Next-generation LGADs: A Measurement-Simulation Synergy to Quantify Donor Removal

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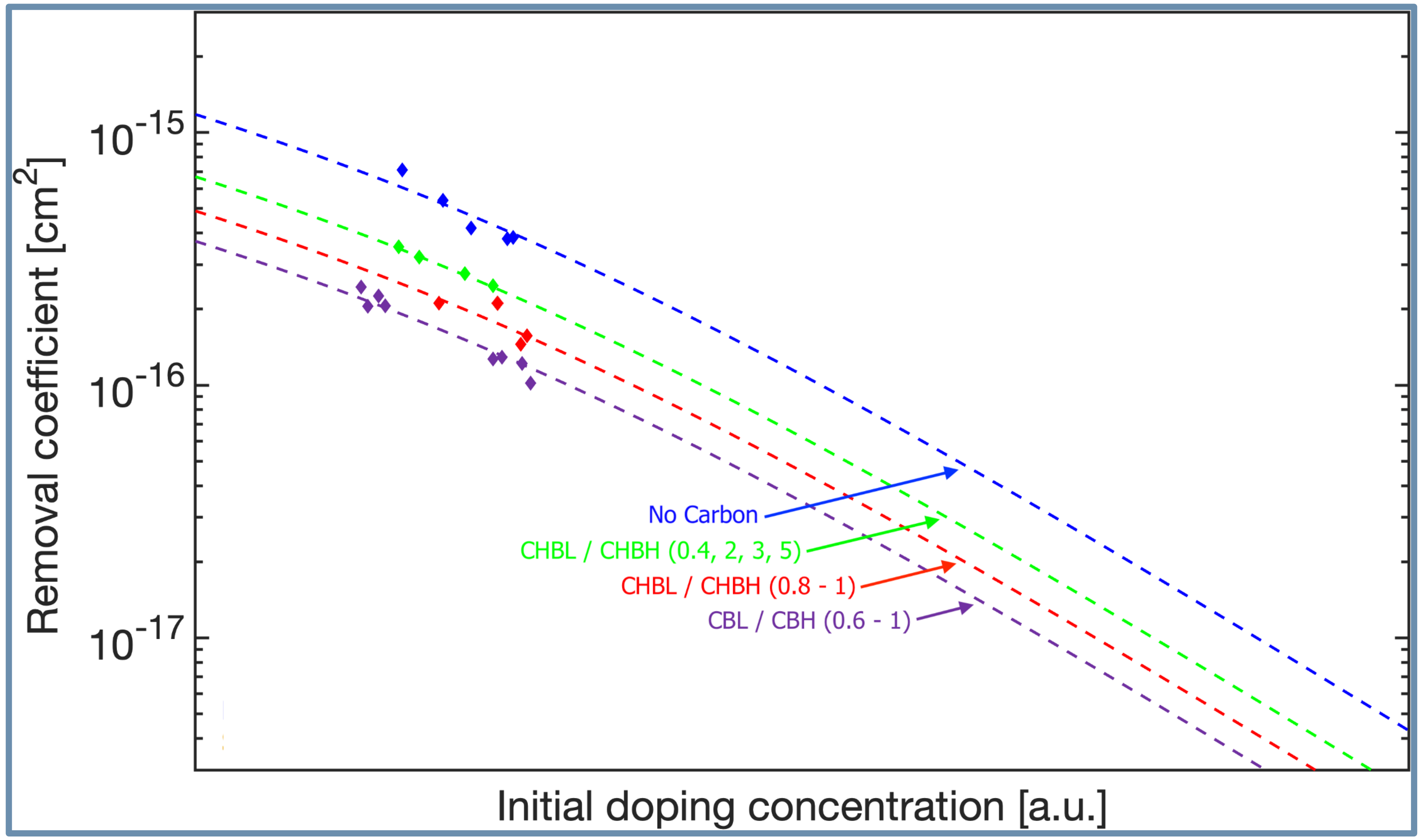
iOM ISTITUTO OFFICINA DEI MATERIALI
KIT Karlsruher Institut für Technologie

VERTEX 2025: 33rd International Workshop on Vertex Detectors

Defining the Challenge

Acceptor removal (→ lower gain → worse timing resolution) has been studied in detail for many years and is at the core of the LGADs' radiation hardness.

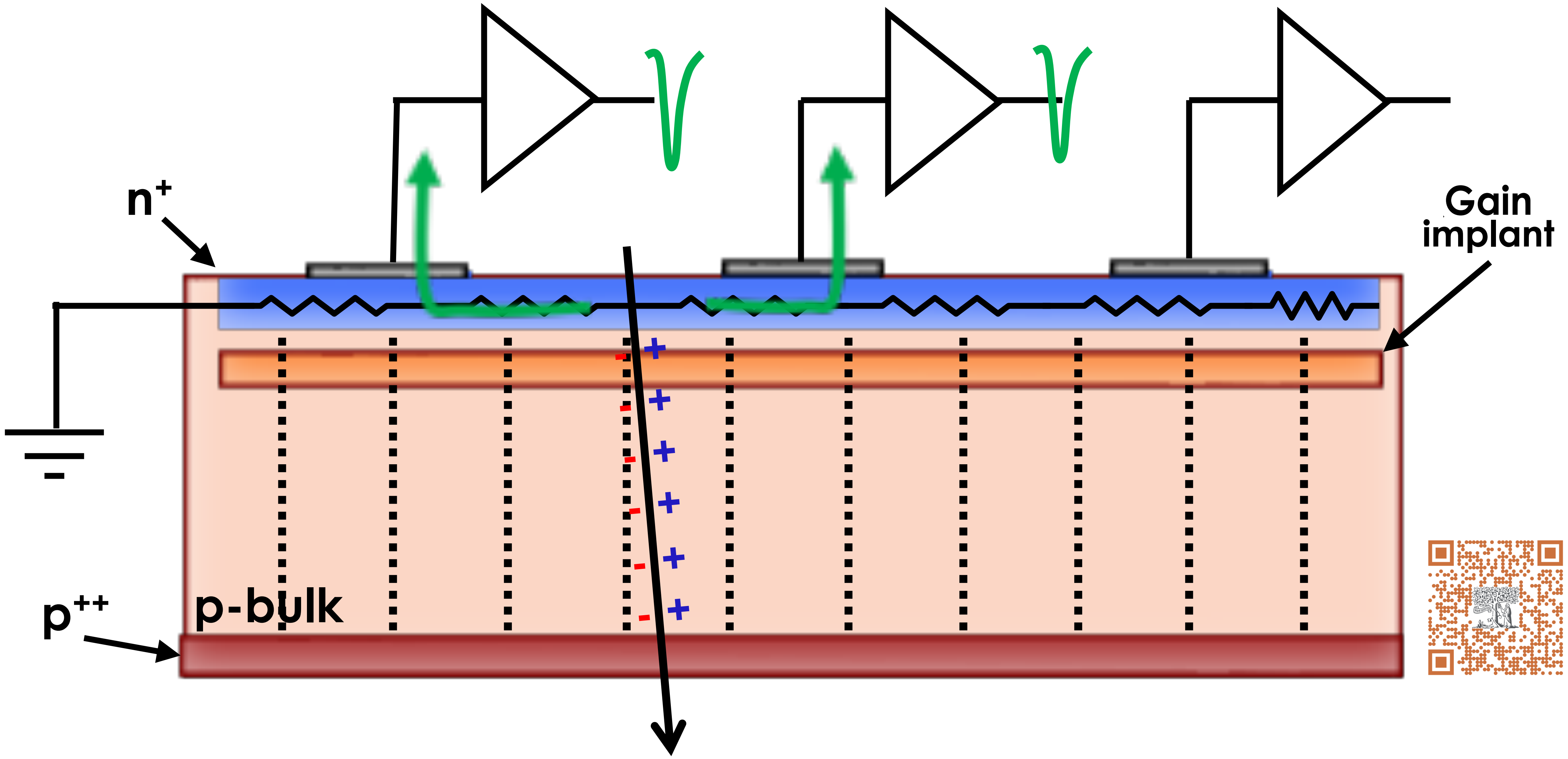


Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and compensated LGADs.

Defining the Challenge

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of **resistive LGADs** and compensated LGADs.

Donor removal = change in sheet resistance → could impact charge sharing and degrade spatial resolution.



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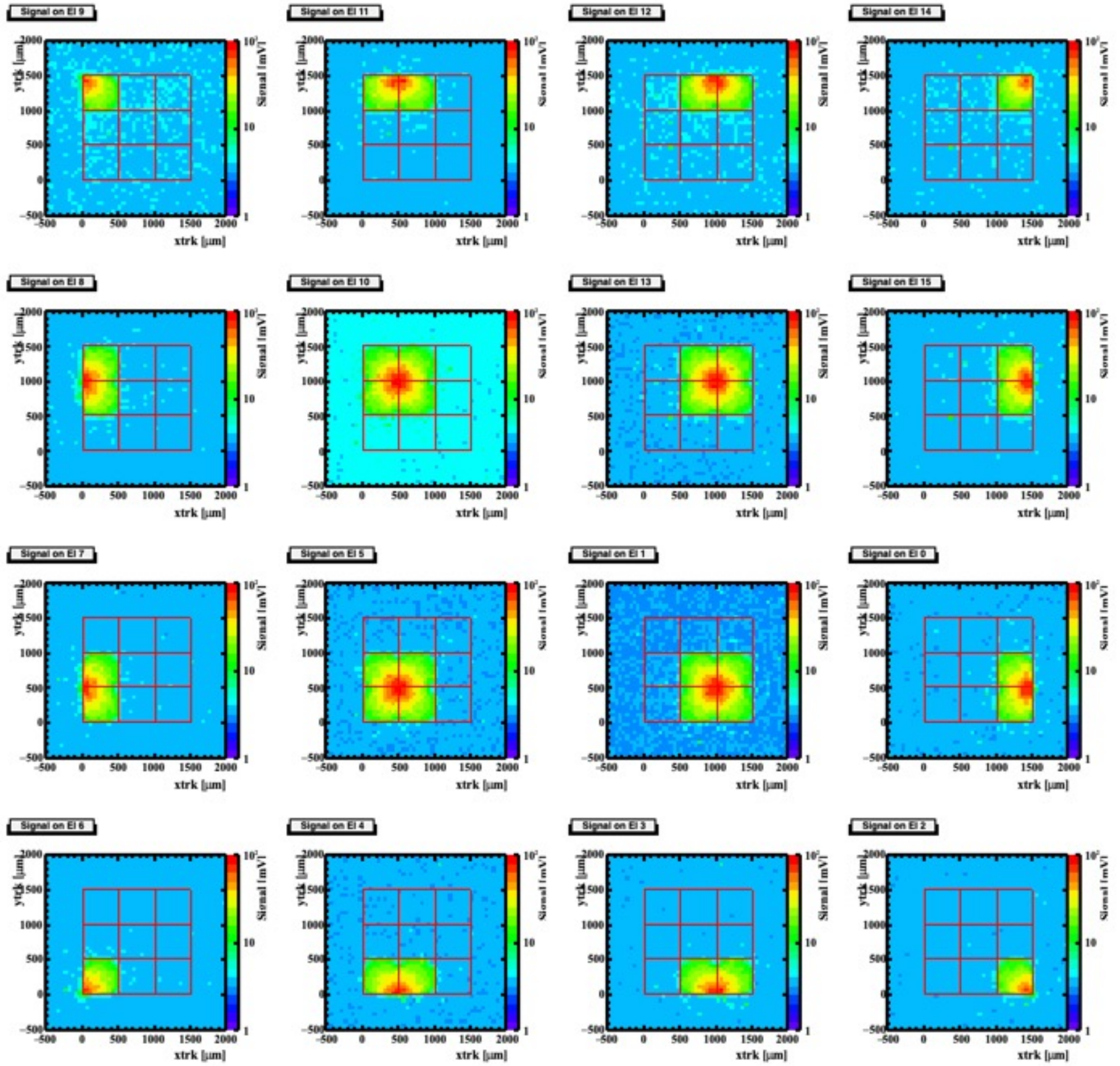

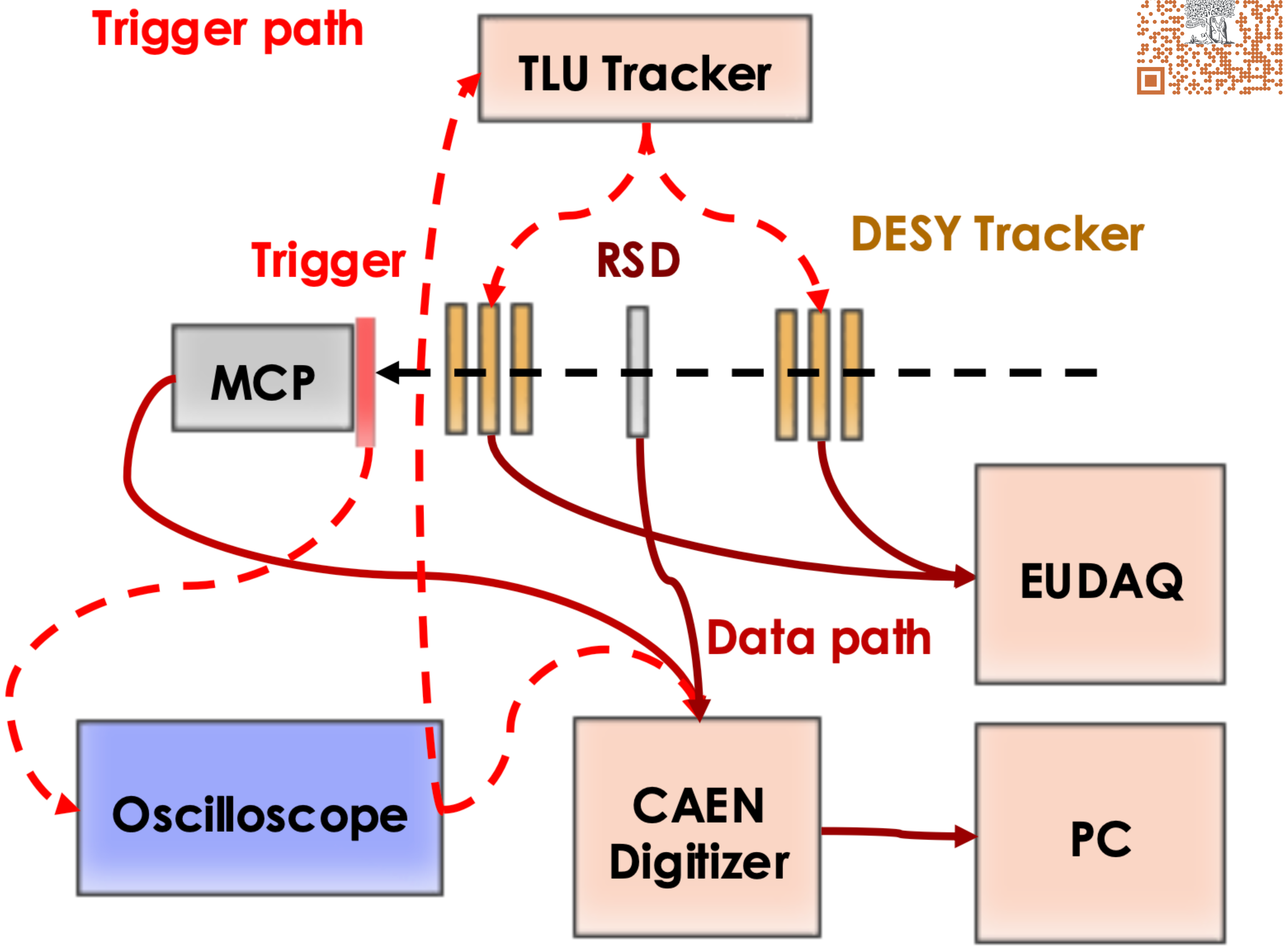

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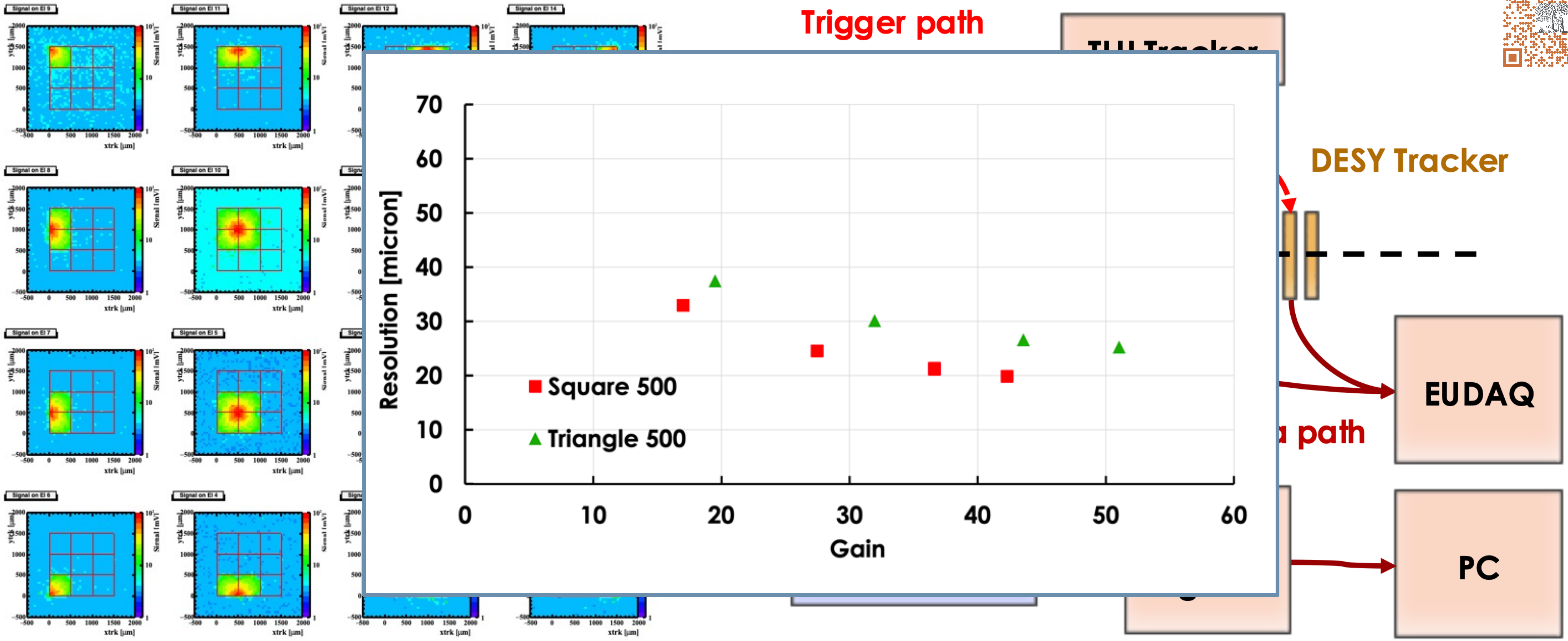

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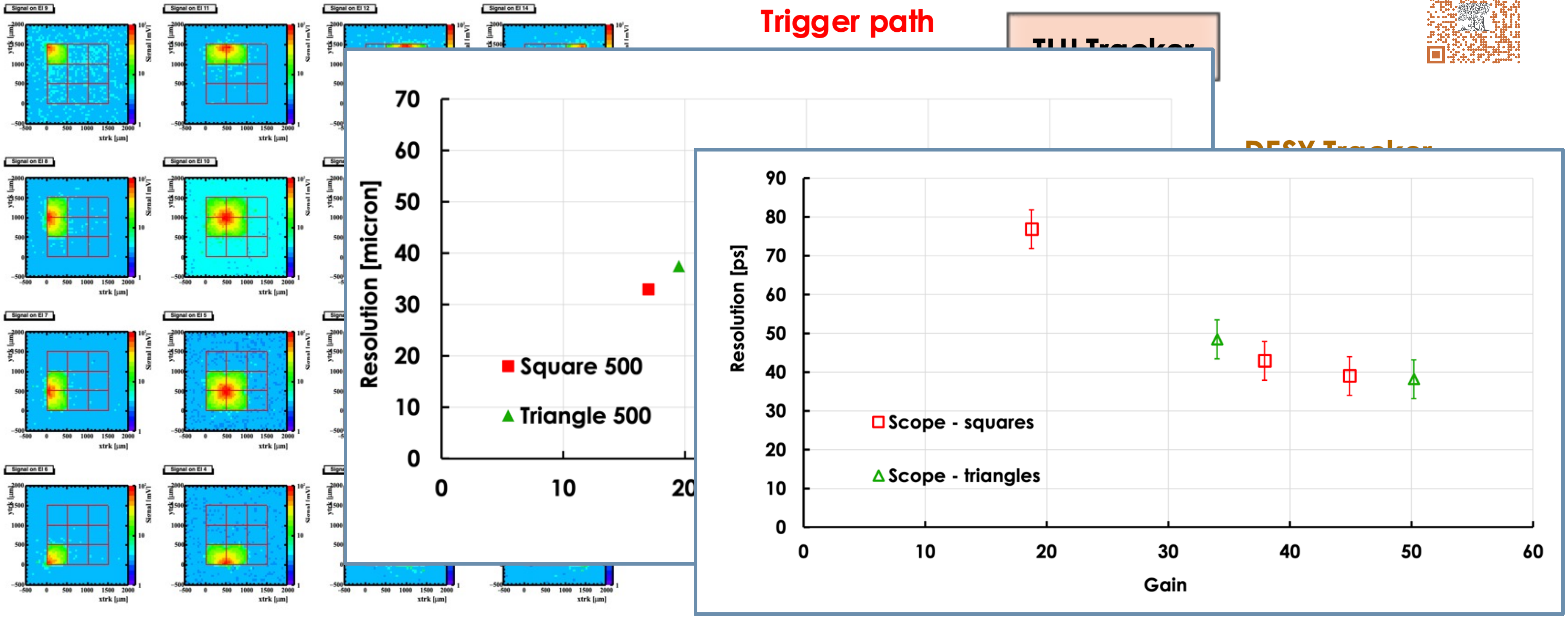

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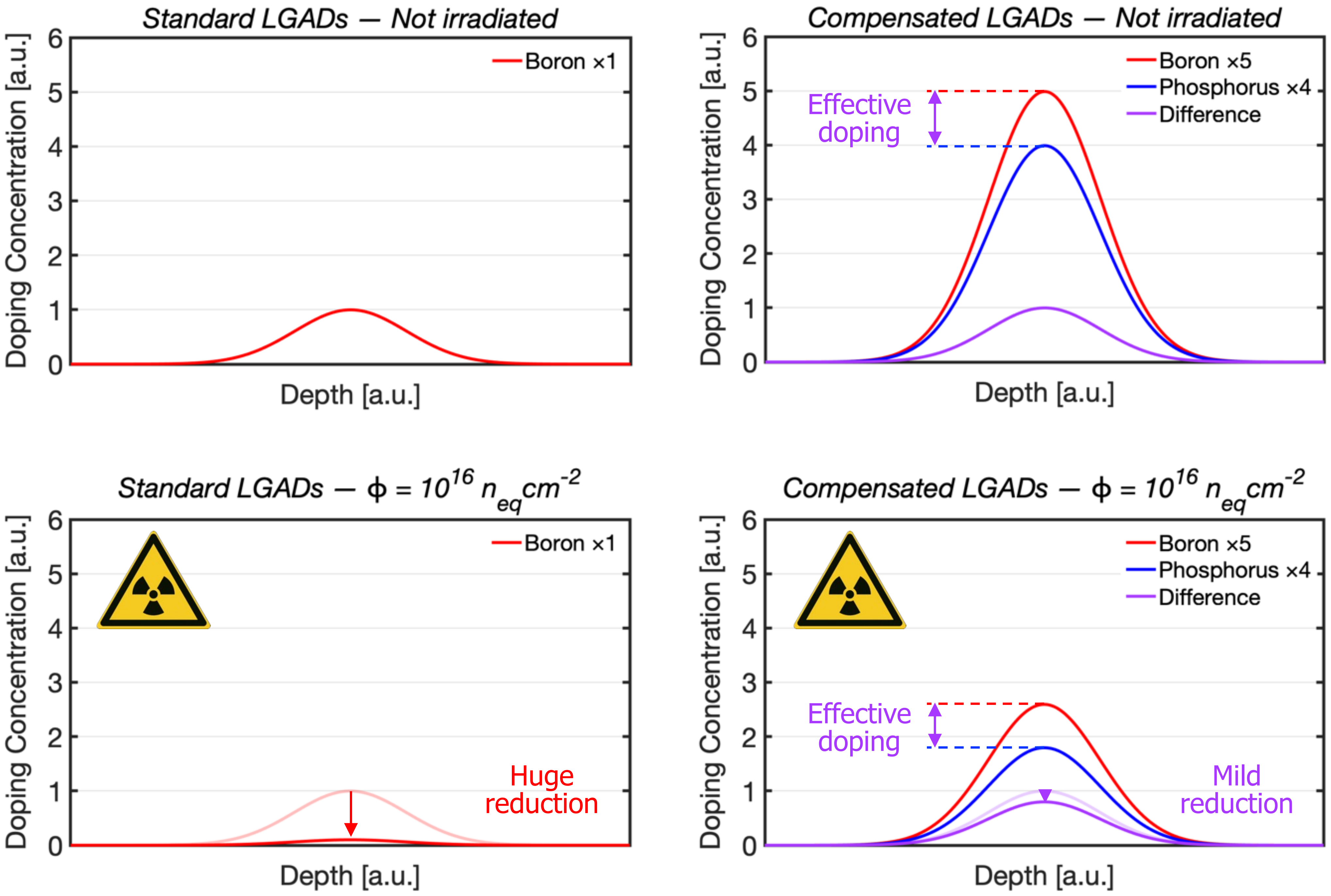

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Defining the Challenge

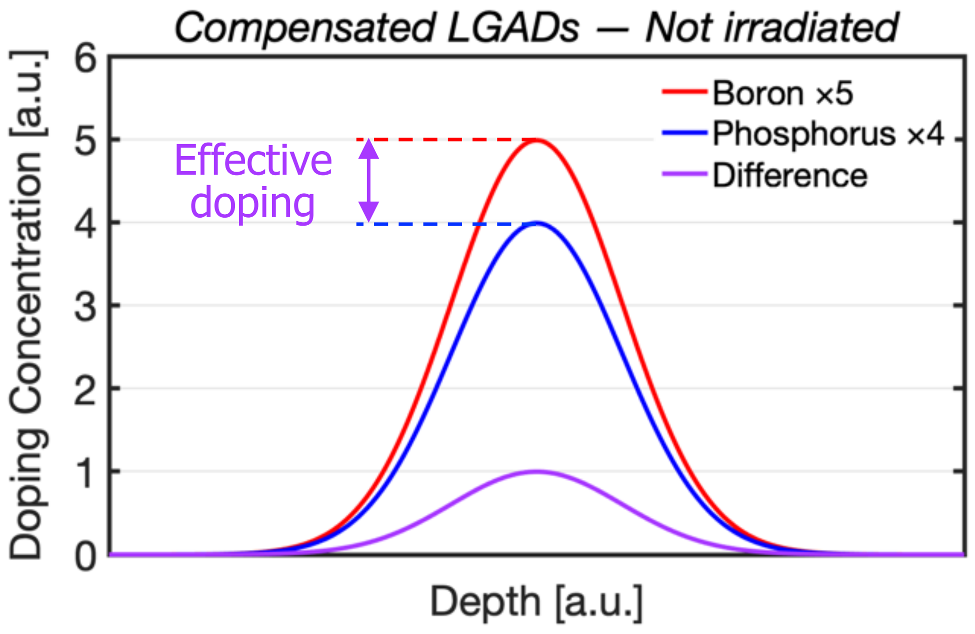
Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and **compensated LGADs**.

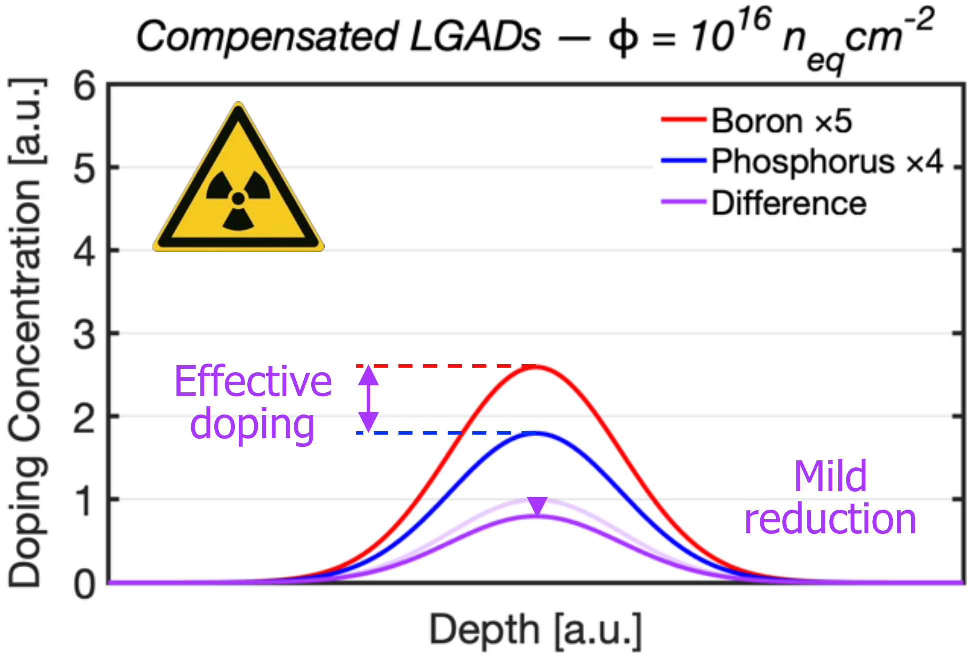
EXFLU1's split table

[a < b < c]
[2c < 3a]

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

Active thickness 30 µm





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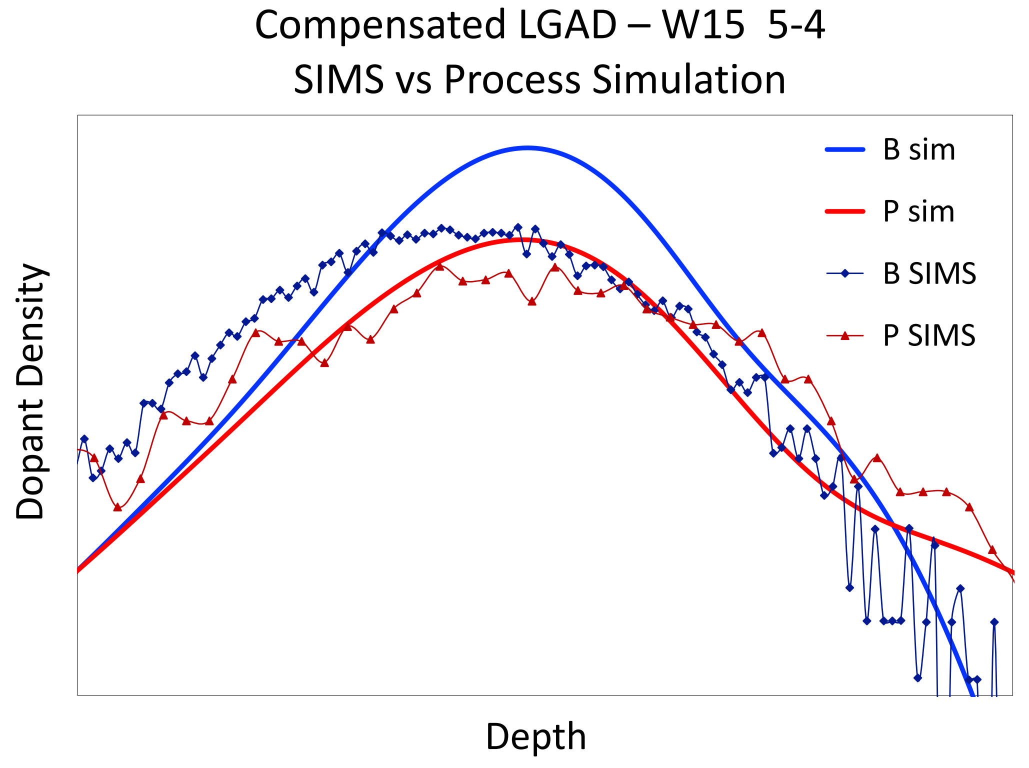
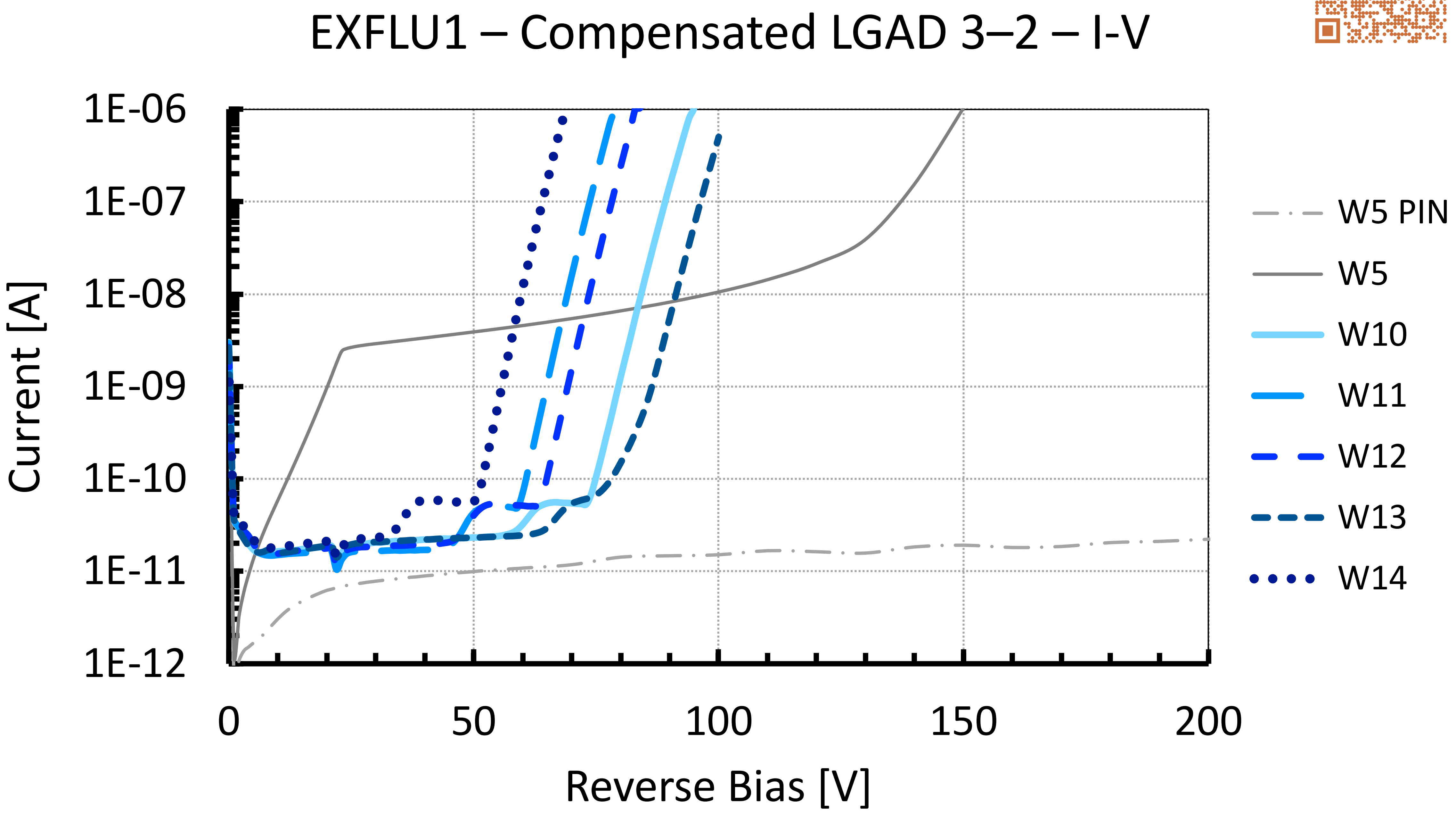


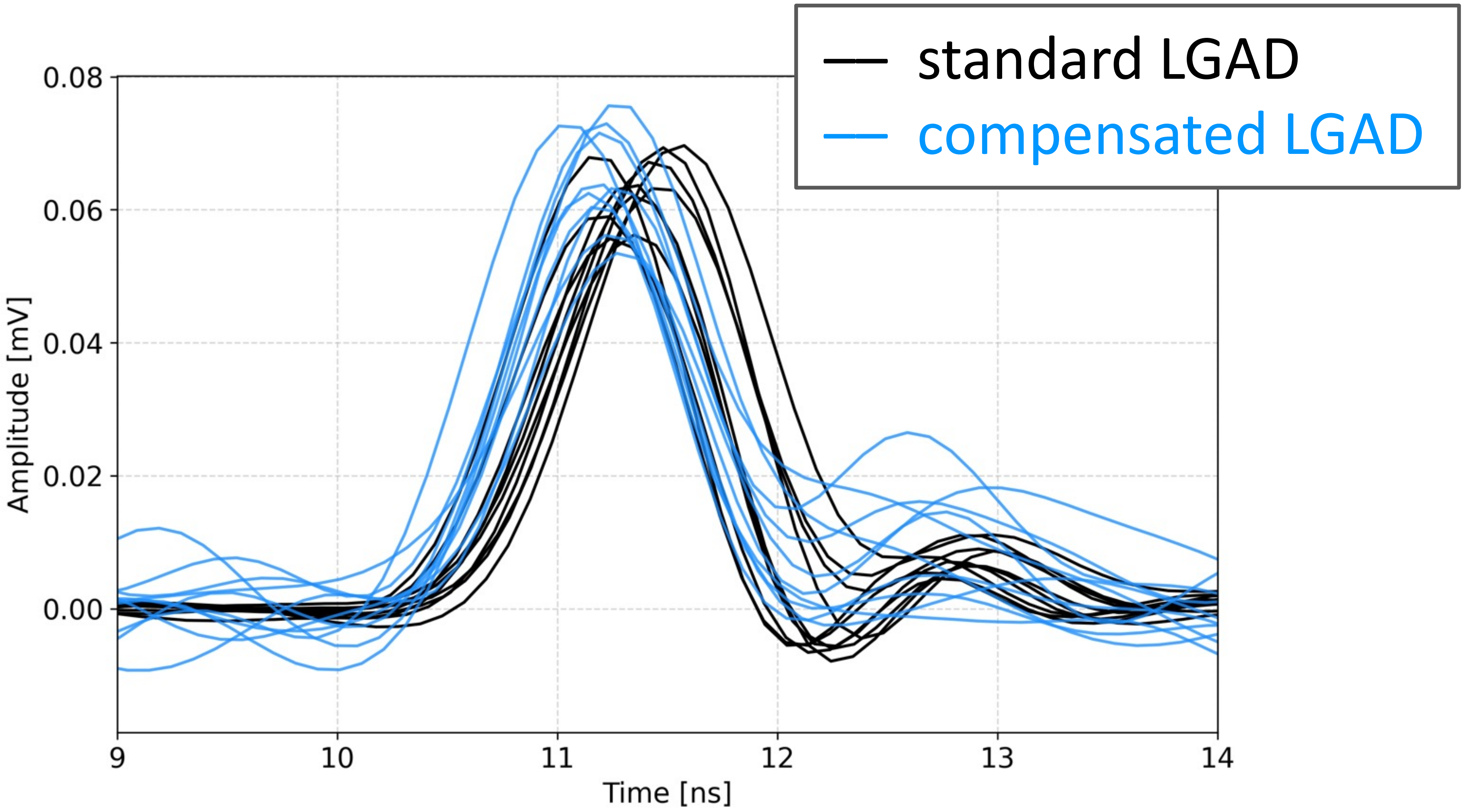
- Boron peak is shallower than phosphorus;
- Boron peak is lower than predicted from process simulation.

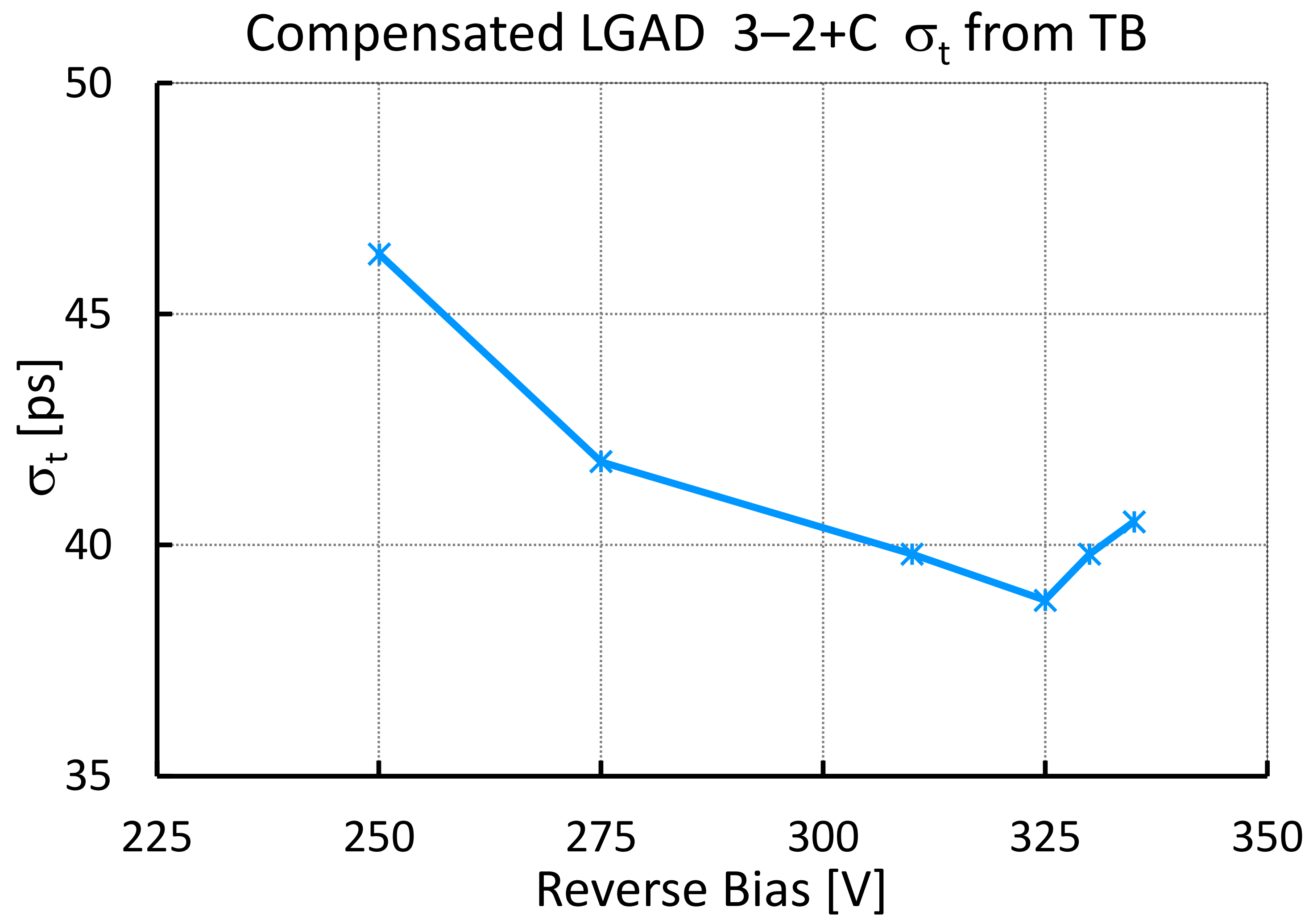


Defining the Challenge

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and **compensated LGADs**.

3–2+C compensated LGAD from W13 irradiated to **$2.5\cdot10^{15}$ n_{eq}/cm^2**



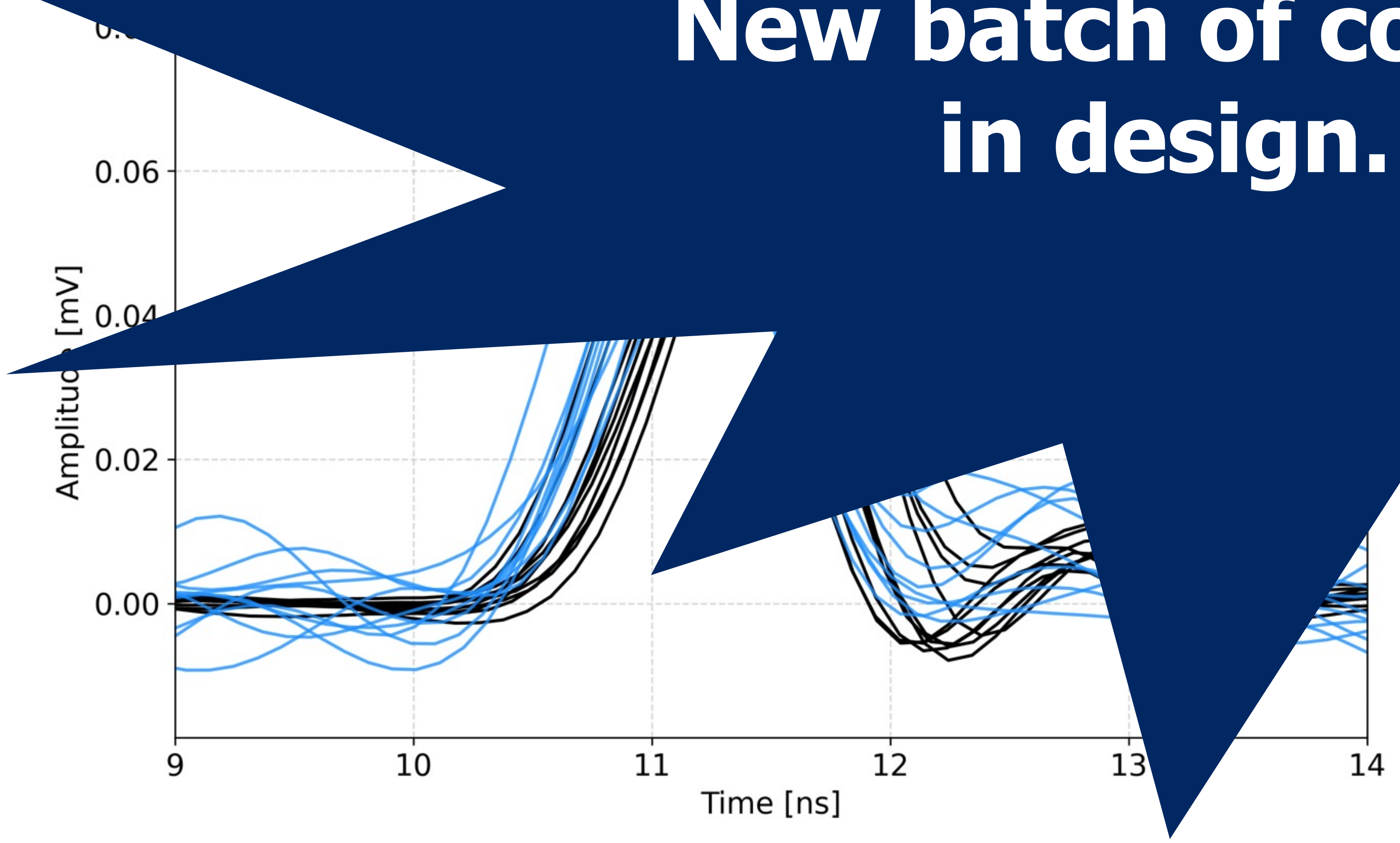


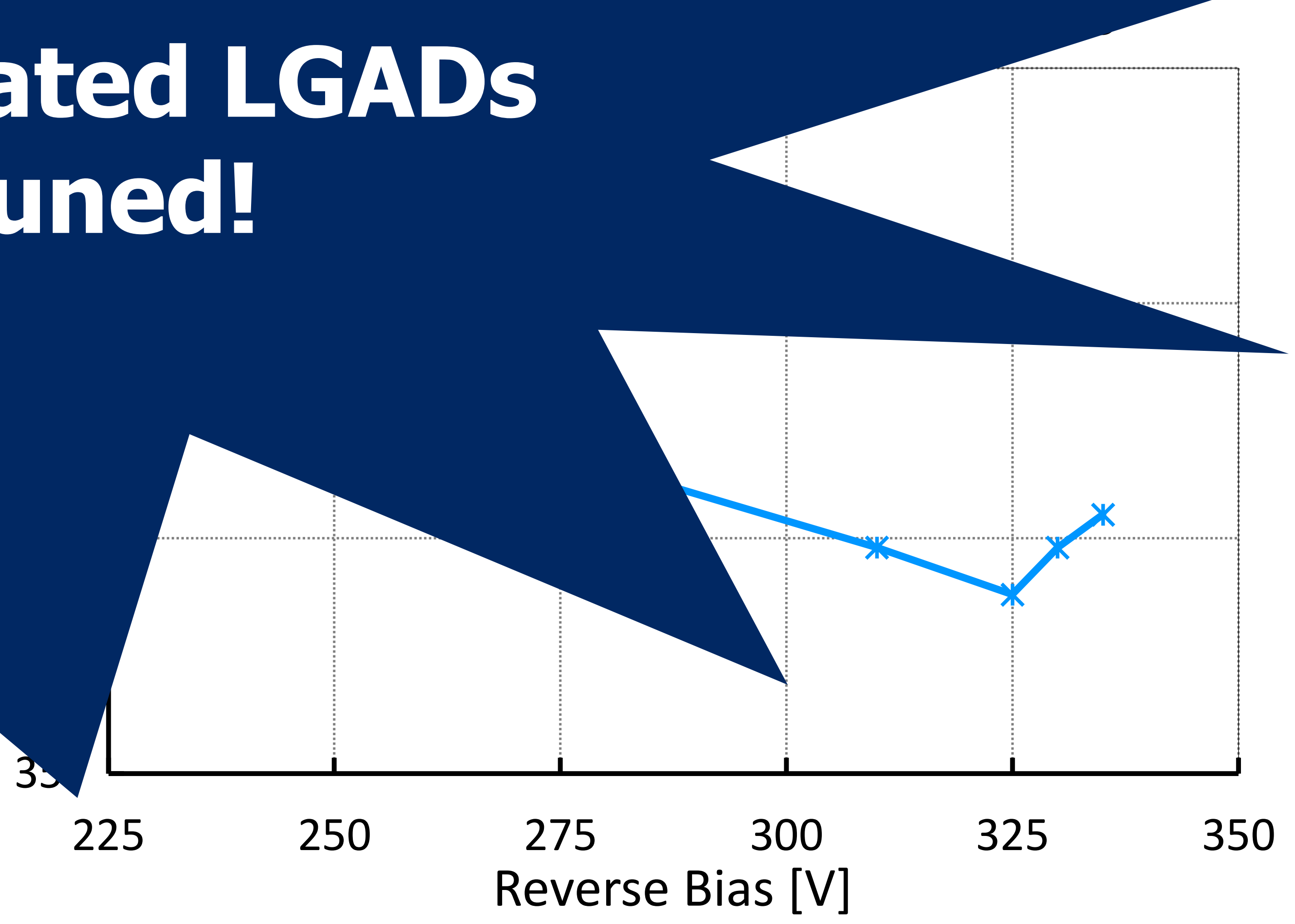
Defining the Challenge

Donor removal is now becoming very interesting as i plays a crucial role in the functioning of resistive LGADs and **compensate ADs**.

3- ensated W1 $_{eq}$**/cm^2**

New batch of compensated LGADs in design… stay tuned!





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Defining the Challenge, Designing the Approach

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and compensated LGADs.

A Measurement – Simulation Synergy to Quantify Donor Removal at high initial concentrations ($N_D > 10^{15}$ atoms/cm^3)

Van der Pauw test structures

A clean environment (a dedicated test structure for each implant under study) to investigate donor removal by examining the change in sheet resistance with irradiation.

RSD2 batch NPLUS test structures (TS) irradiated (n and p) and analysed; DC-RSD1 batch NPLUS TS irradiated (n) and analysed; NLGAD batch NGAIN TS will be analysed once FBK realises the batch.

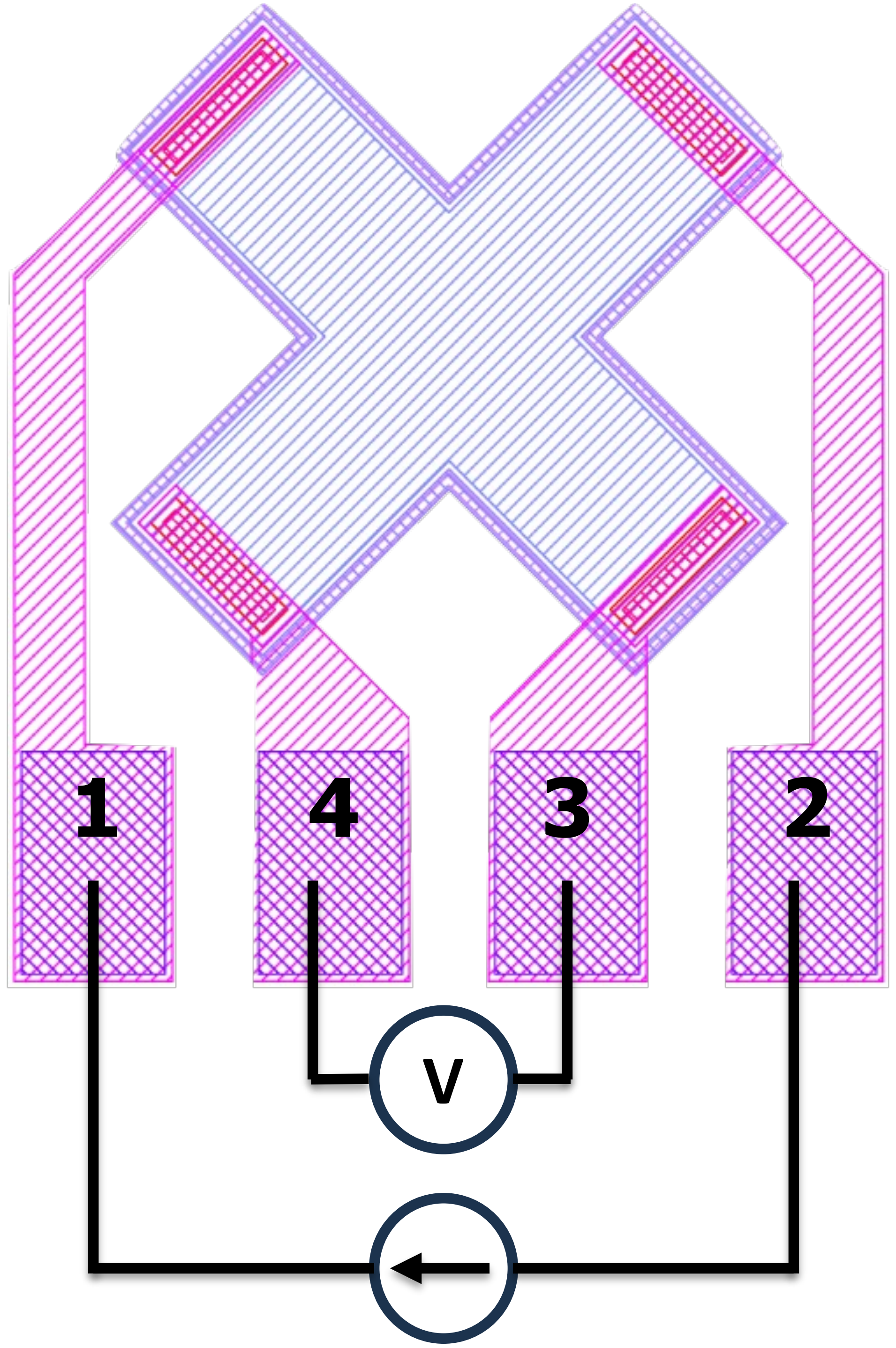
Compensated LGADs

EXFLU1 batch samples offer an opportunity to study donor removal to further initial donor concentrations than those of the previously mentioned samples by reproducing in simulation the capacitance variation with irradiation.

These samples will also enable us to begin examining the interplay between donor removal and acceptor removal (Do acceptor and donor removals behave identically together or alone?).

Van der Pauw test structure

MEASUREMENT SETUP



STEP1 Apply a known current $\mathbf{I_{12}}$

STEP2 Measure the voltage difference $\mathbf{V_{34}}$

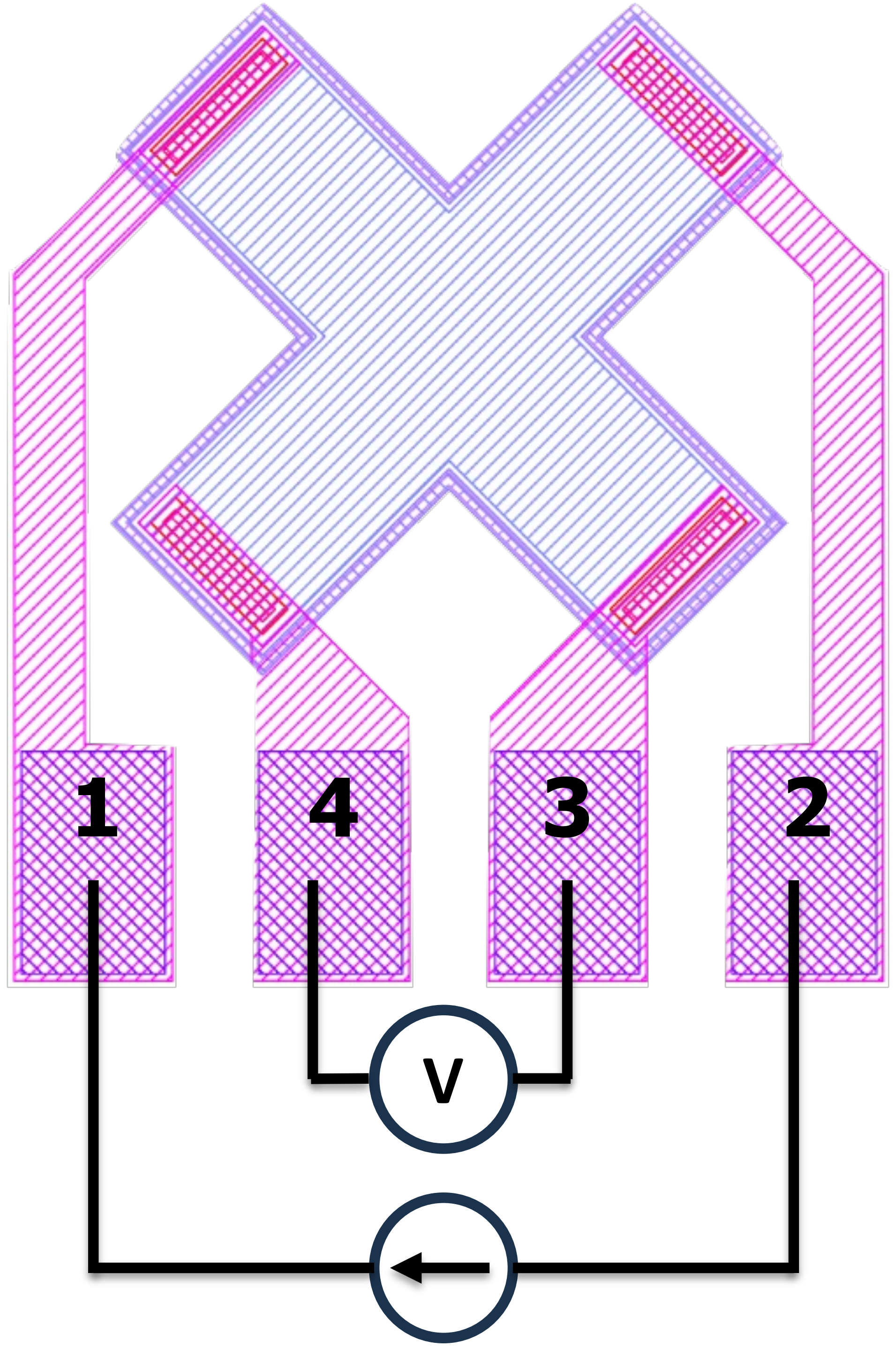
STEP3 Calculate the sheet resistance as

$$R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{34}}{I_{12}}$$

Beware of substrate's parasitic contribution

Van der Pauw test structure

MEASUREMENT SETUP



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Beware of substrate's parasitic contribution

SIMULATION SETUP

Synopsys® Sentaurus Technology CAD (TCAD) enriched with the New University of Perugia radiation damage model

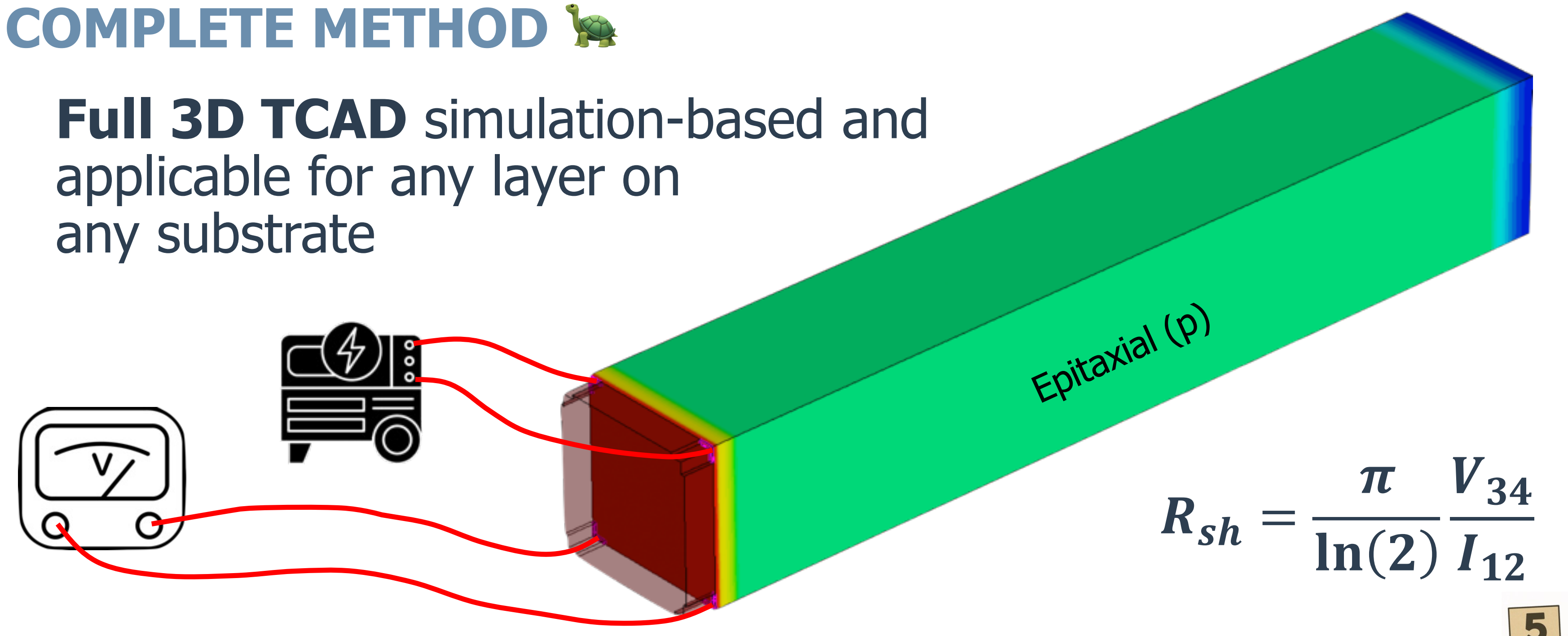
FAST METHOD 🐇

Analytical and only for *p*-layers on a *n*-substrate or *n*-layers on p-substrates

$$R_{sh} = \left[\int_0^d q[n(x)\mu_n(x) + p(x)\mu_p(x)]dx\right]^{-1}$$

COMPLETE METHOD 🐢

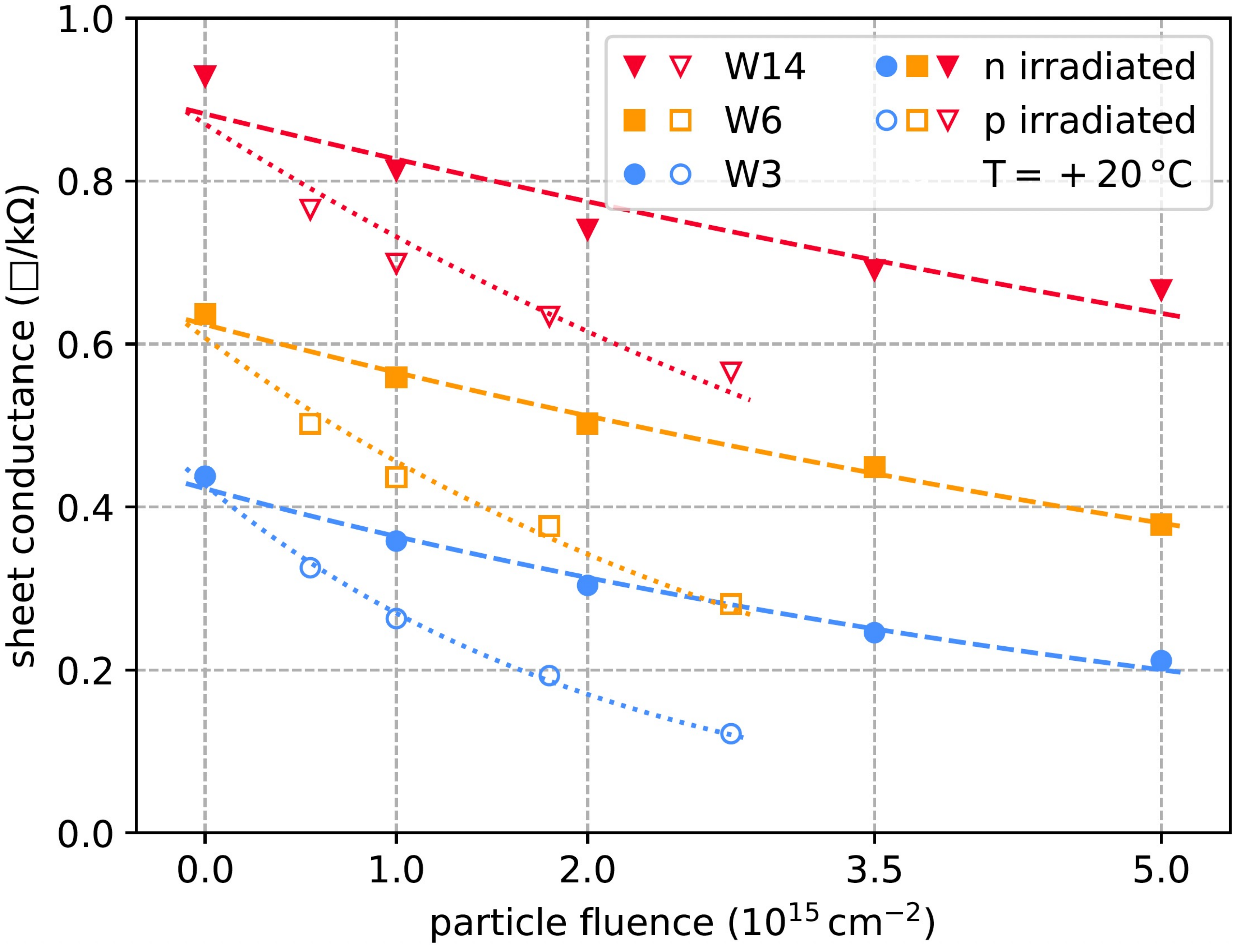
Full 3D TCAD simulation-based and applicable for any layer on any substrate



$$R_{sh} = \frac{\pi}{\ln(2)}\frac{V_{34}}{I_{12}}$$

RSD2 batch — NPLUS

Wafer n.	Sub	Carbon	NPLUS Dose	Dose PGAIN	Met. Thickness
1	Si-Si 55um	N	0.25	2.4	thick
2	Si-Si 55um	N	0.25	2.4	normal
➡ 3	Si-Si 55um	N	0.25	2.45	normal
4	Si-Si 55um	N	0.25	2.5	normal
5	Si-Si 55um	N	0.5	2.5	normal
➡ 6	epi 45 um	N	0.5	2.5	normal
7	Si-Si 55um	N	0.5	2.45	normal
8	epi 45 um	N	0.5	2.4	normal
9	epi 45 um	N	0.5	2.4	normal
10	epi 45 um	Y (1)	0.5	2.4	normal
11	epi 45 um	N	1	2.4	normal
12	epi 45 um	Y (0.8)	1	2.4	normal
13	Si-Si 55um	N	1	2.45	normal
➡ 14	epi 45 um	N	1	2.45	normal
15	Si-Si 55um	N	1	2.35	normal



RSD2 batch — N

c_D donor removal coefficient values $[10^{-16}\ \mathrm{cm}^2]$				
Location	Irradiation	W3	W6	W14
KIT	Neutron	1.5 ± 0.2	1.0 ± 0.2	0.6 ± 0.2
	Proton	4.6 ± 0.4	2.9 ± 0.4	1.7 ± 0.3
Perugia	Neutron	1.6 ± 0.2	1.0 ± 0.2	0.7 ± 0.1
	Proton	4.7 ± 0.6	2.9 ± 0.4	1.7 ± 0.3

	Wafer n.	Sub	Carbon	NPLUS Dose	Dose PGAIN	Met. Thickness
	1	Si-Si 55um	N	0.25	2.4	thick
	2	Si-Si 55um	N	0.25	2.4	normal
➡	3	Si-Si 55um	N	0.25	2.45	normal
	4	Si-Si 55um	N	0.25	2.5	normal
	5	Si-Si 55um	N	0.5	2.5	normal
➡	6	epi 45 um	N	0.5	2.5	normal
	7	Si-Si 55um	N	0.5	2.45	normal
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	11	epi 45 um	N	1	2.4	normal
	12	epi 45 um	Y (0.8)	1	2.4	normal
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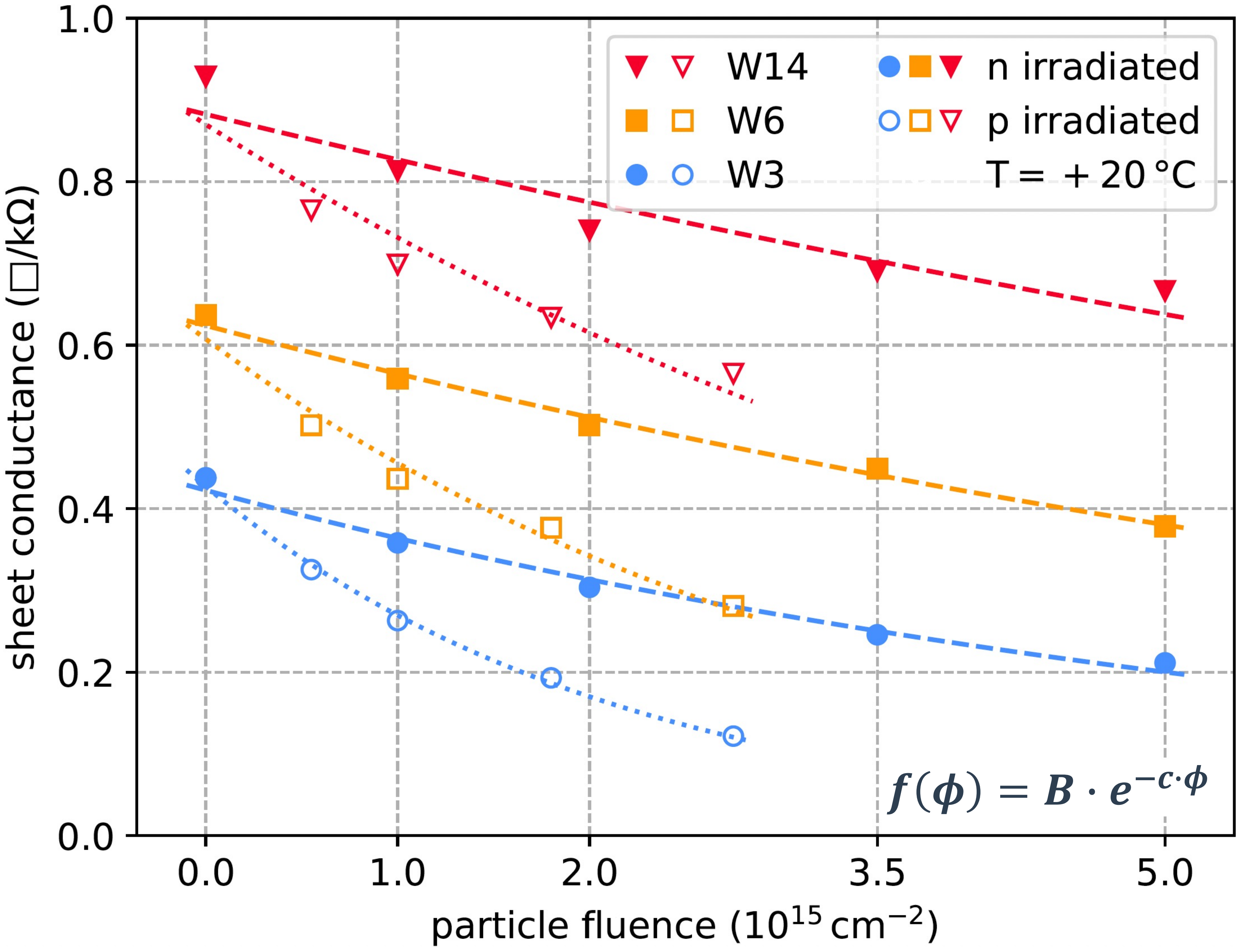
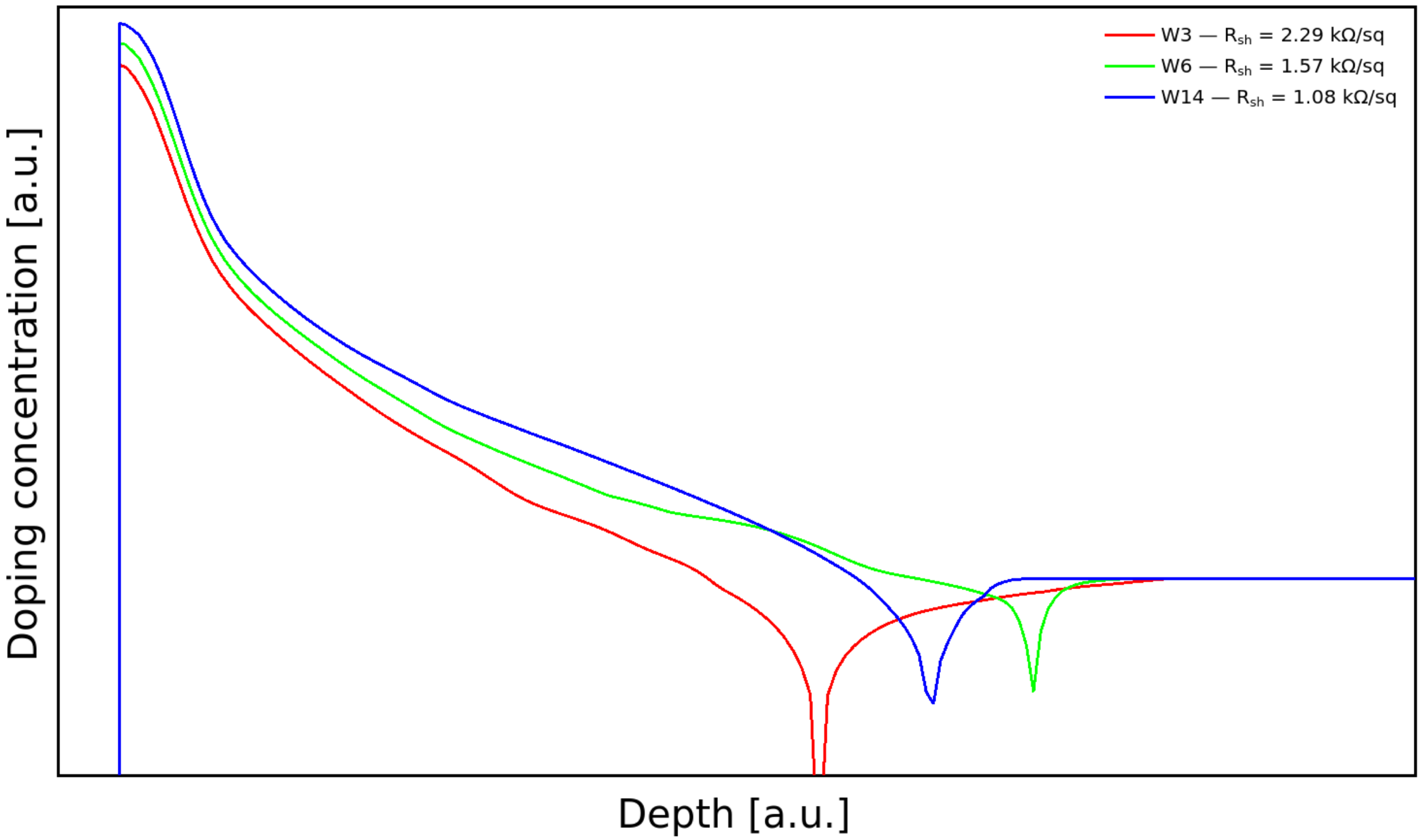
	15	Si-Si 55um	N	1	2.35	normal

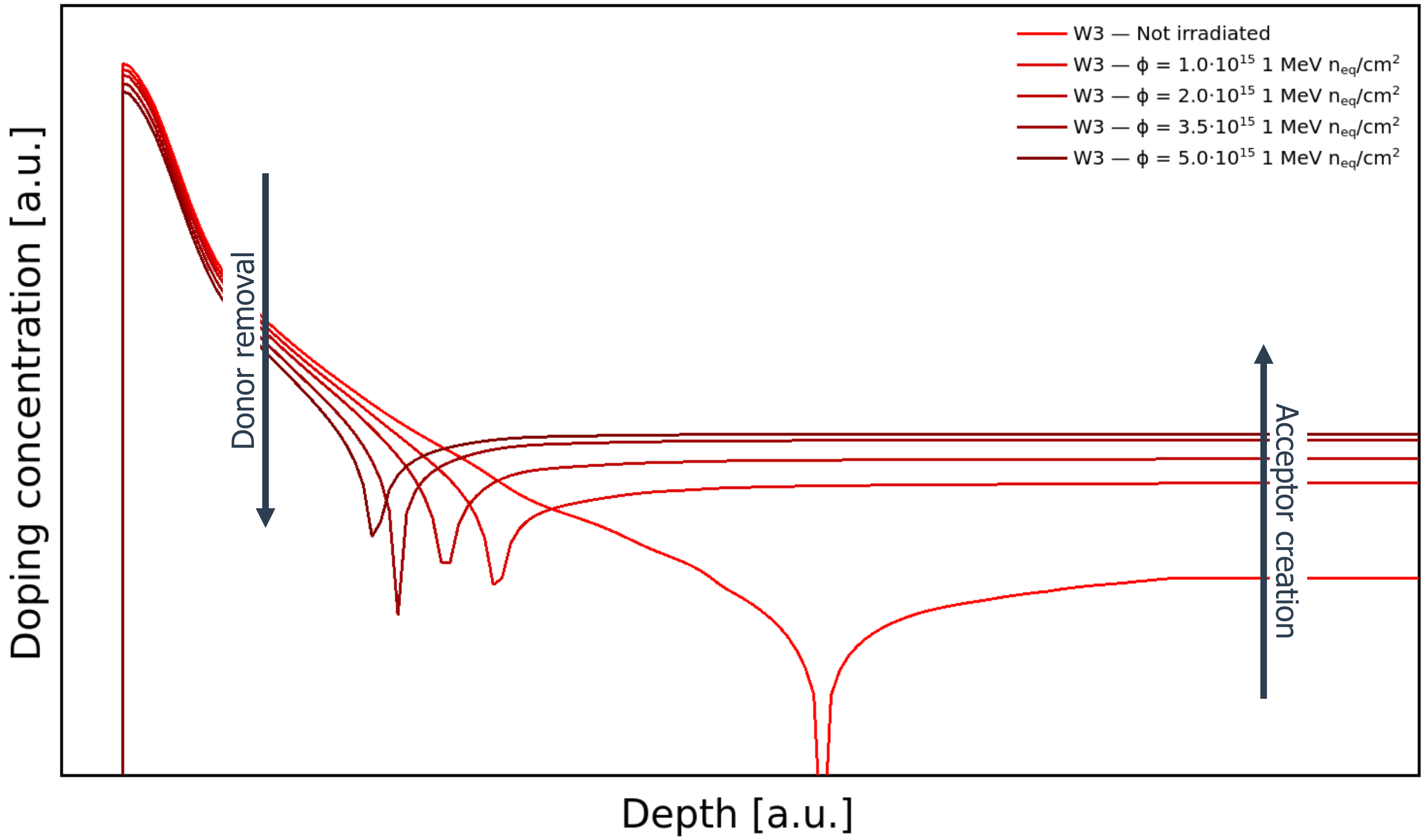


NPLUS profiles before irradiation



New University of Perugia radiation damage model

Doping analytical parameterisation



Donor removal

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

c_D **donor removal coefficient values** $[10^{-16}\ \mathrm{cm}^2]$

Location	Irradiation	W3	W6	W14
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Acceptor creation

$$N_{A,Bulk}(\Phi_{n^0}) = \begin{cases} N_{A,Bulk}(0) + g_c \cdot \Phi_{n^0} & \phi_{n^0} \le 3 \cdot 10^{15}\ 1\ \mathrm{MeV\ n_{eq}/cm^2} \\ 4.17 \cdot 10^{13} \cdot \ln \Phi_{n^0} - 1.41 \cdot 10^{15} & \phi_{n^0} > 3 \cdot 10^{15}\ 1\ \mathrm{MeV\ n_{eq}/cm^2} \end{cases}$$

$$\Phi_{n^0}\,[1\ \mathrm{MeV\ n_{eq}/cm^2}] = \underbrace{2}_{} \cdot \Phi_{p^+}\,[23\ \mathrm{MeV\ p^+/cm^2}]$$

https://www.etp.kit.edu/english/1669.php

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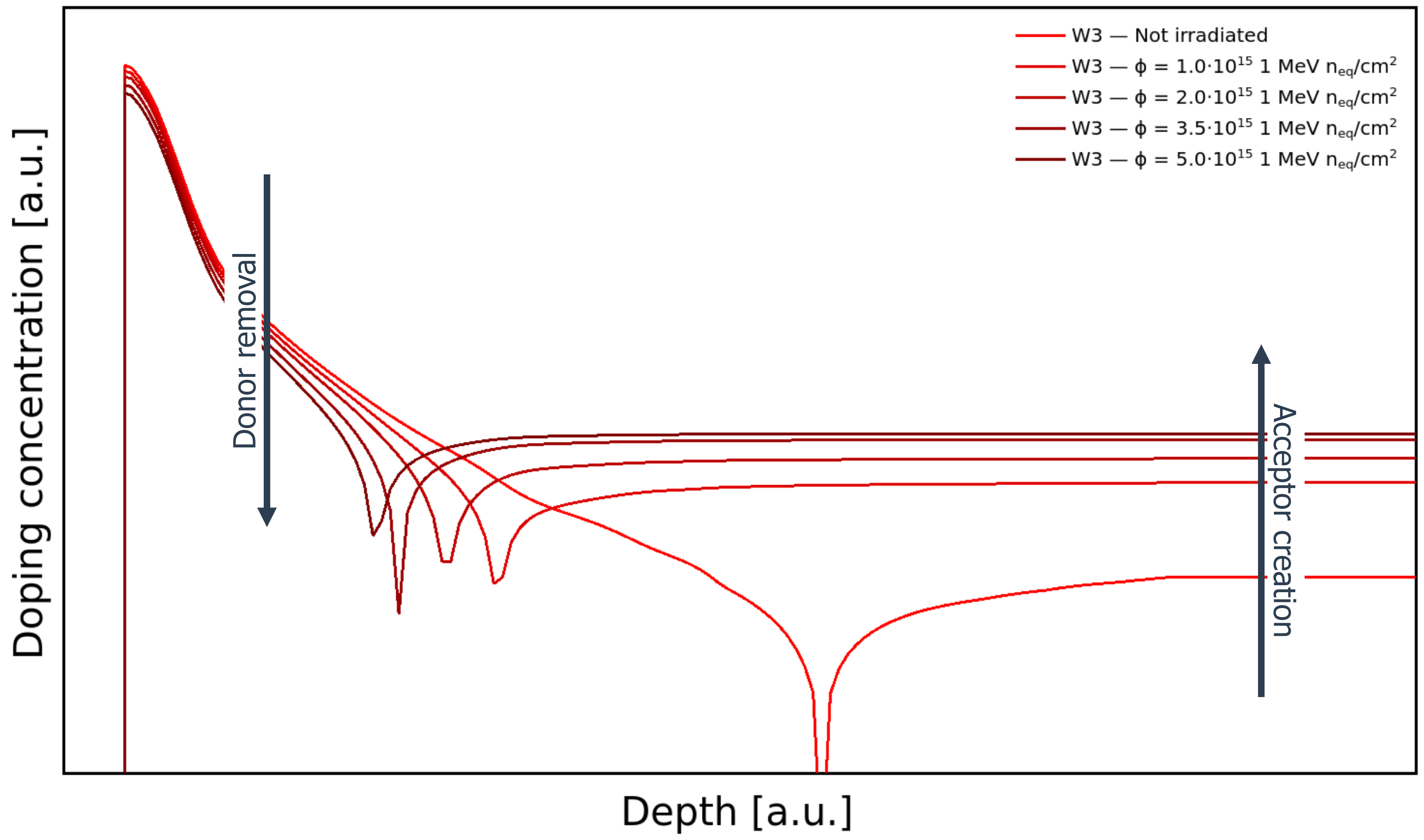

Donor removal

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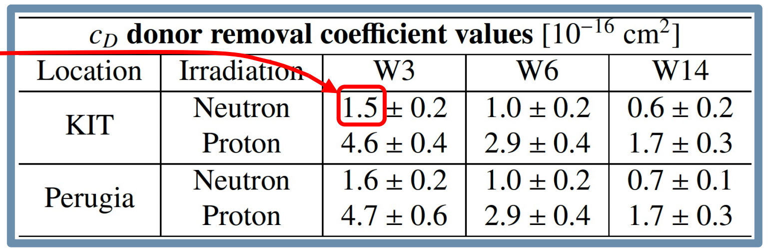

c_D **donor removal coefficient values** $[10^{-16}\ \mathrm{cm}^2]$

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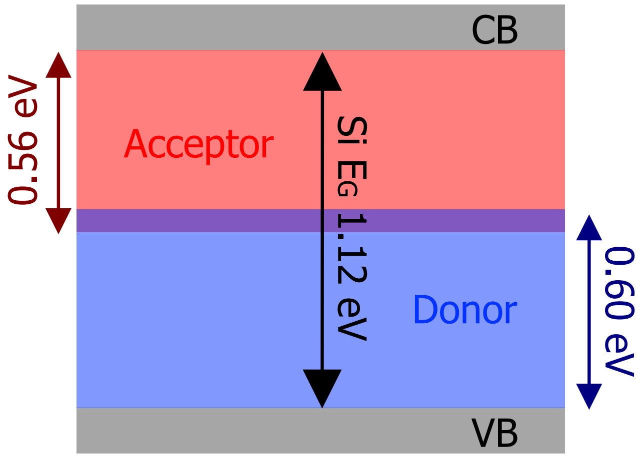
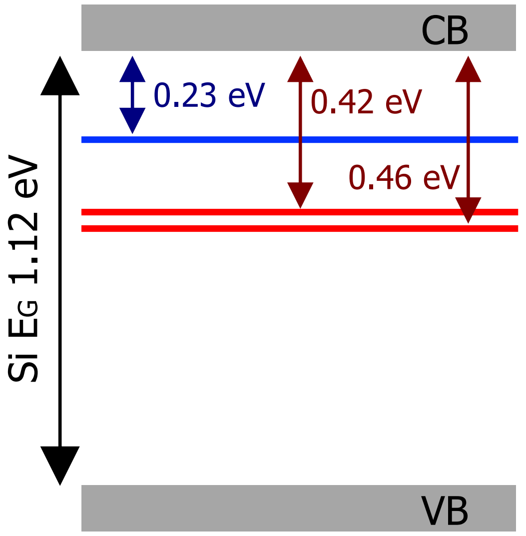
Traps in the bandgap

Surface damage (+Q_{ox})

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





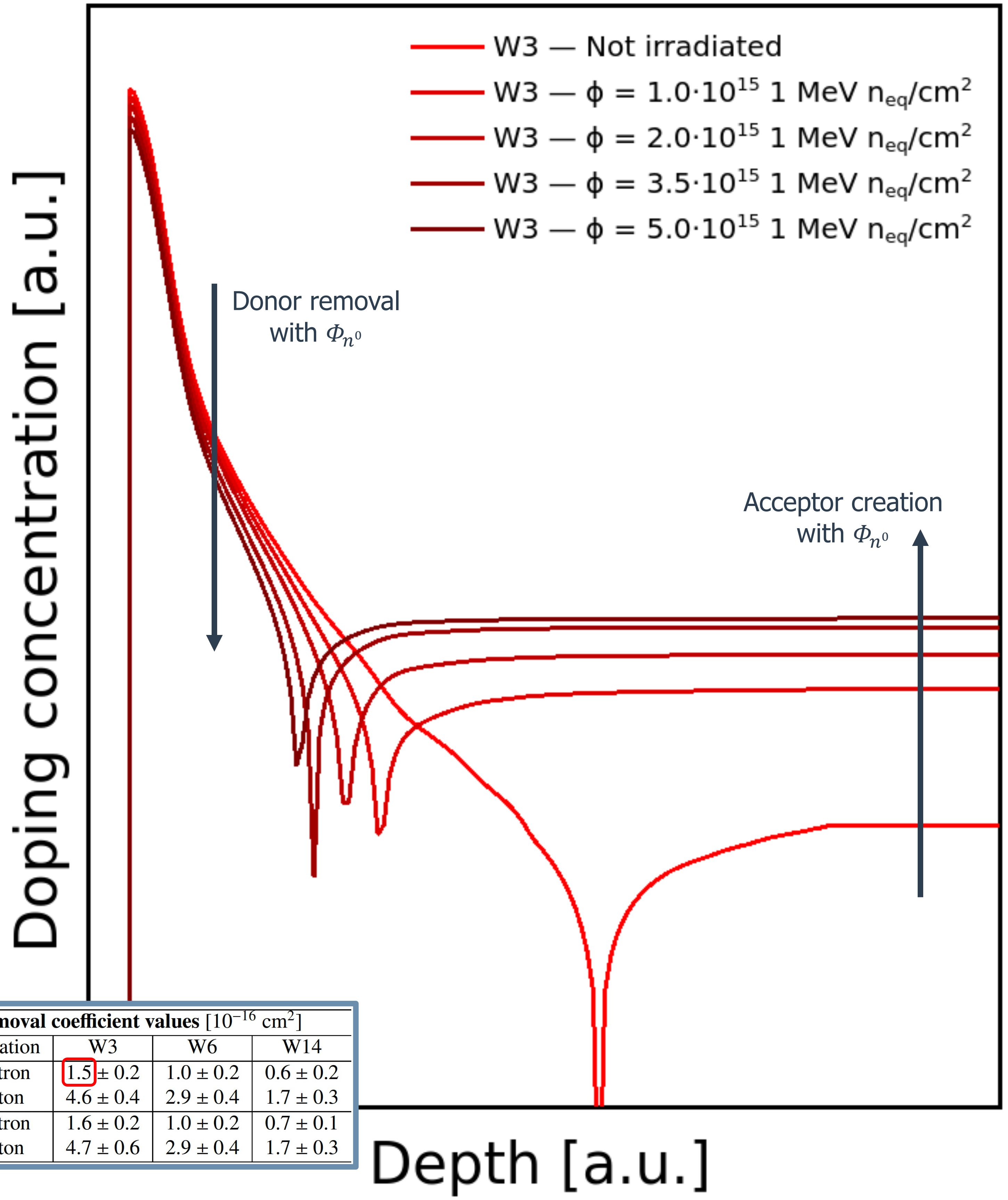
Bulk damage

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

$$\Phi_{n^0}\ [1\ \mathrm{MeV\ n_{eq}/cm^2}] = 2 \cdot \Phi_{p^+}\ [23\ \mathrm{MeV\ p^+/cm^2}]$$

https://www.etp.kit.edu/english/1669.php

RSD2 NPLUS W3 — Neutron Proton



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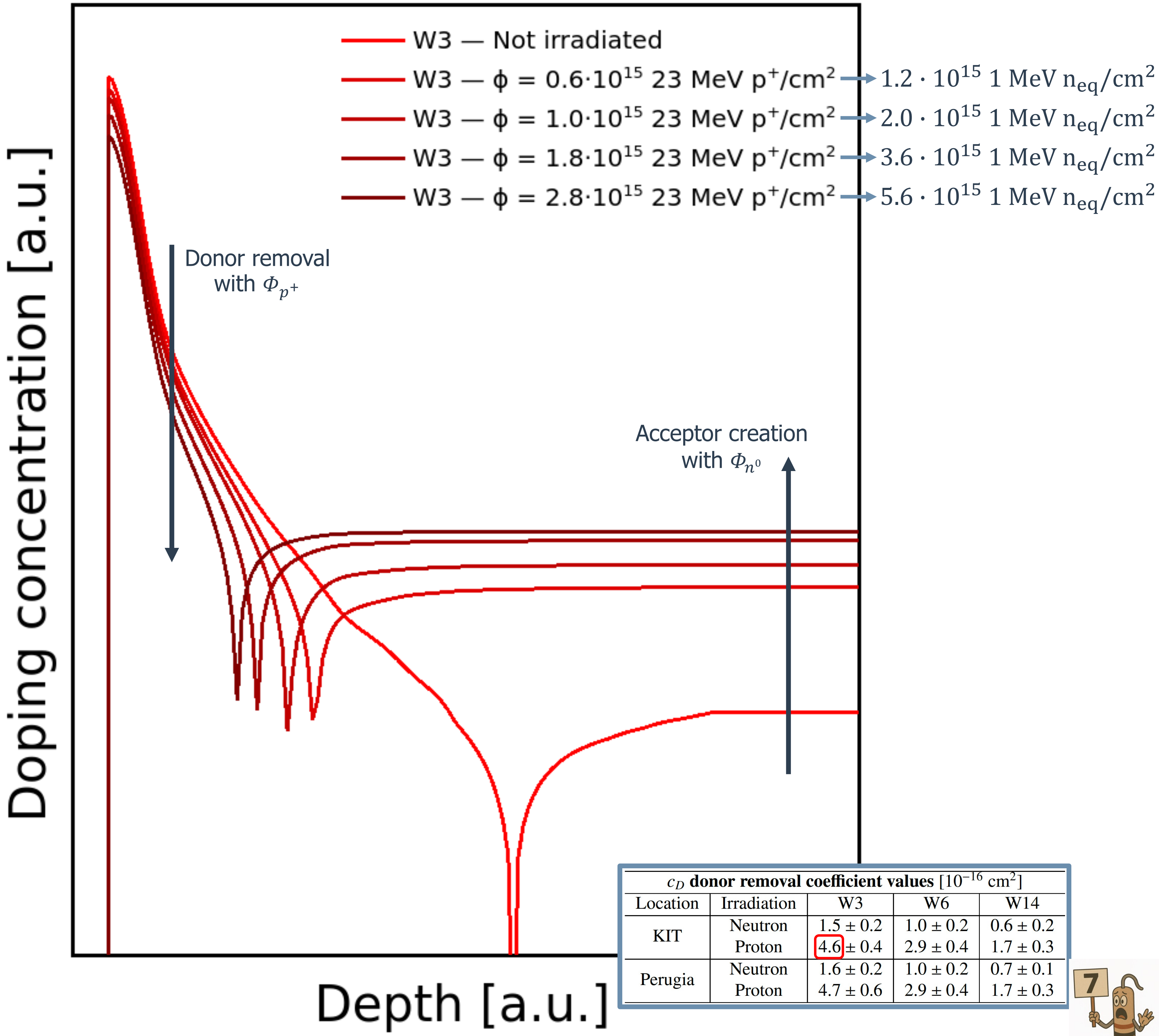

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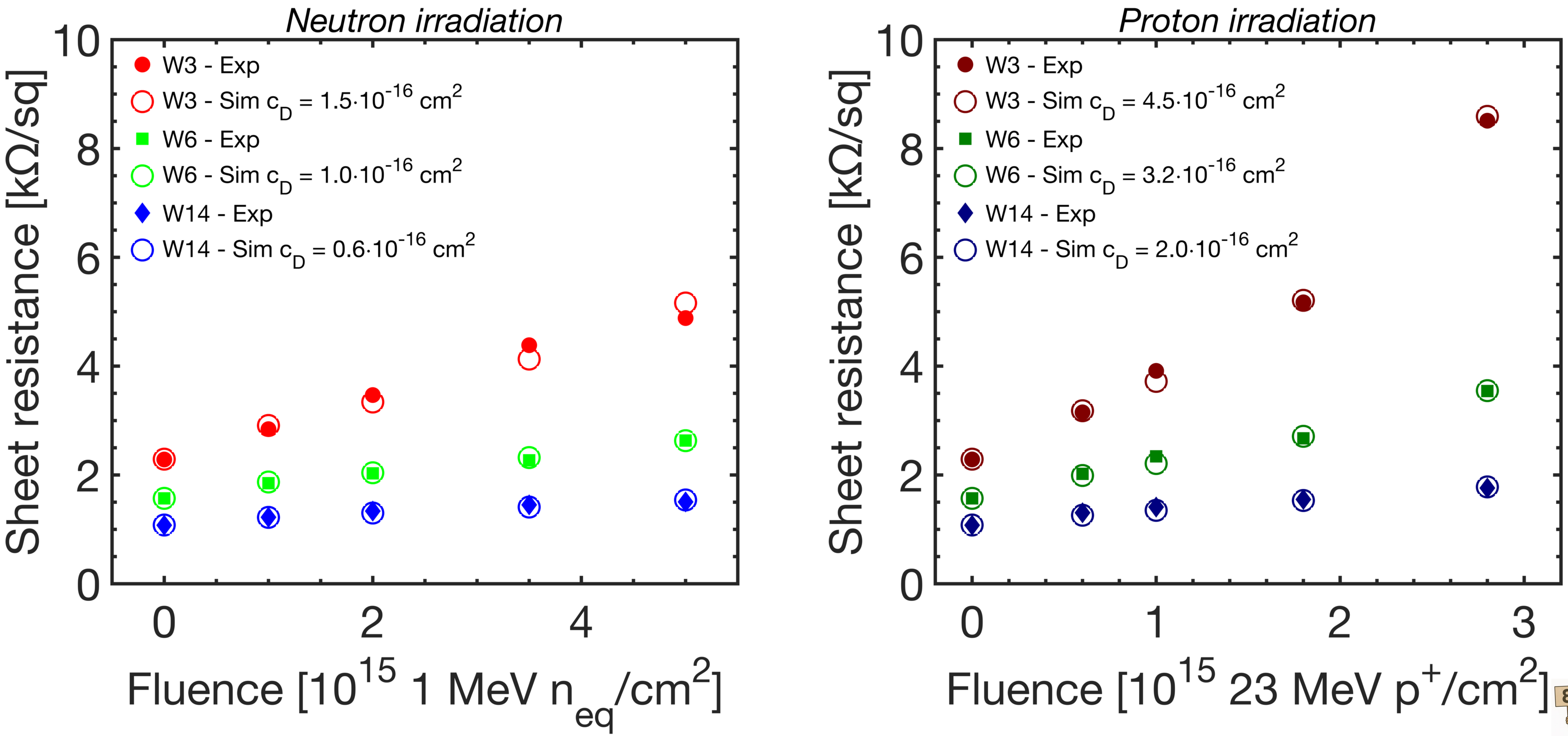
RSD2 batch — NPLUS — TCAD ↔ Measurements



RSD2 batch – Measurements

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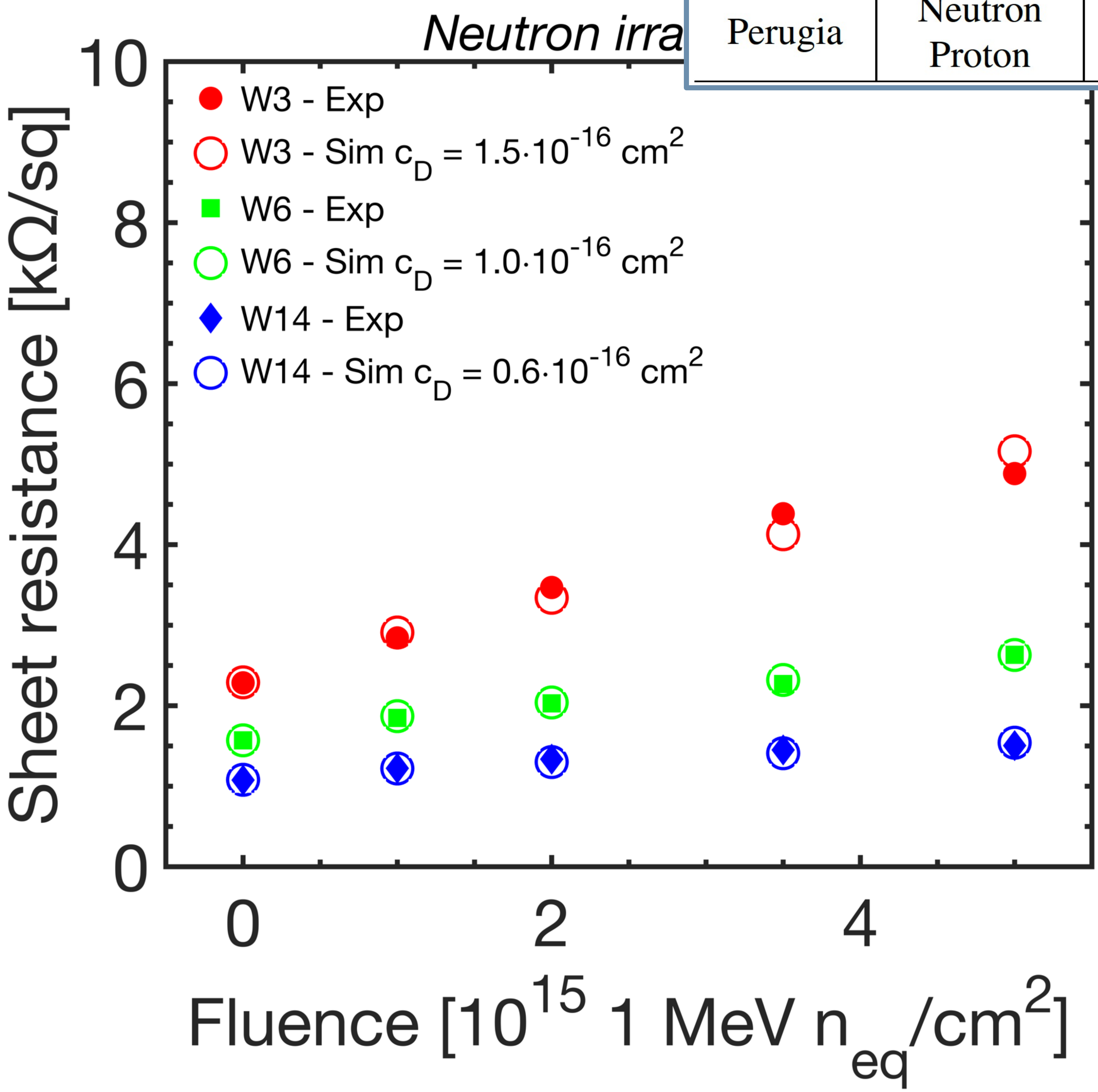
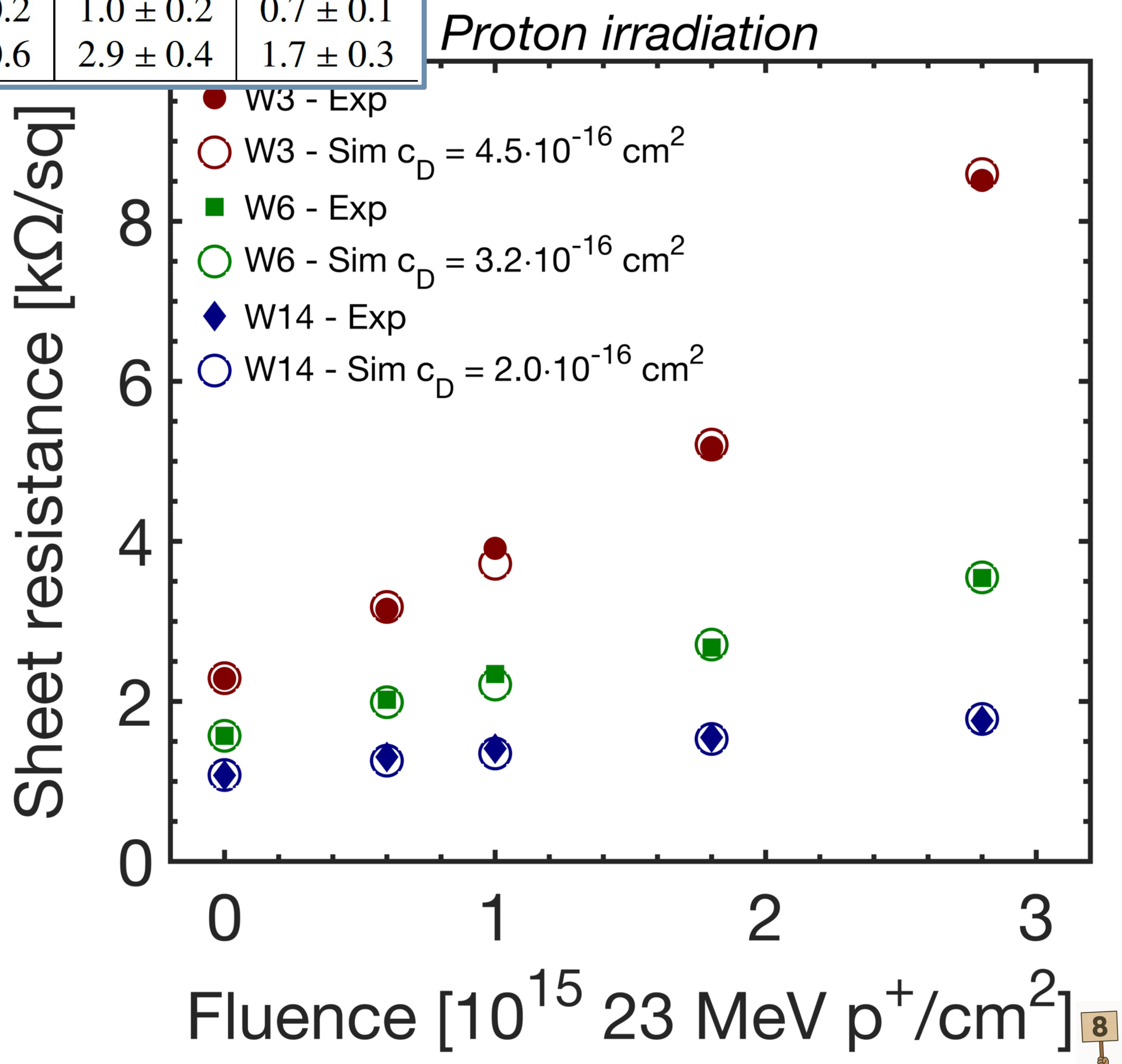
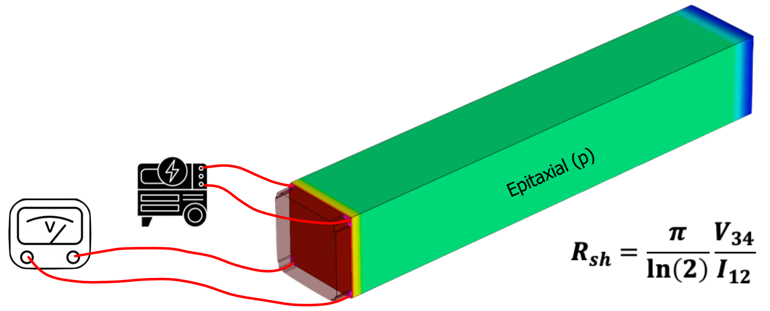
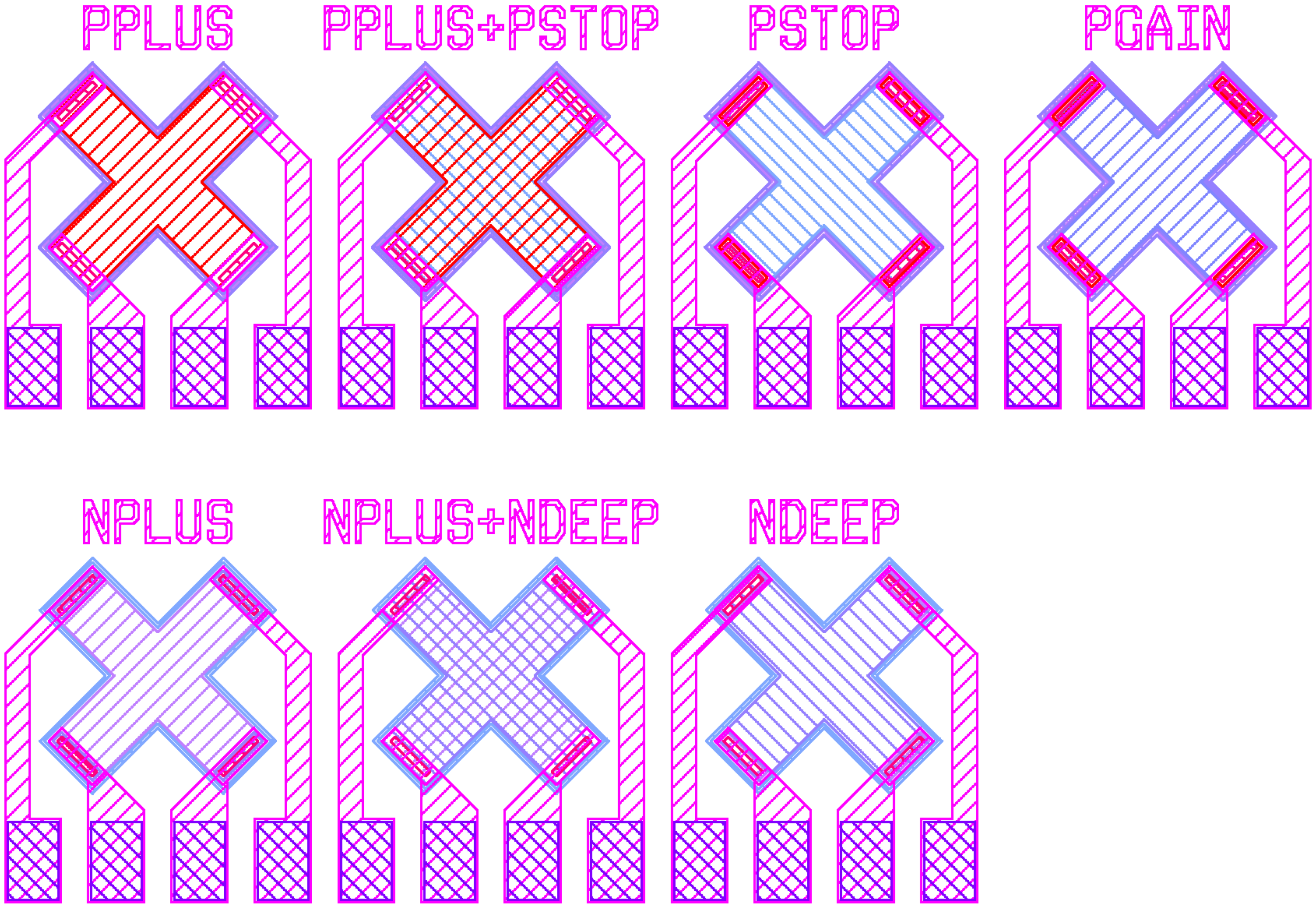




EXFLU1 batch - PGAIN



$R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{34}}{I_{12}}$



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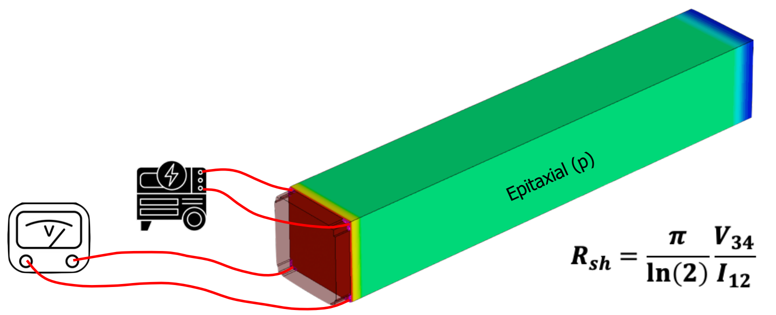
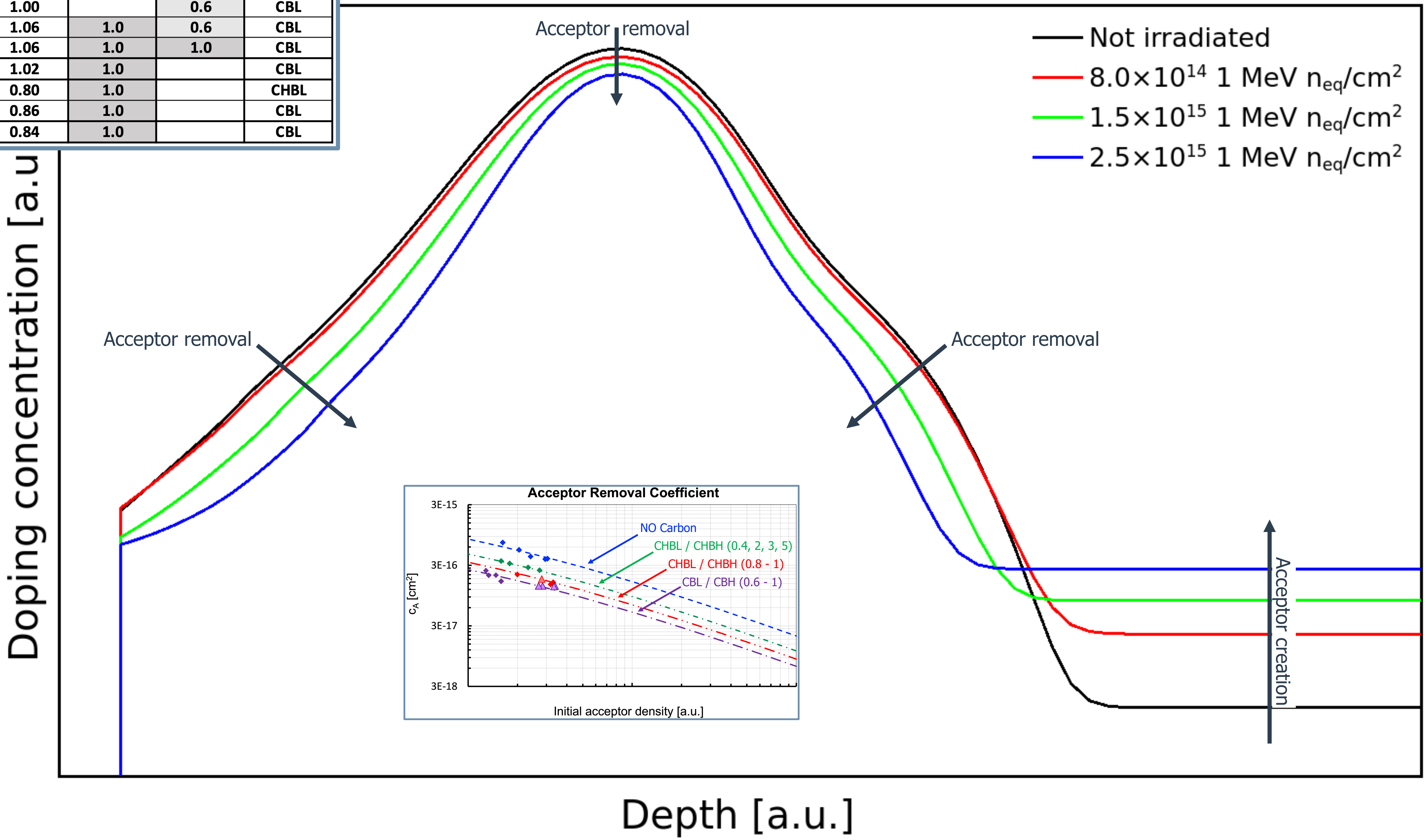
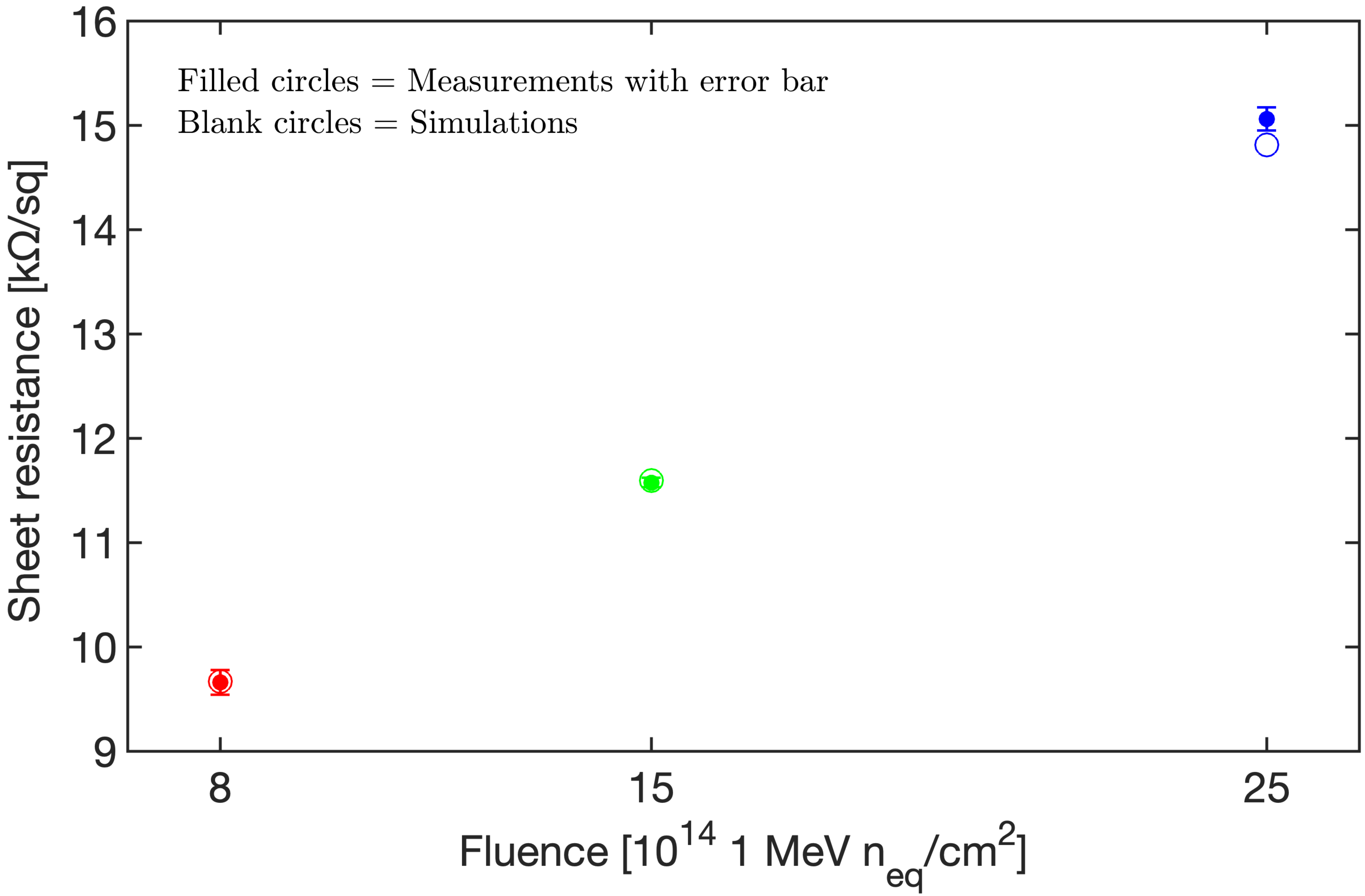


$$R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{34}}{I_{12}}$$

Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion
1	45	1.04	1.0		CBL
2 *	45	1.00		0.6	CBL
3 *	45	1.06	1.0	0.6	CBL
4 *	45	1.06	1.0	1.0	CBL
5	30	1.02	1.0		CBL
16	20	0.80	1.0		CHBL
17	20	0.86	1.0		CBL
18	15	0.84	1.0		CBL



EXFLU1 batch — PGAIN — TCAD ↔ Measurements



EXFLU1 batch – Compensated LGADs

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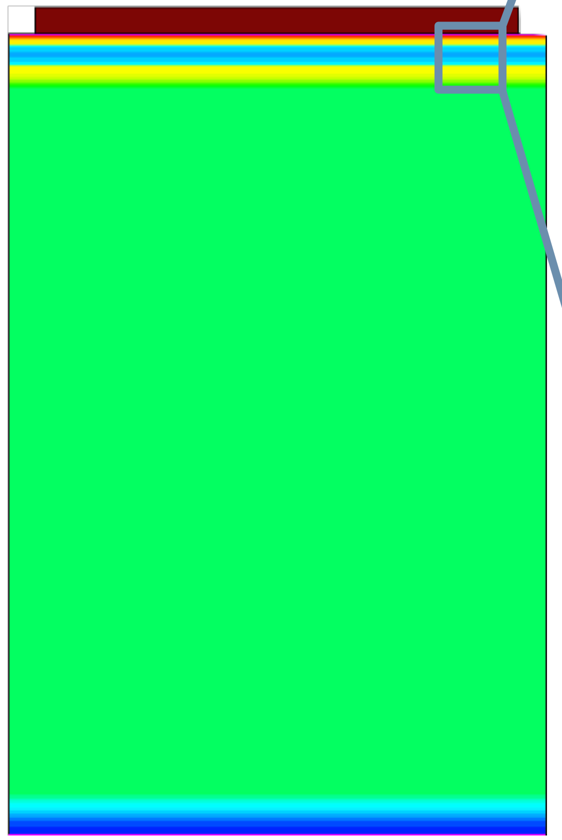
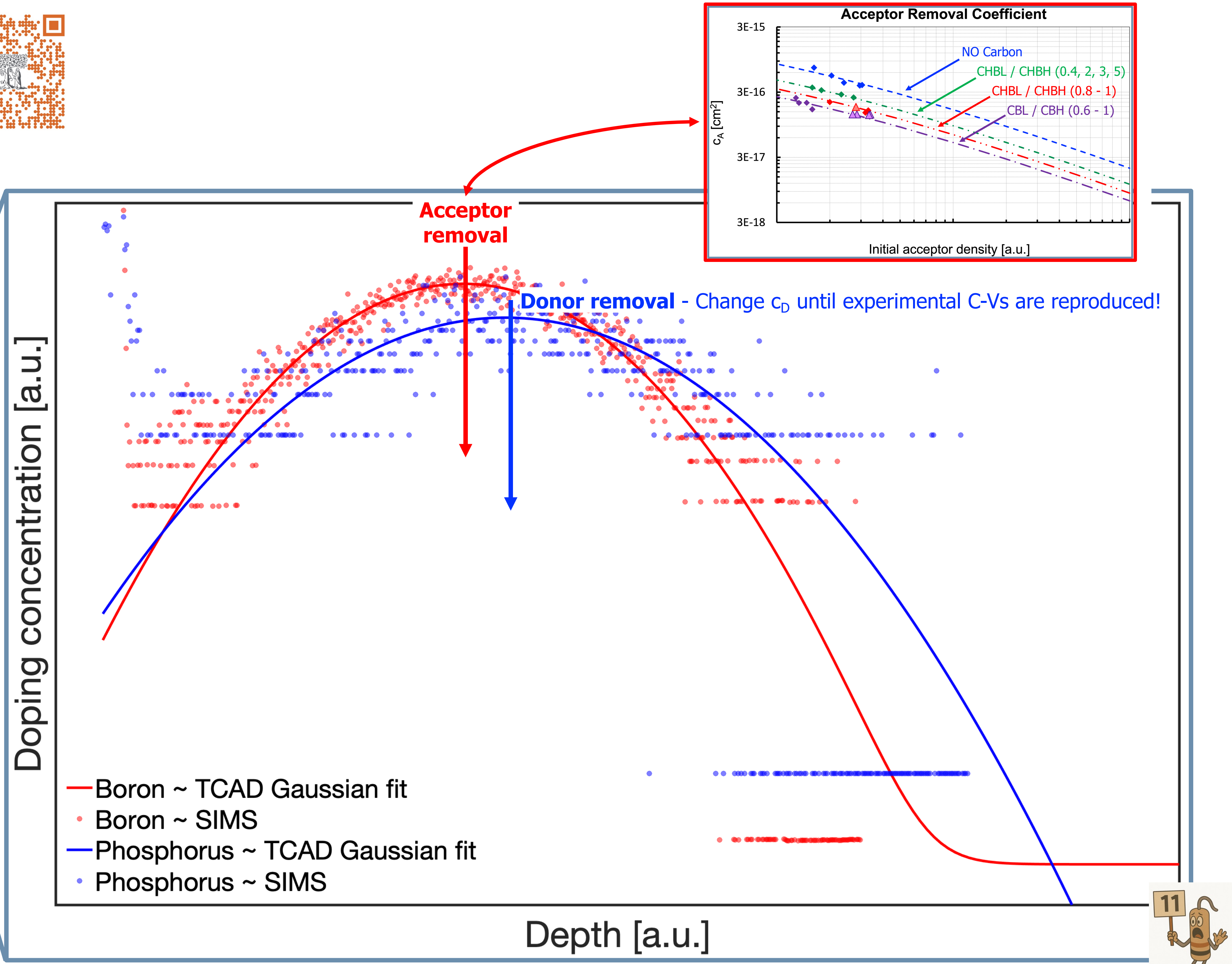
Established by the European Commission

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c] & [2c < 3a]



Single pad Compensated LGAD



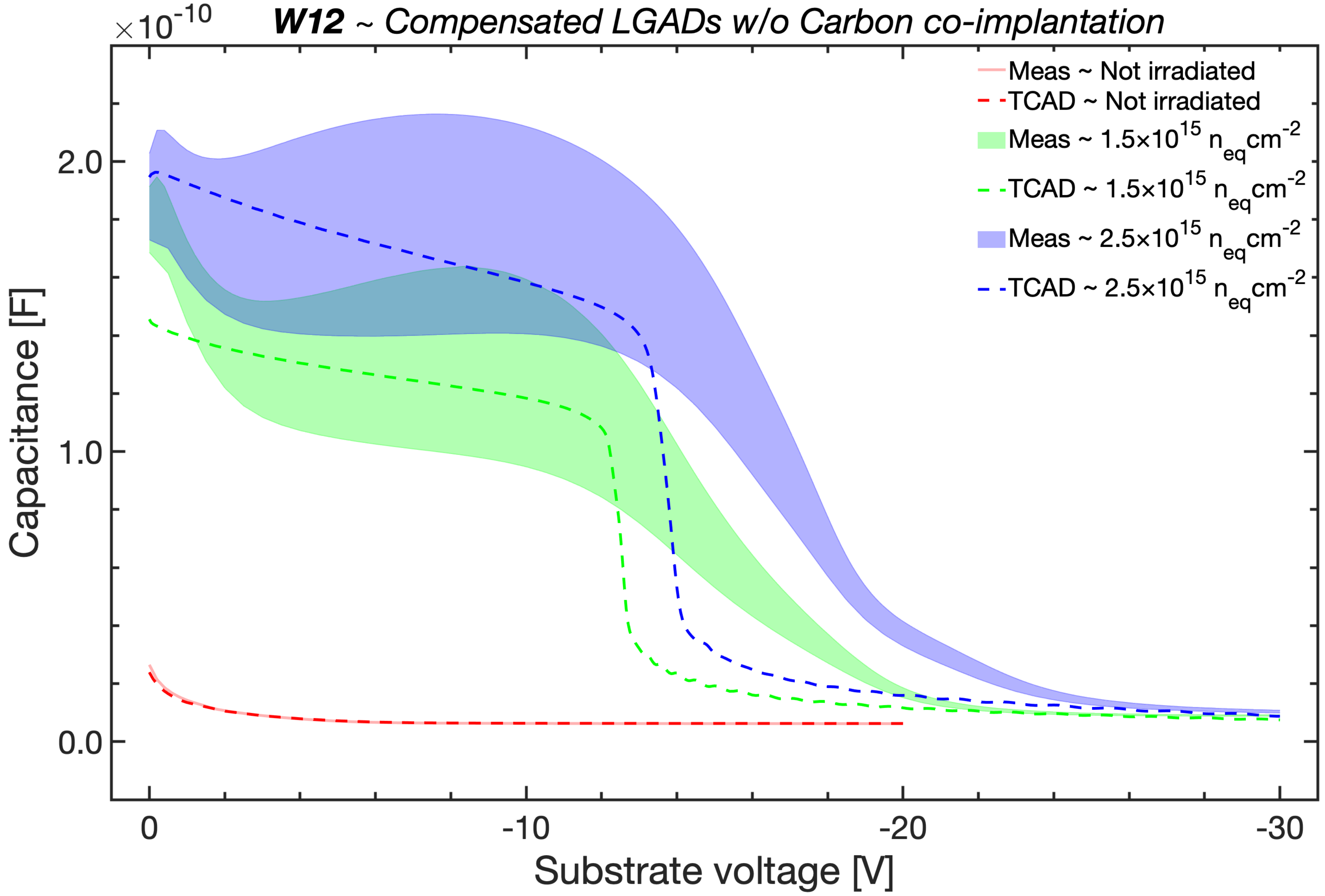
Donor removal - Change c_D until experimental C-Vs are reproduced!

EXFLU1 batch – Compensated LGADs

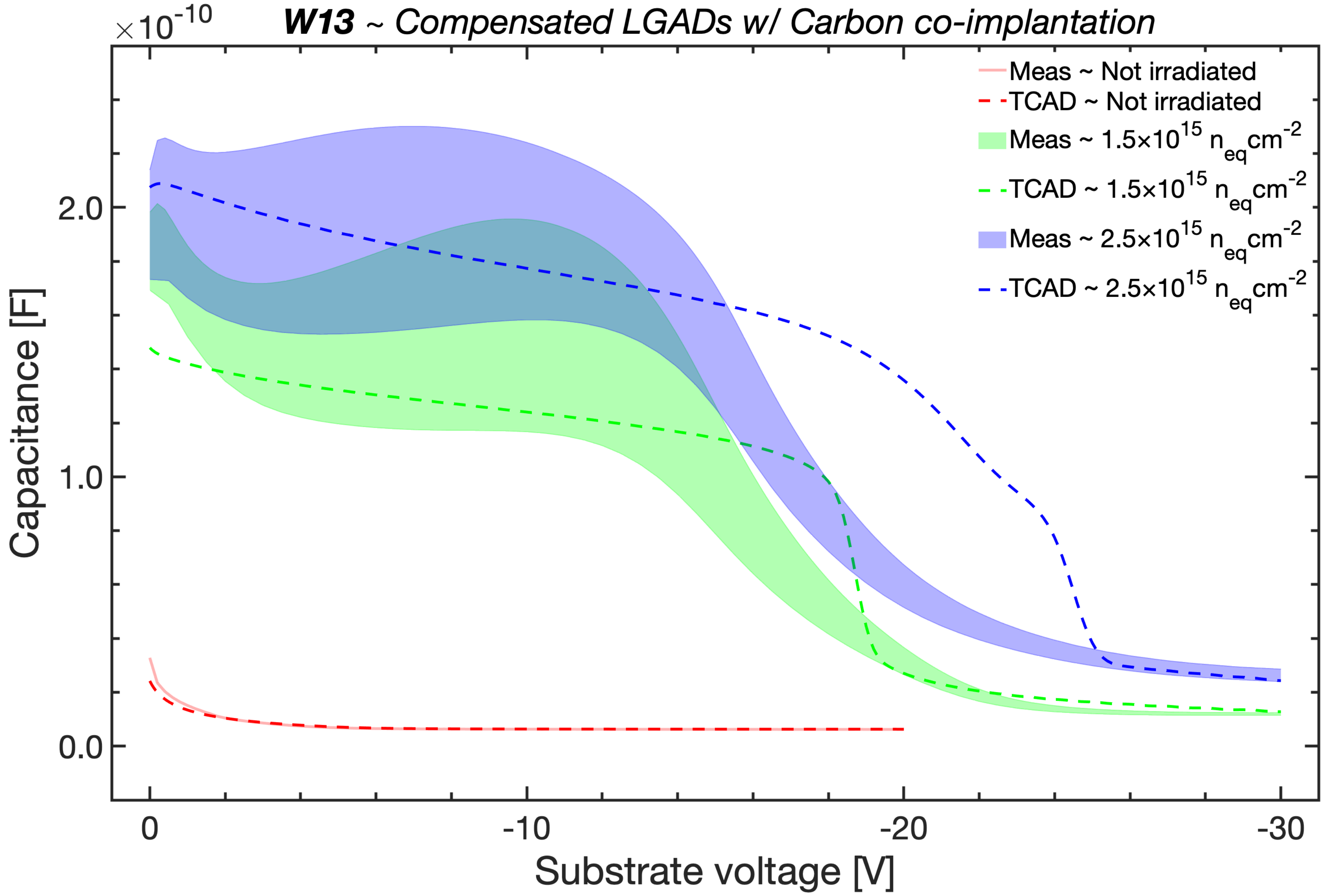
Funded by the European Union

European Research Council
Established by the European Commission

Wafer #	Thickness	p+ dose	n+ dose	C dose
12	30	3 b	2	
13	30	3 b	2	1.0

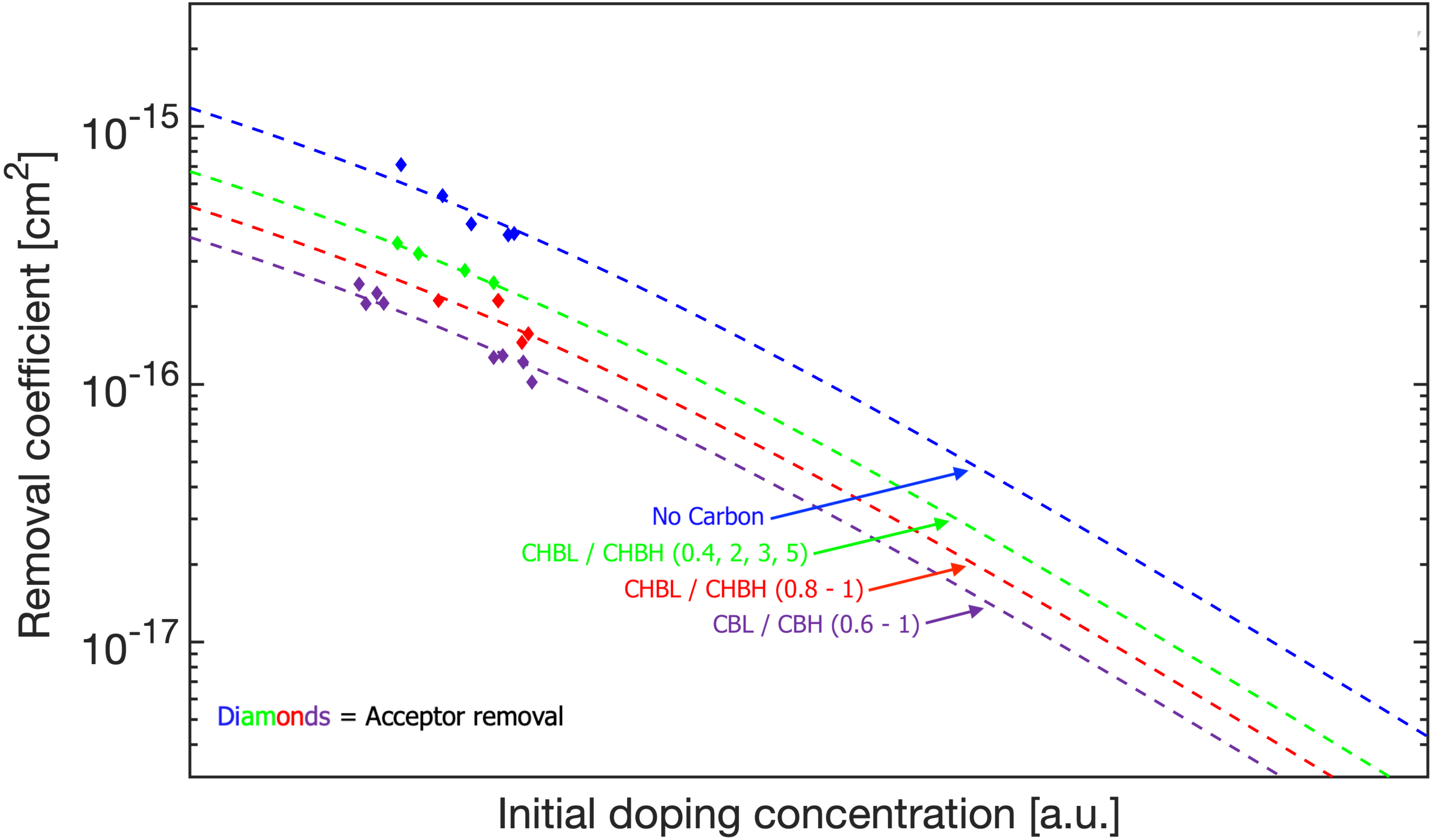

W12 *~ Compensated LGADs w/o Carbon co-implantation*

By exploiting the experimental acceptor removal coefficient $c_A = 2.50 \cdot 10^{-16}$ cm², agreement with C-V measurements is achieved using a donor removal coefficient $c_D = 6.50 \cdot 10^{-16}$ cm².

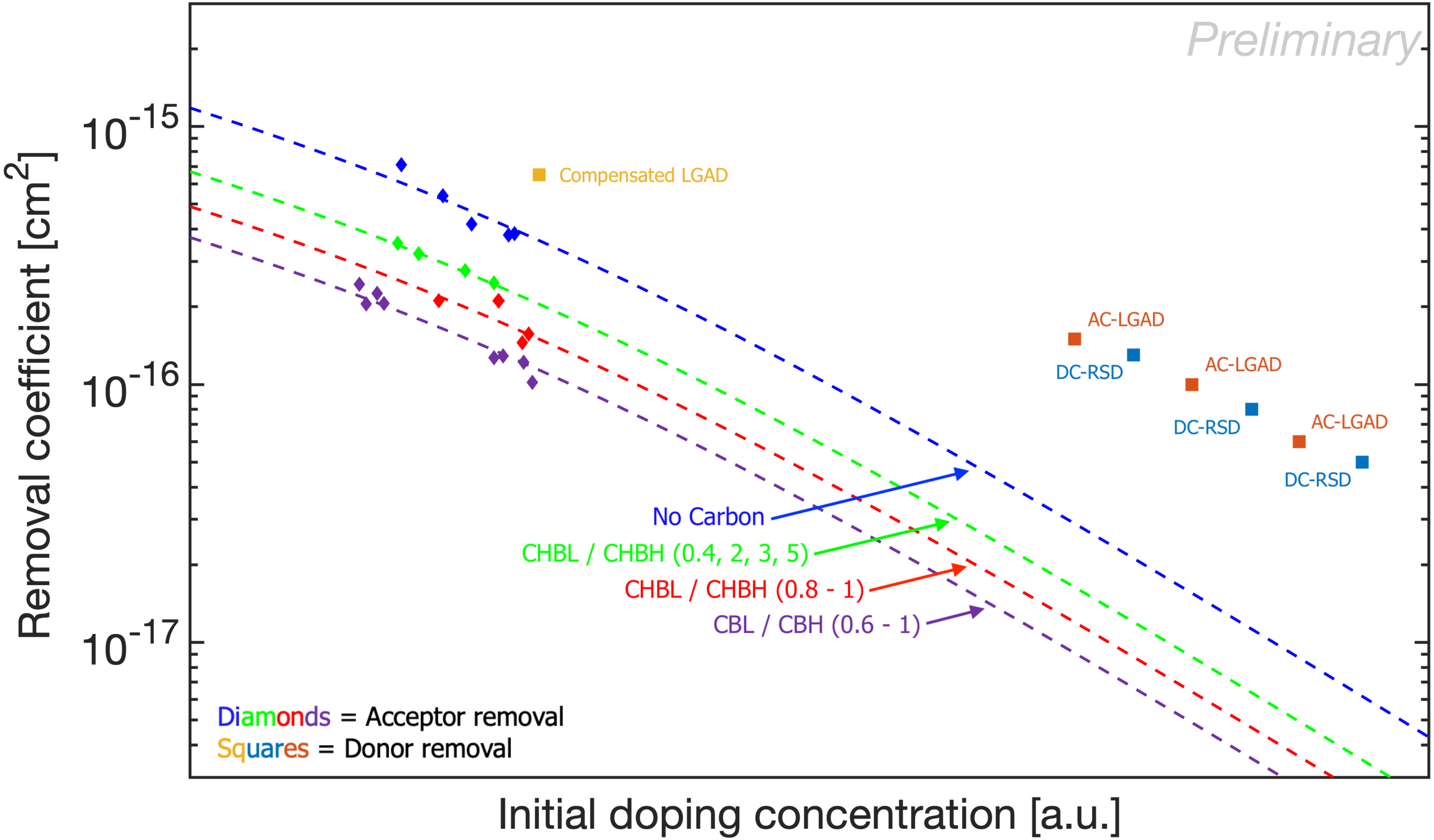

W13 *~ Compensated LGADs w/ Carbon co-implantation*

By exploiting the extracted c_D ($6.50 \cdot 10^{-16}$ cm²) and the experimental $c_A = 8.26 \cdot 10^{-17}$ cm² for the carbonated gain implant, a good agreement between measurements and simulations was achieved.

Preliminary c_D at high initial donor concentrations



Preliminary c_D at high initial donor concentrations



Conclusion

Doping removal can be estimated via **changes in sheet resistance** under irradiation:

- **For surface implants of opposite conductivity to the substrate:** van der Pauw measurements alone are sufficient;
- **For deep and/or same conductivity type implants:** simulation is required to interpret van der Pauw measurements.

Preliminary analyses indicate:

- **Correlation** between **C-V** and **van der Pauw** extracted **removal coefficients;**
- **A more pronounced donor removal than acceptor removal.**

New analyses (EXFLU1, RSD2, DC-RSD1, NLGAD) aim **to** strengthen and **validate these results.**

Thank you for your attention!