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European Research Council

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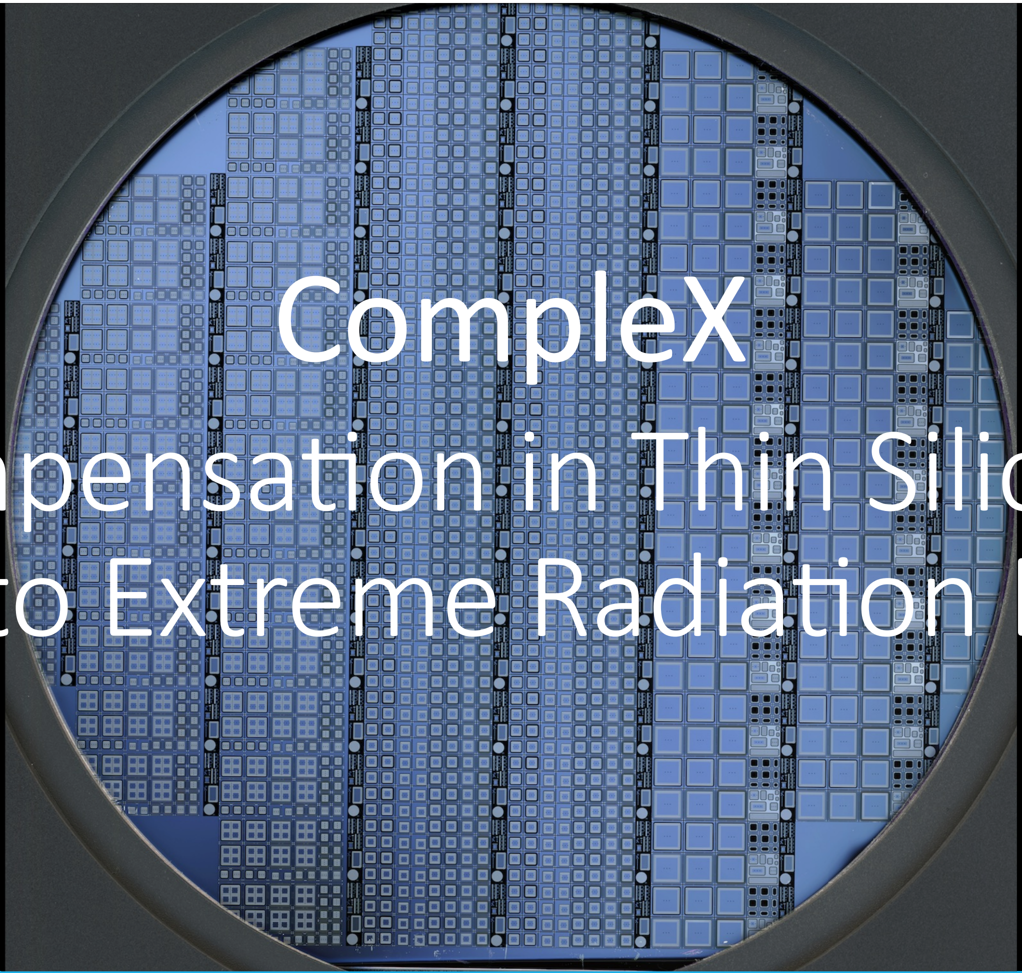


CompleX

Doping Compensation in Thin Silicon Sensors: the pathway to Extreme Radiation Environments

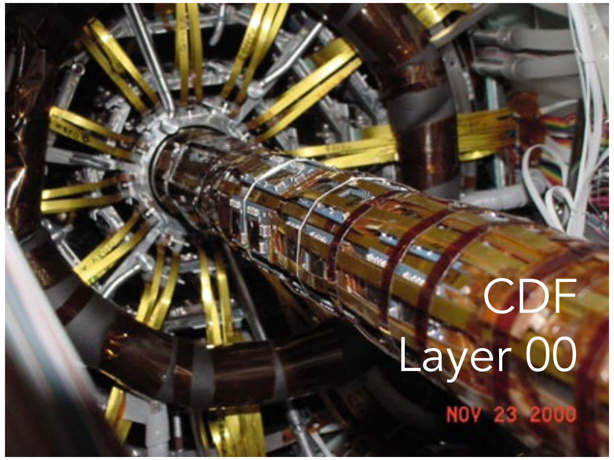
BANDO PRIN 2022

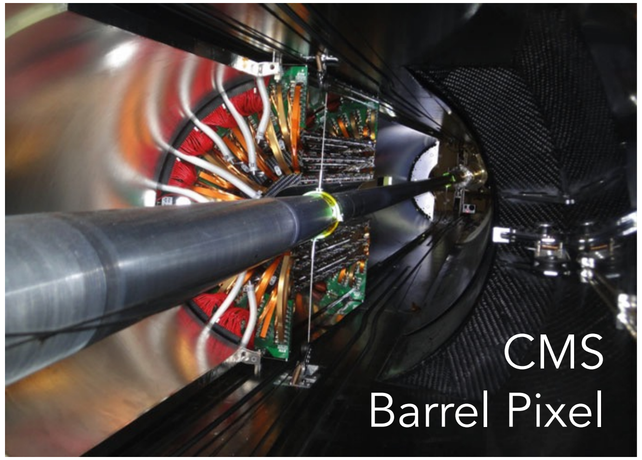
Outline

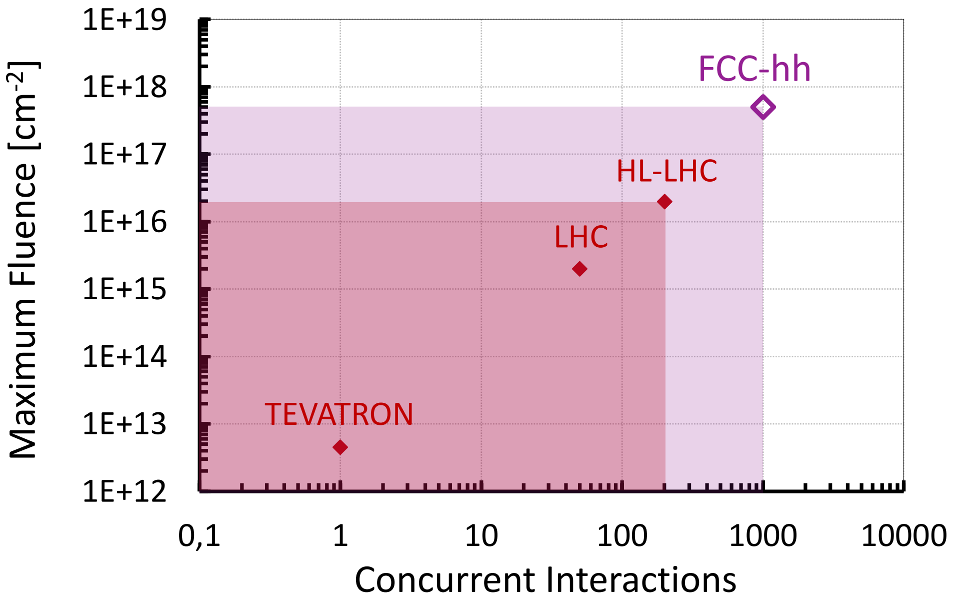
- ▻ The challenge
- ▻ The state-of-the-art
- ▻ The technology
- ▻ The strategy
- ▻ The target

The Extreme Fluence Challenge

Silicon detectors have been enabling technology for discoveries on particle physics at colliders





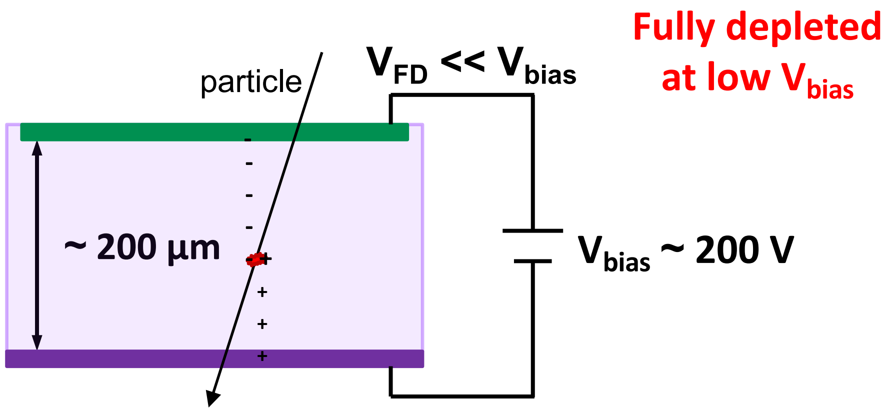


Present silicon frontier

- Precise tracking down to ~ 10 μm → 1 fC up to $2 \cdot 10^{16}$ n_{eq}/cm^2
- Precise timing down to ~ 30 ps → 5 fC up to $3 \cdot 10^{15}$ n_{eq}/cm^2

→ CompleX will enable 4D tracking with planar silicon sensors up to the fluence of $5 \cdot 10^{17}$ n_{eq}/cm^2

Silicon Sensors Working Principles



Sketch of an n-in-p silicon sensor

Silicon sensors are the passive elements of the tracking detector system

Incident particles generate e^-/h^+ pairs that are collected to the electrode once a reverse bias is applied

The movement of the charge carriers induces a signal on the sensor electrodes, which can be read out by the electronics

Requirements from state-of-the art electronics at hadron colliders

- ▻ Precise tracking → 1 fC
- ▻ Precise timing → 5 fC

NB: power budget at high-energy physics experiments has to be kept as low as possible

Silicon Sensors at Very High Fluences

Planar silicon sensors can operate up to 10^{16} n_{eq}/cm^2

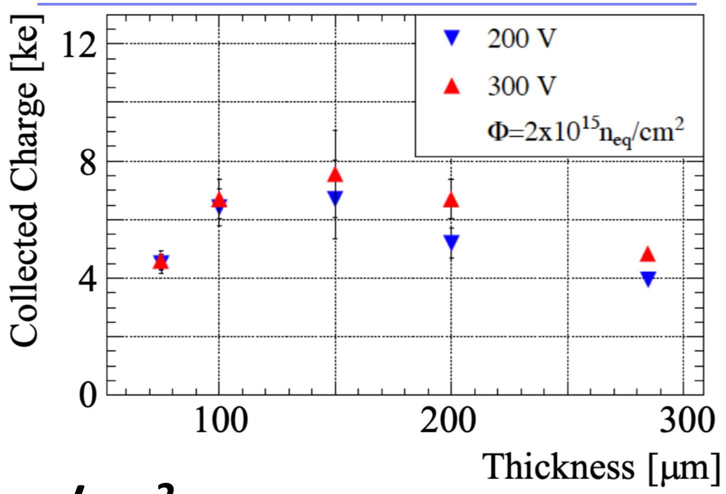
<u>Signals from planar silicon sensors become too small</u>

➢ Non-uniformities in the electric field

➢ Impossible to fully deplete the sensors

➢ Collected charge independent from thickness

[doi: 10.1088/1748-0221/9/05/C05023]



Models of the radiation damage in silicon are validated till ~ 10^{16} n_{eq}/cm^2

<u>Mismatch between data and predictions arises at higher fluences</u>

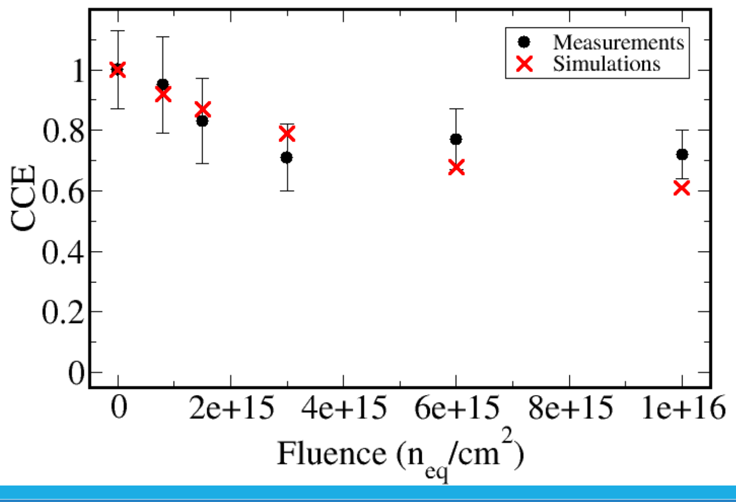
➢ Dark current increase is smaller than expected

➢ Charge collection efficiency is higher than predicted

➢ Increase of the acceptor states slows

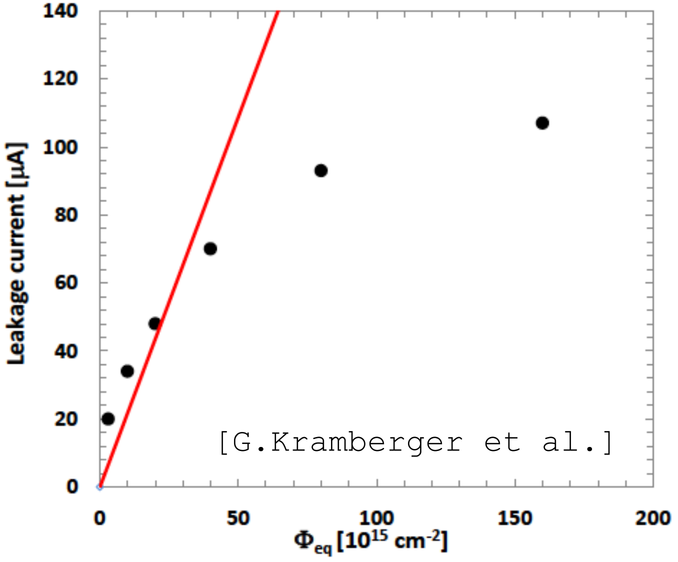
→ **Hints of saturation of the radiation damage effects**

[doi: 10.22323/1.373.0050]



Saturation of the Radiation Effects

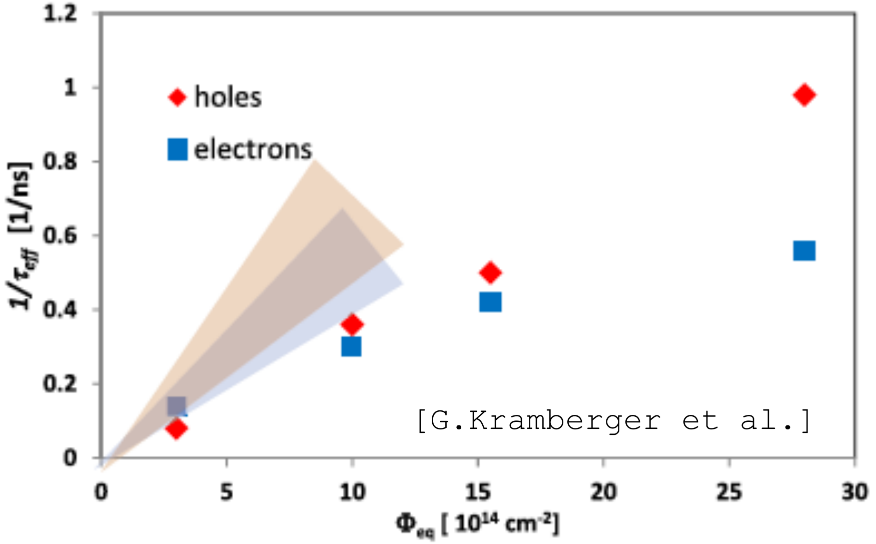
At fluences above $5 \cdot 10^{15}$ n_{eq}/cm^2 → **Saturation of radiation effects observed**



Leakage current saturation

$I = \alpha V \Phi$

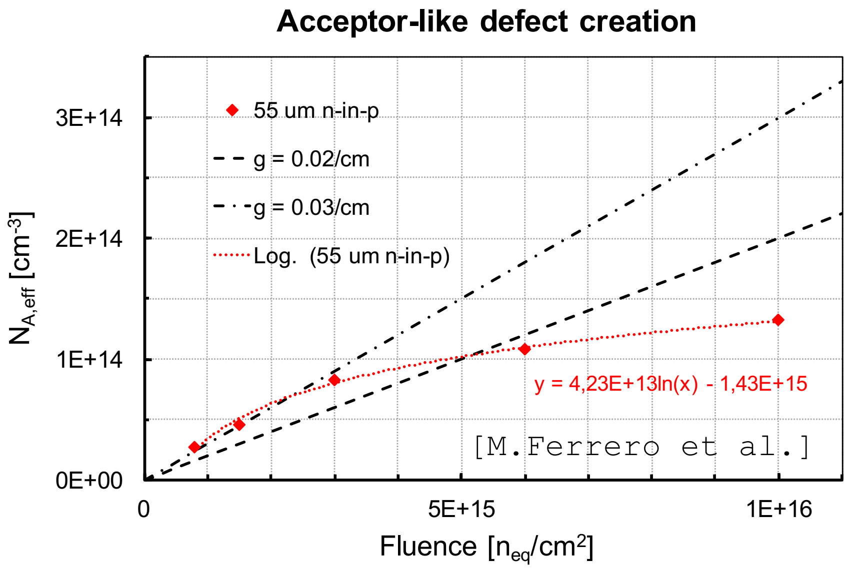
α from linear to logarithmic



Trapping probability saturation

$1/\tau_{eff} = \beta\Phi$

β from linear to logarithmic



Acceptor creation saturation

$N_{A,eff} = g_c\Phi$

g_c from linear to logarithmic

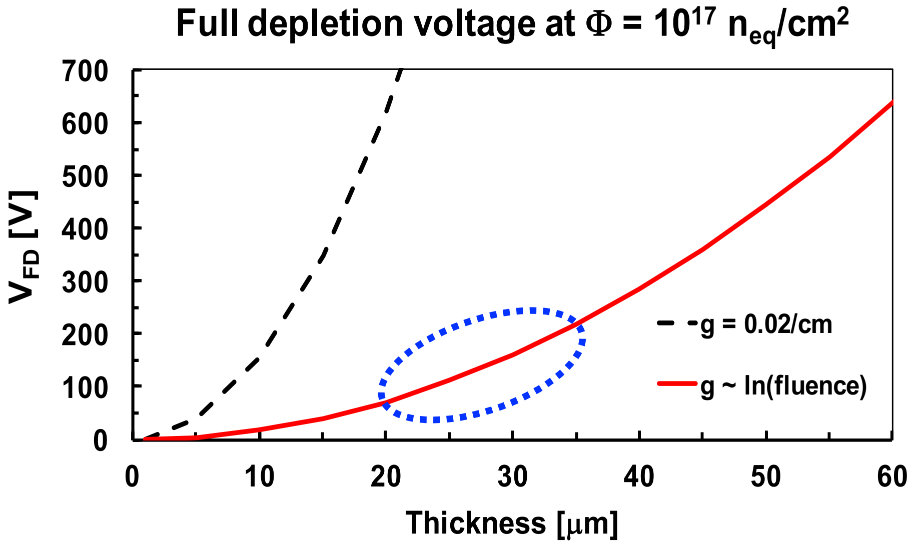
Silicon detectors irradiated at fluences 10^{16} – 10^{17} n_{eq}/cm^2 do not behave as expected → They behave better

The Advantages of Thin Sensors

$V_{FD} = e|N_{eff}|d^2/2\varepsilon$

Saturation **Reduce thickness**

Thanks to saturation effects, thin sensors can still be depleted and operated at $V_{bias} \leq 500$ V



What does it happen to a 20 μm sensor after a fluence of $5 \cdot 10^{16}$ n_{eq}/cm^2?

- It can still be depleted
- Trapping is almost absent
- Dark current is low (small volume)

However: charge deposited by a MIP ~ 0.2 fC

→ **This charge is lower than the minimum charge requested by the electronics (~ 1 fC)**

→ **Need a gain of at least ~ 5 in order to provide enough charge**

Towards the eXtreme Fluences – CompleX

CompleX will design a new generation of silicon sensors

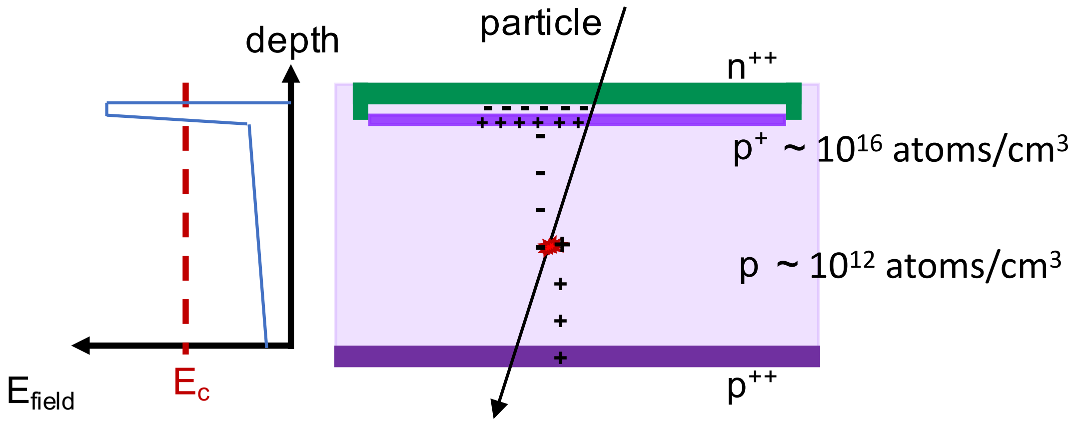
- ▻ exploit saturation of the radiation damage
- ▻ use thin substrates (20 – 40 μm)
- ▻ use internal gain to enhance the signal

→ CompleX will develop a new generation of planar silicon sensors with gain to operate in extreme fluence environments

Accurate modelling of silicon damage and sensor behaviour at very high fluences is necessary to design the next generation of silicon detectors

→ CompleX will extend the understanding and modelling of radiation damage in silicon to the fluence of $5 \cdot 10^{17}$ n_{eq}/cm^2

Low-Gain Avalanche Diodes

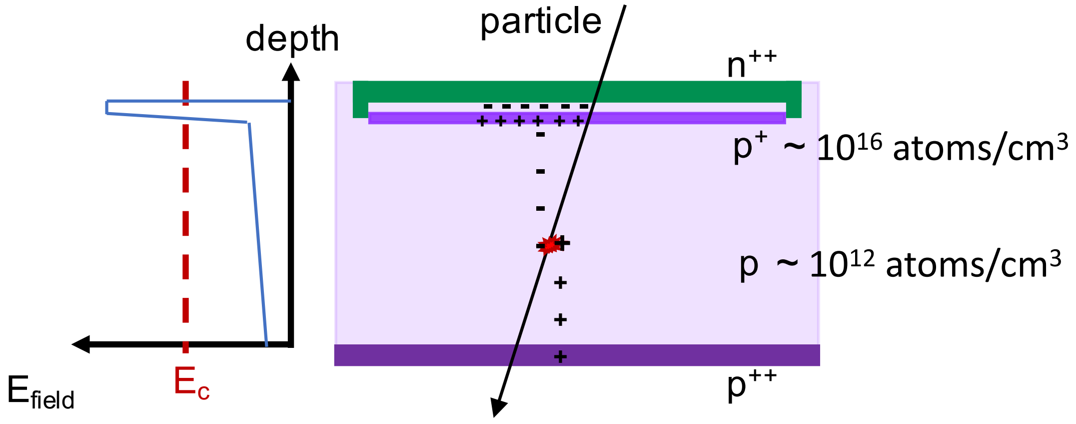


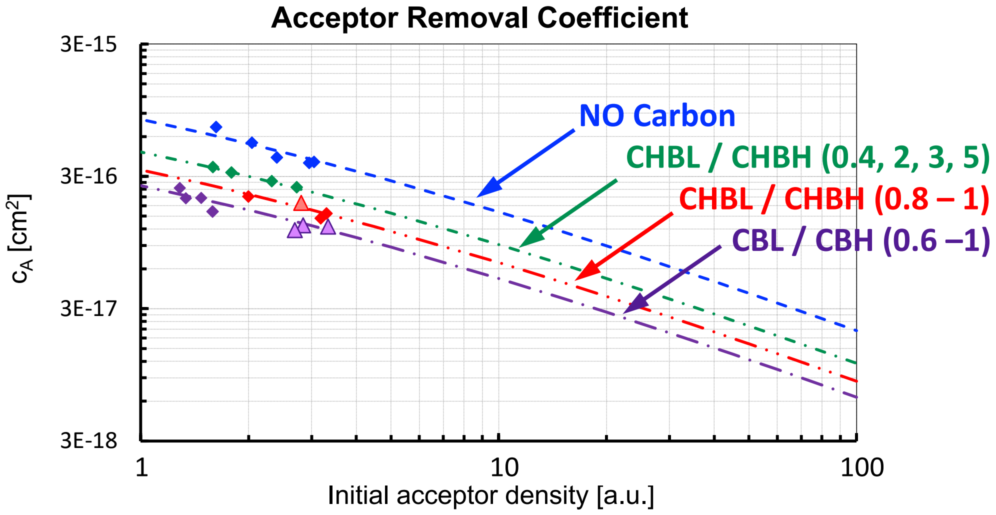
LGADs are n-in-p planar silicon sensors

Operated in low-gain regime (20–30) controlled by the external bias

Critical electric field E_c ~ 20–30 V/µm

Gain Removal Mechanism in LGADs





The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

$$p^+(\Phi) = p^+(0)\cdot e^{-c_A \Phi}$$

where c_A is the acceptor removal coefficient

c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms

Single Event Burnout 💥

Once operated at high electric field, thin sensors fatally break if exposed to particle beams

The effect is called Single Event Burnout (SEB) and apply both to LGAD and PIN sensors

Death Mechanism:

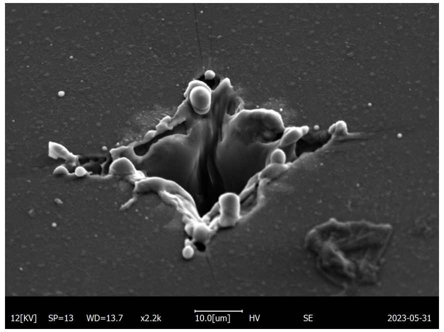
- ▻ Rare, large ionization event – Highly Ionising Particle
- ▻ Excess charge leads to highly localized conductive path
- ▻ Collapse of the depleted active thickness
- ▻ Large current flows in a narrow path – Single Event Burnout

SEB consequence:

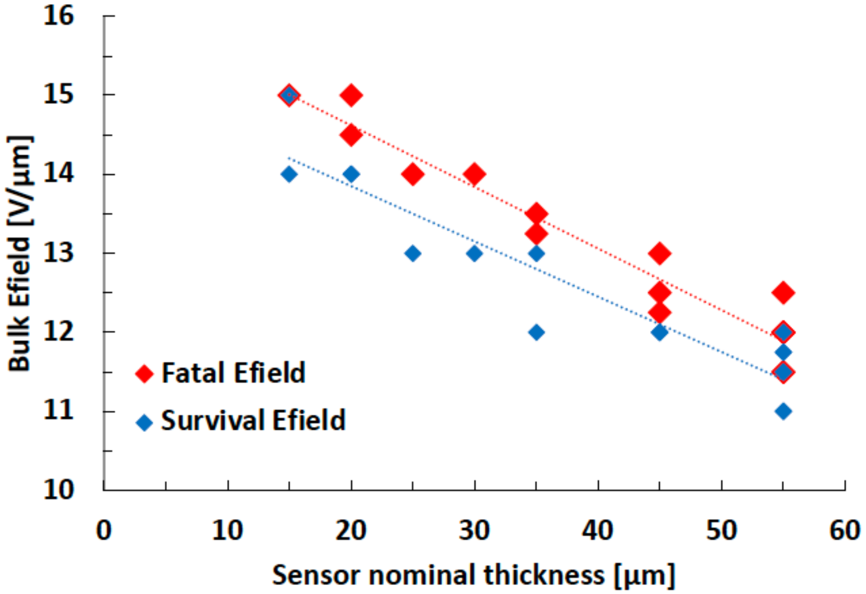
→ Impossible to operate irradiated thin sensors above the critical electric field (E_{SEB})

→ The E_{SEB} value is higher for thinner sensors

Localized melt and vaporization of silicon



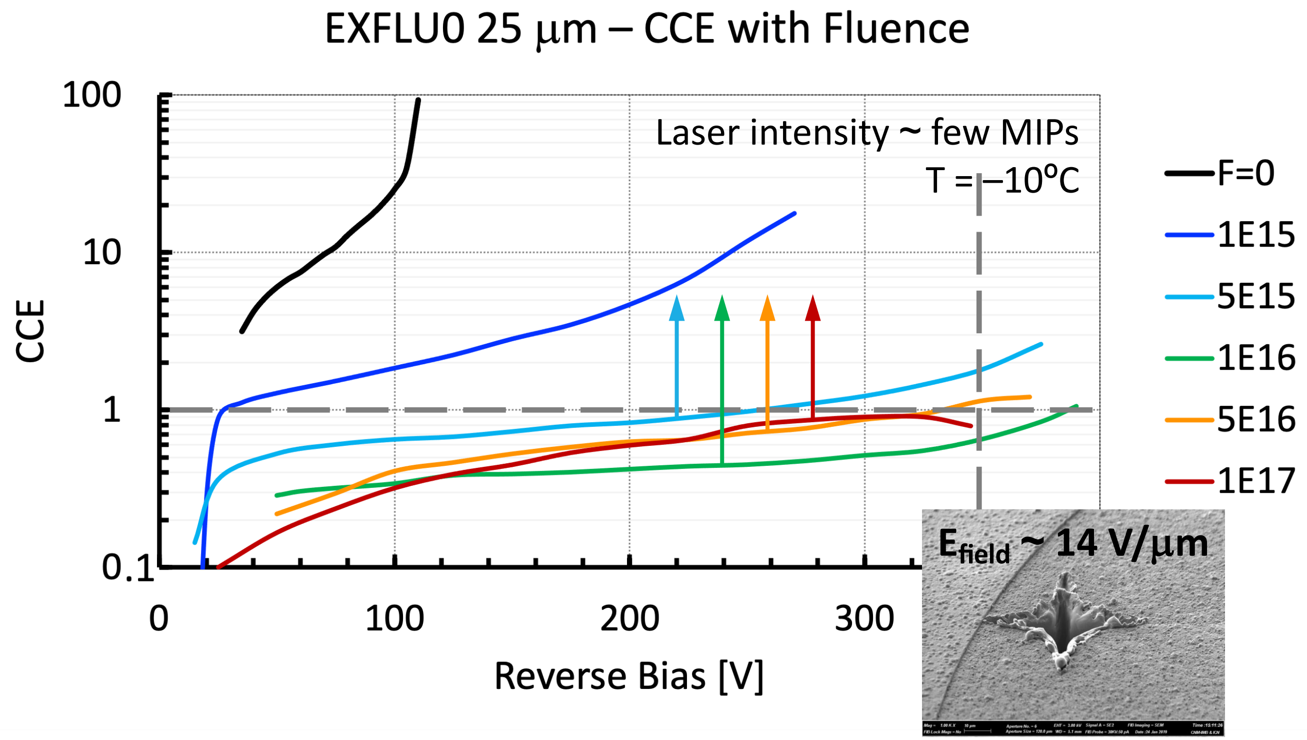
SEM picture [SSP group, UniTO]



[M. Ferrero et al., indico.cern.ch/event/1334364/contributions/5672087]

25 μm Thin LGADs

Measurements of **charge collection efficiency** (CCE) with an infra-red laser stimulus show that sensors can be operated up to the highest fluences – **25 μm thick LGADs**



- The LGAD multiplication mechanism ceases existing at ~ $5 \cdot 10^{15}$ n_{eq}/cm^2
- From 10^{16} to 10^{17} n_{eq}/cm^2 the collected signal is roughly constant
- For electric fields above 14 V/μm, 25 μm thick silicon sensors undergo fatal death once exposed to particle beams (SEB)

→ **Necessary to increase the radiation tolerance of the gain mechanism for 5E15 n_{eq}/cm^2 and above**

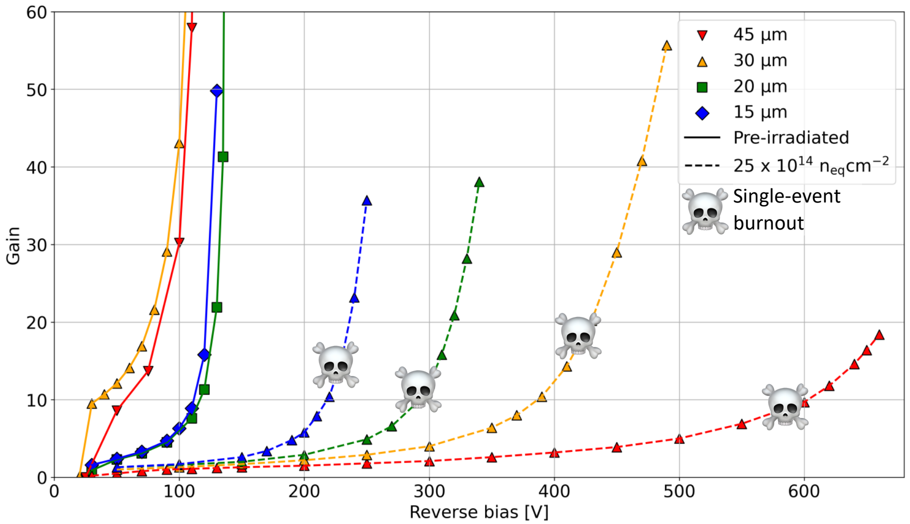
LGAD Engineering – State-of-the-Art

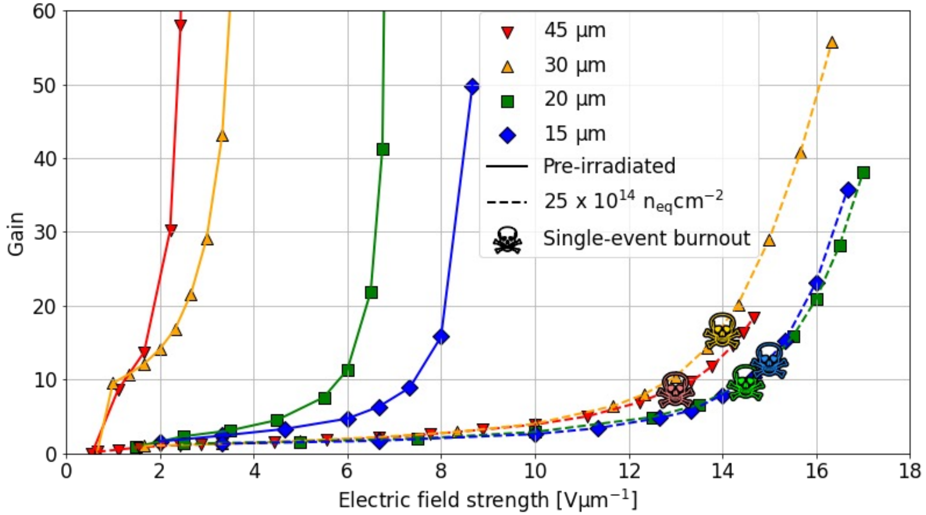
Thin sensors from the EXFLU1 batch of FBK are the **sensors most resilient to radiation** ever produced by the FBK foundry

The technology exploits defect engineering through carbon co-implantation in the gain implant region

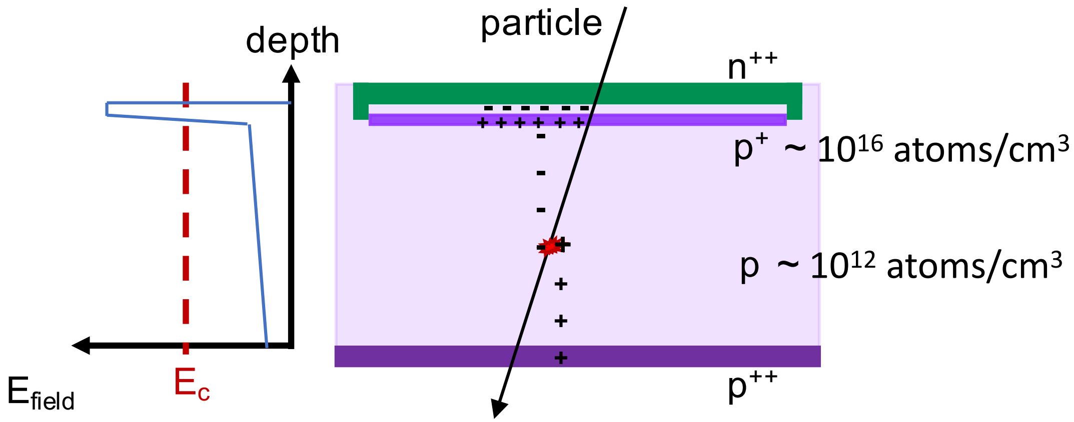
→ After a fluence of 2.5·10^{15} n$_{eq}$/cm^2, all sensors maintain a gain of about 10 up to the SEB limit

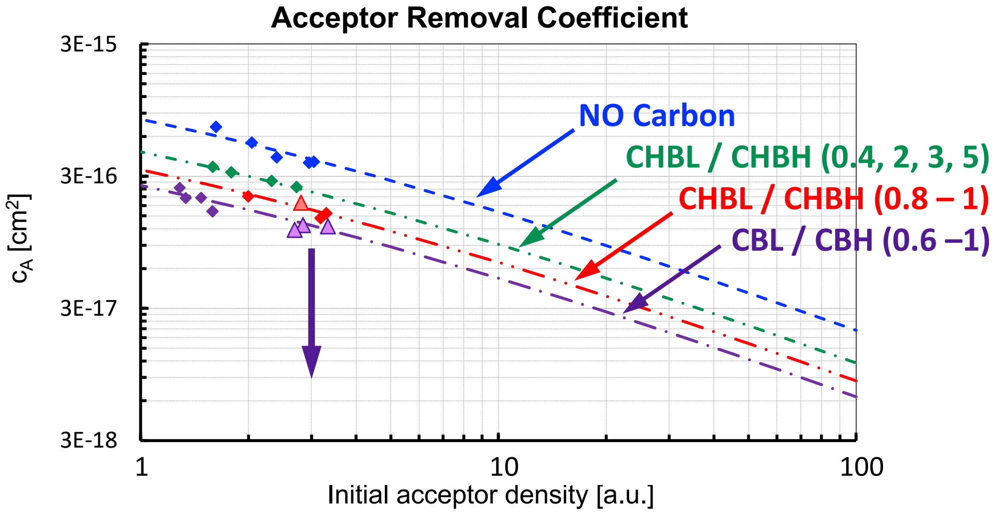
c_A [x 10^{-16} cm^{2}n$_{eq}^{-1}$]	45	1.39
	30	1.34
	20	1.37
	15	1.37





State-of-the-Art Removal Mechanism in LGADs





The acceptor removal mechanism deactivates the p^{+}-doping of the **gain layer** with irradiation according to

$$\mathbf{p^{+}(\Phi) = p^{+}(0) \cdot e^{-c_A \Phi}}$$

where c_A is the acceptor removal coefficient

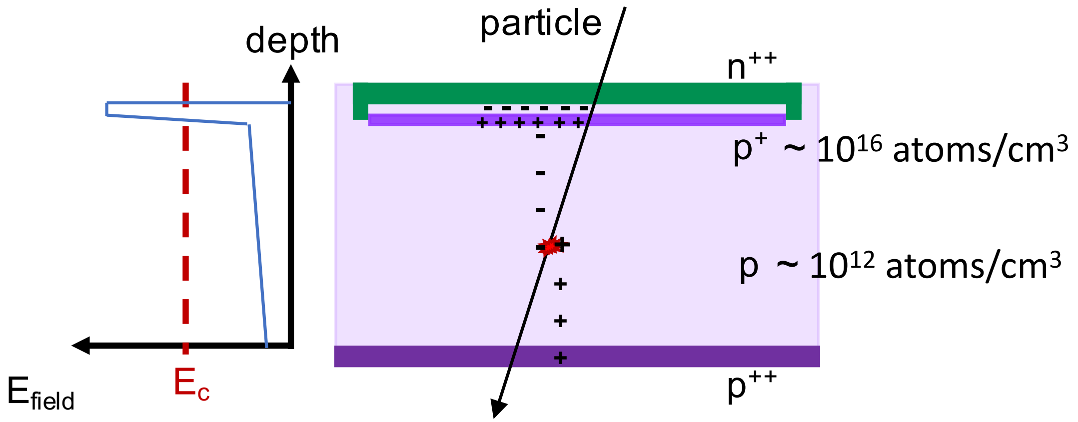
c_A depends on the initial acceptor density, $p^{+}(0)$, and on the defect engineering of the gain layer atoms

▲ thin sensors from the EXFLU1 batch

[R.S. White, 43rd RD50 Workshop (2023) CERN]

⇒ Is it possible to improve c_A further?

Towards a Radiation Resistant Design

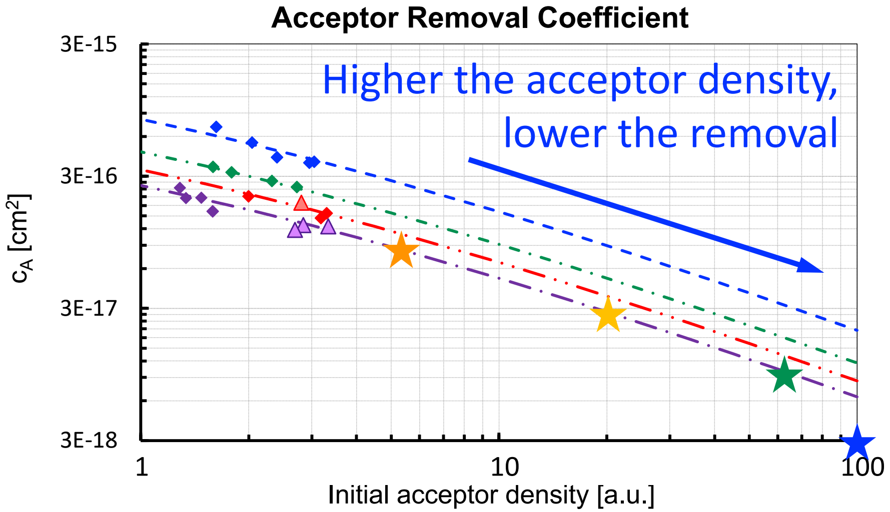


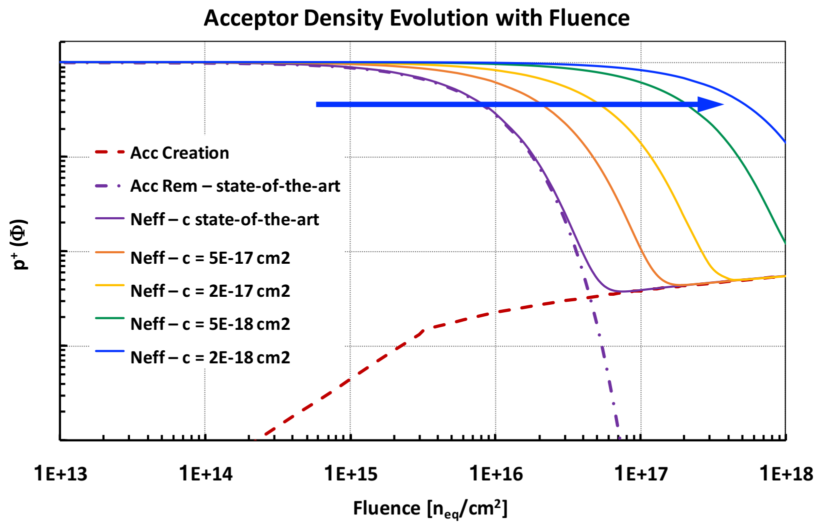
The acceptor removal mechanism deactivates the p^+-doping of the **gain layer** with irradiation according to

$$p^+(\Phi) = p^+(0) \cdot e^{-c_A \Phi}$$

where c_A is the acceptor removal coefficient

To substantially reduce c_A, it is necessary to increase $p^+(0)$, the initial acceptor density

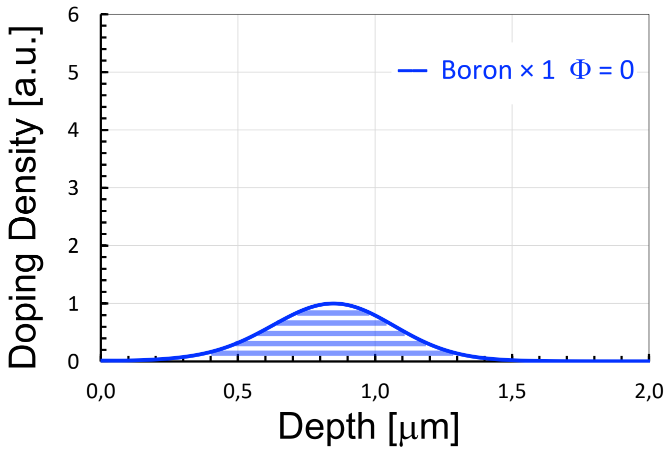


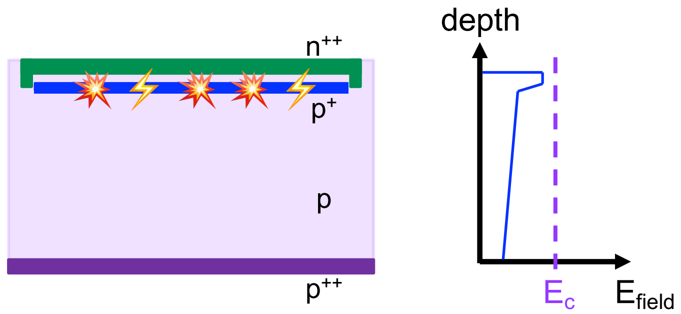


Lowering c_A can extend the gain layer survival up to $\Phi \geq 10^{17}$ n_{eq}/cm^2

Planar Silicon Sensors for eXtreme Fluences

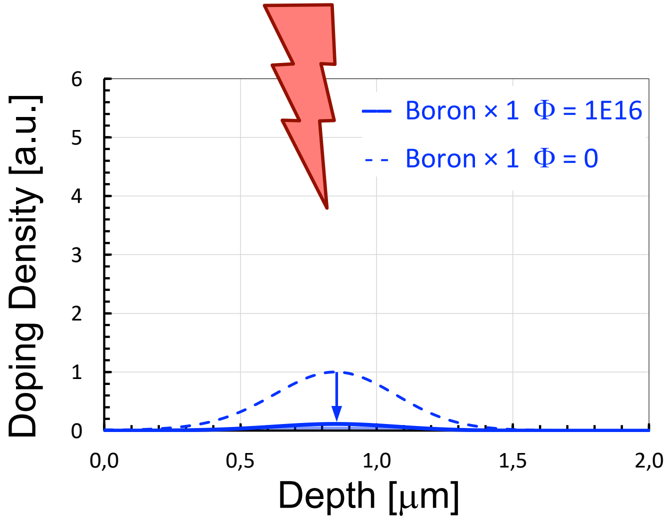
Doping Profile – Standard LGAD





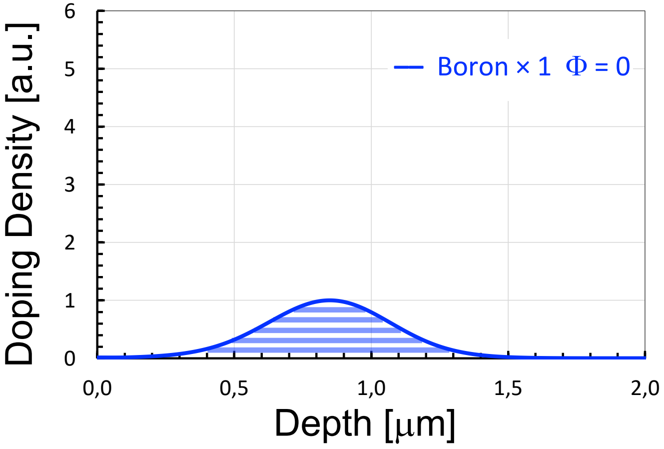
Low-Gain Avalanche Diode
LGAD

Irradiation
$\Phi = 1\times10^{16}\ n_{eq}/cm^2$

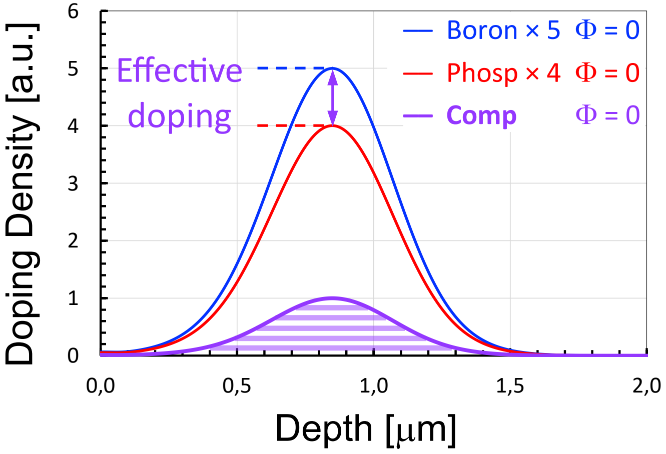


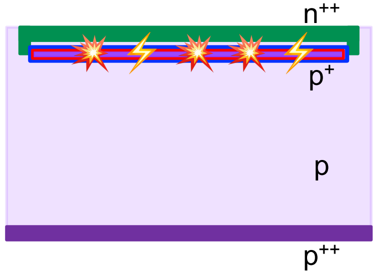
Compensated LGADs for eXtreme Fluences

Doping Profile – Standard LGAD



Doping Profile – Compensated LGAD

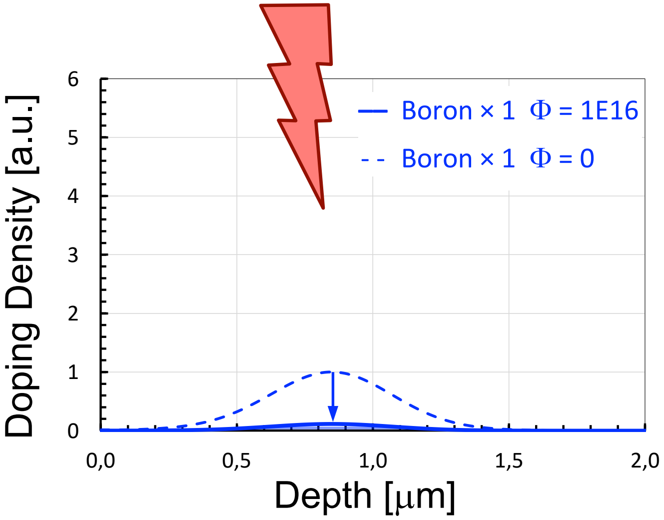


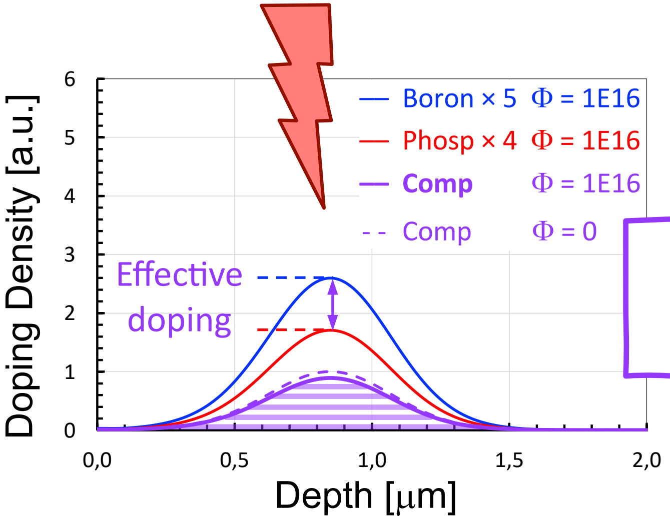


Compensated LGAD

Irradiation

$\Phi = 1{\times}10^{16}\ n_{eq}/cm^2$

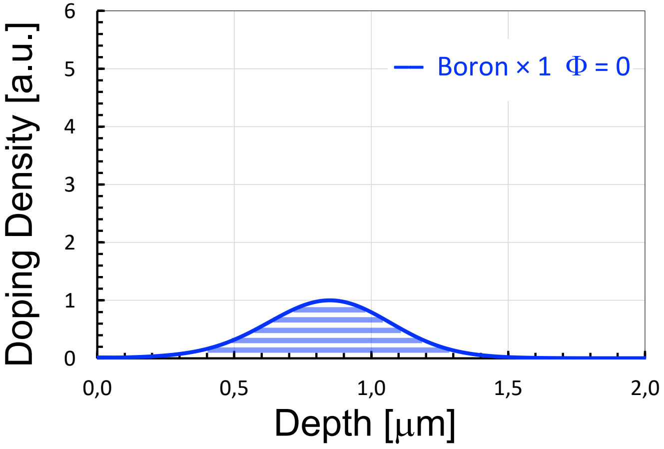




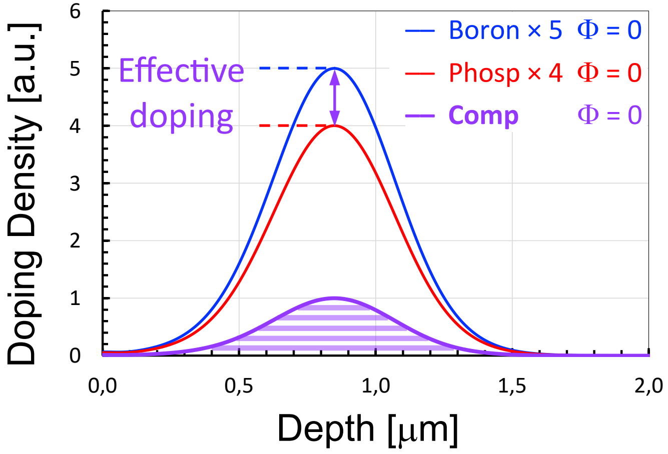
CompleX target

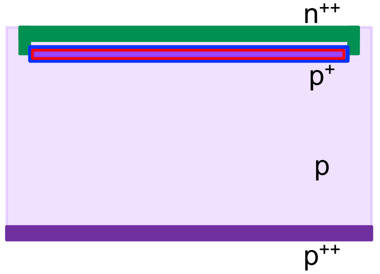
Compensated LGADs for eXtreme Fluences

Doping Profile – Standard LGAD



Doping Profile – Compensated LGAD

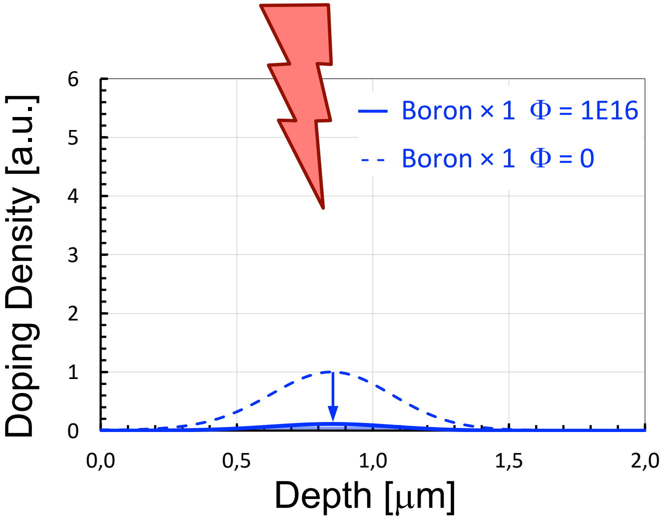


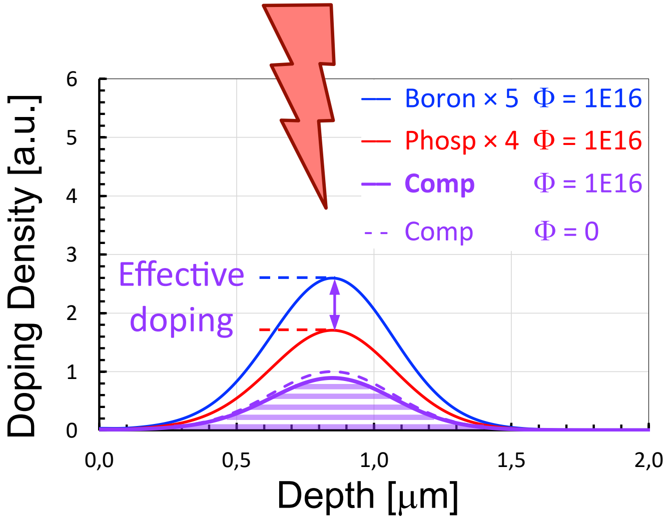


Compensated LGAD

Irradiation

$\Phi = 1{\times}10^{16}\ n_{eq}/cm^2$





V. Sola et al.,

NIM A 1040 (2022) 167232

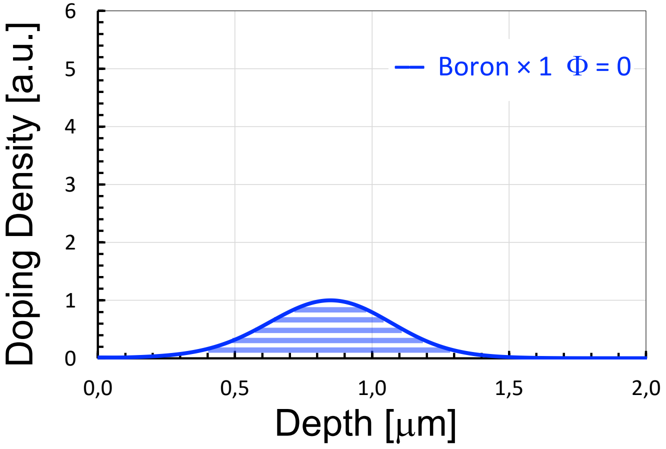
A compensated design of the LGAD gain layer

Patent #102022000003359

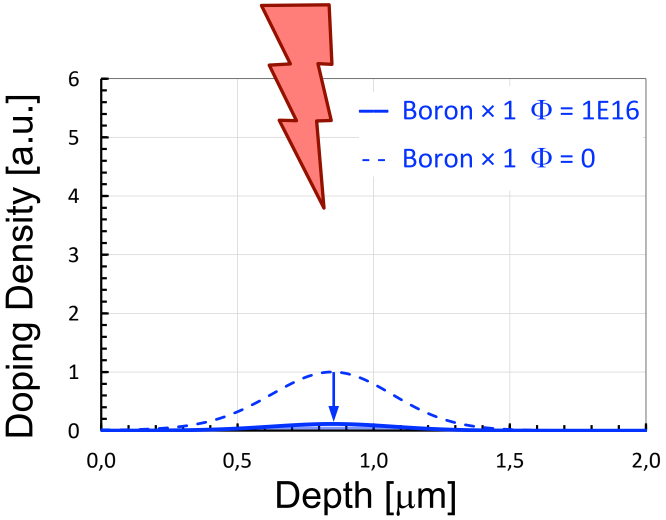
Enhanced radiation resistance via doping compensation

Compensated LGADs for eXtreme Fluences

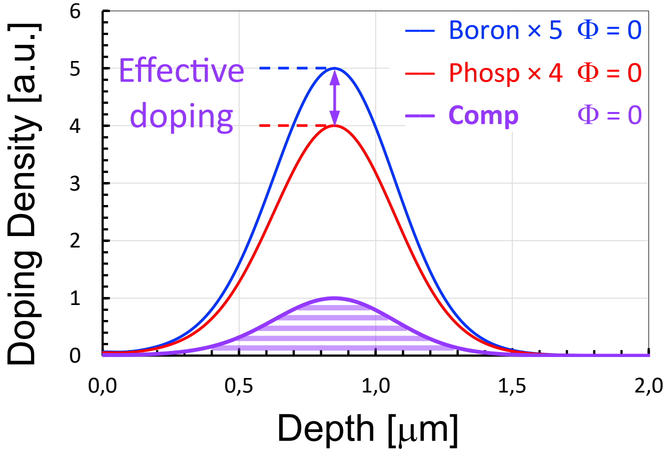
Doping Profile – Standard LGAD

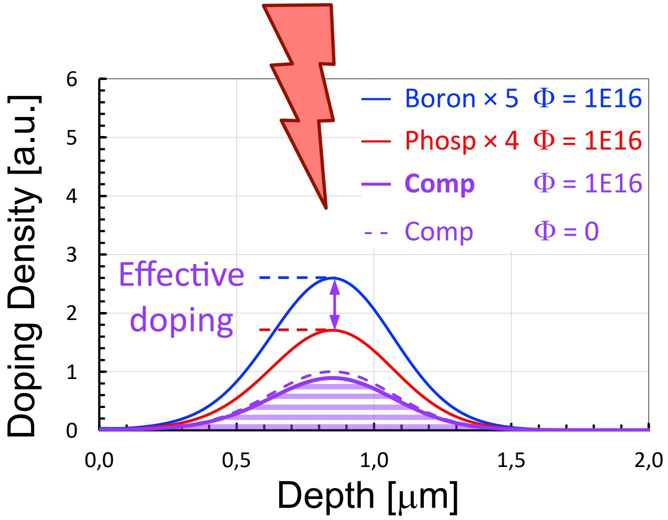


Irradiation
$\Phi = 1\times10^{16}\ n_{eq}/cm^2$



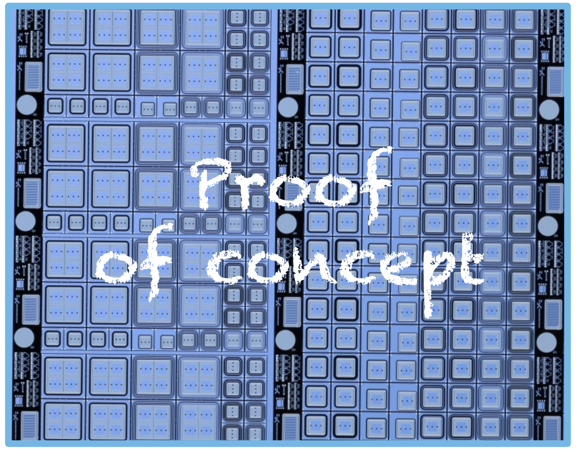
Doping Profile – Compensated LGAD





First production of compensated LGADs

EXFLU1 batch released end of 2022



First Compensated LGADs – EXFLU1

First compensated LGAD sensors have been released by FBK in the framework of the EXFLU1 batch

Other R&D paths pursued by the EXFLU1 batch to extend the radiation tolerance of the LGAD sensors:

- new guard ring design
- decrease of the acceptor removal – carbon shield
- **thin substrates (15–45 µm)**

Design and preparatory studies have been performed in collaboration with the **Perugia group**

→ The EXFLU1 wafers exited the FBK clean room at the end of 2022

[V. Sola, TREDI 2024, Torino]

Compensated Gain Layer Design – Split Table

Active thickness 30 μm

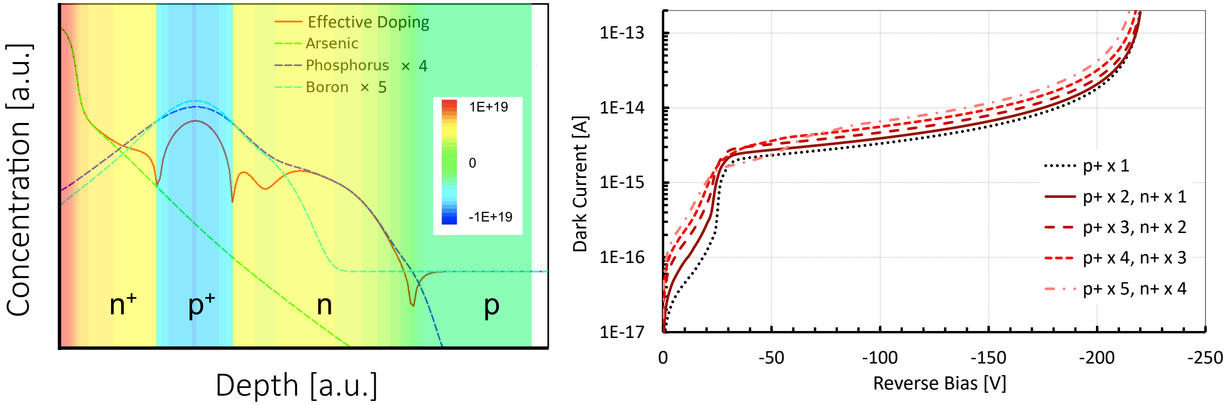
Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c]

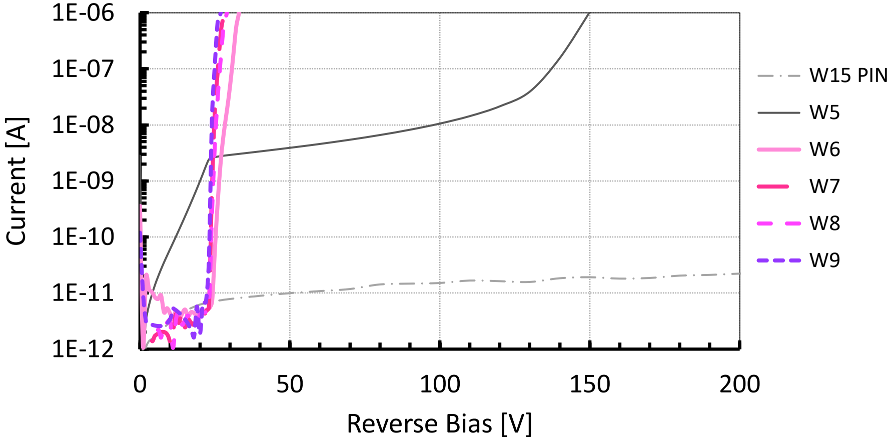
3 different combinations of $p^+ - n^+$ doping: 2 – 1, 3 – 2, 5 – 4

Compensated LGAD – I-V on wafer

Simulation



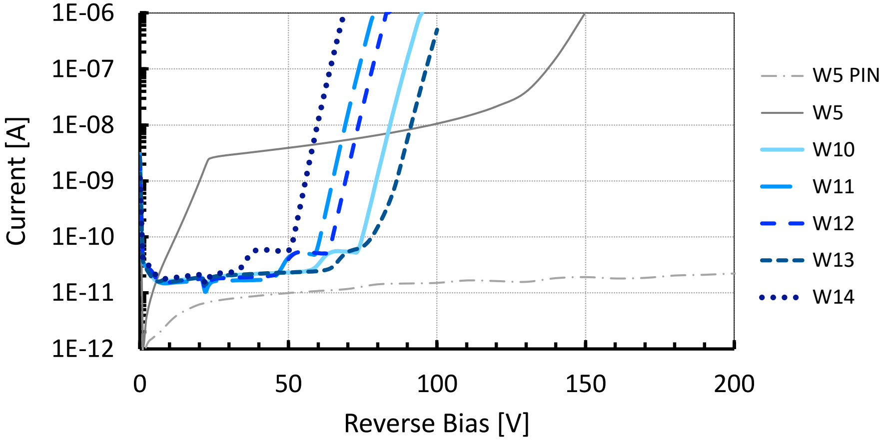
EXFLU1 – Compensated LGAD 2–1 – I-V



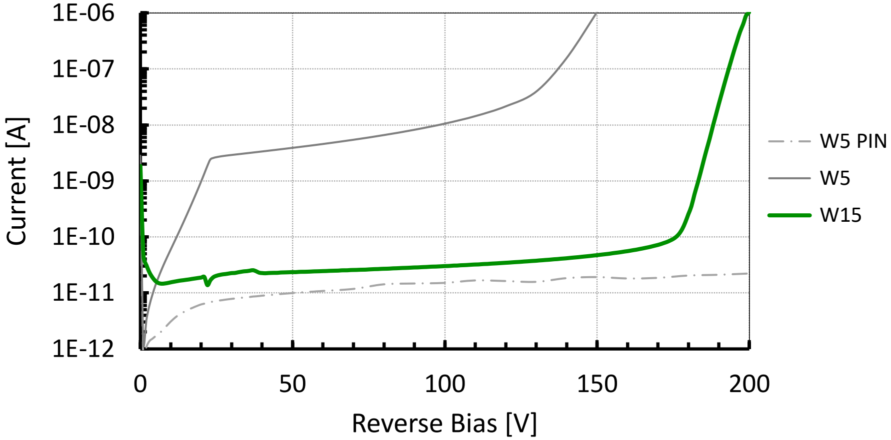
2 – 1

EXFLU1 – Compensated LGAD 3–2 – I-V

3 – 2



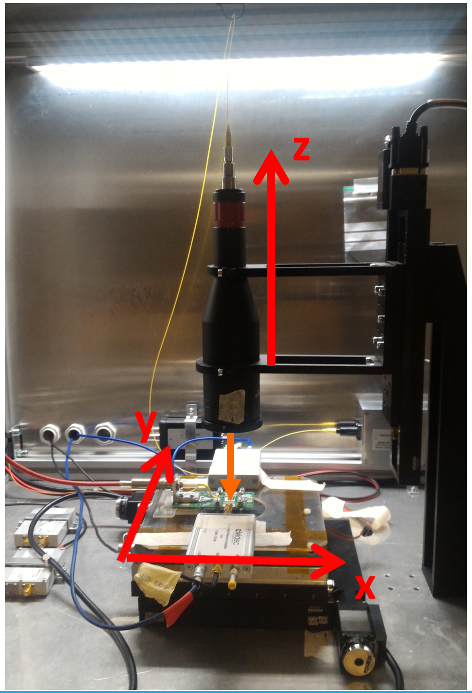
EXFLU1 – Compensated LGAD 5–4 – I-V



5 – 4

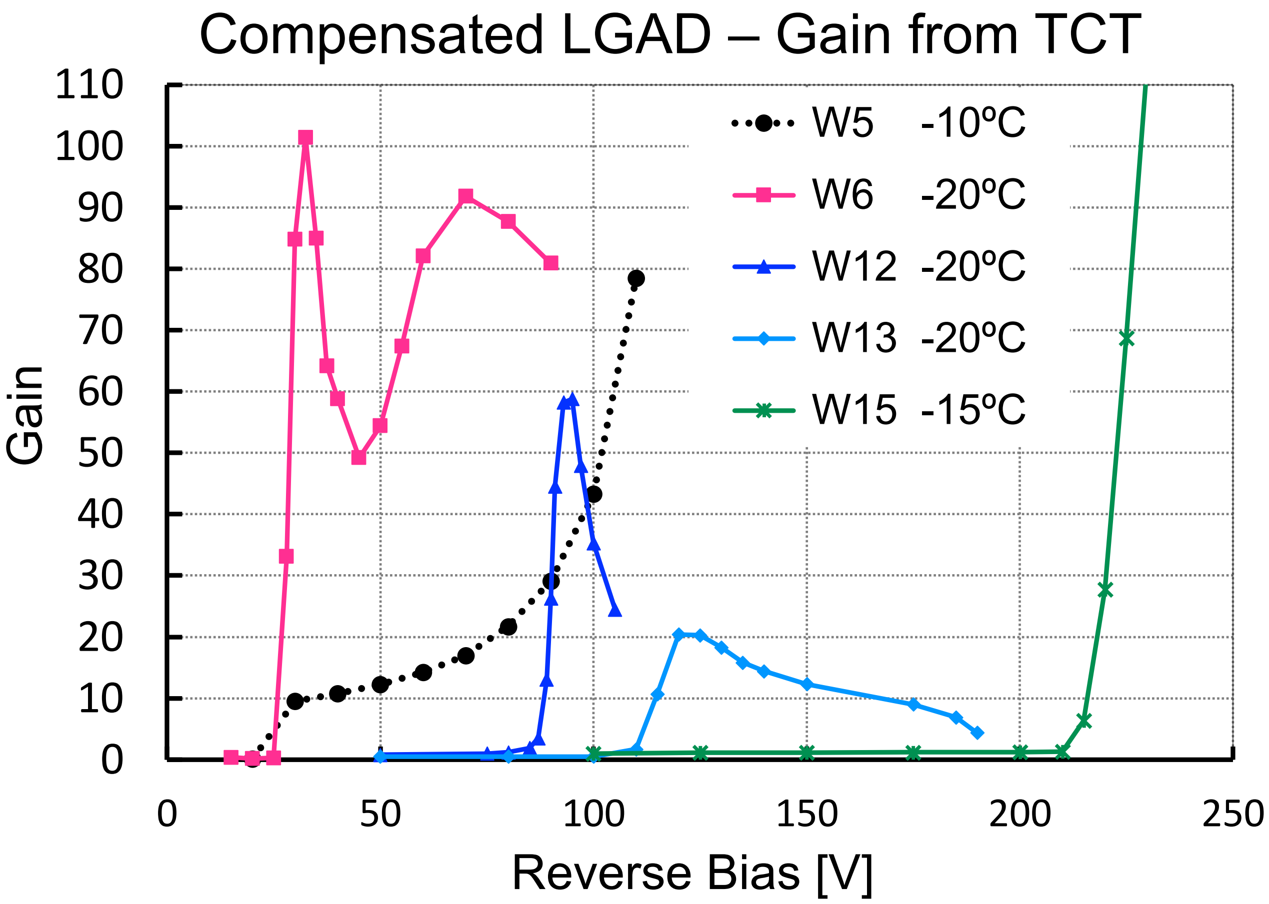
IR Laser Stimulus on Compensated LGAD

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Laser intensity ~ 4 MIPs



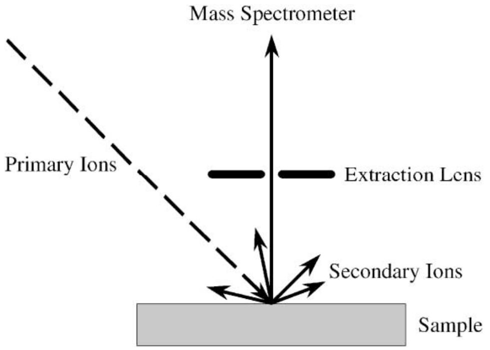
Laser stimulus on LGAD-PiN structures

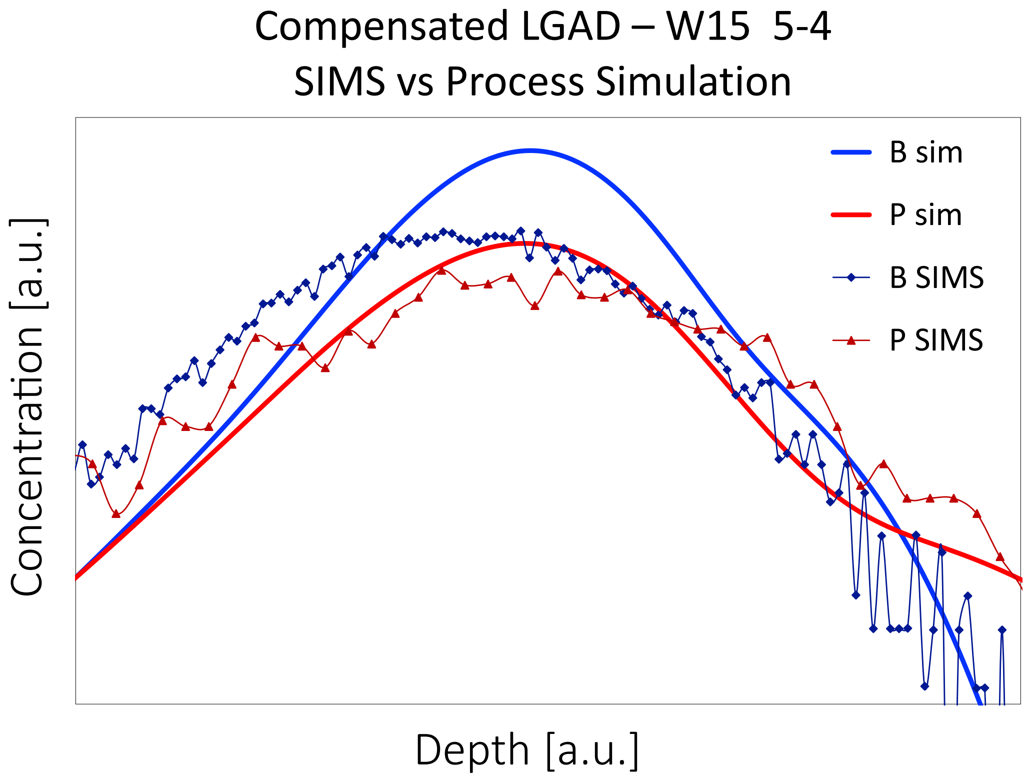
$$\mathbf{Gain} = \frac{\mathbf{Q_{LGAD}}}{< \mathbf{Q_{PiN}} >}$$



→ **Not trivial to operate compensated LGAD sensors**

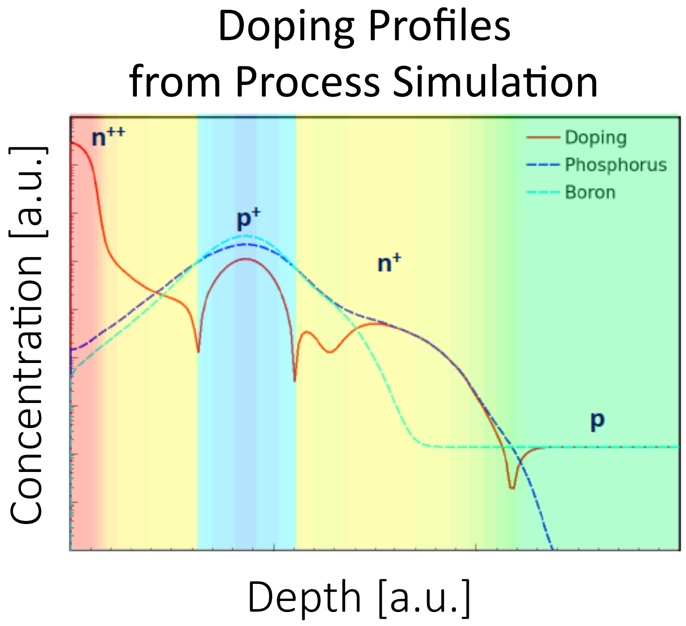
Secondary Ion Mass Spectroscopy – W15

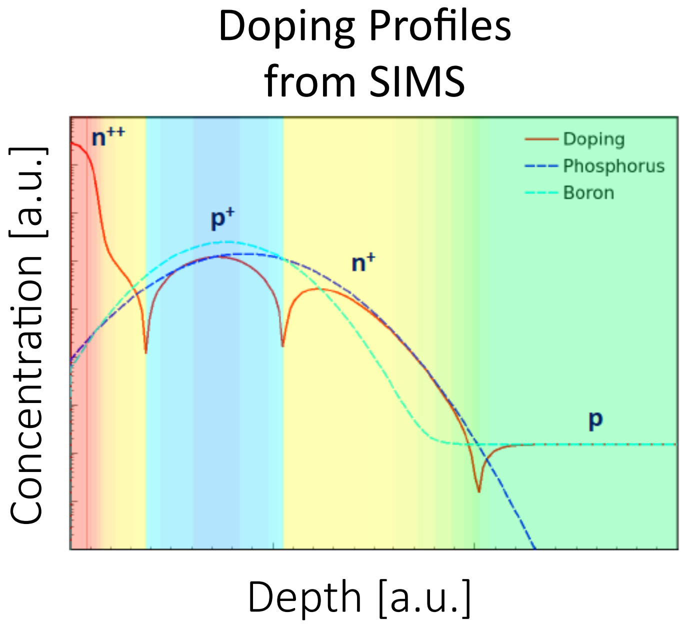


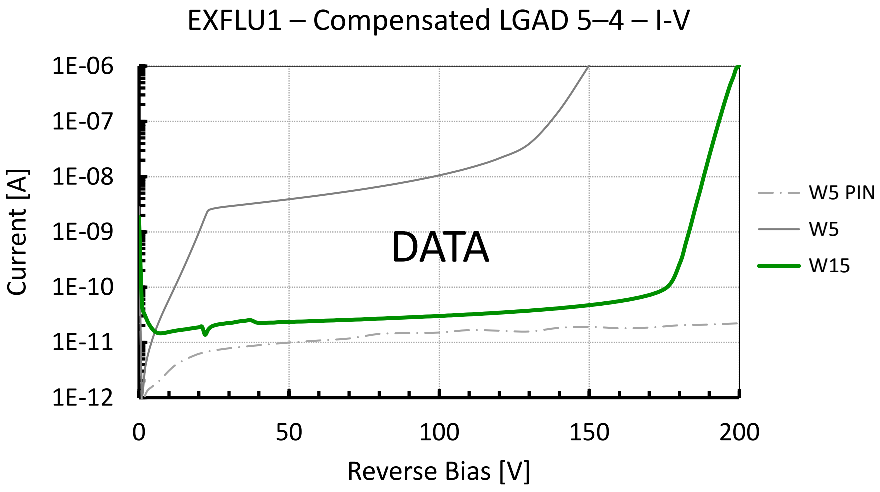


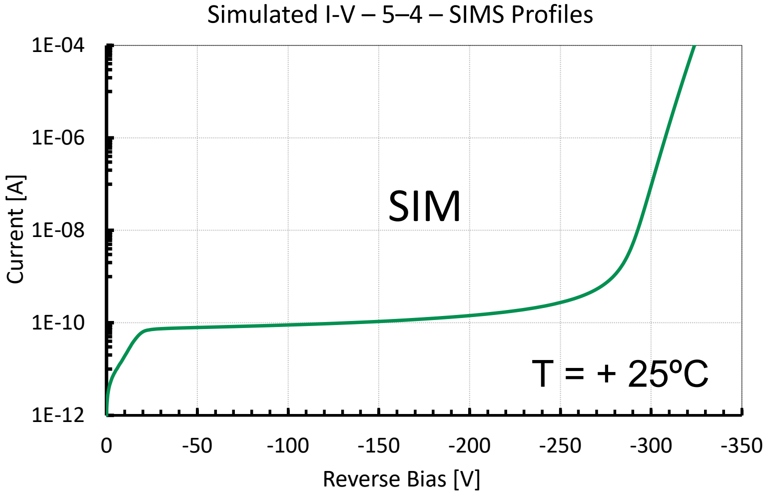
- Boron peak is shallower than phosphorus
- Boron peak is lower than predicted from simulation

SIMS Profile & I-V – 5–4



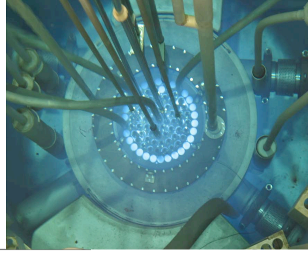






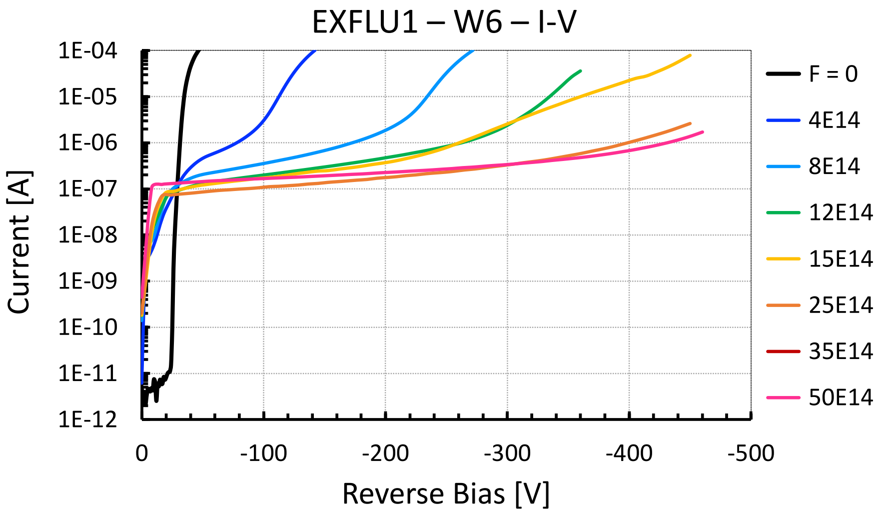
→ **The simulated I-V reproduces the trend of the measured I-V from W15**

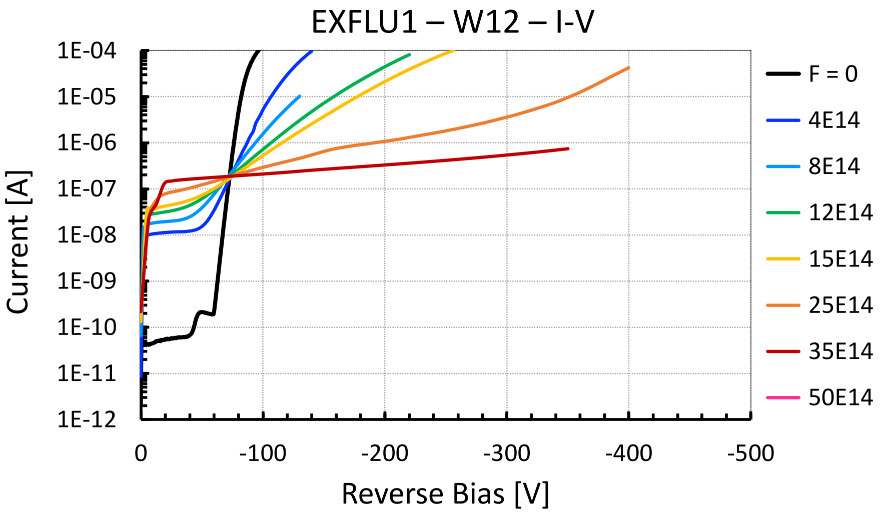
I-V from Compensated LGAD – Irradiated



Irradiated from 1E14 to 5E15 n_{eq}/cm^2

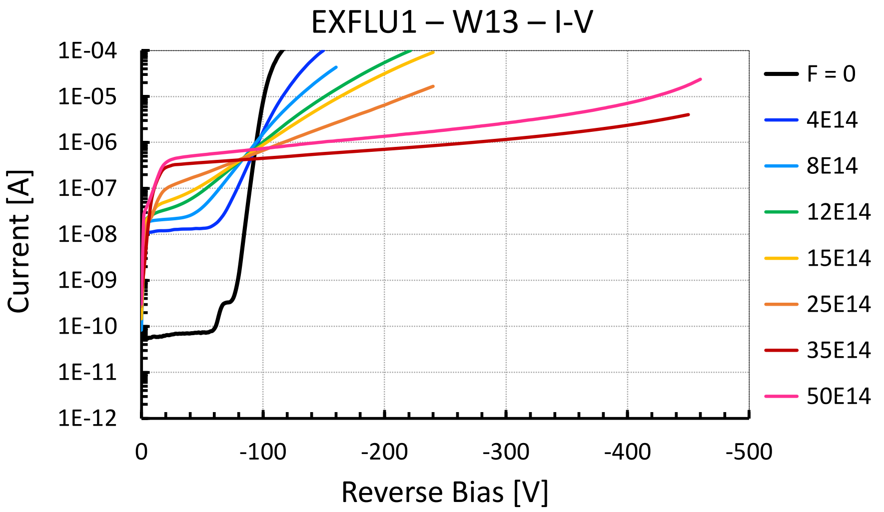
W6
2 – 1

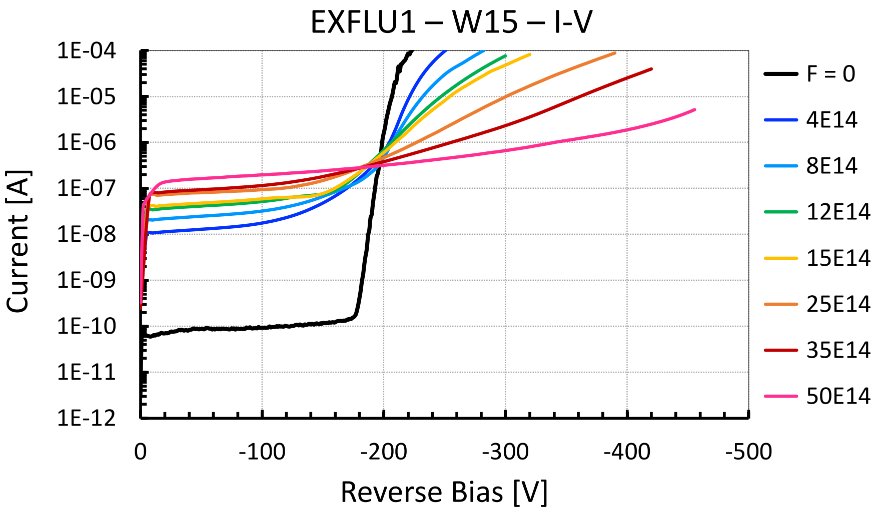




W12
3 – 2

W13
3 – 2 + C





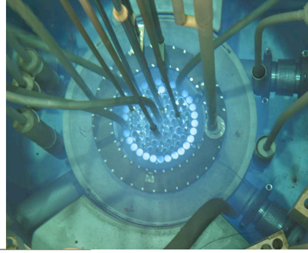
W15
5 – 4

$[\Phi] = n_{eq}/cm^2$

$T_{F=0} = + 20^oC$

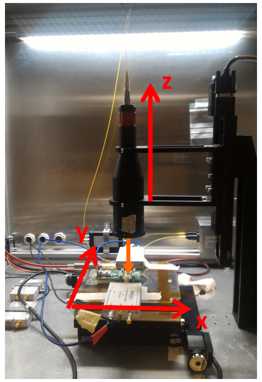
$T_{IRR} = - 20^oC$

IR Laser Stimulus on Compensated LGAD



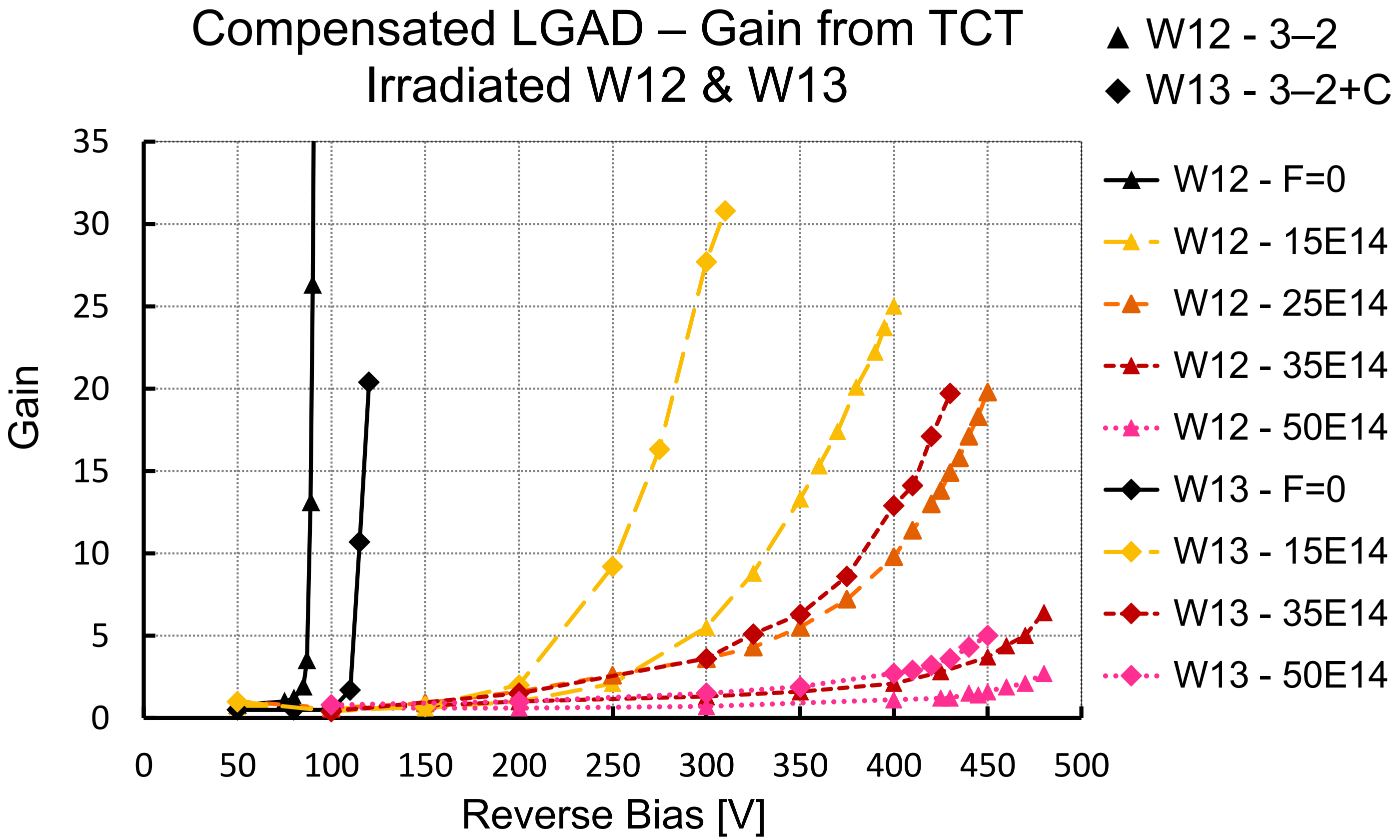
TCT Setup from Particulars

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Laser intensity ~ 4 MIPs
T = -20°C



Laser stimulus on a LGAD-PiN structures before and after irradiation

$$\text{Gain} = \frac{Q_{LGAD}}{< Q_{PiN}^{No\ Gain} >}$$



→ Good gain behaviour of the compensated LGAD sensors after irradiation

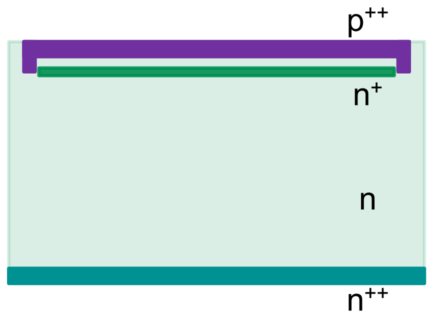
→ Even in compensated LGADs, **the usage of carbon mitigates the acceptor removal**

Strategies to Investigate Donor Removal

A p-in-n LGAD batch will be used to study the donor removal coefficient, $\mathbf{c_D}$

Donor removal has been studied for doping densities of $10^{12} – 10^{14}$ atoms/cm^3

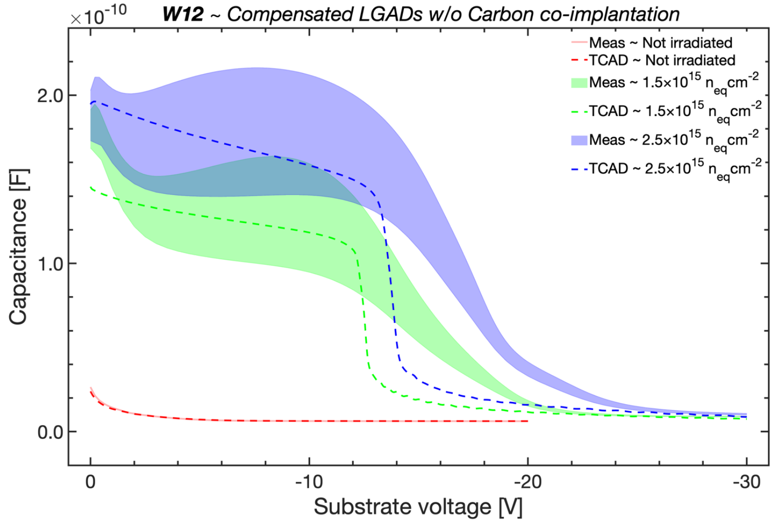
We need to study donor removal in a range $10^{16} – 10^{18}$ atoms/cm^3



p-in-n LGAD

By means of the TCAD simulation, the donor removal is extracted from the C-V characteristics of the compensated LGAD sensors

Exploiting the experimental acceptor removal coefficient $\mathbf{c_A = 2.5 \cdot 10^{-16}}$ **cm^2**, agreement with C-V measurements is achieved using a donor removal coefficient $\mathbf{c_D = 6.5 \cdot 10^{-16}}$ **cm^2**



[A. Fondacci et al., agenda.infn.it/event/37033/contributions/227539]

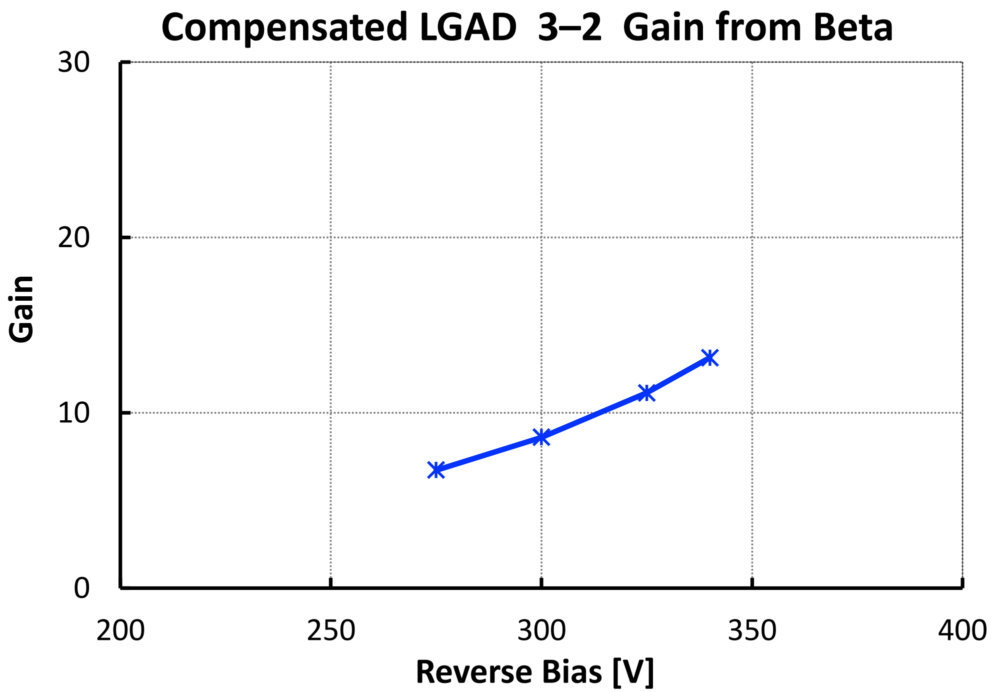
β Particles on Compensated LGAD

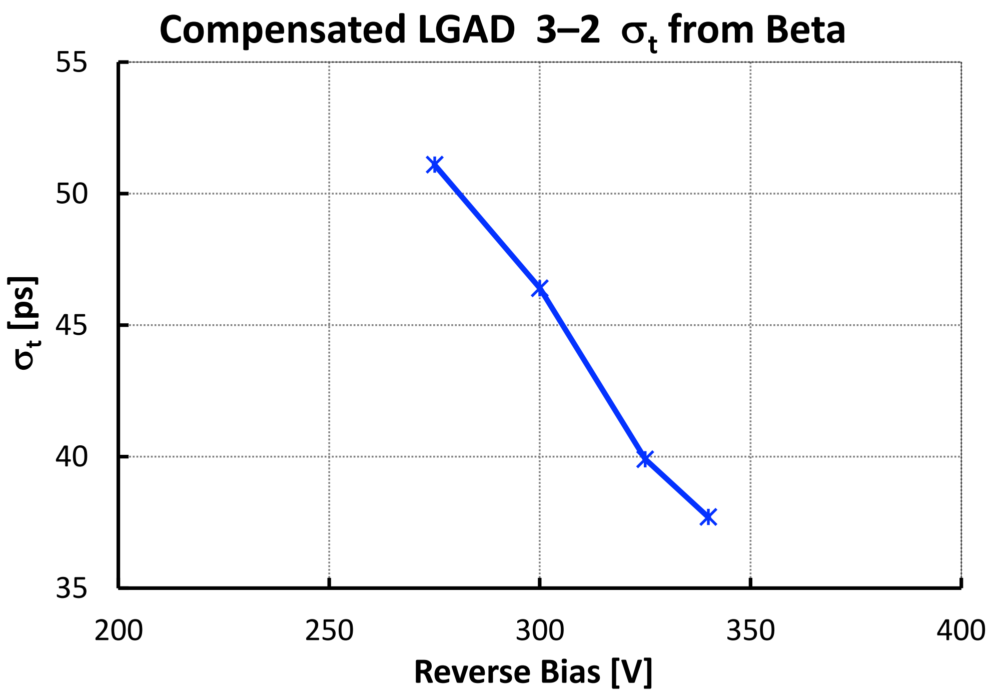
β Setup
Oscilloscope: LeCroy 9254M (2.5GHz - 40Gs/s)
HV Power supply: CAEN DT1471ET
UCSC Board + Cividec Broadband Amplifier (20dB)
Time reference: Photonis MCP-PMT – $\sigma_t \sim 15$ ps
β source: Sr90 – activity ~ 37 kBq
T = -25°C

3–2 compensated LGAD from W12 irradiated to 2.5E15 n_{eq}/cm^2 has been tested with beta particles

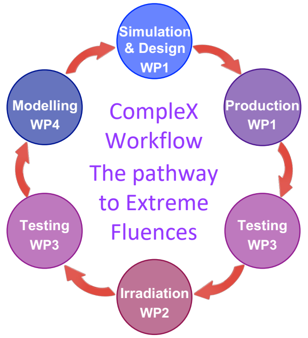
→ **Good timing performances of compensated LGAD sensors irradiated to 2.5E15 n_{eq}/cm^2**

W12
3–2
Φ = 2.5E15





The CompleX Flow



CompleX work packages:

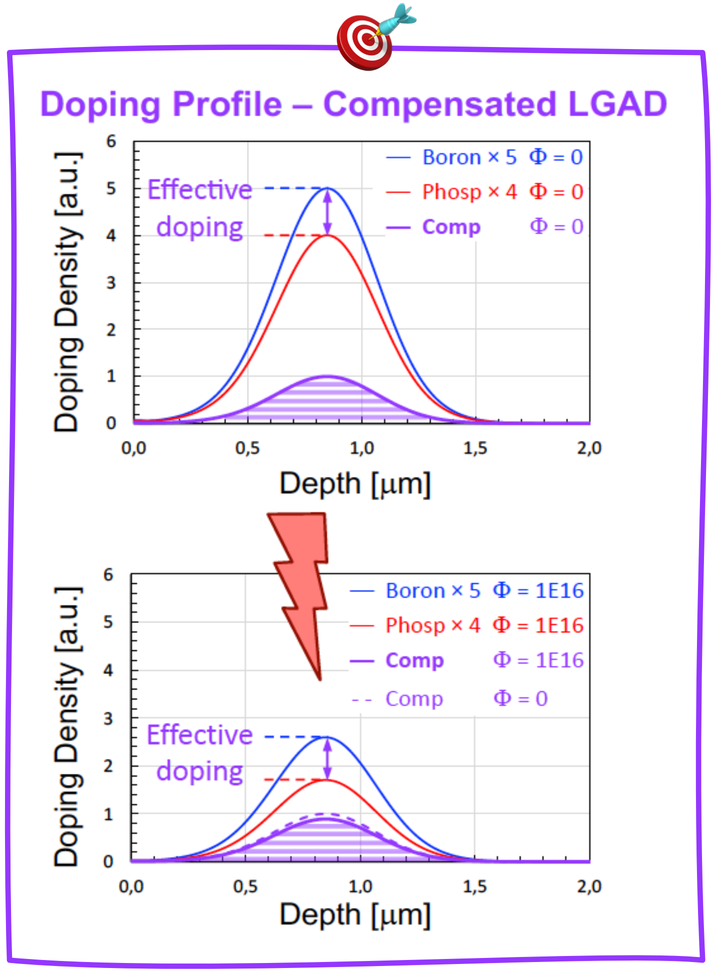
WP1 – Sensor design and production

WP2 – Sensor irradiation

WP3 – Testing and data analysis

WP4 – Modelling of radiation effects

iterating over 3 times



The CompleX Team

Torino University

CompleX work packages:

WP1 – Sensor design and production

WP2 – Sensor irradiation

WP3 – Testing and data analysis

WP4 – Modelling of radiation effects

Fondazione Bruno Kessler

INFN

The CompleX Objectives

CompleX work packages:

WP1 – Sensor design and production

WP2 – Sensor irradiation

WP3 – Testing and data analysis

WP4 – Modelling of radiation effects

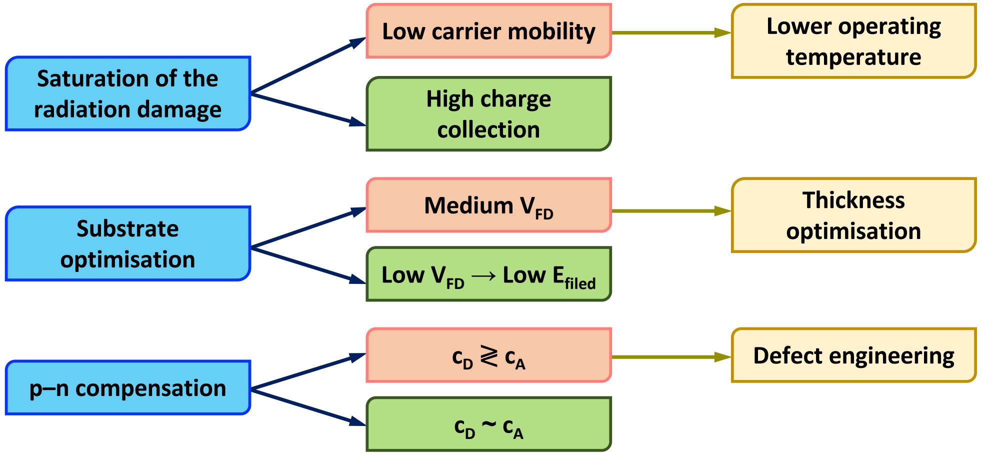
CompleX objectives

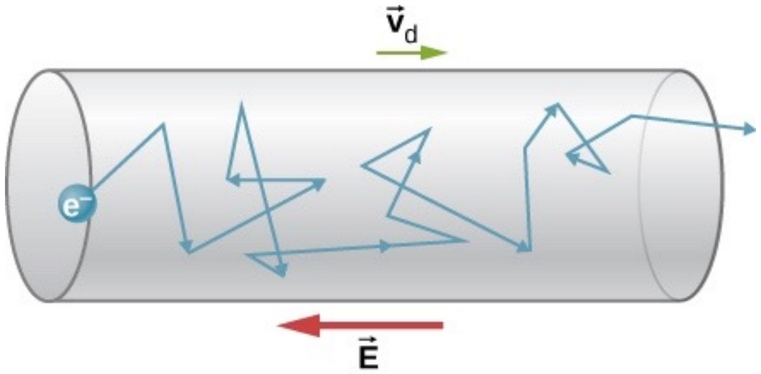
(i) Extend and develop a **radiation damage model** able to describe silicon behaviour, including saturation effects, under irradiation up to $5 \cdot 10^{17}$ n_{eq}/cm^2

(ii) Design LGAD silicon sensors that provide a **charge of ~ 5 fC per particle hit** up to fluences of $5 \cdot 10^{17}$ n_{eq}/cm^2

(iii) Define a production process to build cost-effective radiation-tolerant detectors through the **p–n dopant compensation**

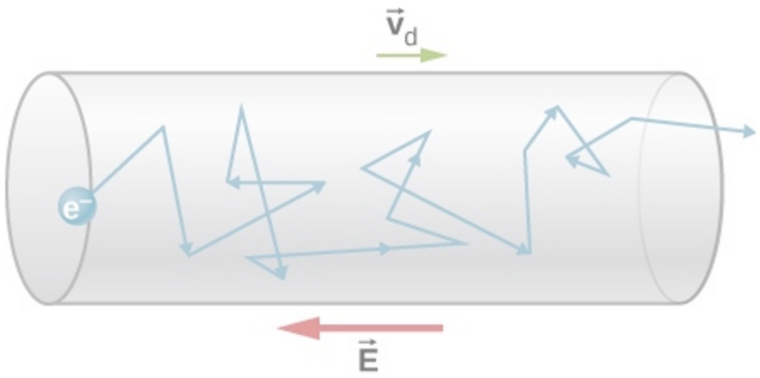
The CompleX Strategy





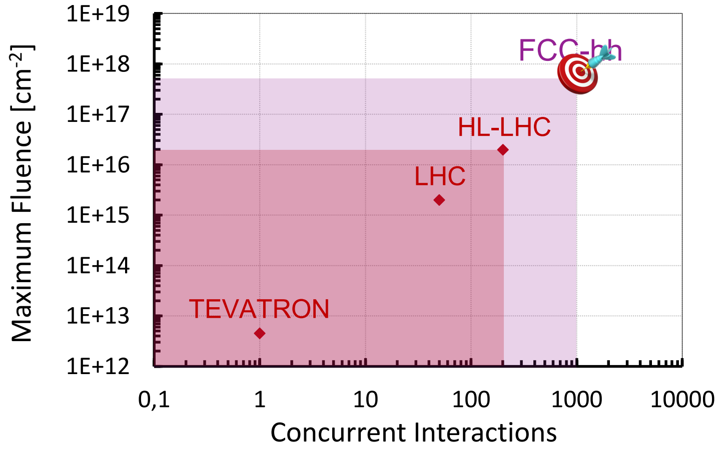
The CompleX Outcome

- Saturation of the radiation damage
  - Low carrier mobility → Lower operating temperature
  - High charge collection
- Substrate optimisation
  - Medium V_{FD} → Thickness optimisation
  - Low V_{FD} → Low E_{filed}
- p–n compensation
  - $c_D \gtrsim c_A$ → Defect engineering
  - $c_D \sim c_A$



	Precise Tracking	Precise Timing
Worst Case Scenario	$\Phi = 5 \cdot 10^{16}/cm^2$ Gain = 5 – 10	$\Phi = 1 \cdot 10^{16}/cm^2$ Gain = 20 – 30
Intermediate Scenario	$\Phi = 1 \cdot 10^{17}/cm^2$ Gain = 5 – 10	$\Phi = 5 \cdot 10^{16}/cm^2$ Gain = 20 – 30
CompleX Target	$\Phi = 5 \cdot 10^{17}/cm^2$ Gain = 20 – 30	

The CompleX Impact



- **Fundamental advance in silicon detector understanding** up to the fluence of $5 \cdot 10^{17}$ n_{eq}/cm^2
- Enable the **design of silicon 4D tracker detectors for future** high-energy and high-intensity hadron collider experiments
- Boost the **technology in all extreme radiation environments** e.g. monitoring at nuclear fusion reactors

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