TCAD investigation of Compensated LGAD Sensors for extreme fluence

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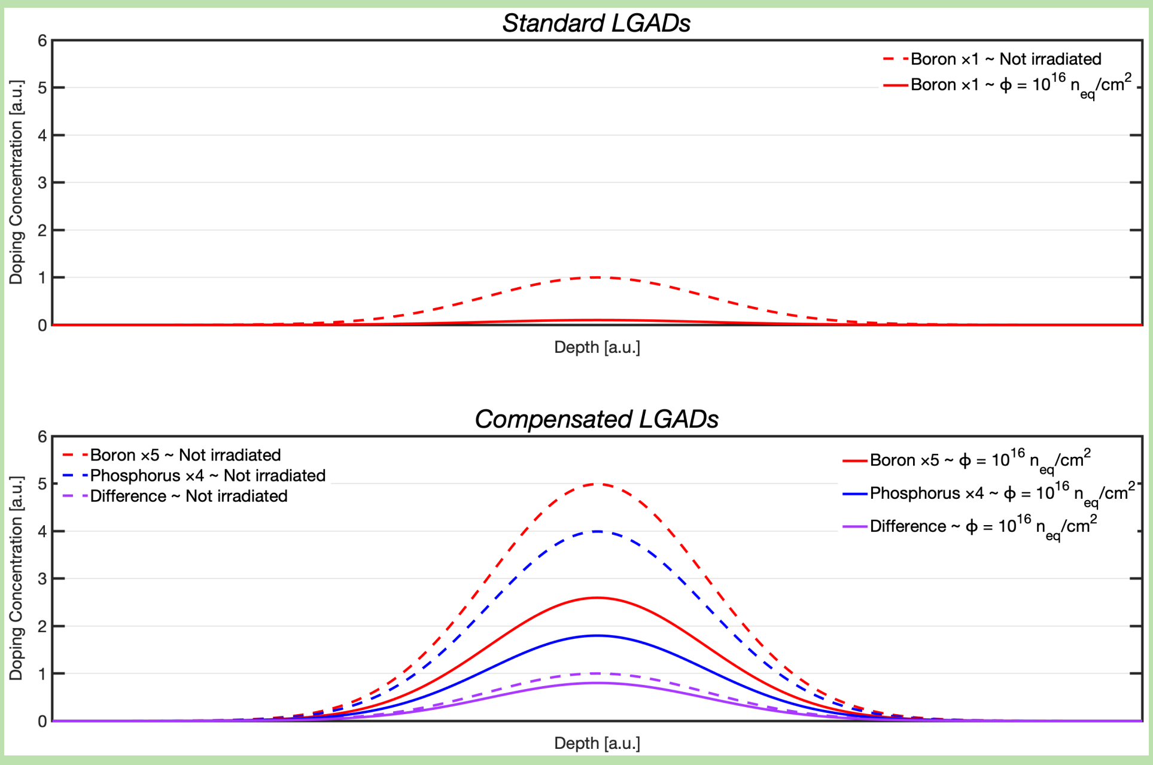
Compensated LGADs

Ultra-fast timing is the **cornerstone** of the detectors in **future HEP experiments**.

Thin LGADs can achieve time resolutions of $20 \div 30\, ps$, but **only up to** a fluence of $2.5 \cdot 10^{15}\, n_{eq}/cm^2$ due to the acceptor removal.

Their radiation resistance must be boosted to make them ideal candidates for **future experiments** characterised by extreme fluences ($\simeq 10^{17}\, n_{eq}/cm^2$)

$\Longrightarrow$ **Compensated LGADs !!!**



In **Compensated LGADs**, the **gain layer** results from the **difference** between **overlapping acceptor and donor doping**.

Both implants will undergo radiation removal, but **if properly engineered**, their **difference** will be **kept constant**, ensuring an **operating life** well **beyond** $10^{17}\, n_{eq}/cm^2$.

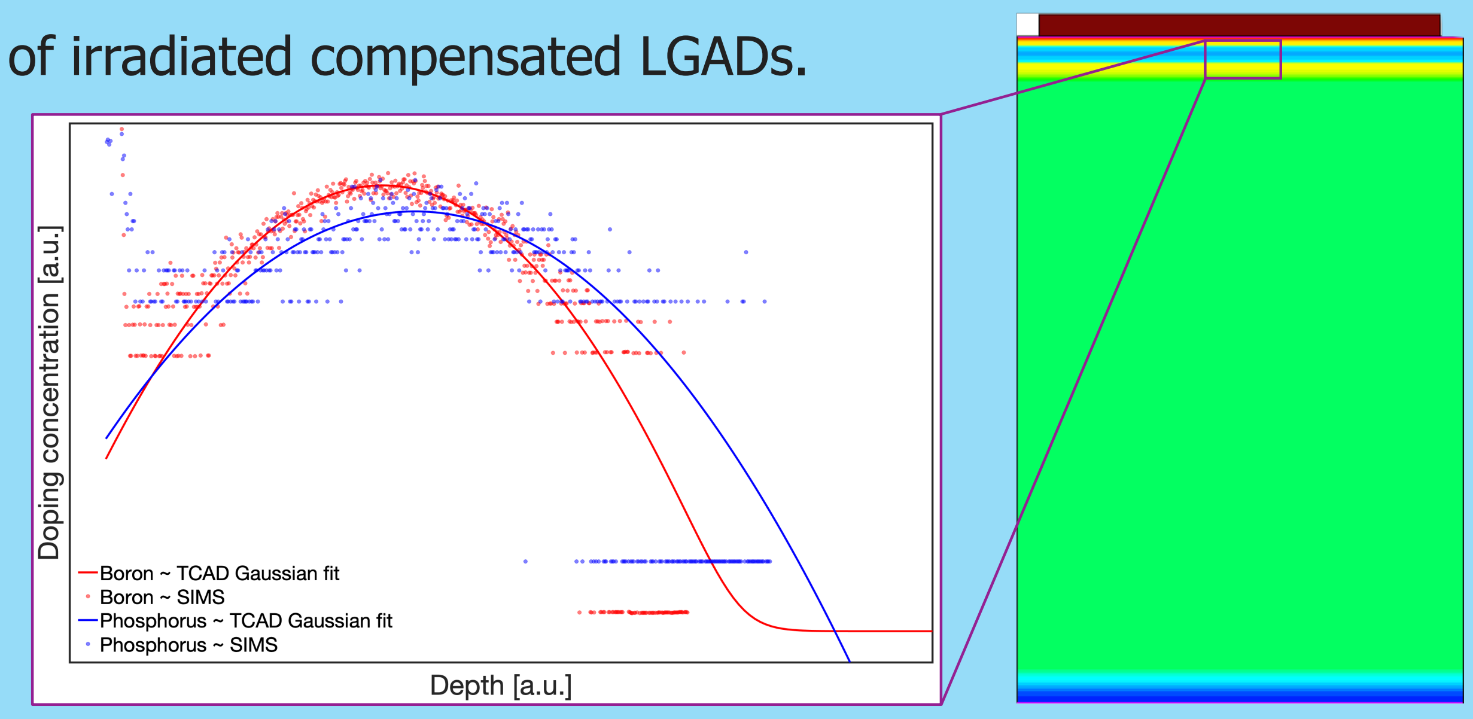
Two unknowns (*Donor removal coefficient* & *Interplay between donor and acceptor removal*) were **analysed** using Synopsys© Sentaurus **TCAD** tools.

TCAD Simulations: Methods and Results

Goal: **Extract** the donor removal coefficient (c_D) by **comparing TCAD simulations and measurements** of irradiated compensated LGADs.

Procedure:

1. Tuning of substrate active thickness and doping concentration by C-V measurement-simulation comparison of **non-irradiated PIN diodes**;
2. Compensated gain layer profiles extracted from SIMS are inserted and fine-tuned to match the C-V measurements of **non-irradiated Compensated LGADs**;
3. The Phosphorus peak concentration is varied to match C-V measurements of **irradiated Compensated LGADs** at various fluences, trying to reproduce the gain-layer depletion properly.

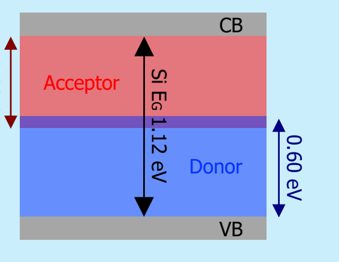


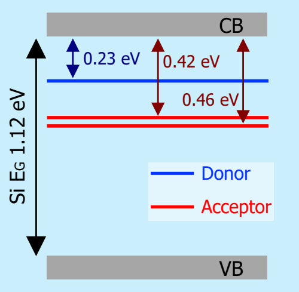
RADIATION DAMAGE MODELLING

New University of Perugia Radiation Damage Model

Surface damage ($+Q_{OX}$)

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





Bulk damage

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

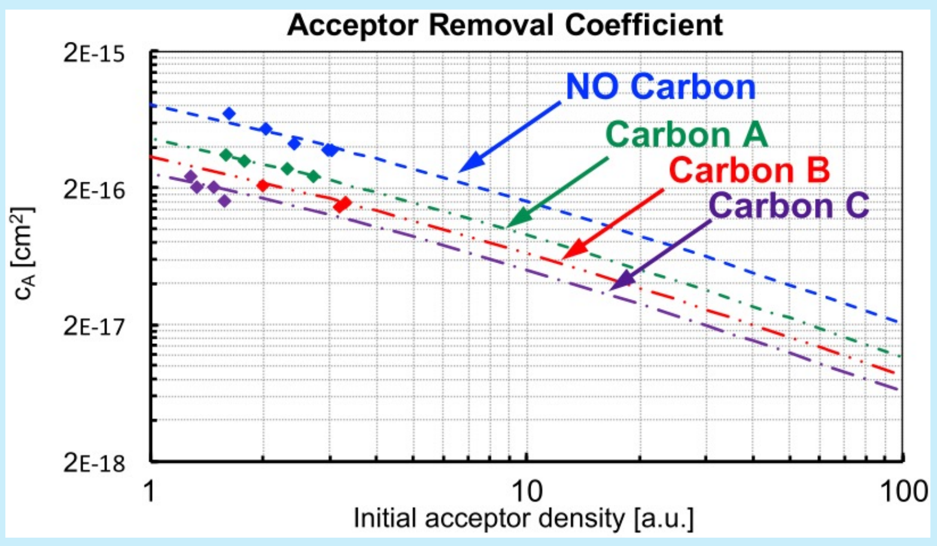
Physically meaningful
deep-level radiation-induced traps

Acceptor Removal

Transformation of electrically active acceptor atoms into neutral defect complexes.

It can be parameterised as

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



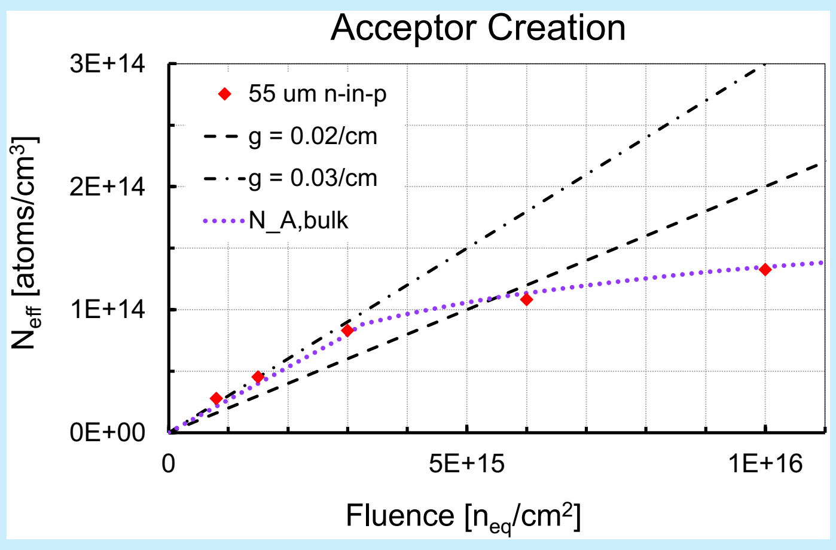
Acceptor Creation

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

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

else

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

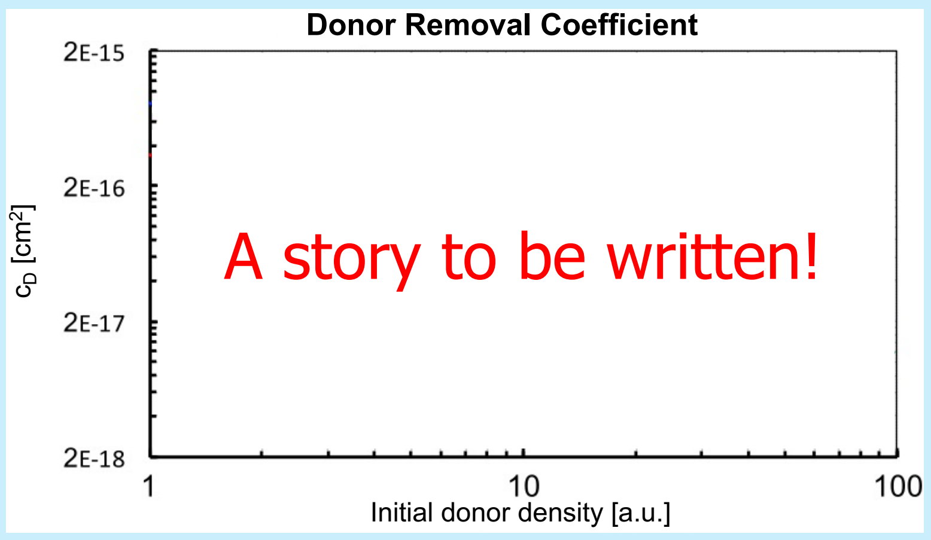


Donor Removal

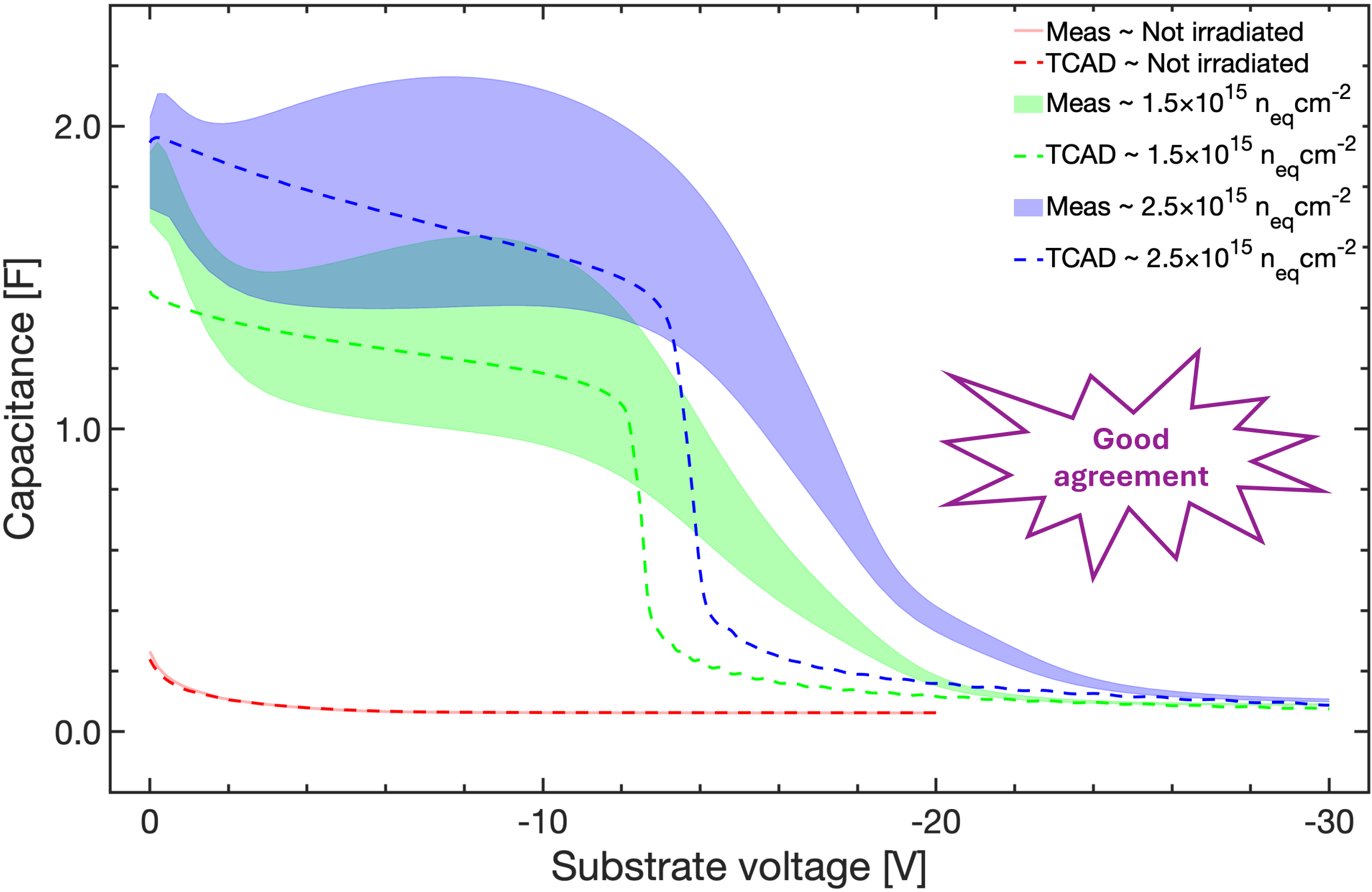
Transformation of electrically active donor atoms into neutral defect complexes.

It can be parameterised as

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

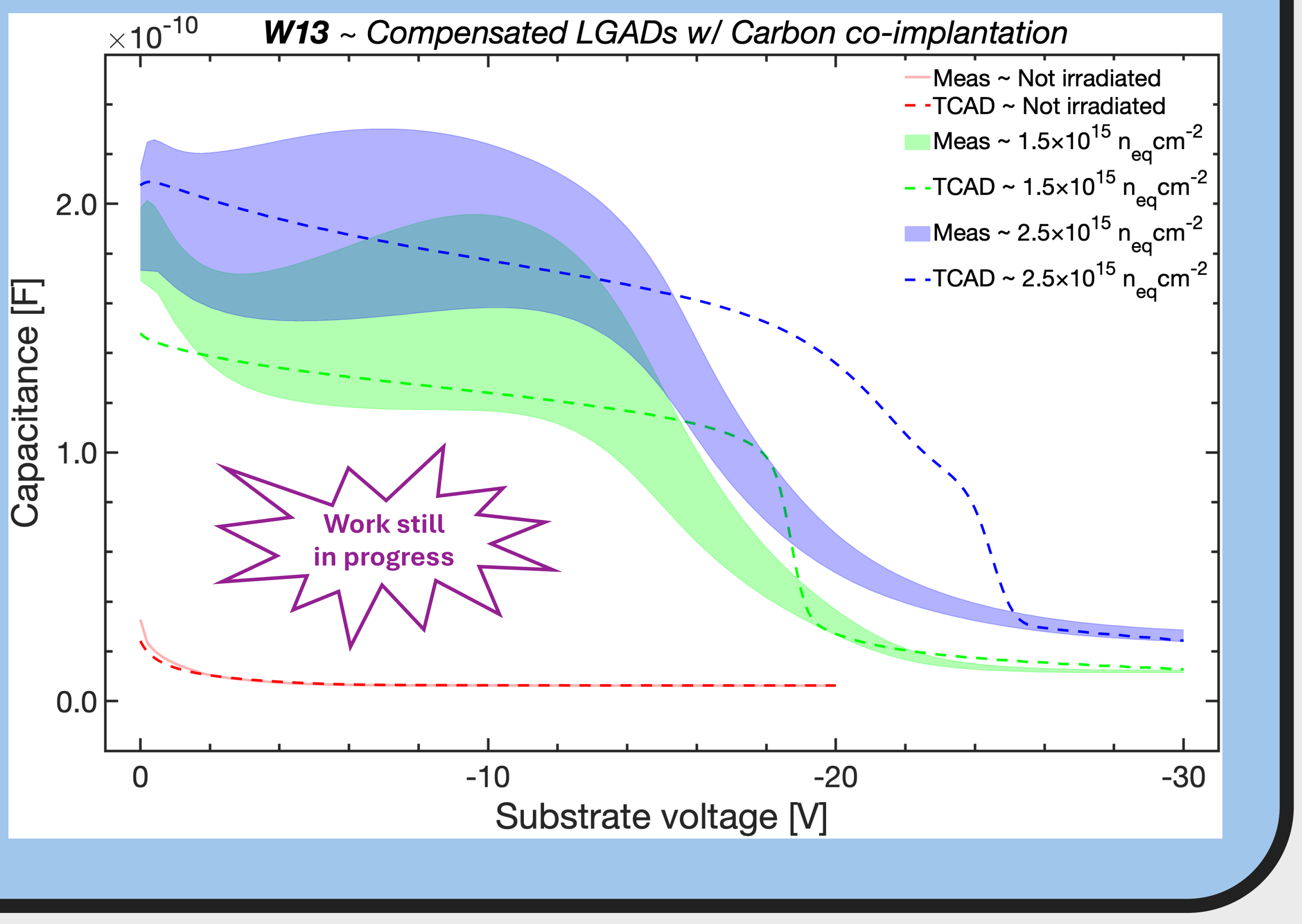


Exploiting the experimental acceptor removal coefficient $c_{A_{W12}} = 2.50 \cdot 10^{-16}\, cm^2$, agreement with C-V measurements for $W12$ was achieved using a donor removal coefficient $c_D = 6.50 \cdot 10^{-16}\, cm^2$. With the latter and $c_{A_{W13}} = 8.26 \cdot 10^{-17}\, cm^2$, the C-V simulations-measurements accordance is good for $W13$ as well.



EXFLU1 ~ Split Table [a < b < c]

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	



Conclusions & Next Steps

- The c_D extracted from the C-V measurements and simulations comparison suggests that **donor removal is faster than acceptor removal**;
- The presence of **Phosphorus** seems **not** to **change** the **acceptor removal** mechanism **and** the **beneficial effect of Carbon co-implantation** compared to those observed in standard LGADs;
- The c_D extracted from $W12$ (3-2 compensation strategy) simulations, will also be tested for the other compensations strategies (2-1 and 5-4, see the Split Table).

References & Funding

An in-depth introduction to Compensated LGADs is available in

- V. Sola et al., NIM. A In Press (2024) 169453.

For an extended description of the radiation damage modelling, please refer to

- A. Morozzi et al., PoS Vertex2019 (2020) 050;
- M. Ferrero et al., CRC Press (2021).

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