42nd RD50 Workshop – 21st June 2023

Gain degradation study after neutron and proton irradiations in Low Gain Avalanche Diodes

E. Curras[a], M. Moll[a], A. la Rosa[a] , F. Zareef[b],

[a]Solid State Detector (SSD) Lab, CERN.
[b]Department of Interactions and Particle Detection, AGH-UST Krakow.

arXiv:2306.11760

fasih.zareef@cern.ch

AGH

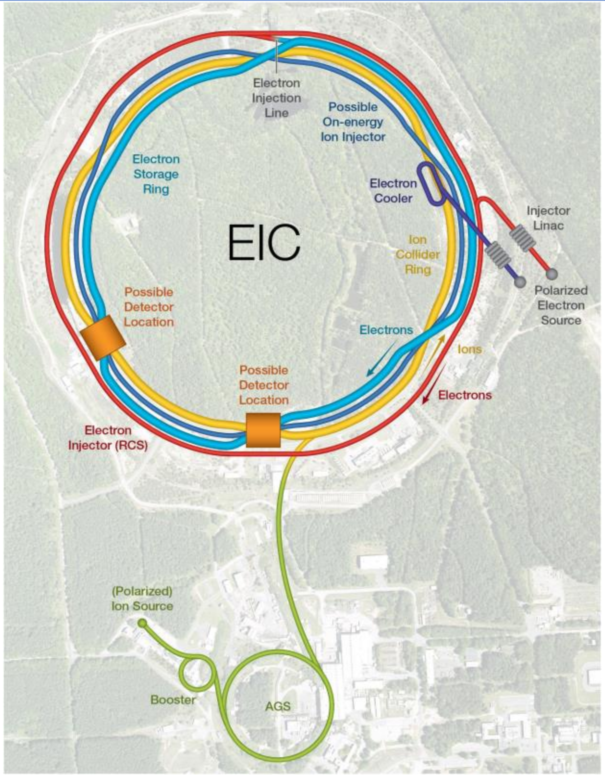
AGH University of Science and Technology

Outline

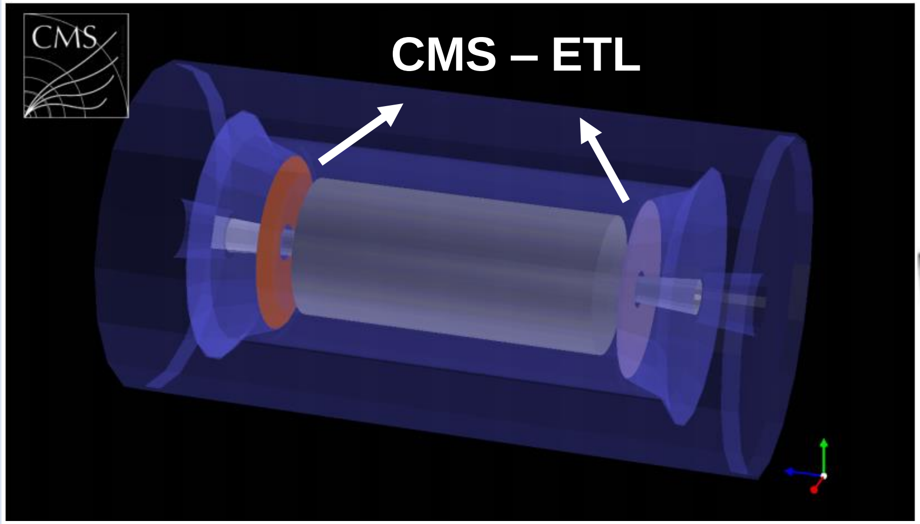
- Motivation and challenges
- Low Gain Avalanche Diodes (LGADs)
- Devices under test
- Electrical Characterizations
    - Reverse Current Damage Coefficient
    - IV and CV Measurements
- Laser Characterizations
    - Gain Measurements
- Gain Layer Degradation Study
    - V_{GL} Extraction
    - Acceptor Removal Coefficient
- Summary and Future Work

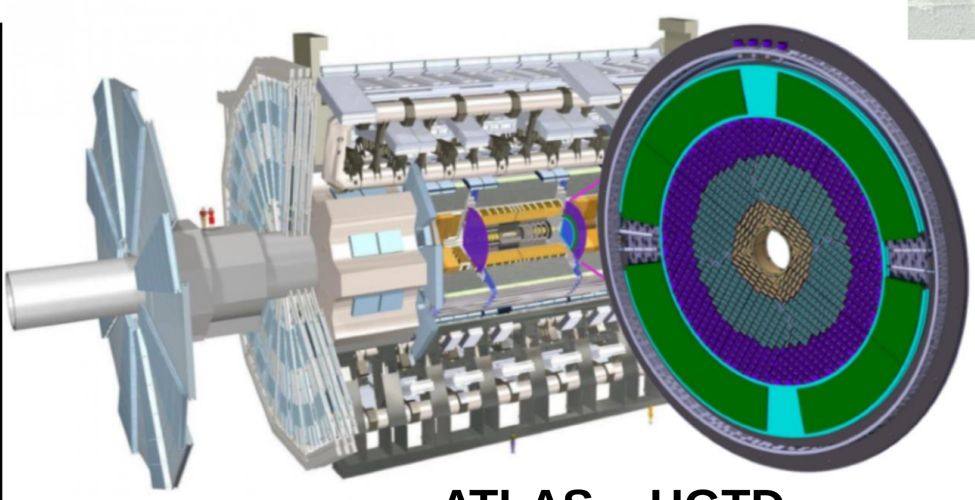
Motivation

- To study the radiation damage of LGADs for the HL-LHC MIP timing detectors of CMS and ATLAS
- To study the comparison between radiation damage introduced by neutrons and high energy protons
- A very limited literature on the study of 24 GeV/c protons on the devices from HPK-P2 and CNM-12916
- Comparison of the sensors from different productions: HPK-P2 and CNM-12916



Electron – Ion Collider at BNL



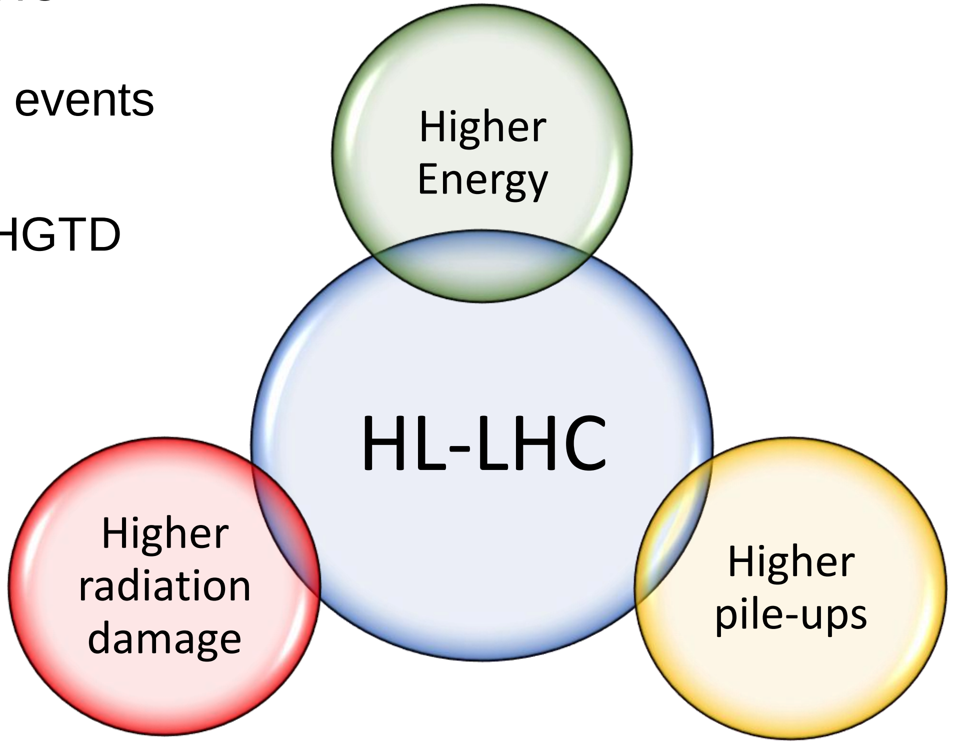


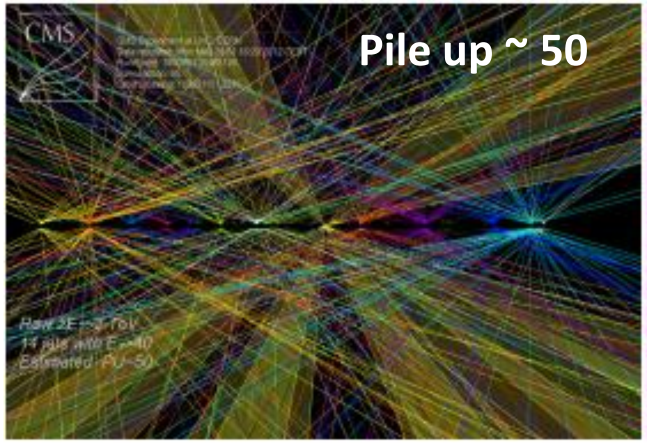
ATLAS – HGTD

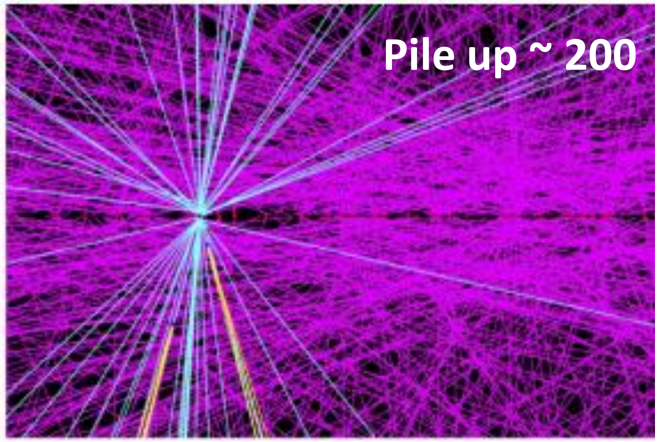
The Need for New Timing Detectors

- Pile-up is one of the major challenges for tracking at the HL-LHC
- Timing information will be used to disentangle the overlapping events
- Radiation tolerance up to $\sim 2.5 \text{ x } 10^{15} n_{eq} cm^{-2}$ for ATLAS – HGTD

  and $\sim 1.5 \text{ x } 10^{15} n_{eq} cm^{-2}$ for CMS – ETL is required
- Time resolutions < 50ps per-hit for a MIP





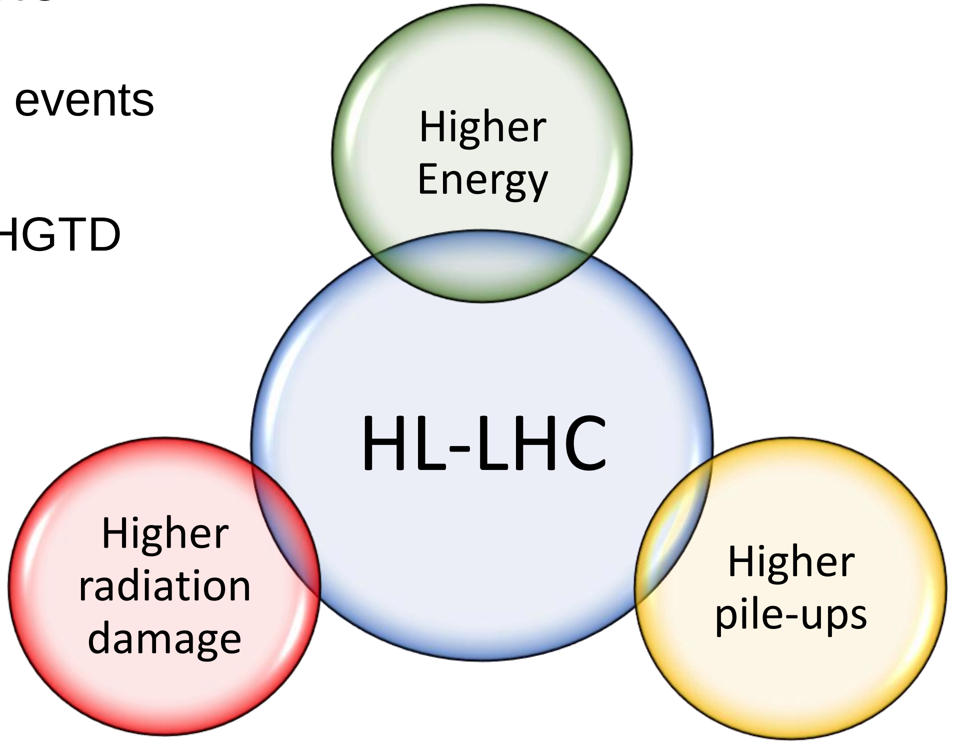


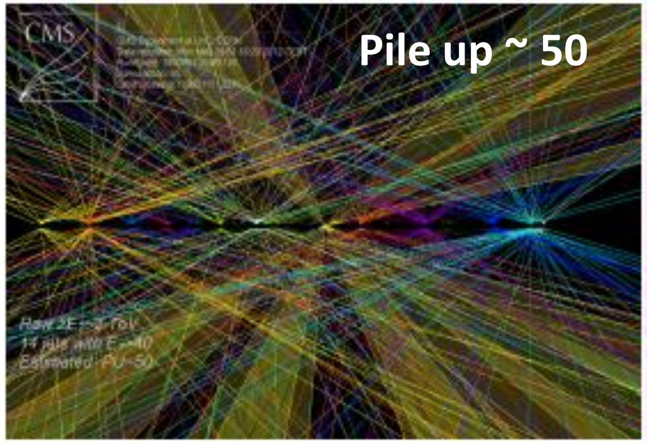
Sofia Otero, PoS (2019) [1]

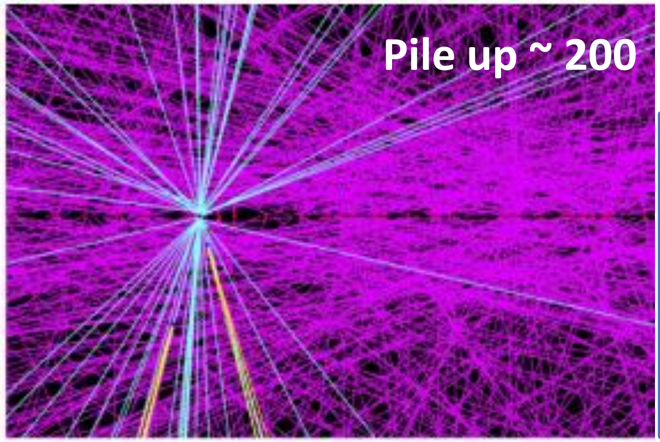
The Need for New Timing Detectors

- Pile-up is one of the major challenges for tracking at the HL-LHC
- Timing information will be used to disentangle the overlapping events
- Radiation tolerance up to ~ $2.5 \text{ x } 10^{15} n_{eq} cm^{-2}$ for ATLAS – HGTD

  and ~ $1.5 \text{ x } 10^{15} n_{eq} cm^{-2}$ for CMS – ETL is required
- Time resolutions < 50ps per-hit for a MIP







Sofia Otero, PoS (2019) [1]

FCC-hh

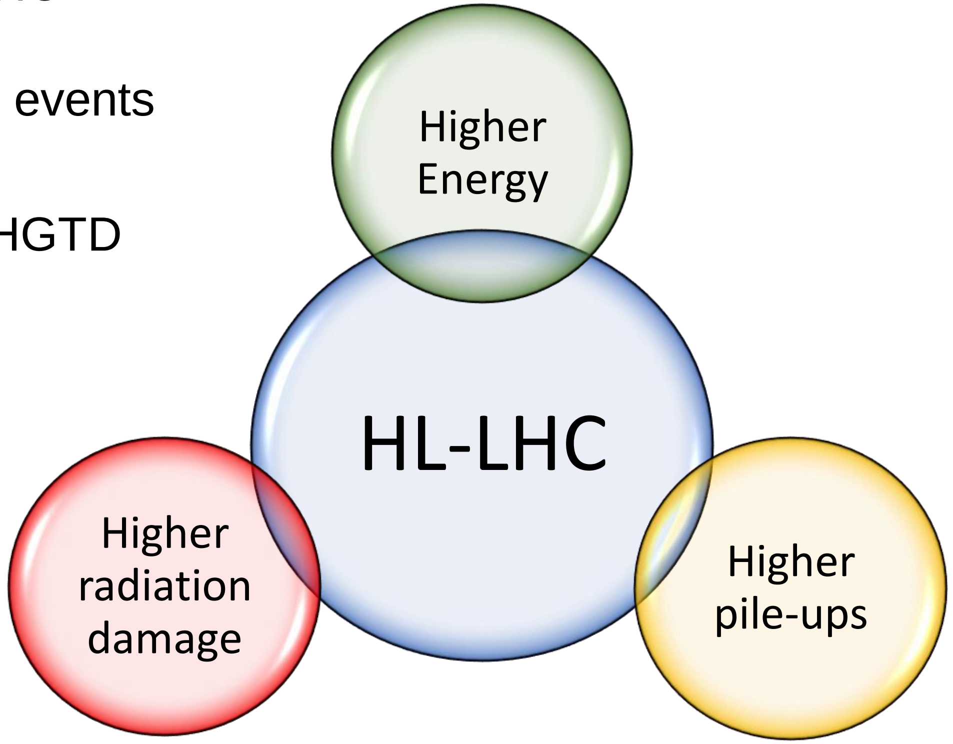
- Pile up mitigation ~ 1000
- Time resolution ~ 10 ps per-hit for a MIP
- Much higher radiation tolerance ~$10^{17} n_{eq} cm^{-2}$!!!

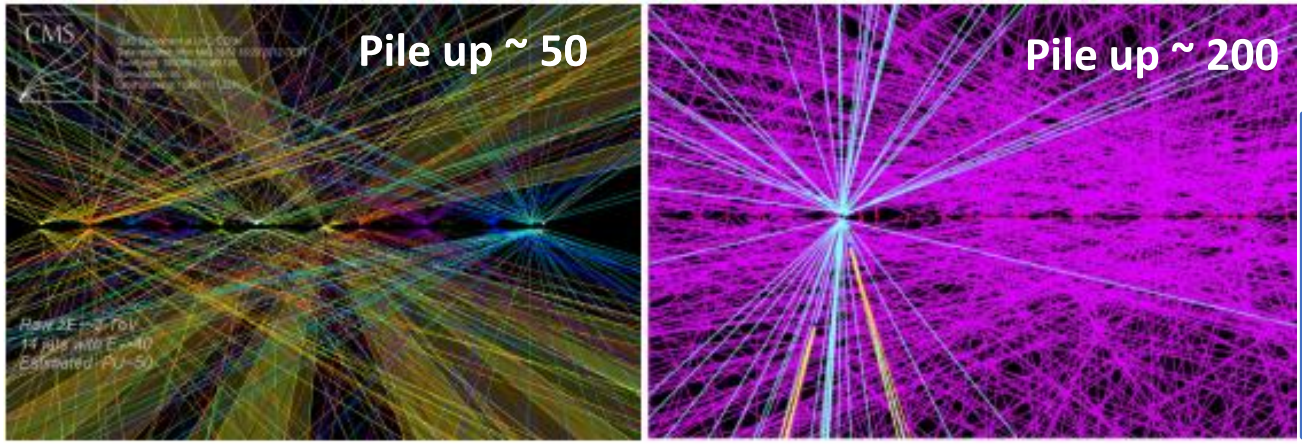
The Need for New Timing Detectors

- Pile-up is one of the major challenges for tracking at the HL-LHC
- Timing information will be used to disentangle the overlapping events
- Radiation tolerance up to ~ $2.5 \text{ x } 10^{15} n_{eq} cm^{-2}$ for ATLAS – HGTD

  and ~ $1.5 \text{ x } 10^{15} n_{eq} cm^{-2}$ for CMS – ETL is required
- Time resolutions < 50ps per-hit for a MIP

ATLAS-HGTD and CMS-ETL will be using LGADs as timing detectors





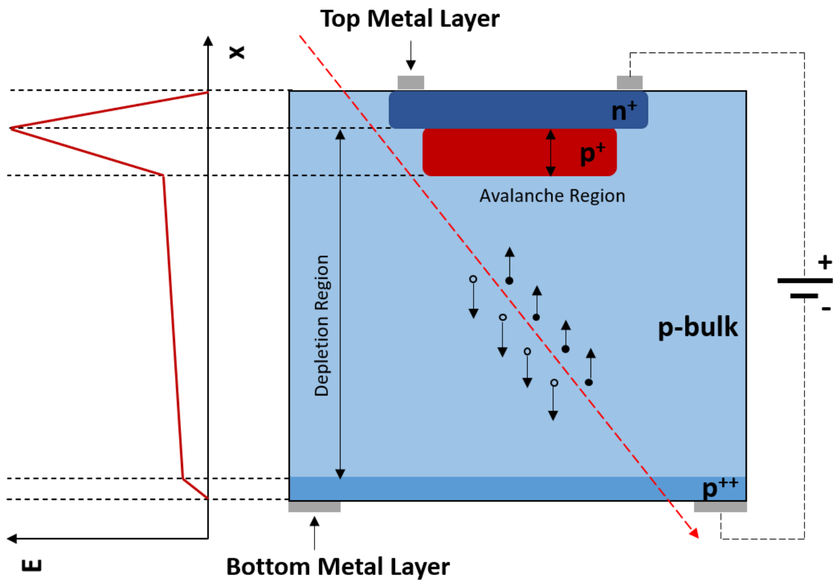
Sofia Otero, PoS (2019) [1]

FCC-hh

- Pile up mitigation ~ 1000
- Time resolution ~ 10 ps per-hit for a MIP
- Much higher radiation tolerance $\sim 10^{17} n_{eq} cm^{-2}$!!!

Low Gain Avalanche Diodes (LGADs)

- **L**ow **G**ain **A**valanche **D**iode, a detector with:
  - Internal charge multiplication
  - Improved signal-to-noise ratio (SNR)
  - Improved timing capabilities (< 30ps) achievable with thin – LGADs (50µm)
  - Low to moderate gain (a few 10s) provided by p^+ multiplication layer



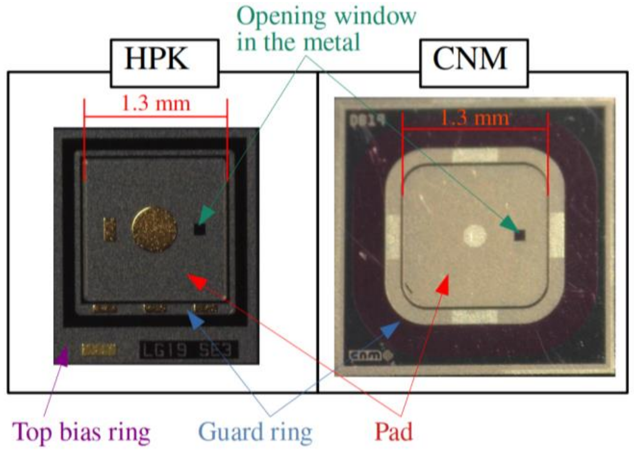
- Gain depends on:
  - Doping profile and concentration of the dopant in gain layer (GL)
  - Bias voltage
  - Temperature

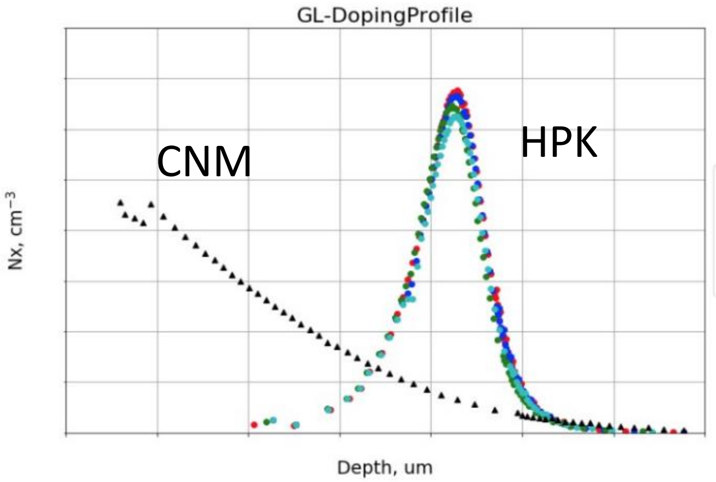
- Producers:

  CNM (Barcelona, ES), FBK (Trento,IT), **HPK (Japan),** IHEP-NDL and IME (China), Micron(UK), BNL(USA), CIS(Erfurt, Germany) ...

Devices Under Test

- HPK – Prototype2:
  - 1.3 x 1.3 mm^2 pad-like LGADs with 48µm thick epitaxial layer.
  - Gaussian profile doping -> deep.
  - 150µm low resistivity support wafer
- CNM – 12916:
  - 1.3 x 1.3 mm^2 pad-like LGADs with 42µm thick FZ wafer.
  - Narrow and highly doped implant, but also shallow.
  - 300µm low resistivity Czochralski support wafer
- Neutron irradiation took place in TRIGA-II Reactor, JSI Ljubljana and the fluences are 4e14, 8e14, and 1.5e15 n_{eq}/cm^2.
- 24 GeV/c Proton irradiation was carried out at IRRAD Facility, CERN and the fluences are 4.3e14, 1.18e15, and 1.55e15 n_{eq}/cm^2 (Hardness factor = 0.62)





Parameters of the LGADs used in this work

Sample	V_{dep} [V]	V_{gl} [V]	V_{bd} (20°C) [V]	C_{end} [pF]	d [µm]
HPK-P2	61.7	54.5	145	3.6	48
CNM12916	42.8	39.4	80-100	4.2	42

All devices were annealed after irradiation at 60˚C for 80 minutes

Reverse Current Damage Coefficient (α)

- Volume considered:
  - **HPK2**: (1.3x1.3) mm^2 x 48µm
  - **CNM12916**: (1.3x1.3) mm^2 x 42µm
- Pad current measured after full depletion at 50V.

For Neutrons:

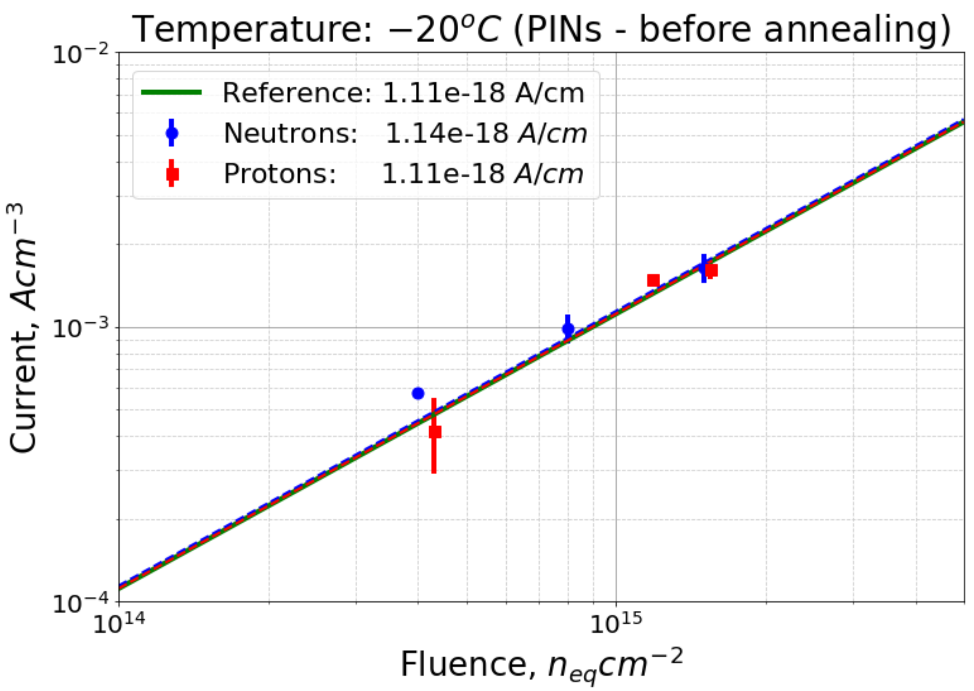
$\alpha = 1.14 \times 10^{-18}$ A/cm^{-3}

For Protons:

$\alpha = 1.11 \times 10^{-18}$ A/cm^{-3}

Reference:

$\alpha = 1.11 \times 10^{-18}$ A/cm^{-3} [2]



Electrical Characterizations

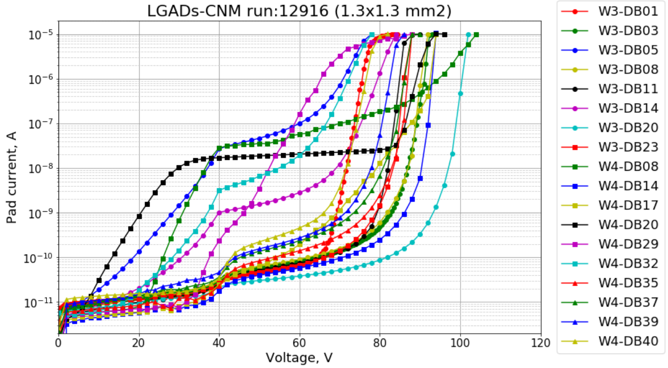
Motivation
LGADs
DUT
Electrical Charac.
Laser Charac.
GL Degradation
Summary

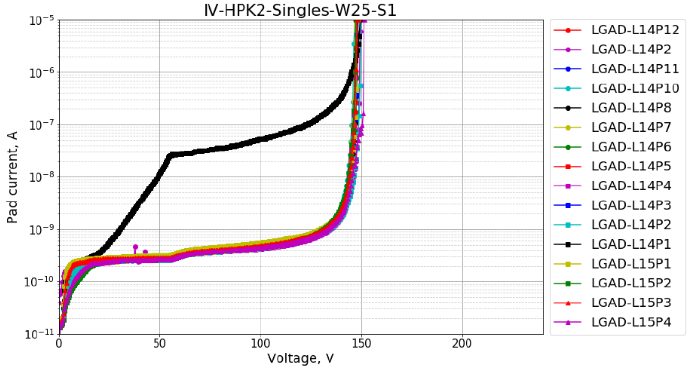
- Preliminary results of the sensors before irradiations

CNM – Run 12916

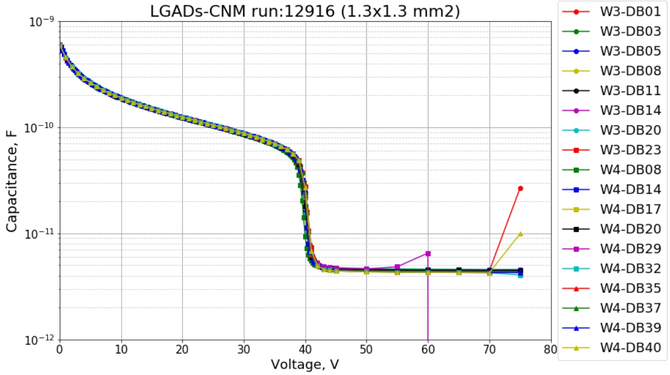
HPK – Prototype 2

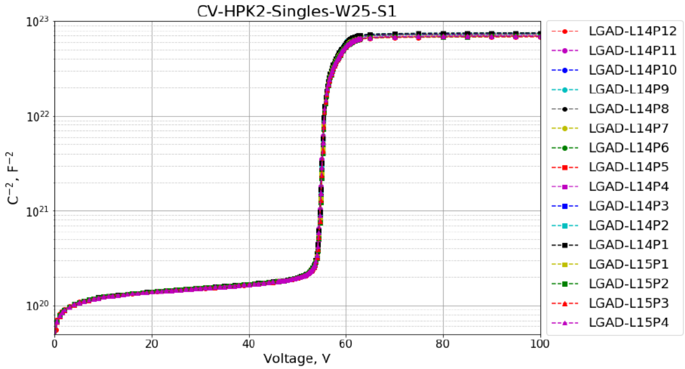
Leakage Current





Capacitance



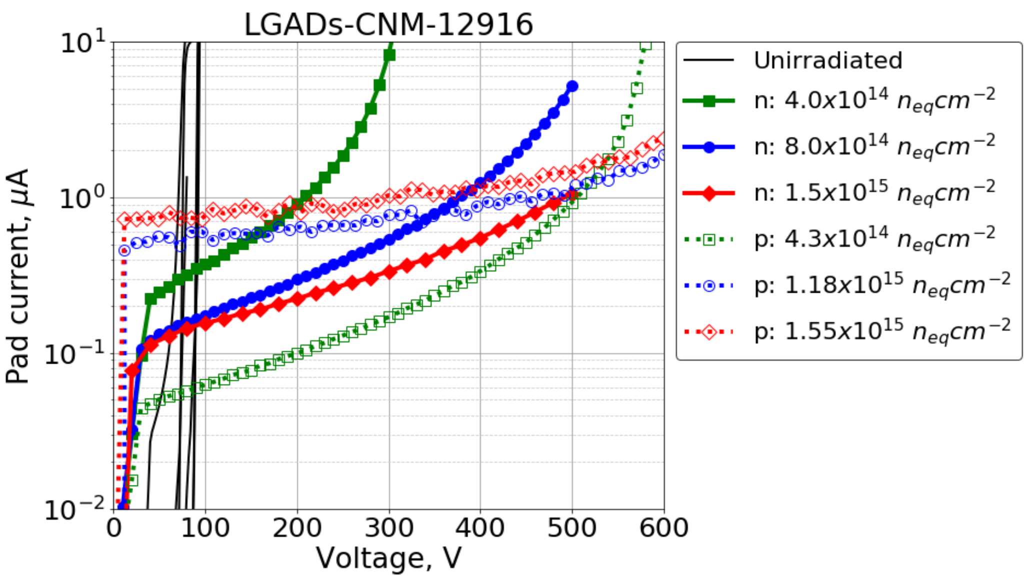


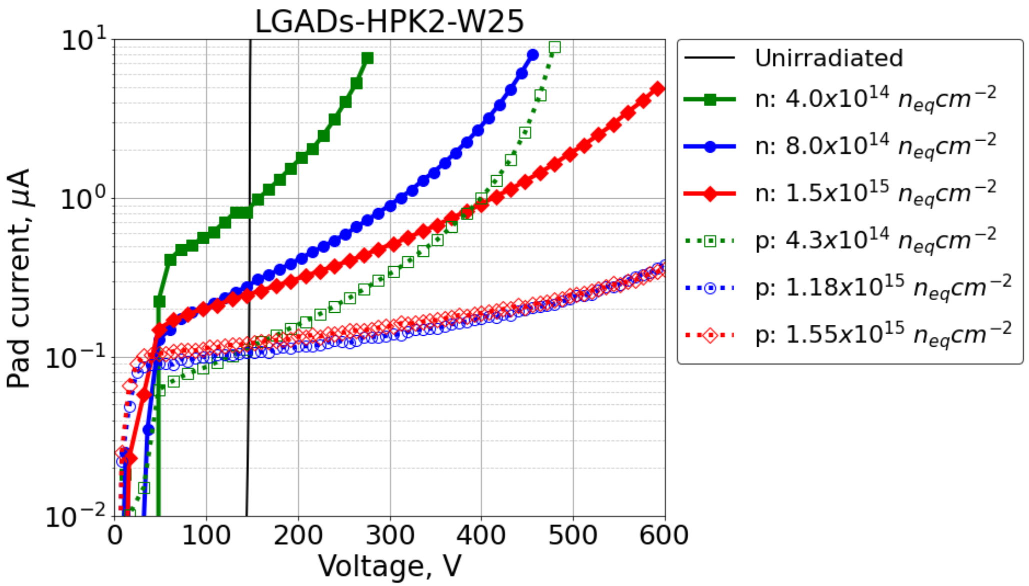
(E. Curras, EP-R&D 2021) [3]

A set of devices from these were selected for irradiation

Leakage Current

- Current – Voltage characteristics after irradiation, measured at T = - 20°C

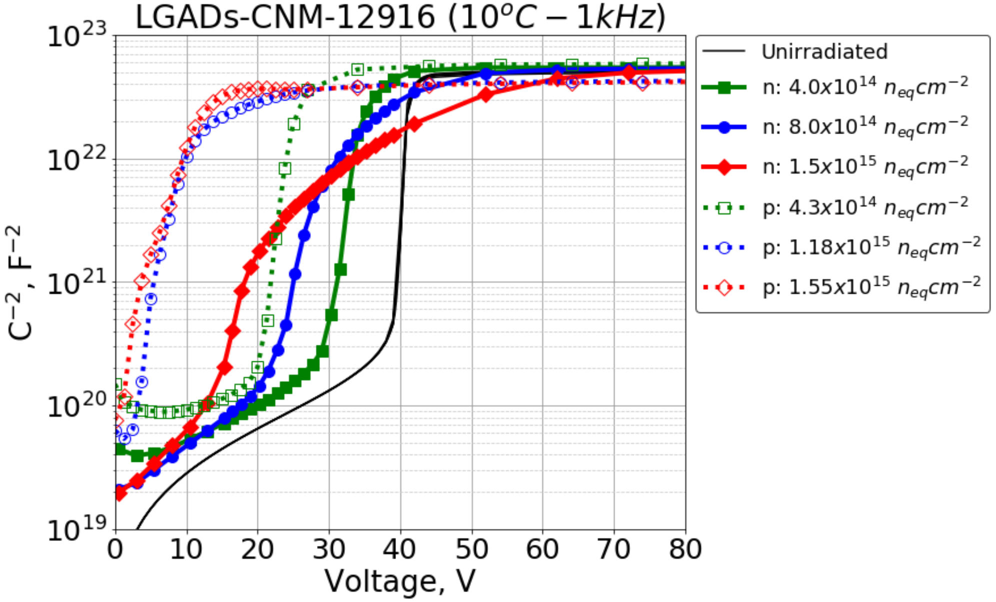


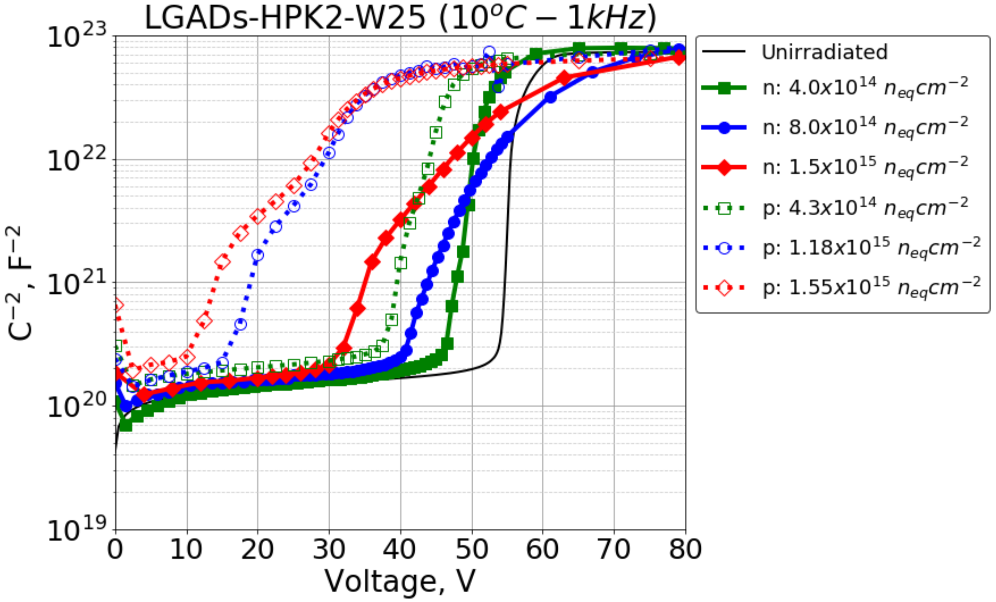


- Pad current increases with fluence.
- Breakdown voltage increases with fluence, the samples can be operated at higher voltages.
- This is already an indication that the gain decreases with fluence.
- Depletion voltage of the gain layer decreases, easy to see in the CV curves (next slide)
- The impact of protons is greater than neutrons: can be seen in both CNM and HPK sensors.

Capacitance

- Capacitance – Voltage characteristics after irradiation, measured at T = 10°C and freq = 1kHz.





- End capacitance does not change with fluence.
- Full depletion voltage increases with the increase in fluence.
- Depletion voltage of the gain layer decreases: indication of less active boron in gain layer.
- The impact of protons is greater than neutrons: can be seen in both CNM and HPK sensors.

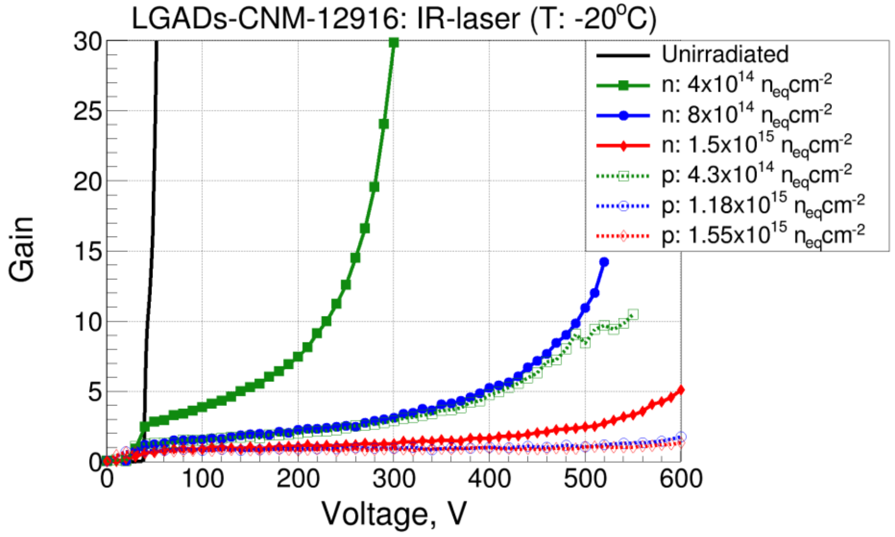
LASER Characterizations

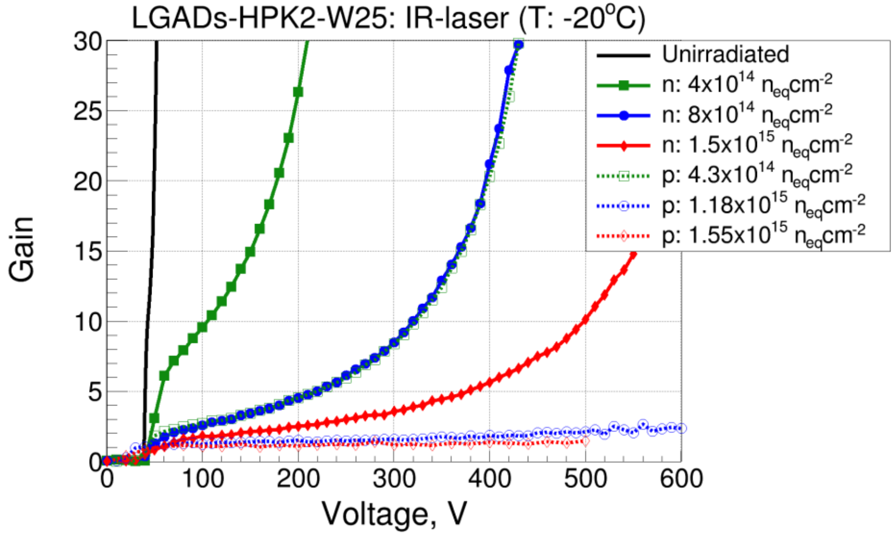
- Laser characterizations were carried out using Transient Current Technique (TCT) at SSD lab at CERN.
- Pulsed IR-Laser (1060nm) with 250ps pulse width.
- Laser intensity ~ 1 MIPs
- Calculation of gain was carried out using the following equation:

$$Gain\,[V] = \frac{CC_{LGAD}\,[V]}{CC_{PIN}\,[V \geq V_{FD}]}$$

Gain Measurements

- TCT measurements taken at temp = - 20˚C

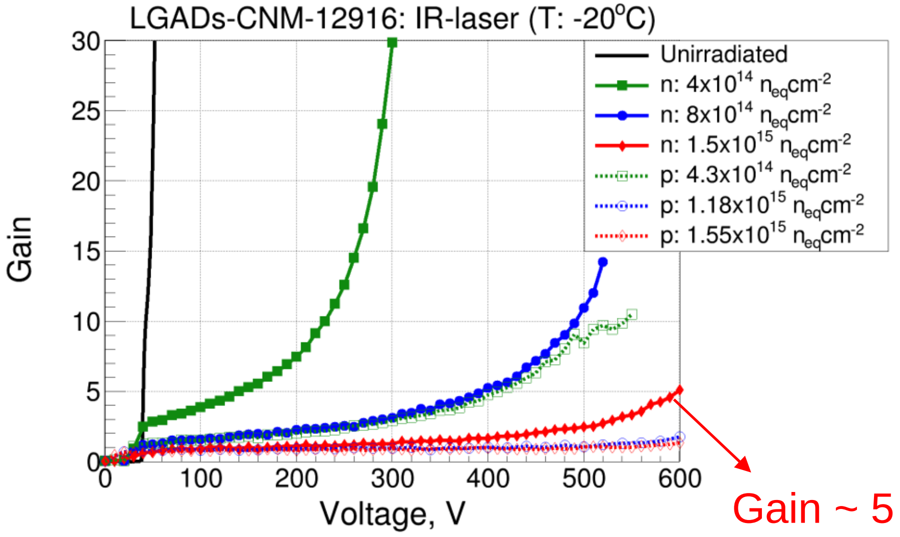


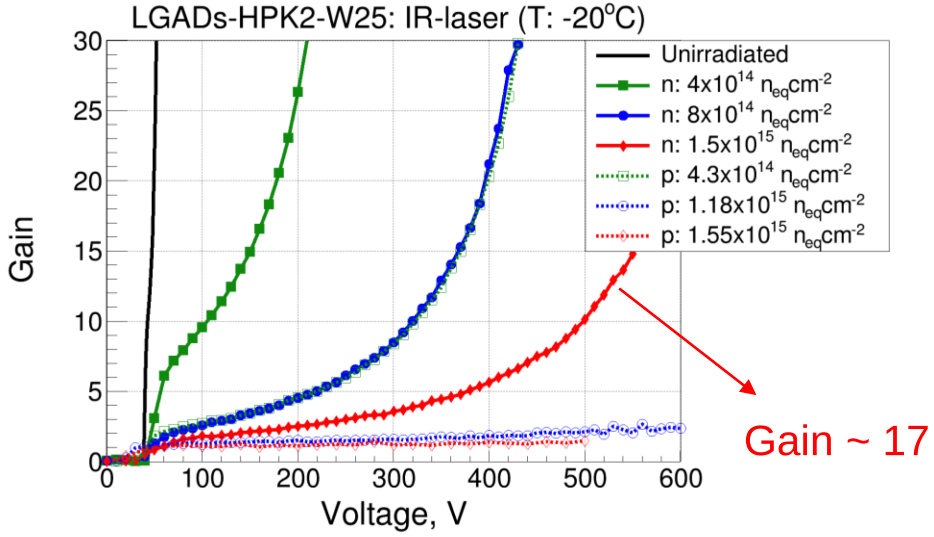


- PINs, unirradiated LGADs and irradiated LGADs were measured under same conditions.
- A reduction in gain is observed with the increase in fluence.

Gain Measurements

- TCT measurements taken at temp = - 20˚C

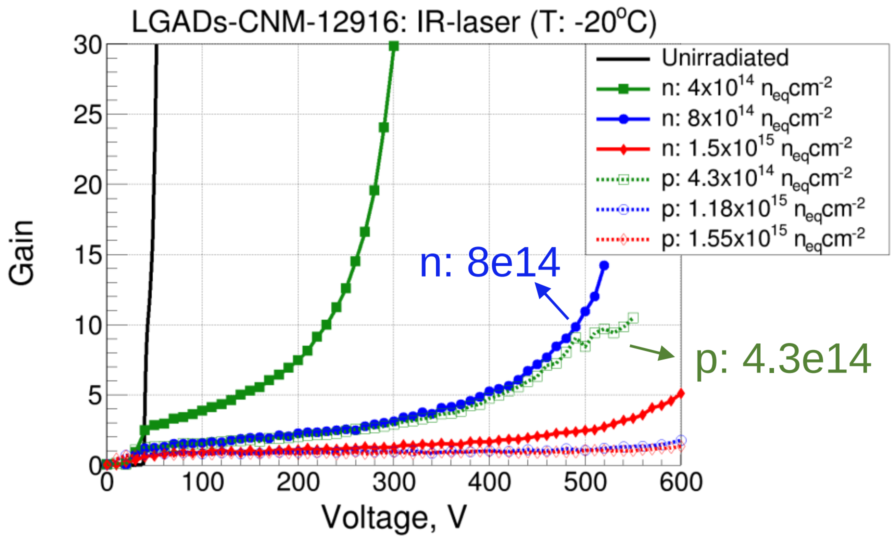


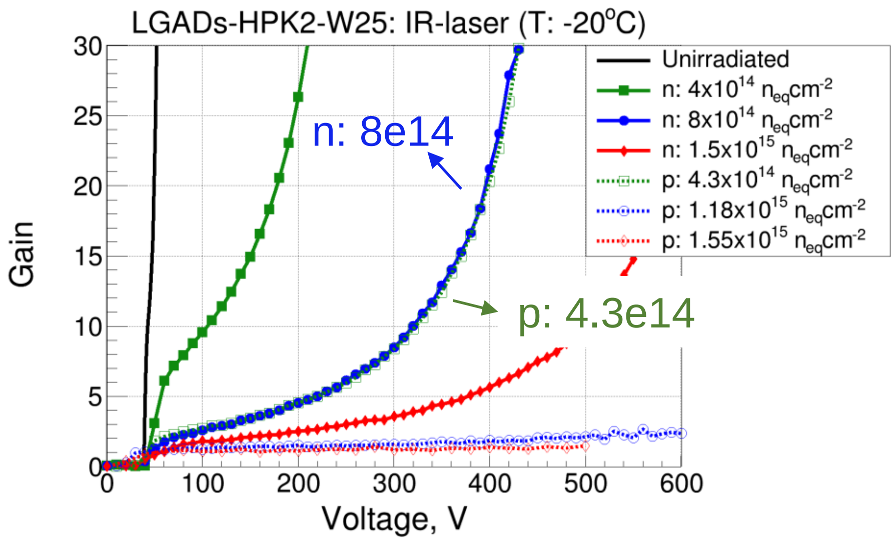


- PINs, unirradiated LGADs and irradiated LGADs were measured under same conditions.
- A reduction in gain is observed with the increase in fluence.
- LGADs from HPK-P2 show greater resistance to irradiation as compared to CNM-12916.

Gain Measurements

- TCT measurements taken at temp = - 20˚C

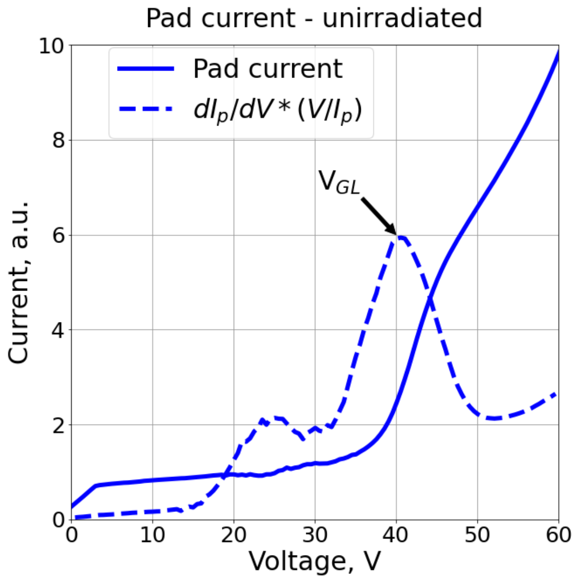




- PINs, unirradiated LGADs and irradiated LGADs were measured under same conditions.
- A reduction in gain is observed with the increase in fluence.
- LGADs from HPK-P2 show greater resistance to irradiation as compared to CNM-12916.
- Impact of 24 GeV/c protons (normalized to 1 MeV neutrons) is more than twice as that of neutrons for both HPK-P2 and CNM-12916.

Extraction of V_{GL}

- Three different methods to extract gain layer depletion voltage (V_{GL}) are used in this work

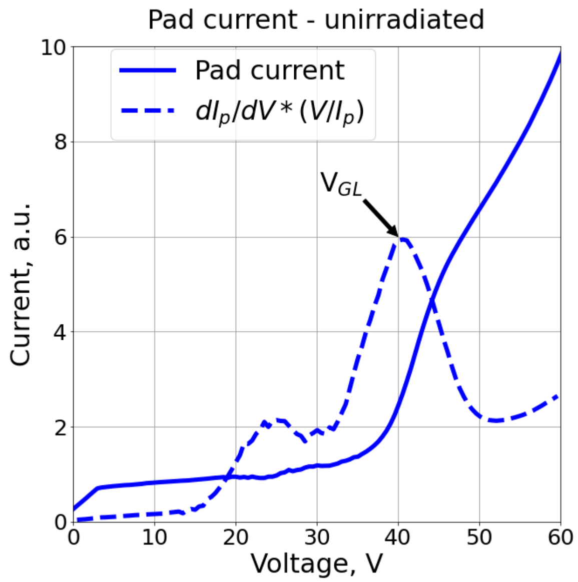


The IV method

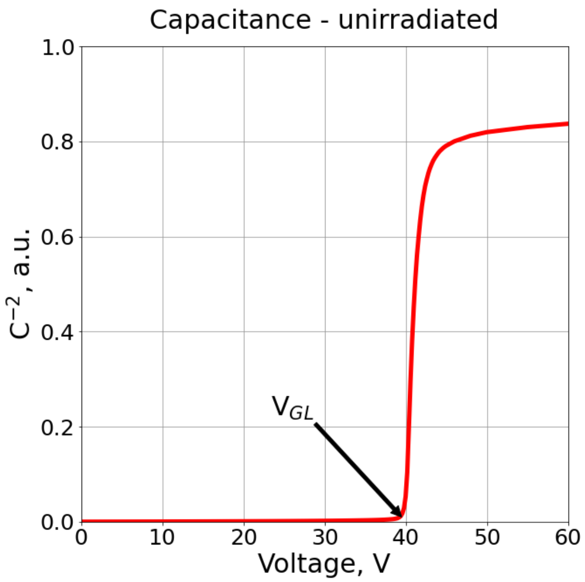
- The derivate of the pad current w.r.t voltage gives a peak around V_{GL}
- The maxima of peak can be obtained by Gaussian / Lorentzian fitting

Extraction of V_{GL}

- Three different methods to extract gain layer depletion voltage (V_{GL}) are used in this work



The IV method

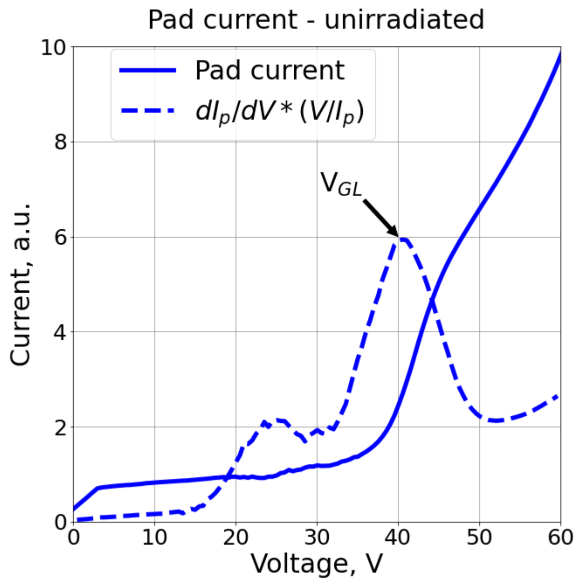


The CV method

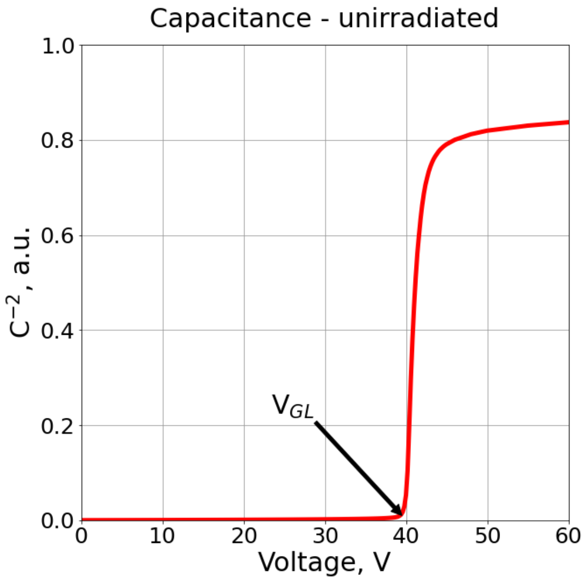
- Plotting $1/C^2$ versus voltage
- The bend represents V_{GL}

Extraction of V_{GL}

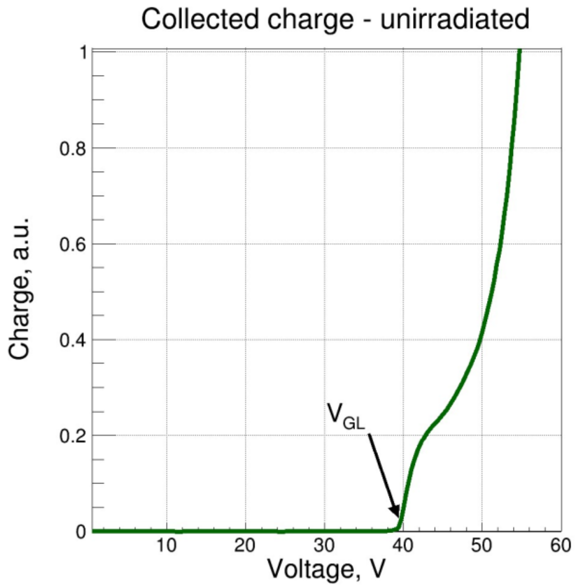
- Three different methods to extract gain layer depletion voltage (V_{GL}) are used in this work



The derivative method



The CV method

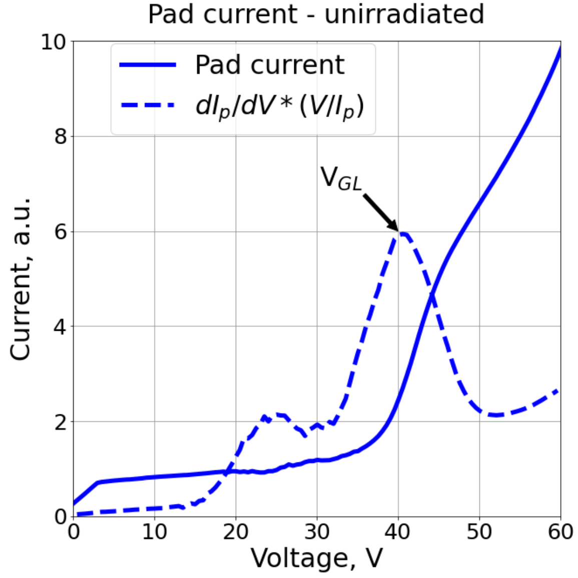


The TCT method

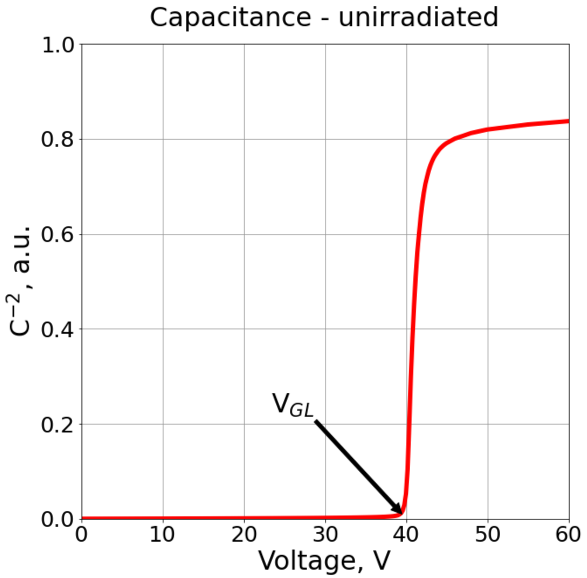
- Plotting charge collection versus voltage
- The bend represents V_{GL}

Extraction of V_{GL}

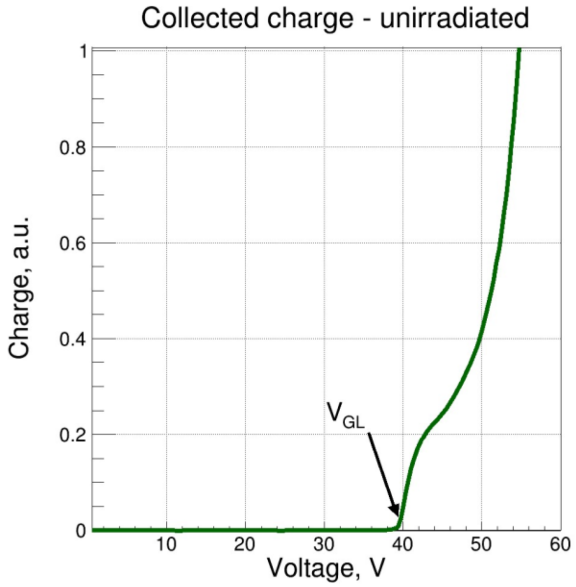
- Three different methods to extract gain layer depletion voltage (V_{GL}) are used in this work



The IV method



The CV method



The TCT method

- Before irradiation, these methods are in good agreement with each other.
- After irradiation, the V_{GL} extraction gets tricky.
- We averaged out the values of V_{GL} obtained from all these methods.

$$V_{GL} = \frac{V_{GL}\,(IV) + V_{GL}\,(CV) + V_{GL}\,(TCT)}{3}$$

Acceptor Removal Coefficient (*c*)

- GL fraction is calculated using the values of V_{GL} obtained by the methods explained in previous slide, where:

$$GL\ fraction = \frac{V_{GL}(\varphi)}{V_{GL}(0)}$$

- The gain layer depletion voltage at a given fluence is related to the acceptor removal coefficient ‘*c*’ by:

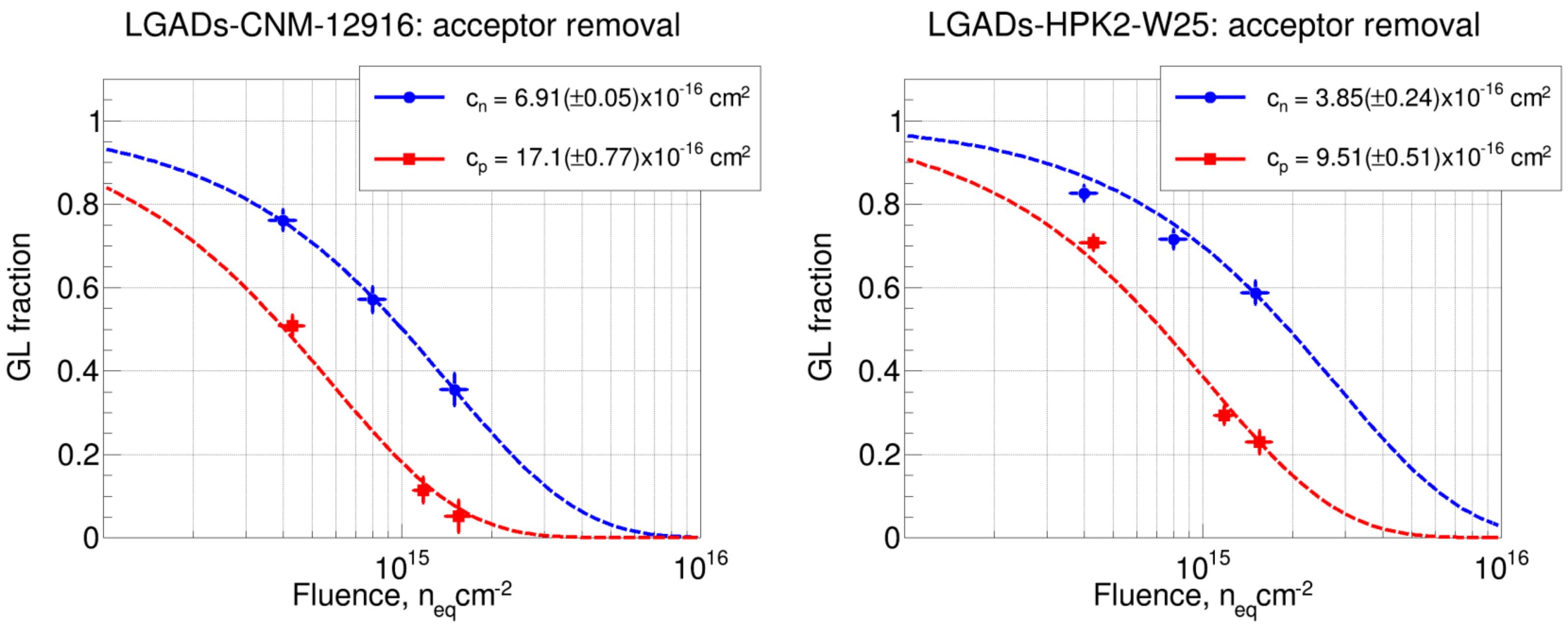
$$V_{GL}(\varphi) = V_{GL}(0)\, e^{-c\varphi}$$

- Acceptor removal coefficient can be obtained by fitting this equation on the V_{GL} curve versus fluence

Acceptor Removal Coefficient (*c*)

- GL fraction versus fluence

$$V_{GL}(\varphi) = V_{GL}(0)\, e^{-c\varphi}$$

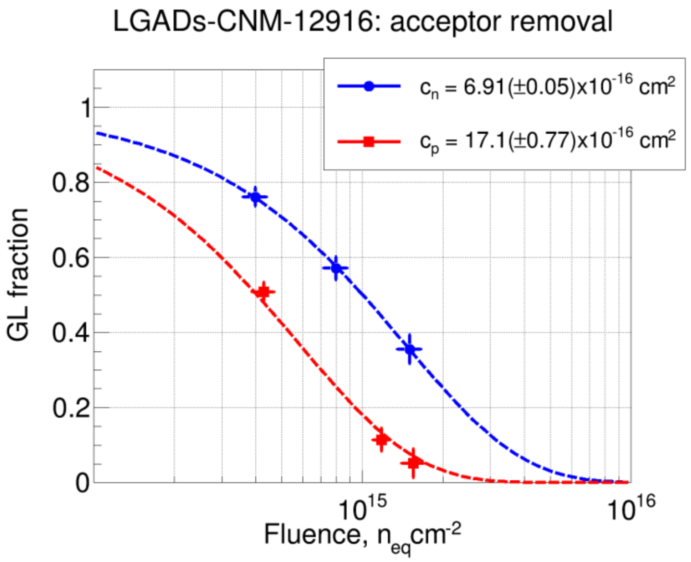


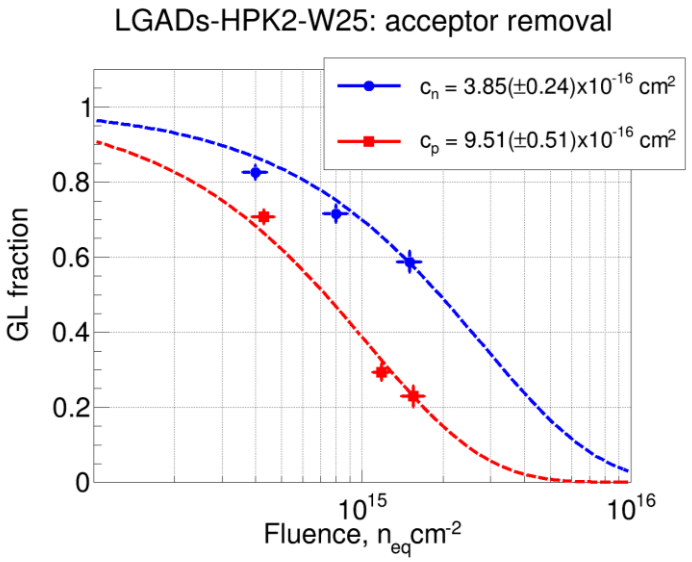
- LGADs from CNM-12916 shows higher values of ‘c’ as compared to HPK-P2, irrespective of irradiation type.
- This shows that degradation of gain layer also depends on shape, position, and concentration of the GL doping profile

Acceptor Removal Coefficient (c)

- 24 GeV/c protons introduce damages in gain layer almost 2.5 times higher than the neutrons, normalized to 1 MeV neutrons .
- ‘c’ value of LGADs from CNM-12916 is almost 1.8 times higher than the ones from HPK-P2 for both the proton and neutron irradiations.

c (10^{-16} cm^{-2})	c_n	c_p	c_p / c_n
CNM-12916	6.91 ± 0.05	17.1 ± 0.77	2.475
HPK-P2	3.85 ± 0.24	9.51 ± 0.51	2.470
c_{CNM}/c_{HPK}	1.795	1.798	-

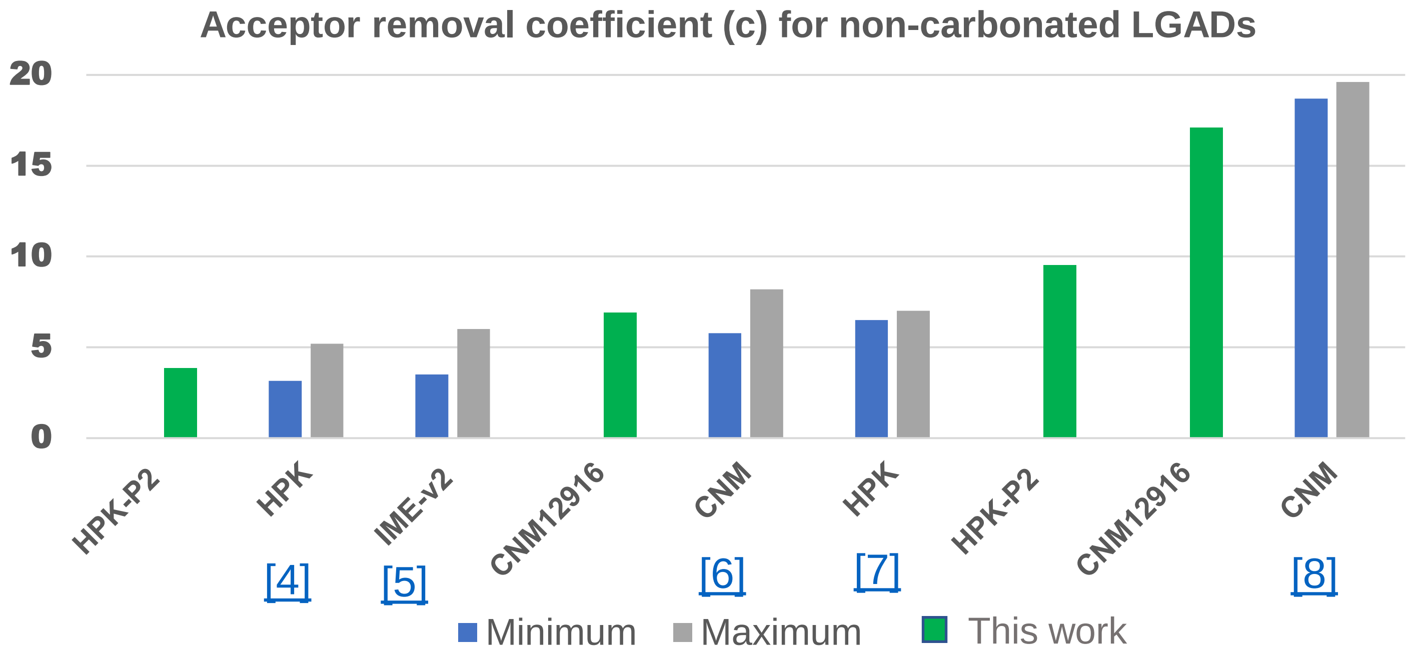




Acceptor Removal Coefficient (*c*)

- 24 GeV/c protons introduce damages in gain layer almost 2.5 times higher than the neutrons, normalized to 1 MeV neutrons .
- ‘c’ value of LGADs from CNM-12916 is almost 1.8 times higher than the ones from HPK-P2 for both the proton and neutron irradiations.

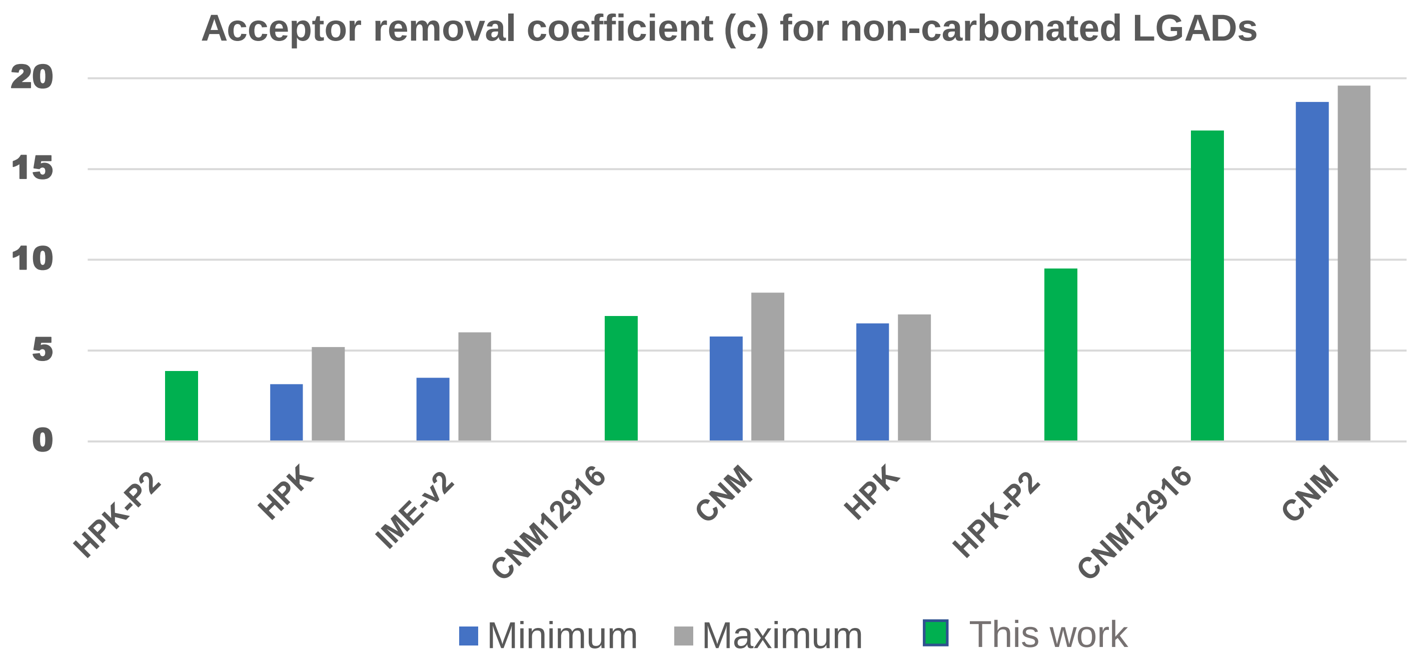
c (10^{-16} cm^{-2})	c_n	c_p	c_p / c_n
CNM-12916	6.91 ± 0.05	17.1 ± 0.77	2.475
HPK-P2	3.85 ± 0.24	9.51 ± 0.51	2.470
c_{CNM}/c_{HPK}	1.795	1.798	-



Acceptor Removal Coefficient (*c*)

- 24 GeV/c protons introduce damages in gain layer almost 2.5 times higher than the neutrons, normalized to 1 MeV neutrons .
- 'c' value of LGADs from CNM-12916 is almost 1.8 times higher than the ones from HPK-P2 for both the proton and neutron irradiations.

c (10^{-16} cm^{-2})	c_n	c_p	c_p /c_n
CNM-12916	6.91 ± 0.05	17.1 ± 0.77	2.475
HPK-P2	3.85 ± 0.24	9.51 ± 0.51	2.470
c_{CNM}/c_{HPK}	1.795	1.798	-

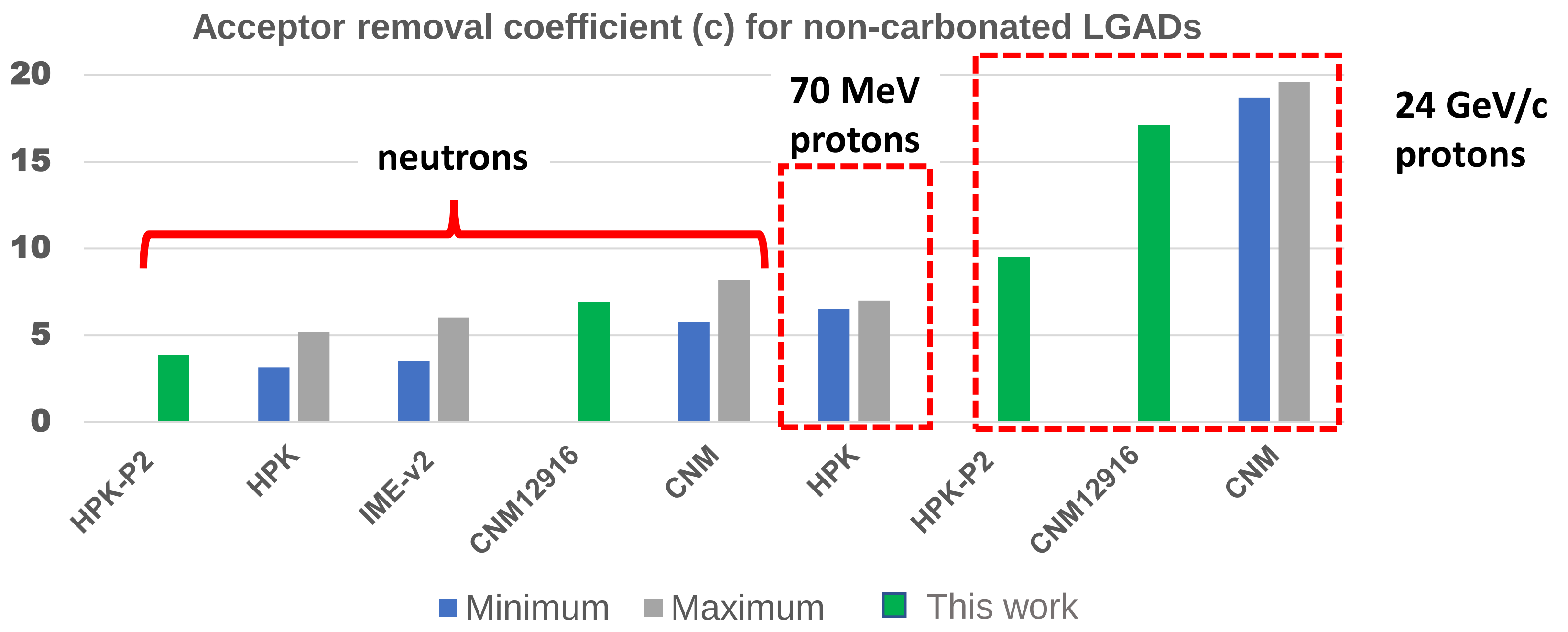


Disclaimer!
The sensors in literature are not from the same production batches

Acceptor Removal Coefficient (*c*)

- 24 GeV/c protons introduce damages in gain layer almost 2.5 times higher than the neutrons, normalized to 1 MeV neutrons .
- ‘c’ value of LGADs from CNM-12916 is almost 1.8 times higher than the ones from HPK-P2 for both the proton and neutron irradiations.

c (10^{-16} cm^{-2})	c_n	c_p	c_p /c_n
CNM-12916	6.91 ± 0.05	17.1 ± 0.77	2.475
HPK-P2	3.85 ± 0.24	9.51 ± 0.51	2.470
c_{CNM}/c_{HPK}	1.795	1.798	-



Summary & Future Work

- Neutron and proton irradiated LGADs with different fluences from HPK-P2 and CNM-12916 were studied.
- The ratio of damage coefficient of protons to neutrons shows that 24 GeV/c protons damage the gain layer almost 2.5 times higher than the neutrons, when normalized to 1 MeV neutrons.
- CNM-12916 LGADs produced with a shallow gain layer doping profile presented more degradation than the HPK-P2 LGADs produced with a deep and Gaussian gain layer doping profile.
- The acceptor removal constants (for protons and neutrons) gave a value for the CNM-12916 LGADs ~ 1.8 times higher than in the HPK-P2 ones.
- Time resolution measurements will be carried out in the next step.
- In future, the impact of long-term annealing will be studied.
- The paper is submitted to JINST, here is the link: arXiv:2306.11760

References

1. Ugobono, Sofia Otero. "SISSA: LGAD and 3D as Timing Detectors." *PoS* (2019): 035.
2. M. Moll. Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties. PhD thesis (1999).
3. E. Curras. Low Gain Avalanche Detectors for timing applications in high energy physics. EP – R&D 2021
4. Jin, H. Ren, S. Christie, Z. Galloway, C. Gee, C. Labitan et al., Experimental Study of Acceptor Removal in UFSD, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 983 (2020) 164611.
5. Feng, X. Huang, C. Yu, X. Jia, S. Li, M. Li et al., Study of the Acceptor Removal Effect of LGAD, IEEE Transactions on Nuclear Science 69 (2022) 2324.
6. Currás et al., Timing performance and gain degradation after irradiation with protons and neutrons of low gain avalanche diodes based on a shallow and broad multiplication layer in a float-zone 35 μm and 50 μm thick silicon substrate, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment (2023).
7. Howard et al., LGAD measurements from different producers, in 37th RD50 Workshop, Zagreb, 2020.
8. E. Gkougkousis, Acceptor removal - Radiation Hardness and breakdown, in 36th RD50 Workshop, Geneva, 2020.

Thank you for your attention!