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THE UNIVERSITY OF NEW MEXICO

# Investigation of low gain avalanche detectors exposed to proton fluences beyond $\mathbf{1 \times 10^{15}\ n_{eq}/cm^2}$

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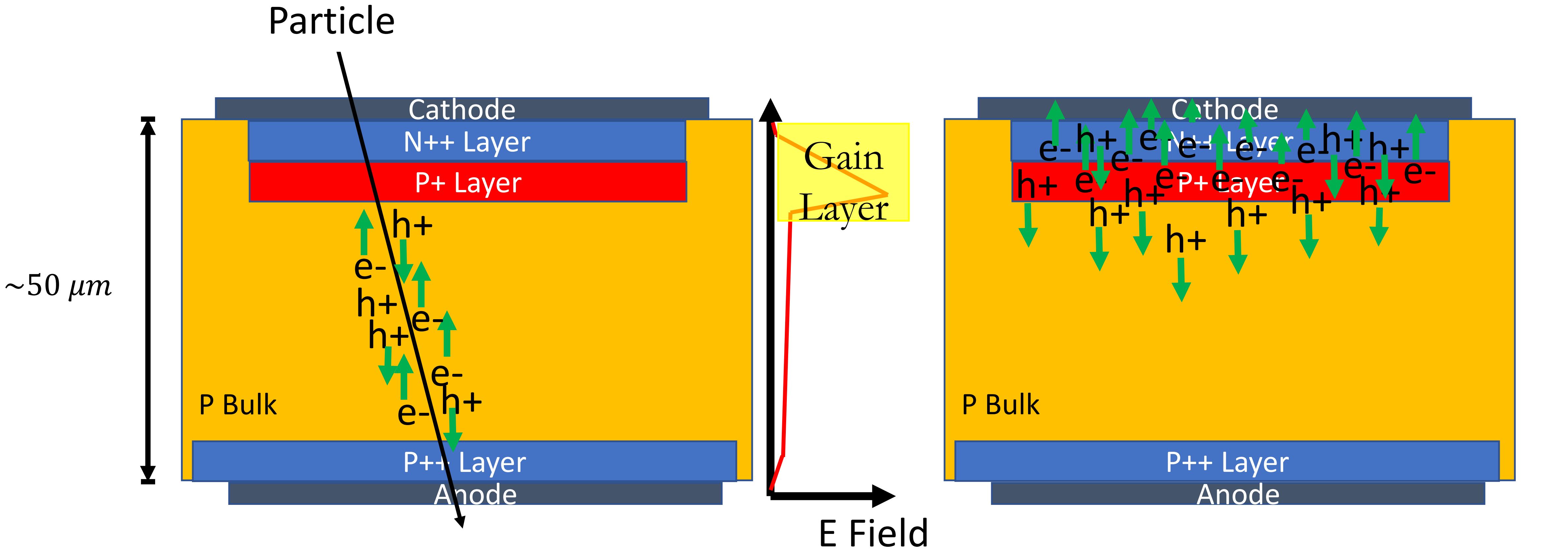
**arXiv:2311.02027 (submitted to JINST)**

# Motivation

- The High Luminosity (HL) upgrade will increase the luminosity of the Large Hadron Collider (LHC) by a factor of ~10. Increased luminosity causes (1) increased fluence which degrades sensor performance and (2) increased readout complexity because of the pileup.
- Low Gain Avalanche Detectors (LGAD) will be primarily used for fast timing measurement in HL-LHC for the High-Granularity Timing Detector (HGTD) in ATLAS or the Endcap Timing Layer (ETL) of CMS. They are required to operate at a fluence up to $2.5 \times 10^{15}$ $n_{eq}/cm^2$ (including a safety factor of 1.5).
- It is required that the HGTD be able to measure the times of arrival of minimum-ionizing particles (MIPs) with an average time resolution of approximately 35 ps per track at the beginning of the operation of the HL-LHC, 70 ps at the end of the operation of the HL-LHC.
- Carbon was co-implanted with boron in the gain layer of some LGAD prototypes. The carbon co-implantation has shown improved radiation hardness to neutrons[1] but has not yet been studied with charged hadrons.
- Our goal is to study the effect of proton damage to different LGAD prototypes by Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK). HPK LGADs are not co-implanted by carbon, while FBK ones are.

[1].M. Ferrero et al. Radiation resistant LGAD design, Nucl. Inst. and Meth. A 919 (2019)

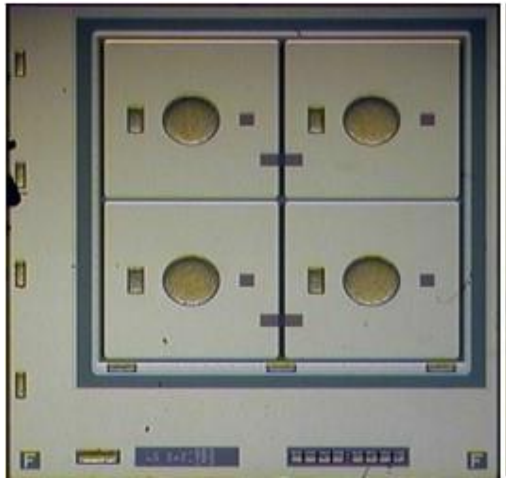
# How do LGADs work?



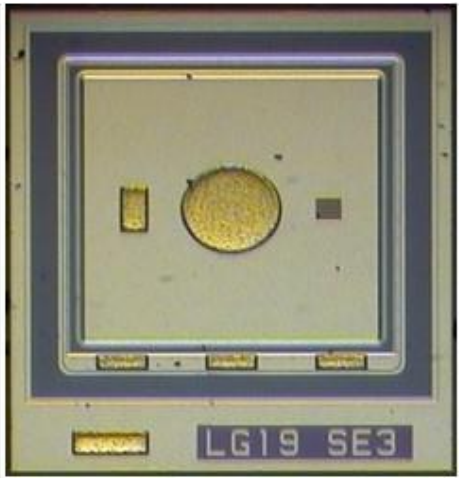

In silicon sensors, charge multiplication happens when charge carriers drift in a region with an electric field (E) greater than about 300 kV/cm. The additional P+ (or gain) layer, when depleted, locally generates an electric field high enough to activate the avalanche process.

# Our study includes LGADs manufactured by Hamamatsu Photonics (HPK).

Quad



Single




n ++ (electrode) – 1.3 x 1.3 $mm^2$
p + (gain layer) – 0.7 µm thickness 1.8 µm depth
p (bulk)
p ++ (backside)

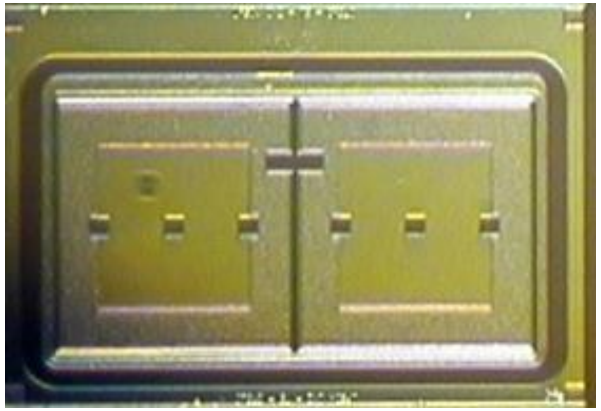
50 µm thick active layer
200 µm total thickness
single guard ring
epitaxial Si grown on Czochralski substrate

| HPK2 Wafer ID | Gain Layer Doping Profile | $V_{gl,0}$ [V] | $V_{fd,0}$ [V] |
|---|---|---|---|
| 25 | 1 | 53.0 | 55.0 |
| 31 | 2 | 52.0 | 54.0 |
| 36, 37 | 3 | 49.5 | 52.0 |
| 42, 43 | 4 | 49.0 | 51.0 |

# As well as LGADs manufactured by Fondazione Bruno Kessler (FBK).

Quad

Double



Single

n ++ (electrode) – 1.3 x 1.3 mm$^2$

p + (gain layer): 0.7-2µm thick

p (bulk)

p ++ (backside)

55 µm thick active layer

Multiple guard rings

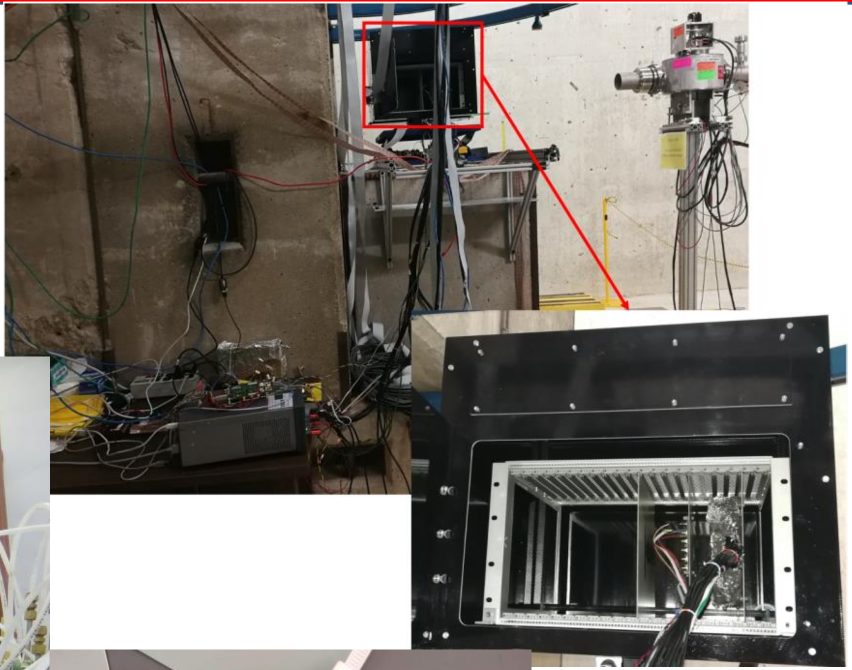
The depth of the gain implant varies in different samples (1-2 µm).

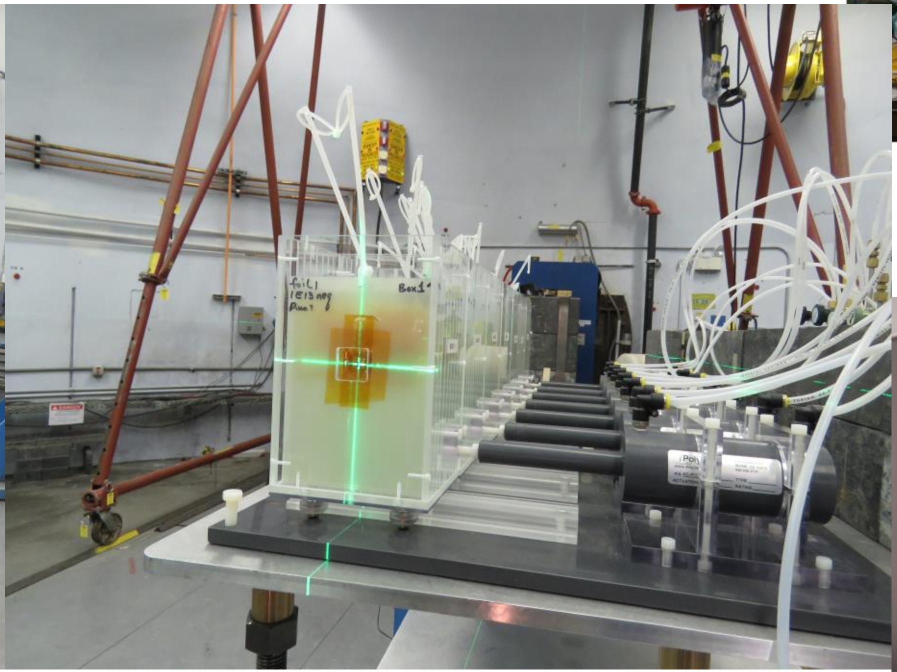
Carbon co-implantation in the gain layer is used to improve radiation resistance. The carbon dose varies in different samples.

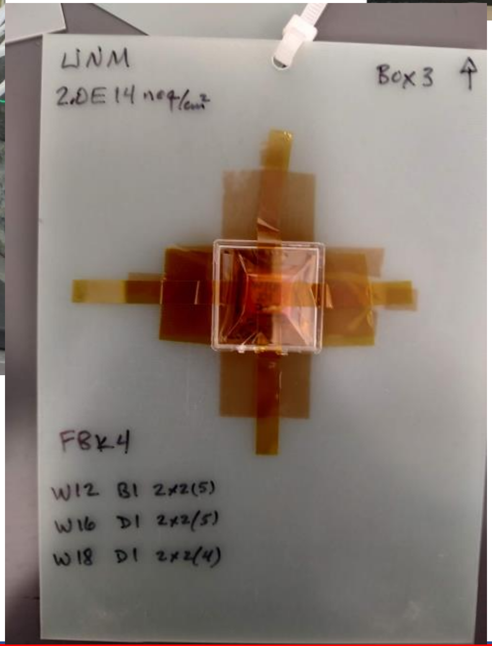
| FBK4 Wafer ID | Gain Layer Depth | Relative Boron Concentration | Relative Carbon Concentration | Diffusion | $V_{gl,0}$ [V] | $V_{fd,0}$ [V] |
|---|---|---|---|---|---|---|
| 1 | Shallow | 0.98 | 0.6 | CH-BL | 21.5 | 23.0 |
| 2 | Shallow | 1.02 | 1 | CH-BL | 22.0 | 23.5 |
| 5 | Shallow | 1.04 | 1 | CH-BL | 22.5 | 24.0 |
| 9 | Shallow | 1.06 | 1 | CH-BL | 22.5 | 24.5 |
| 12 | Deep | 0.77 | 0.6 | CH-BH | 50.5 | 51.5 |
| 16 | Deep | 0.81 | 0.6 | CL-BL | 48.0 | 49.0 |
| 18 | Deep | 0.93 | 0.6 | CL-BL | 48.5 | 49.5 |

# LANSCE/FNAL Proton Irradiation

In 2022, HPK LGADs & PINs were irradiated by UNM at FNAL with 400 MeV protons in May, and FBK LGADs & PINs were at LANSCE with 500 MeV protons in July.





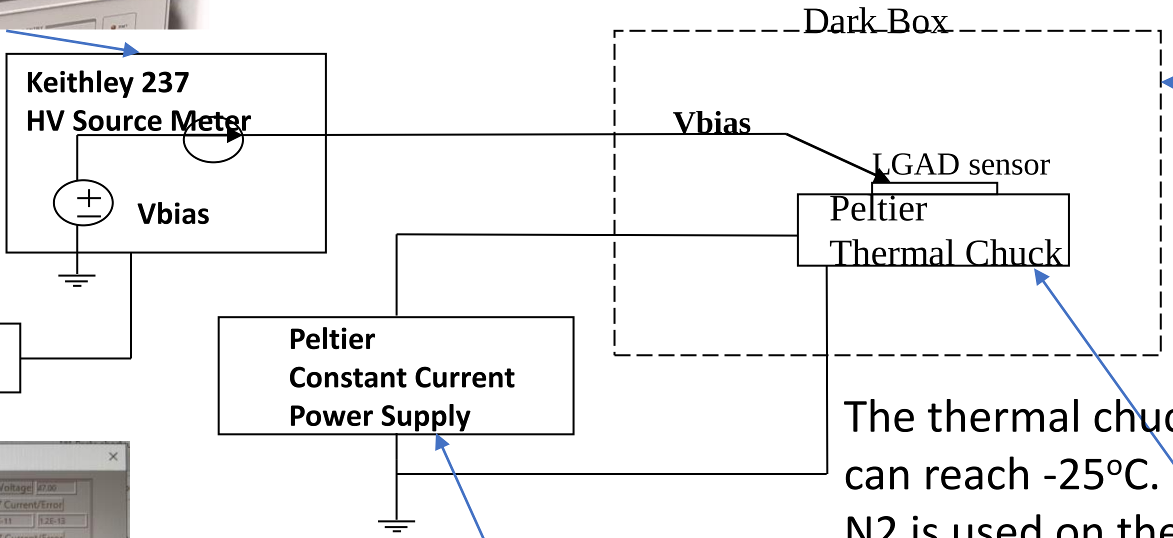


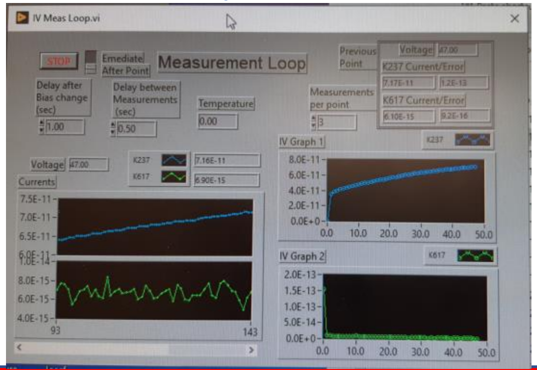

LGADs mounted on G-10 boards

Irradiated samples are stored in -25$^{o}$C freezer. Prior to the start of the measurement process, every device was subjected to a standard annealing regimen of 60 $^{o}$C for 80 minutes.

# Current vs. Voltage (IV) measurements are used to measure leakage currents, breakdown voltages, and determine the operational ranges.

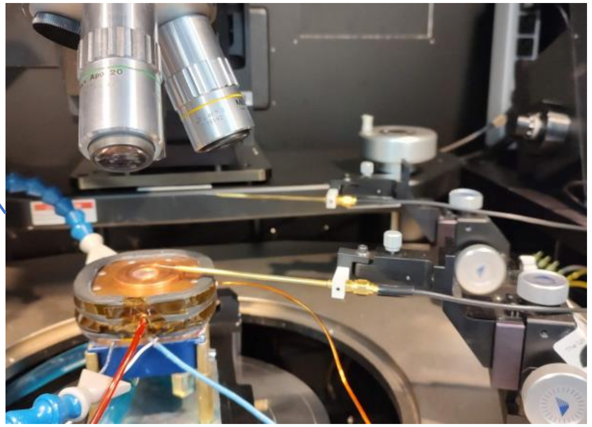

Keithley 237 source meter provides bias voltage and reads out the leakage current.



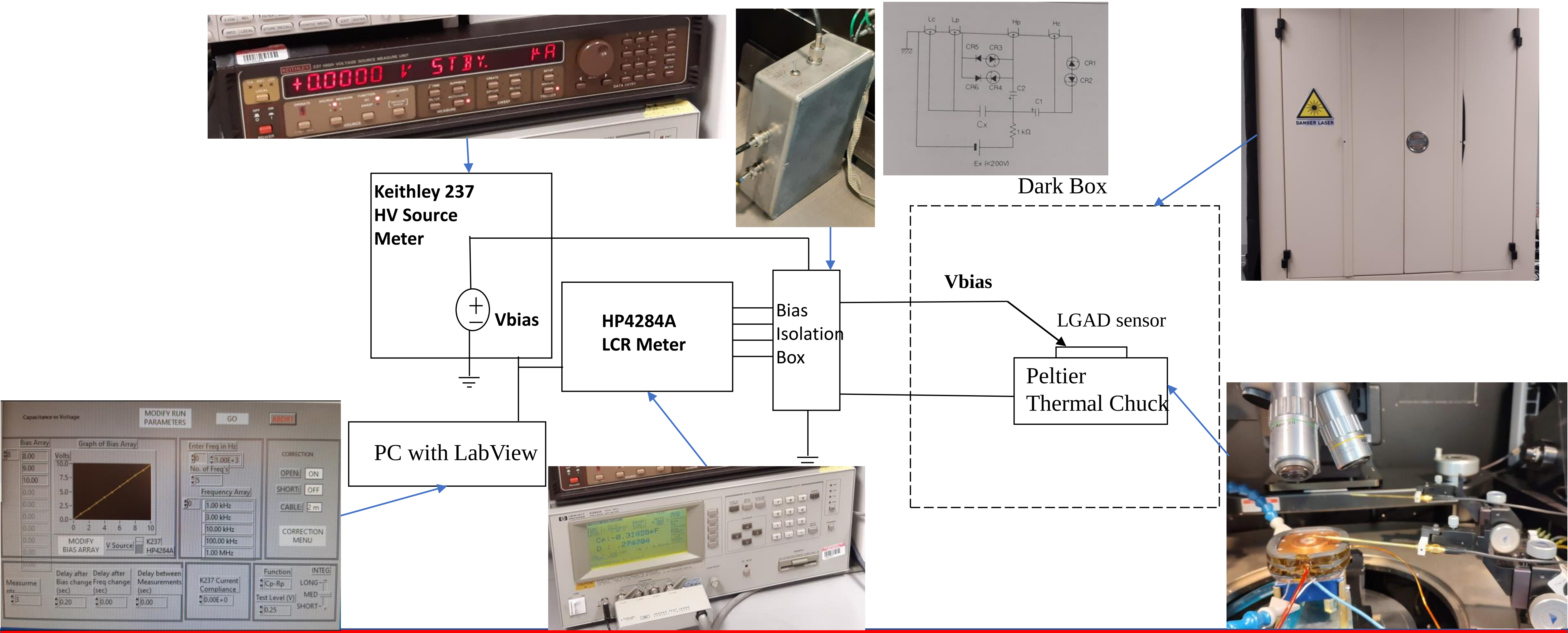





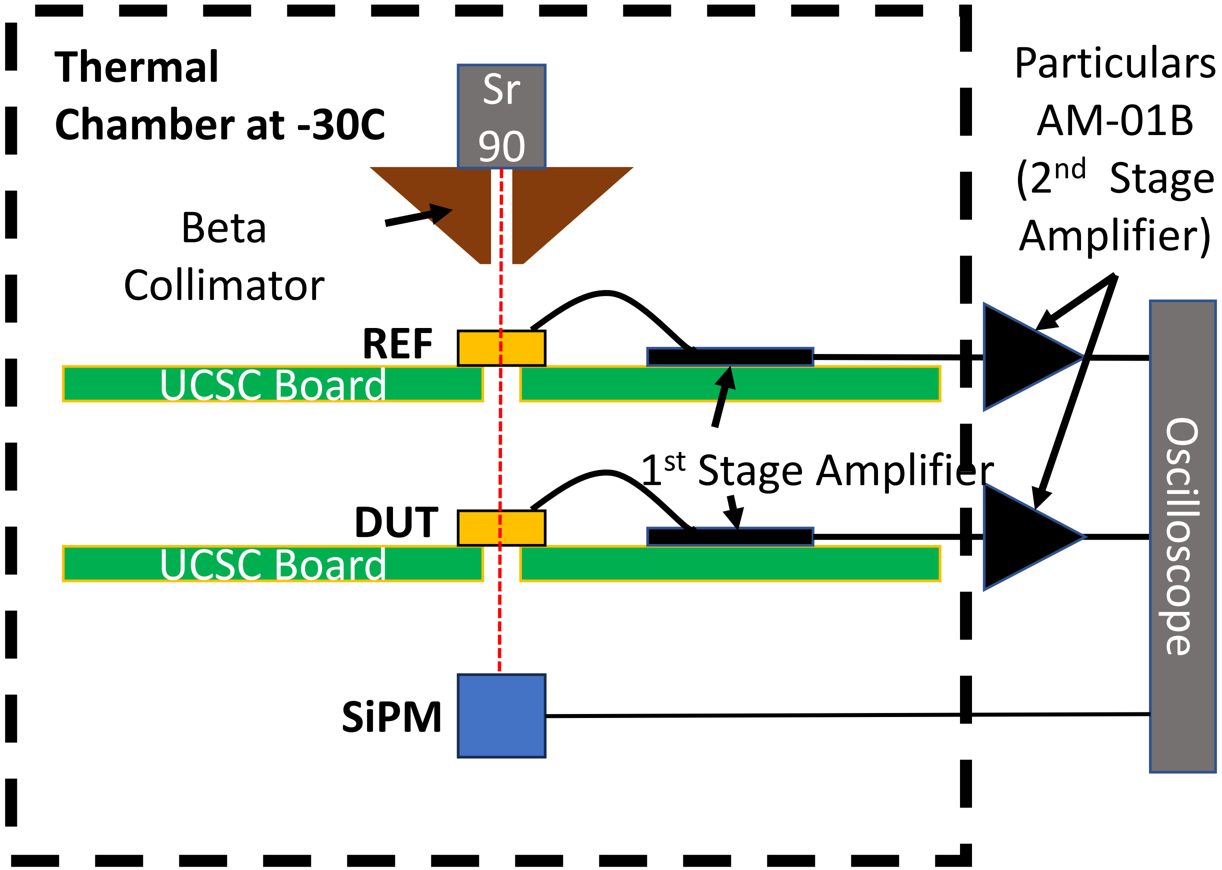
The thermal chuck can reach -25$^{o}$C. N2 is used on the sample to prevent condensation.

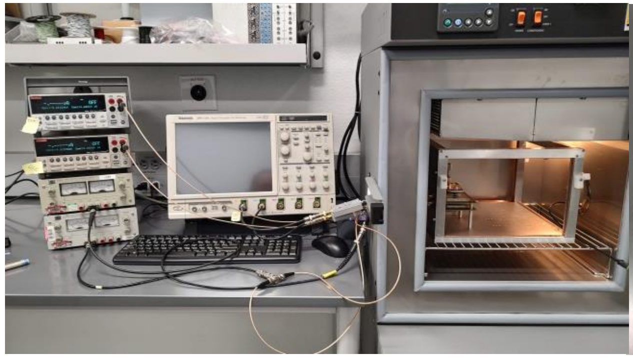


# Capacitance vs. Voltage (CV) Measurements are used to measure the depletion voltage



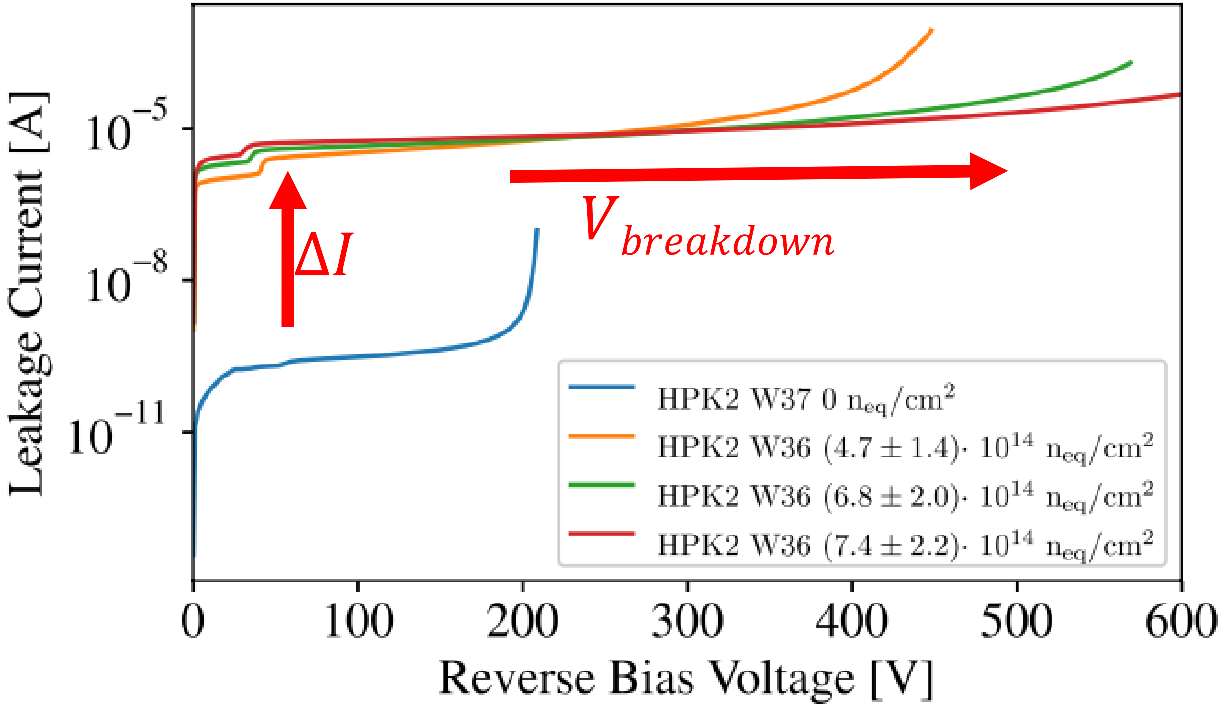
# β-source setup is used to study the timing performance and charge collection of LGADs

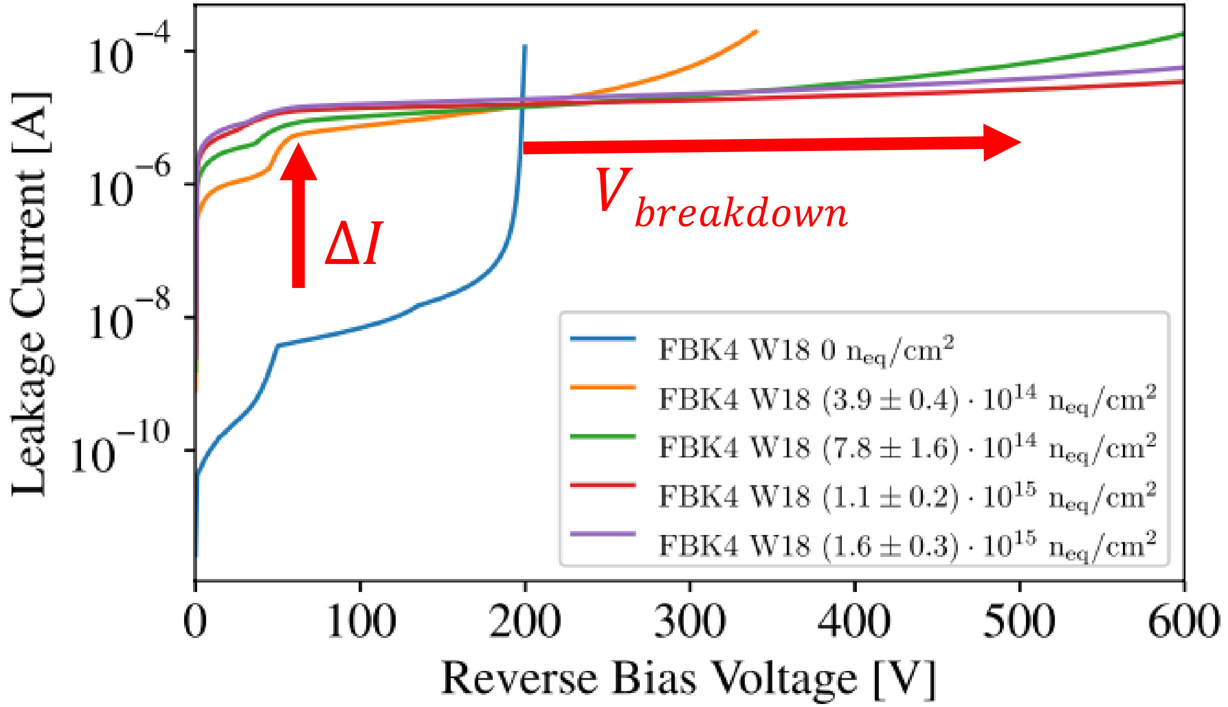


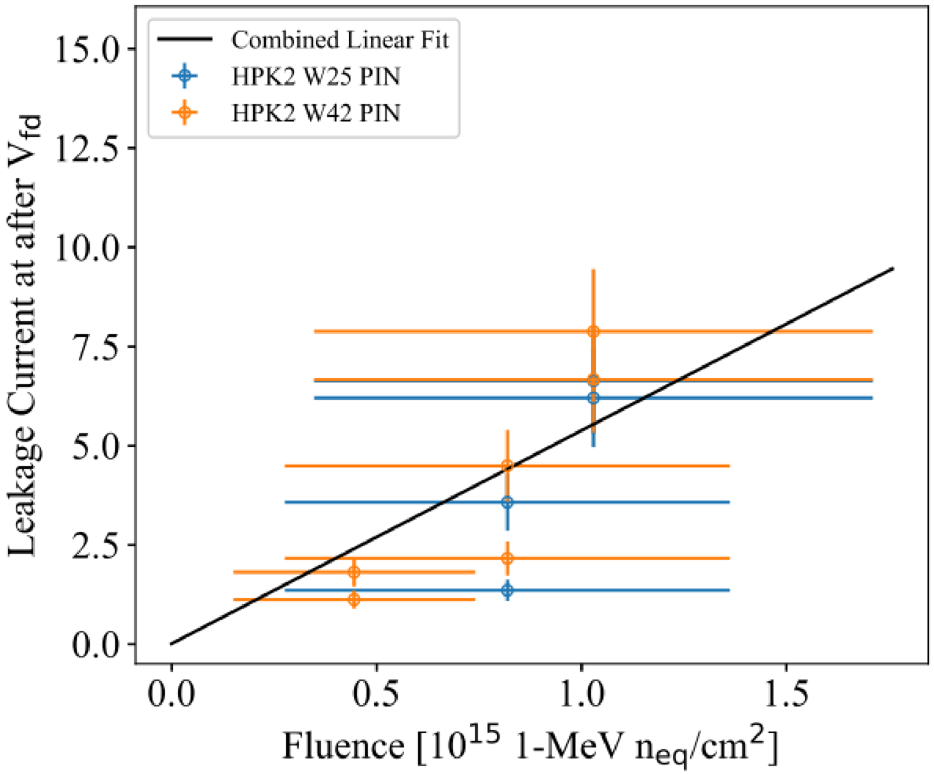
- LGADs are mounted on the single channel readout board developed by UCSC.
- Tektronix DPO 7254 Oscilloscope with 2.5GHz bandwidth, 40GS/s sampling rate is used.
- Shortest cables are used to connect to the oscilloscope for best signal-to-noise performance.

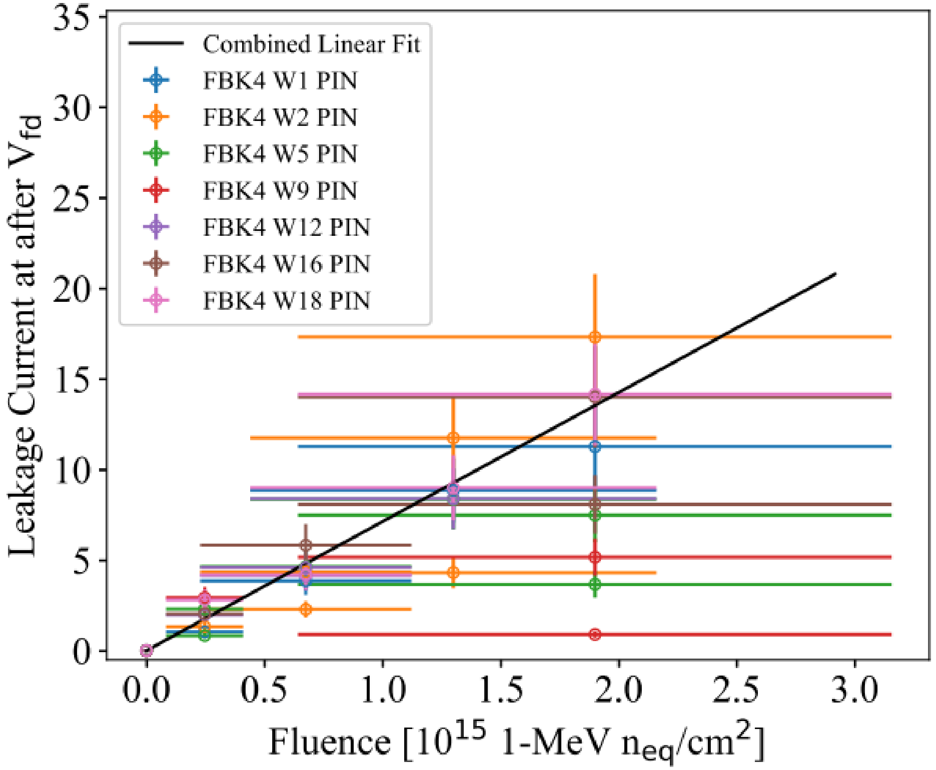
# Leakage current increases with fluences received, as well as breakdown voltage.



# Damage constant $\alpha$'s of HPK and FBK prototypes are calculated by fitting $\Delta I = \alpha \cdot \phi \cdot Volume$ with data



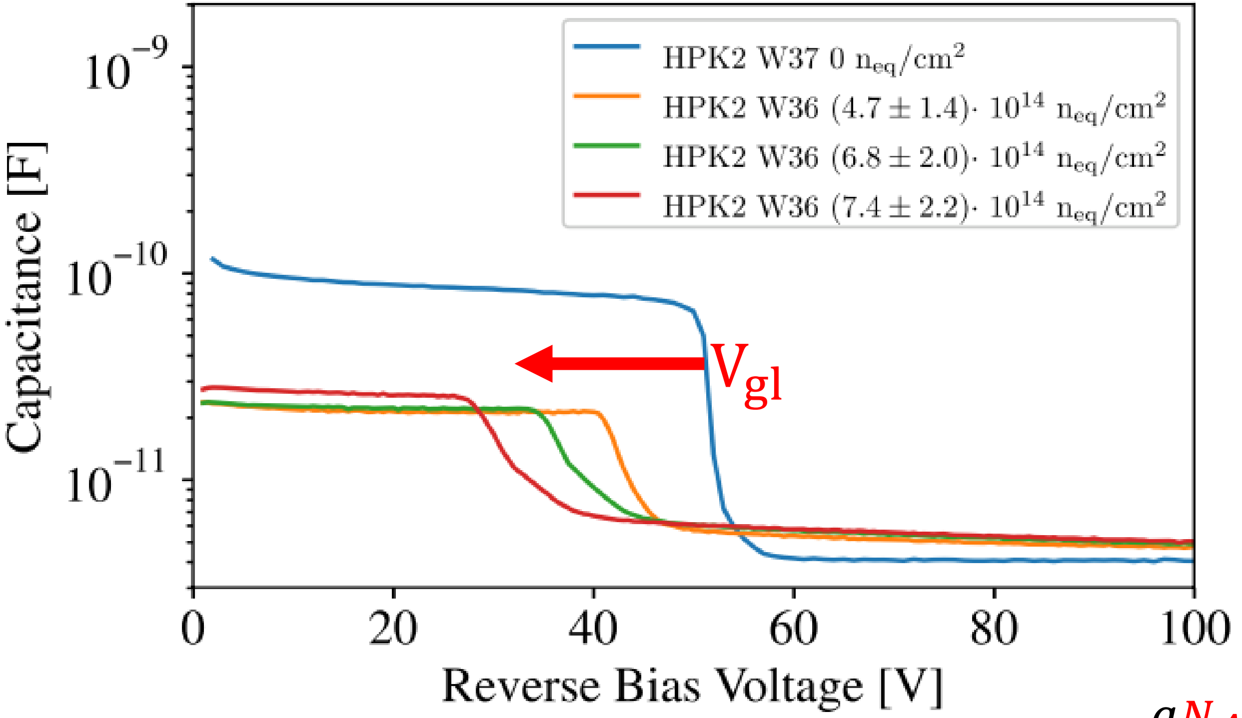



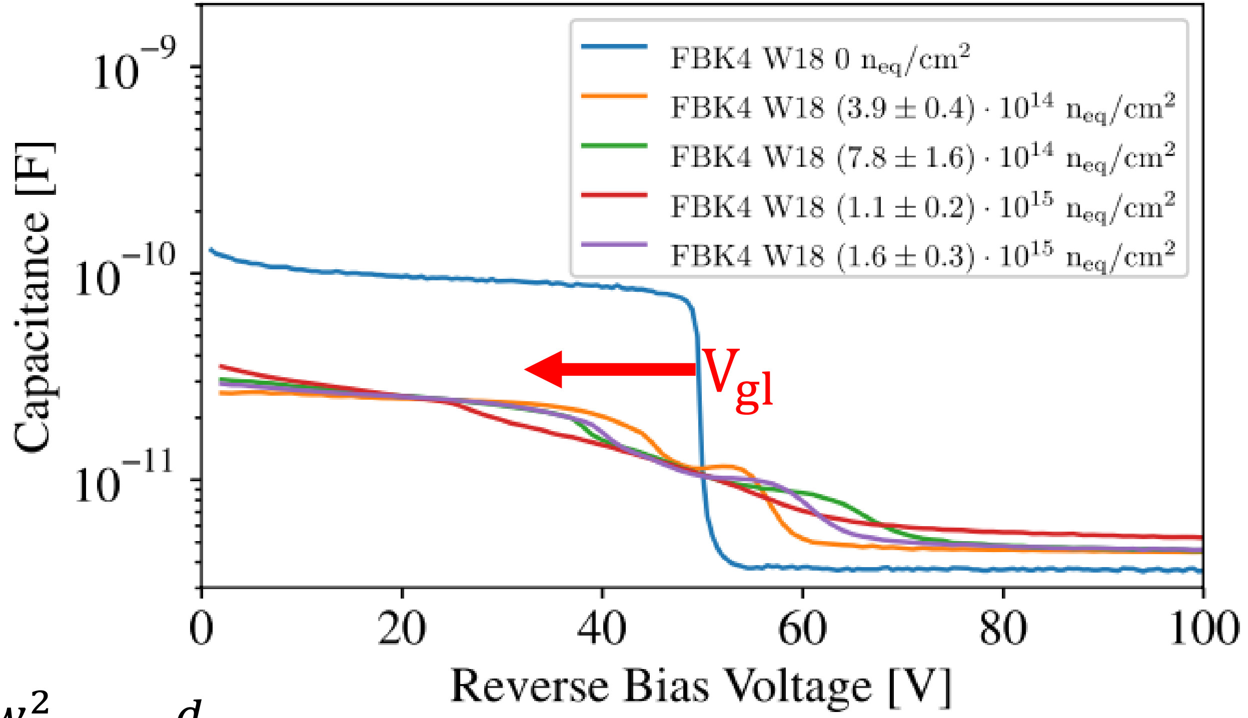

**Measured $\alpha$'s**

| HPK2 | FBK4 |
|---|---|
| $(5.3 \pm 0.7) \cdot 10^{-17}$ A/cm | $(6.9 \pm 0.4) \cdot 10^{-17}$ A/cm |

The damage constants are used to calculate the fluence received by individual LGADs.

# Gain layer depletion voltage ($V_{gl}$) is linearly proportional to acceptor concentration. Proton irradiation reduces the effective acceptor concentration, hence the $V_{gl}$.

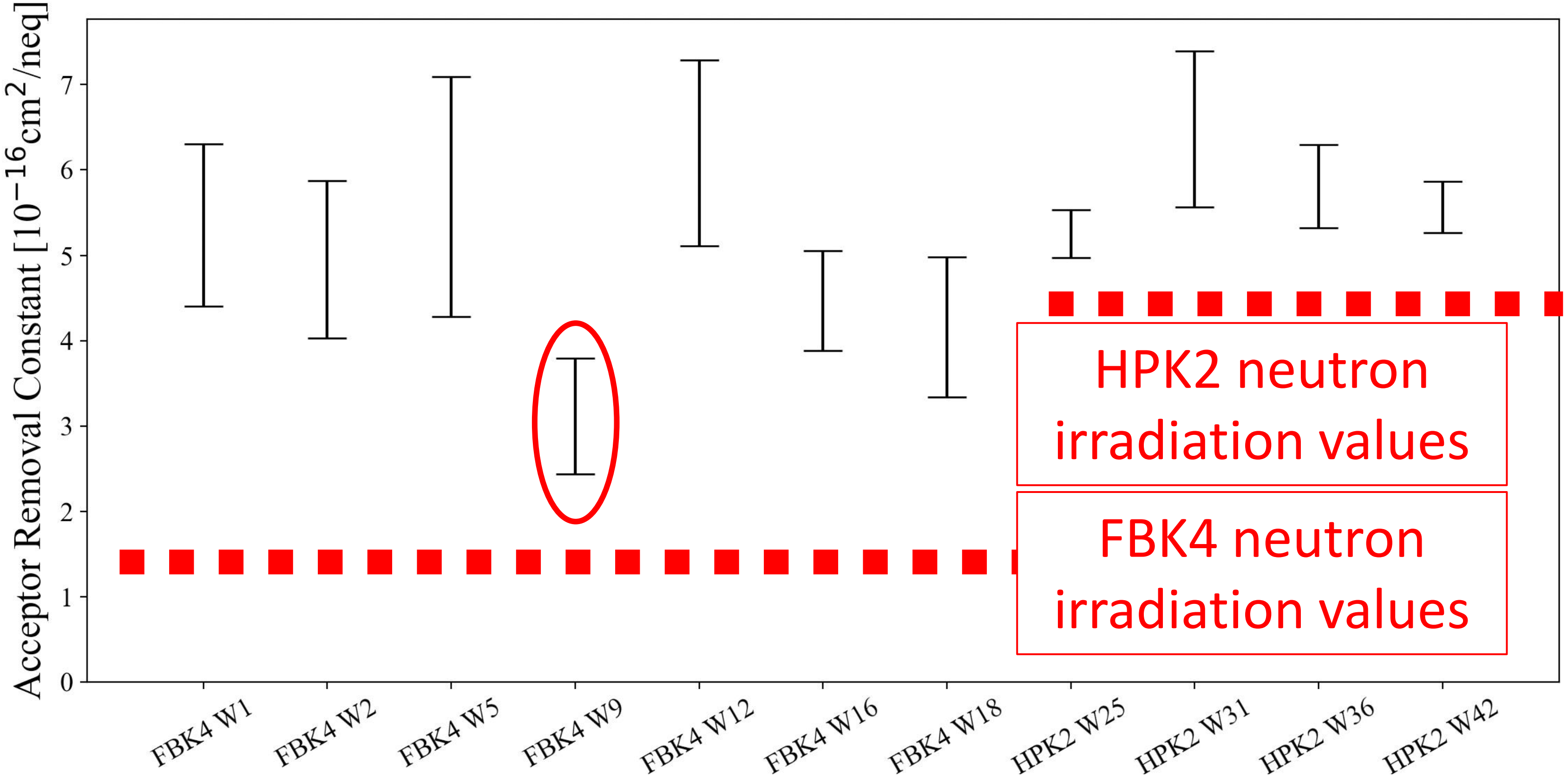



$$V_{gl} = \frac{qN_A w^2}{2\epsilon}(1+2\frac{d}{w}) \quad [2]$$


[2]. Ferrero, M., et al. (2021). An Introduction to Ultra-Fast Silicon Detectors (1st ed.). CRC Press.

# We observed that the acceptor removal constant is higher in proton irradiations than in comparable neutron irradiations.

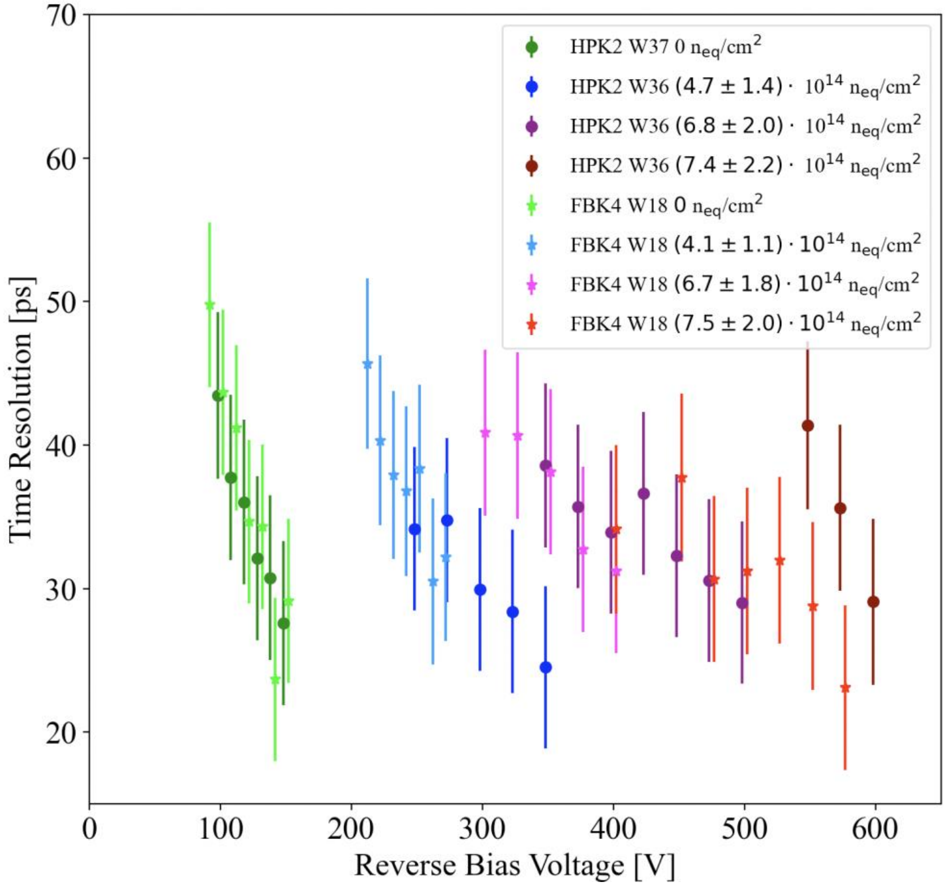


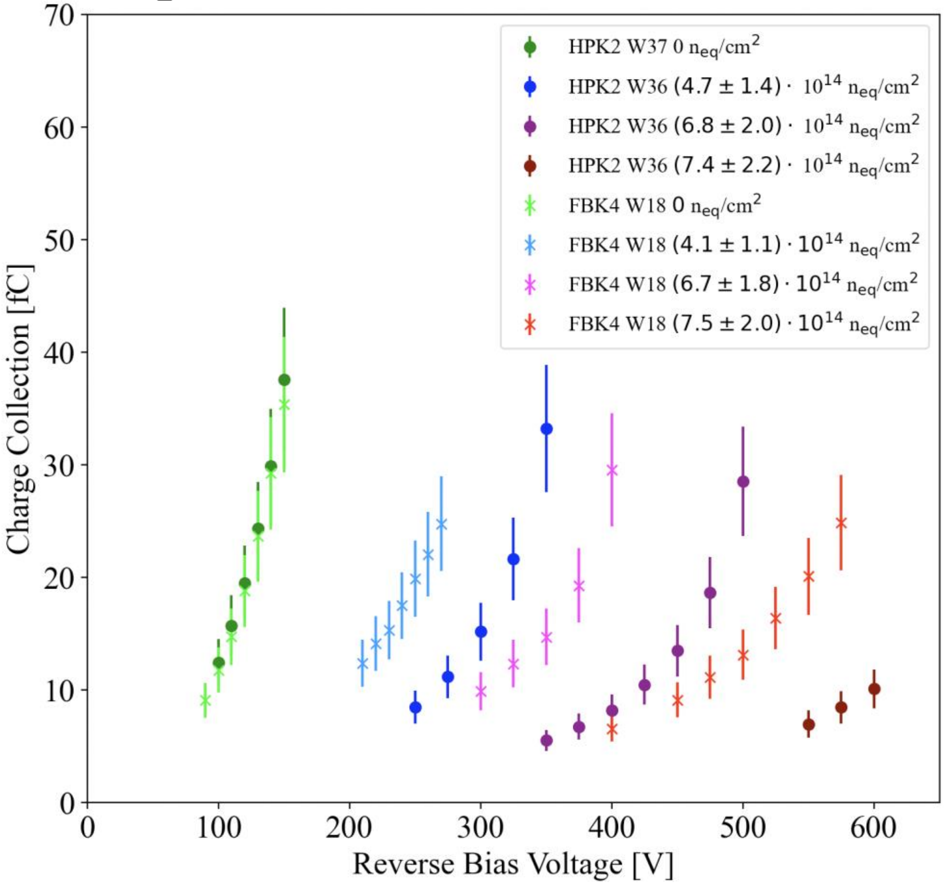

Fluence causes a decrease in the gain layer depletion voltage: $V_{gl}(\phi) = V_{gl,0} \cdot e^{-c \cdot \phi}$.

Carbon co-implanted FBK4 W9 prototype has the least value.

Neutron irradiation Acceptor Removal Constant values are from
Y. Jin et al. Experimental Study of Acceptor Removal in UFSD, Nucl. Inst. and Meth. A 983 (2020)

# Both HPK P2 and FBK4 protypes can achieve <35 ps timing resolution up to $7 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$, with charge >10 fC.



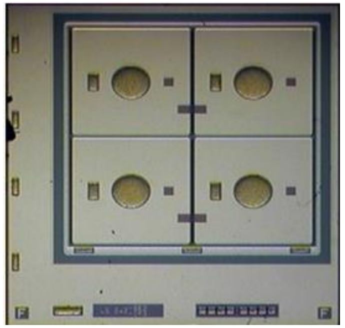

The FBK wafers have better charge collection at lower voltage.

The FBK wafers irradiated to $11 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$ and $15 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$ had no measurable charge collection below $600\ \mathrm{V}$.

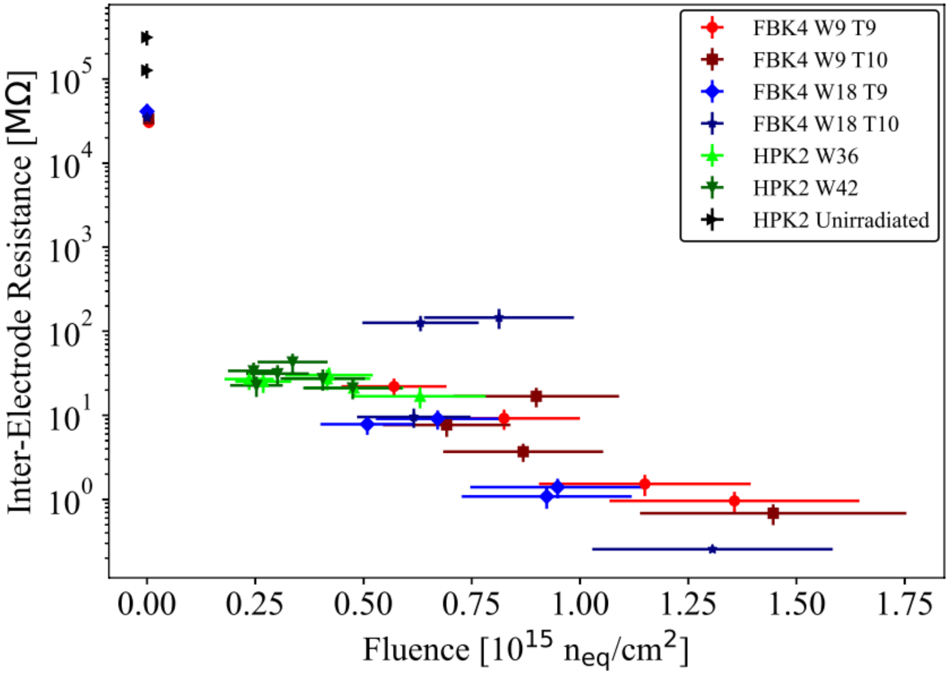
Biasing above 600 V can lead to single event burnout which renders the LGAD inoperable. (G. Laštovička-Medin et al. A brief overview of the studies on the irreversible breakdown of LGAD testing samples irradiated at the critical LHC-HL fluences, JINST 17 C07020 (2022).)

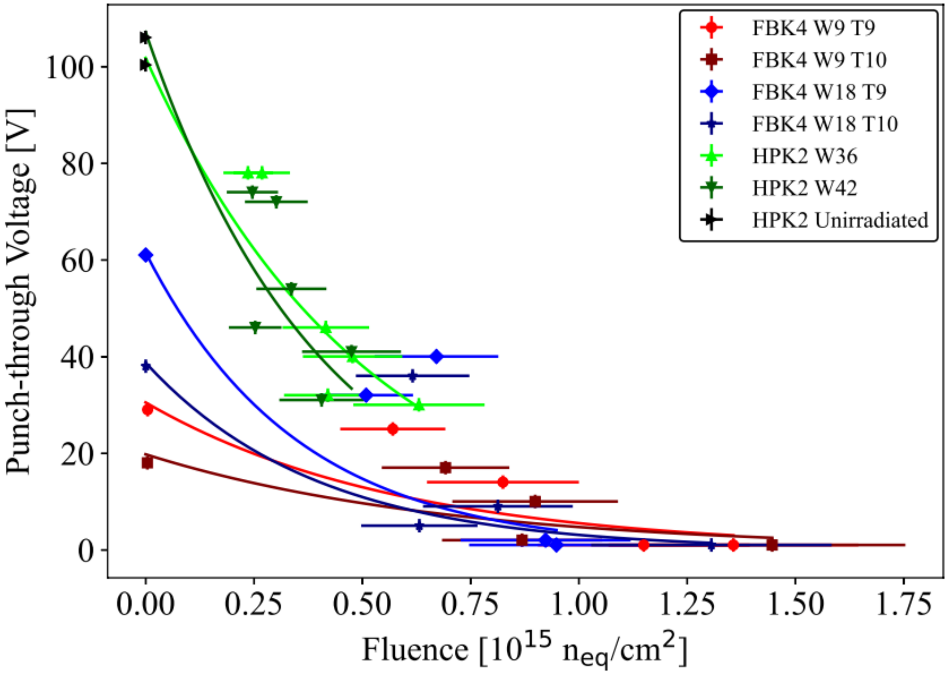
# Measurements on quads shows that the inter-pad resistance and punch-through voltage decline with fluence

HPK P2 Quad



FBK4 Quad




Measurements of charge collection in electrodes adjacent to an electrode being pulsed with a 1060 nm pulsed laser show no cross-talk between the sensors, even with low inter-electrode resistance.

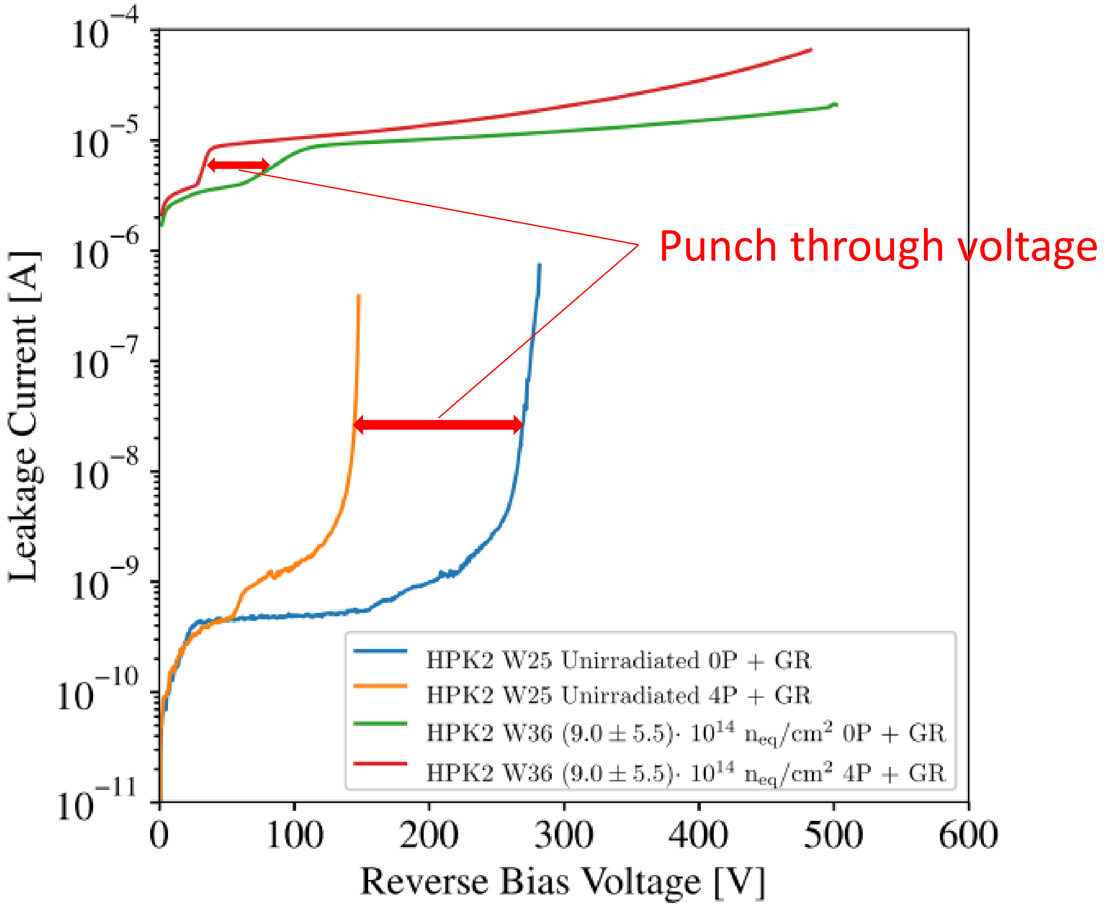
# Summary

- We carried out IV, CV, timing and charge collection measurements.
- Two proton irradiation runs were performed at FNAL and LANSCE in 2022.
- The resulted acceptor removal constants of LGADs are greater than for neutron damage, even when scaled with the NIEL hypothesis.
- Both the FBK4 and HPK2 wafers reach <35 ps and charge collection >10 fC up to $\sim 7 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$, but the FBK4 wafers reach the required charge collection with lower voltage.
- Inter-pad isolation of both HPK and FBK deteriorates as fluence increases. However, no cross-talk between the sensors was observed using a 1060 nm pulsed laser.

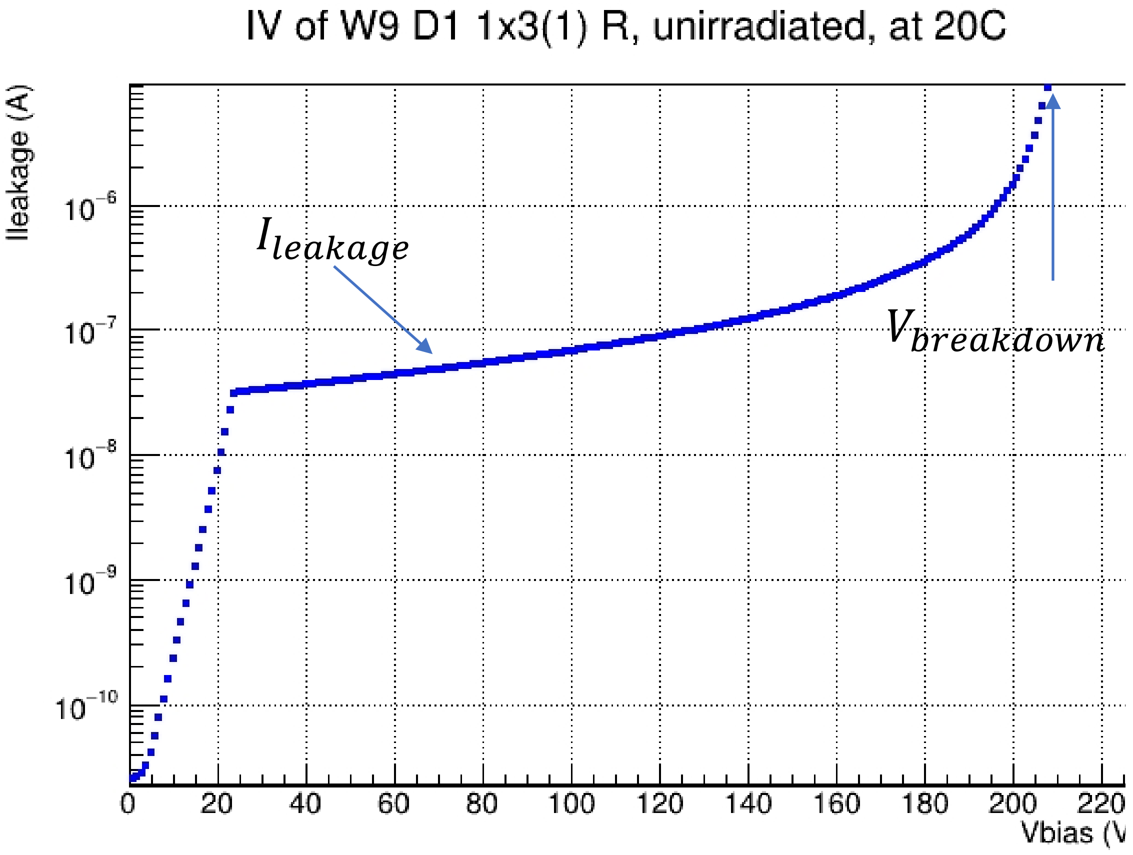
# Thank You!

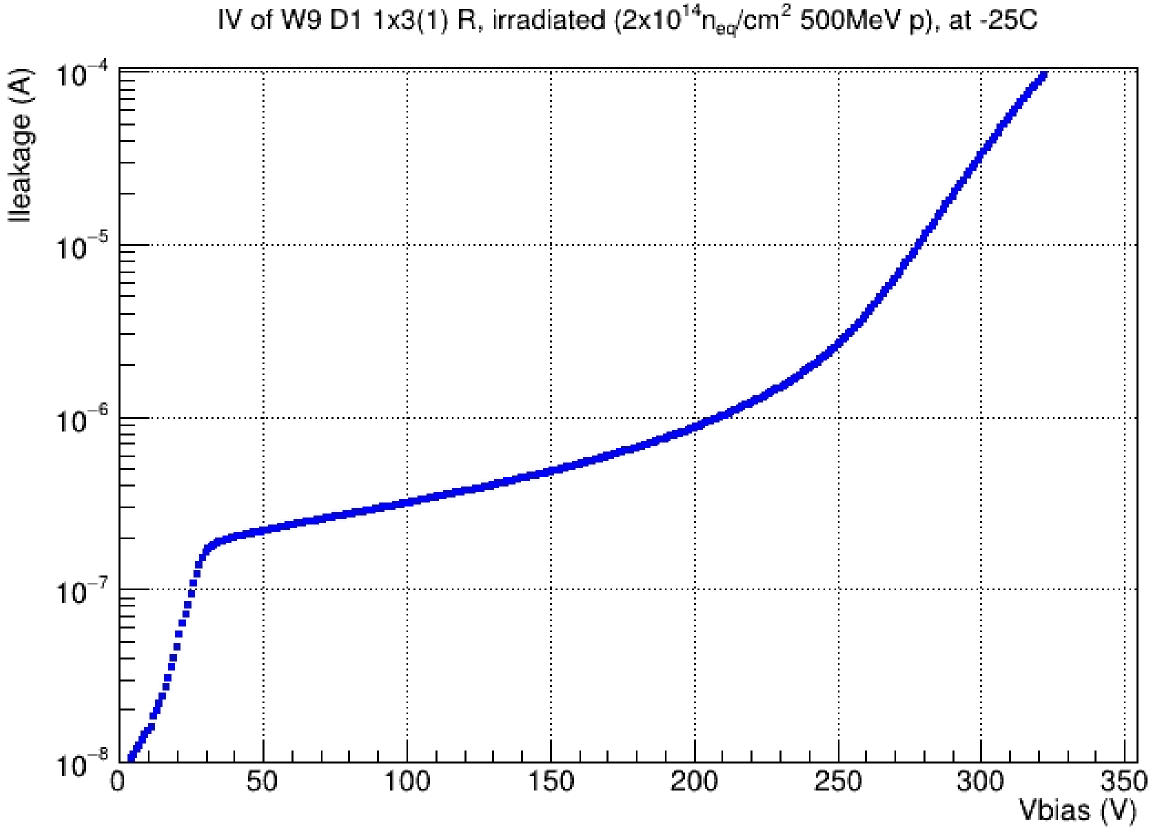
# Backup Slides

# Punch through voltage was estimated by comparing between IV curves of quad with only the guard ring biased and that of with 4 pads and guard ring biased

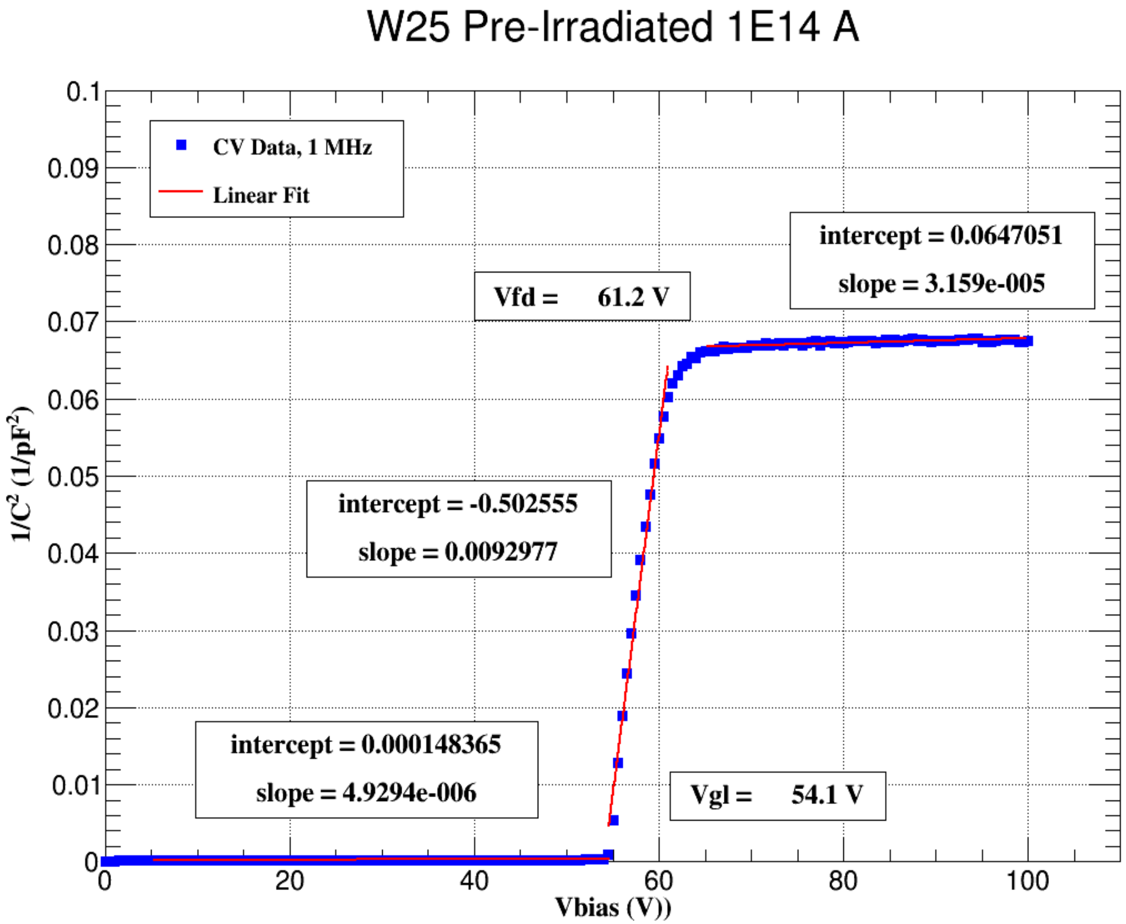


# Irradiation increases leakage currents and breakdown voltages of LGADS



# CV Measurements are used to extract the gain layer depletion voltage $V_{gl}$ and full depletion voltage $V_{fd}$



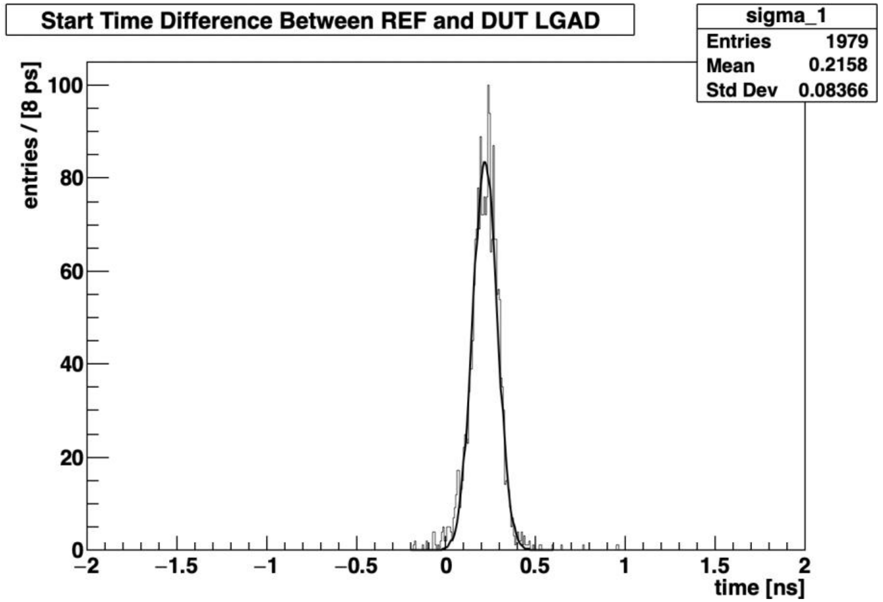

The depletion voltage of the gain layer depends on the dopant concentration, which is impacted by radiation fluence

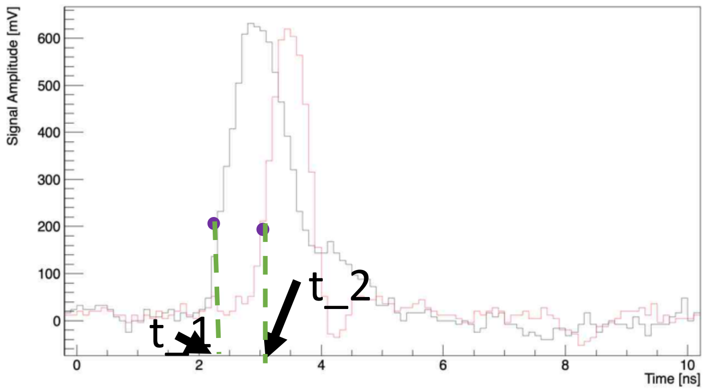
$$V_{gl} = \frac{qN_A w^2}{2\epsilon}(1+2\frac{d}{w})$$

- Gain layer depletion voltage: $V_{gl}$
- Electron charge: $q$
- Dopant Concentration: $N_A$
- Gain Layer depth: $d$
- Gain Layer Thickness: $w$
- Permittivity of Silicon: $\epsilon$

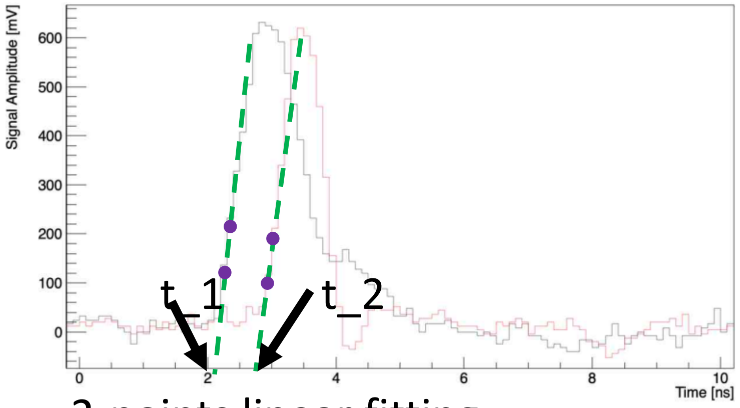
# 3 methods were used to calculate the resolution

- Only signals triggering both REF and DUT channels are collected.
- The resolution is calculated from the temporal deviation of ~2000 events.
- Constant Fraction Discriminator (CFD) method of 25%, 2-point linear fitting, and 4-point linear fitting were used, the differences are within a few percent.
- Equation $\sigma_{tot}^2 = \sigma_{REF}^2 + \sigma_{DUT}^2$ is used to calculate the resolution.

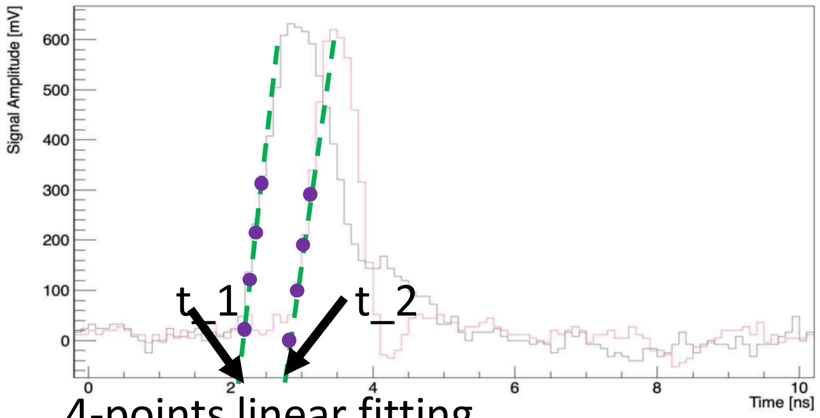


CFD of 25%



2-points linear fitting

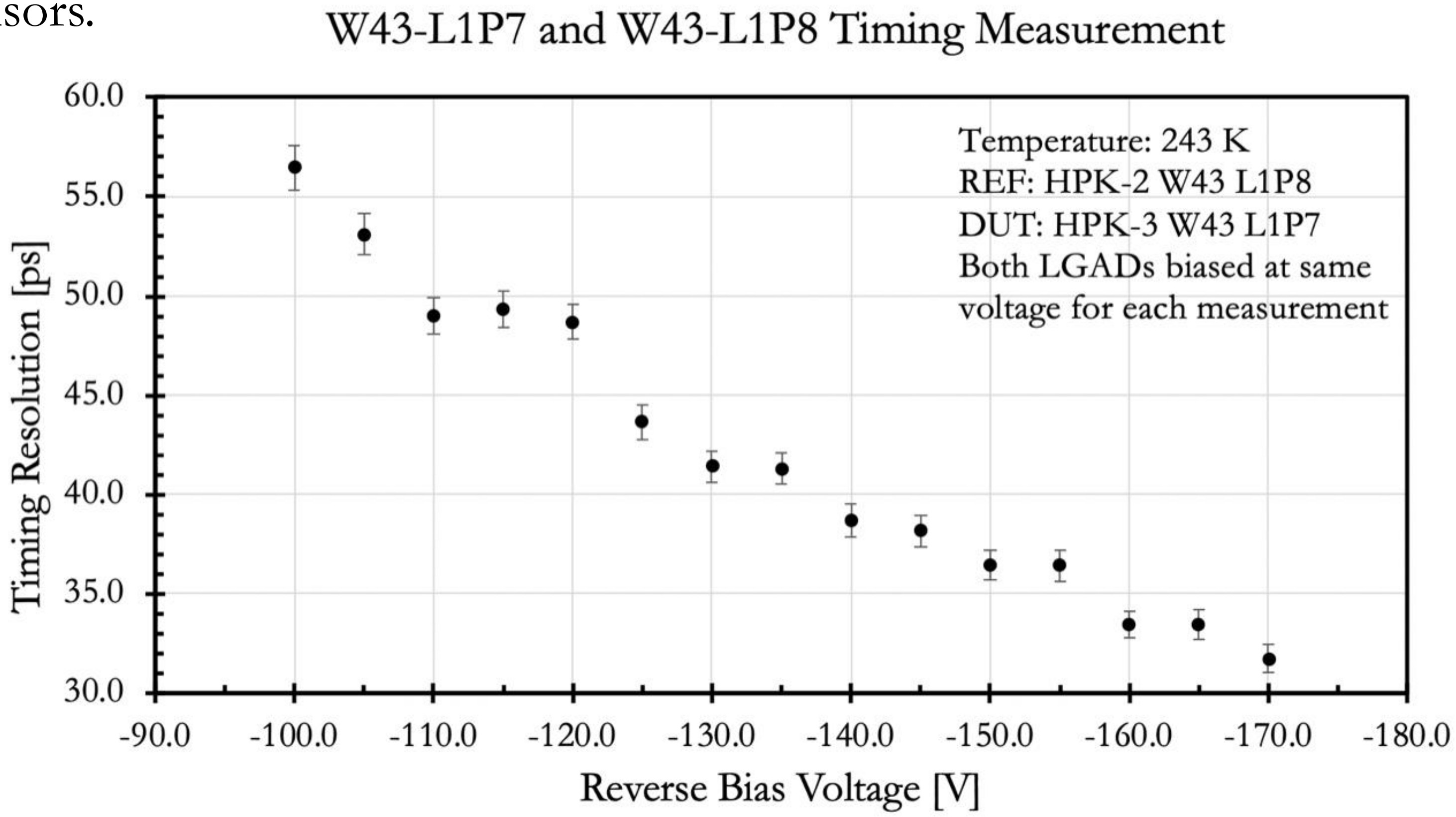


4-points linear fitting

# Two identical HPK sensors (unirradiated) are used as the references for timing measurements

When measuring the timing of two identical sensors, $\sigma_{REF} = \sigma_{DUT}$ so a single measurement will give you the temporal resolution of both sensors.

Either of the unirradiated sensors can be used as the reference for the timing measurements for the irradiated sensors.



From Technical Design Report:
A High-Granularity Timing Detector for the
ATLAS Phase-II Upgrade p88
ATLAS-TDR-031.pdf

| | |
|---|---|
| Technology | Silicon Low Gain Avalanche Detector (LGAD) |
| Time resolution | $\approx$ 35 ps (start); $\approx$ 70 ps (end of lifetime) |
| Time resolution uniformity | No requirement |
| Min. gain | 20 (start); 8 (end of lifetime) |
| Min. charge | 4 fC |
| Min. hit efficiency | 95% |
| Granularity | 1.3 mm $\times$ 1.3 mm |
| Max. inter-pad gap | 100 µm |
| Max. physical thickness | 300 µm |
| Active thickness | 50 µm |
| Active size | 39 mm $\times$ 19.5 mm (30 $\times$ 15 pads) |
| Max. inactive edge | 500 µm |
| Radiation tolerance | $2.5 \times 10^{15}\ n_{eq}\ cm^{-2}$, 1.5 MGy |
| Max. operation temperature on-sensor | −30 °C |
| Max. leakage current per pad | 5 µA |
| Max. bias voltage | 800 V |
| Max. power density | $100\ mW/cm^2$ |

Table 5.1: Sensor parameters and requirements.

From Technical Design Report:
A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade p110
ATLAS-TDR-031.pdf

**Annealing**

Most of the measurements with irradiated sensors were done after annealing for 80 min at 60 °C, which roughly simulates the operational conditions in one year of LHC operation since higher temperature accelerates the annealing (the Arrhenius factor between 60 °C and –30 °C is more than $1 \times 10^6$, 80 min simulates hundreds of years at –30 °C, and tens of days at room temperature).

# Acceptor Removal constant

| Manufacturer | Wafer | Carbon Co-Implantation | Gain Layer Depth | $c$ [$10^{-16} n_{eq}^{-1} cm^2$] |
|---|---|---|---|---|
| FBK4 | W1 | Yes | Shallow | $5.4 \pm 0.9$ |
| FBK4 | W2 | Yes | Shallow | $5.0 \pm 0.9$ |
| FBK4 | W5 | Yes | Shallow | $5.7 \pm 1.4$ |
| FBK4 | W9 | Yes | Shallow | $3.1 \pm 0.7$ |
| FBK4 | W12 | Yes | Deep | $6.2 \pm 1.1$ |
| FBK4 | W16 | Yes | Deep | $4.5 \pm 0.6$ |
| FBK4 | W18 | Yes | Deep | $4.2 \pm 0.8$ |
| HPK2 | W25 | No | Deep | $5.3 \pm 0.3$ |
| HPK2 | W31 | No | Deep | $6.5 \pm 0.9$ |
| HPK2 | W36 | No | Deep | $5.8 \pm 0.5$ |
| HPK2 | W42 | No | Deep | $5.6 \pm 0.3$ |