Valentina Sola

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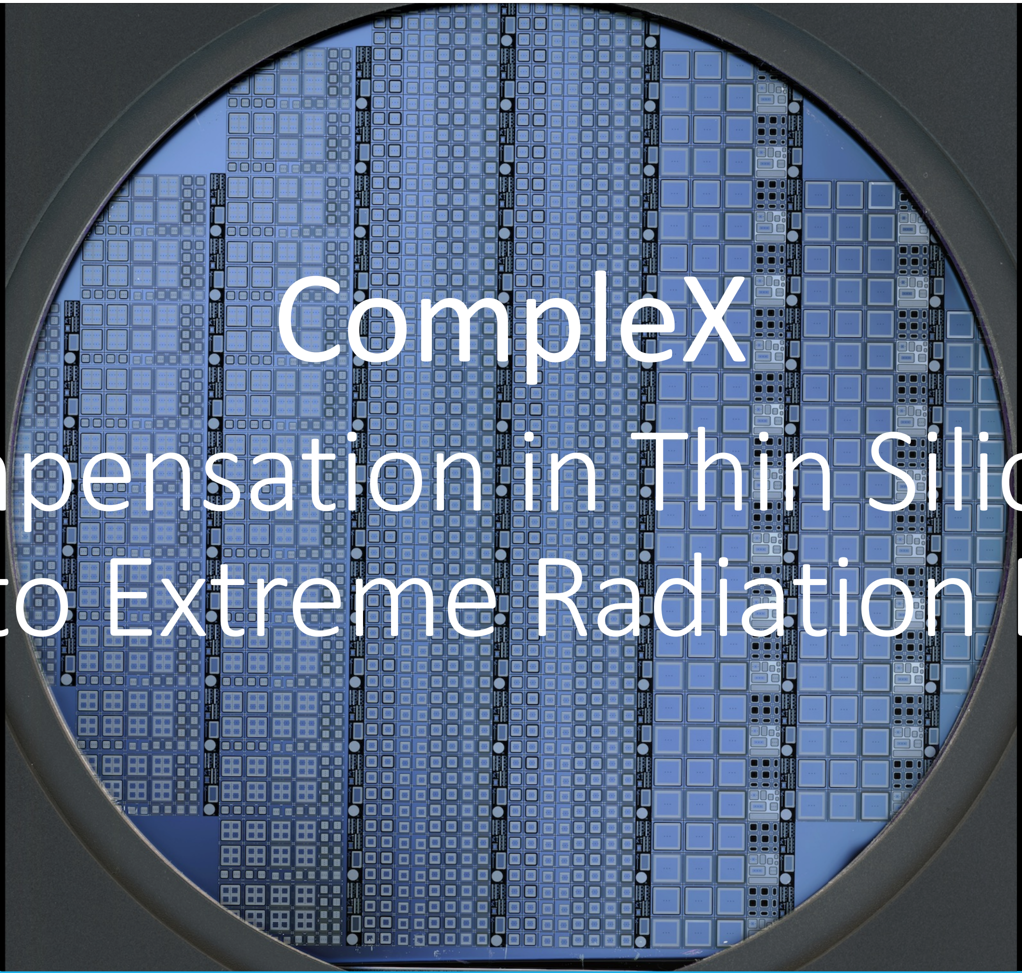
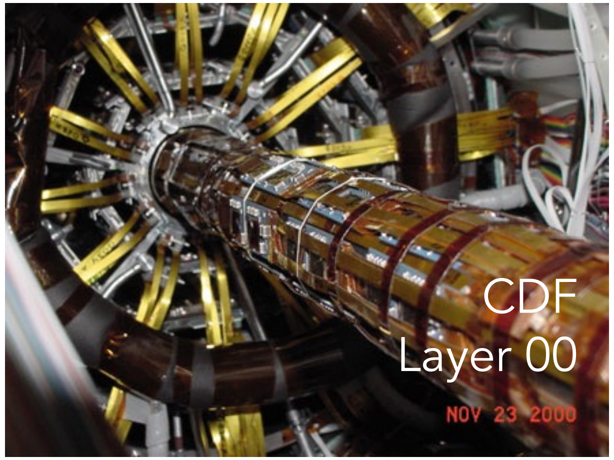


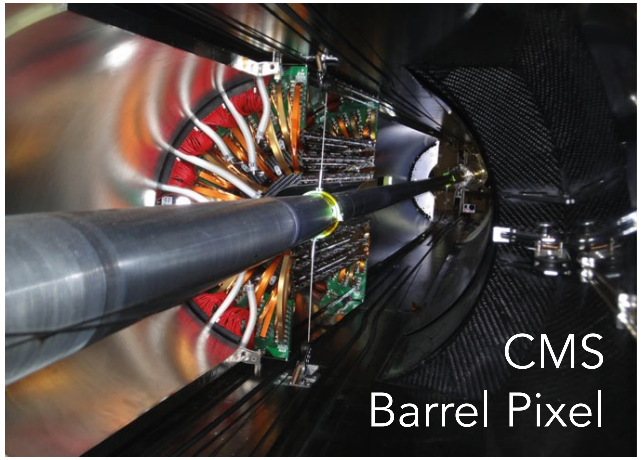
CompleX

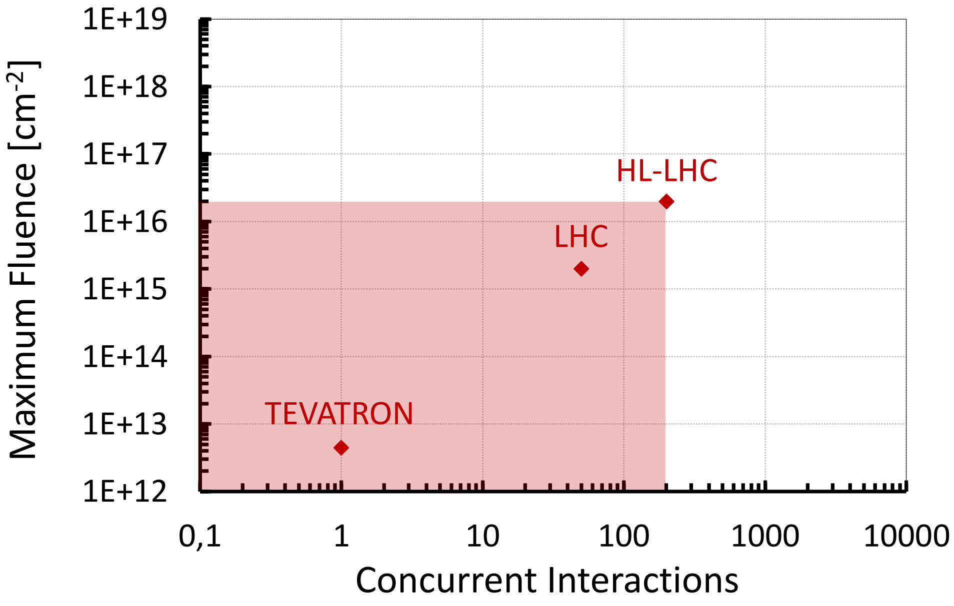
Doping Compensation in Thin Silicon Sensors: the pathway to Extreme Radiation Environments

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

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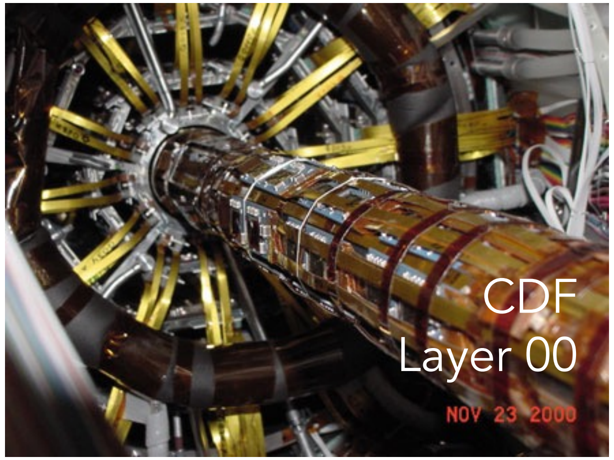

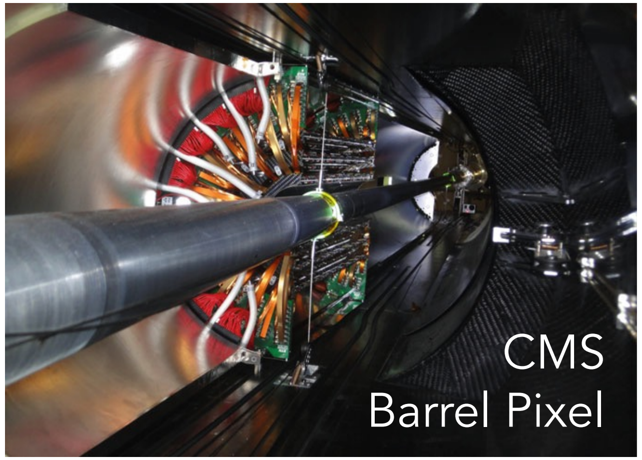

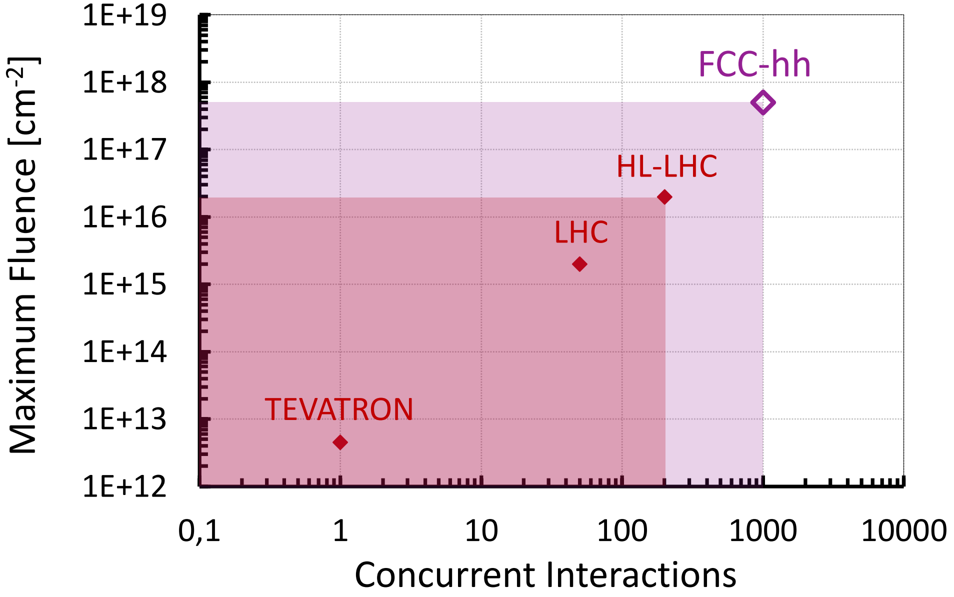

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→ **CompleX will enable 4D tracking with planar silicon sensors up to the fluence of $5 \cdot 10^{17}/cm^2$**

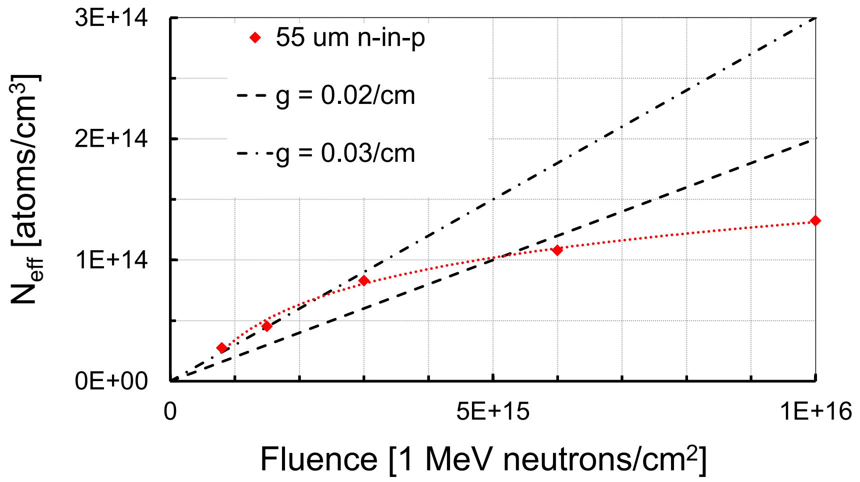
Silicon Modelling at Very High Fluences

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

A mismatch between data and the predictions arises at very high fluences

- ➢ 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**



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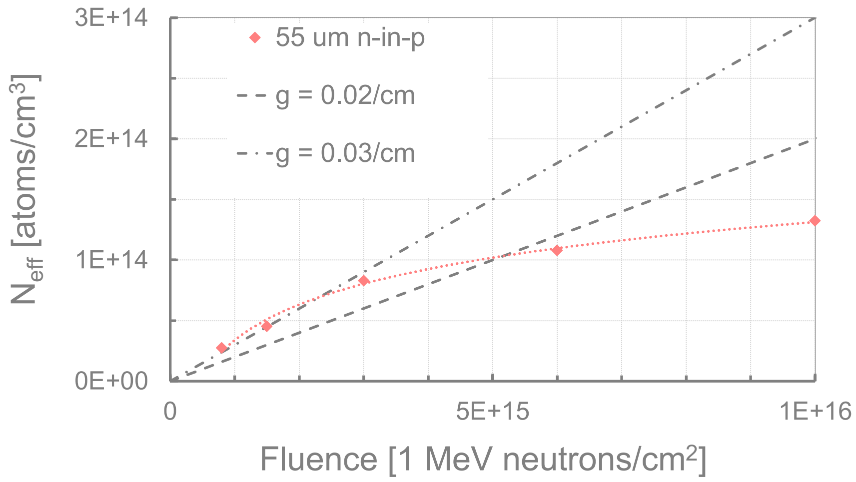


Accurate modelling of silicon damage and sensor behaviour at very high fluences is necessary to design the next generation of silicon detectors

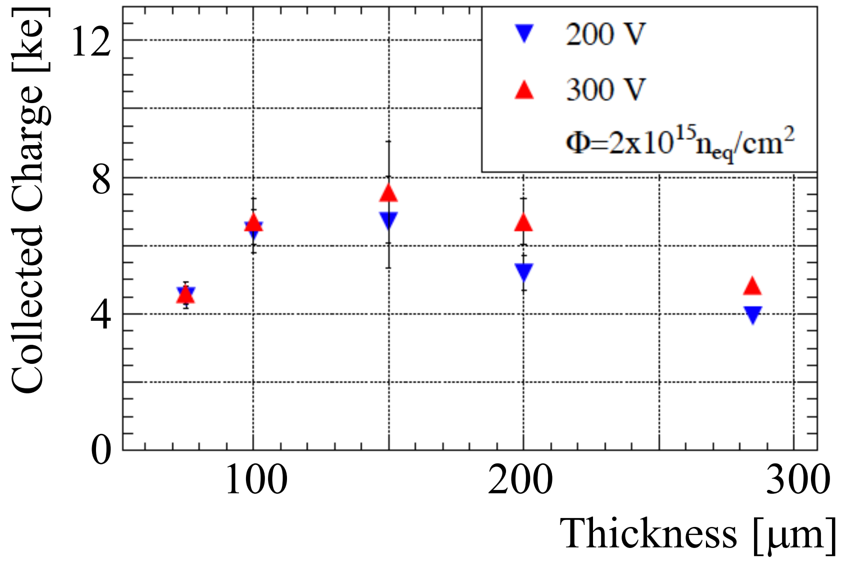
→ **CompleX will extend the understanding and modelling of radiation damage in silicon to the fluence of $5 \cdot 10^{17}$ n_{eq}/cm^2**

Towards the eXtreme Fluences – CompleX

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]

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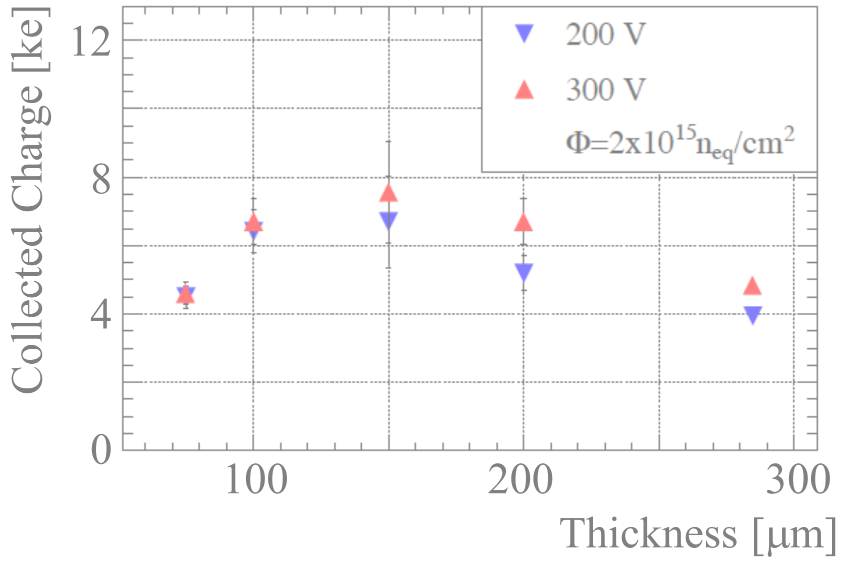


[doi: 10.1088/1748-0221/9/05/C05023]

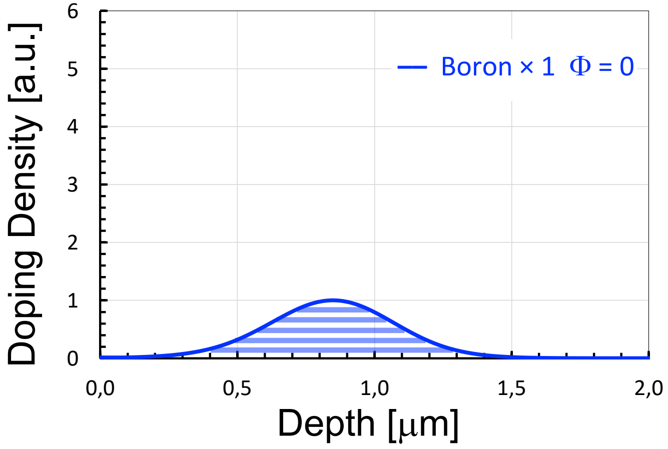
CompleX will design a new generation of silicon sensors

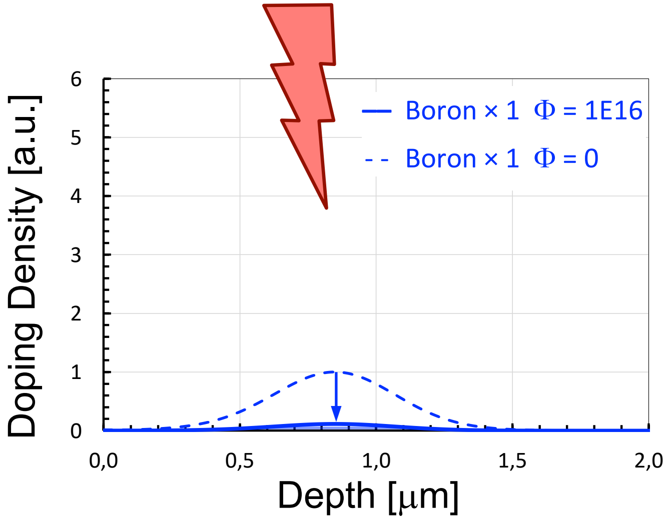
- exploit saturation of the radiation damage
- use thin substrates (20 – 40 μm)
- use internal gain to enhance the signal

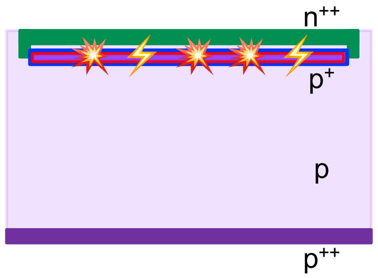
→ **CompleX will develop a new generation of planar silicon sensors with gain to operate in extreme fluence environments**

Compensated LGADs for eXtreme Fluences

Doping Profile – Standard LGAD

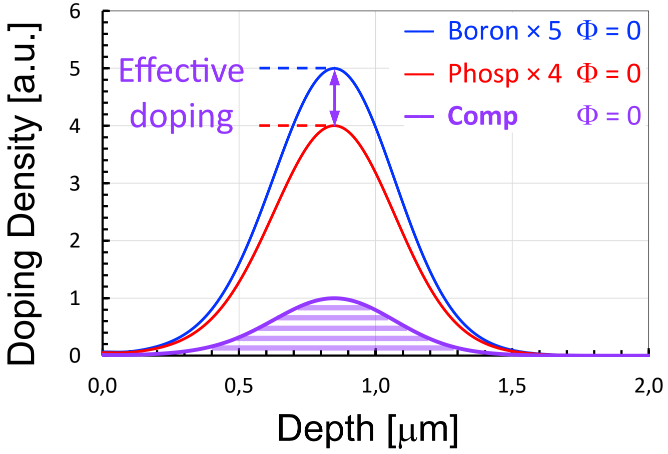


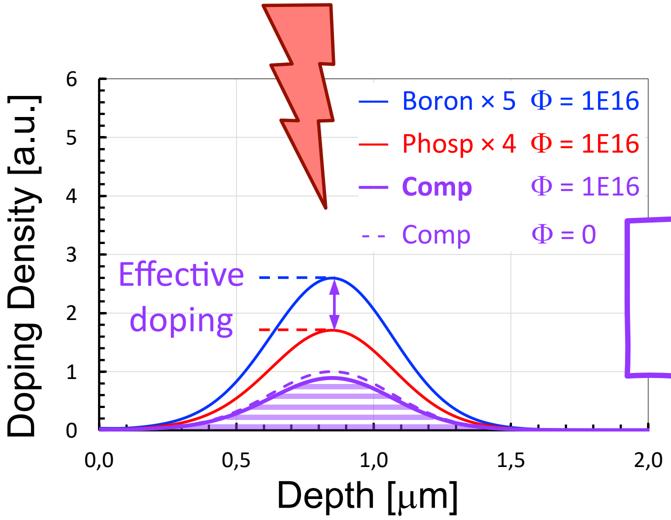




Irradiation
$\Phi = 1 \times 10^{16}\ n_{eq}/cm^2$

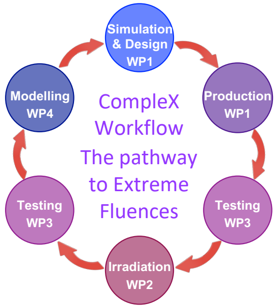
Doping Profile – Compensated LGAD

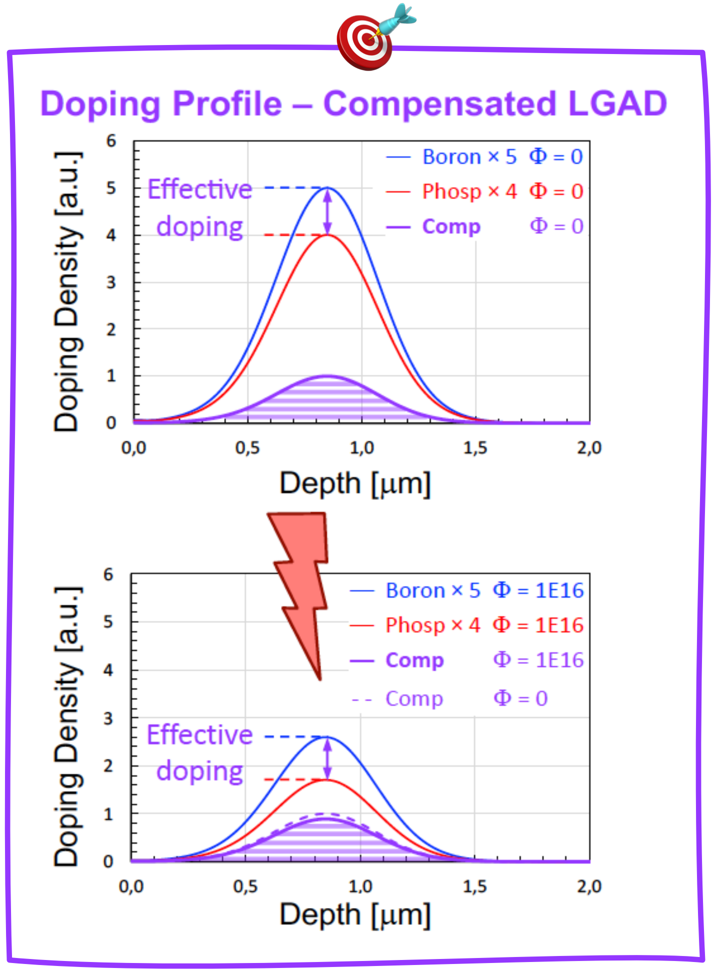




CompleX target

The CompleX Objectives





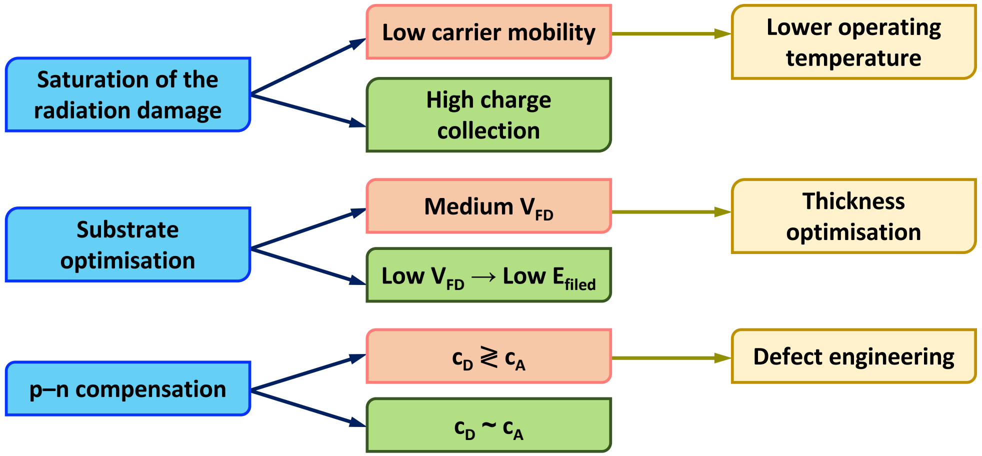
CompleX objectives

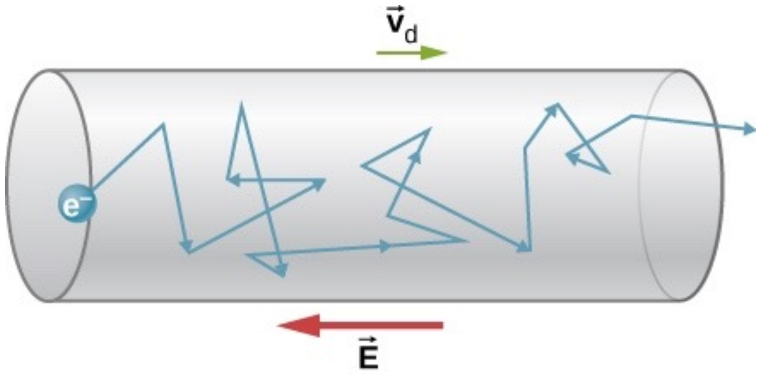
(i) Extend and develop a **radiation damage model** able to describe silicon behaviour, including saturation effects, under irradiation up to $5 \cdot 10^{17}$ n_{eq}/cm^2

(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**

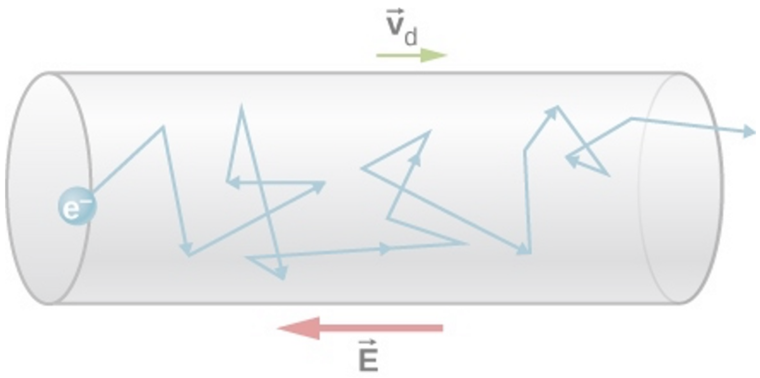
The CompleX Strategy





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

CompleX to HEP

- The capability of performing 4D tracking up to $1\cdot10^{16}$ n_{eq}/cm^2 will allow building vertex detectors with timing capability and searching for long living particles in detector regions with high radiation
  $\longrightarrow$ Muon Collider

- The capability of performing 4D tracking up to $5\cdot10^{17}$ n_{eq}/cm^2 will allow to build trackers in experiments at very high-energy and high-intensity colliders
  $\longrightarrow$ FCC-hh

$\Rightarrow$ The R&D is compatible with the experiments' timescale

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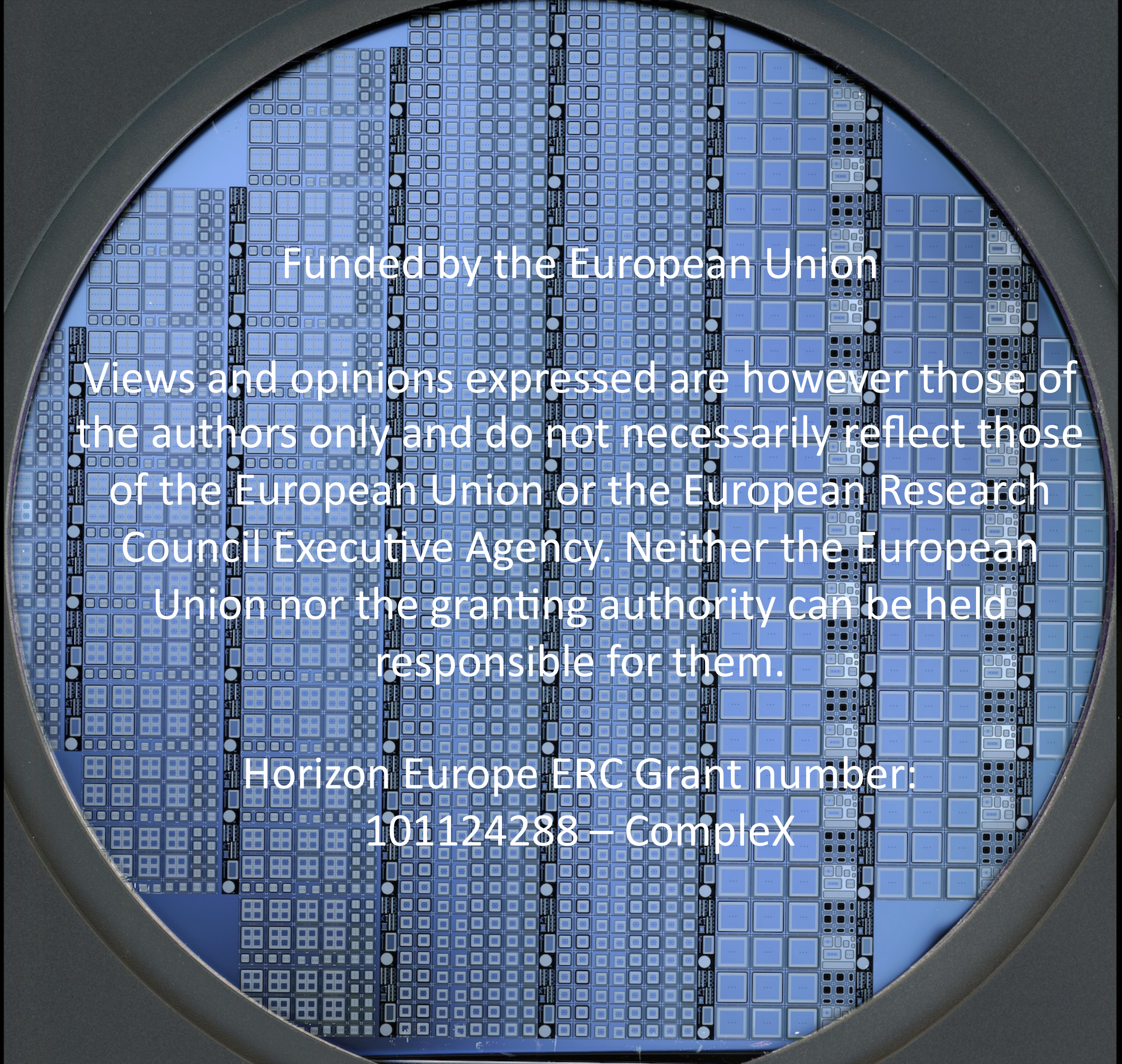
⇒ The R&D is compatible with the experiments' timescale

Synergic to CSN1

European Research Council
Established by the European Commission



Funded by the European Union

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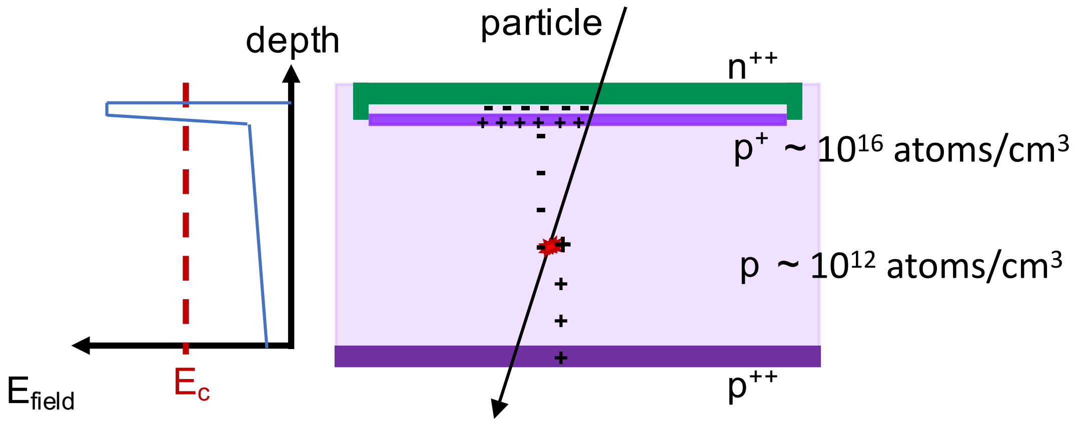
Horizon Europe ERC Grant number:
101124288 – ComplexX

Low-Gain Avalanche Diodes

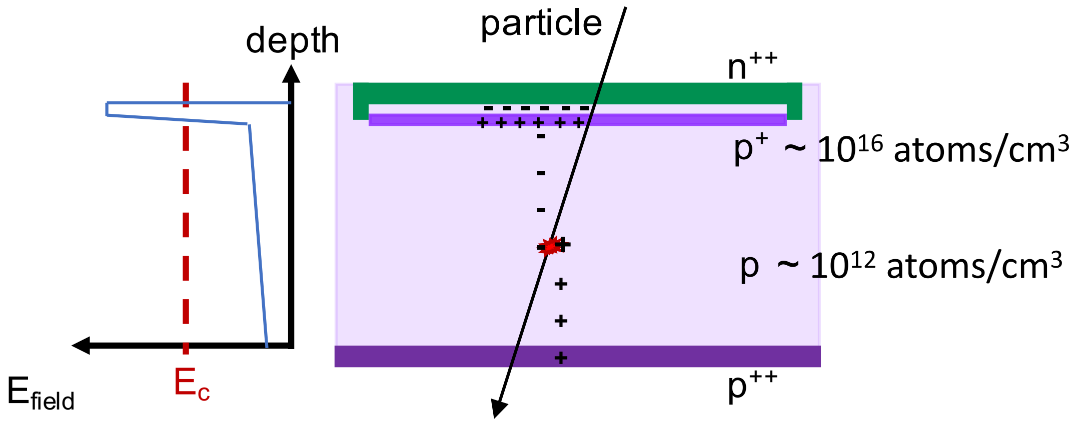


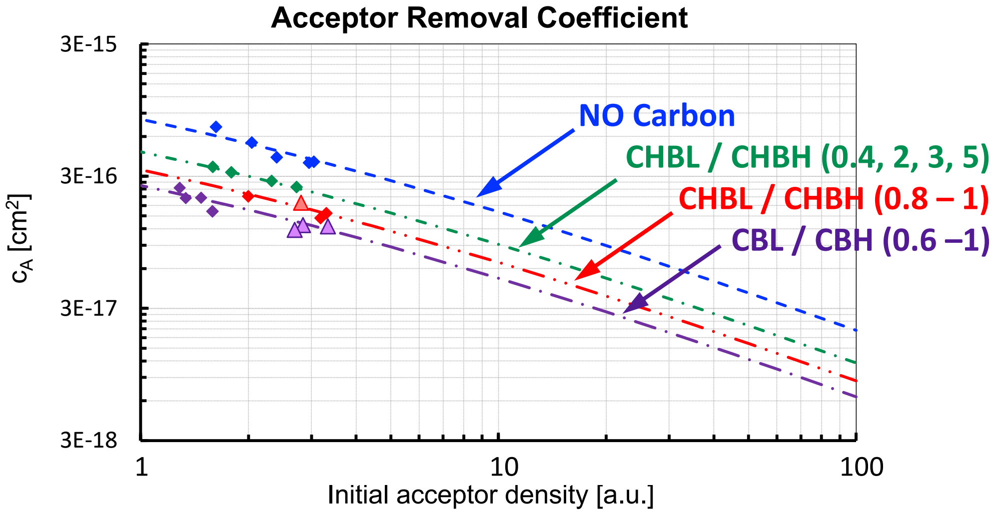
LGADs are n-in-p planar silicon sensors

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

Critical electric field $E_c \sim 20-30$ 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

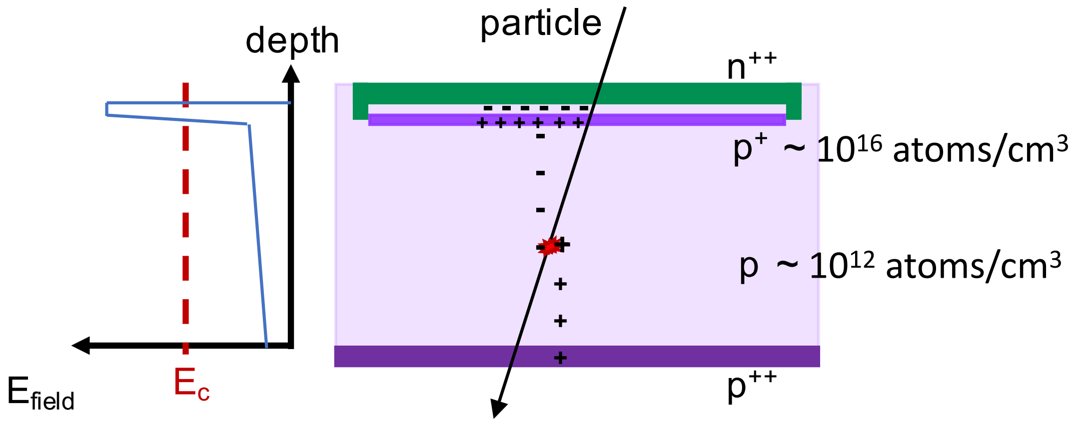
c_A depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms

▲ 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



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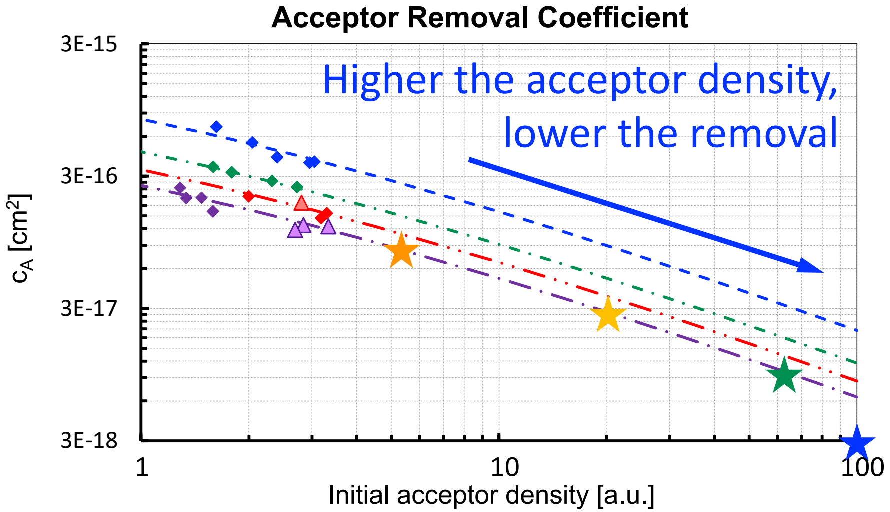
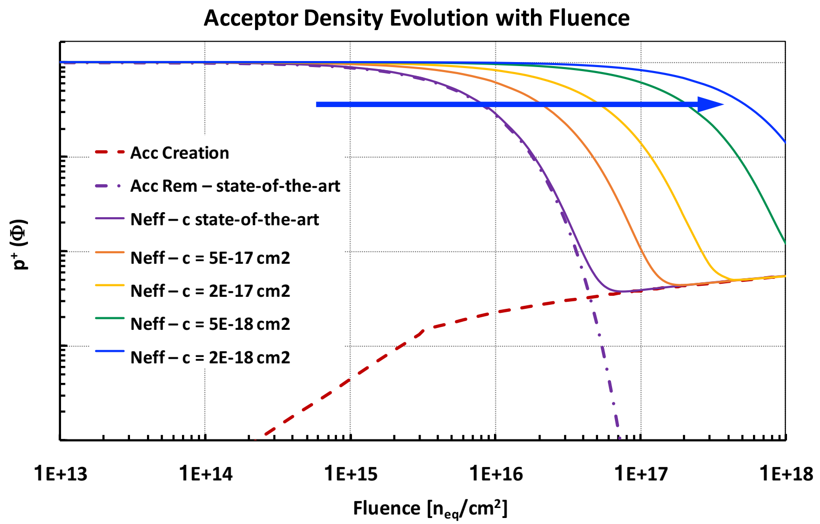
To substantially reduce c_A, it is necessary to increase $p^+(0)$, the initial acceptor density





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

UFSD to CompleX

- **UFSD** – Ultra-Fast Silicon Detectors: Enabling Discoveries — 2016
  PI: N. Cartiglia – INFN — ERC Advanced Grant
- **4DInSiDe** – Innovative Silicon Detectors for particle tracking in 4Dimensions — 2019
  PI: N. Cartiglia – INFN, CNR, UPO, UniPG, UniTO — PRIN 2017 – MIUR
- **eXFlu** – Silicon Sensors for Extreme Fluences — 2020
  PI: VS – INFN, FBK — Grant Giovani CSN5
- **eXFlu-innova** – Thin Silicon Sensors for Extreme Fluences — 2022
  PI: VS – INFN, FBK, CNR — AIDAinnova Blue Sky
- **FLEX** – Sensori sottili per fluenze estreme — 2022
  PI: VS – UniTO, JSI — Compagnia di San Paolo
- **ComonSens** – A Compensated Design of Thin Silicon Sensors for Extreme Fluences — 2023
  PI: VS – UniTO, CNR, INFN — PRIN 2022 – MUR
- **CompleX** – Doping Compensation in Thin Silicon Sensors: the pathway to Extreme Radiation Environments
  PI: VS – UniTO, FBK, INFN — ERC Consolidator Grant