# 41st RD50 Workshop

Radiation hard semiconductor devices for very high luminosity colliders

# A two-prong Approach to the Simulation of DC-RSD: TCAD and Spice


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# Outline

- Innovations in the design of silicon sensors (LGAD + RSD)
- Simulation of DC-RSD devices
  - Spice (circuit level)
  - TCAD (device level)
- Reconstruction of the particle impact positions
  - Spatial resolution analysis
- Design and optimization of DC-RSD


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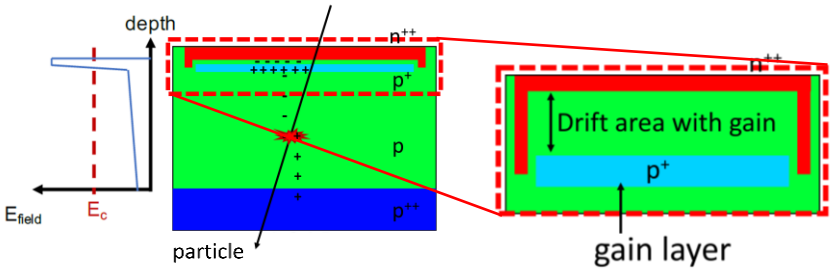
# Innovations in the design of silicon sensors (1/2)

## Low-Gain Avalanche Diode (LGAD)



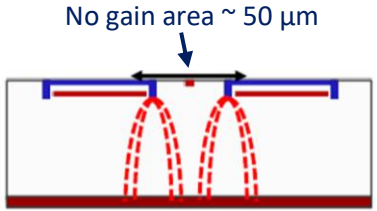

### PRO ☺

- ✓ **Internal low-gain**
  - ⇒ large signals & low noise
  - ⇒ excellent temporal precision

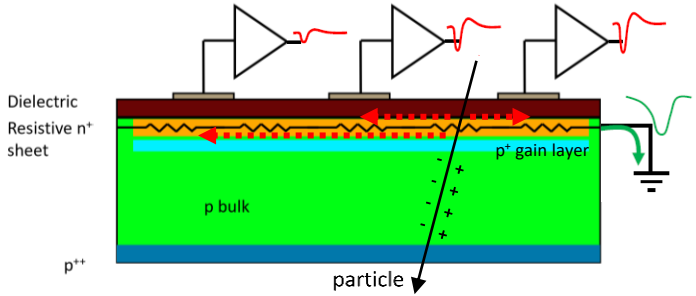
Ideal for timing

### CONS ☹

- ✓ **Segmentation**
  - ⇒ fill factor < 100%
  - ⇒ low spatial precision




## Resistive Silicon Detector (RSD or AC-LGAD)




### PRO ☺

- ✓ **Internal low-gain**
  - ⇒ excellent temporal precision

Ideal for timing

- ✓ **Resistive read-out**
  - ⇒ signal sharing
  - ⇒ 100% fill factor
  - ⇒ excellent spatial precision

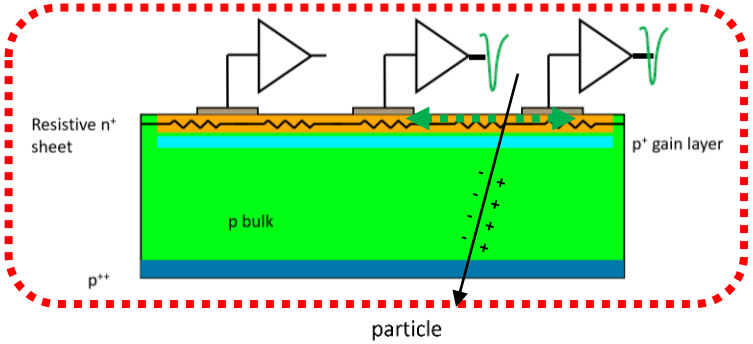
Ideal for position resolution

### CONS ☹

- ✓ **AC-coupled read-out**
  - ⇒ long-tail bipolar signals
  - ⇒ baseline fluctuation
  - ⇒ position-dependent resolution
  - ⇒ not easily scalable to large area sensors

# Innovations in the design of silicon sensors (2/2)

## DC-coupled RSD (DC-RSD)




Ideal for timing

✓**Internal low-gain**
⇒ excellent temporal precision

Ideal for position resolution

✓**Resistive read-out**
⇒ excellent spatial precision

✓**DC-coupled read-out**
⇒ unipolar signals
⇒ absence of baseline fluctuation
⇒ controlled charge sharing
⇒ large sensitive areas (~ cm)

# Simulation of DC-RSD devices

- ✓ **Issue**: **charge sharing** over **large distances** (~mm)
- ✓ **Hybrid** simulation **approach**

**Spice** + **TCAD**

✓ **Circuit level**

⇒ Fast simulations

⇒ High abstraction level

⇒ Proof of principle, but limited information

✓ **Device level**

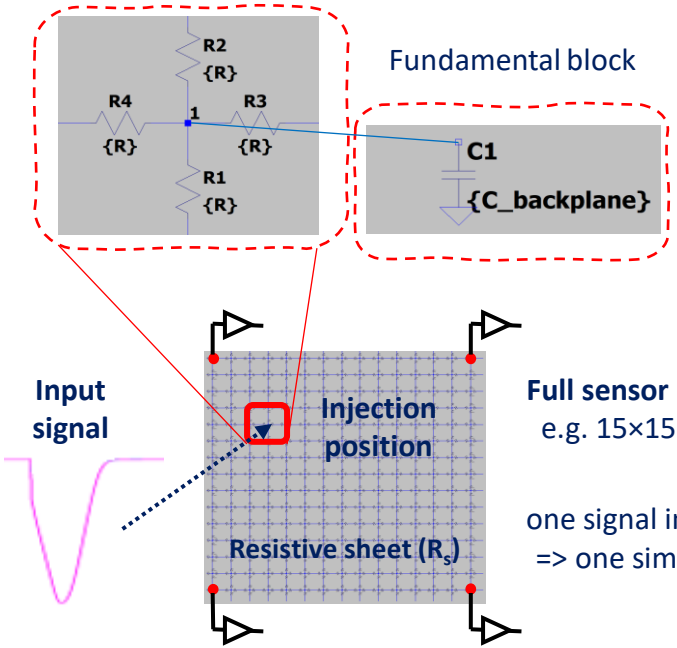
⇒ High accuracy, but time consuming

⇒ Added values

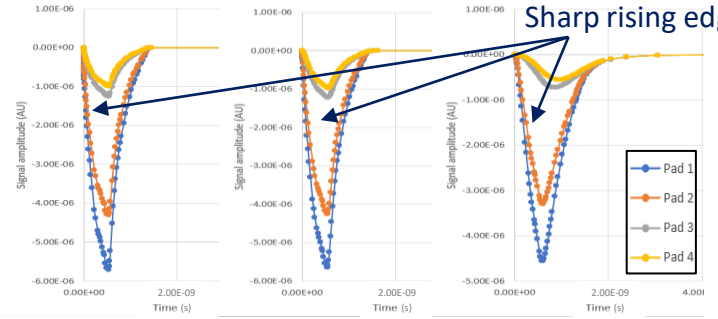
1. technological/design optimization
2. accurate modelling of particle hit (position, energy deposition)
3. radiation damage effects

# Spice simulation (1/2)

✓ Equivalent lumped-element electrical model

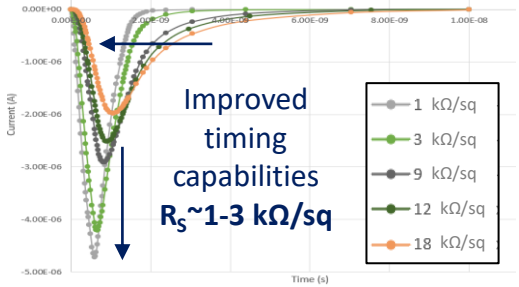



**Output waveforms** for different pitch sizes




133 µm-pitch 340 µm-pitch 1020 µm-pitch

**Signal shape** for different $R_S$



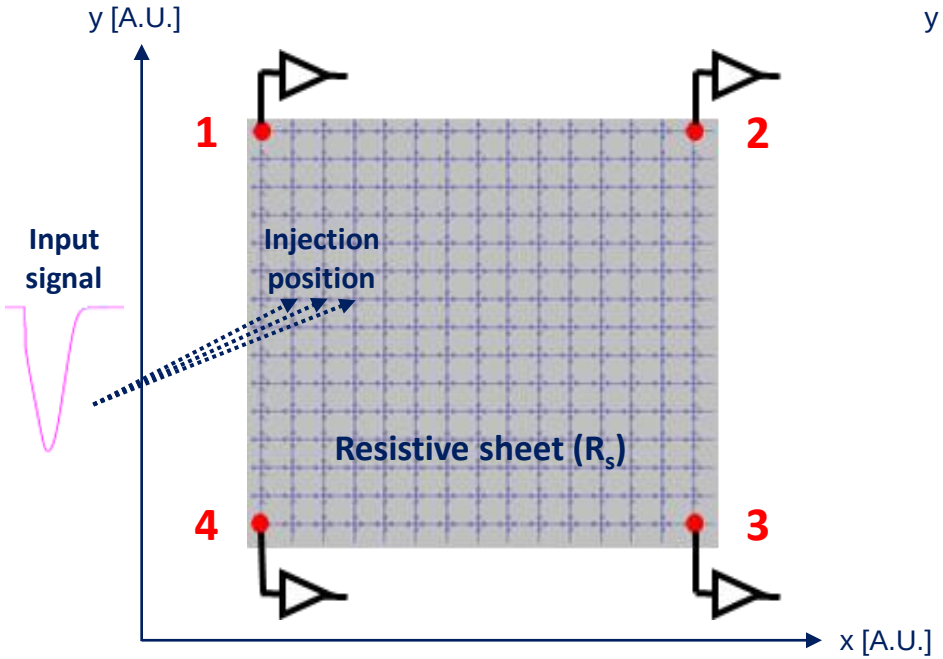

1020 µm-pitch

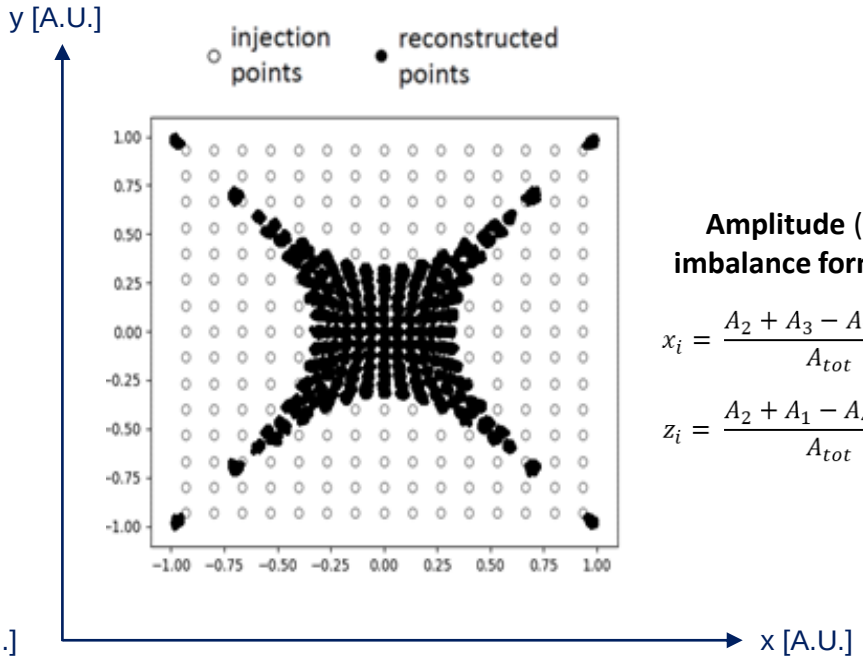
**Very short simulation times!!!**

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

# Spice simulation (2/2)

✓ **Reconstruction** of the **particle impact positions**




**Amplitude** (A) **imbalance formula**

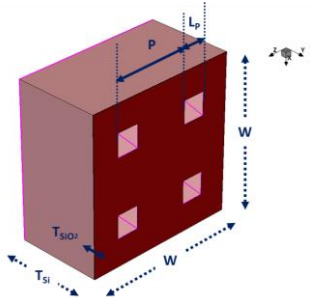
$$x_i = \frac{A_2 + A_3 - A_1 - A_4}{A_{tot}}$$

$$z_i = \frac{A_2 + A_1 - A_4 - A_3}{A_{tot}}$$

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

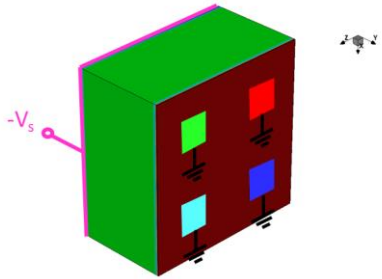
# TCAD simulation (1/3)

## ✓ Simulated **layout** (full 3D geometry)



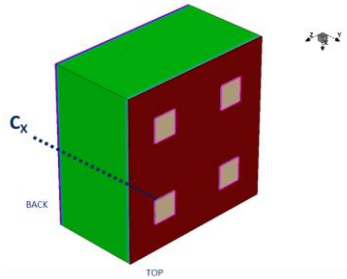

- Width (W) 100 µm
- Thickness (T) 55 µm
- Pad Length ($L_P$) 15 µm
- Pitch (P) 50 µm

## ✓ **Biasing** condition (inverse region)




- ❑ **BACK => $-V_s$**
- ❑ **PAD1 => GND**
- ❑ **PAD2 => GND**
- ❑ **PAD3 => GND**
- ❑ **PAD4 => GND**

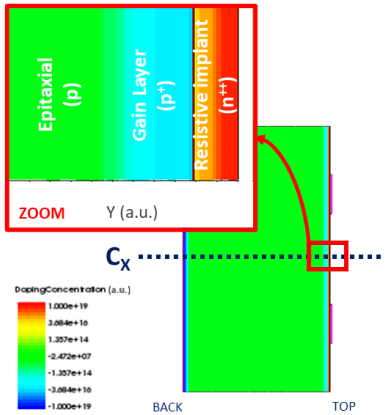
## ✓ Simulated **doping profile** (LGAD)

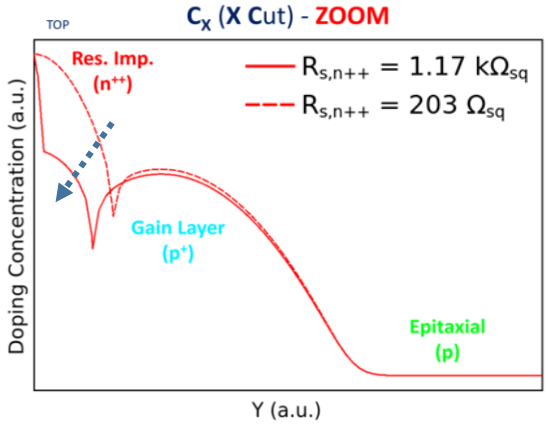



**Sheet resistance**

$$R_S = \frac{\rho_{Si\,n}}{t} \; [\Omega_{sq}]$$

$$\rho_{Si,n} = \frac{1}{q\mu_n(N_D - N_A)} \; [\Omega\mu m]$$





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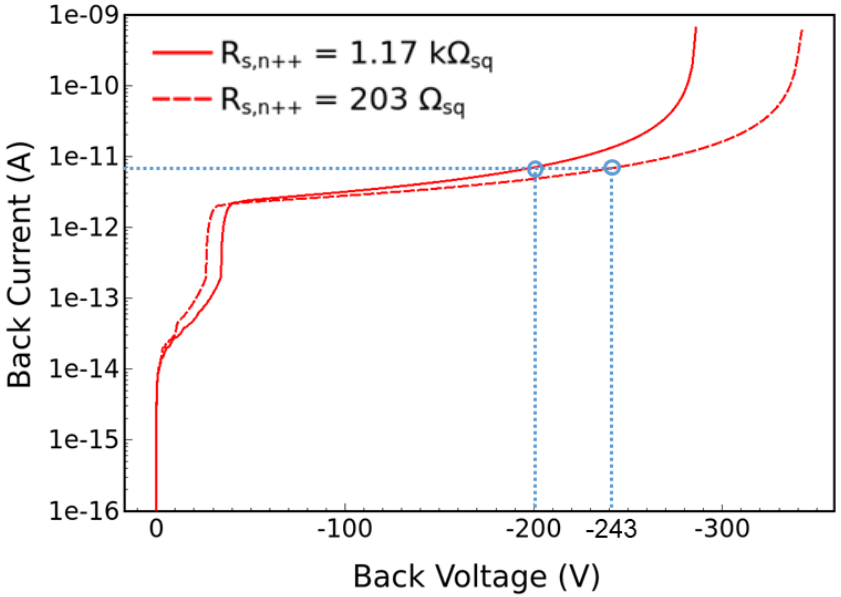
# TCAD simulation (2/3)

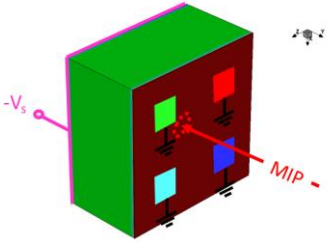
✓ **Static** (DC) behaviour

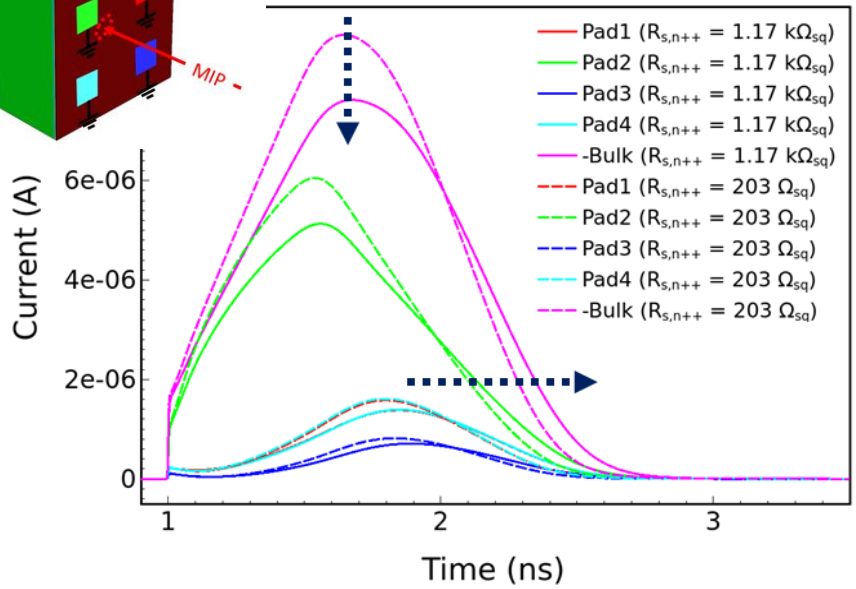
**I-V,** not irr.




✓ **Transient** (TV) behaviour

**I-t,** not irr. (ZOOM)




Avalanche model: **Massey**. Temperature **300 K**. Minimum Ionizing Particle (**MIP**)

**$R_{s,n++}$ ≈ 203 $\Omega_{sq}$ ---> $R_{s,n++}$ ≈ 1,17 k$\Omega_{sq}$**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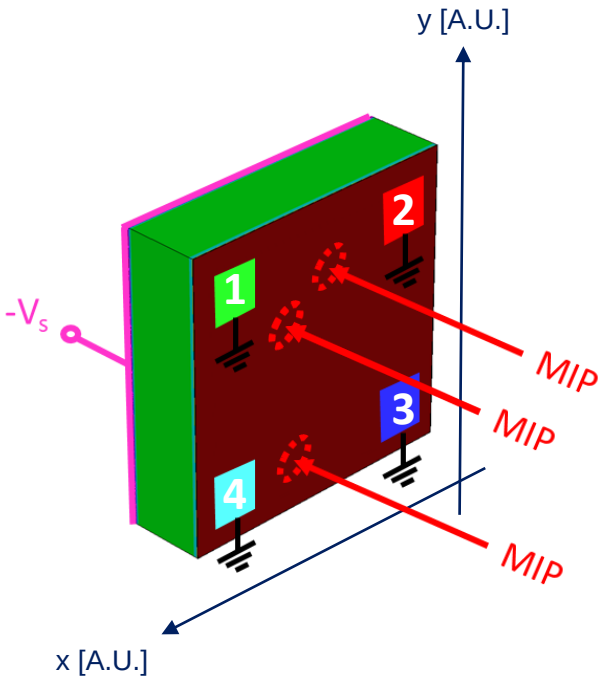
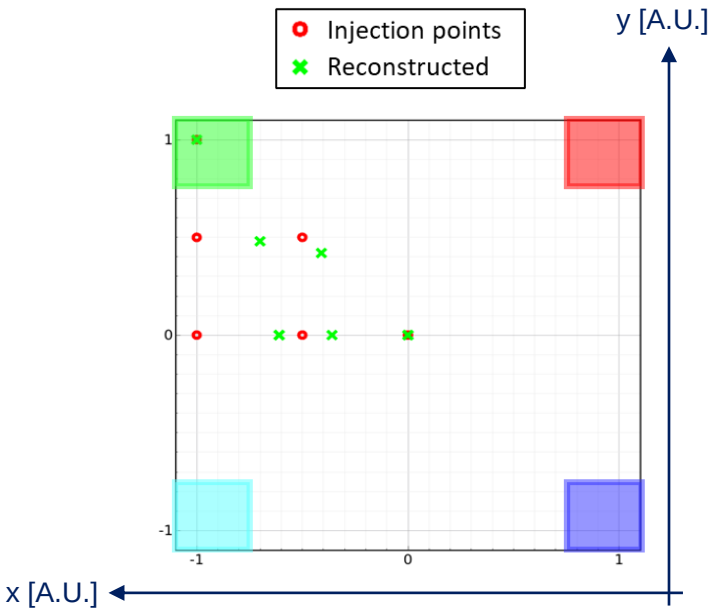
# TCAD simulation (3/3)

✓ **Reconstruction** of the **particle impact positions**




**Charge (Q) imbalance formula**

$$x_i = \frac{Q_2 + Q_3 - Q_1 - Q_4}{Q_{tot}}$$

$$z_i = \frac{Q_2 + Q_1 - Q_4 - Q_3}{Q_{tot}}$$



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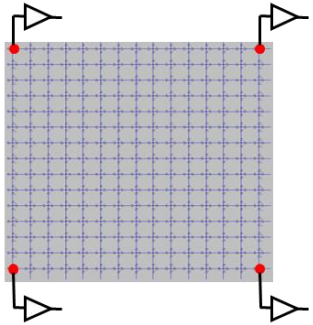
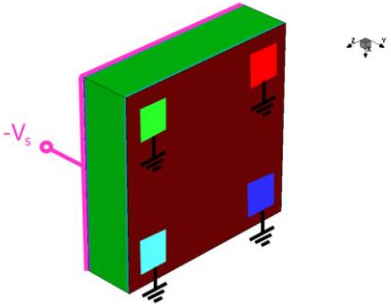
# Reconstruction of the impact positions

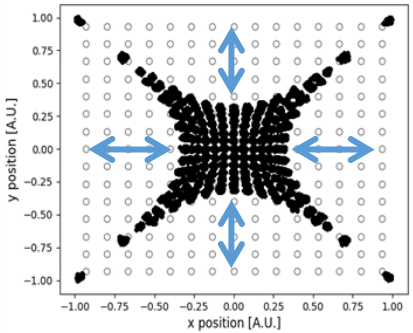
**Results** from *Spice* simulations **VS.** **Results** from *TCAD* simulations



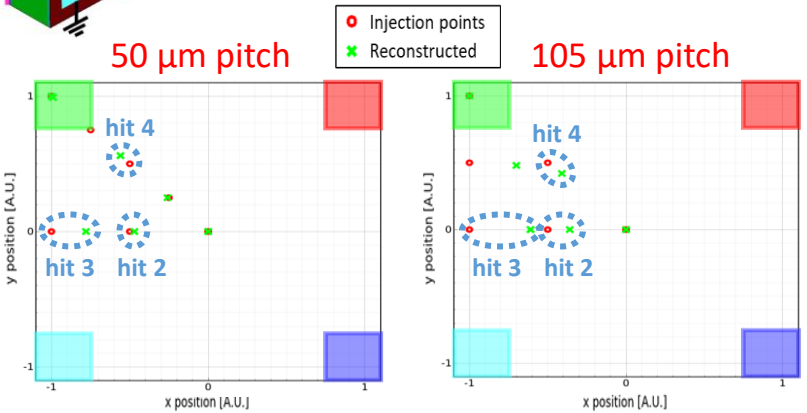
The **reconstructed points** tend to **cluster in the centre.** Such **distortion** is **typical of resistive devices** [*]




The **larger** the **pitch size**, the **higher** the **distortion**



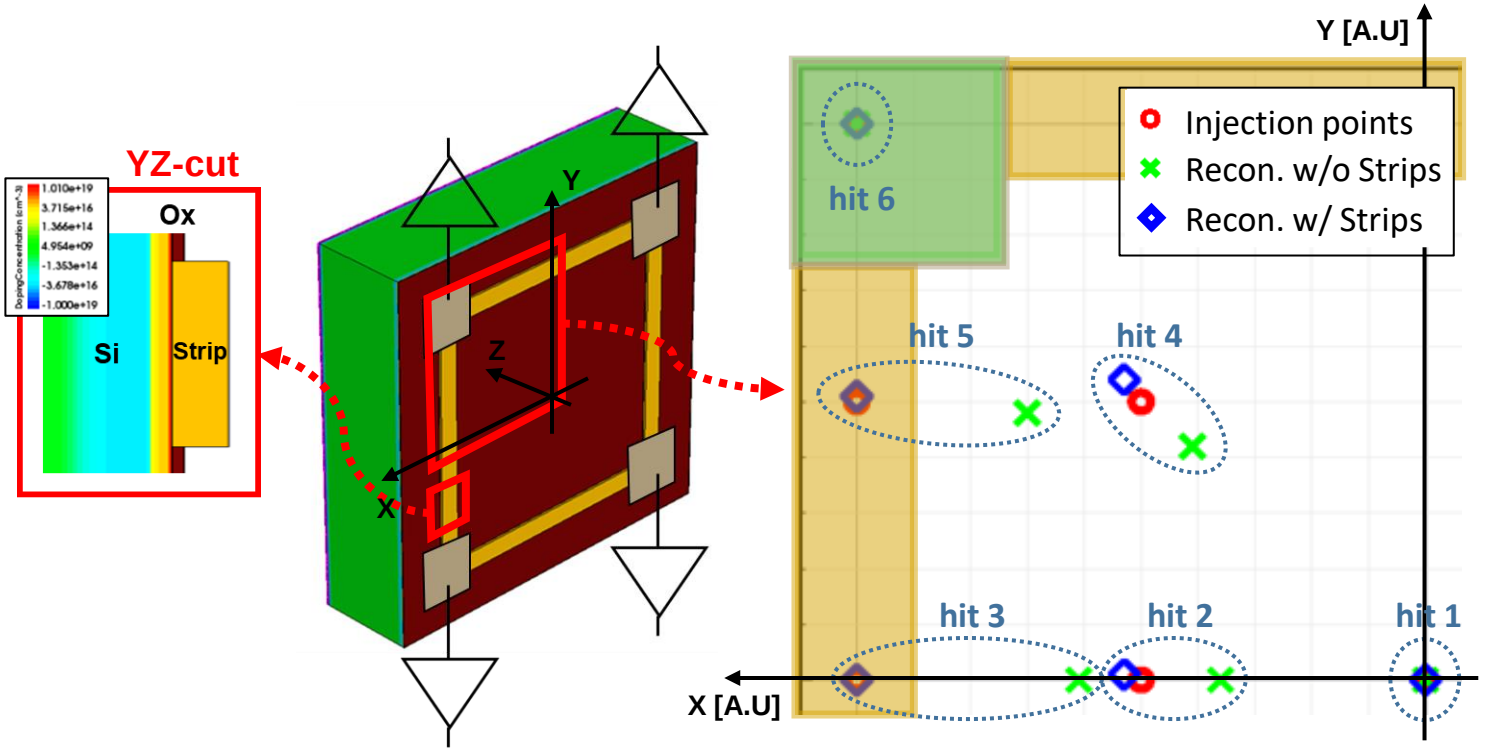

- injection points
- reconstructed points




[*] H. Wagner et al., *On the dynamic two-dimensional charge diffusion of the interpolating readout structure employed in the MicroCAT detector*, Nuclear Instr. Meth. in Phys. Res. A, Vol. 482, 2002.

# Design and optimization of DC-RSD

✓ **Reduced distortion** by adding **resistive strips** between the read-out pads





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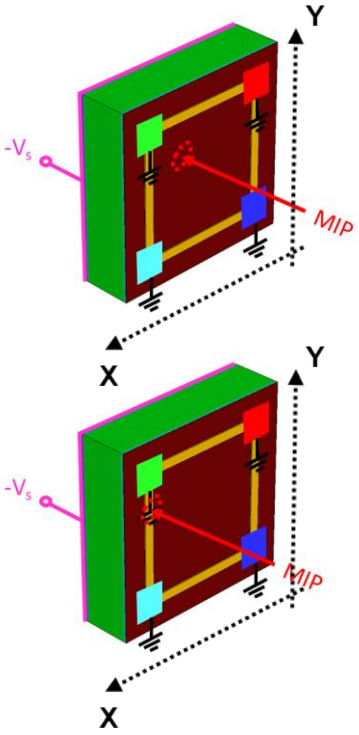
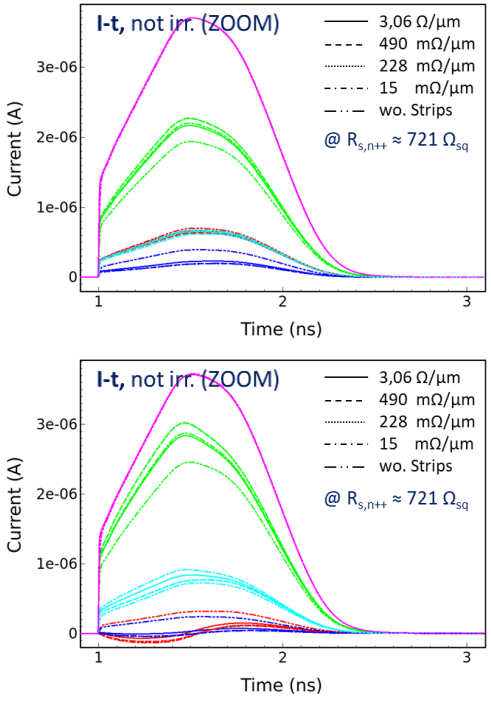
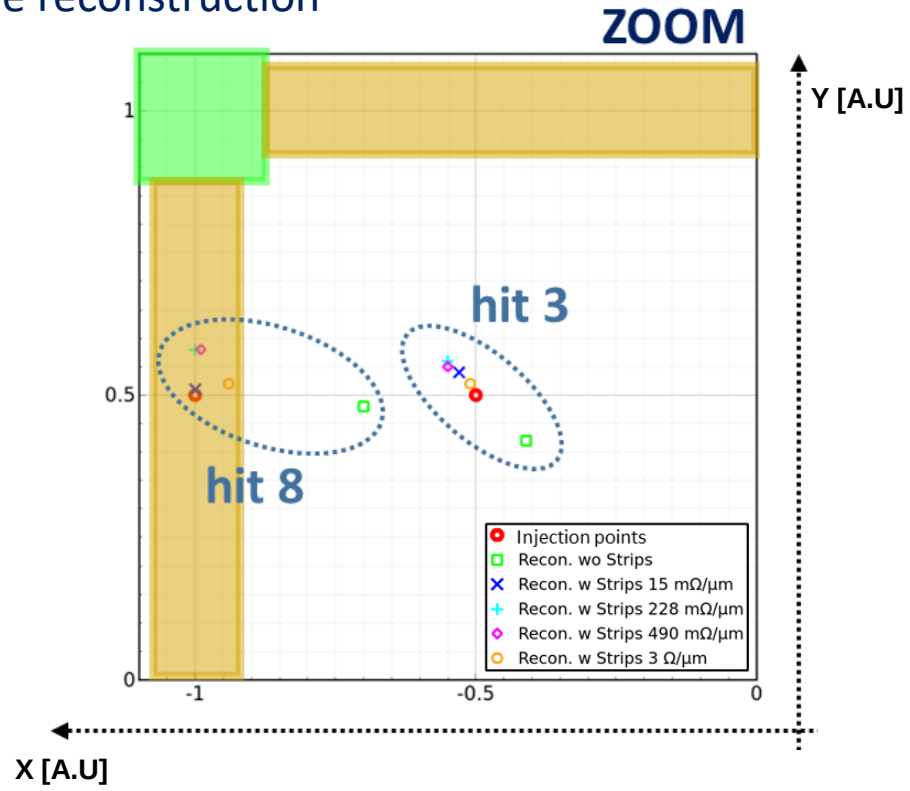
# Design and optimization of DC-RSD

- ✓ Impact of different **strip resistivity ($R_{Strip}$)** on the reconstruction

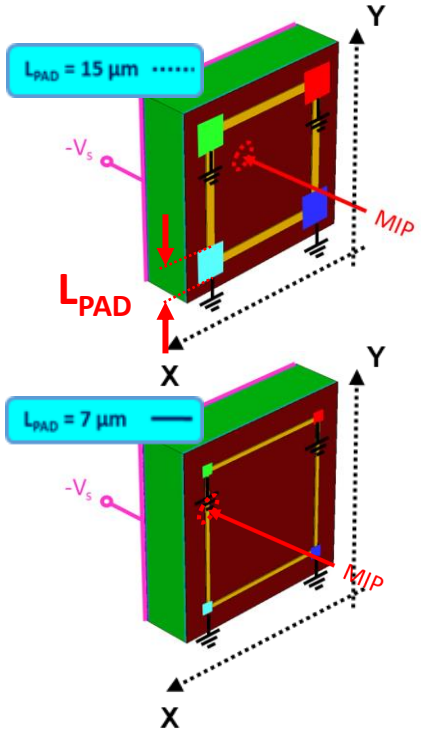


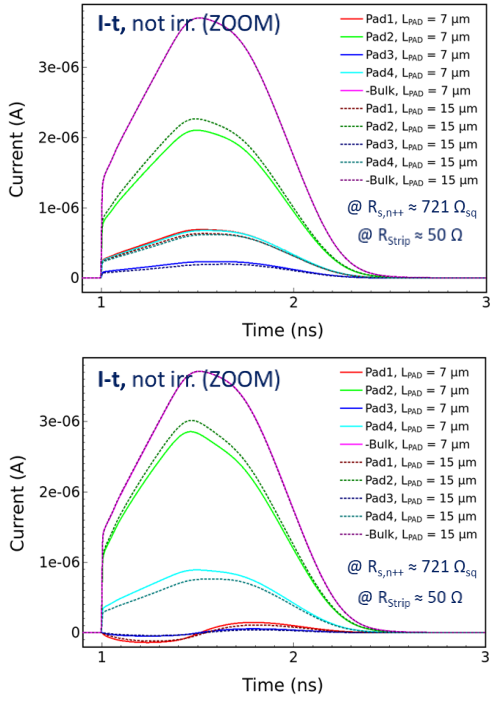



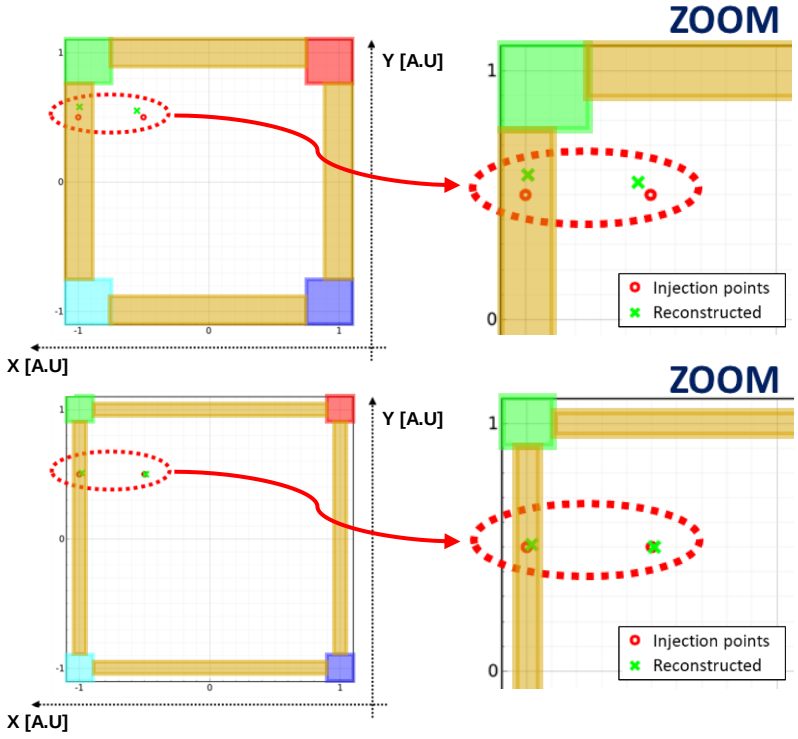



# Design and optimization of DC-RSD

✓ Impact of the **pad size ($L_{PAD}$)** on the reconstruction



# Conclusions

- ✓ **Novel evolution** of the **LGAD resistive silicon detector** design: the **DC**-coupled **RSD** (**DC-RSD**)
- ✓ **Strategy** for the **simulation** of DC-RSD devices: **hybrid approach**

  => combination of **TCAD** and **Spice** simulation tools

  => **signal spreading** and **100% fill factor** preserved in the DC-RSD design
- ✓ **Optimization** of the **performance**, e.g. accuracy of the **position reconstruction**

  => **improvement** by using **resistive strips** between the read-out electrodes
- ✓ A **first batch** of DC-RSD is planned **in the next few months** (produced by FBK, Italy)
- ✓ Extensive **campaign of measurements** on both **not irradiated and irradiated** DC-RSD structures
- ✓ New batch of **TCAD simulations** taking into account the **radiation damage effects**
- ✓ **Guidelines** for future production of **radiation-resistant DC-RSD**

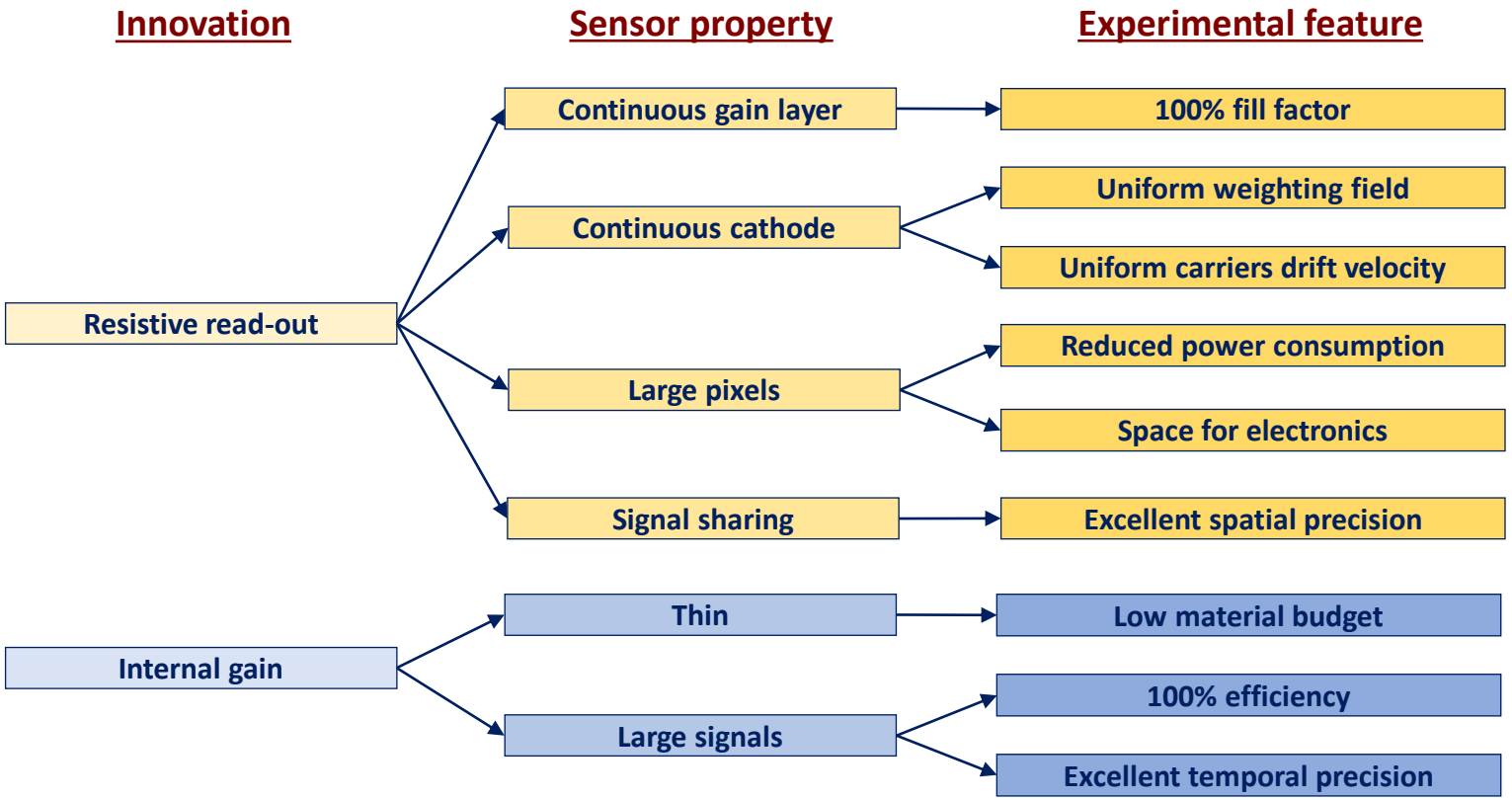
# 41st RD50 Workshop

Radiation hard semiconductor devices for very high luminosity colliders

*Thank you for the attention!*

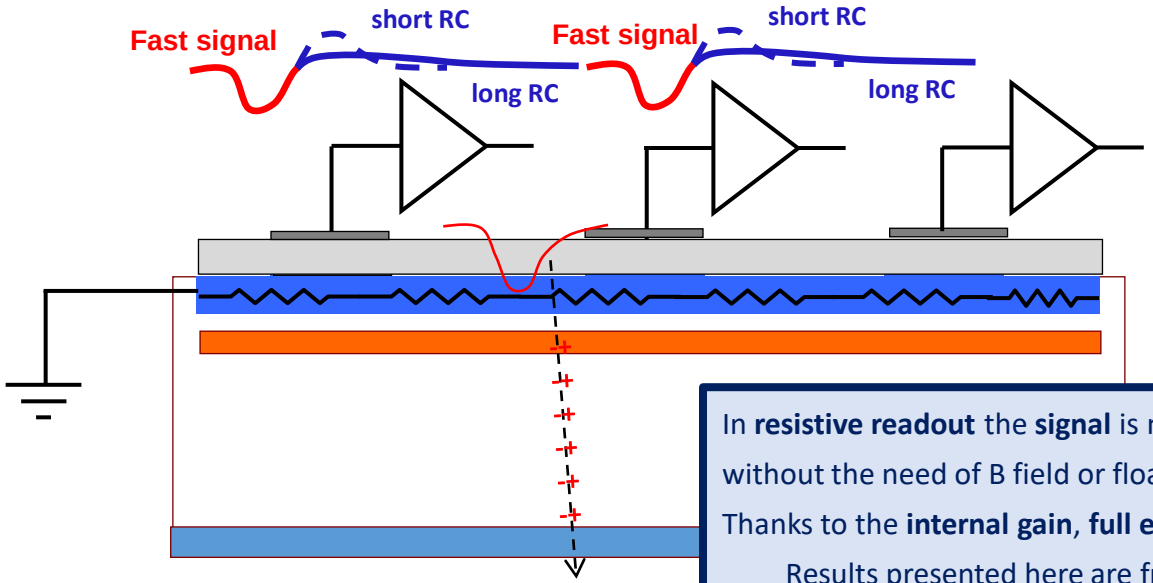
# BACKUP SLIDES

# Innovations in the design of silicon sensors



# Second design innovation: resistive read-out

- The **signal** is **formed on** the **n⁺ electrode** => **no signal** on the **AC pads**
- The **AC pads** offer the **smallest impedance to ground** for the **fast signal**
- The **signal discharges to ground**




(Tredi conf. 2015)

In **resistive readout** the **signal** is naturally **shared among pads** (4-6) without the need of B field or floating pads

Thanks to the **internal gain**, **full efficiency even with sharing**

Results presented here are from the **FBK RSD2 production**

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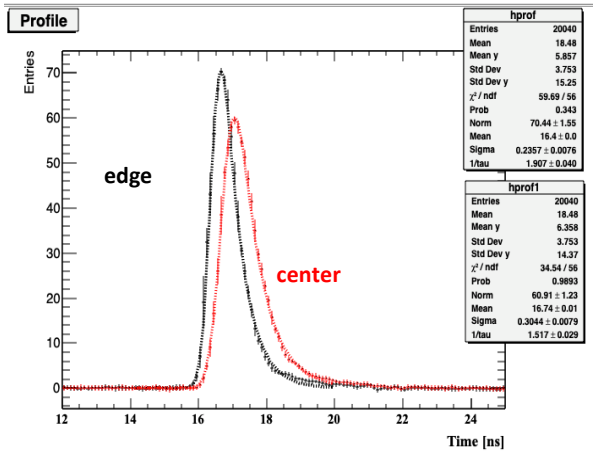
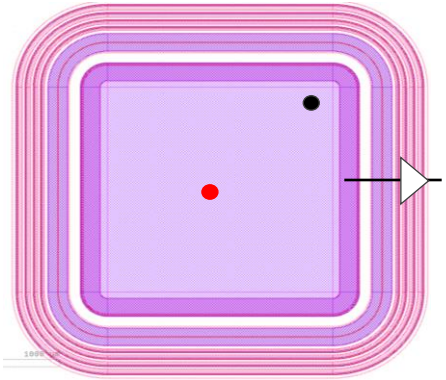
# Signal propagation on a resistive surface

**Pre-requisite:** study the signal propagation on a silicon resistive surface

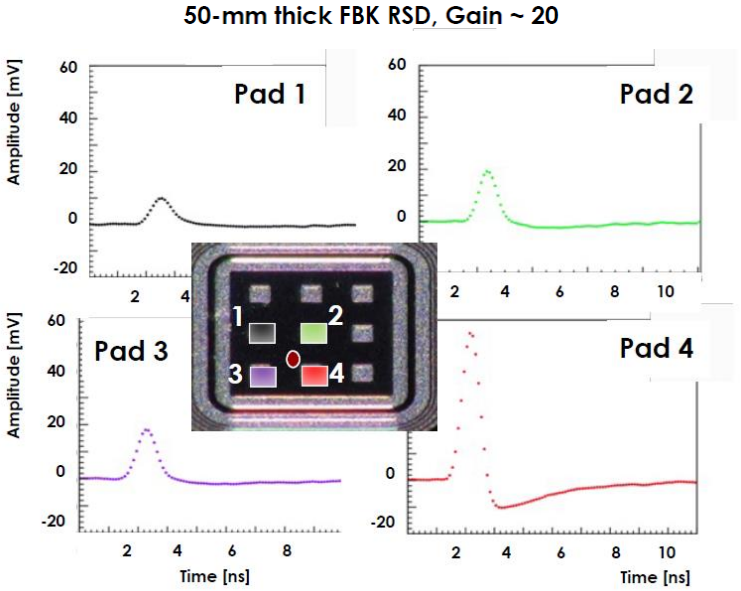
- Large structures (2 $mm^2$ resistive sheet from **RSD1 production**)
- Contact at the periphery to read-out the $n^{++}$

- The **shape changes** with propagation: **smaller and longer with distance**



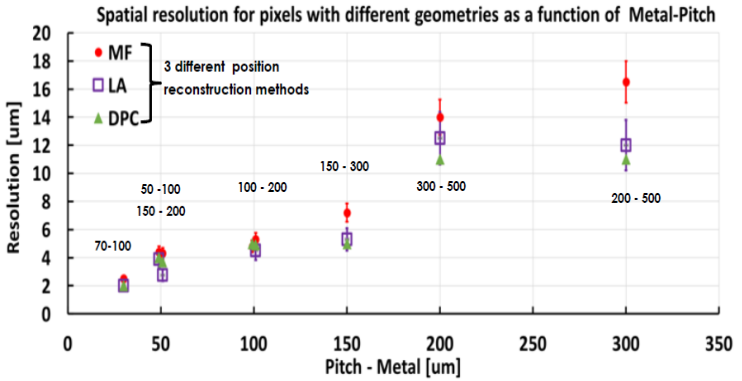



# Example of signal sharing



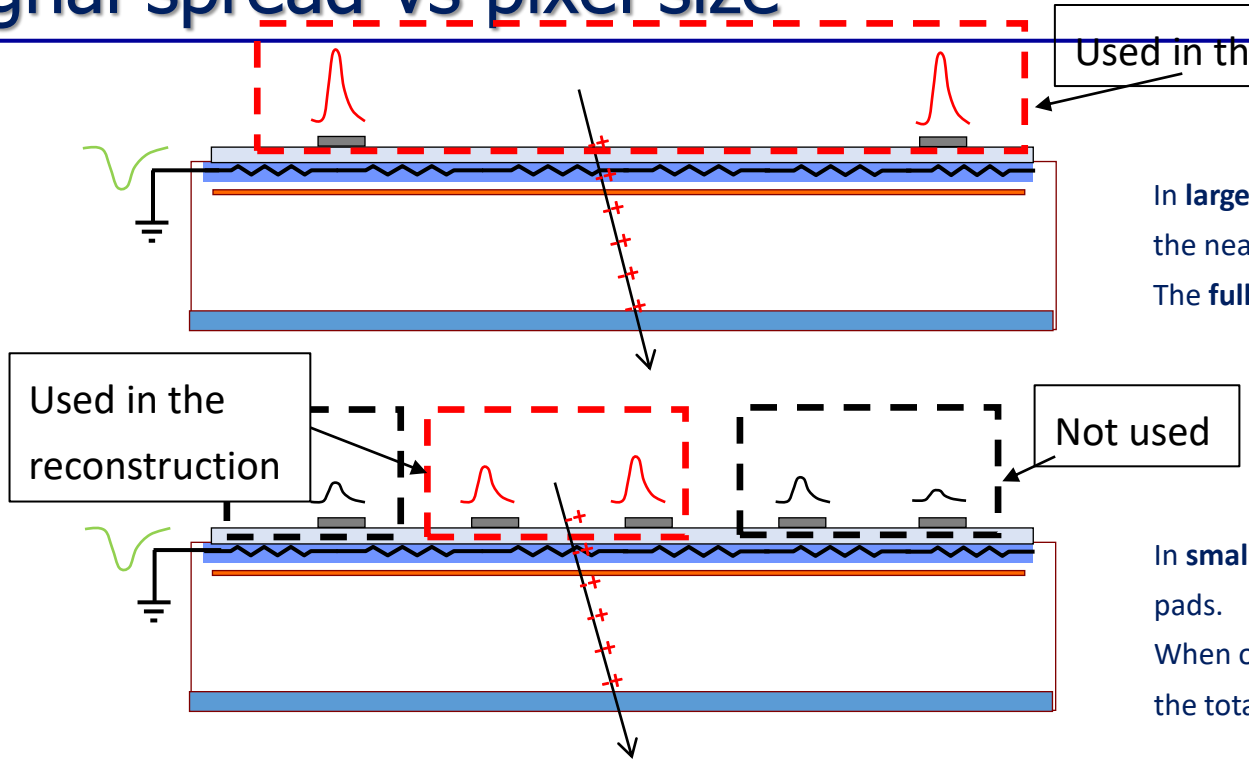

The laser is shot at the position of the red dot: the signal is seen in 4 pads

## Spatial precision of resisitive read-out




- ✓ **RSDs** reach a **spatial resolution** that is about 5% of the inter-pad distance => **5 µm resolution with 150 µm pitch**
- ✓ RSDs have the «usual» UFSD **temporal resolution** of **30-40 ps**

# Signal spread vs pixel size

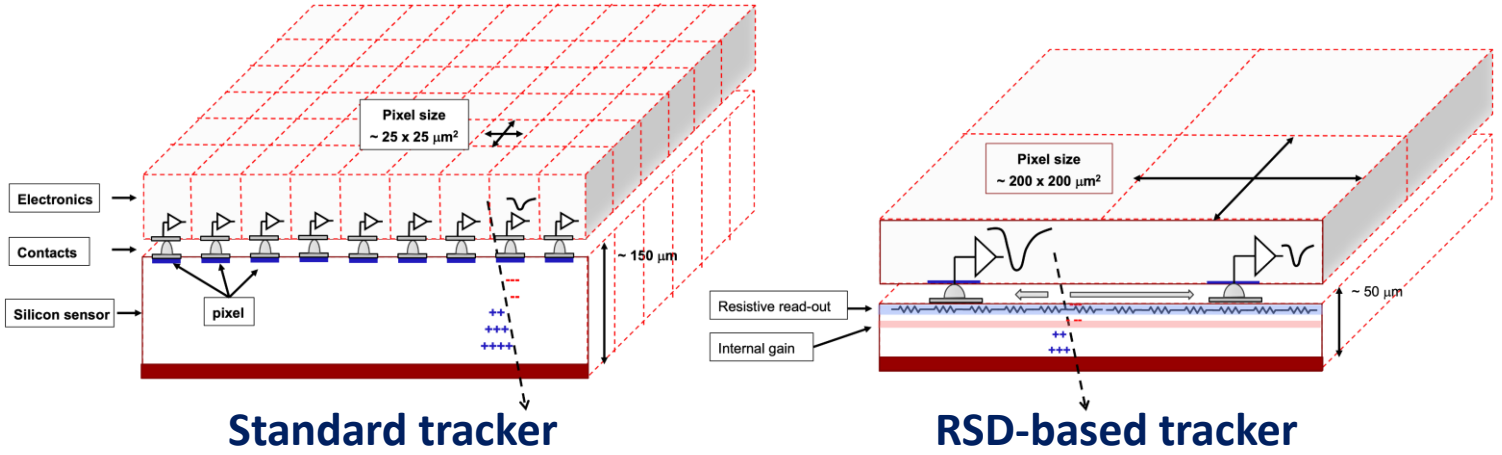



In **large pixels**, the signal is visible only on the nearest pads.
The **full signal** is **used in the reconstruction**

In **small pixels**, the signal is visible on many pads.
When only 4 pads are used, **only a part** of the total signal is **used in the reconstruction**

**In small pixels, for equal gain, the signal-to-noise ratio is worse since part of the signal leaks to pads not used in the reconstruction**

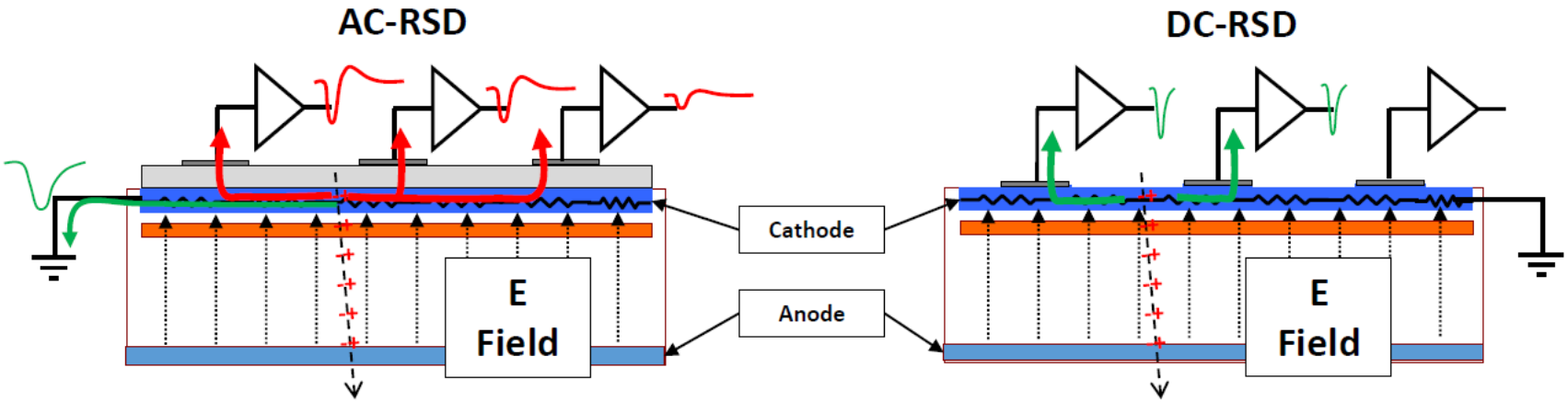
# Final goal of RSD R&D: a completely new tracker




**The design of a tracker based on RSD is truly innovative**:

- It delivers ~ 20 -30 ps temporal resolution
- For the same spatial resolution, the number of pixel is reduced by 50-100
- The electronic circuitry can be easily accomodated
- The power consumption is much lower, it might even be air cooled (~ 0.1-0.2 W/cm$^2$)
- The sensors can be really thin

# RSD and DC-RSD




This design has been manufactured in several productions by FBK, BNL, and HPK

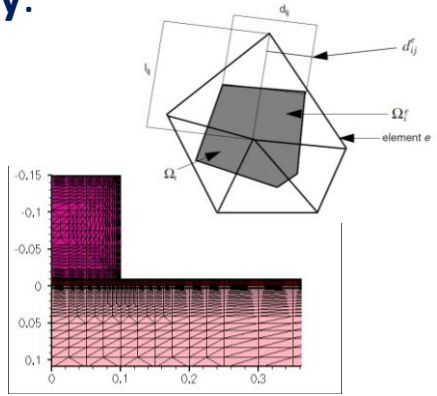
This design is presently under development by FBK

The main advantage of the DC-RSD design is to limit the signal spread

# Technology-CAD simulations

- **TCAD simulation tools** solve fundamental, physical partial differential equations, such as diffusion and transport equation for discretized geometries (finite element meshing).
- This deep physical approach gives TCAD simulation **predictive accuracy**.
- **Synopsys© Sentaurus TCAD**

$$\begin{cases} \nabla \cdot (-\varepsilon_s \nabla \phi) = q \ \ (N_D^+ - N_A^- + p - n) & \text{Poisson} \\ \dfrac{\partial n}{\partial t} - \dfrac{1}{q} \nabla \cdot \vec{J}_n = U_n & \text{Electron continuity} \\ \dfrac{\partial p}{\partial t} + \dfrac{1}{q} \nabla \cdot \vec{J}_p = U_p & \text{Hole continuity} \end{cases}$$

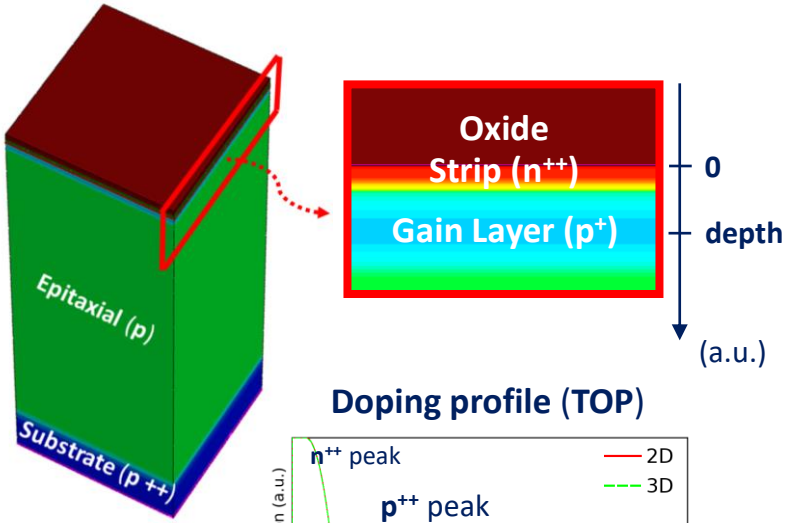



$\vec{J}_n, \vec{J}_p$

$$U_{n,p} = G - R$$

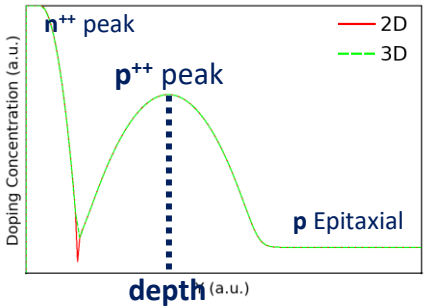
# TCAD simulation of LGAD devices

✓ **Fully-3D** structure

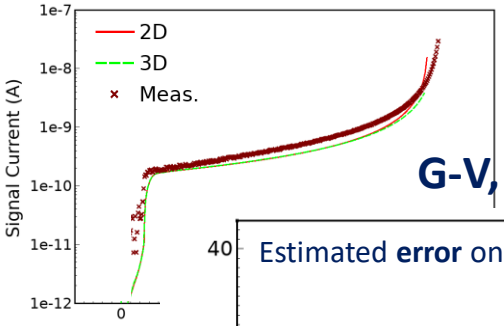



**Gaussian** Gain Layer **profile**

**Doping profile (TOP)**

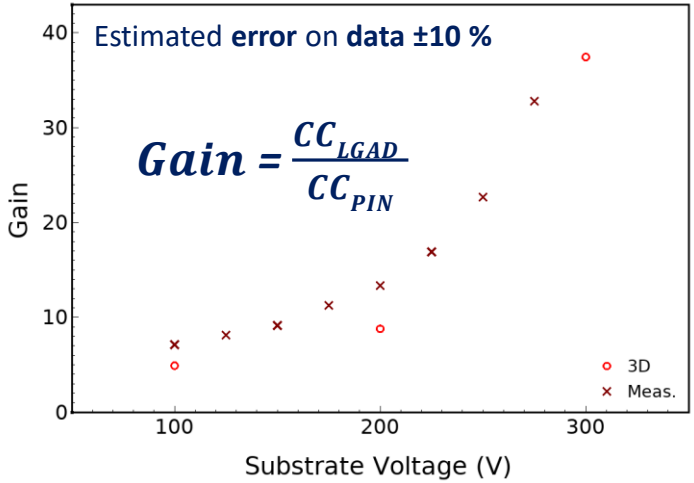



**I-V,** before irradiation




**Good agreement!**

**G-V,** before irradiation




Avalanche model: **Massey**. Temp. **300 K**. Electrical contact area **1mm²**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# Methodology

## DC / AC analysis → Transient analysis → Gain calculation

- **DC biasing (static)**
  - n cathode: 0 V
  - p anode: *sweep*
    - ✓ start = 0 V
    - ✓ step = - 25 V (from 100 V)
    - ✓ stop = - 1000 V
  - Temperature
    - ✓ 300 K for not irr., 253 K for irr. [7]
- **AC biasing (small-signal)**
  - For each DC bias step, superimposition of a 1 $V_{pp}$, 1 kHz sinusoid
  - Impedance matrix for each node of the discretized grid
  - Temperature 300 K for not irr. / irr.

- For each DC bias step, one **Time-Variant (TV)** simulation of impinging particle (**MIP**), following the **"HeavyIon" model**
  - instant of penetration 1 ns
  - through the whole device
  - Linear Energy Transfer (LET)

$$LET_f = \frac{E_{LOSS}}{E} \quad \frac{pC}{\mu m}$$

where

$$E = 3{,}68 \ eV$$

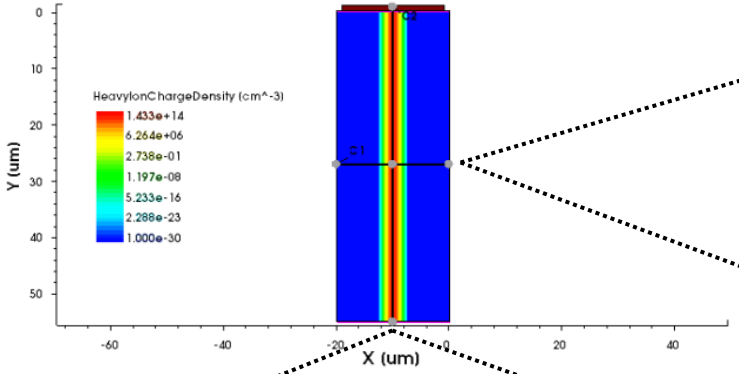
[5] $$E_{LOSS} = 0{,}027\, log(y) + 0{,}126 \quad \frac{keV}{\mu m}$$

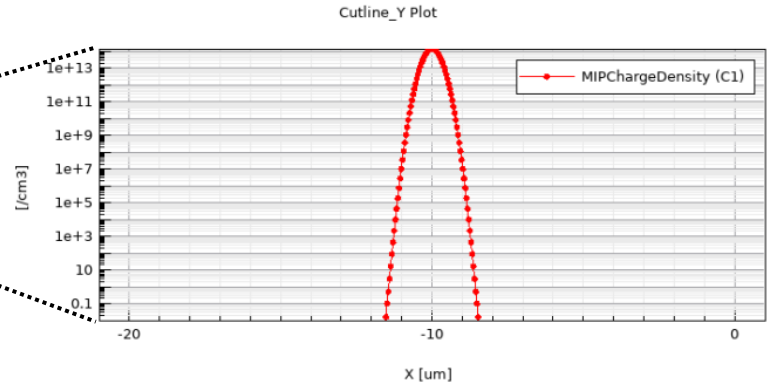
- Leakage current calculation
  - instant = 0,9 ns
- Leakage current offset subtracted from the simulated I(t) curve
- Calculation of **Collected Charge (CC)** as the **integral of the current**

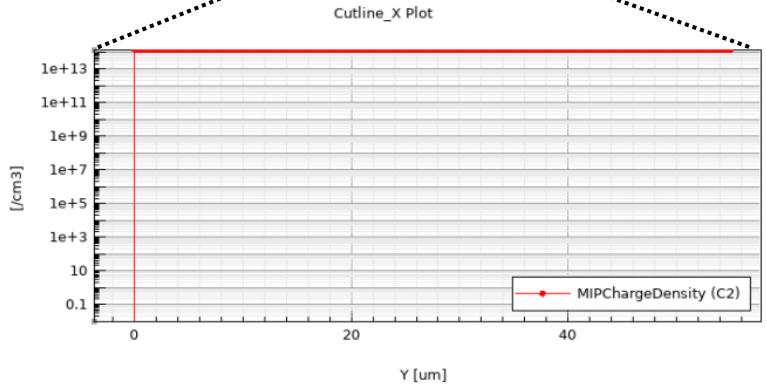
$$Gain = \frac{CC_{LGAD}}{CC_{PIN}}$$ [6]

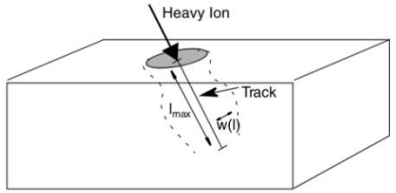

**[5]** S. Meroli et al., *Energy loss measurement for charged particles in very thin silicon layers*, JINST 6 P06013, 2011
**[6]** V. Sola et al., *First FBK production of 50 µm ultra-fast silicon detectors*, Nucl. Instrum. Methods Phys. Res. A, 2019
**[7]** A. Chilingarov, *Temperature dependence of the current generated in si bulk*, JINST 8 P10003, 2013.

# Transient responce: “HeavyIon” model




$$G(l,w,t) = G_{LET}(l)\, R(w,l)\, T(t)$$ → Gaussian

$$G_{LET}(l) = a_1 + a_2 l + a_3 e^{a4\, l} + k' [c_1 (c_2 + c_3 l)^{c4} + LET\_f(l)$$

# Simulation setup

## Physical models

- ✓ **Generation/Recombination rate**
  - => Shockley-Read-Hall (SRH), Band-To-Band Tunneling (BTBT), Auger
  - => **Avalanche Generation**: the impact ionization model is *Massey*
- ✓ **Carriers mobility variation**
  - => doping and field dependent
- ✓ **Physical parameters**
  - => $s_0$ = 0 cm/s
  - => $\tau_n = \tau_p$ = 1E-3 s

## Radiation damage model

- ✓ **"Perugia0"**
  - => combined **surface** and **bulk** damage scheme

| | energy (eV) | intr. rate ($cm^{-1}$) | eXsect ($cm^2$) | hXsect ($cm^2$) |
|---|---|---|---|---|
| **Donor** | $E_C$-0.23 | 0.006 | 2.3e-14 | 2.3e-15 |
| **Acceptor** | $E_C$-0.42 | 1.6 | 1.0e-15 | 1.0e-14 |
| **Acceptor** | $E_C$-0.46 | 0.9 | 7.0e-14 | 7.0e-13 |

| | Acceptor-like | Donor-like |
|---|---|---|
| Energy (eV) | $E_C - 0.56 \le E_T \le E_C$ | $E_V \le E_T \le E_V + 0.60$ |
| Width (eV) | 0.56 | 0.60 |
| $D_{IT}$ ($eV^{-1}cm^{-2}$) | $D_{IT_{acc}}(\phi)$ | $D_{IT_{don}}(\phi)$ |
| $N_{IT}$ ($\phi$) ($cm^{-2}$) | $N_{IT_{acc}}(0) + \Delta N_{IT_{acc}}(\phi)$ | $N_{IT_{don}}(0) + \Delta N_{IT_{don}}(\phi)$ |
| $\sigma_{electrons}$ ($cm^2$) | $1.00 \times 10^{-16}$ | $1.00 \times 10^{-15}$ |
| $\sigma_{holes}$ ($cm^2$) | $1.00 \times 10^{-15}$ | $1.00 \times 10^{-16}$ |
| **Fixed oxide charge** | | |
| $Q_{OX}$ ($\phi$) ($cm^{-2}$) | $Q_{OX}(0) + \Delta Q_{OX}(\phi)$ | |

**Pre-irradiation values**

$Q_{OX}(0) = 8.0 \times 10^{+10}$
$N_{IT_{acc}}(0) = 7.0 \times 10^{+09}$
$N_{IT_{don}}(0) = 7.0 \times 10^{+09}$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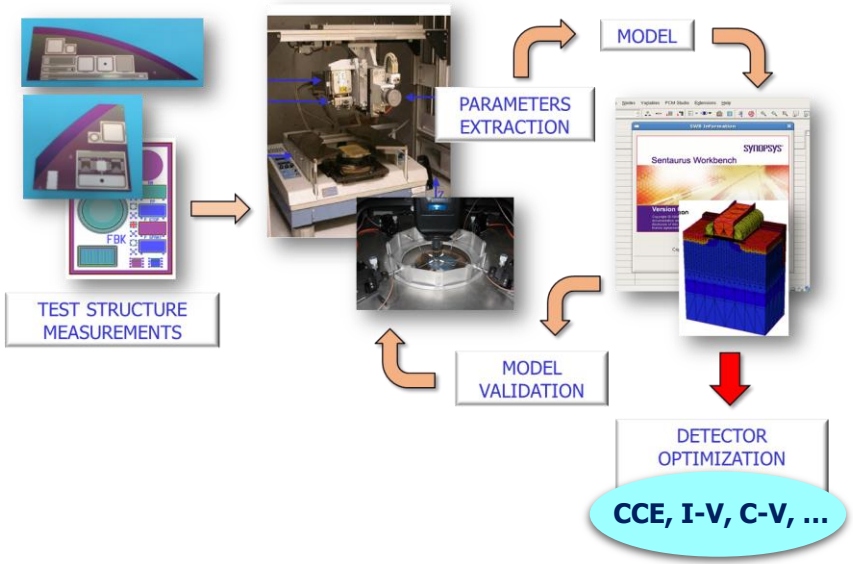
# TCAD radiation damage models used

- **"New University of Perugia model"**
  - ✓ **Combined surface and bulk** TCAD damage modelling scheme[3]
  - ✓ Traps generation mechanism
- **Acceptor removal mechanism**

$$N_{GL}(\phi) = N_A(0)e^{-c\phi}$$

where

- **G**ain **L**ayer (**GL**)
- **c**, removal rate, evaluated using the **Torino parameterization**[4]




**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

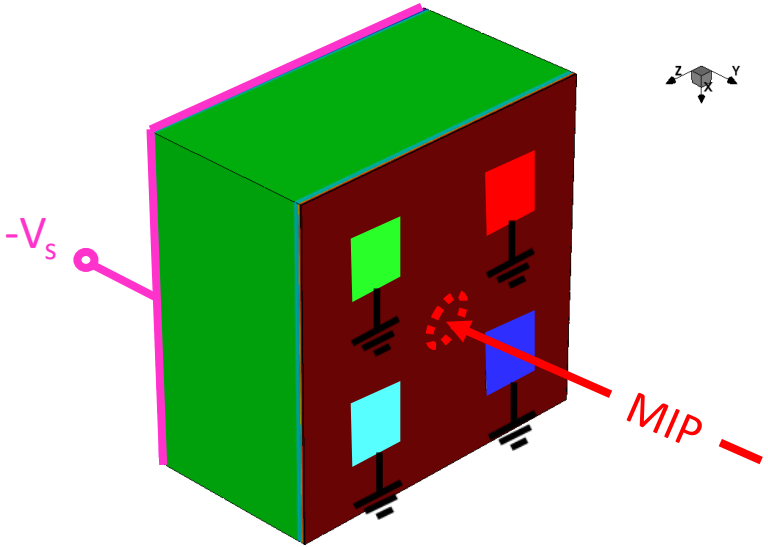
| Type | Energy (eV) | η ($cm^{-1}$) | $\sigma_n$ ($cm^2$) | $\sigma_h$ ($cm^2$) |
|---|---|---|---|---|
| Donor | $E_C$ - 0.23 | 0.006 | $2.3\times10^{-14}$ | $2.3\times10^{-15}$ |
| Acceptor | $E_C$ - 0.42 | 1.6 | $1\times10^{-15}$ | $1\times10^{-14}$ |
| Acceptor | $E_C$ - 0.46 | 0.9 | $7\times10^{-14}$ | $7\times10^{-13}$ |


**[3]** AIDA2020 report, *TCAD radiation damage model - CERN Document Server*
**[4]** M. Ferrero et al., *Radiation resistant LGAD design*, Nucl. Inst. And Meth. In Phys. Res. A, November 30, 2018.

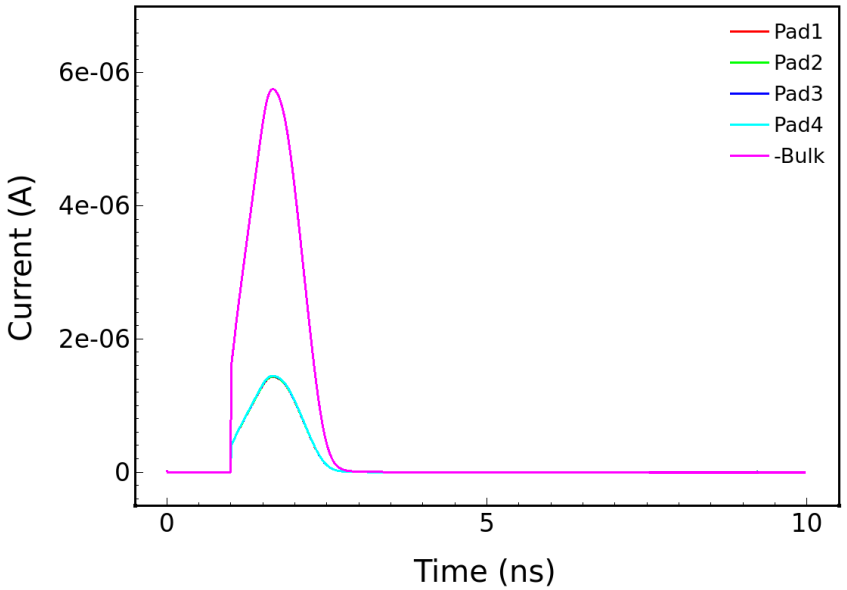
# Transient (TV) behavior

- ✓ **3D** structure, **2x2 PADs**
  - **hit 1** (center hit), **1 MIP**
  - $V_s$ = **-200 V**

@ $R_{s,n++} \approx 203\ \Omega_{sq}$




**I-t,** not irr.

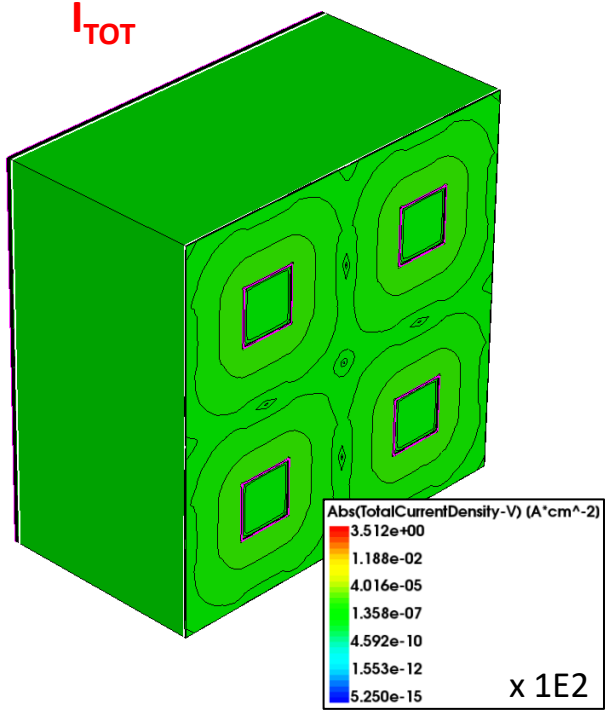


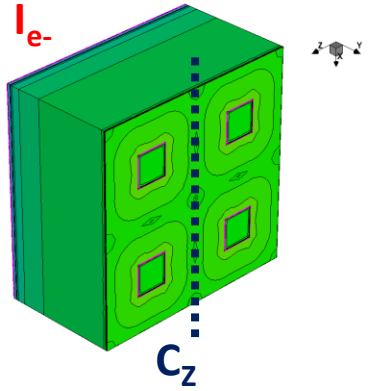

Avalanche model: **Massey**. Temperature **300 K**

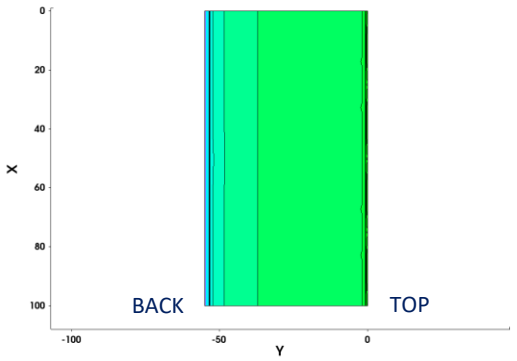
# Transient (TV) behavior

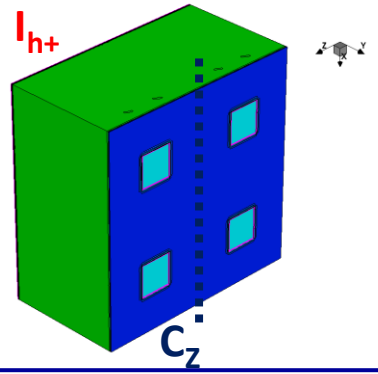
## $C_z$ (Center Cut)

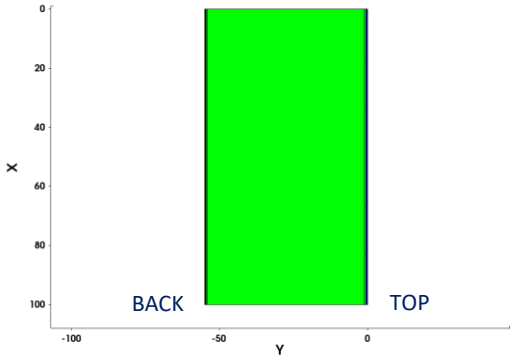
✓ **t = 0.00 ns**





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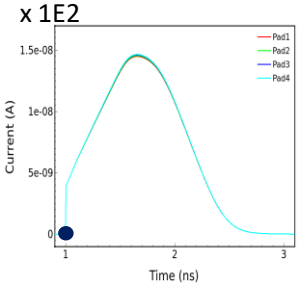
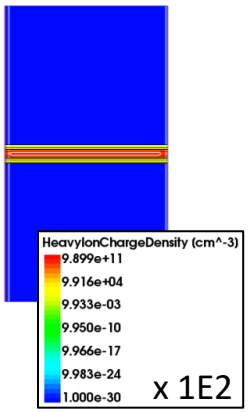
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

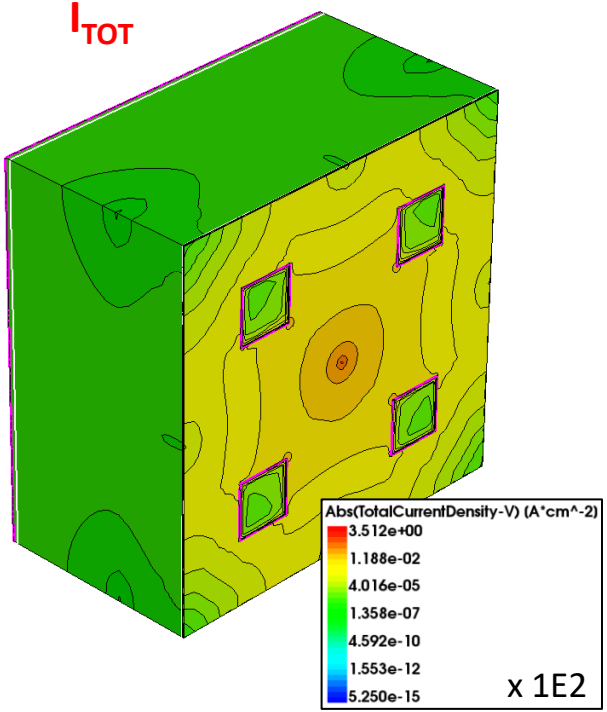
✓ t = 1.00 ns (hit)



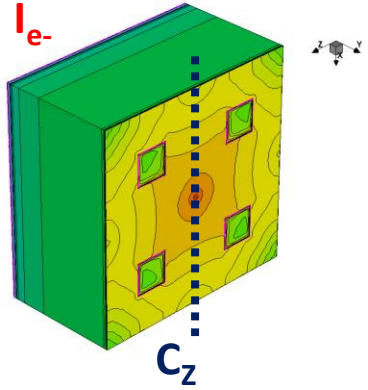

MIP

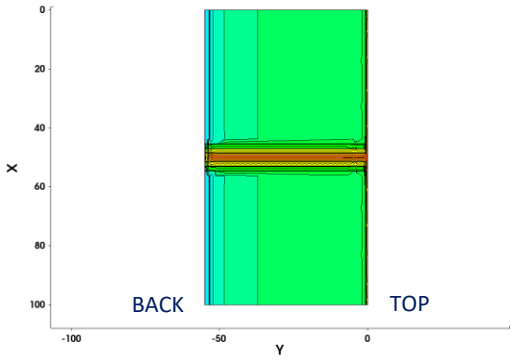



$I_{TOT}$

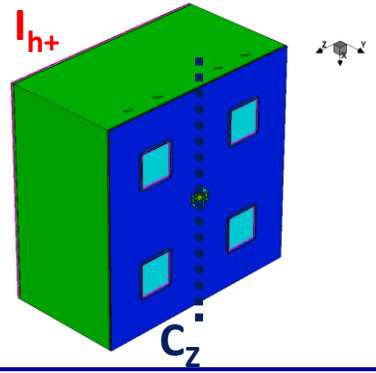


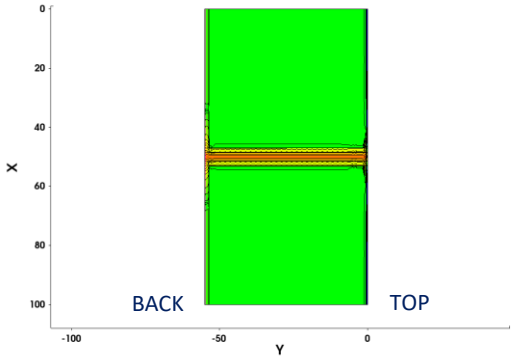

$I_{e-}$




$I_{h+}$

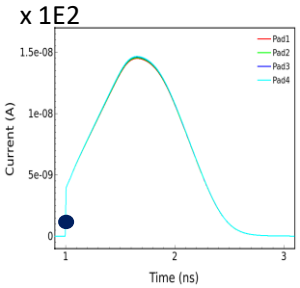


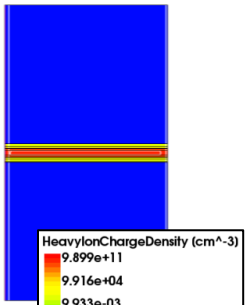
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

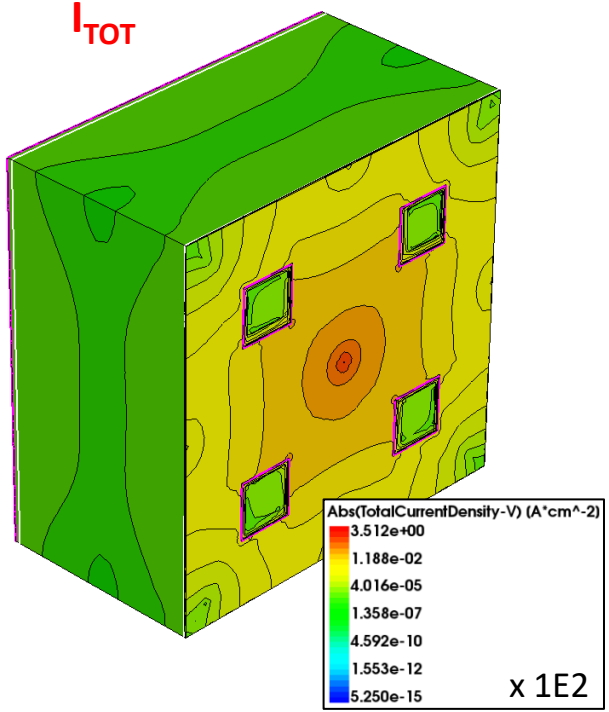
✓ t = 1.01 ns



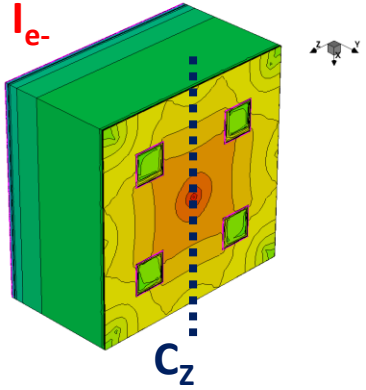

MIP

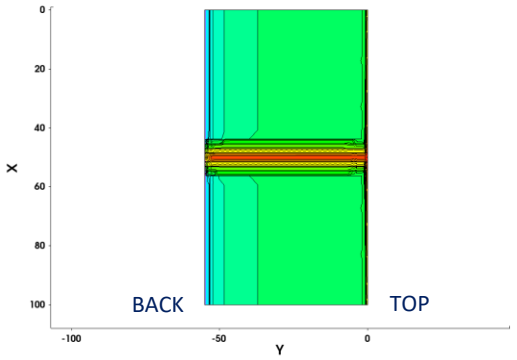



$I_{TOT}$

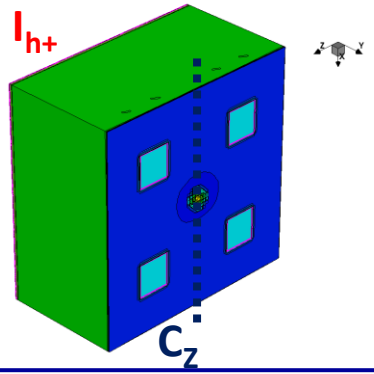


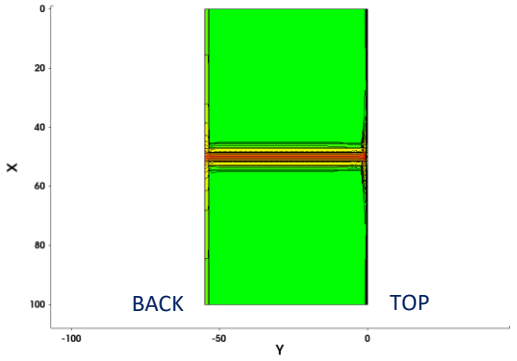

$I_{e-}$




$I_{h+}$

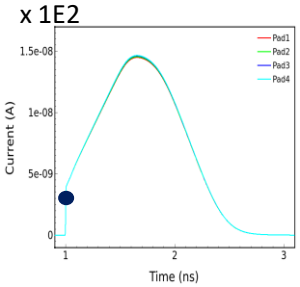


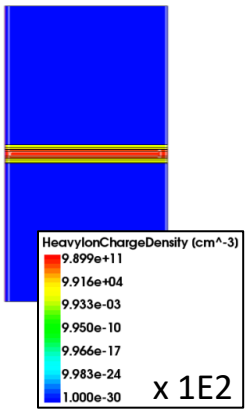
# Transient (TV) behavior – hit 1

## $C_z$ (Center Cut)

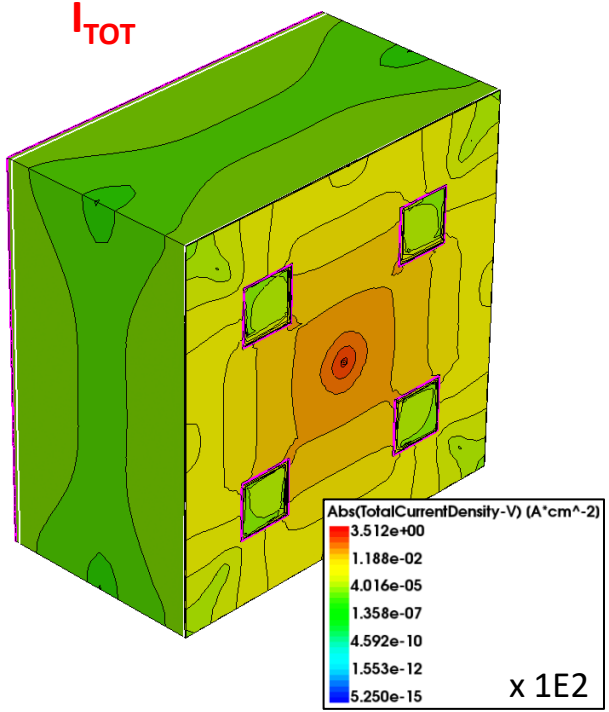
✓ t = 1.03 ns



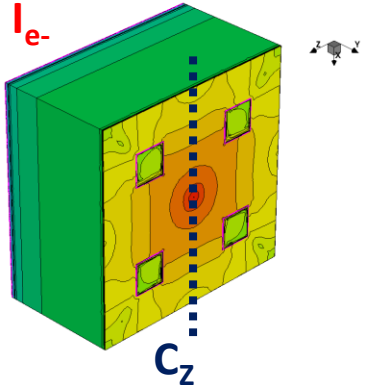

MIP

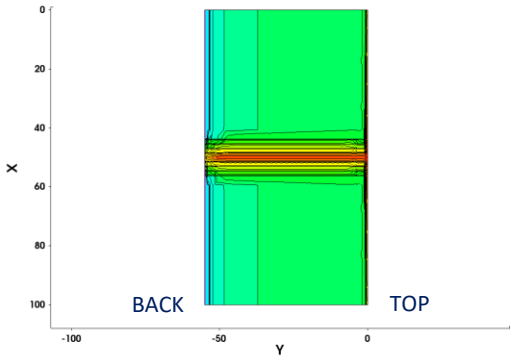



$I_{TOT}$

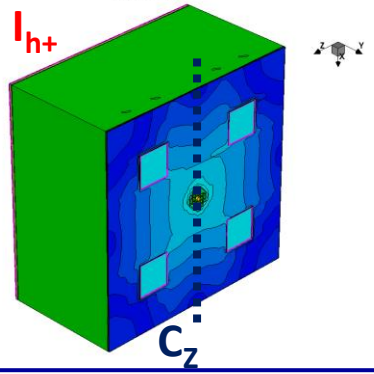


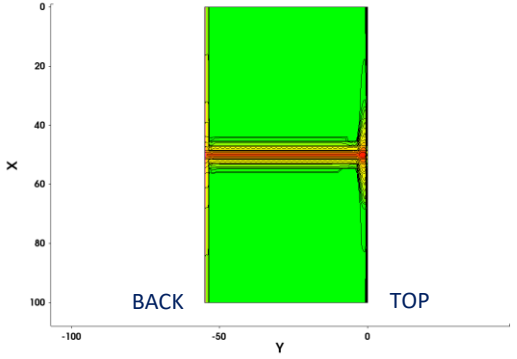

$I_{e-}$




$I_{h+}$

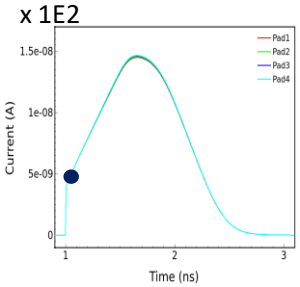


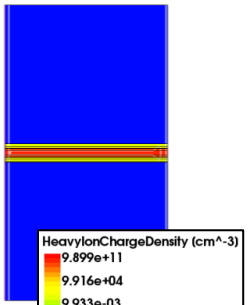
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

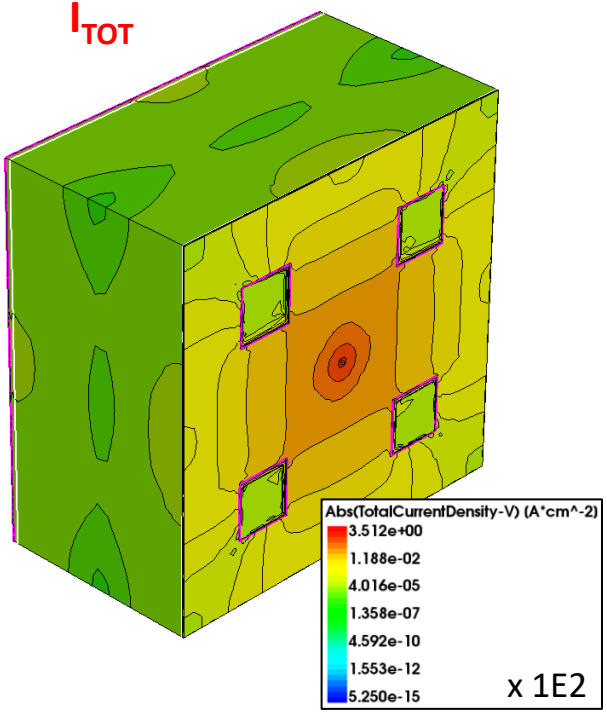
✓ t = 1.05 ns



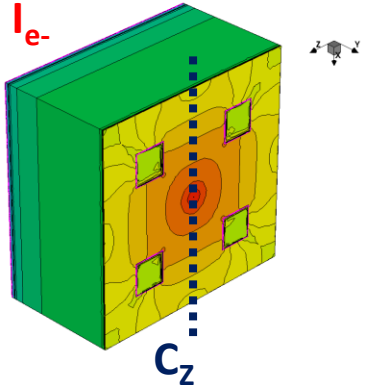

MIP

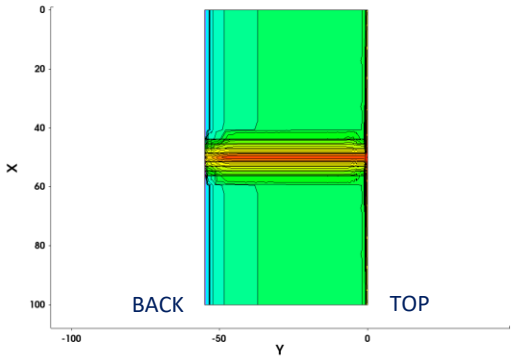



$I_{TOT}$

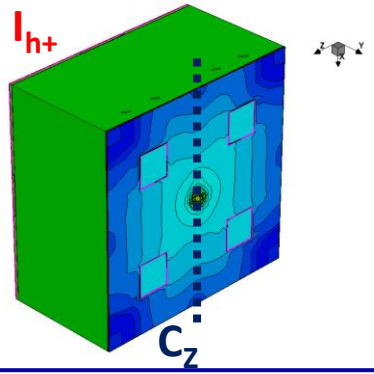


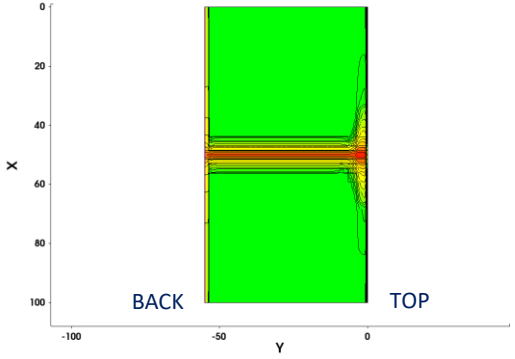

$I_{e-}$




$I_{h+}$

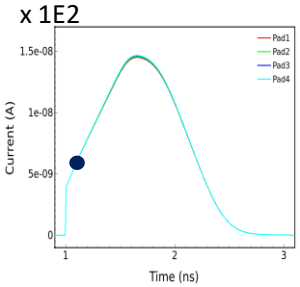


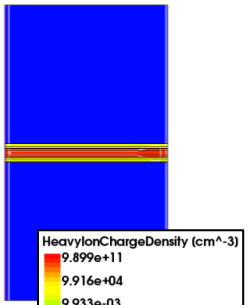
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

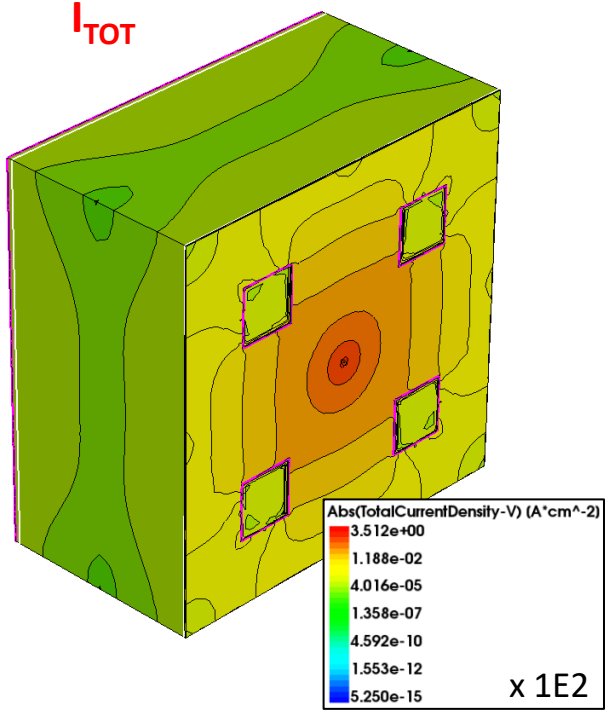
✓ t = 1.10 ns



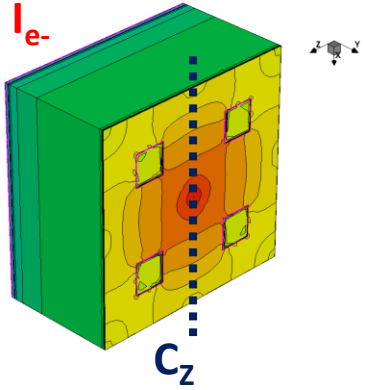

MIP

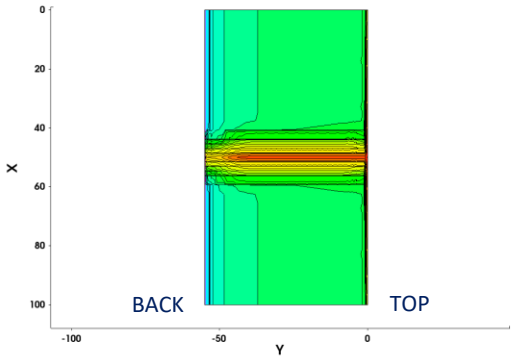



$I_{TOT}$

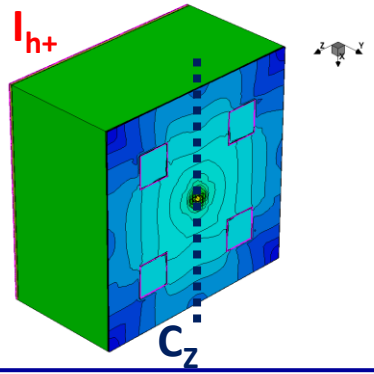


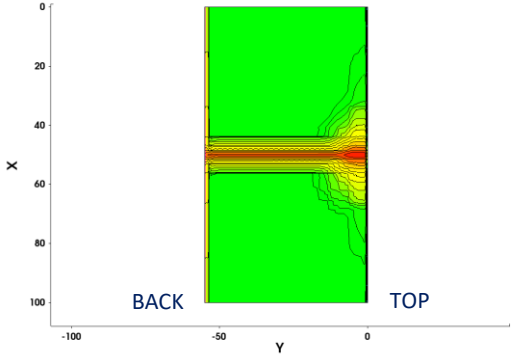

$I_{e-}$




$I_{h+}$

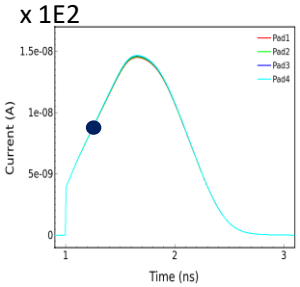


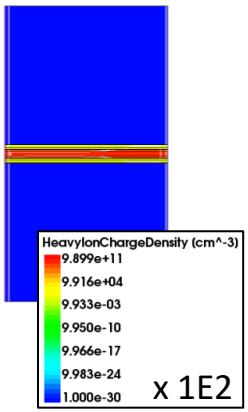
# Transient (TV) behavior – hit 1

## $C_z$ (Center Cut)

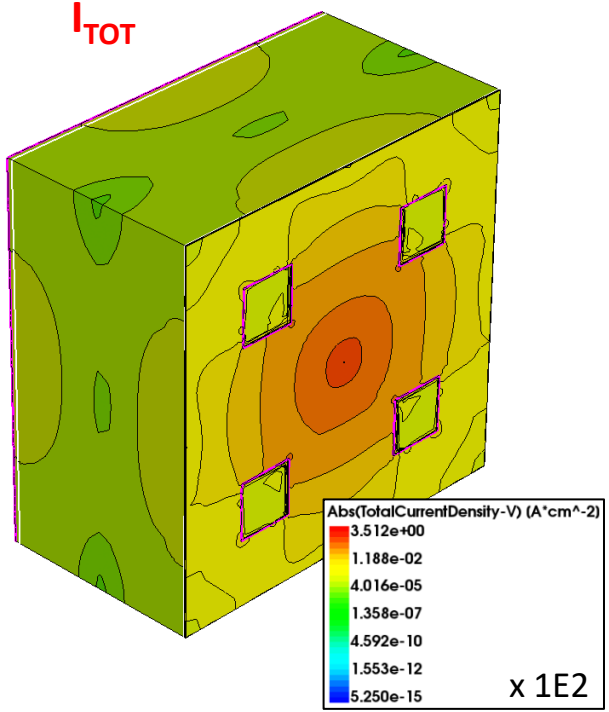
✓ t = 1.25 ns



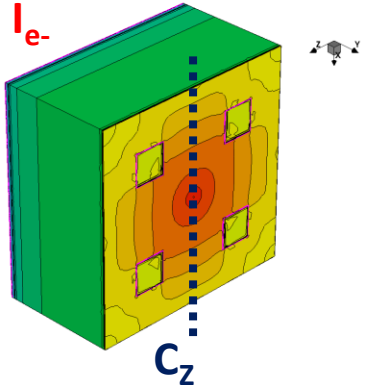

MIP

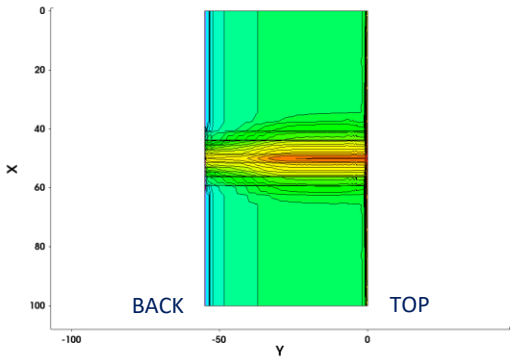



$I_{TOT}$

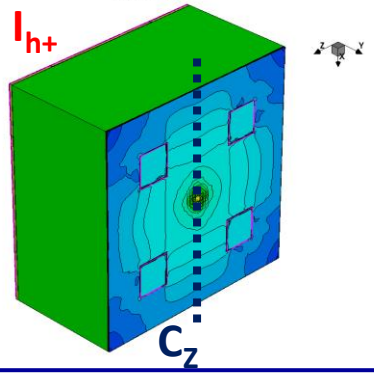


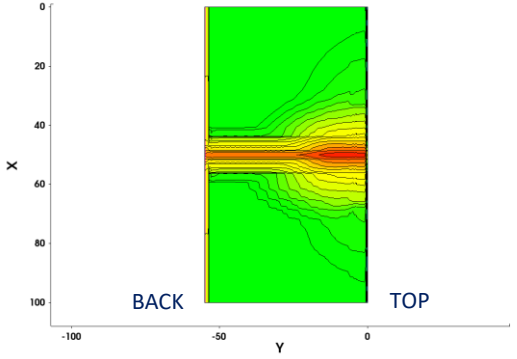

$I_{e-}$




$I_{h+}$

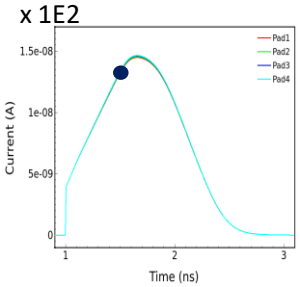


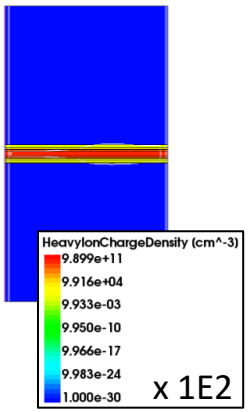
# Transient (TV) behavior – hit 1

## $C_z$ (Center Cut)

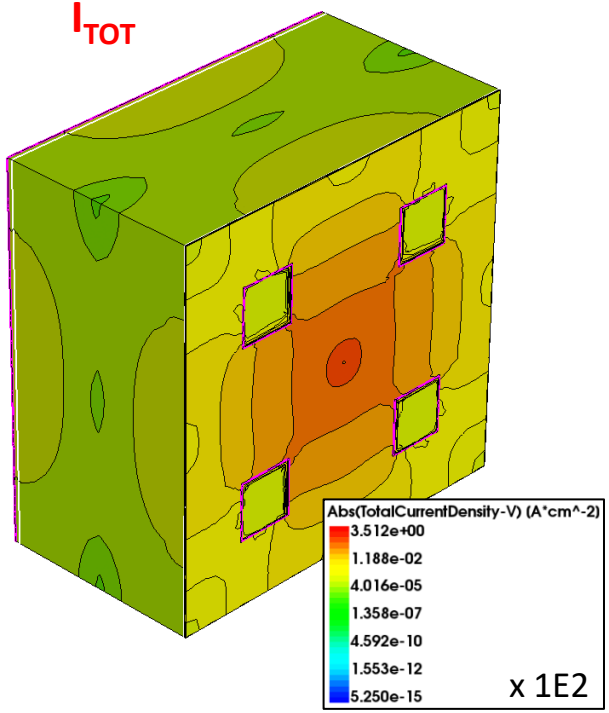
✓ t = 1.50 ns



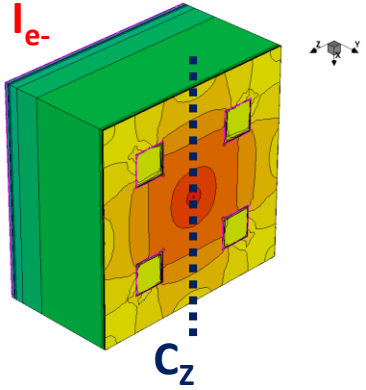

MIP

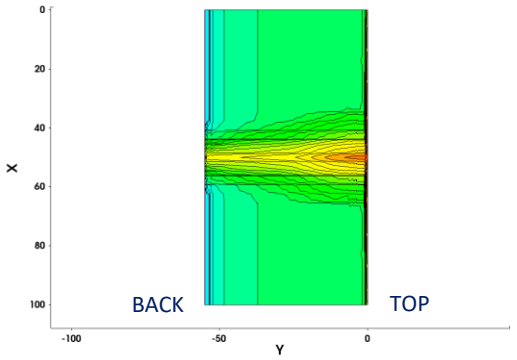



$I_{TOT}$

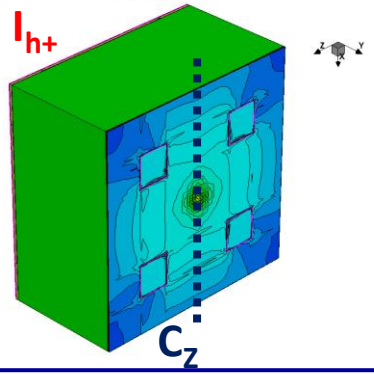


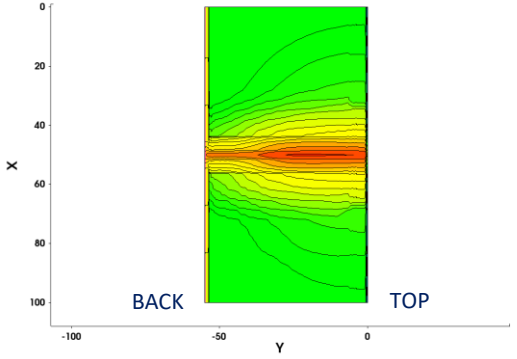

$I_{e-}$




$I_{h+}$

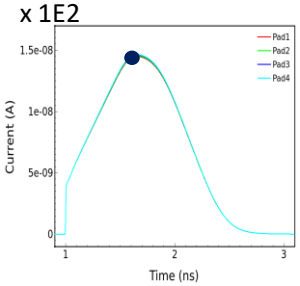


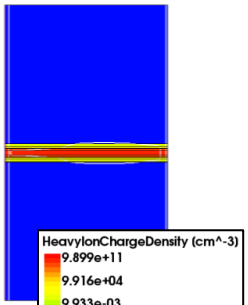
# Transient (TV) behavior – hit 1

## $C_z$ (Center Cut)

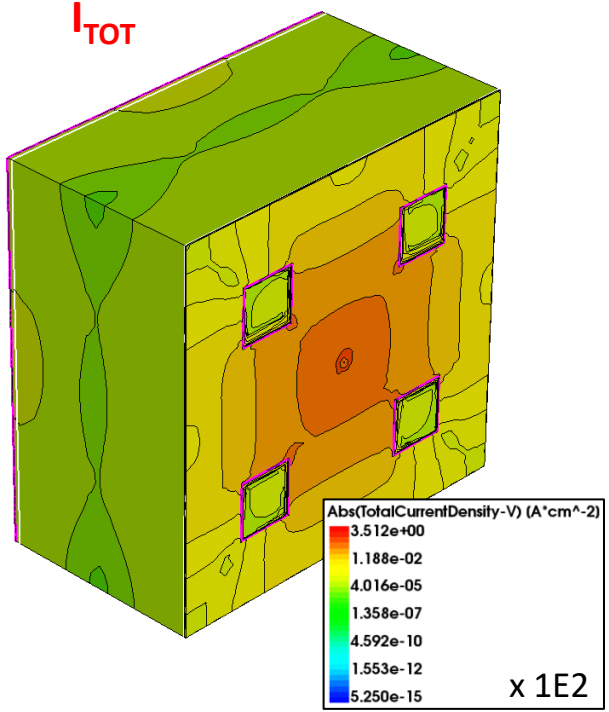
✓ t = 1.60 ns



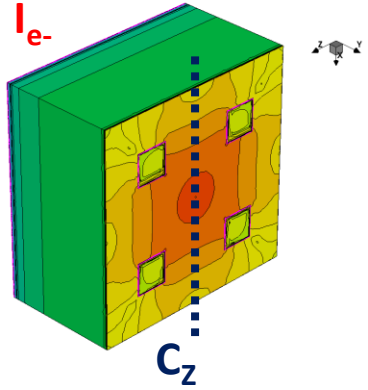

MIP



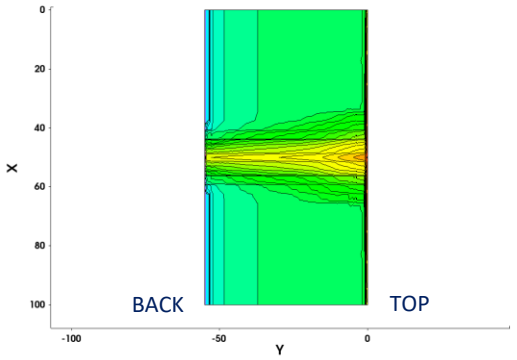

$I_{TOT}$



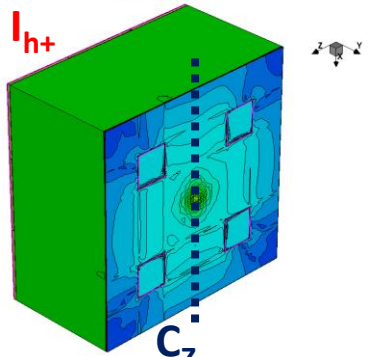

$I_{e-}$



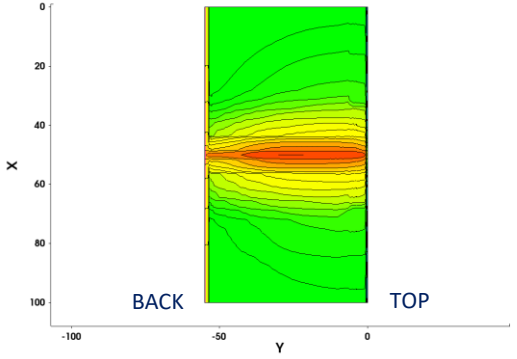

$C_Z$




$I_{h+}$



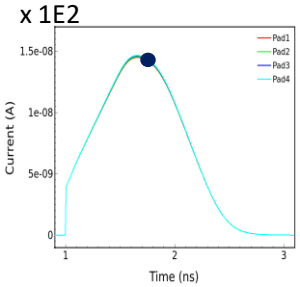

$C_Z$



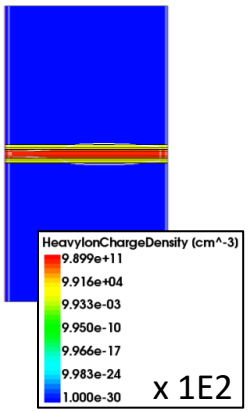
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

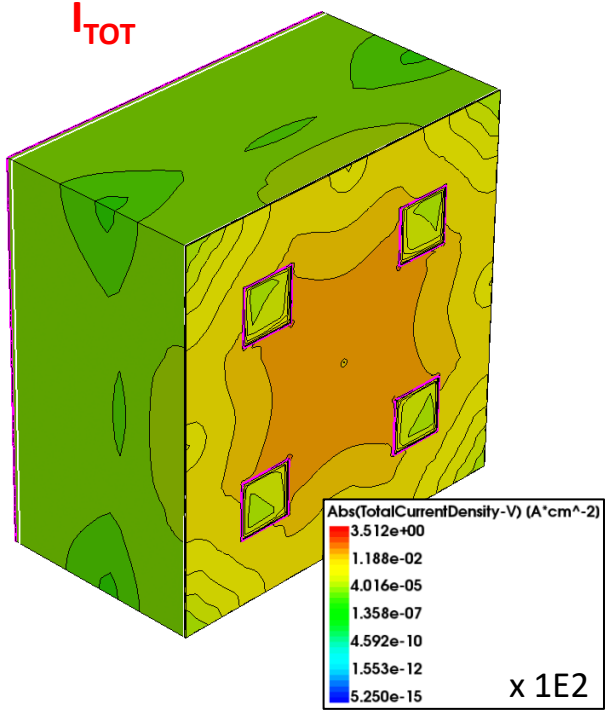
✓ t = 1.75 ns



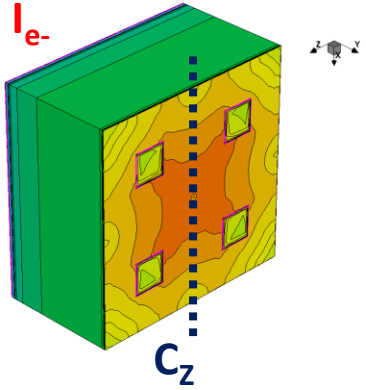

MIP

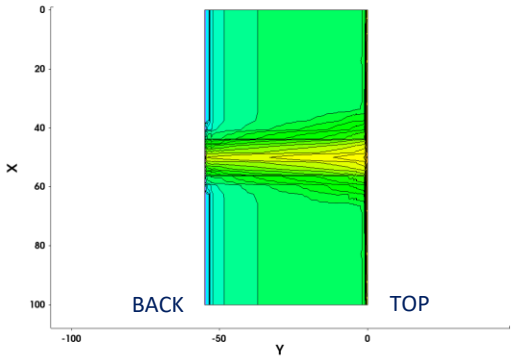



$I_{TOT}$

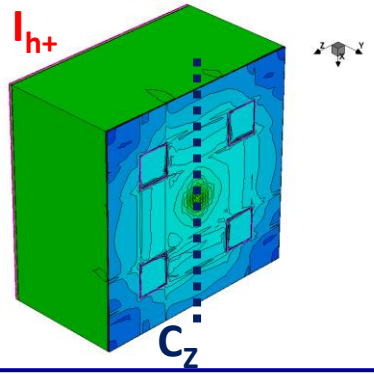


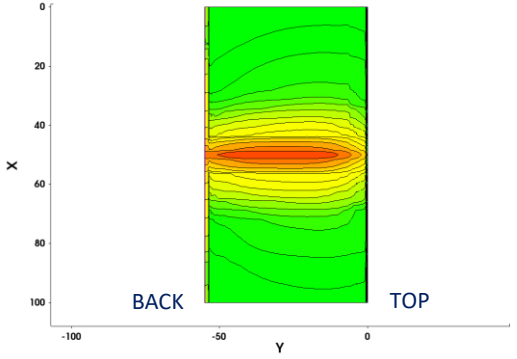

$I_{e-}$




$I_{h+}$

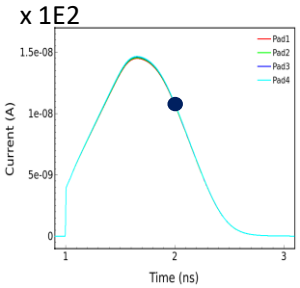


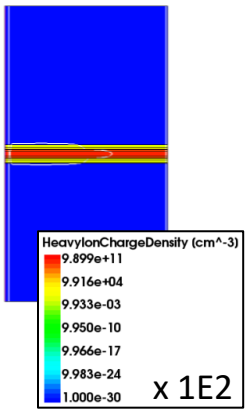
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

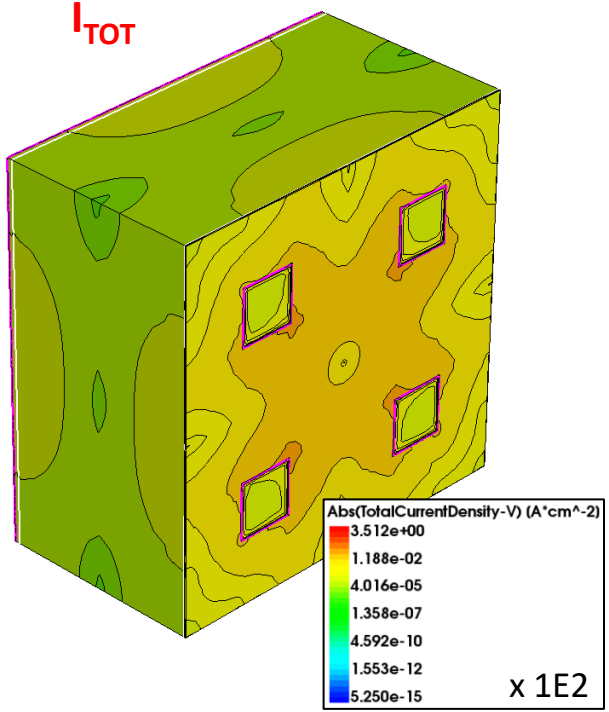
✓ t = 2.00 ns



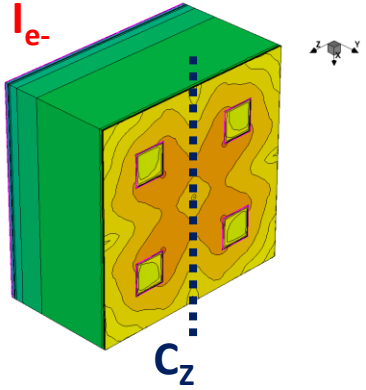

MIP

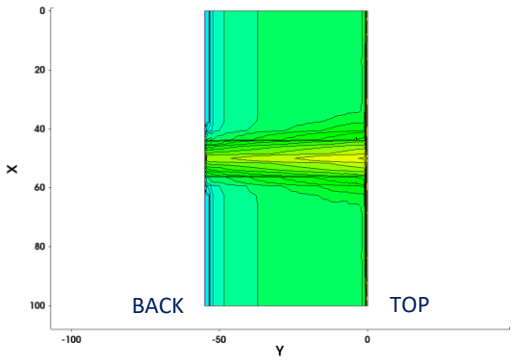



$I_{TOT}$

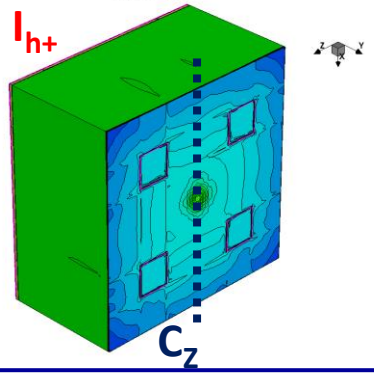


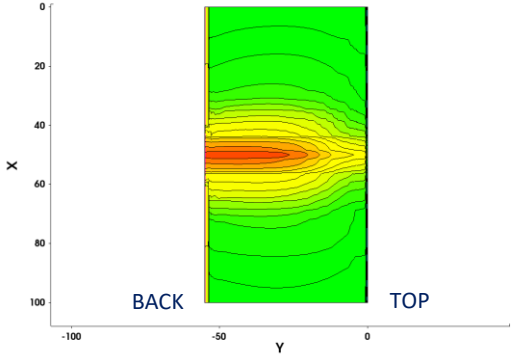

$I_{e-}$




$I_{h+}$

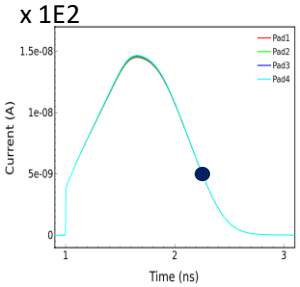


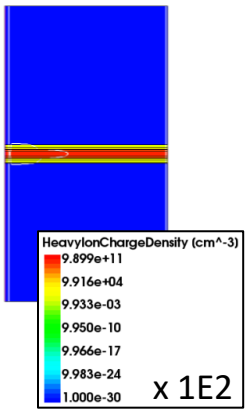
# Transient (TV) behavior – hit 1

## $C_z$ (Center Cut)

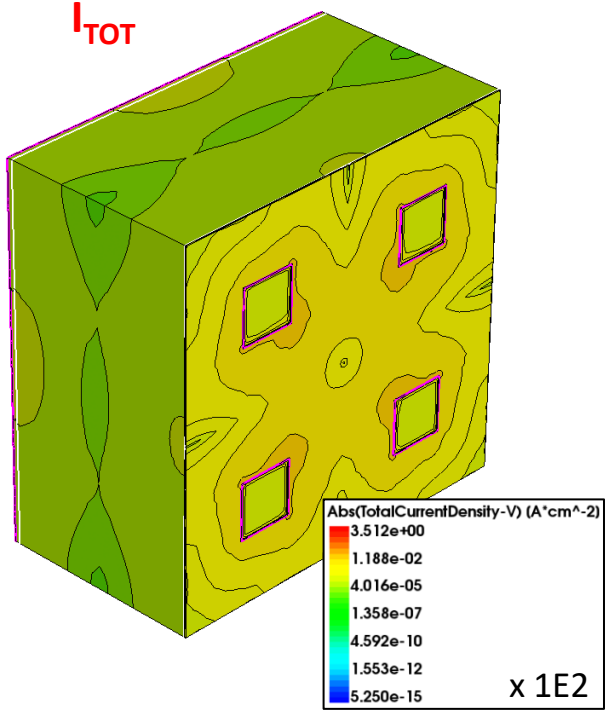
✓ t = 2.25 ns



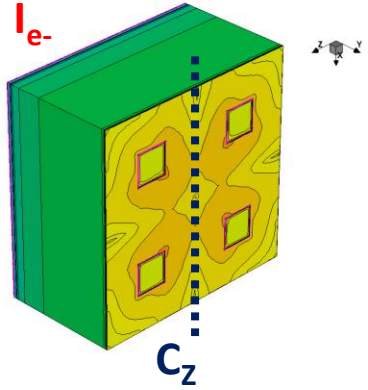

MIP

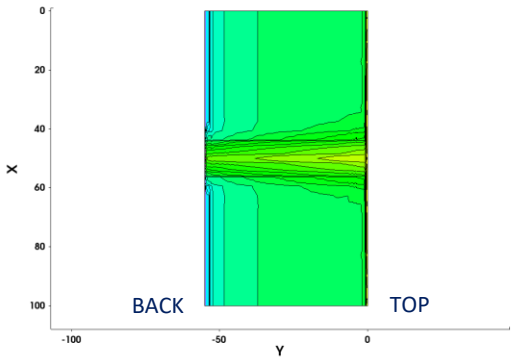



$I_{TOT}$

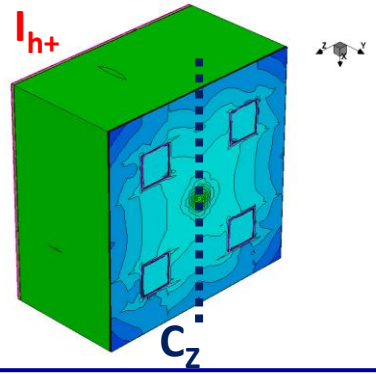


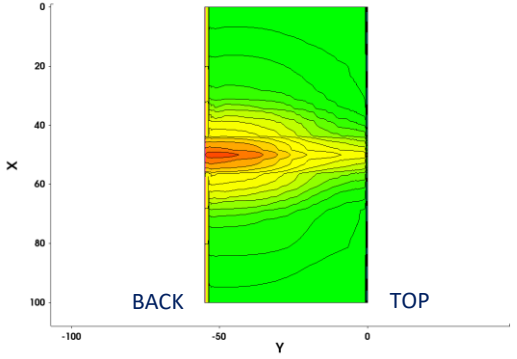

$I_{e-}$




$I_{h+}$

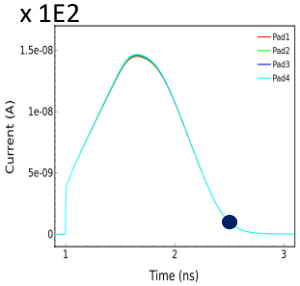


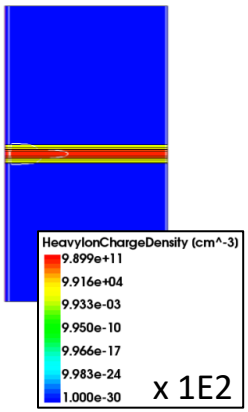
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

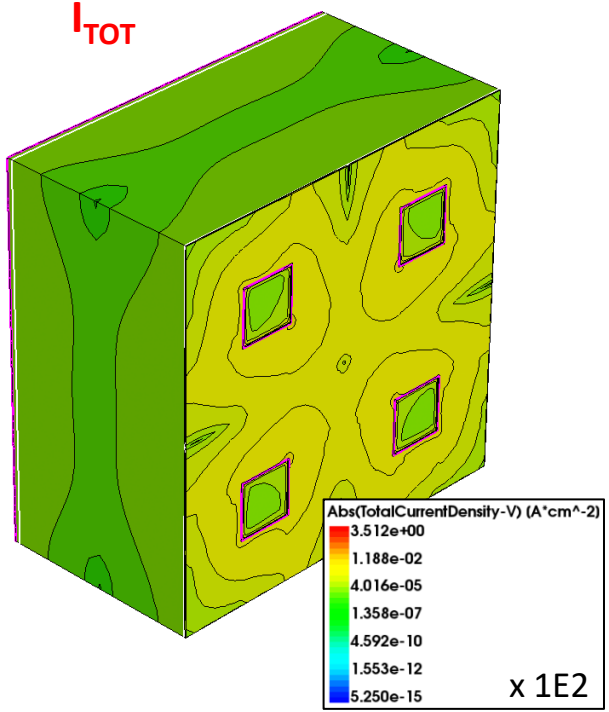
✓ t = 2.50 ns



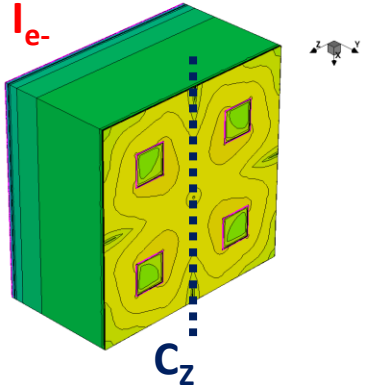

MIP

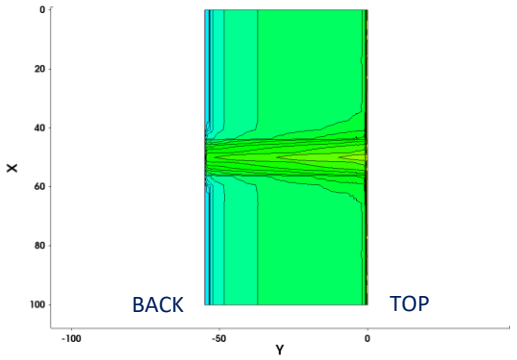



$I_{TOT}$

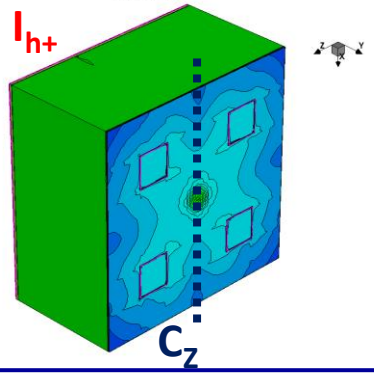


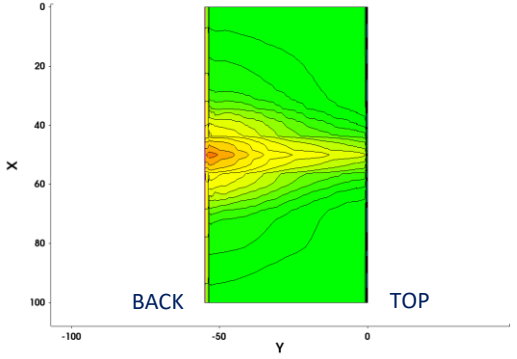

$I_{e-}$




$I_{h+}$

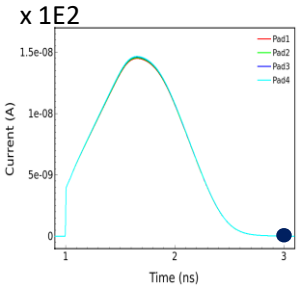


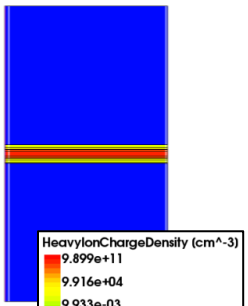
# Transient (TV) behavior – hit 1

$C_z$ (Center Cut)

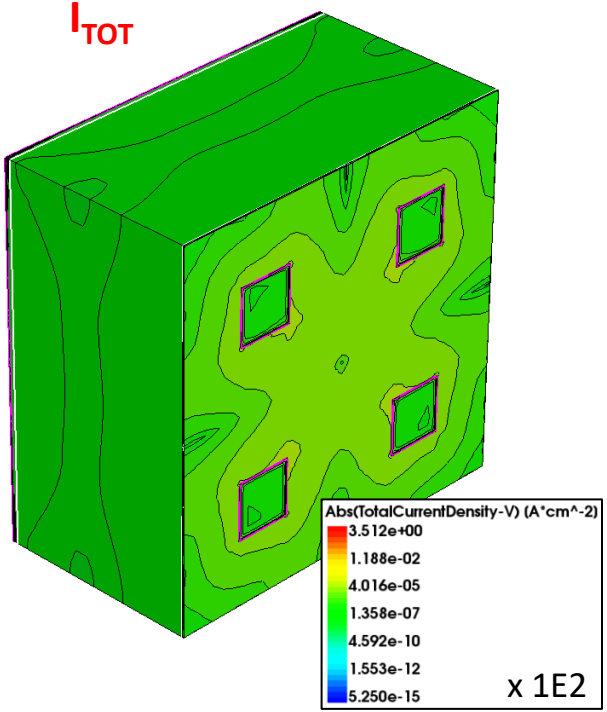
✓ t = 3.00 ns



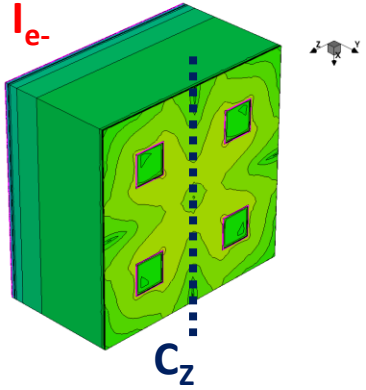

MIP



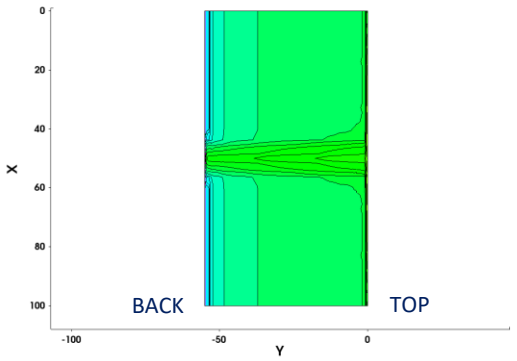

$I_{TOT}$



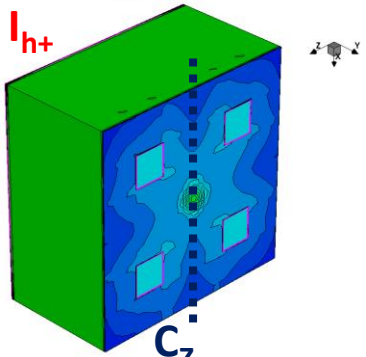

$I_{e-}$



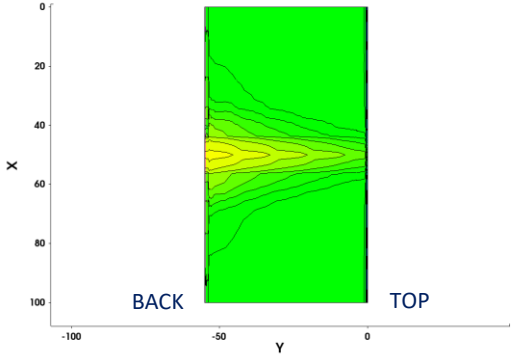

$C_Z$




$I_{h+}$



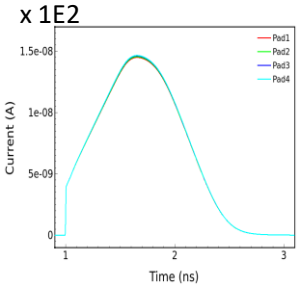

$C_Z$



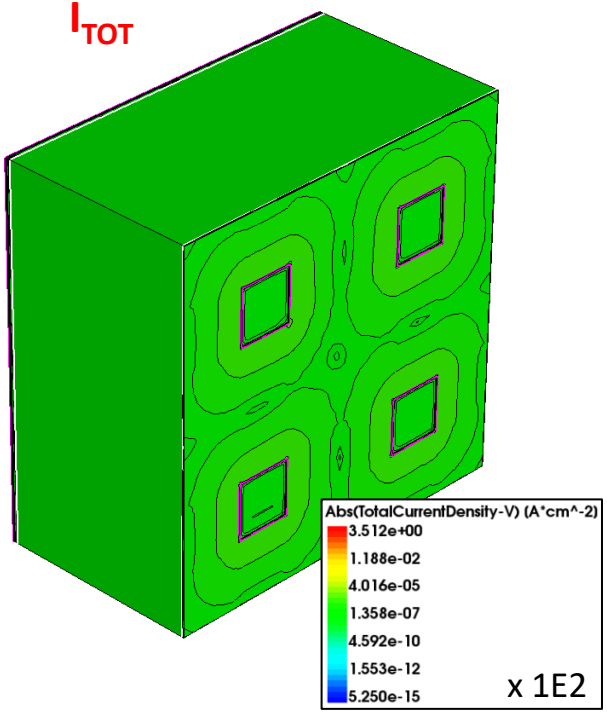
# Transient (TV) behavior

## $C_z$ (Center Cut)

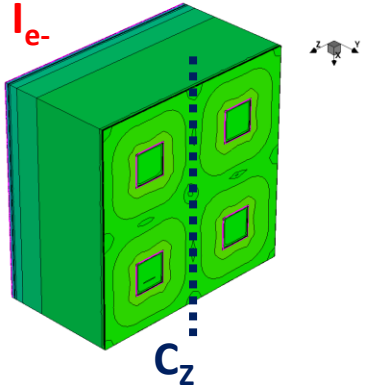
✓ t = 5.00 ns

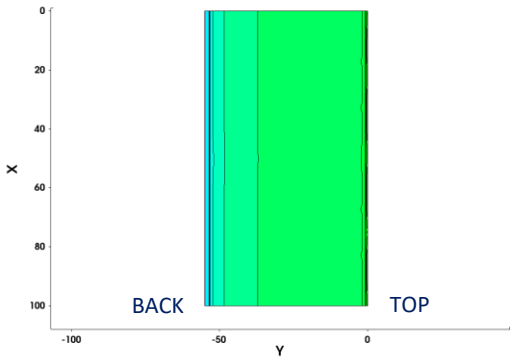



$I_{TOT}$

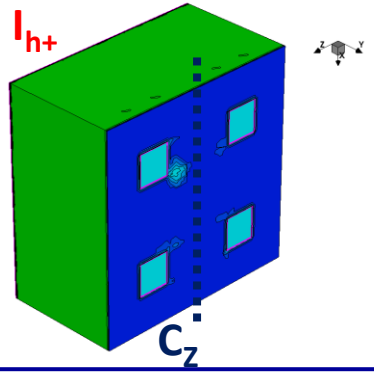


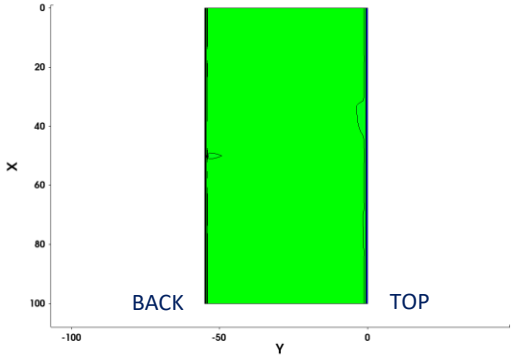

$I_{e-}$




$I_{h+}$



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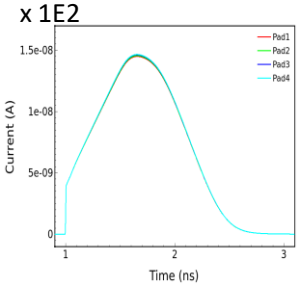
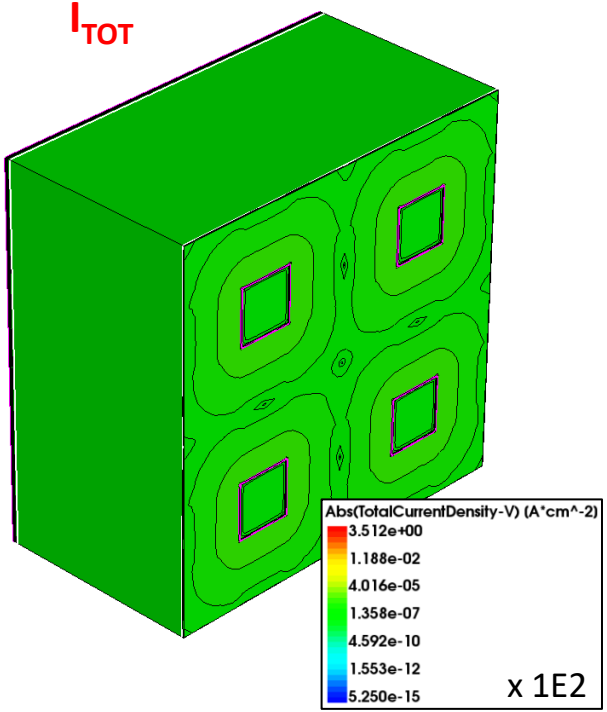
# Transient (TV) behavior

## $C_z$ (Center Cut)

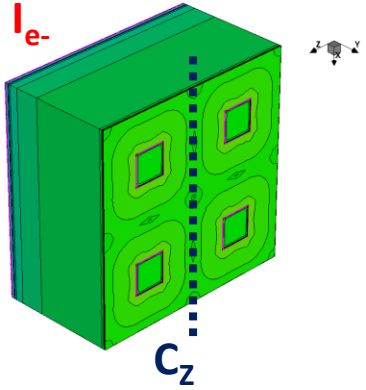
✓ **t = 10.0 ns**

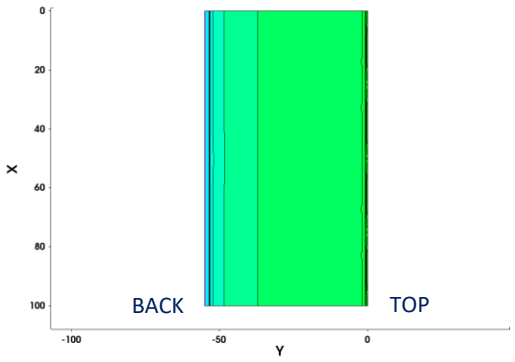



$I_{TOT}$

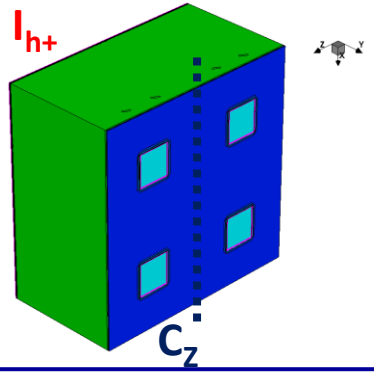


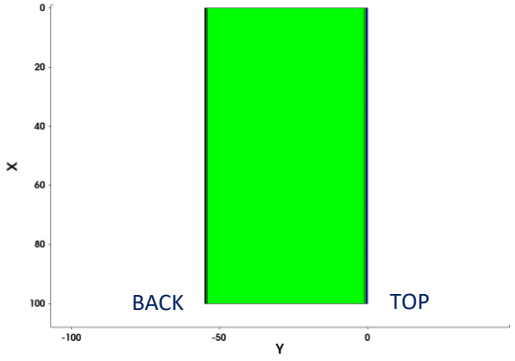

$I_{e-}$




$I_{h+}$

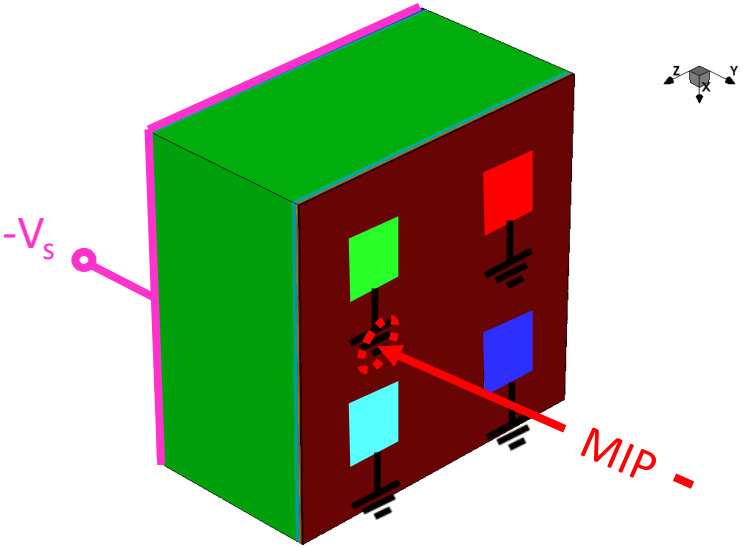


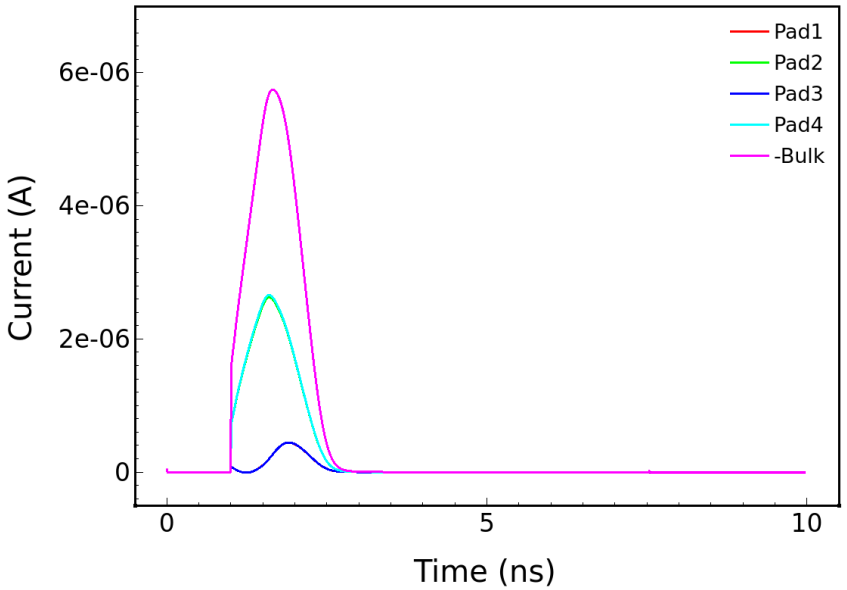
# Transient (TV) behavior (2/7)

- ✓ **3D** structure, **2x2 PADs**
  - **hit 2**, **1 MIP**
  - **$V_s$ = -200 V**

**@ $R_{s,n++} \approx 203\ \Omega_{sq}$**




**I-t,** not irr.

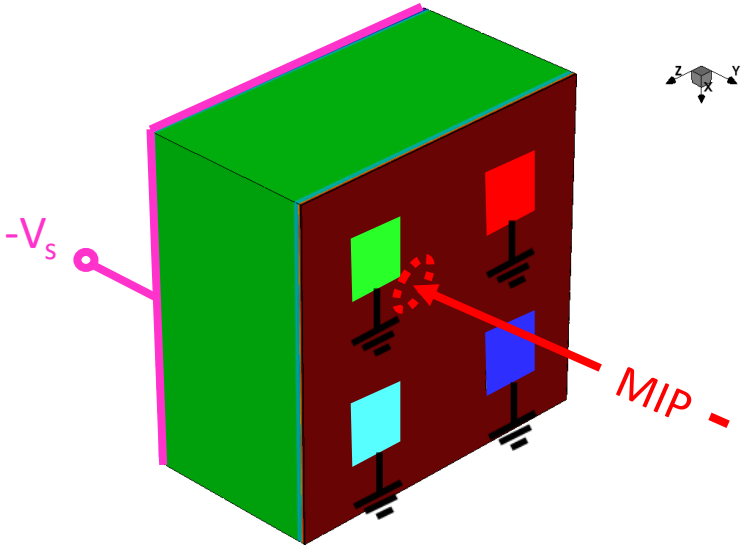



Avalanche model: **Massey**. Temperature **300 K**

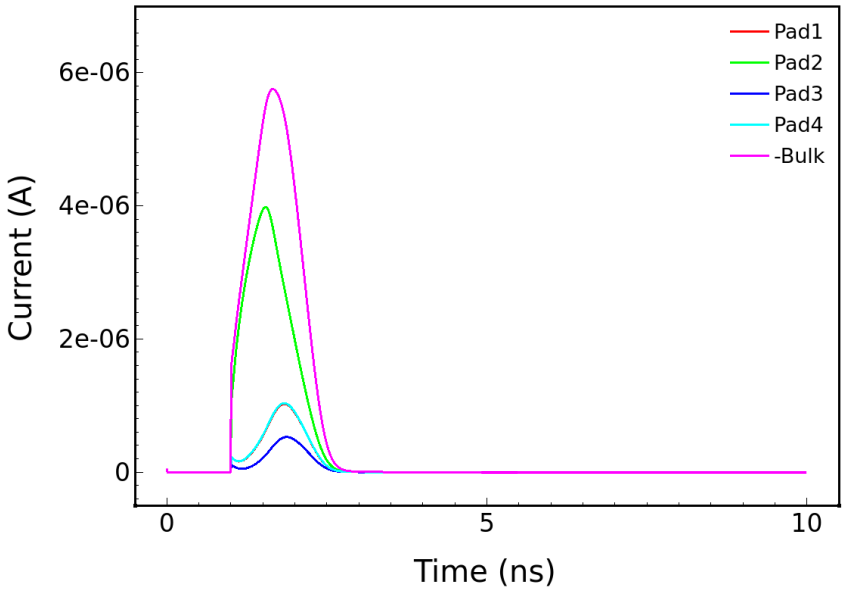
# Transient (TV) behavior (3/7)

- ✓ **3D** structure, **2x2 PADs**
  - **hit 3**, **1 MIP**
  - **$V_s$ = -200 V**

**@ $R_{s,n++} \approx 203\ \Omega_{sq}$**




**I-t,** not irr.

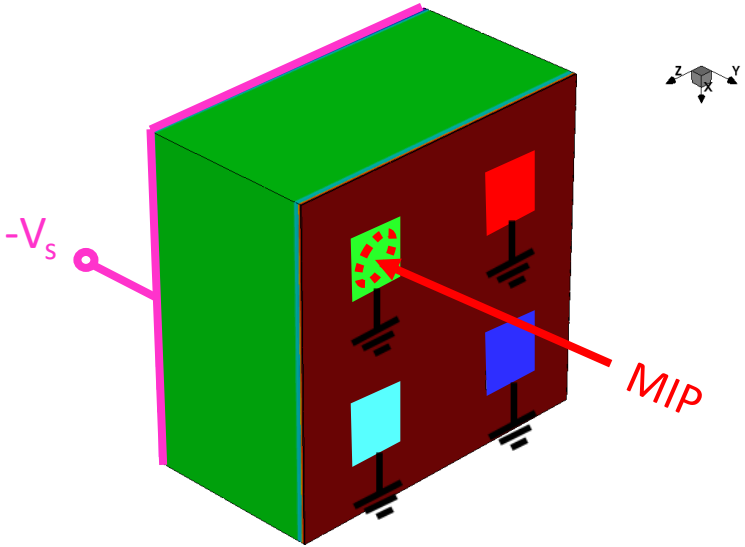



Avalanche model: **Massey**. Temperature **300 K**

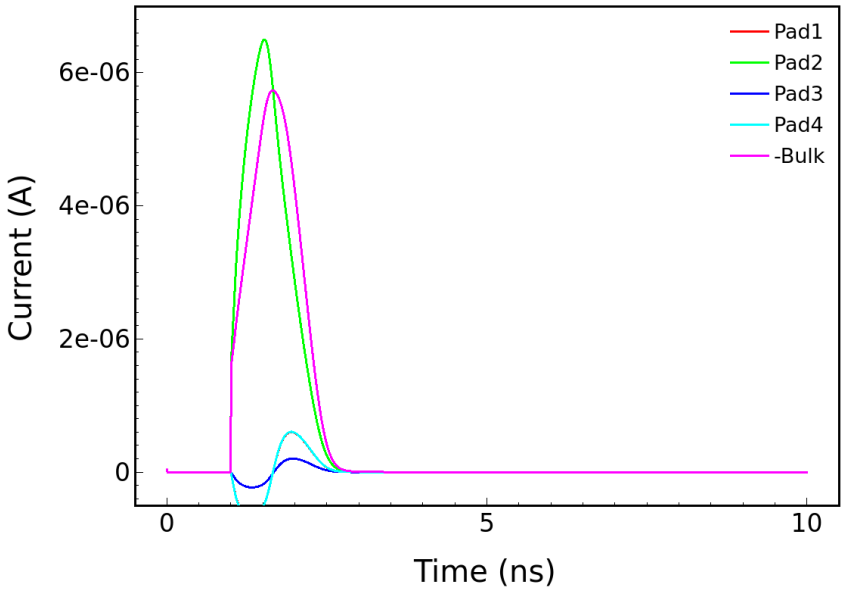
# Transient (TV) behavior (4/7)

- ✓ **3D** structure, **2x2 PADs**
  - **hit 4**, **1 MIP**
  - **$V_s$ = -200 V**

**@ $R_{s,n++} \approx 203\ \Omega_{sq}$**




**I-t,** not irr.

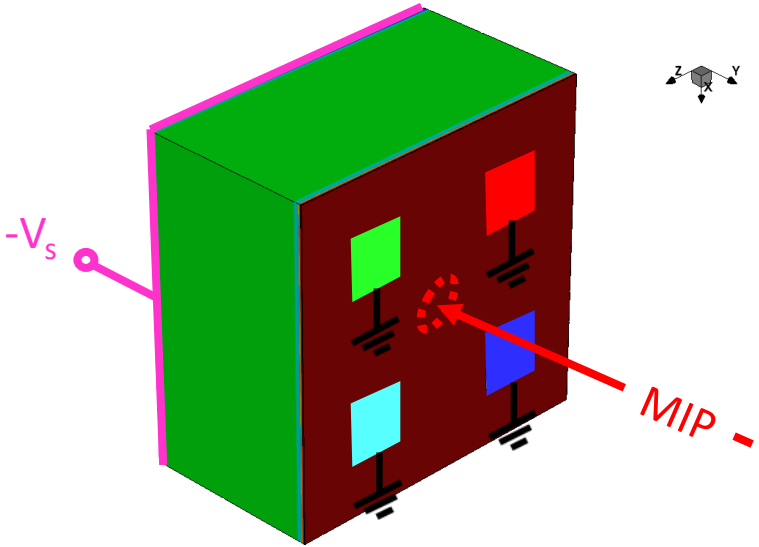



Avalanche model: **Massey**. Temperature **300 K**

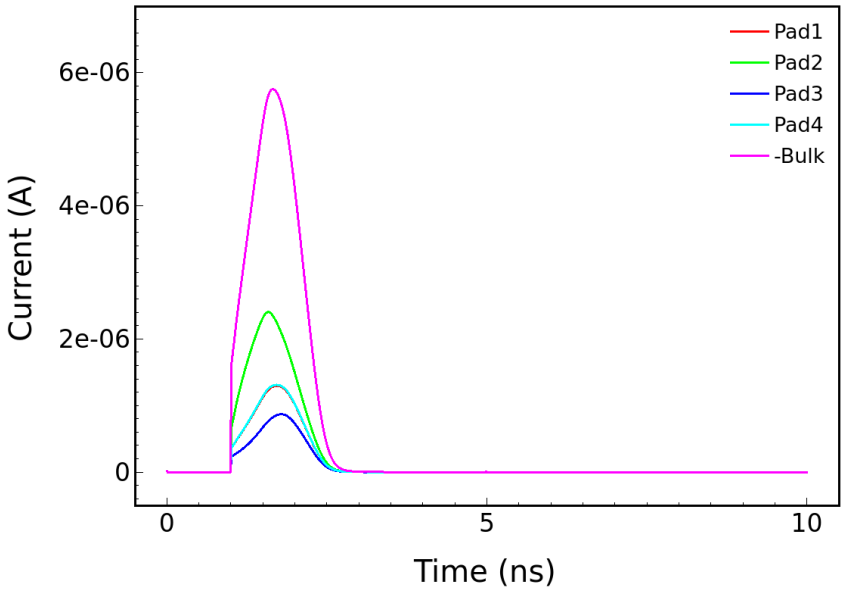
# Transient (TV) behavior (5/7)

- ✓ **3D** structure, **2x2 PADs**
  - **hit 5**, **1 MIP**
  - **$V_s$ = -200 V**

**@ $R_{s,n++} \approx 203\ \Omega_{sq}$**




**I-t,** not irr.

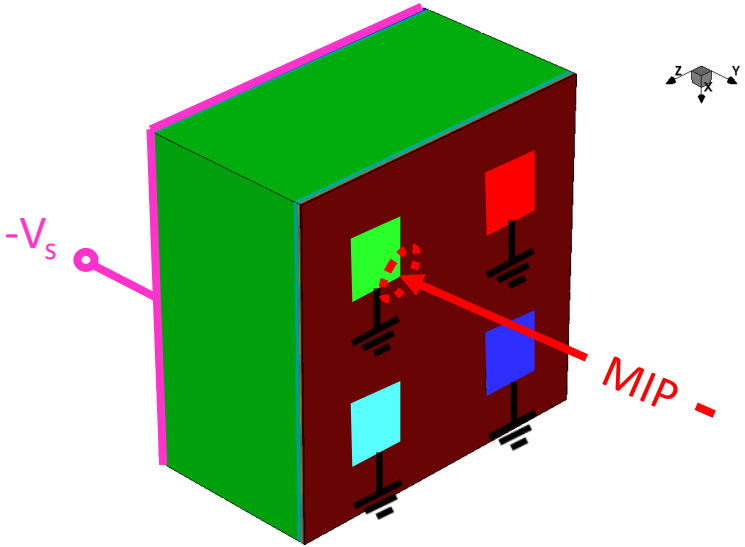



Avalanche model: **Massey**. Temperature **300 K**

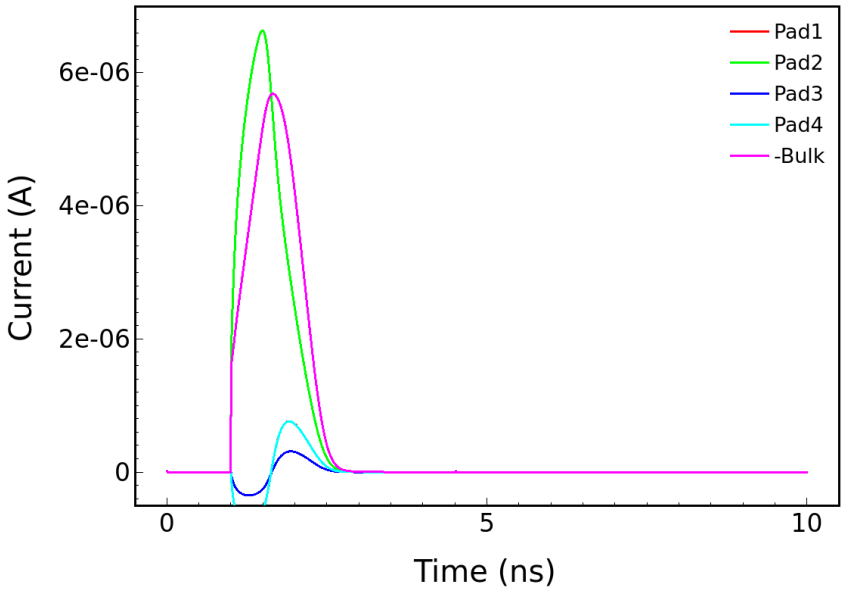
# Transient (TV) behavior (6/7)

- ✓ **3D** structure, **2x2 PADs**
  - **hit 6**, **1 MIP**
  - $V_s$ = **-200 V**

@ $R_{s,n++} \approx 203\ \Omega_{sq}$




**I-t,** not irr.

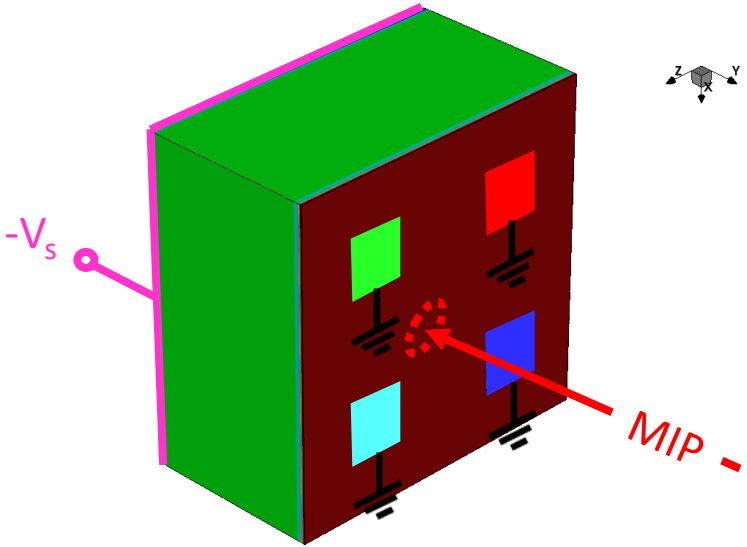



Avalanche model: **Massey**. Temperature **300 K**

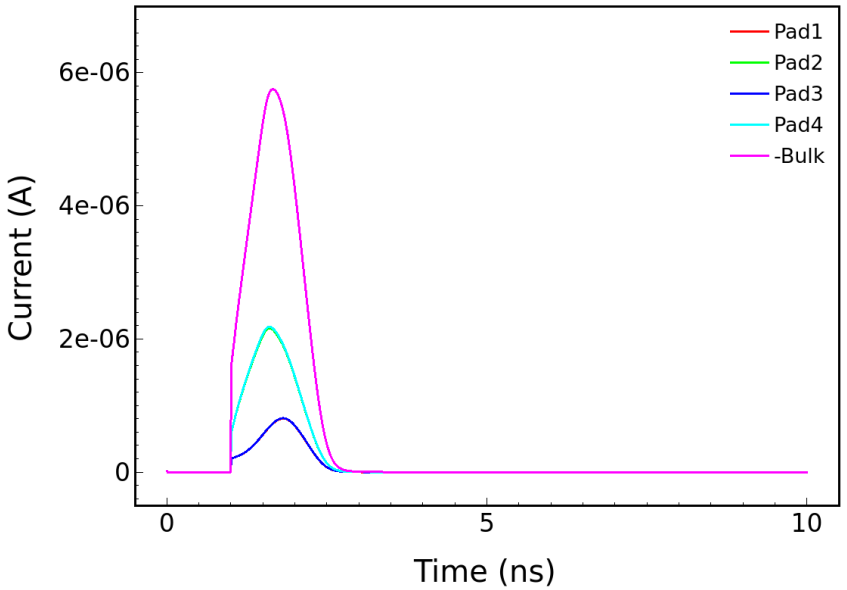
# Transient (TV) behavior (7/7)

- ✓ **3D** structure, **2x2 PADs**
  - **hit 7**, **1 MIP**
  - **$V_s$ = -200 V**

**@ $R_{s,n++} \approx 203\ \Omega_{sq}$**




**I-t,** not irr.




Avalanche model: **Massey**. Temperature **300 K**