



INSTR 2026

October 12-16, 2026 | Hefei, China

Results from 55 μm thick nLGAD sensors from FBK with charged particles and photons



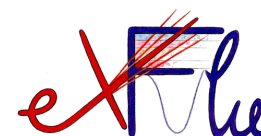
V. Sola, G. Paternoster, A. Morozzi, A.R. Altamura, R. Arcidiacono, A. Bisht, M. Boscardin, N. Cartiglia, M. Centis Vignali, M. Costa, T. Croci, M. Durando, S. Galletto, M. Ferrero, A. Fondacci, O. Hammad Ali, L. Lanteri, F. Maggio, F. Moscatelli, M.M. Obertino, D. Passeri, N. Pastrone, S.M.A. Sarfraz, F. Siviero, M. Tornago, R.S. White, I. Zatocilova



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The 2026 International Conference on Instrumentation for Colliding Beam Physics – USTC, Hefei, China

Outline

- ▷ Why nLGAD
- ▷ What nLGAD
- ▷ How nLGAD
- ▷ Where nLGAD
- ▷ The nLGAD !



nLGAD = n-type Low-Gain Avalanche Diode

Motivation

Three good reasons to investigate n-type LGAD sensors

- 👉 To investigate the design of the n-type gain implant, useful in the design of compensated LGAD
- ✌️ To directly investigate donor removal at the donor concentration used in compensated LGAD
- 👉 To detect low-penetrating particles, e.g., photons

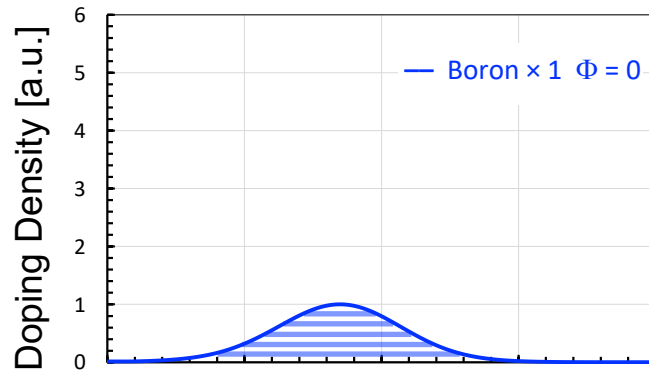
Two n-type LGAD (nLGAD) batches already produced by CNM on 300 μm thick substrates

[\[J. A. Villegas Dominguez et al., 41st RD50 Workshop\]](#)

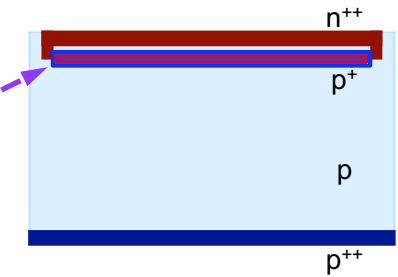
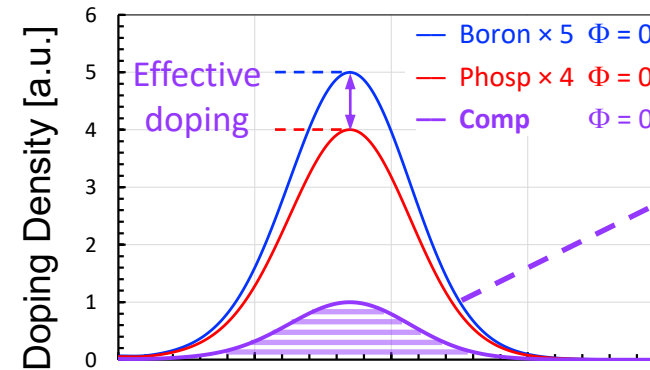
[\[J. A. Villegas Dominguez et al., TREDI 2024\]](#)

Compensated LGAD at a glance

Doping Profile – Standard LGAD

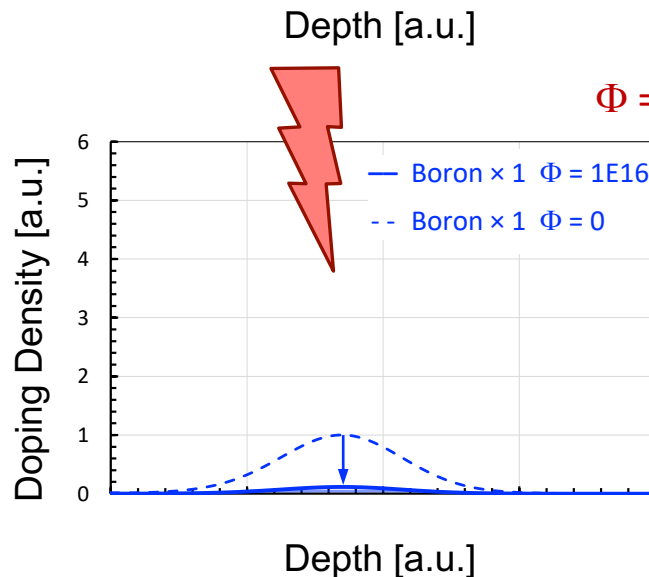


Doping Profile – Compensated LGAD

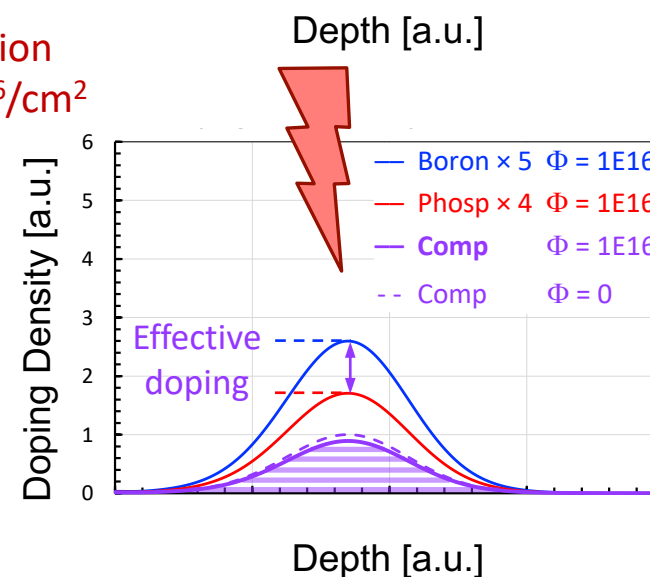


Compensated LGAD

Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density



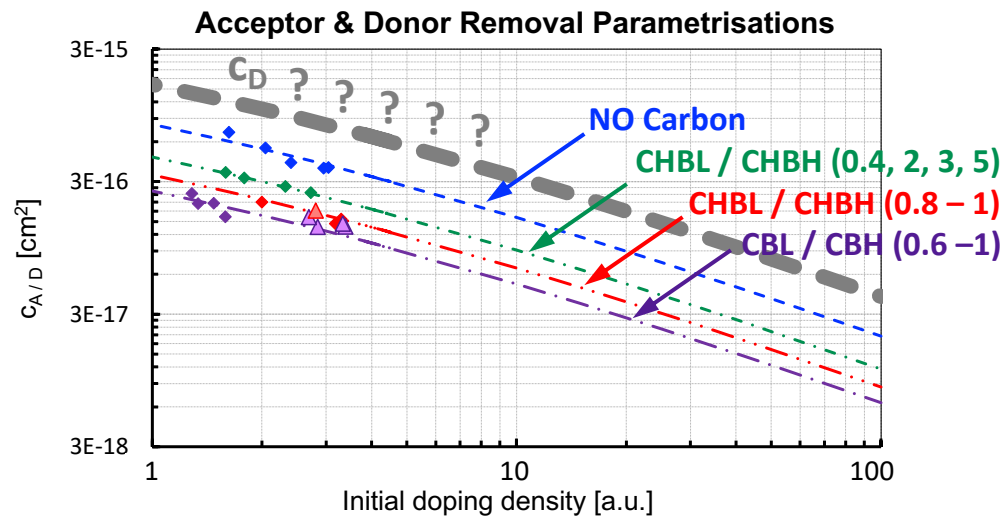
Irradiation
 $\Phi = 1 \times 10^{16} / \text{cm}^2$



Many unknowns:

- donor removal coefficient, from $n^+(\Phi) = n^+(0) \cdot e^{-c_D \Phi}$
- interplay between donor and acceptor removal (c_D vs c_A)
- effects of substrate impurities on the removal coefficients

The NLGAD batch to extract donor removal



Several open questions:

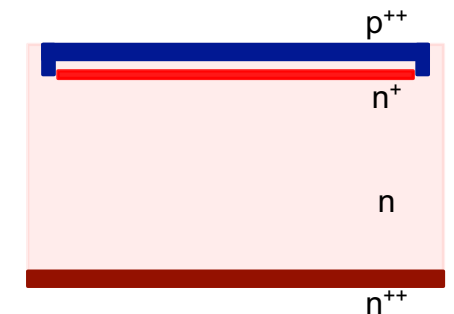
- Is donor removal **faster** than acceptor removal?
- How can we **extract** the donor removal over a wide range of doping densities?
- Should donor removal follow the **same** parametrisation as acceptor removal?
- Can we **mitigate** it by co-implanting other dopants, e.g., Oxygen?

The NLGAD sensors will be used to study the donor removal coefficient, c_D

Donor removal has been studied for doping densities of $10^{12} - 10^{14}$ atoms/cm³

→ **We will study donor removal for concentrations of $\sim 10^{15} - 10^{17}$ atoms/cm³**

[[A. Fondacci et al., 5th DRD3 week](#)]



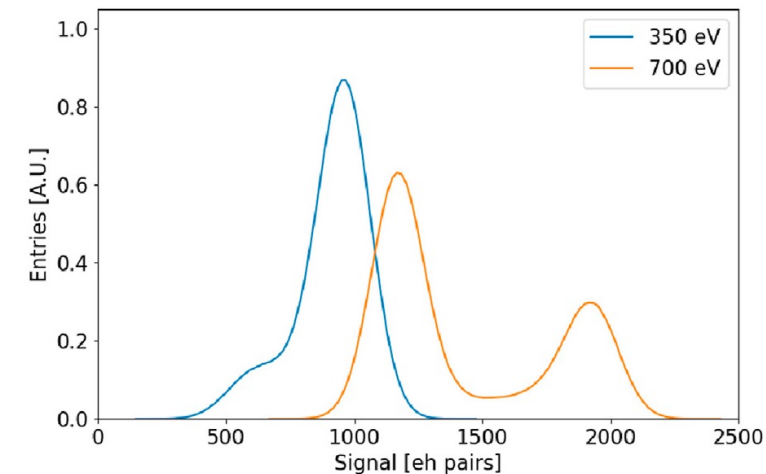
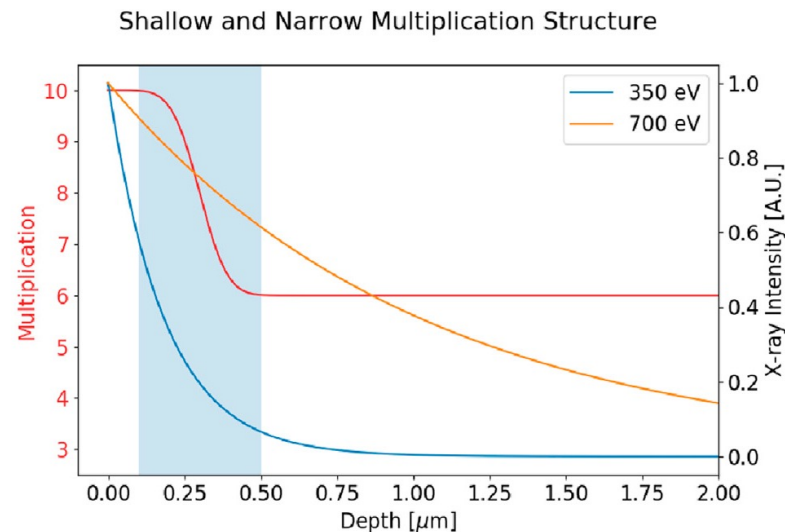
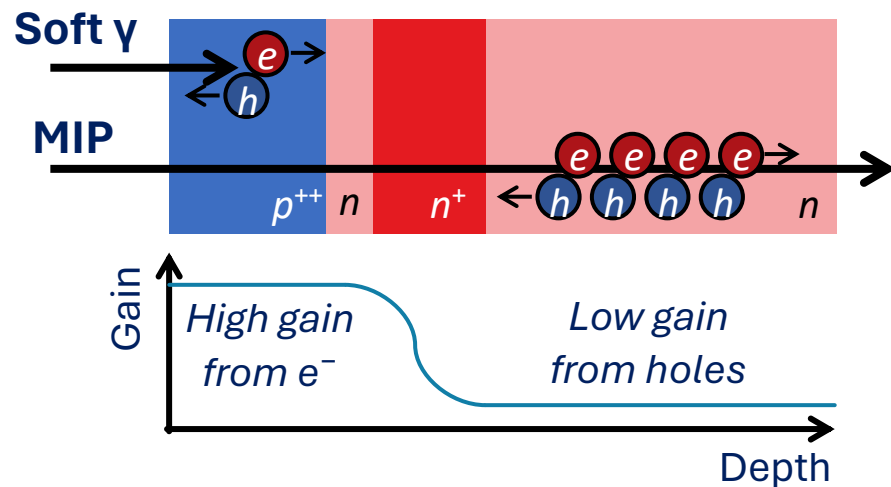
p-in-n LGAD

Detection of low-penetrating particles

If e-h pairs are generated between a p^{++} ohmic contact and an n^+ gain implant, the signal from low penetrating particles is enhanced

[[M. Centis Vignali and G. Paternoster, doi:10.3389/fphy.2024.1359179](#)]

[[J. Villegas et al., doi:10.1016/j.nima.2025.170208](#)]



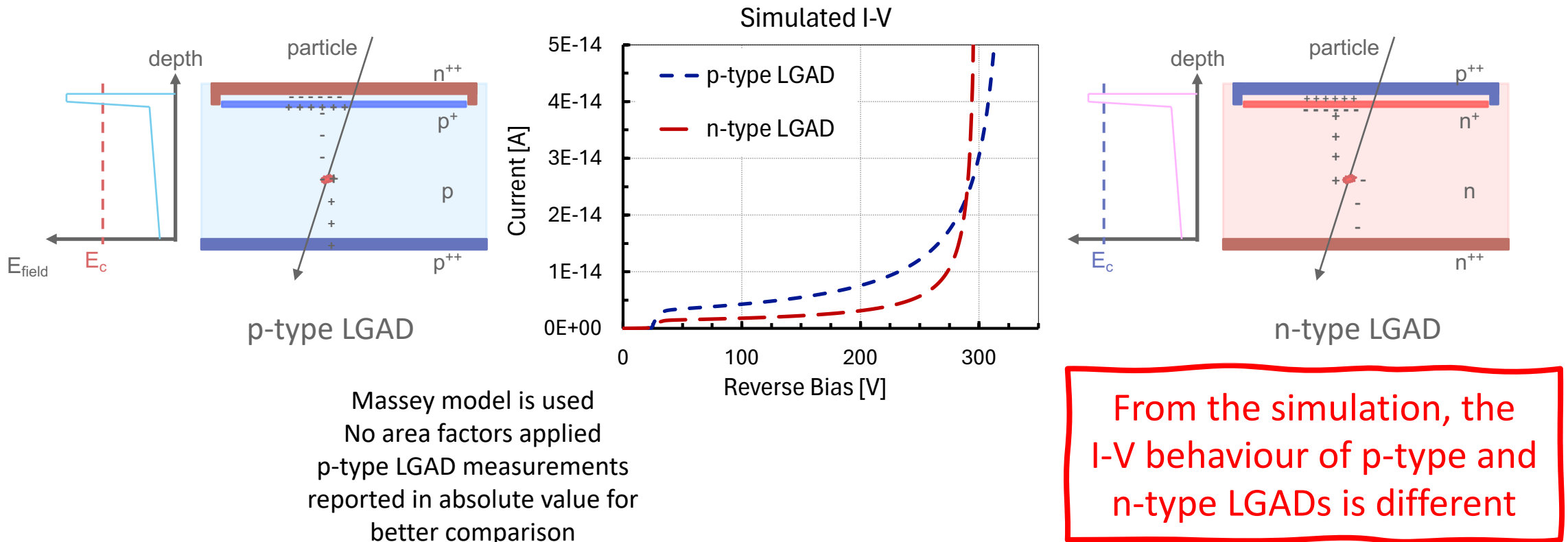
From p-type to n-type LGADs

Assuming that it is possible to swap the type of the implants, while keeping exactly the same shape and concentration



From p-type to n-type LGADs

Assuming that it is possible to swap the type of the implants, while keeping exactly the same shape and concentration

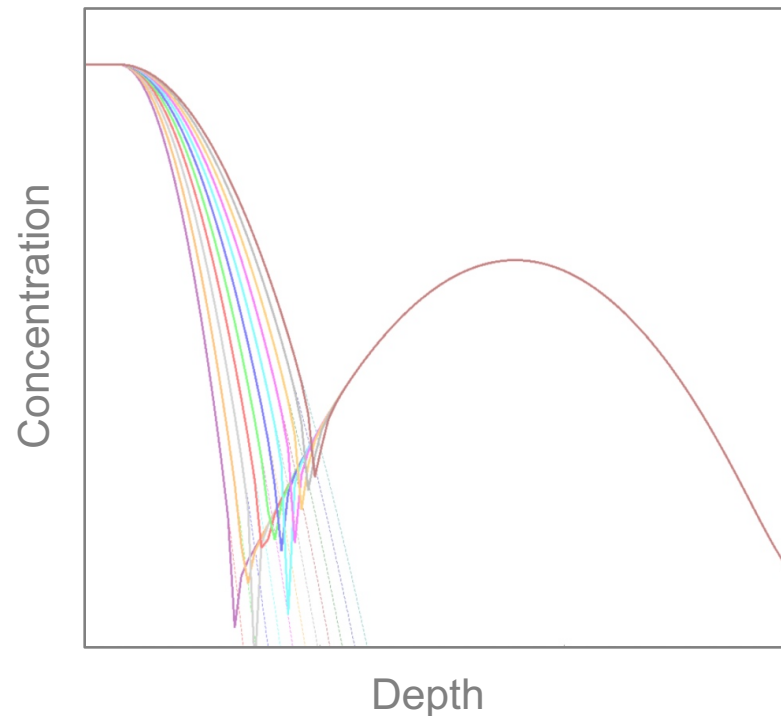


An architectural rendering of a modern building complex, likely a synchrotron facility. The complex consists of several interconnected buildings with a mix of glass facades and solid, light-colored panels. A prominent feature is a large, white, hexagonal lattice structure that appears to be a decorative or functional element on the exterior of one of the buildings. The buildings are set against a clear blue sky. In the foreground, there is a green lawn with a few people walking, and a paved path. The overall style is clean and modern.

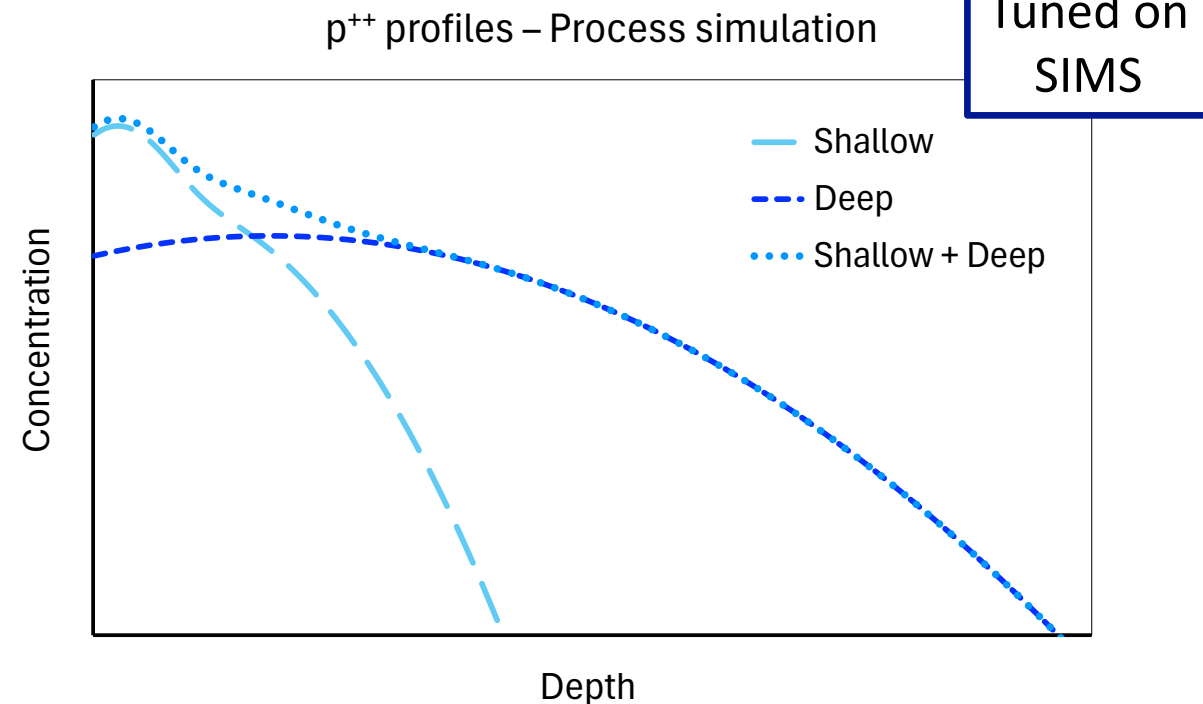
nLGAD Design

Design of the p^{++} read-out contact

p-type and n-type elements have different atomic weights and sizes, and different diffusions in Silicon
→ The p^{++} read-out contact was designed explicitly for the NLGAD sensors



A lot of different simulations have been performed to assess the impact of different p^{++} diffusion

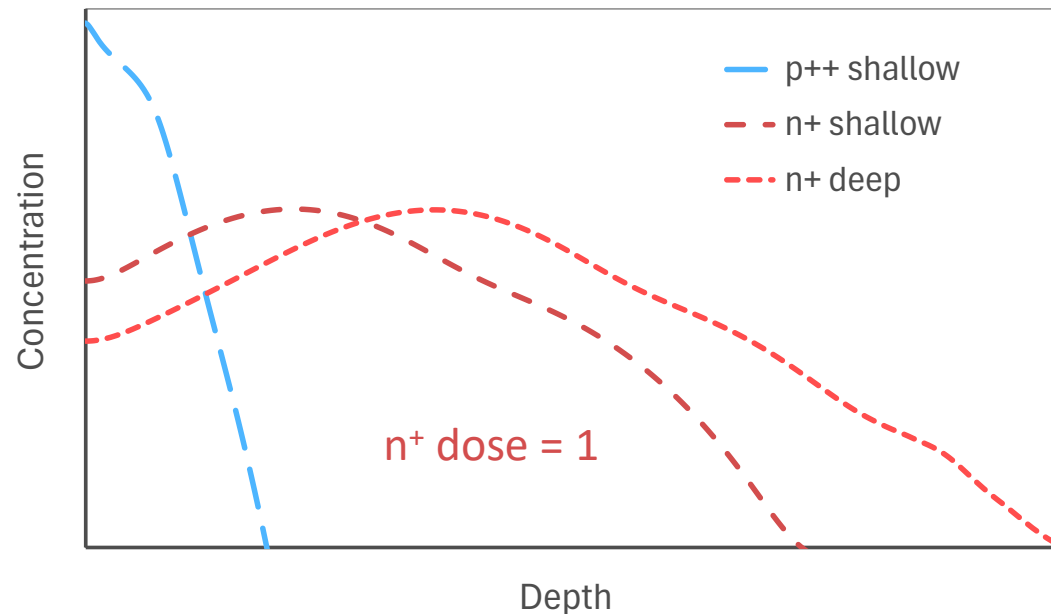


Three different designs of the p^{++} shallow, deep, and shallow + deep

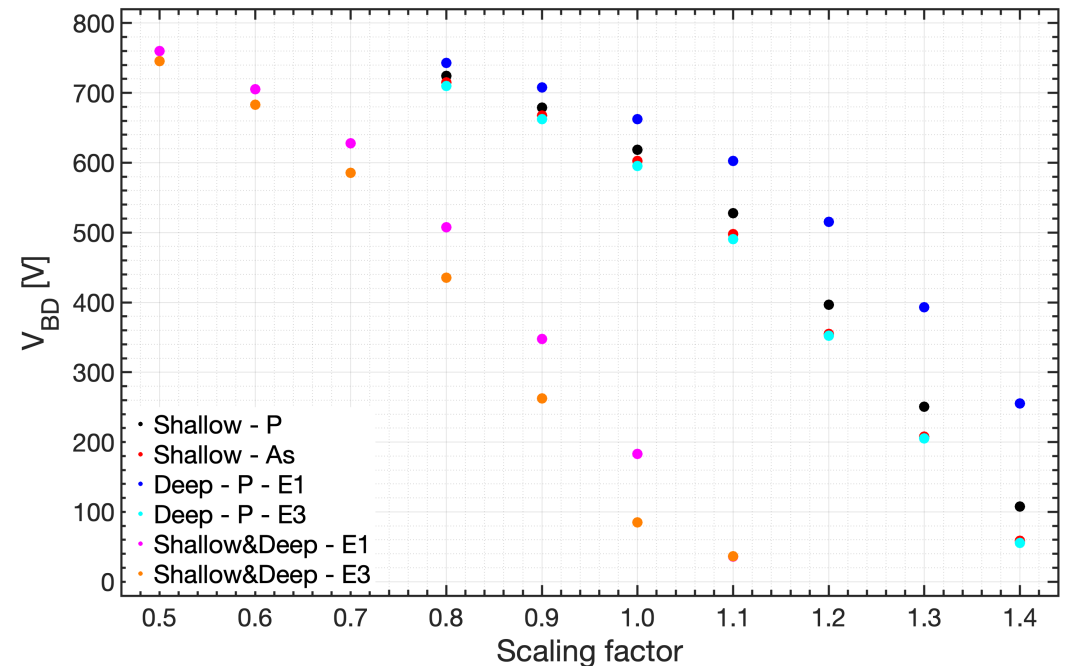
Design of the n^+ gain implant

Different depths and concentrations of the n^+ implant have been investigated
Two n-type elements are used: **Phosphorus** and **Arsenic**

n^+ profiles – Process simulation



A lot of different simulations have been performed
to assess the n^+ implantation energy

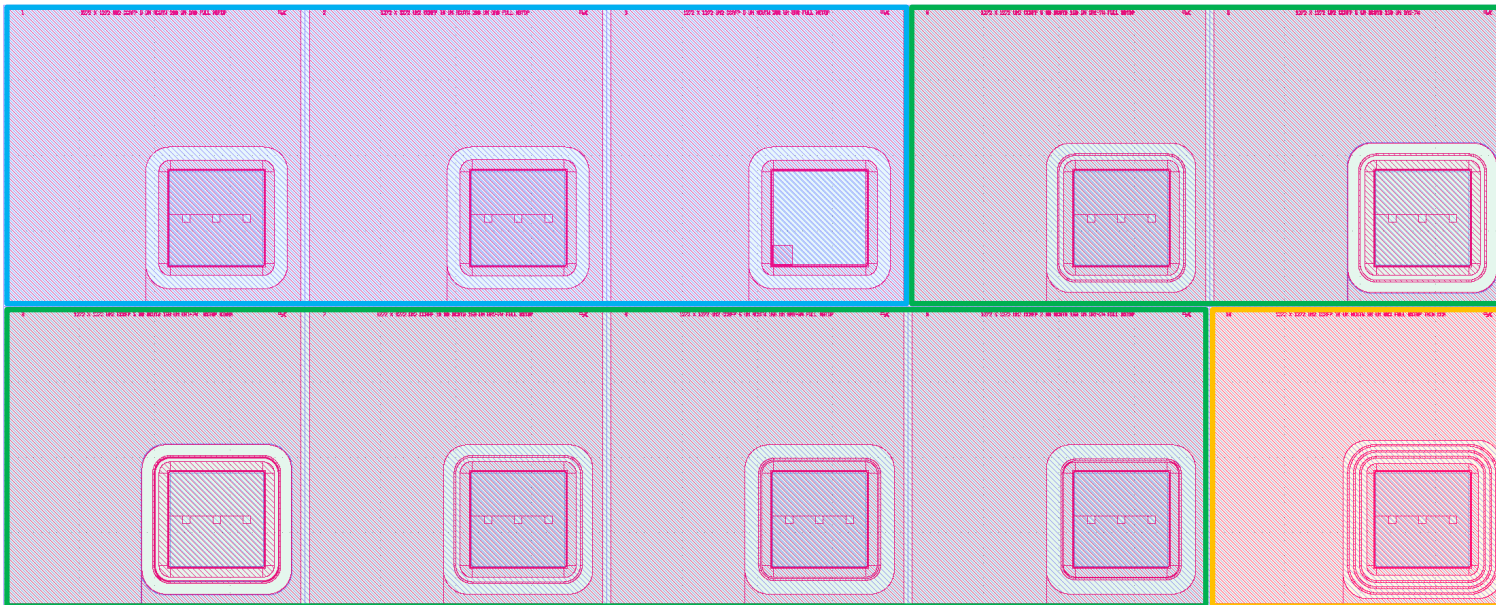


**The simulation guided the designs and
the concentrations of the n^+ gain implants**

Design of the periphery

The sensor periphery was designed to take into account the active thickness of **55 μm** and the very high resistivity, **greater than 10k $\Omega\cdot\text{cm}$** , of the **epitaxial substrates** employed for the nLGAD batch

Ten different sensor layouts have been selected, with an edge size of 500 μm , different numbers of floating guard rings, and different strategies of the n-type isolation



Three floating guard ring options

▷ GR0

▷ GR1

▷ GR3

Two isolation types

▷ n-stop

▷ n-spray

– high dose

– low dose

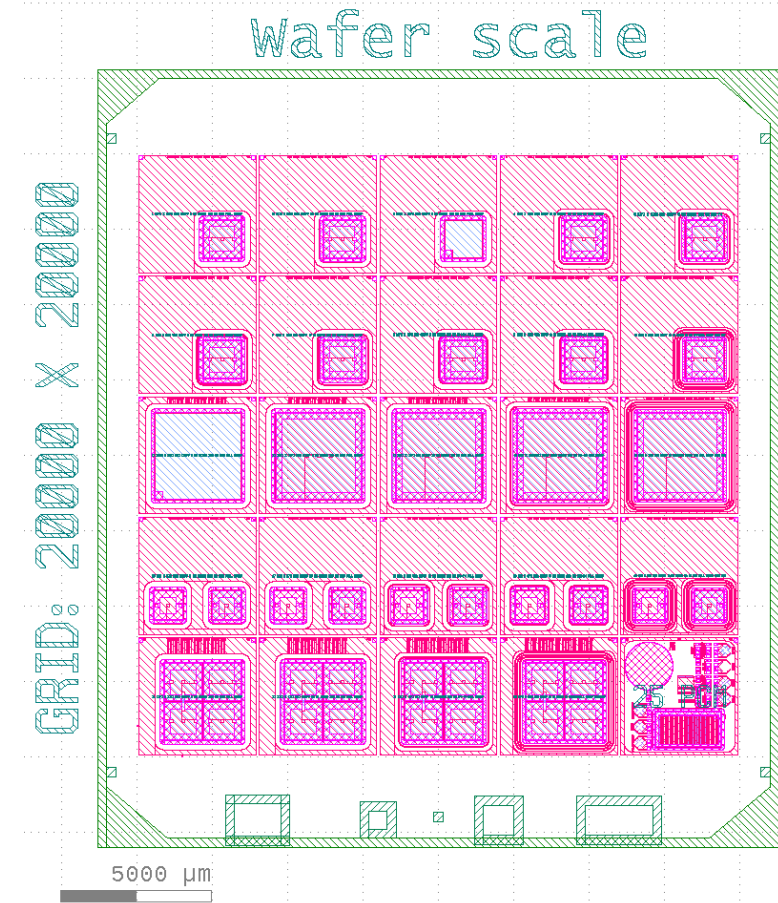
The NLGAD batch at FBK

The NLGAD batch will be used to study the donor removal coefficient, c_D

15 epitaxial substrates with active thickness of 55 μm

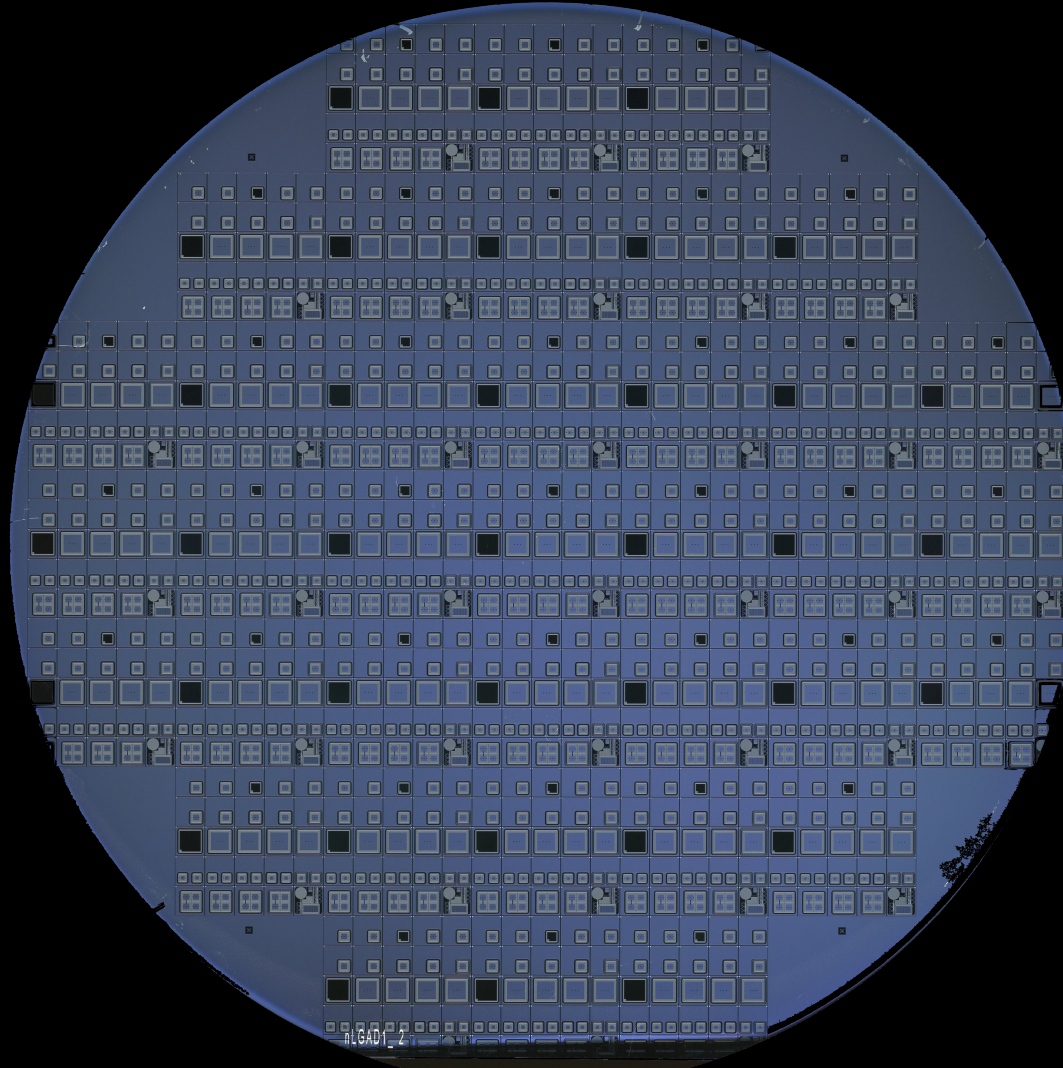
Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
1	Shallow	Shallow	1.20	P
2	Shallow	Shallow	1.26	P
3	Shallow	Shallow	1.30	P
4	Shallow	Shallow	1.36	P
5	Shallow	Shallow	1.40	P
6	Deep	Deep	1.30	P
7	Deep	Deep	1.36	P
8	Deep	Deep	-	P
9	Deep	Deep	1.40	P
10	Shallow	Deep	0.90	P
11	Shallow	Deep	0.96	P
12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As

+ 3 substrates with active thickness of 450 μm



The NLGAD sensors

The NLGAD
wafers exited
the FBK clean
room in mid
September 2025



Measurements:

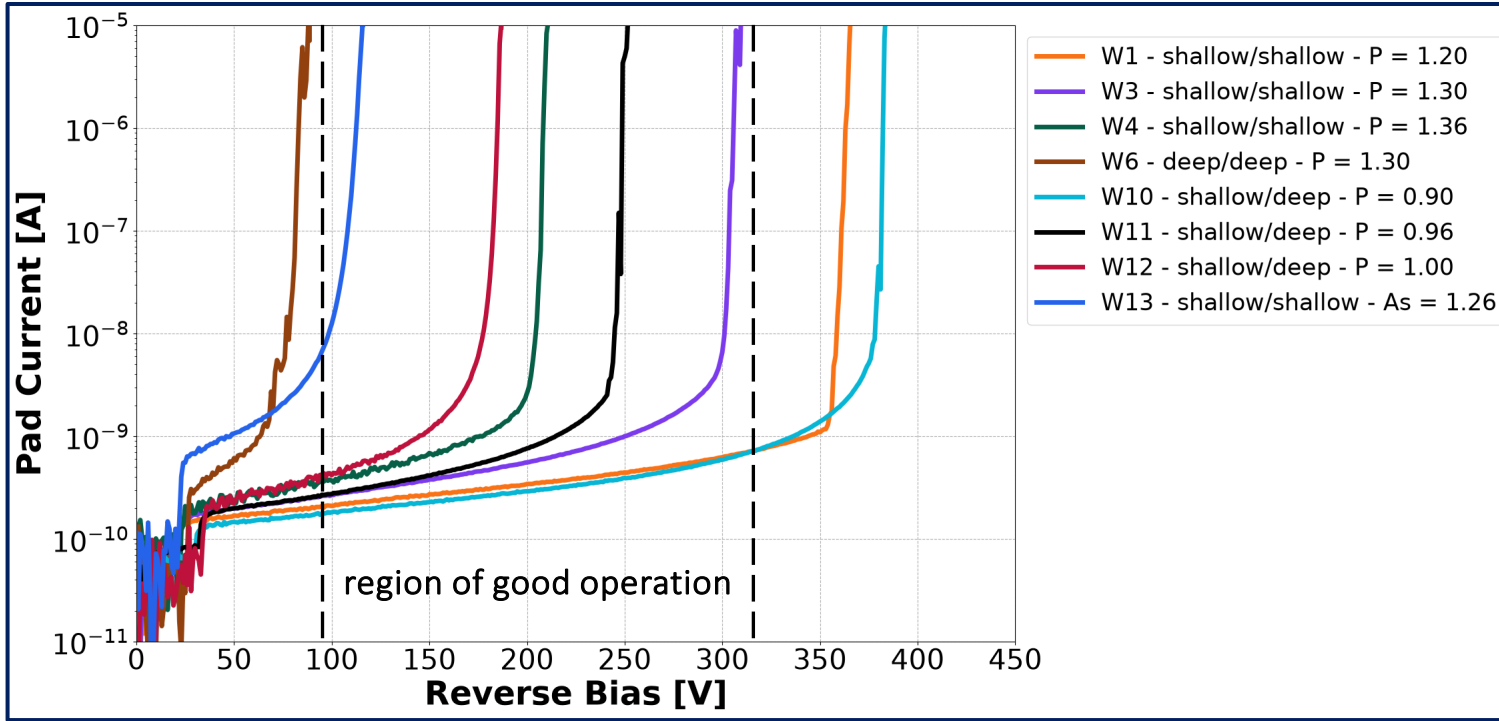
- ▷ I-V
- ▷ C-V
- ▷ TCT
- ▷ β particles
- ▷ Test Beam
- ▷ TPA, X-rays, ...

→ **High quality
production**



nLGAD – Electrical Characterisation

nLGAD – IV

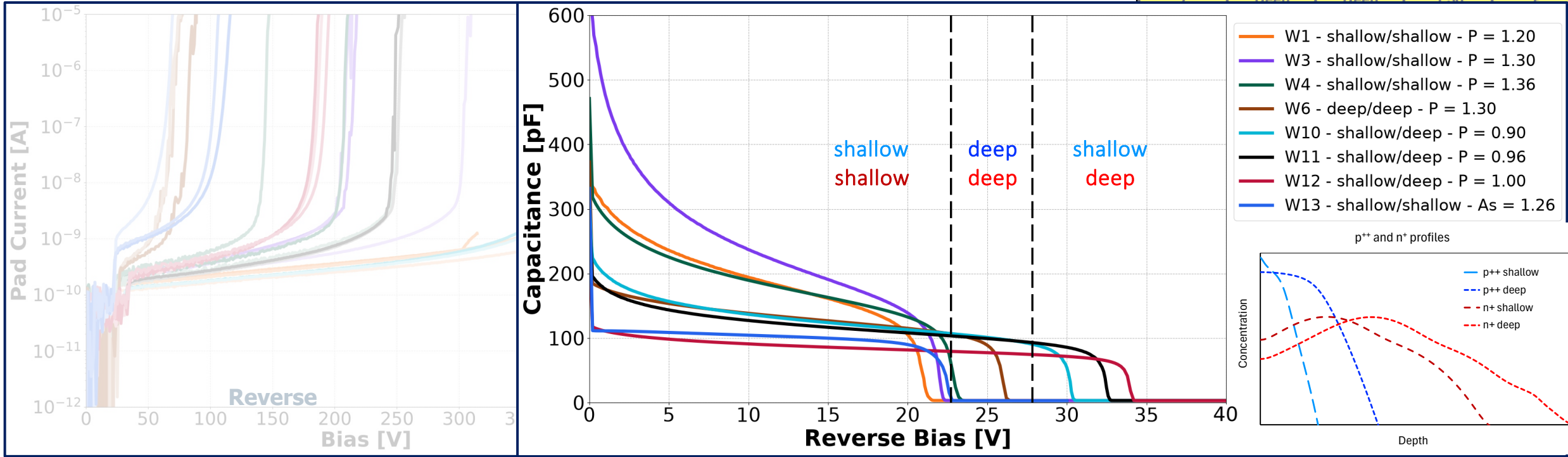


Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
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6	Deep	Deep	1.30	P
7	Deep	Deep	1.36	P
8	Deep	Deep	-	P
9	Deep	Deep	1.40	P
10	Shallow	Deep	0.90	P
11	Shallow	Deep	0.96	P
12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As

- ▷ Largest breakdown voltage reached by **W1** and **W10** → the less doped wafers
- ▷ Smaller breakdown in **W13** (As) than **W4** (P)
 - Same n⁺ design with different dopant elements → **Arsenic less diffused than Phosphorous**
- ▷ Higher current in **W13** (As) than the others

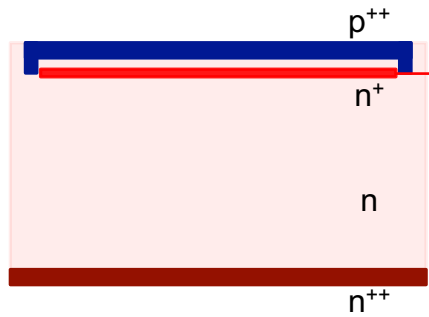
nLGAD – $1/C^2V$

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
1	Shallow	Shallow	1.20	P
2	Shallow	Shallow	1.26	P
3	Shallow	Shallow	1.30	P
4	Shallow	Shallow	1.36	P
5	Shallow	Shallow	1.40	P
6	Deep	Deep	1.30	P
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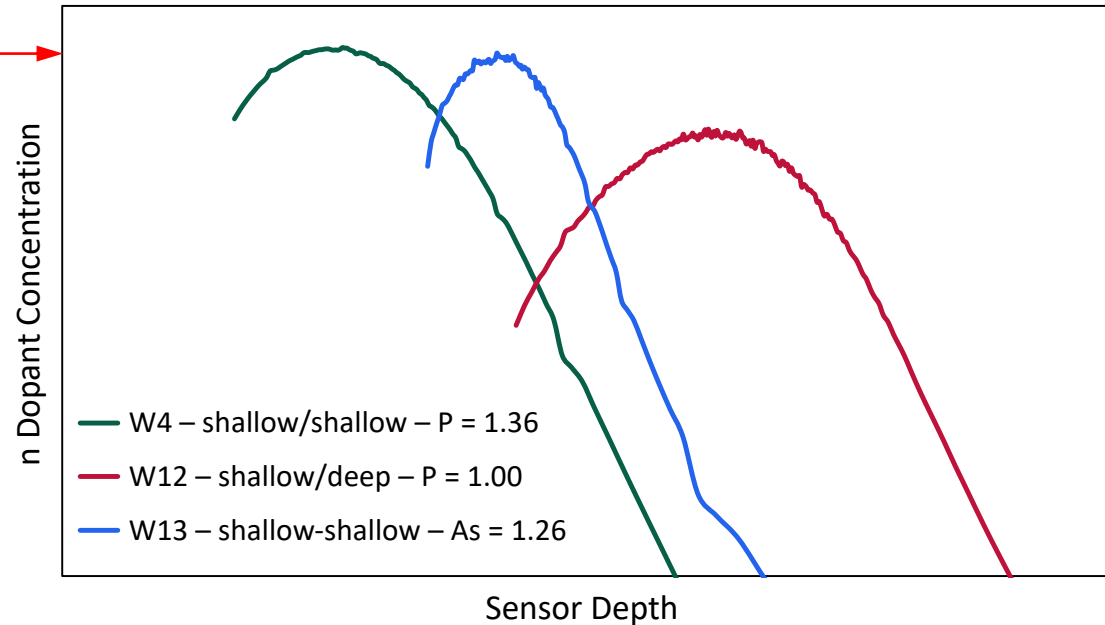


- Largest breakdown voltage reached by **W1** and **W10** → the less doped wafers
- Smaller breakdown in **W13** (As) than **W4** (P)
 - Same n+ design with different dopant elements → **Arsenic less diffused than Phosphorous**
- Higher current in **W13** (As) than the others
- Deep gain implants implies larger V_{gl}
 - Scaling with the dose more evident in deep implants

nLGAD – Doping Profile



p-in-n LGAD



Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
1	Shallow	Shallow	1.20	P
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3	Shallow	Shallow	1.30	P
4	Shallow	Shallow	1.36	P
5	Shallow	Shallow	1.40	P
6	Deep	Deep	1.30	P
7	Deep	Deep	1.36	P
8	Deep	Deep	–	P
9	Deep	Deep	1.40	P
10	Shallow	Deep	0.90	P
11	Shallow	Deep	0.96	P
12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As

$$N_D(d) = \frac{2}{e \cdot \epsilon_{Si} \cdot A^2 \cdot \left[-\frac{1(1/C^2)}{dV} \right]}$$

$$d = \frac{\epsilon_{Si} \cdot A}{C}$$

- Arsenic (**W13**) implant as high as the Phosphorus (**W4**) one but narrower → 10% less implanted dose
- Deep Phosphorus (**W12**) implant lower and larger than the shallow (**W4**) one, as expected

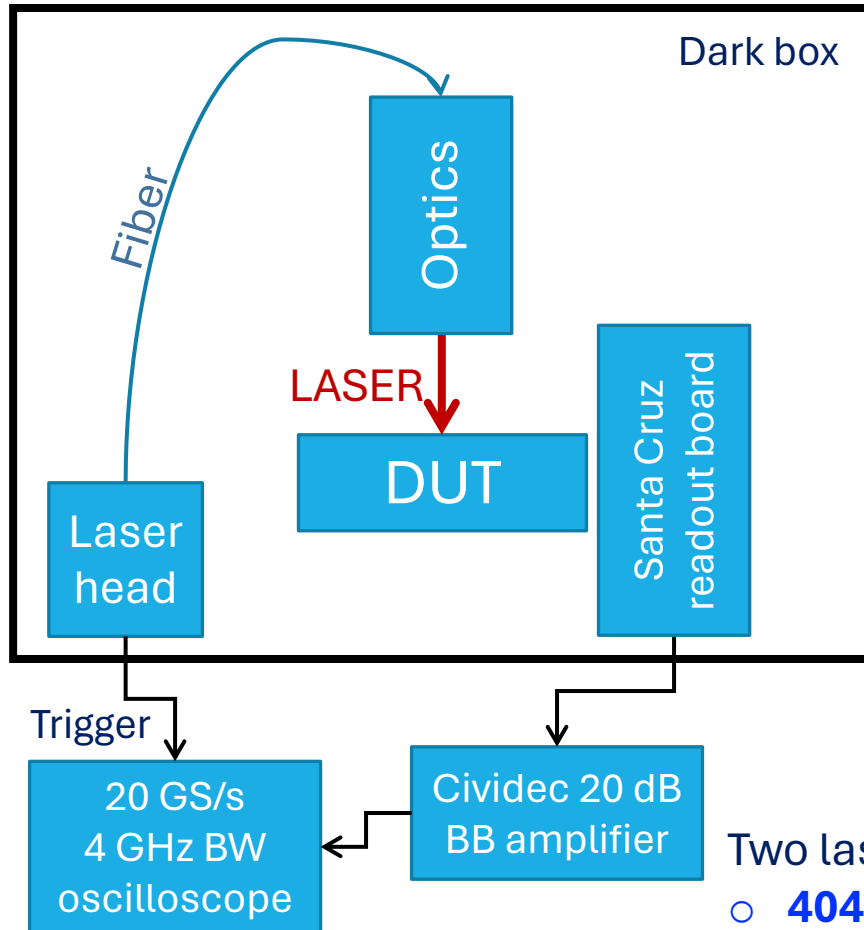


nLGAD Signal – TCT

TCT Setup

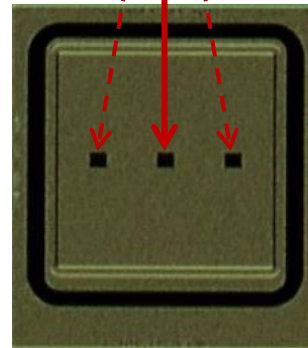
T = 23°C

Laboratory setup



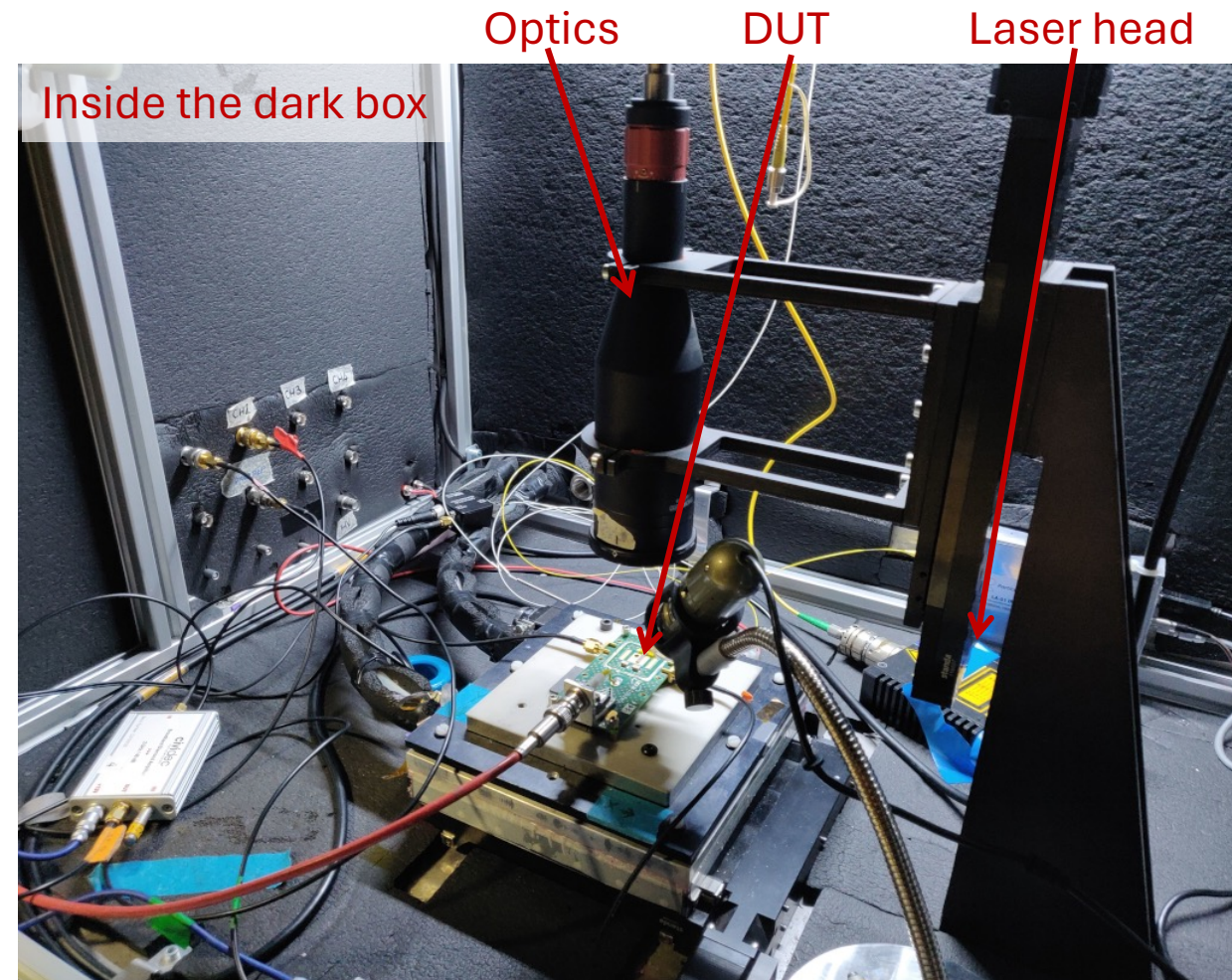
Intensity
 $\sim 1.5 \times 10^4$
photons
per pulse

100 × 100 μm
Optical windows



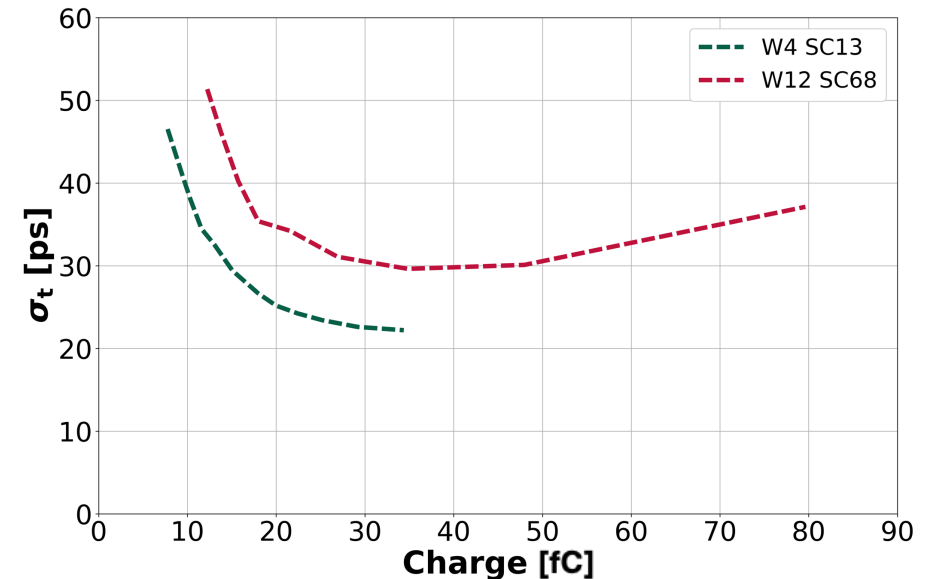
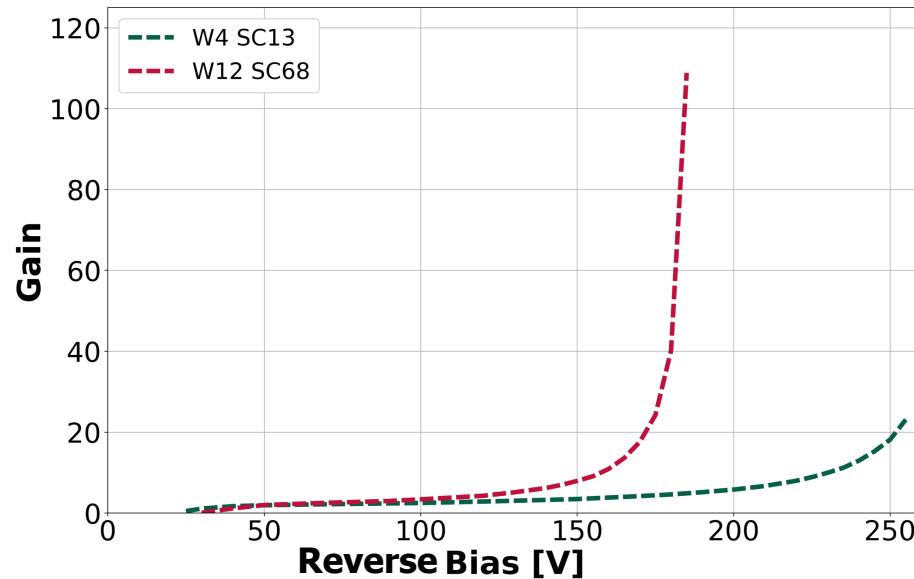
Two lasers used:

- 404 nm by Particulars
- 1060 nm by NKT Photonics



TCT – 1060 nm photons

Contribution to σ_t from
laser timing reference
not subtracted

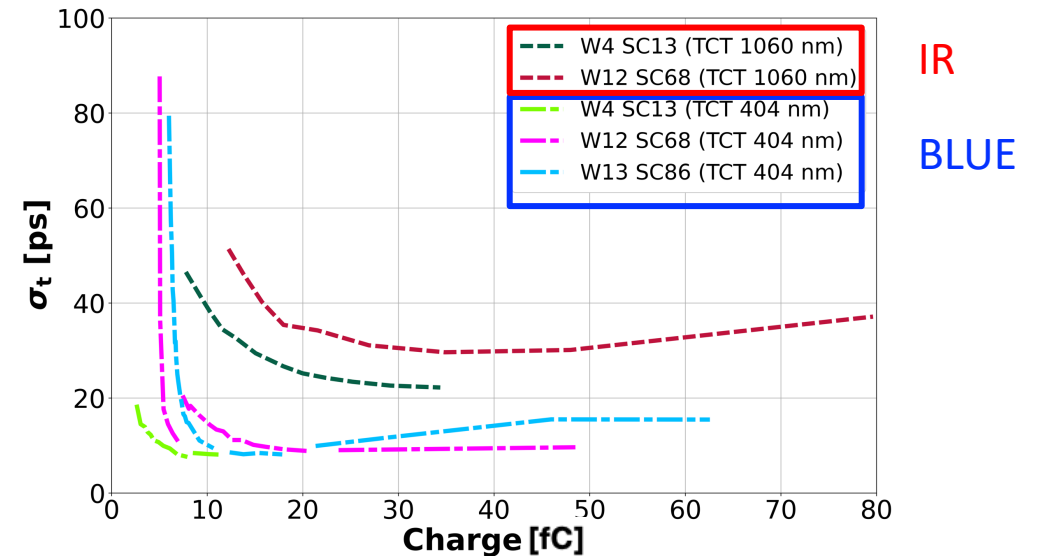
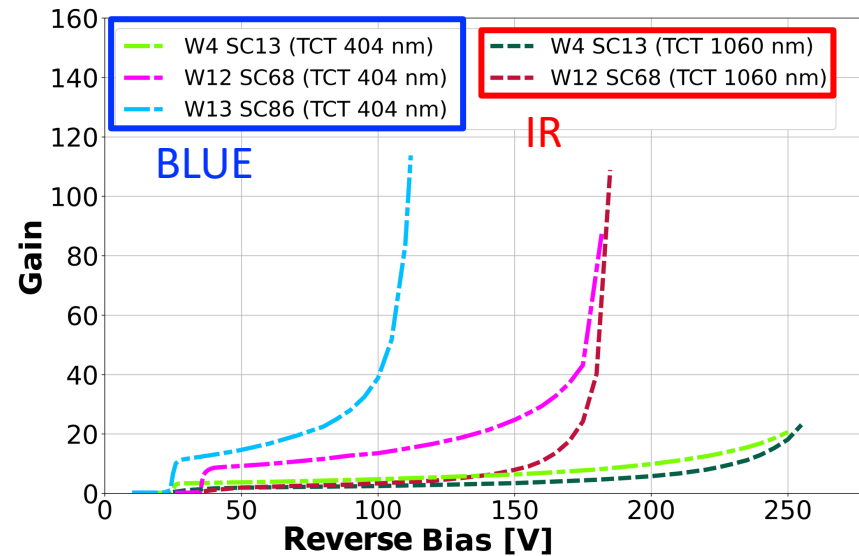


- ▷ **Lower gain for W4** (shallow-shallow $P = 1.36$) **than W12** (shallow-deep $P = 1.00$)
- ▷ **Timing resolution down to 22 ps** at 35 fC for W4

NOTE : IR light penetrates the whole sensors thickness

TCT – 404 nm photons

Contribution to σ_t from
laser timing reference
not subtracted



- Higher gain at 404 nm wrt 1060 nm
- Timing resolution down to 10 ps for all the wafers
 - W4 at 8 fC
 - W12 at 20 fC
 - W13 at 10 fC

NOTE : BLUE light penetrates ~ 1 μ m only in the sensor

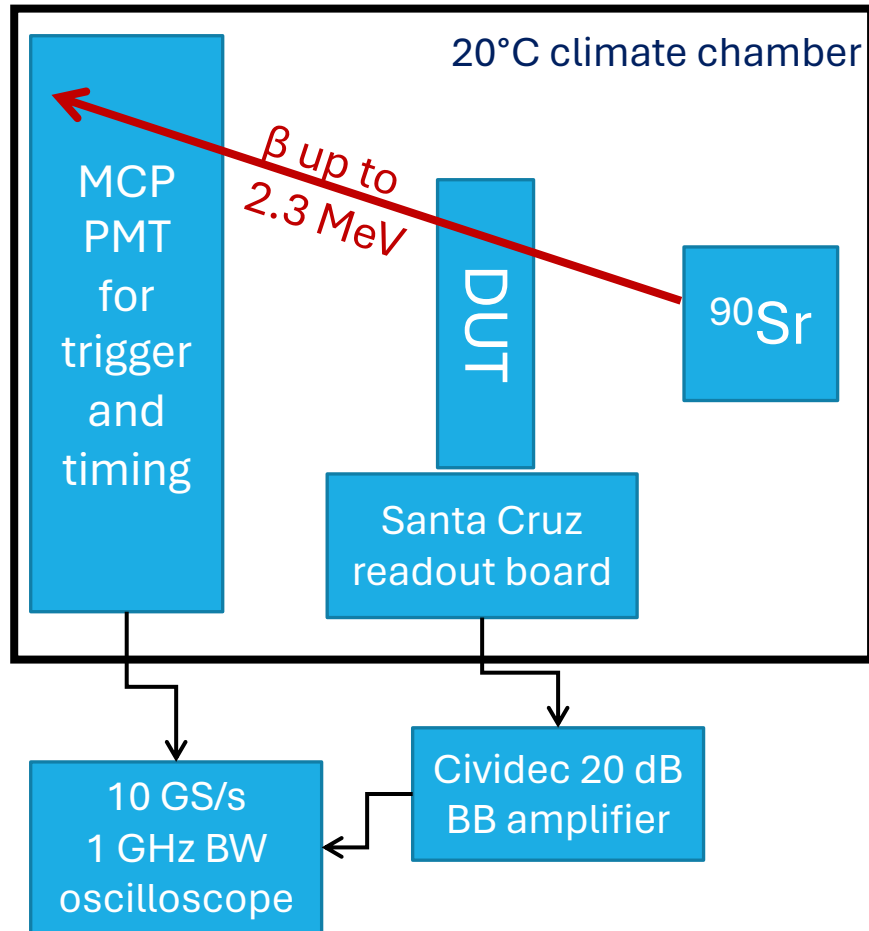
An architectural rendering of a modern, multi-story building complex. The building features a mix of grey and light-colored facades with large glass windows. A prominent feature is a white, hexagonal lattice structure that wraps around parts of the building's exterior. The building is set on a green lawn with some trees and a few people walking in the foreground. The sky is a pale blue with soft clouds.

nLGAD Signal – Electrons

β Setup

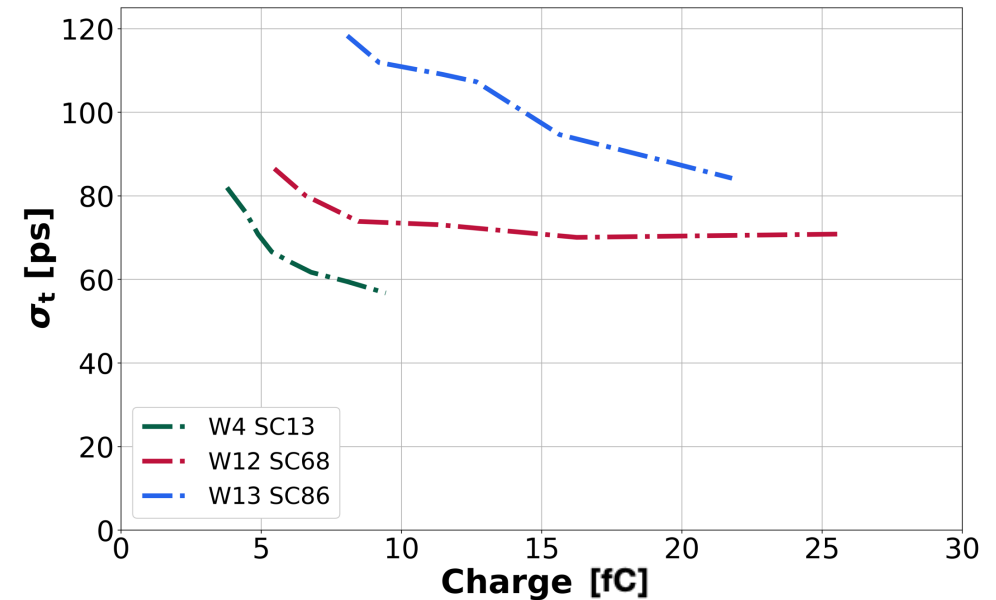
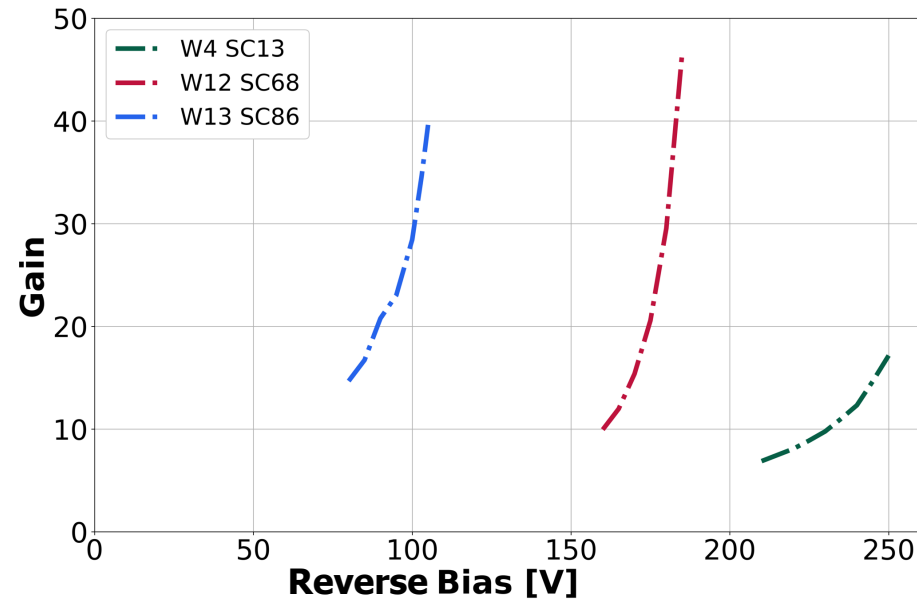
T = 20°C

Laboratory setup



β particles from ^{90}Sr

$T = 20^\circ\text{C}$

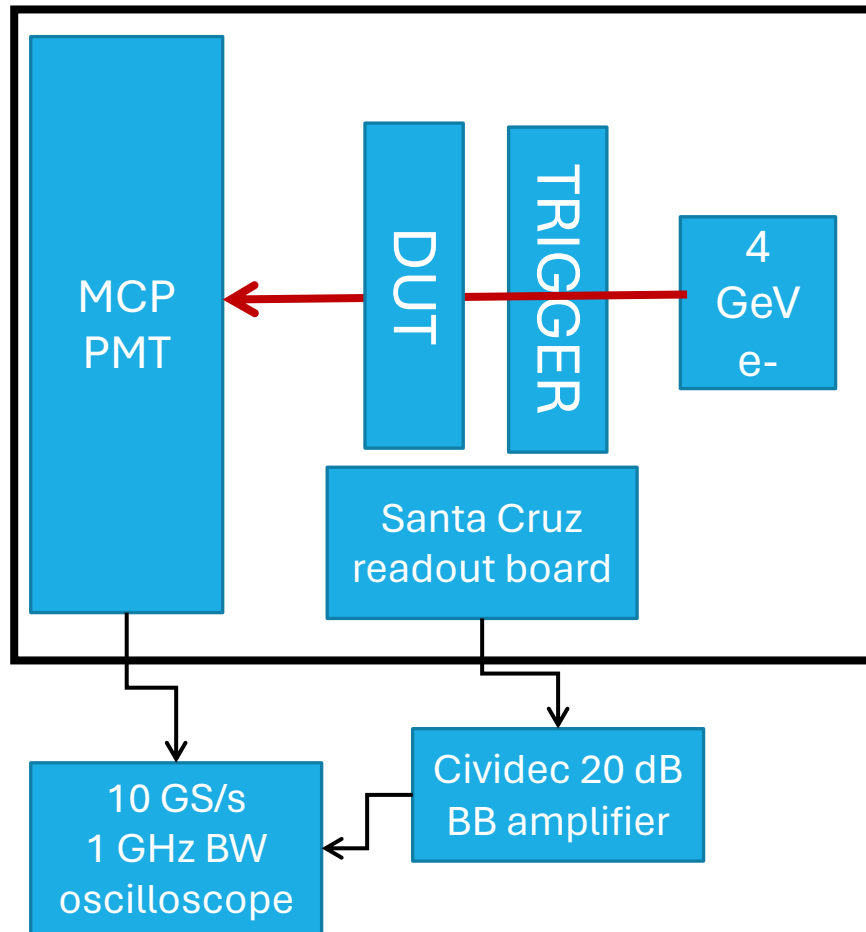


- ▷ **Lower gain for W4** (shallow-shallow $P = 1.36$) **than W12** (shallow-deep $P = 1.00$) **and W13** ($A_s = 1.26$)
- ▷ **Timing resolution from 60 to 80 ps**

TB setup – 4 GeV e^- @ DESY

$T = 20^\circ\text{C}$

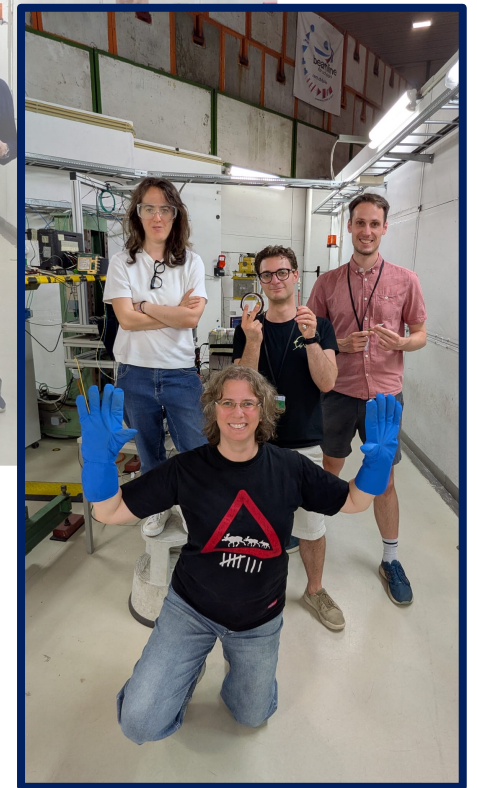
DESY setup



TB DESY 2025



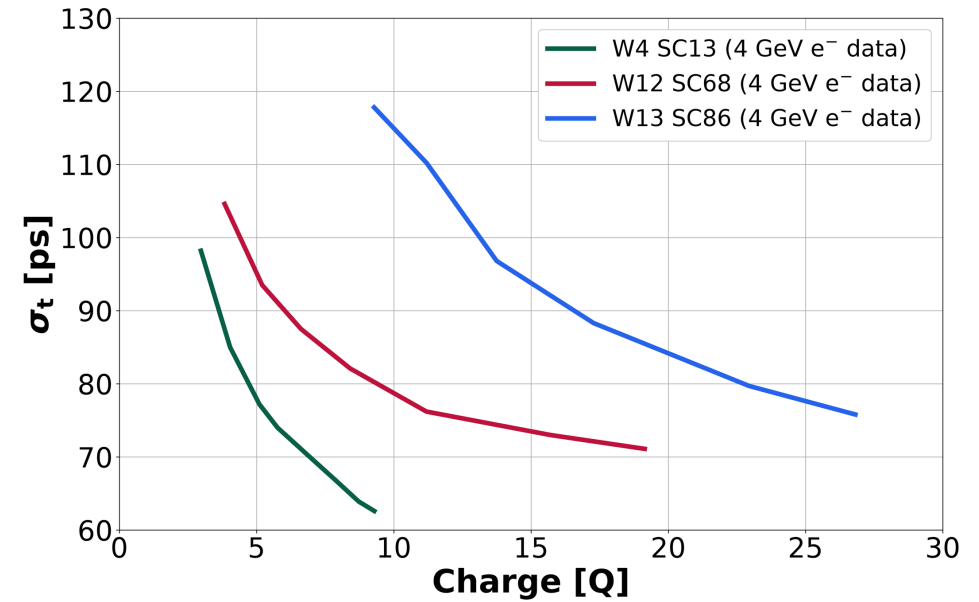
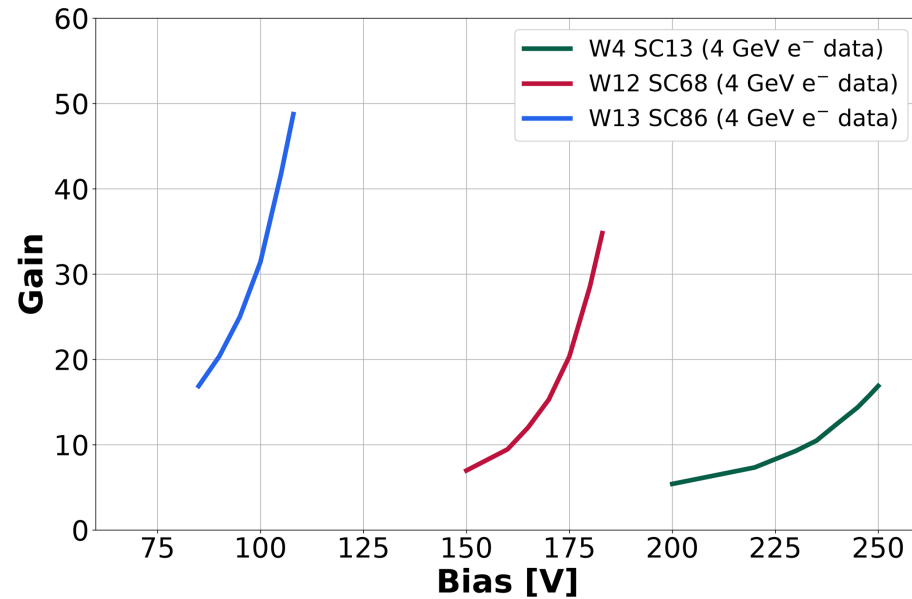
TB SPS 2026



TB DESY 2026

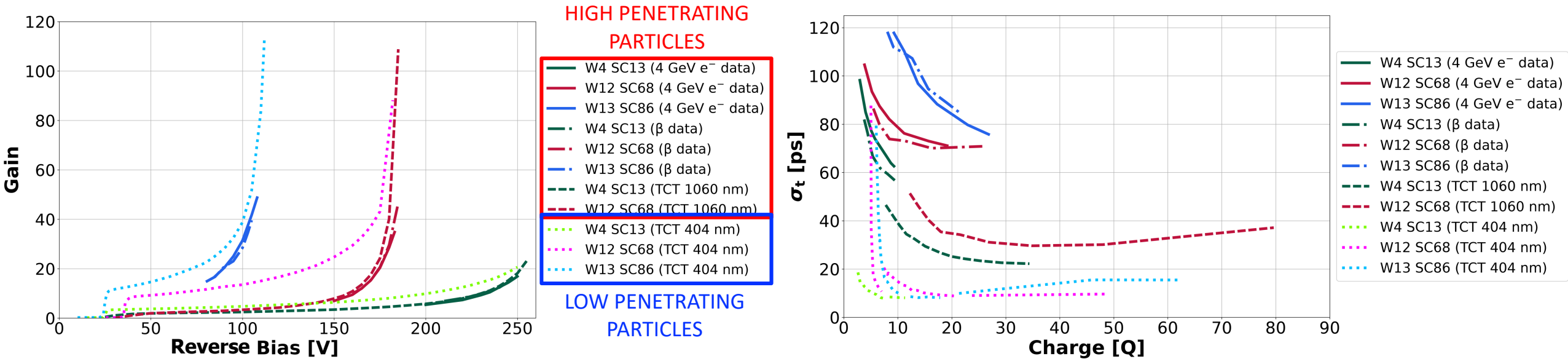
4 GeV electrons – DESY 2026

$T = 20^{\circ}\text{C}$

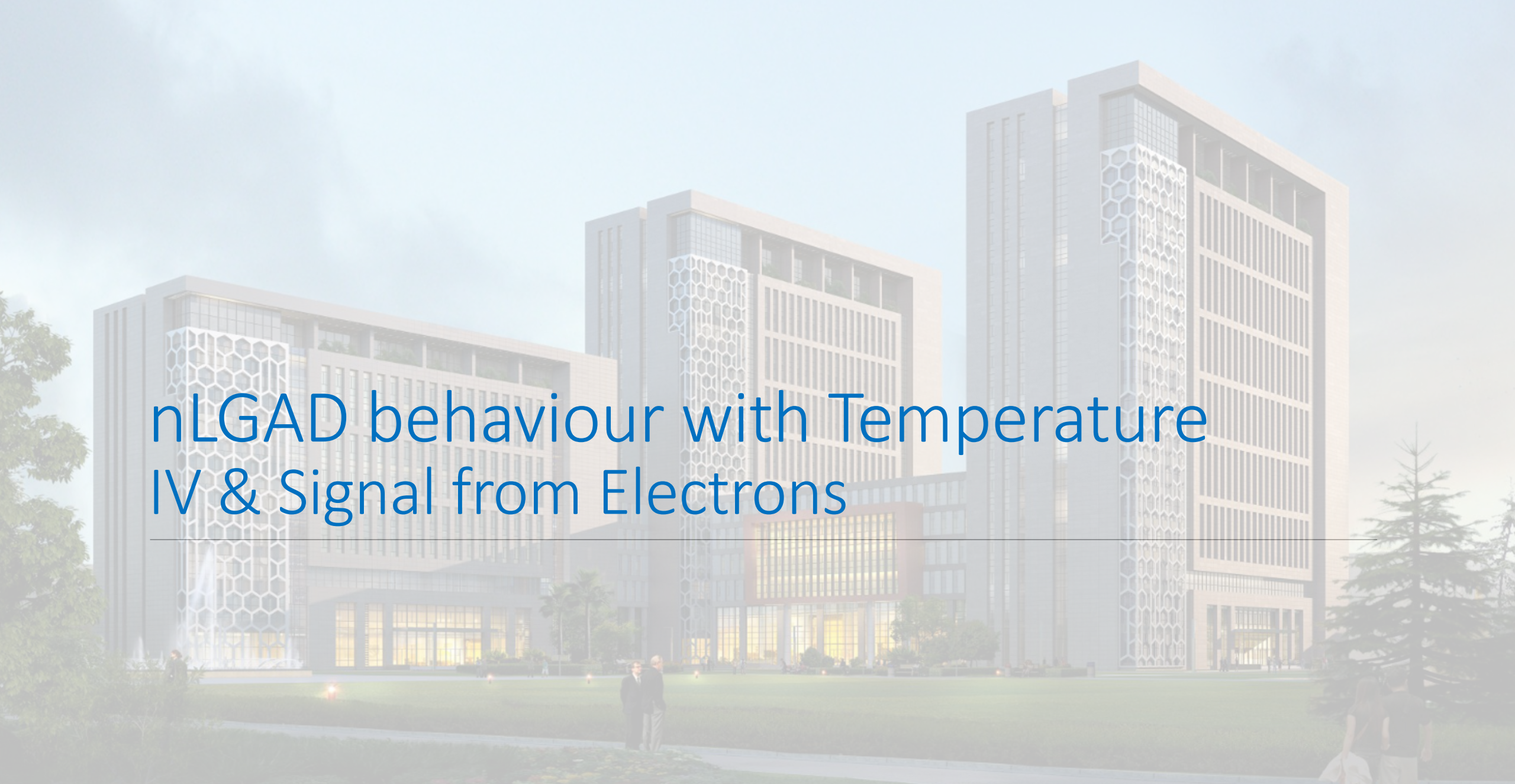


→ Behaviour from β source confirmed

Electrons & Photons



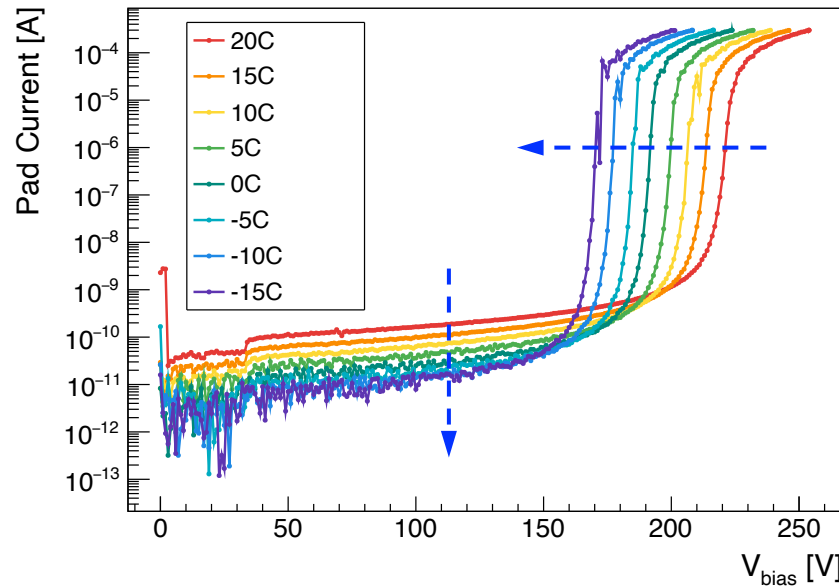
- Higher collected charge reached with **photons**
- Photons faster than MIPs – **NO ionisation term**
- Better timing with **photons** down to **10 ps**



nLGAD behaviour with Temperature IV & Signal from Electrons

IV at different T – W12

LGAD (non-irr)

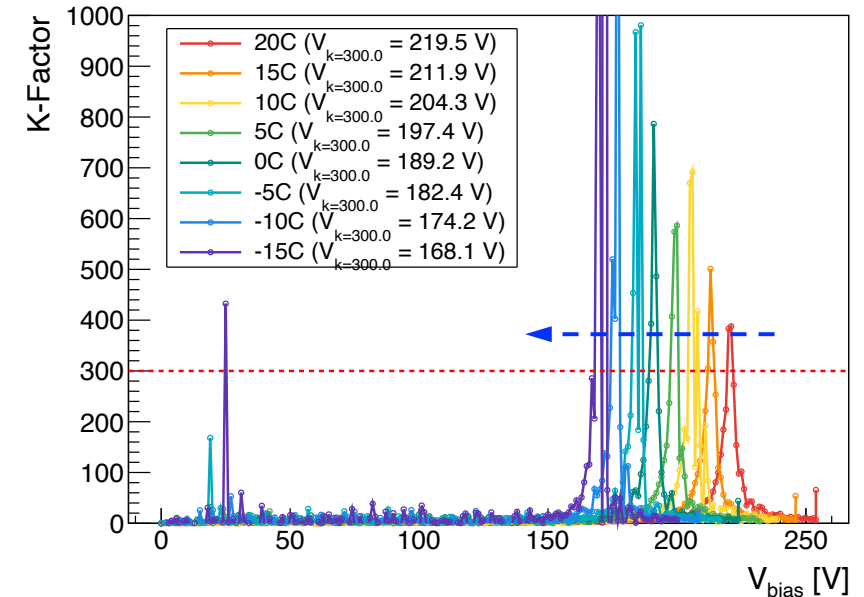


$$K(V) = \frac{V}{I} \frac{dI}{dV}$$

$$\text{If } I_{\text{LGAD}} = M \cdot I_{\text{PIN}}$$

$$K(V) = \frac{V}{M I_{\text{PIN}}} \frac{d(M I_{\text{PIN}})}{dV} = \frac{dM}{dV} \frac{V}{M}$$

K-Factor vs V - LGAD (non-irr)



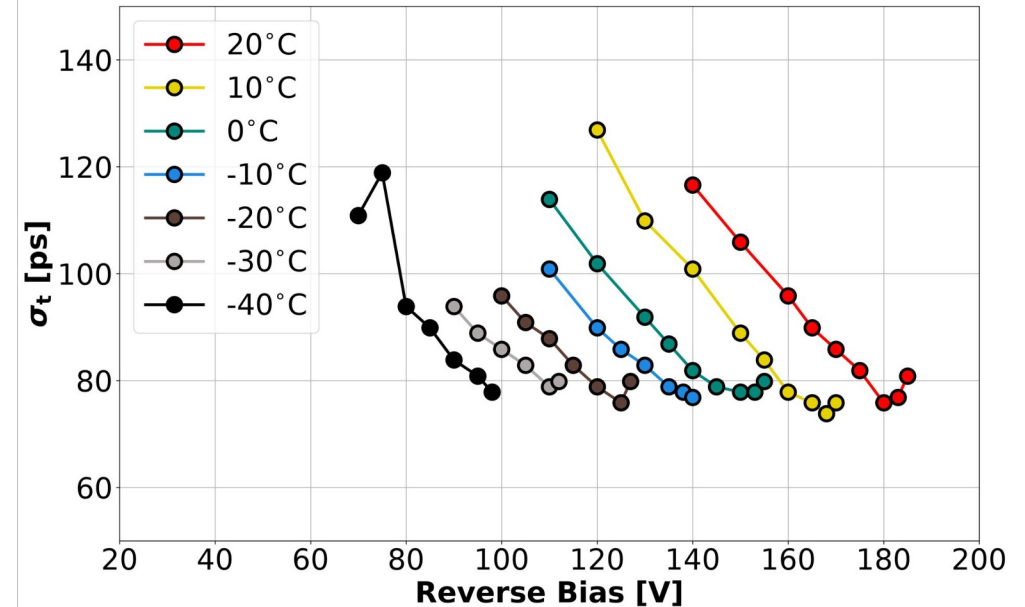
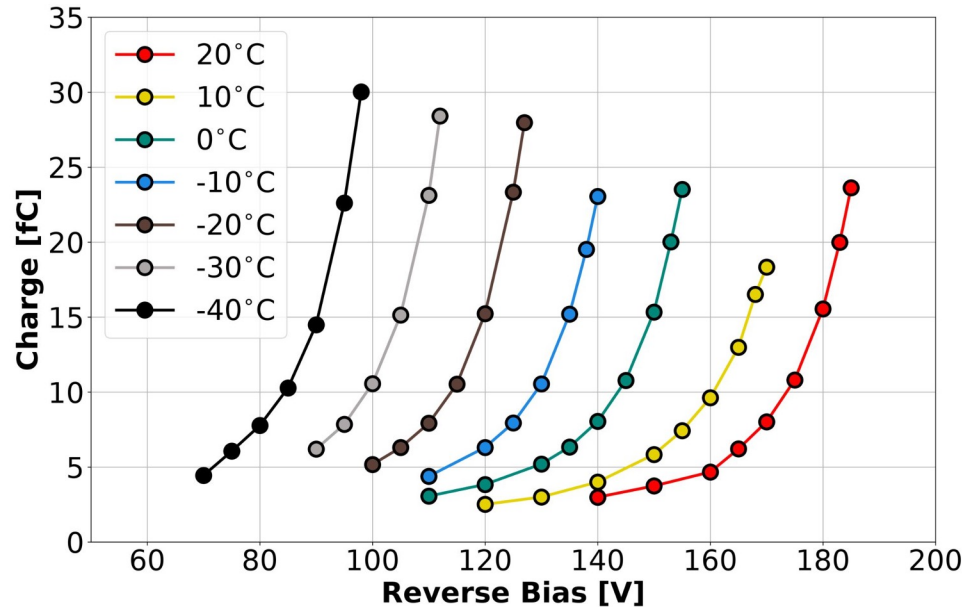
- The bulk current decreases with decreasing temperature, as expected 🧊🧐❄️
- The gain increases with decreasing temperature → The breakdown voltage (V_{BD}) decreases with T
- The K-factor is a measure of the gain variation with the bias → It measures the effect of the electric field

For every 1°C reduction → V_{BD} reduced by ~ 1.5 V

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
12	Shallow	Deep	1.00	P

Signals at different T – W12

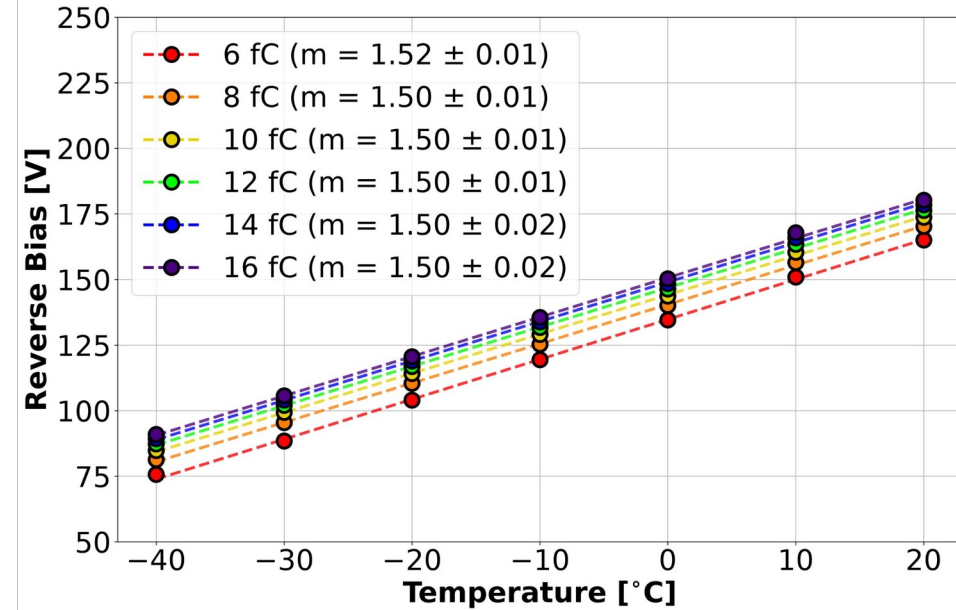
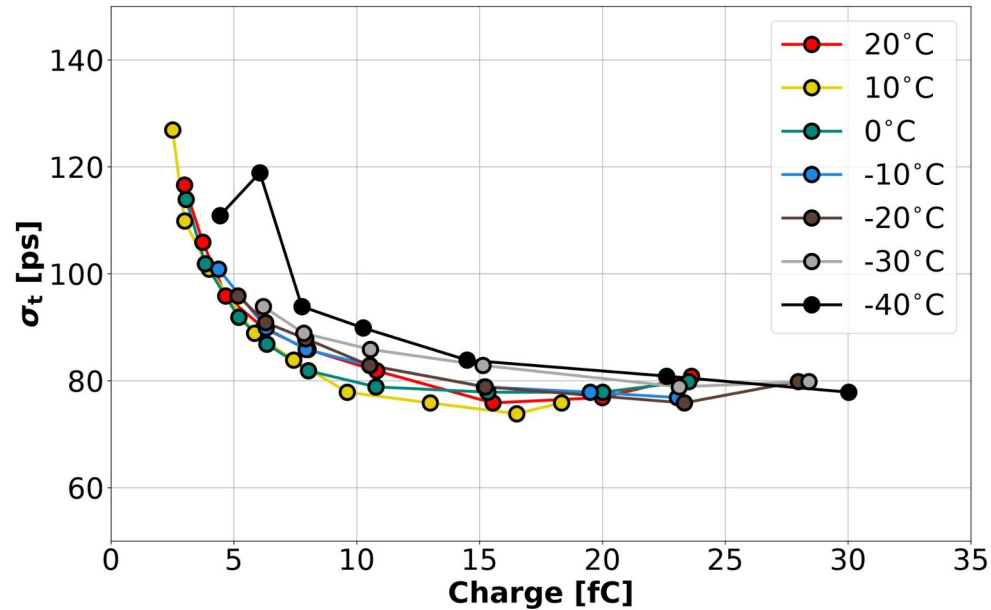
β particles from ^{90}Sr



- ▷ The gain can be estimated by normalizing by the charge collected by the PIN, $Q_{\text{PIN}} \sim 0,55 \text{ fC}$
- ▷ As in the IV, the gain increases with decreasing temperature → Same charge reached at smaller V_{bias}
- ▷ The same behaviour reflects into the timing resolution

Signals at different T – W12

β particles from ^{90}Sr



- Still, the same charge is needed to reach a fixed value of timing resolution
 - Temperature does not modify the intrinsic behaviour of a LGAD sensor, it modifies its working point
- The same temperature scaling as for the electrical characterisation is observed

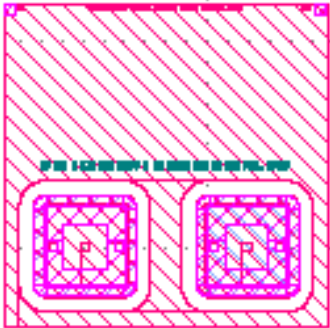
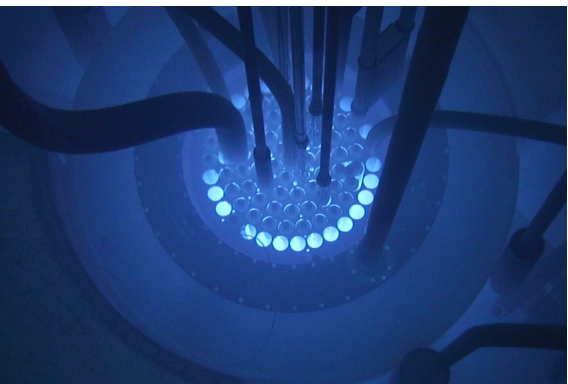
For every 1°C reduction → Operational V_{bias} reduced by ~ 1.5 V

Sensors Irradiation with Neutrons

LGAD-PIN and test structures irradiated with neutrons
at JSI (Ljubljana) at 7 different fluences
0.5 – 1 – 2 – 4 – 5 – 6 – 10E14 n_{eq}/cm²

High resistivity n-type bulk expected to be **type inverted** at all tested fluences

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
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2	Shallow	Shallow	1.26	P
3	Shallow	Shallow	1.30	P
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5	Shallow	Shallow	1.40	P
6	Deep	Deep	1.30	P
7	Deep	Deep	1.36	P
8	Deep	Deep	-	P
9	Deep	Deep	1.40	P
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11	Shallow	Deep	0.96	P
12	Shallow	Deep	1.00	P
13	Shallow	Shallow	1.26	As
14	Shallow	Shallow	1.30	As
15	Shallow	Shallow	1.36	As



nLGAD – nPiN

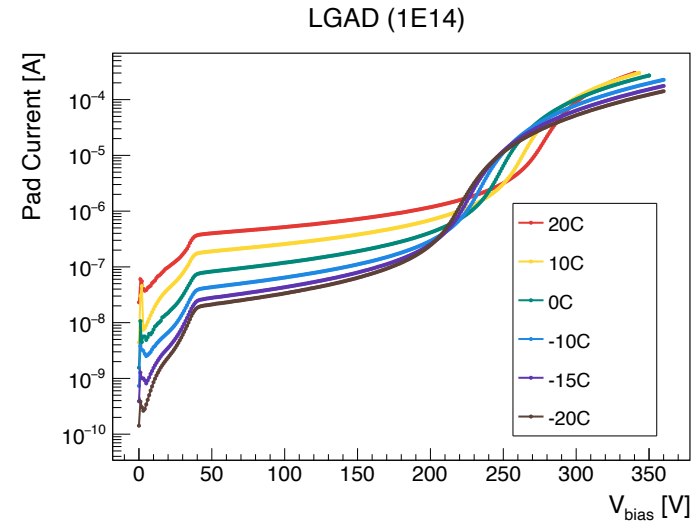
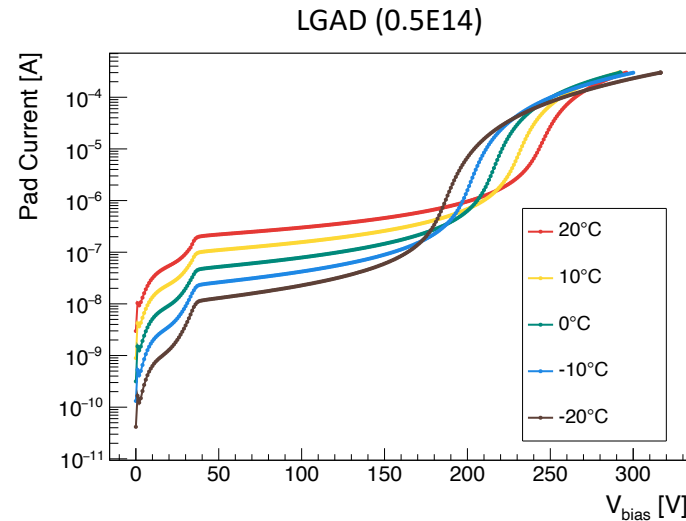


Test structures

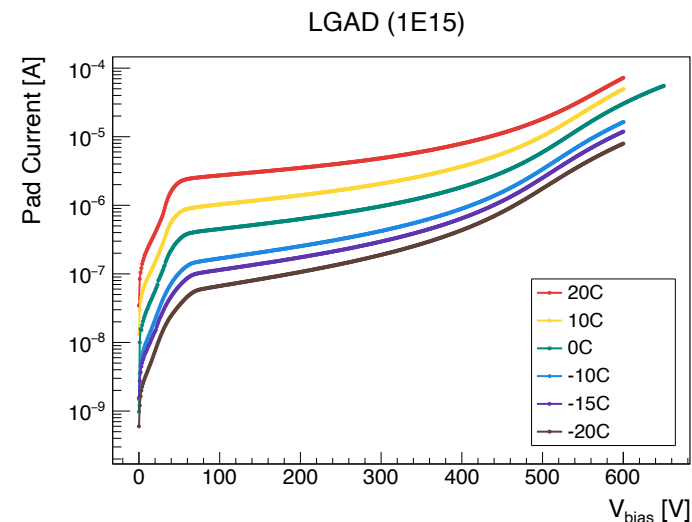
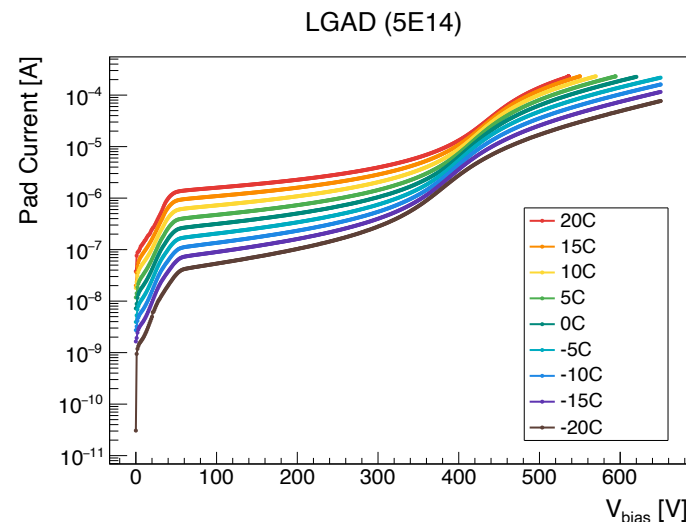
Following results
concentrate on W12

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
12	Shallow	Deep	1.00	P

IV at different T – Irradiated W12



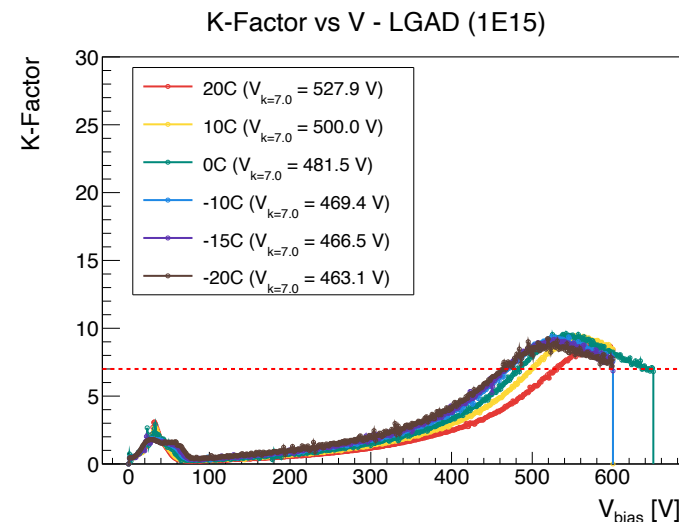
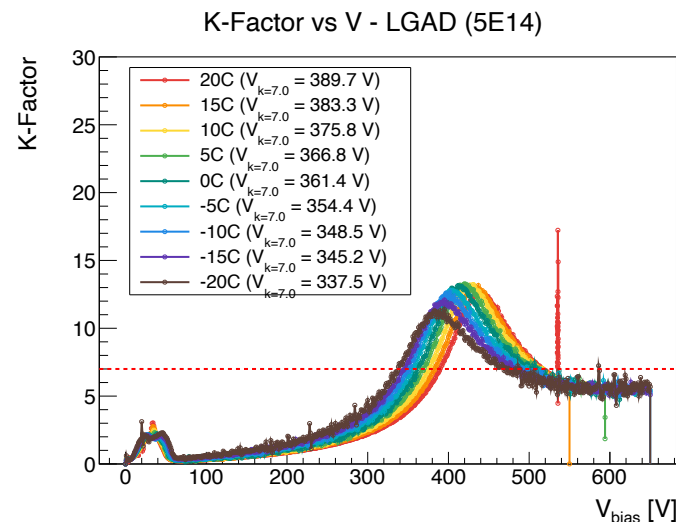
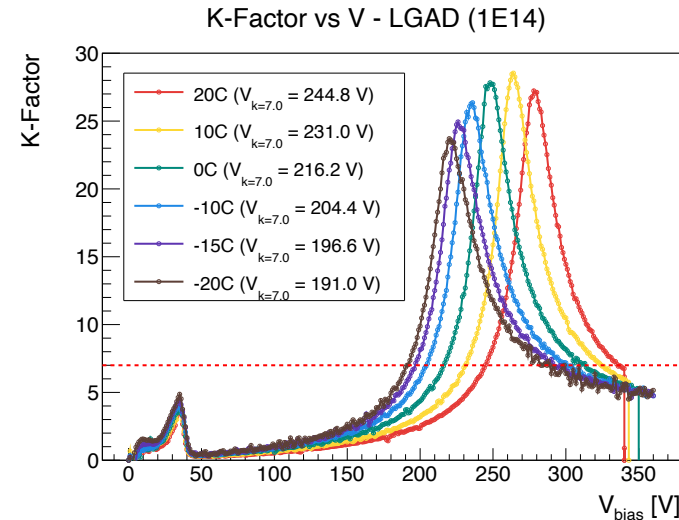
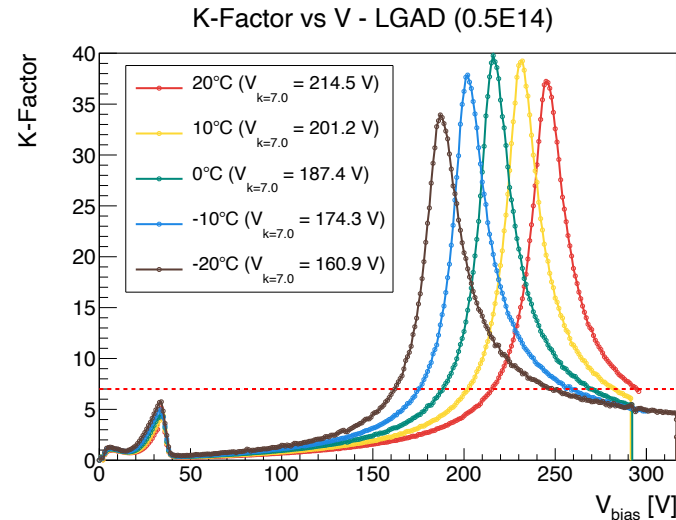
For the lower fluences, the behaviour follow the one of unirradiated nLGAD sensors



For the higher fluences, the the breakdown voltage is not easily defined and its evolution with the temperature is not straightforward

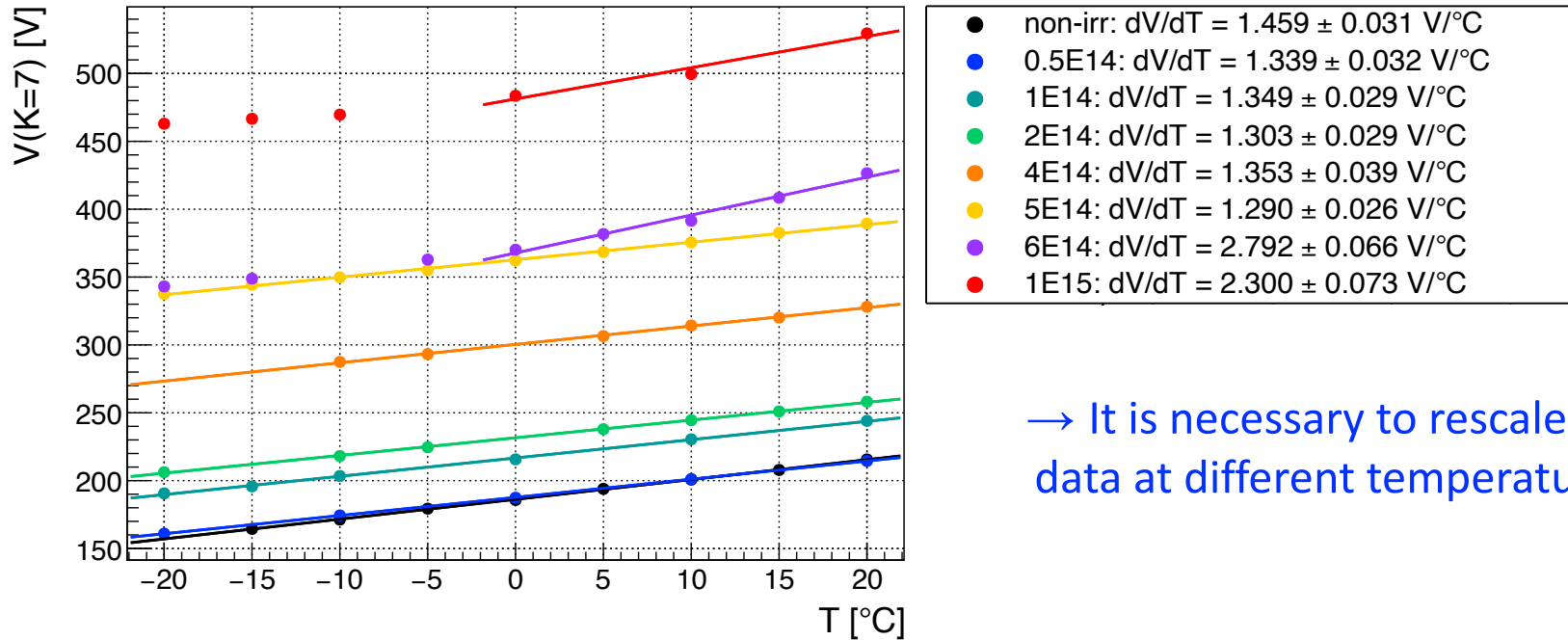
Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
12	Shallow	Deep	1.00	P

K at different T – Irradiated W12



→ The K factor allows to find the breakdown voltages up to the highest fluences

V_{BD} at different T – Irradiated W12



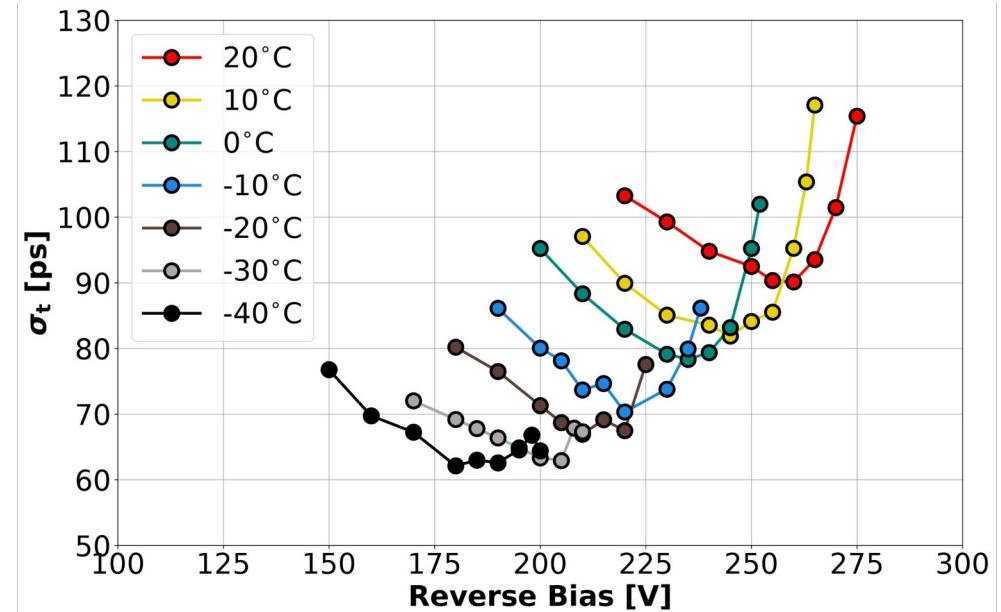
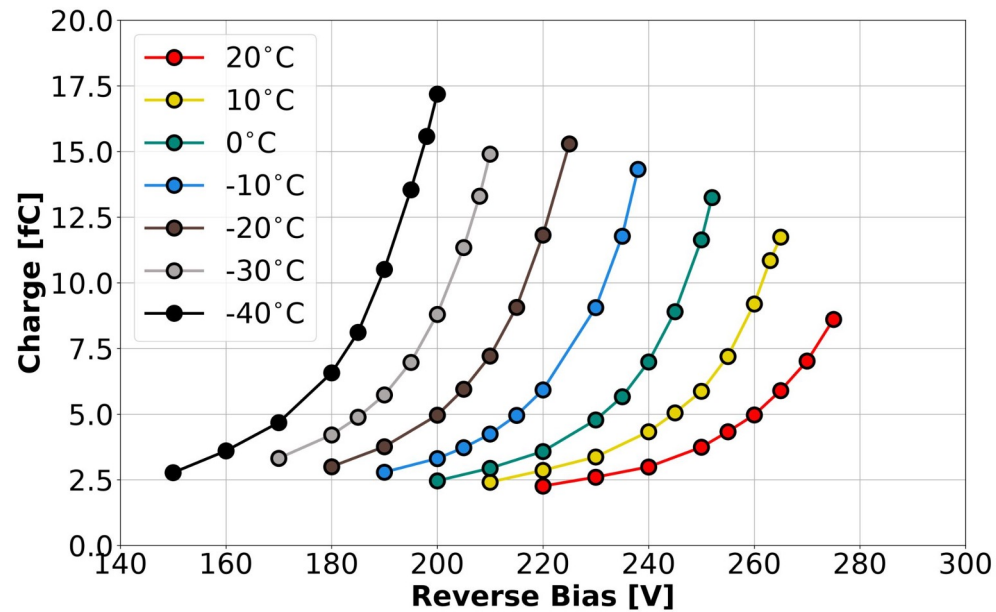
→ It is necessary to rescale the data at different temperatures

- ▷ Before irradiation, the scaling factor is 1.5 V/°C, equivalent to one from the signal analysis
- ▷ For low and medium fluences, up to 4E14 n_{eq}/cm^2 , it slightly reduces reaching ~ 1.3 V/°C
- ▷ At the two highest fluences, the behaviour changes abruptly
→ Is this a hint for the gain loss with fluence?

Wafer #	p++ depth	n+ depth	n+ dose	n+ dopant
12	Shallow	Deep	1.00	P

Signals at different T – W12 @ $1\text{E}14 \text{ n}_{\text{eq}}/\text{cm}^2$

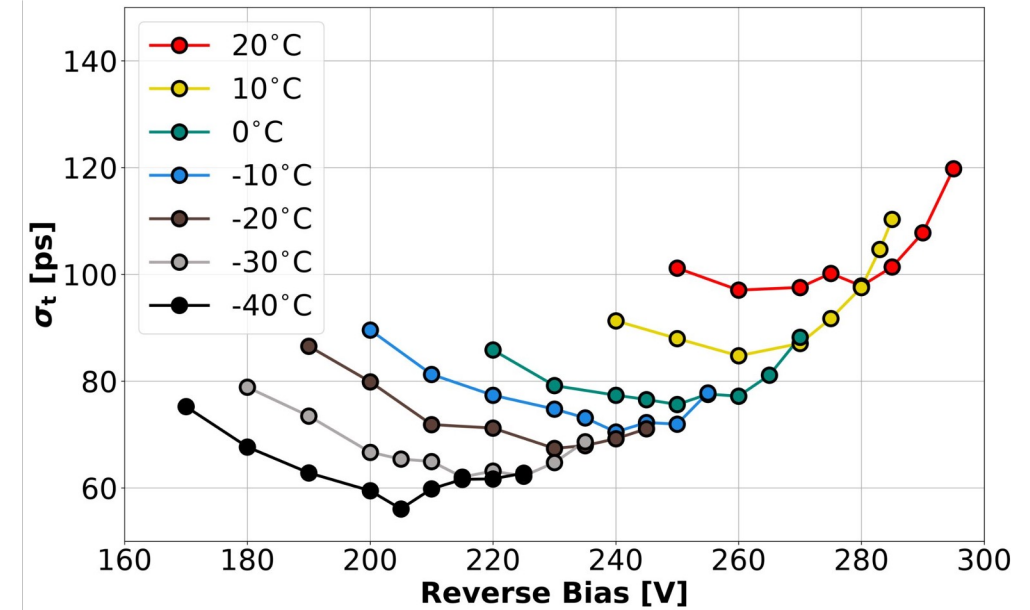
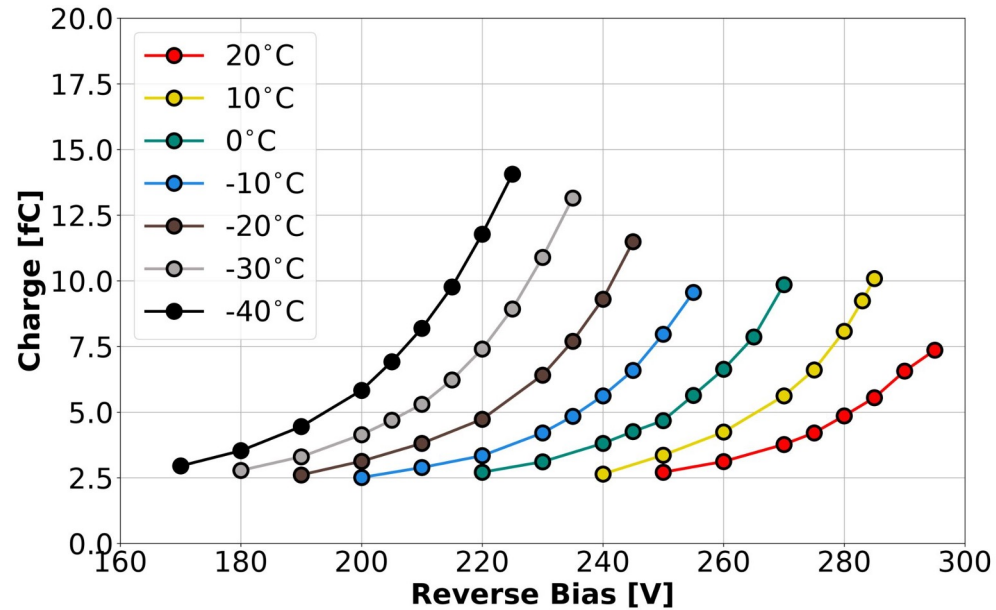
β particles from ^{90}Sr



- The collected charge increases lowering the temperature
- The timing resolution improves by lowering the temperature

Signals at different T – W12 @ $2E14 \text{ n}_{eq}/\text{cm}^2$

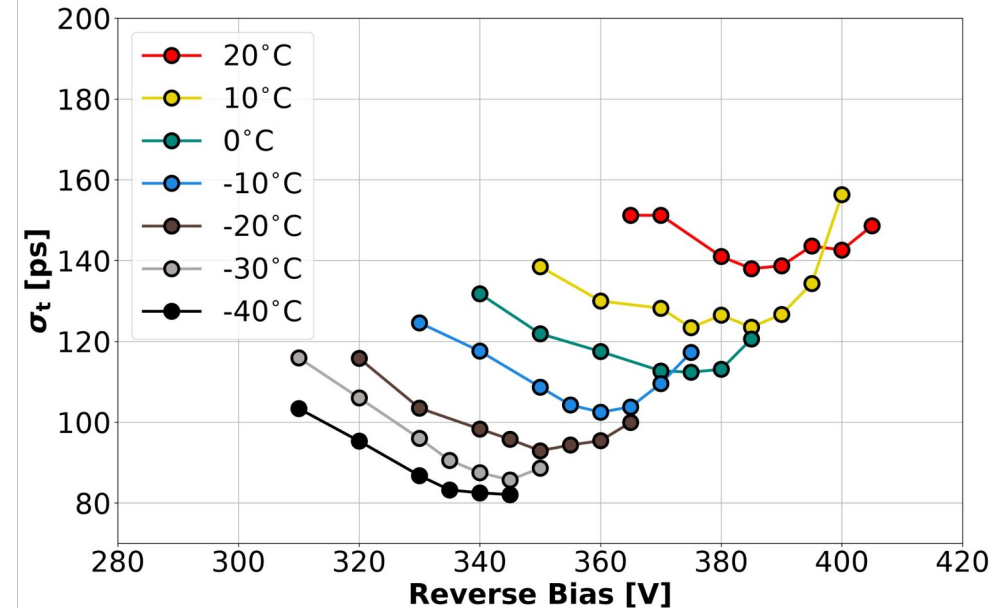
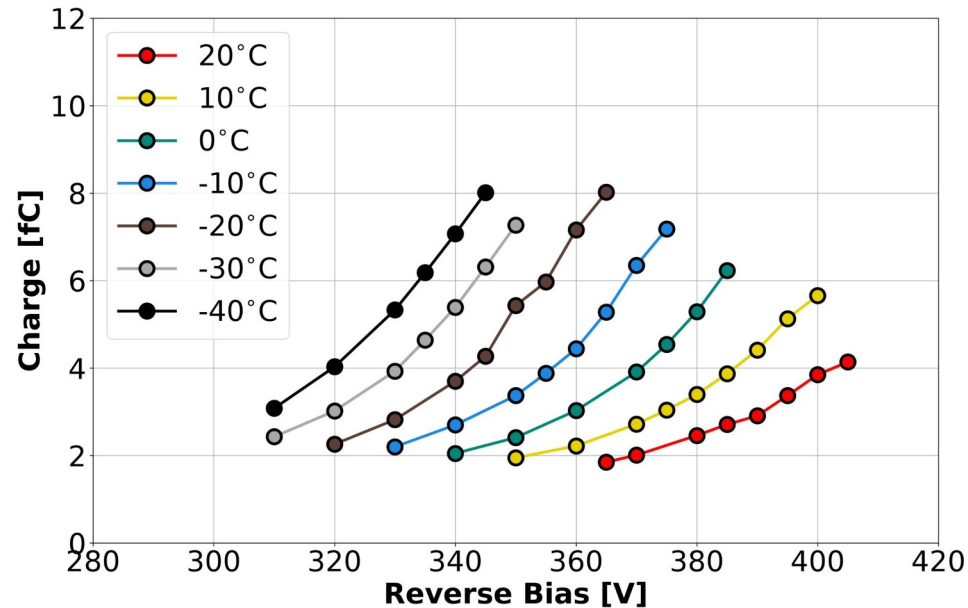
β particles from ^{90}Sr



- The collected charge increases lowering the temperature
- The timing resolution improves by lowering the temperature

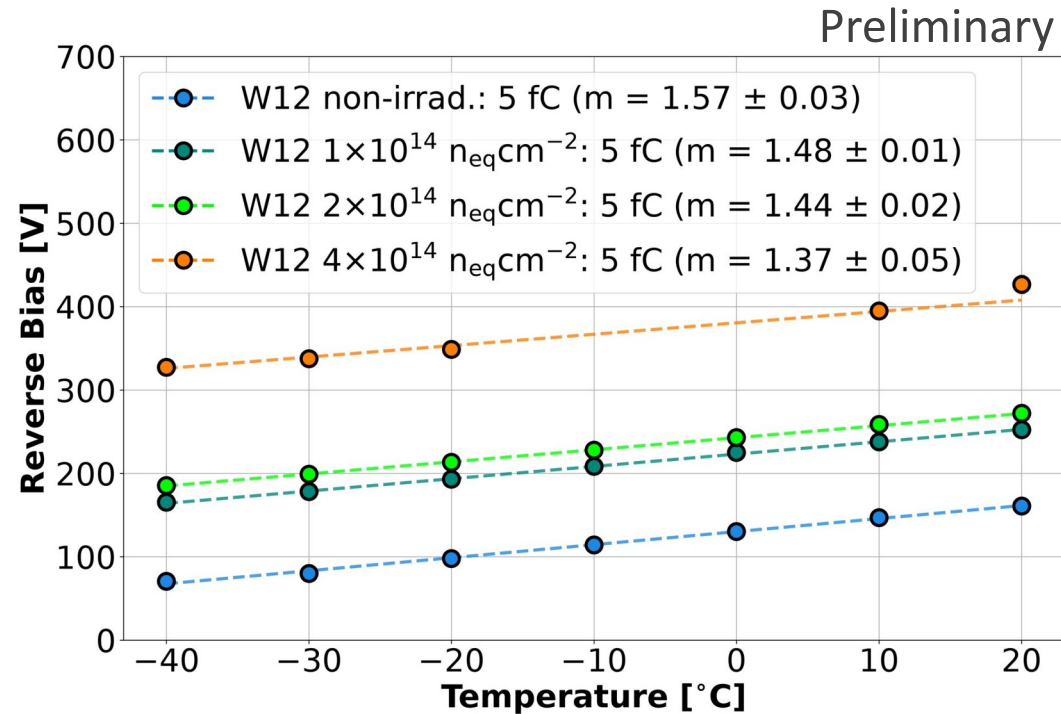
Signals at different T – W12 @ $4E14 \text{ n}_{eq}/\text{cm}^2$

β particles from ^{90}Sr



- The collected charge increases lowering the temperature
- The timing resolution improves by lowering the temperature

Q at different T – Irradiated W12



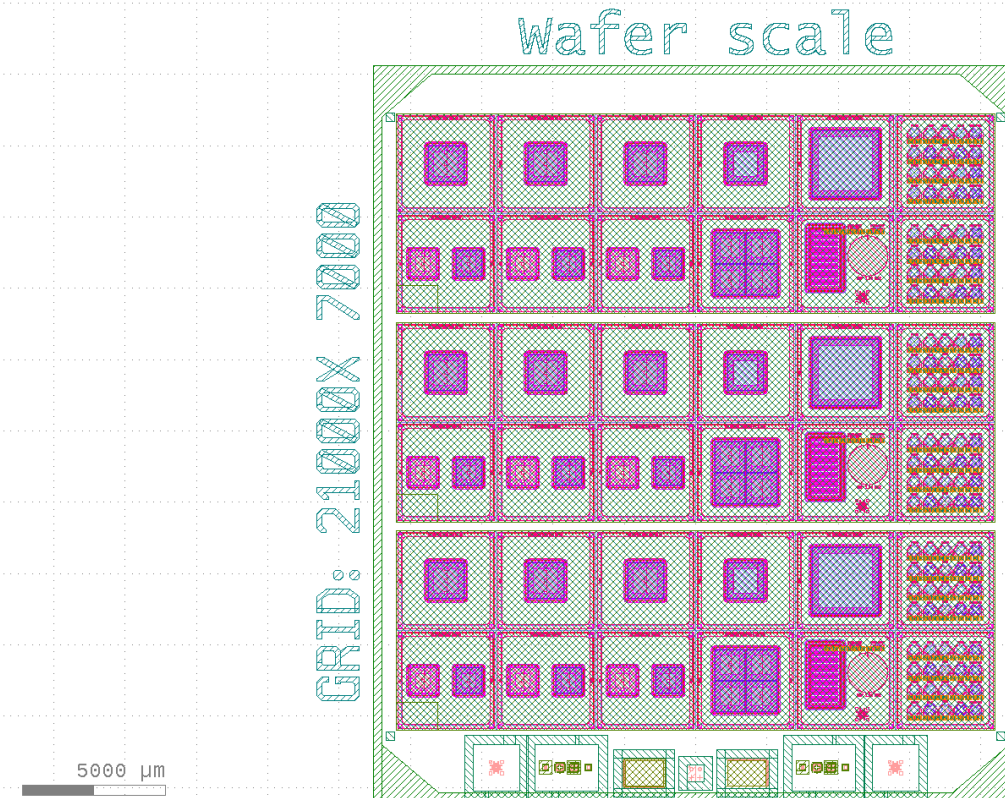
- As for the electrical characterisation, the evolution of V_{bias} to reach a constant charge slowly decreases with the fluences
- Can we correlate the two measurements and use the IV results to predict the gain evolution?



Towards COMPLEX1

The COMPLEX1 Production

Wafer	Boron	Phosphorus	Carbon*
1	1		
2	1		1
3	10		
4	10		1
5	2.8	2	
6	2.9	2	
7	3.0	2	
8	3.1	2	
9	3.2	2	
10	3.8	3	
11	3.9	3	
12	4.0	3	
13	4.1	3	
14	4.7	4	
15	4.8	4	
16	4.9	4	
17	5.0	4	
18	5.1	4	



→ **COMPLEX1 production started the 1st week of May**

The nLGAD Saga

- First n-type LGAD sensors designed by FBK, Perugia and Torino and produced by FBK
- A completely new design was necessary for the p^{++} contact, the n^+ gain implant, and the sensor periphery
- An extensive testing campaign on nLGADs is ongoing
- The COMPLEX1 sensors are around the corner





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*Thank
You*