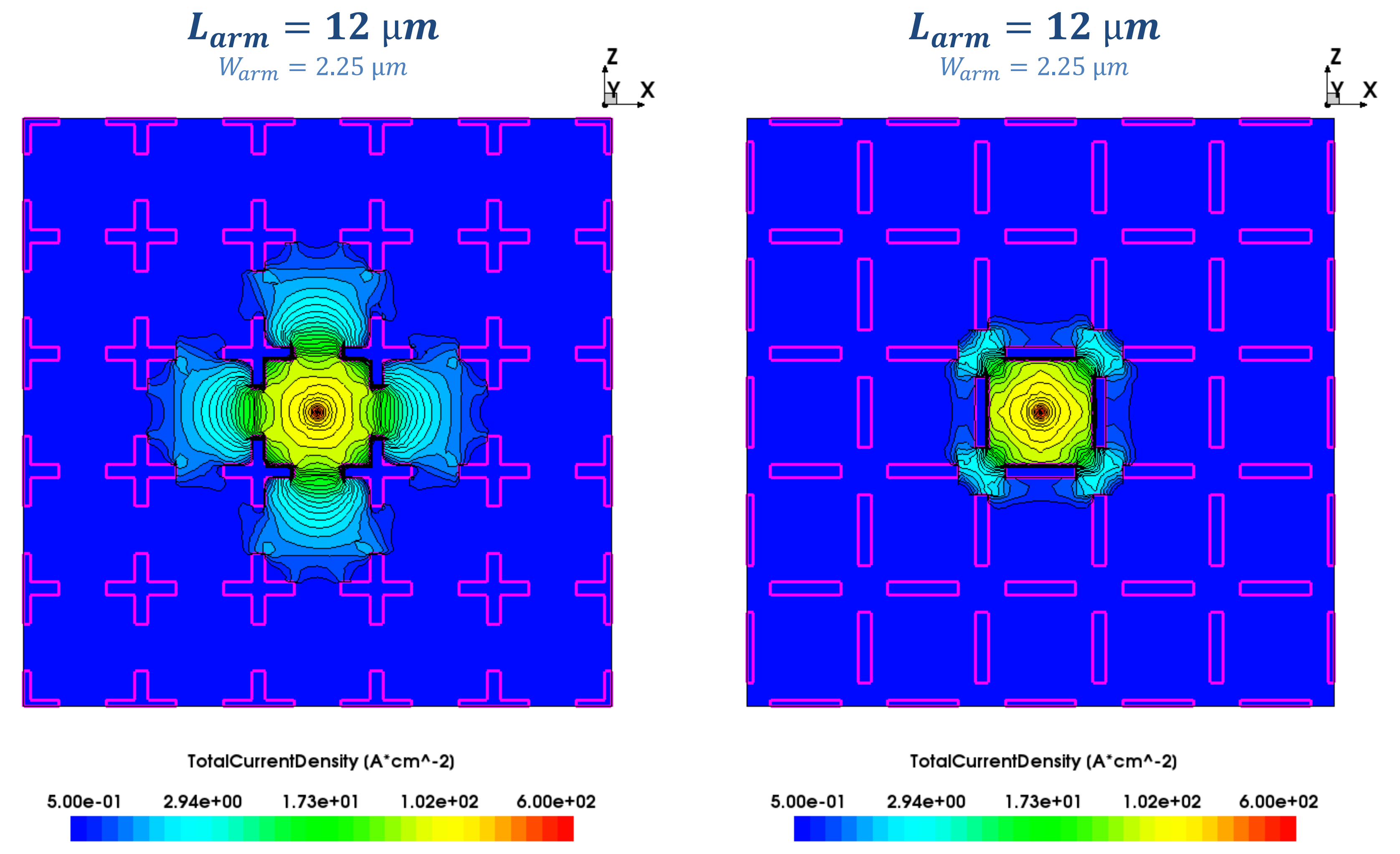

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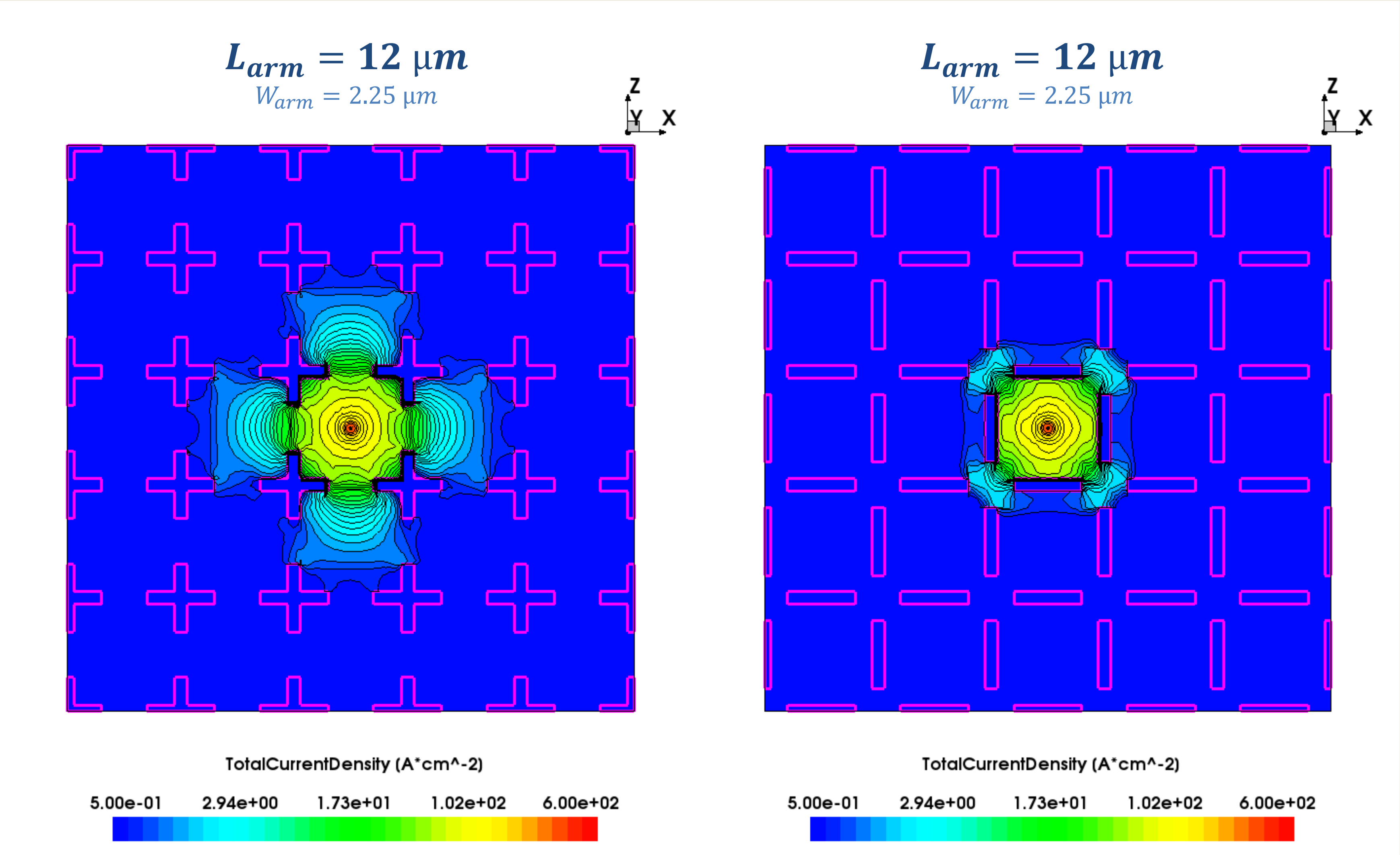
So cross or bar pads?



$L_{arm} = 12\ \mu m$

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$W_{arm} = 2.25\ \mu m$

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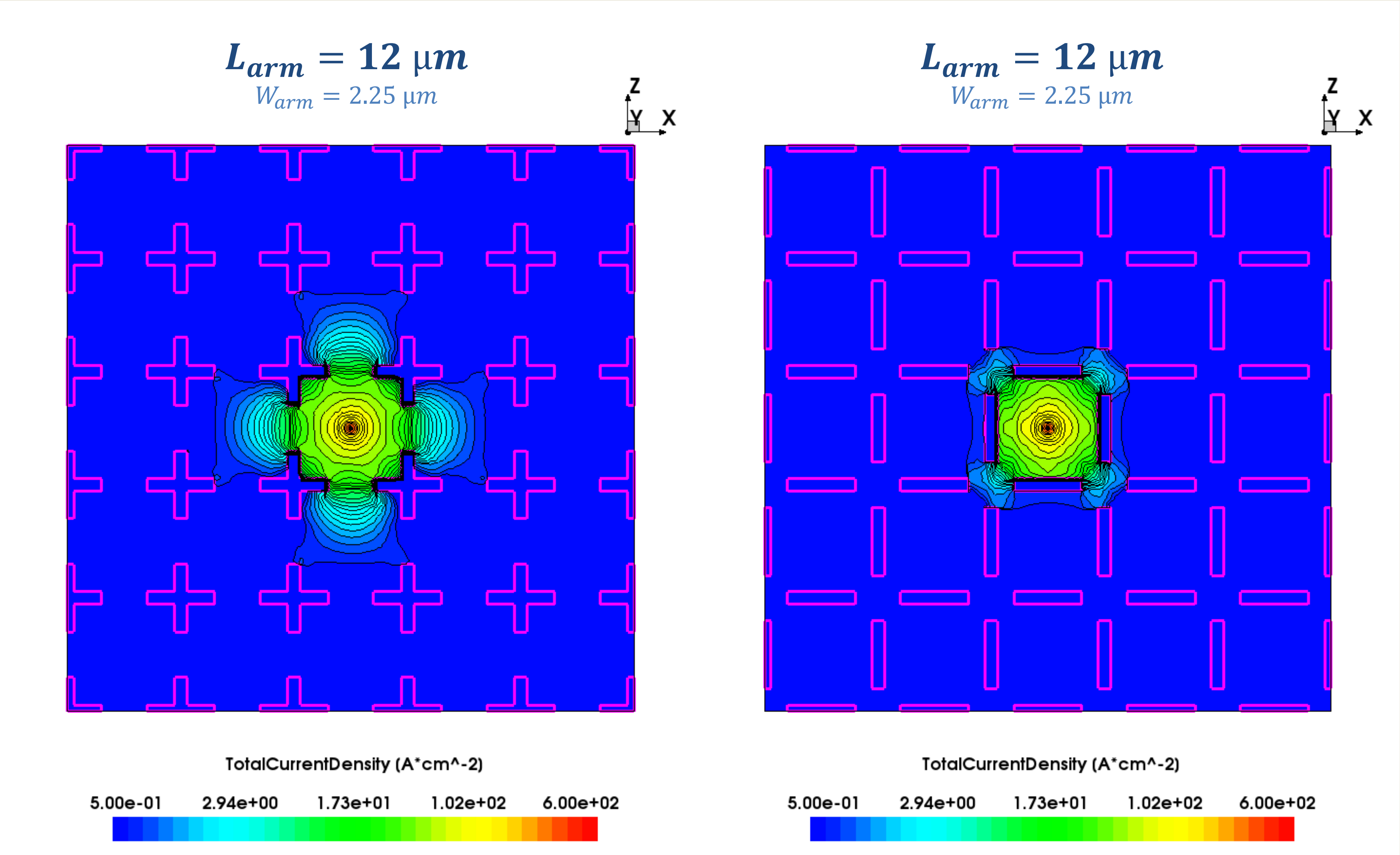

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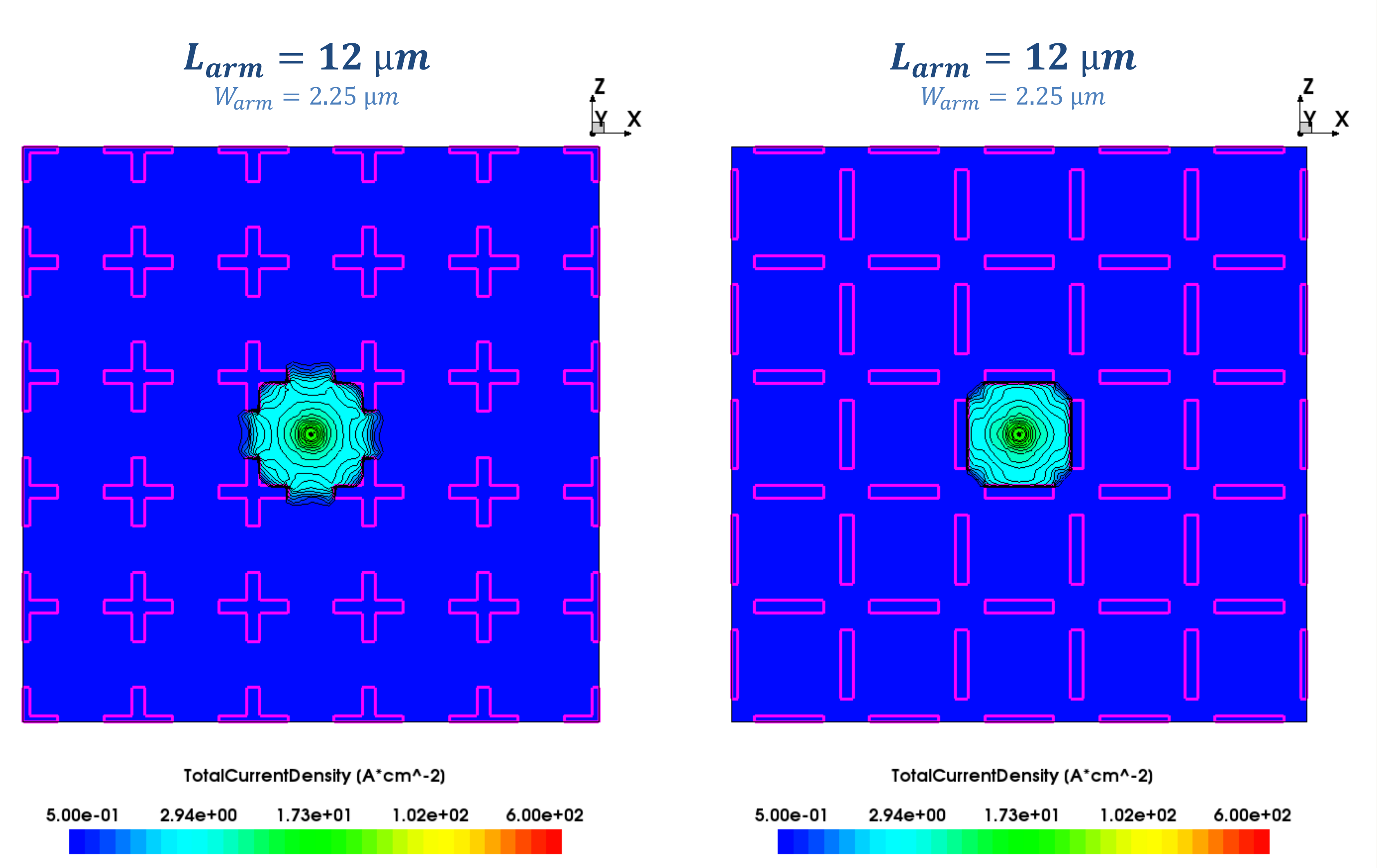
So cross or bar pads?



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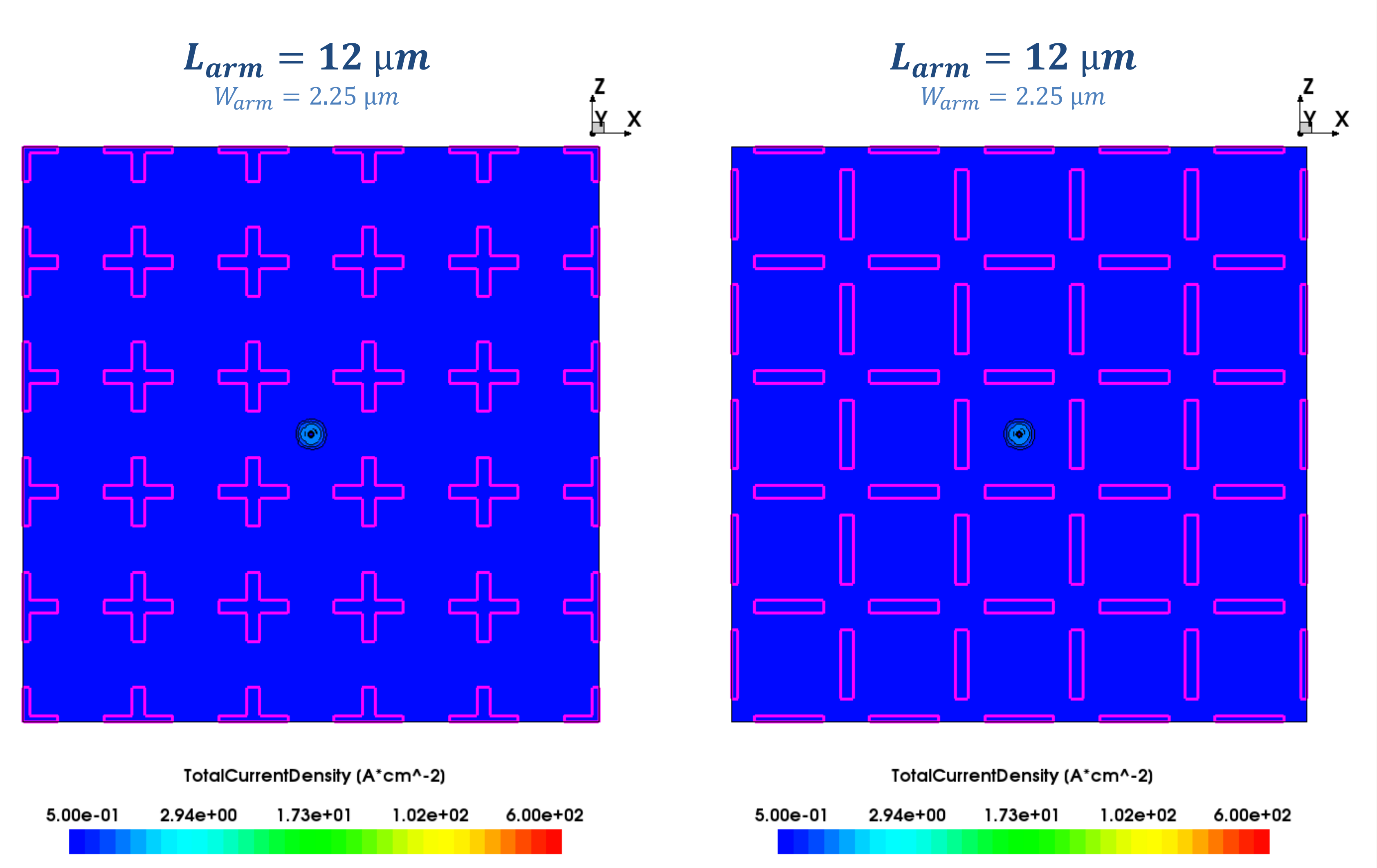
So cross or bar pads?



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Conclusions

- RSD LGAD, a new silicon sensor based on internal multiplication and built-in charge sharing;
- A promising solution to simultaneously meet all the specifications required for the next generation of colliders;
- DC coupling of electrodes (DC-RSD LGAD) for better control of charge sharing;
- TCAD simulations of multi-pixel structures to analyse different layout alternatives to limit charge sharing;
- The use of resistive strips between the electrodes is currently the best solution;
- Alternatives being studied, again using TCAD tools;
- A new batch of TCAD simulations taking into account the radiation damage effects.

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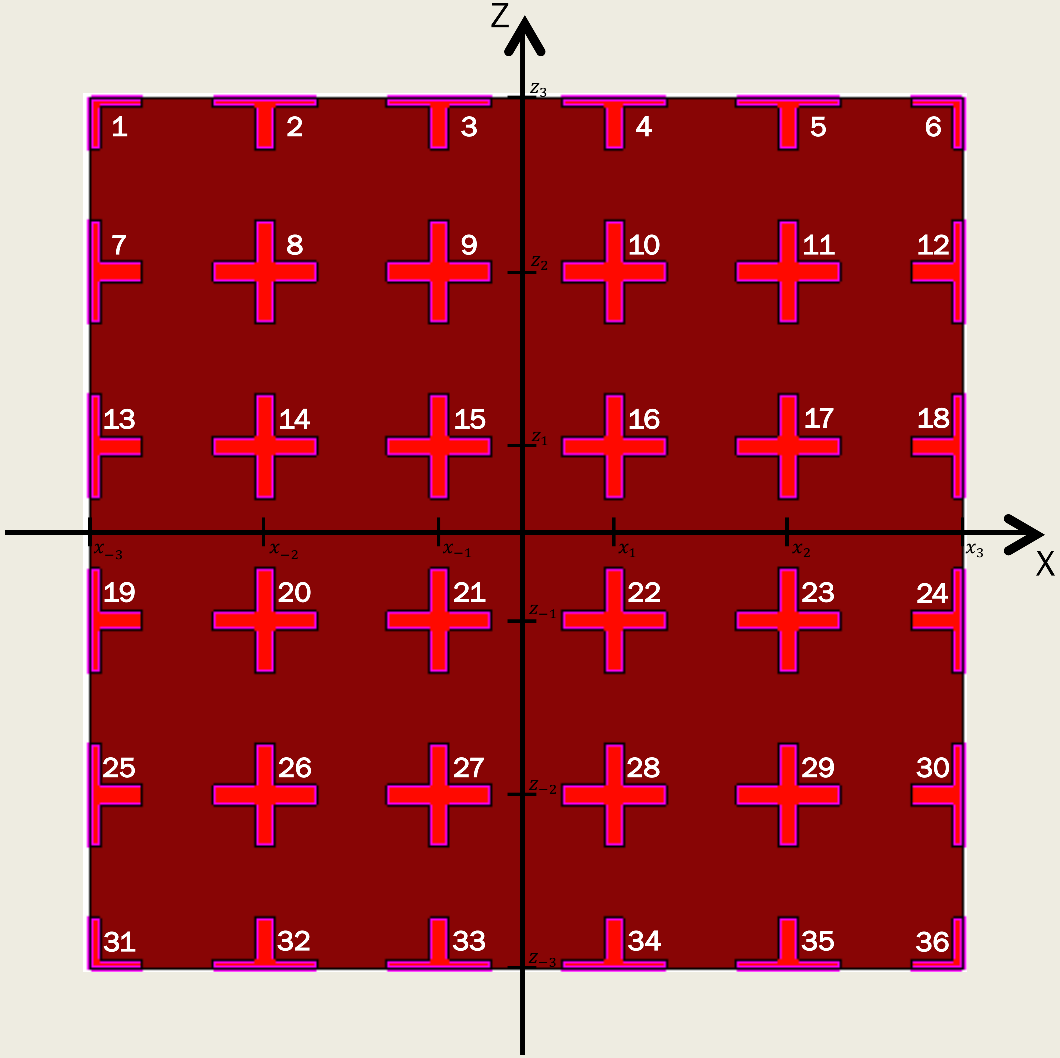
BACKUP

Charge centroid ~ Cross-shaped pads



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

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

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

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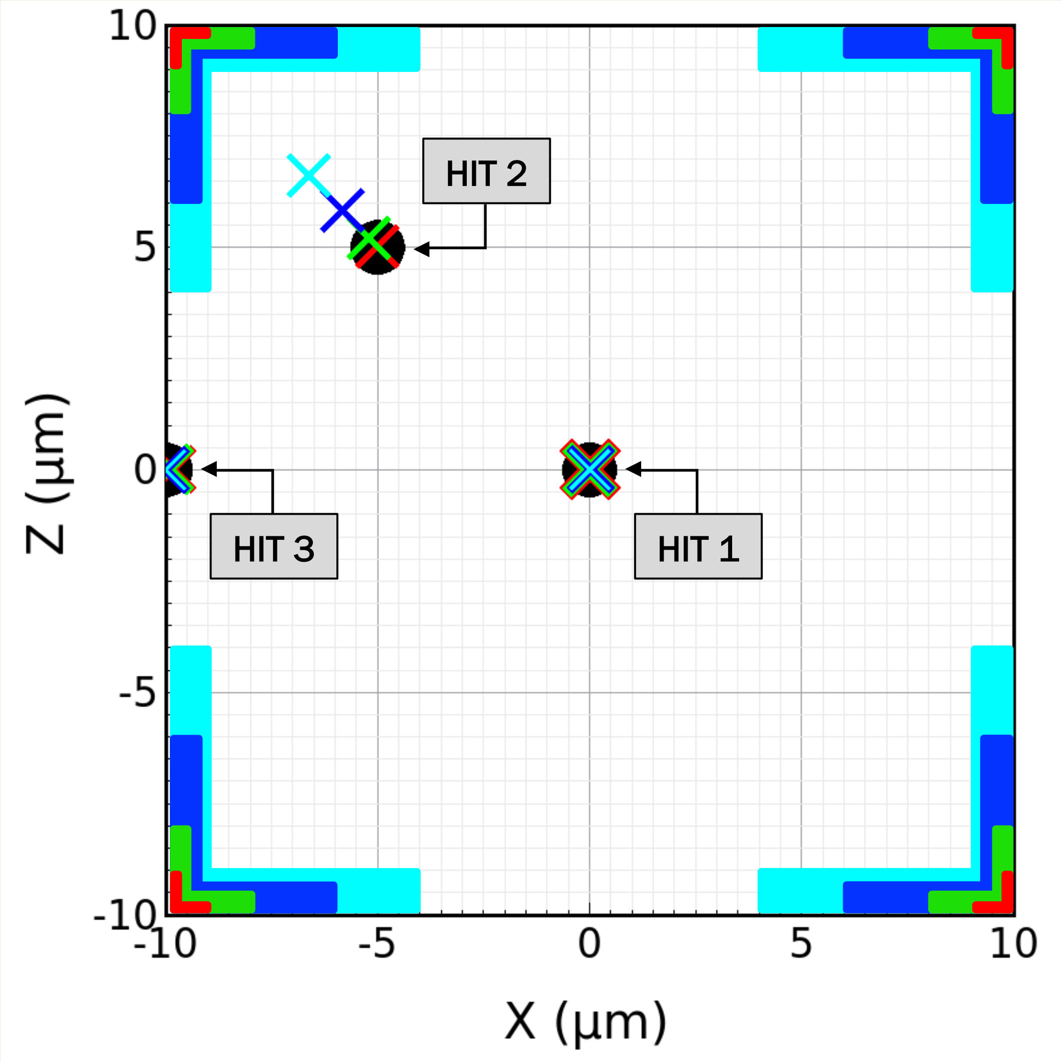
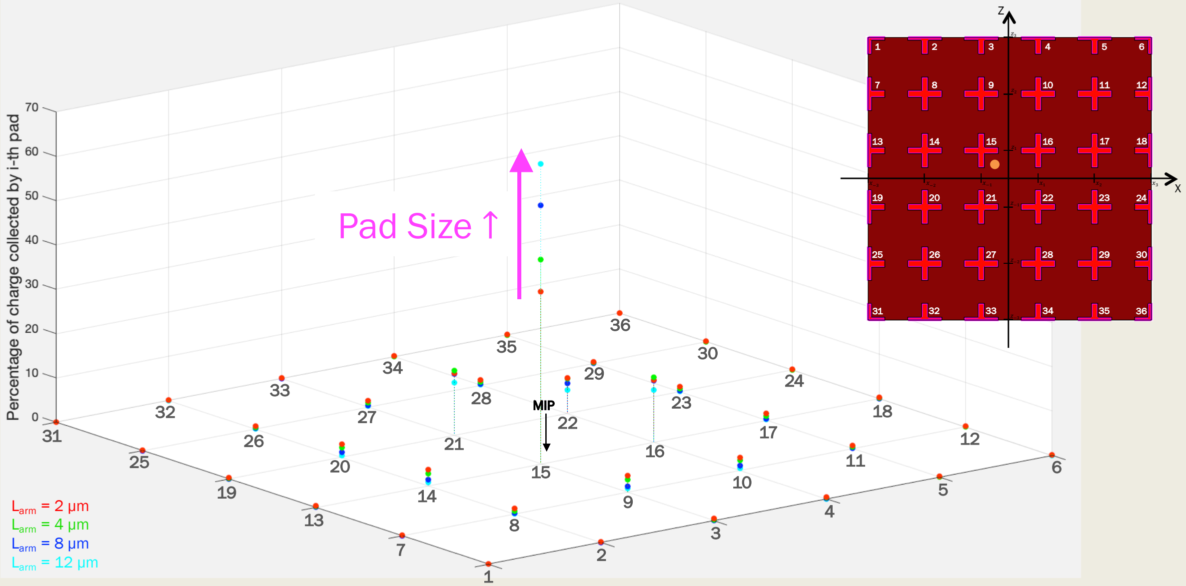
Cross-shaped pads

Position reconstruction using charge imbalance



- Simulation phases:
  - I. *polarization of the substrate contact at -200 V;*
  - II. *crossing of the device by a MIP (Heavy Ion model).*
- Temperature: 300 K;
- Avalanche model: Massey;
- New (non-irradiated) devices.



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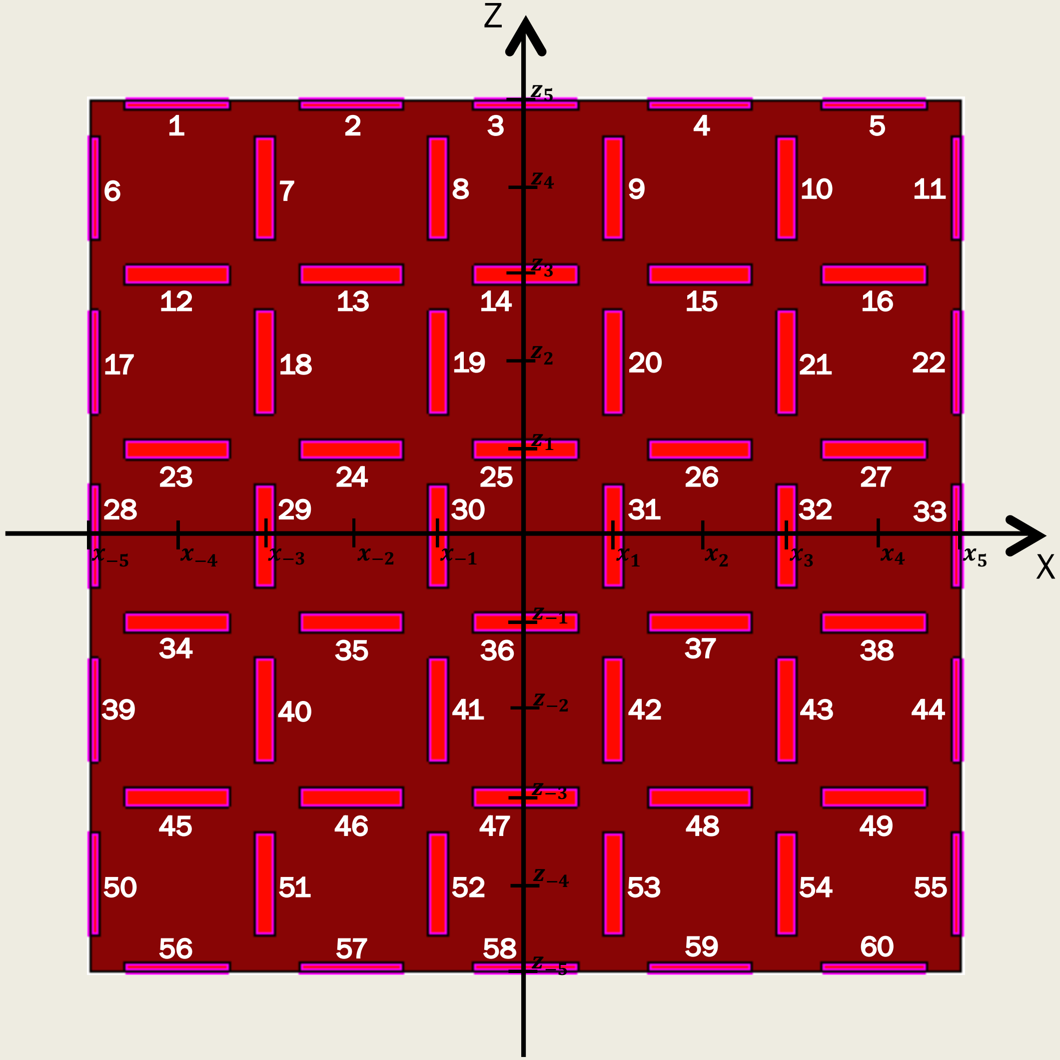
Charge centroid ~ Bar-shaped pads



X-coordinate

$Q_{x_{-5}} = Q_6 + Q_{17} + Q_{28} + Q_{39} + Q_{50}$

$Q_{x_{-4}} = Q_1 + Q_{12} + Q_{23} + Q_{34} + Q_{45} + Q_{56}$

$Q_{x_{-3}} = Q_7 + Q_{18} + Q_{29} + Q_{40} + Q_{51}$

$Q_{x_{-2}} = Q_2 + Q_{13} + Q_{24} + Q_{35} + Q_{46} + Q_{57}$

$Q_{x_{-1}} = Q_8 + Q_{19} + Q_{30} + Q_{41} + Q_{52}$

$Q_{x_1} = Q_9 + Q_{20} + Q_{31} + Q_{42} + Q_{53}$

$Q_{x_2} = Q_4 + Q_{15} + Q_{26} + Q_{37} + Q_{48} + Q_{59}$

$Q_{x_3} = Q_{10} + Q_{21} + Q_{32} + Q_{43} + Q_{54}$

$Q_{x_4} = Q_5 + Q_{16} + Q_{27} + Q_{38} + Q_{49} + Q_{60}$

$Q_{x_5} = Q_{11} + Q_{22} + Q_{33} + Q_{44} + Q_{55}$

$$X_R = \frac{\sum_{\substack{i=-5 \\ i\neq 0}}^{5} Q_{x_i} \cdot x_i}{\sum_{i=1}^{60} Q_i}$$

Z-coordinate

$Q_{z_{-5}} = Q_{56} + Q_{57} + Q_{58} + Q_{59} + Q_{60}$

$Q_{z_{-4}} = Q_{50} + Q_{51} + Q_{52} + Q_{53} + Q_{54} + Q_{55}$

$Q_{z_{-3}} = Q_{45} + Q_{46} + Q_{47} + Q_{48} + Q_{49}$

$Q_{z_{-2}} = Q_{39} + Q_{40} + Q_{41} + Q_{42} + Q_{43} + Q_{44}$

$Q_{z_{-1}} = Q_{34} + Q_{35} + Q_{36} + Q_{37} + Q_{38}$

$Q_{z_1} = Q_{23} + Q_{24} + Q_{25} + Q_{26} + Q_{27}$

$Q_{z_2} = Q_{17} + Q_{18} + Q_{19} + Q_{20} + Q_{21} + Q_{22}$

$Q_{z_3} = Q_{12} + Q_{13} + Q_{14} + Q_{15} + Q_{16}$

$Q_{z_4} = Q_6 + Q_7 + Q_8 + Q_9 + Q_{10} + Q_{11}$

$Q_{z_5} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$

$$Z_R = \frac{\sum_{\substack{i=-5 \\ i\neq 0}}^{5} Q_{z_i} \cdot z_i}{\sum_{i=1}^{60} Q_i}$$

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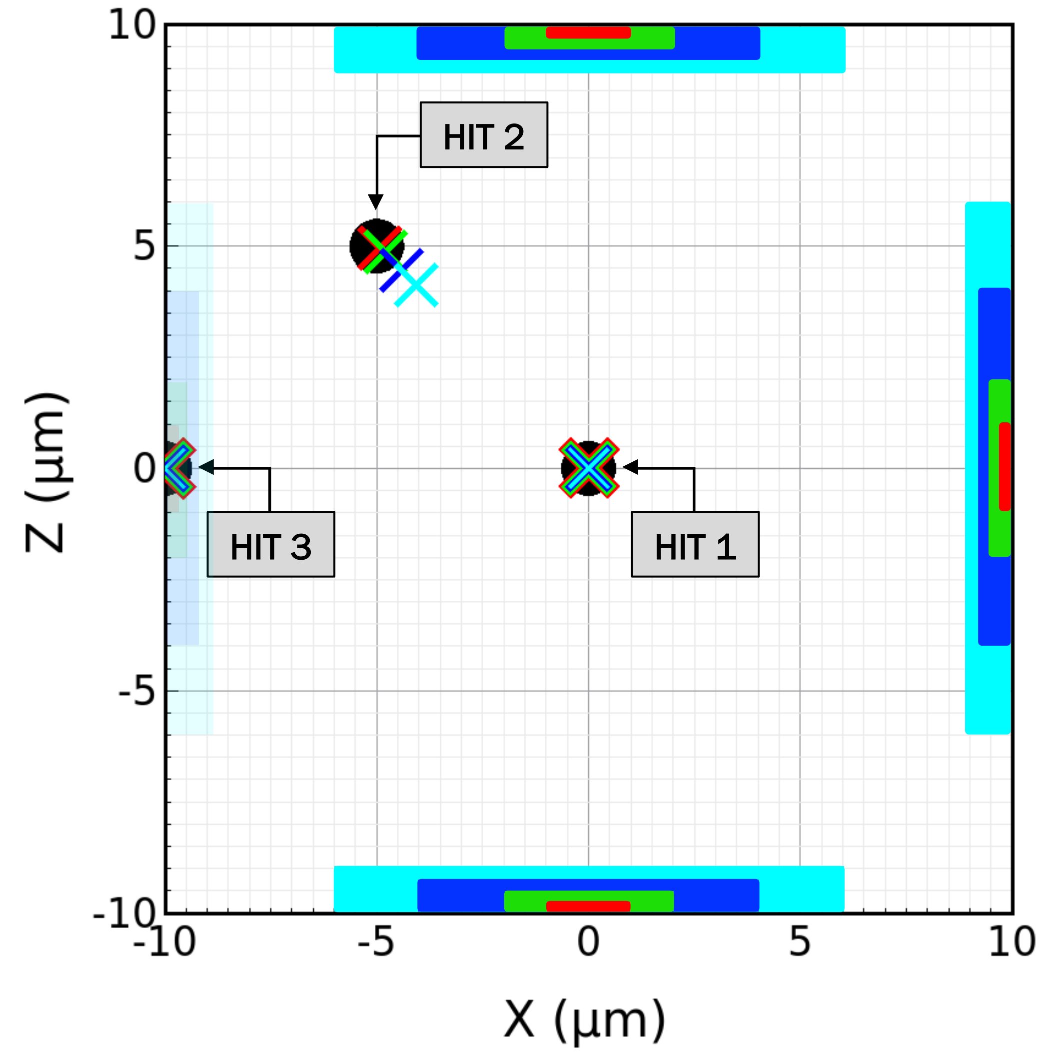
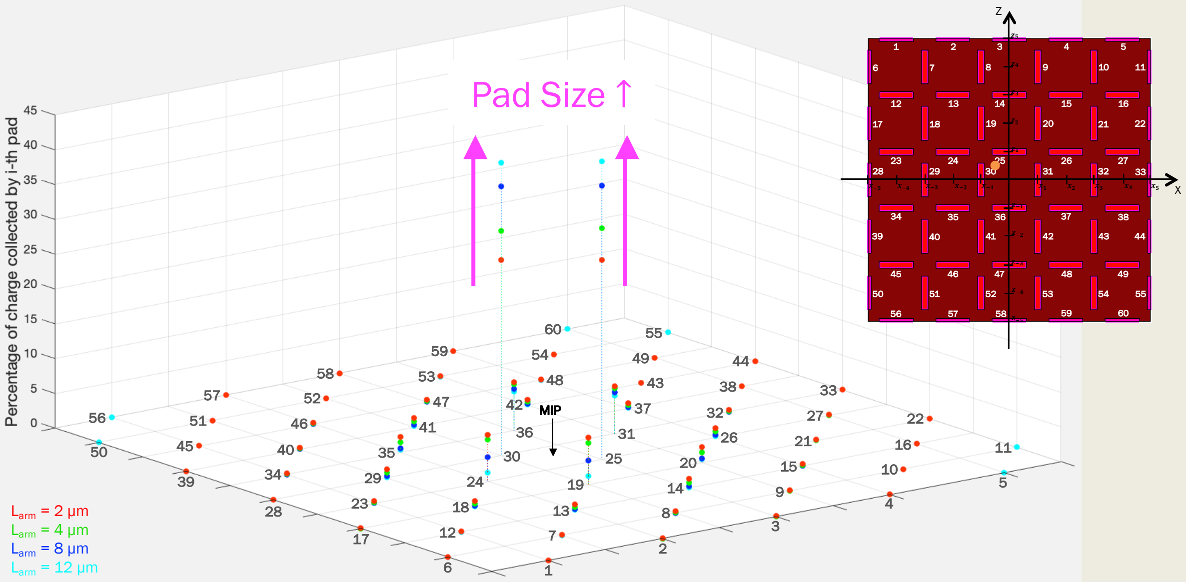
Position reconstruction using charge imbalance



- Simulation phases:
  - *I. polarization of the substrate contact at -200 V;*
  - *II. crossing of the device by a MIP (Heavy Ion model).*
- Temperature: 300 K;
- Avalanche model: Massey;
- New (non-irradiated) devices.



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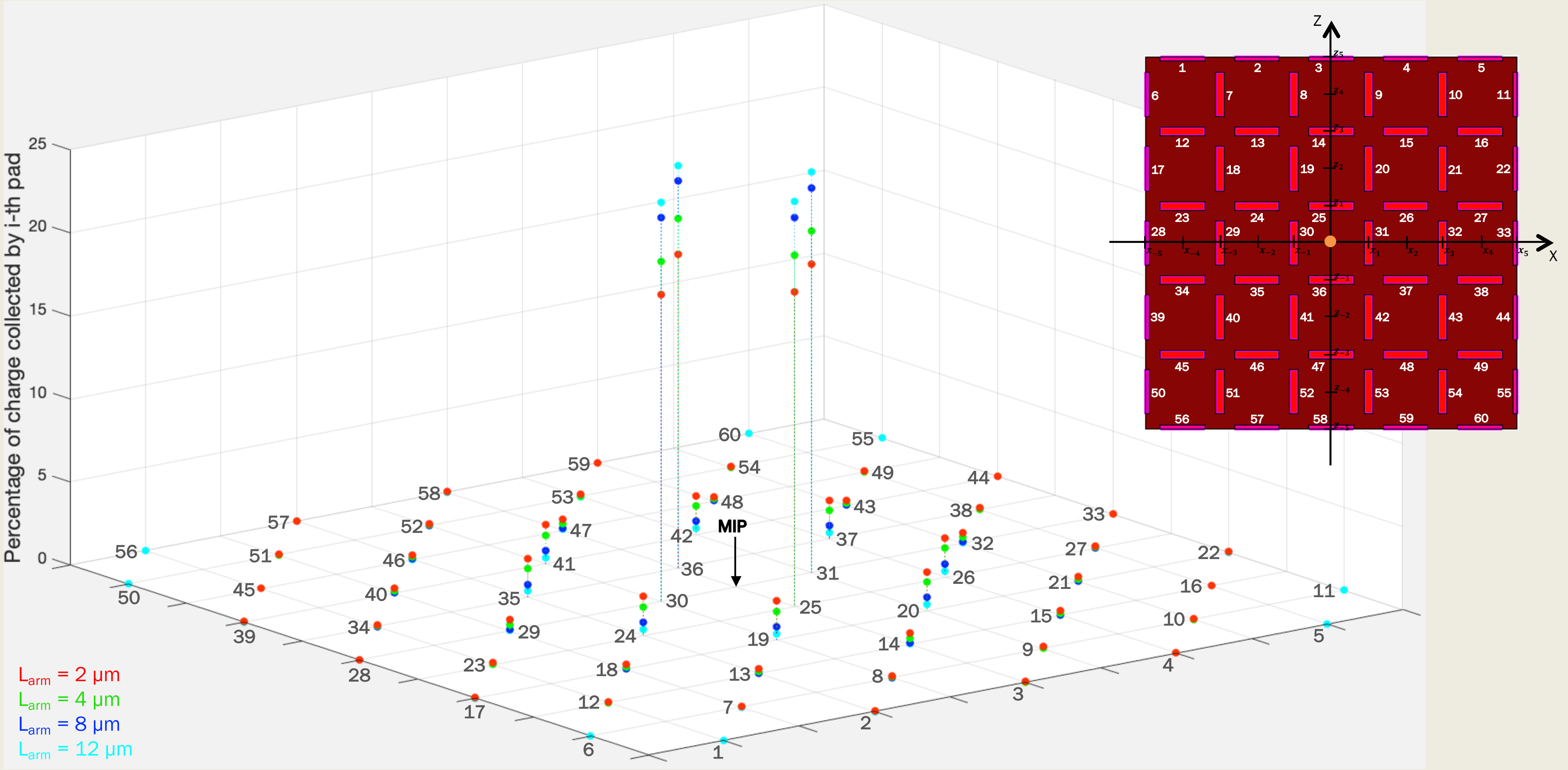
Distribution of collected charge between pads as a function of their size

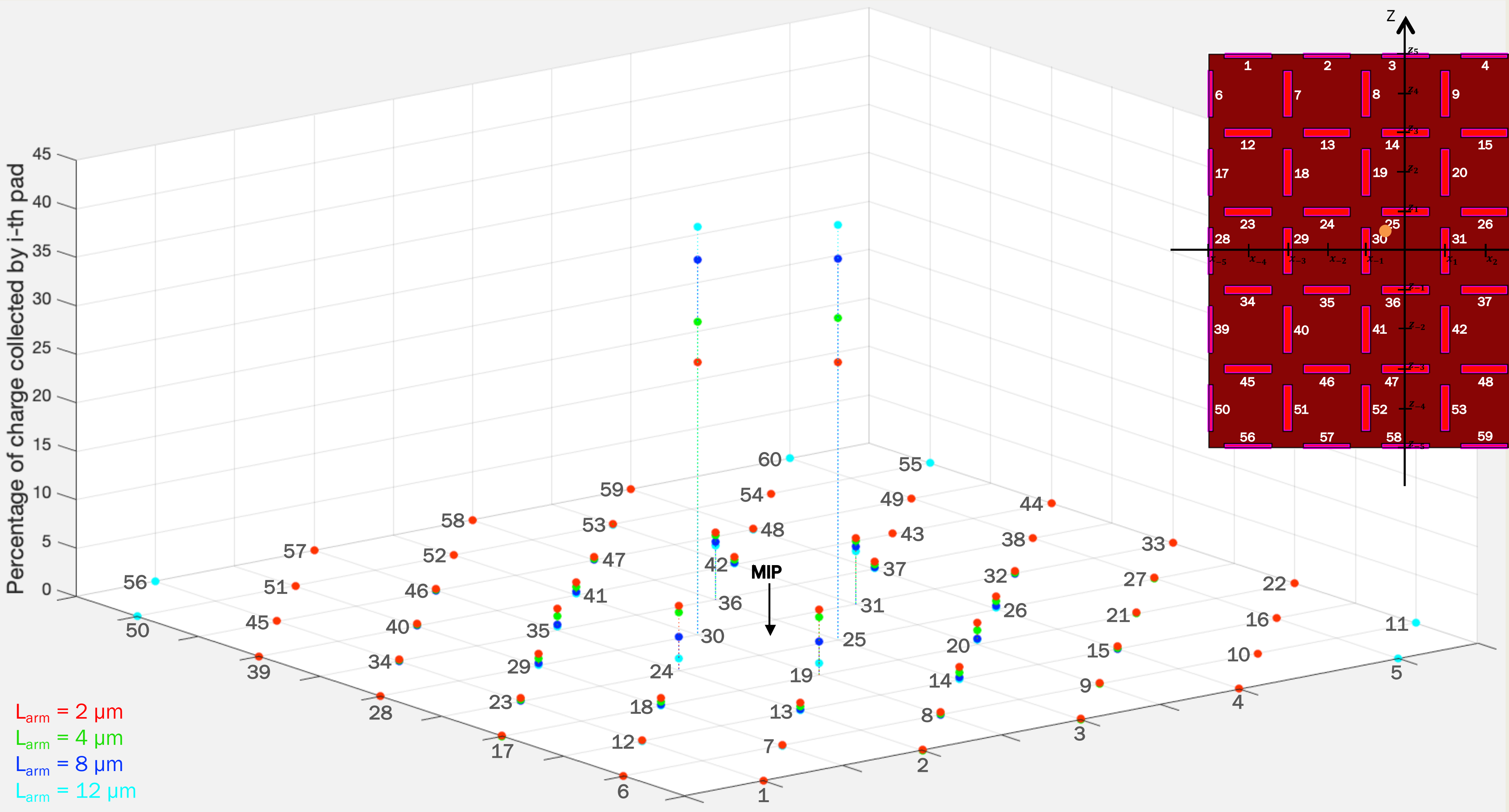


Bar-shaped pads

DC-RSD LGAD

HIT 2

Distribution of collected charge between pads as a function of their size



A. Fondacci et al., FAST 2023 - May 29, 2023

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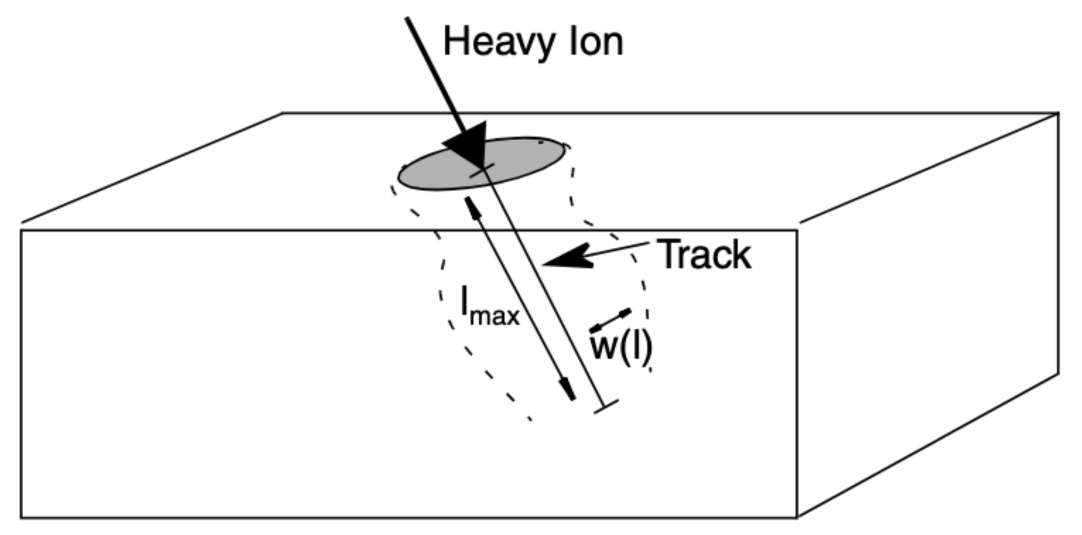
Sentaurus Device manual

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

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