

Radiation damage studies of ATLAS HGTD Preproduction LGAD sensors

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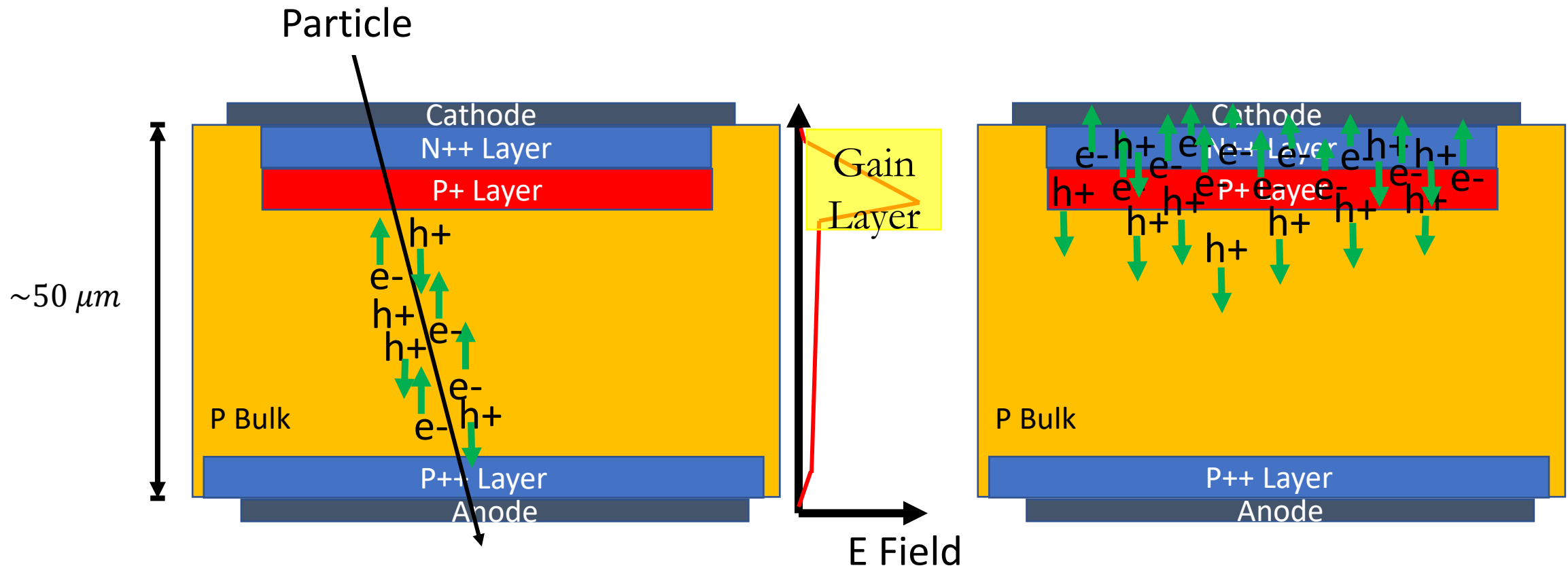
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Introduction

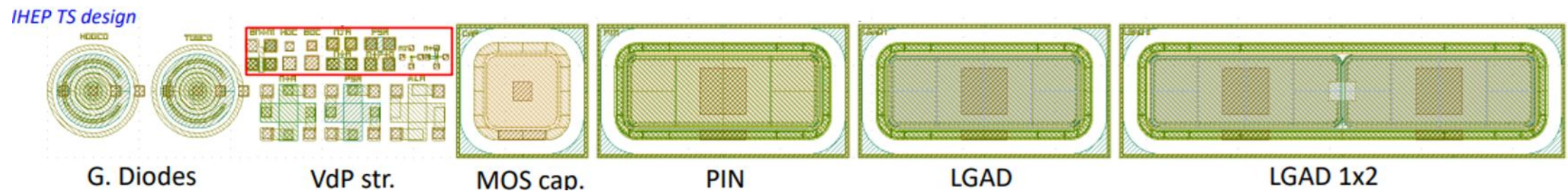
- Low gain avalanche detectors (LGADs) will be used by ATLAS High Granularity Timing Detector (HGTD) for High Luminosity Large Hadron Collider (HL-LHC) to mitigate the pile-up issue.
- Low gain avalanche detectors (LGADs) and p -i- n ("PIN") diode test structures taken from the pre-production series for the ATLAS HGTD were exposed by UNM to 400 MeV protons at the Fermilab Irradiation Test Area (ITA) beamline in 2024.
- Characterization measurements of the test structures are underway at UNM.

LGADs have better timing performance than traditional PIN detectors by introducing a P+ layer with moderate gain (10-100).



- Moderate gain (10~100): Higher Signal-to-Noise Ratio (S/N) and Faster Slew Rate.
- Thinner active volume ($\leq 50\mu m$): shorter carrier drift path, smaller Landau noise.

15 test structures were manufactured by the Institute of Microelectronics (IME) designed by the Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences.

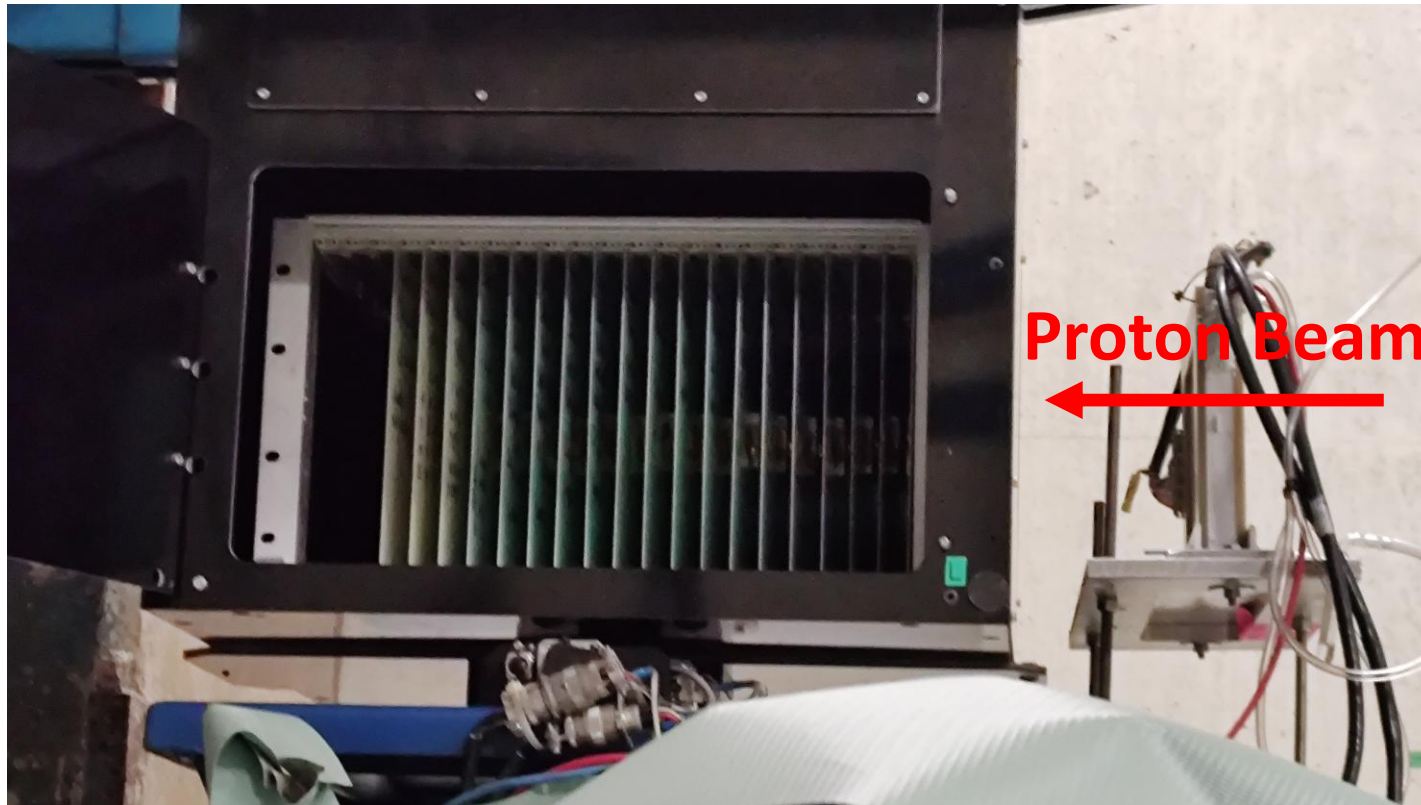
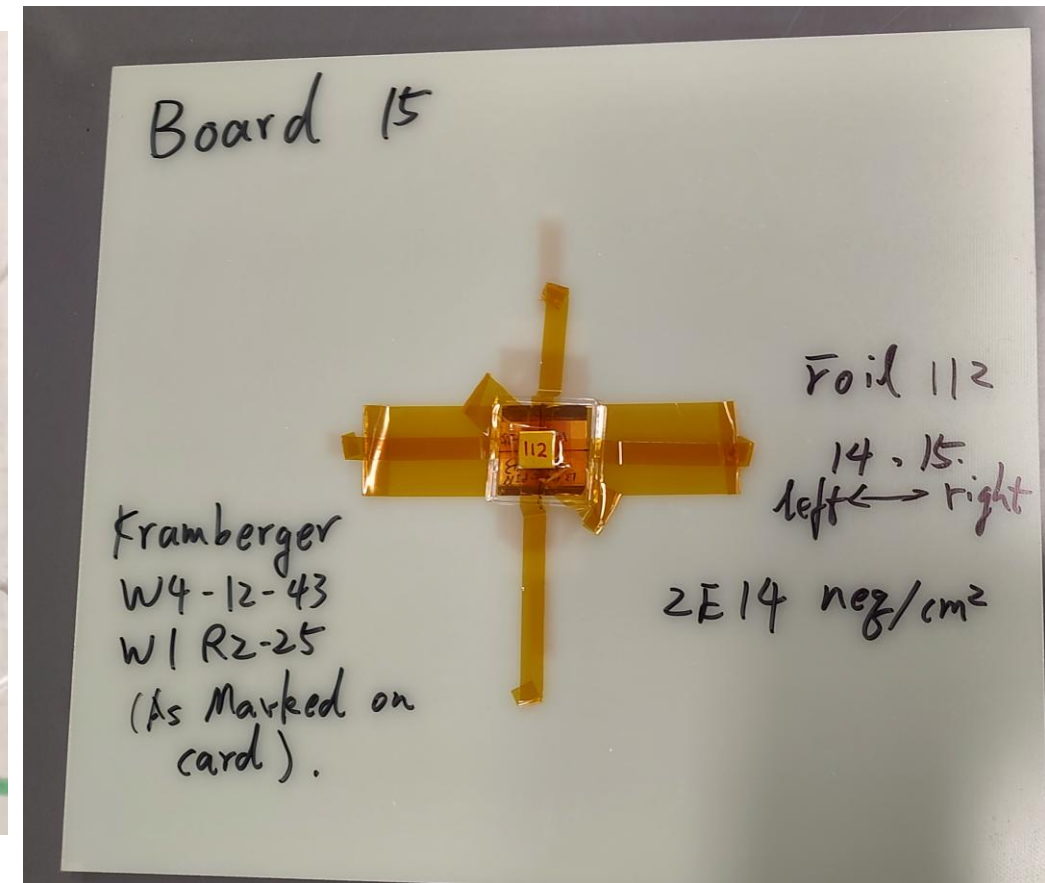


The devices originate from 3 different wafers: V1, W1, and W4.

	V1	W1	W4
Under-bump metallization (UBM)	Yes	No	No
Total thickness	$300 \pm 5 \text{ }\mu\text{m}$	$775 \pm 5 \text{ }\mu\text{m}$	$775 \pm 5 \text{ }\mu\text{m}$
Active thickness	$50 \pm 5 \text{ }\mu\text{m}$	$50 \pm 5 \text{ }\mu\text{m}$	$50 \pm 5 \text{ }\mu\text{m}$
Gain layer thickness	$1 \text{ }\mu\text{m}$	$1 \text{ }\mu\text{m}$	$1 \text{ }\mu\text{m}$
Transverse dimensions	$2.10 \times 0.80 \text{ mm}^2$	$2.10 \times 0.80 \text{ mm}^2$	$2.10 \times 0.80 \text{ mm}^2$
Gain layer dimensions	$2.062 \times 0.750 \text{ mm}^2$	$2.062 \times 0.750 \text{ mm}^2$	$2.062 \times 0.750 \text{ mm}^2$

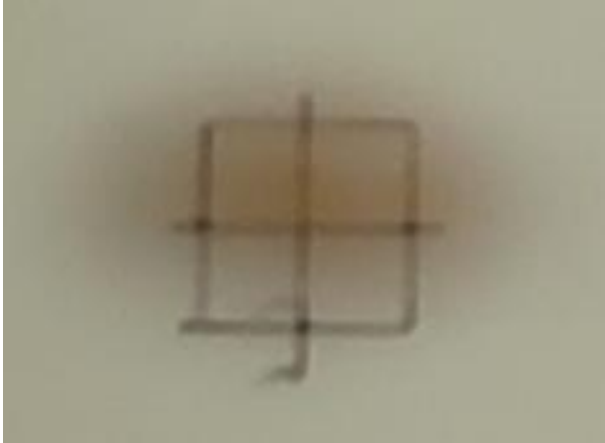
FNAL Proton Irradiation

In 2024, samples were irradiated by UNM at Fermilab ITA with 400 MeV protons in June. The target fluences were 2×10^{14} , 4×10^{14} , 8×10^{14} , and 12×10^{14} Neq/cm².

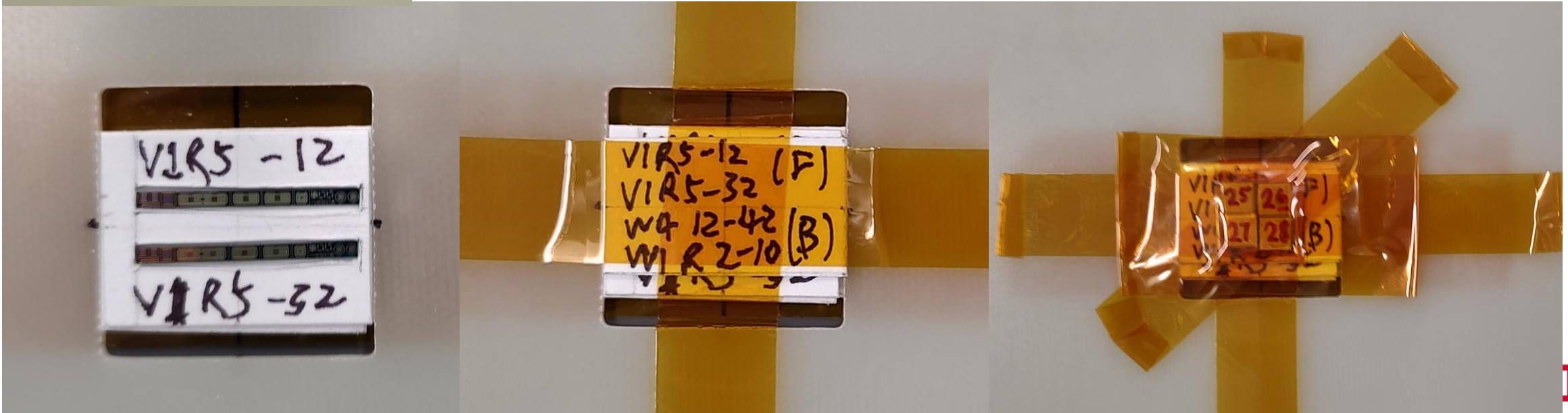


Irradiated samples are stored in -25°C freezer. Prior to the start of the measurement process, every device was subjected to a standard annealing regimen of 60 °C for 80 minutes.

Samples were packed in slotted cardboard. Actual received fluences were tracked by high-purity Aluminum foils.



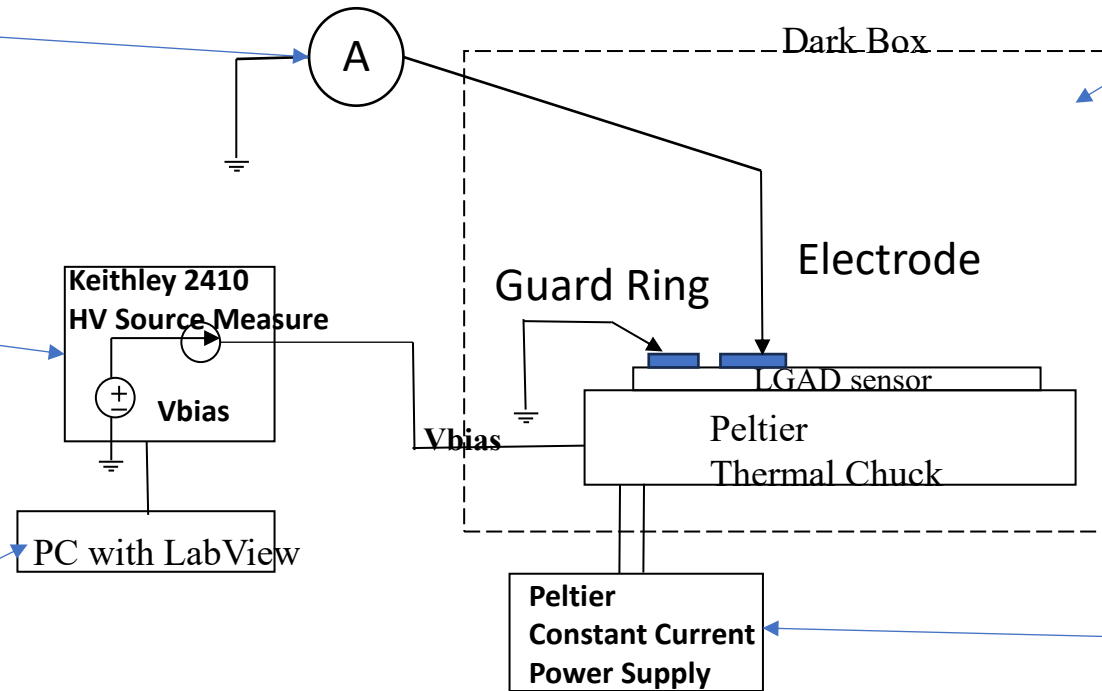
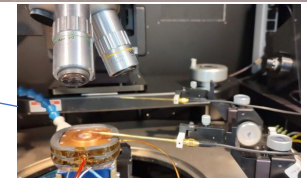
- The proton beam size was set to $R = 1$ cm. However, the actual ITA beam is not round.
- Multiple 0.5cm x 0.5 cm high-purity Al foils were used to obtain more accurate local fluence information.
- From the foil measurements, the actual received fluences range from 1.3×10^{14} To 1.6×10^{15} Neq/cm².



Current vs. Voltage (IV) measurements were performed using a source meter and a picoammeter.



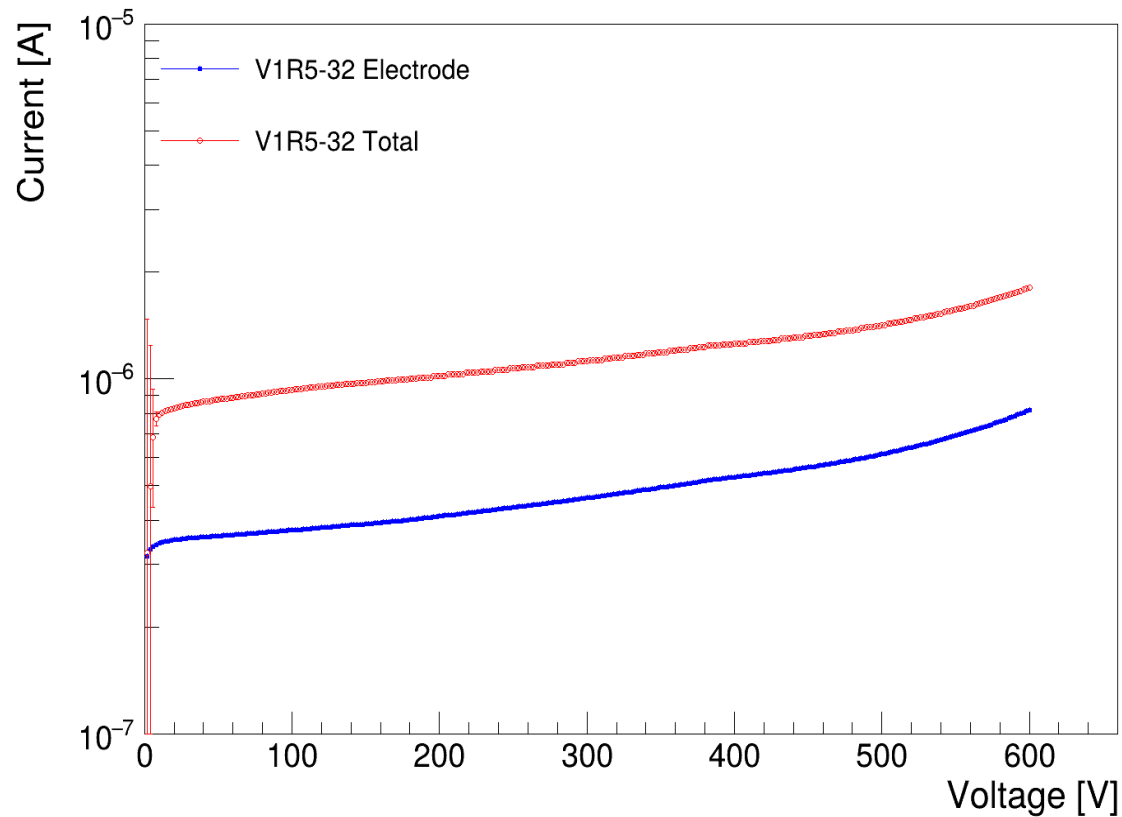
Keithley 6487 picoammeter powered through an isolation transformer



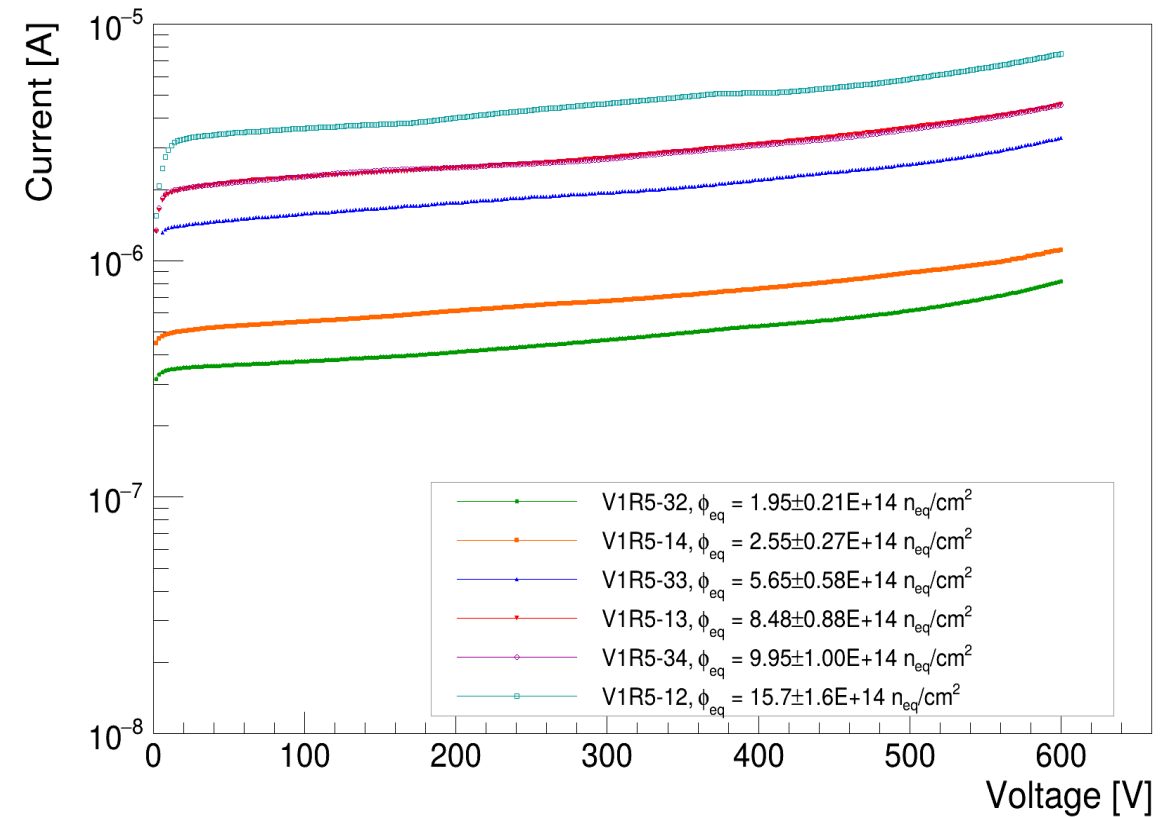
IV measurements were performed at $T = 20 \pm 0.5$ °C.

Leakage current of PINs increases with the received irradiation dose.

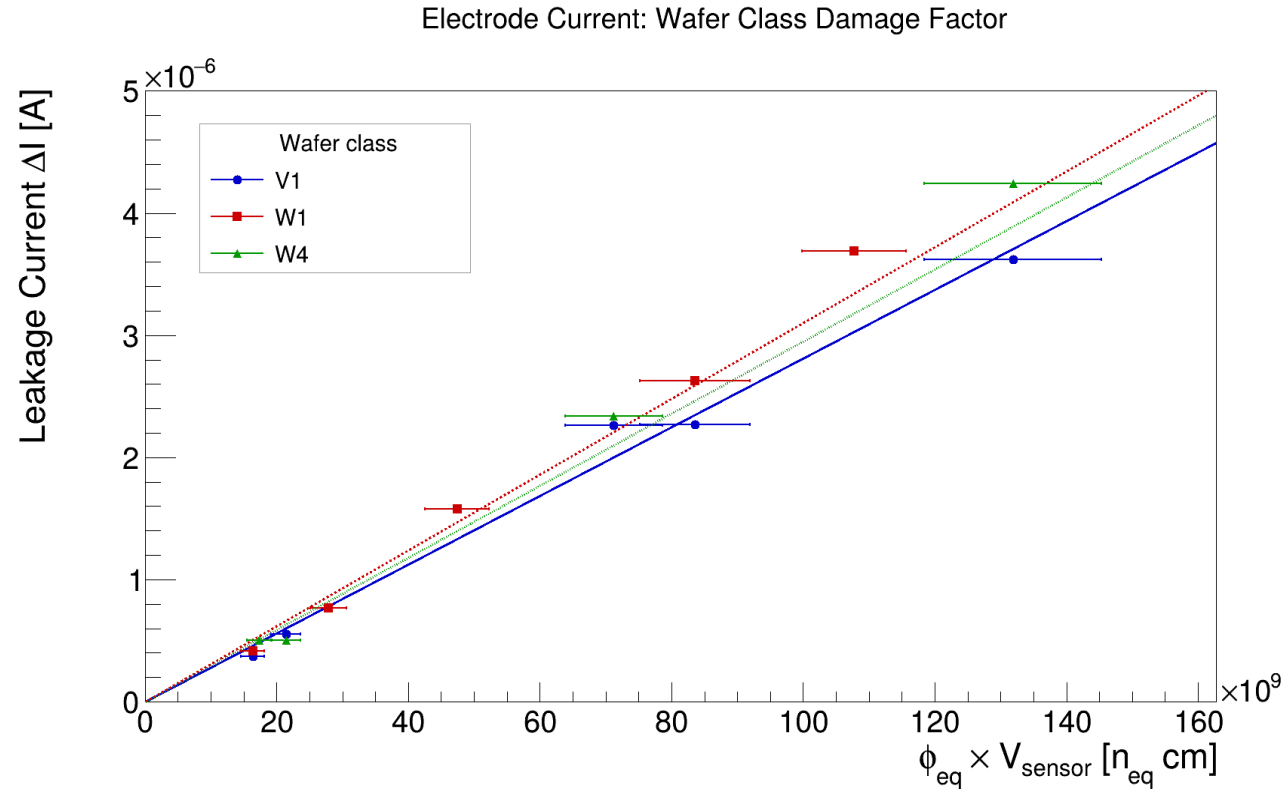
IV Curves



Electrode Current



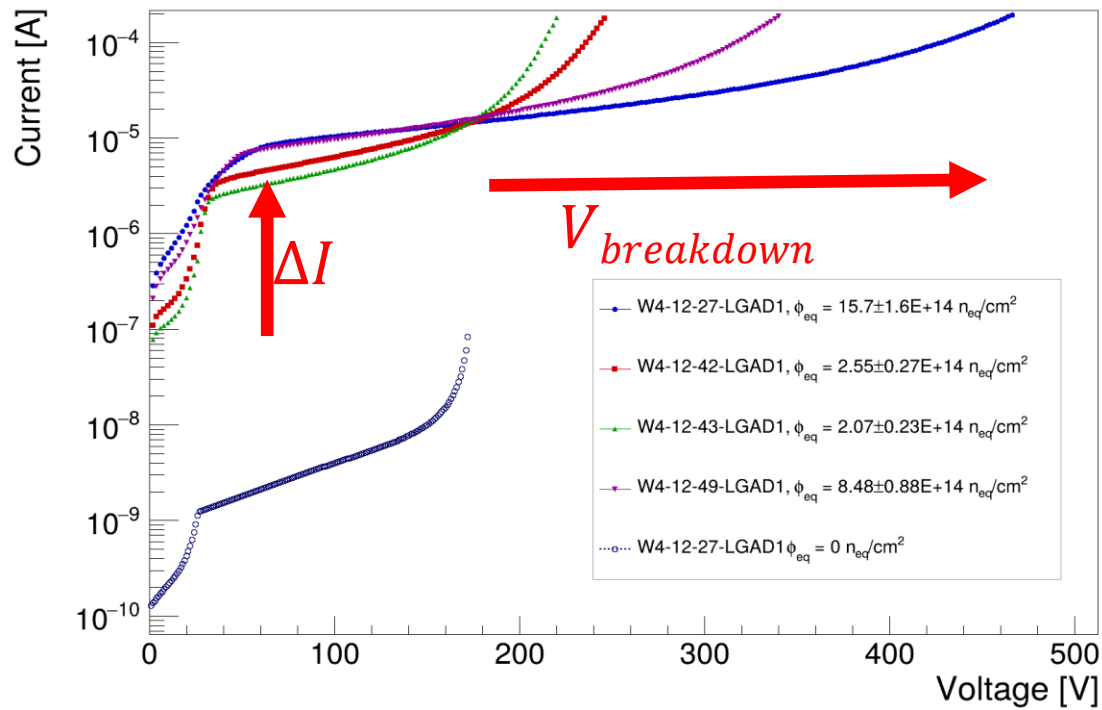
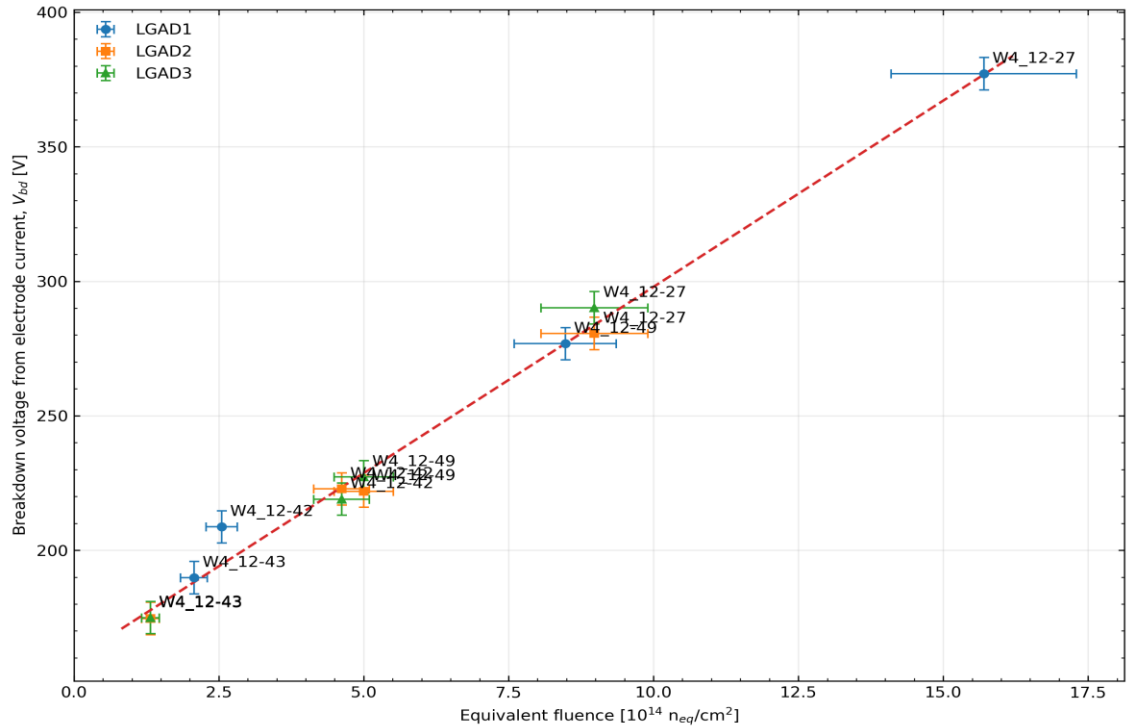
Damage constant α 's are calculated by fitting $\Delta I = \alpha \cdot \phi \cdot Volume$ with data



Measured α 's

V1	W1	W4
$(2.81 \pm 0.119) \times 10^{-17} \text{ A/cm}$	$(3.10 \pm 0.130) \times 10^{-17} \text{ A/cm}$	$(2.95 \pm 0.156) \times 10^{-17} \text{ A/cm}$

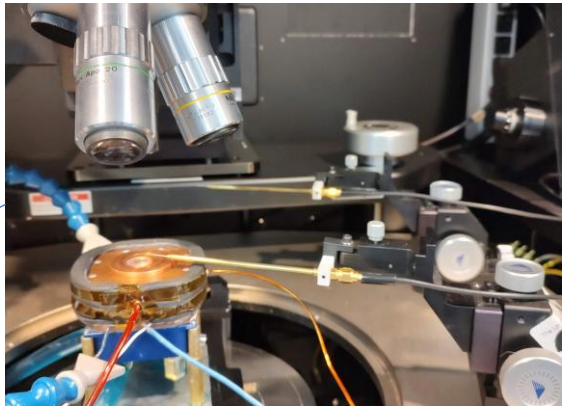
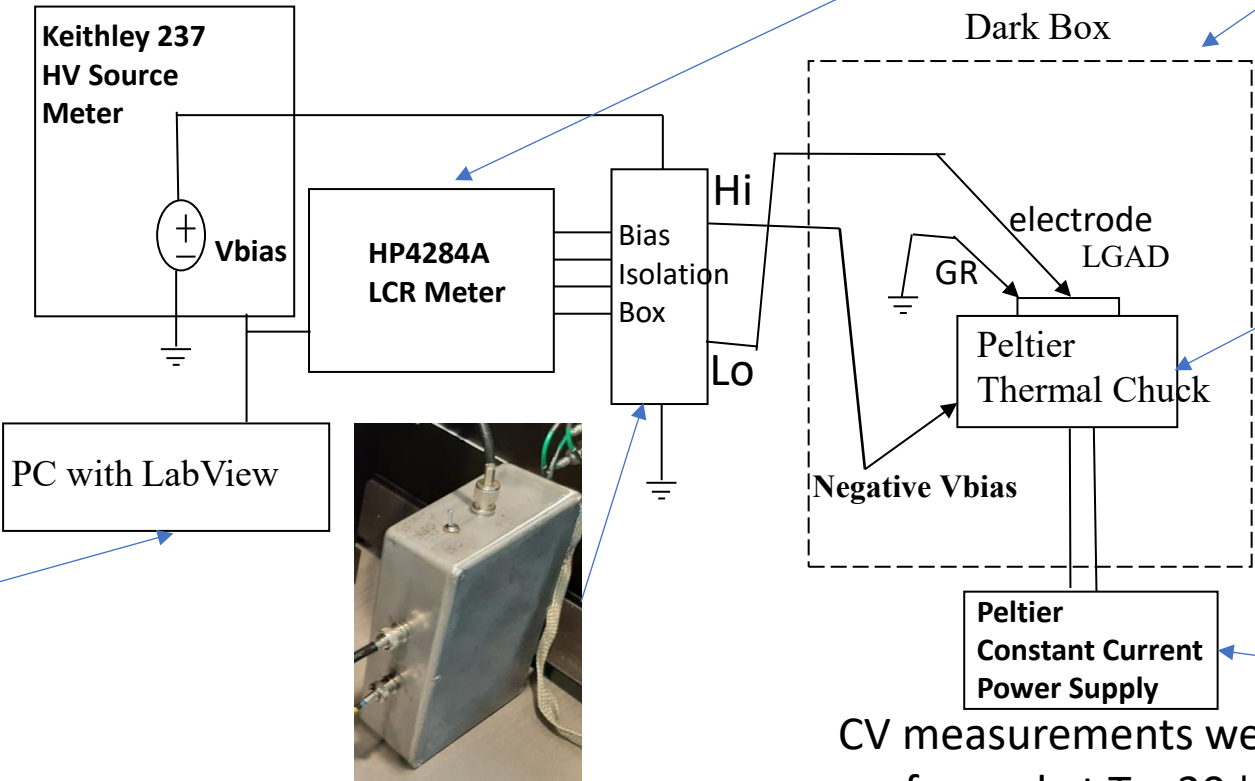
LGAD leakage current and breakdown voltage increases with fluence. Measured breakdown voltages can be fit as a linear function of fluence $V_{breakdown} = \chi \cdot \phi$.



Measured χ 's

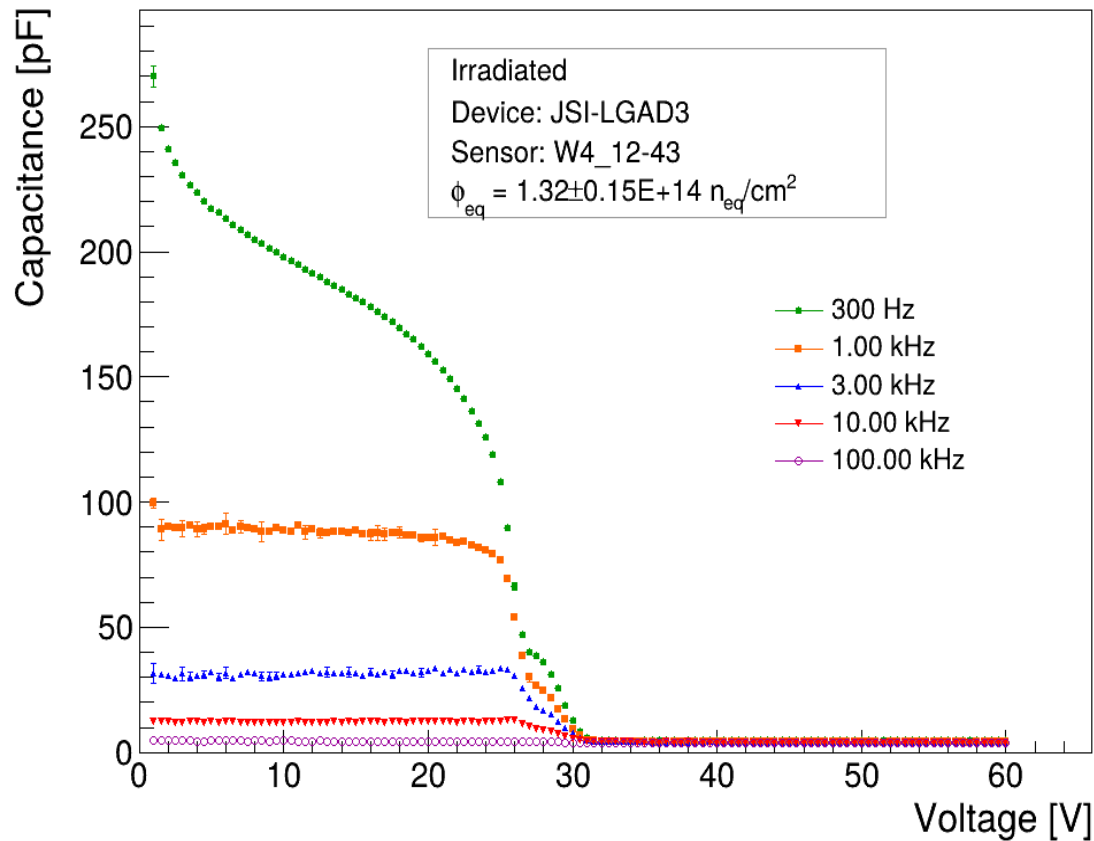
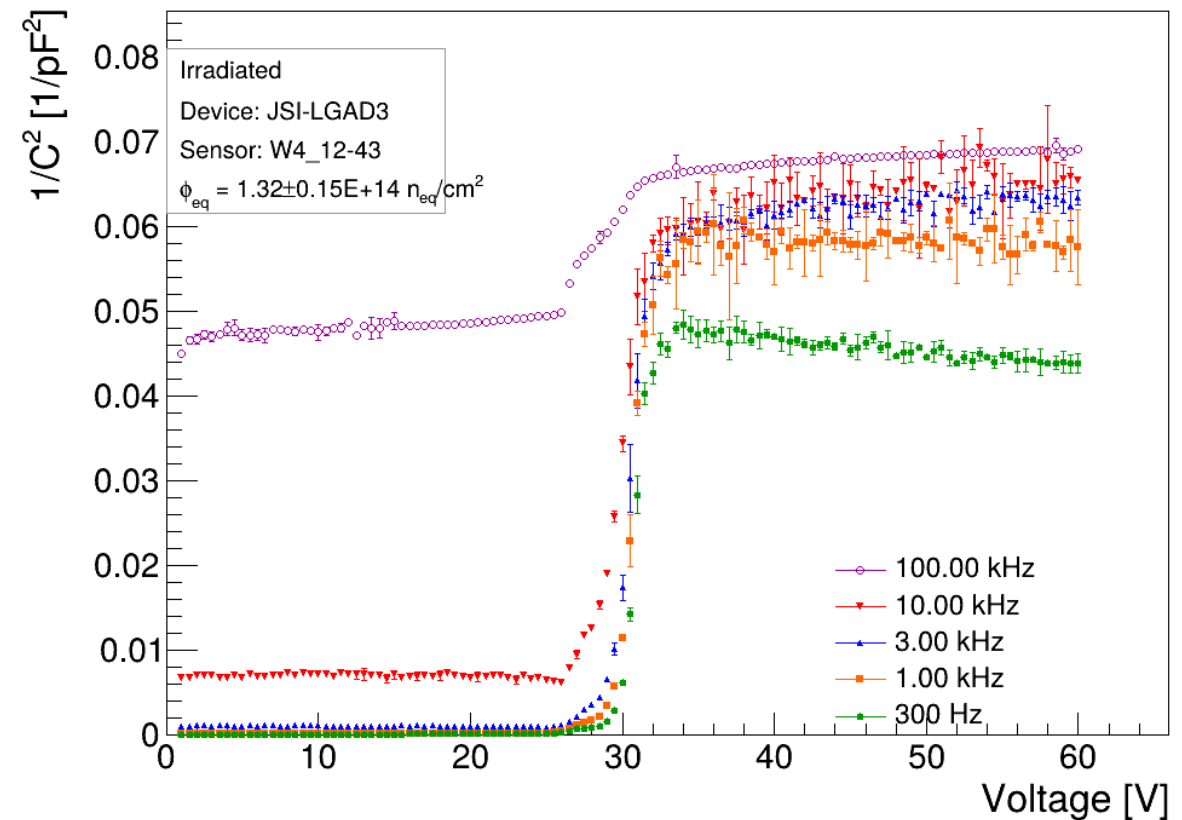
V1	W1	W4
$(11.2 \pm 0.85) \times 10^{-14} \text{ V.cm}^2/\text{n}_{eq}$	$(13.0 \pm 0.84) \times 10^{-14} \text{ V.cm}^2/\text{n}_{eq}$	$(13.8 \pm 0.41) \times 10^{-14} \text{ V.cm}^2/\text{n}_{eq}$

Configuration for CV measurements

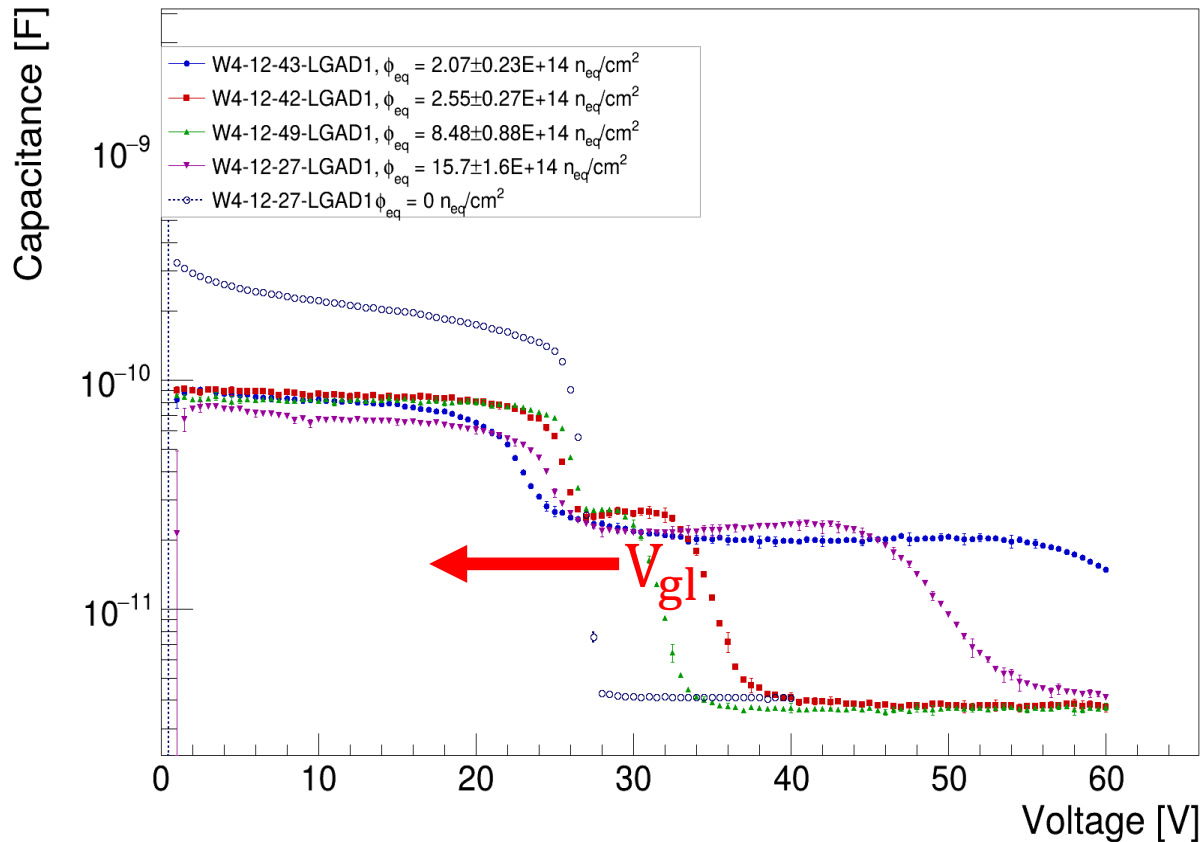


CV measurements were performed at $T = 20 \pm 0.5^\circ\text{C}$.

5 frequencies were used to measure capacitance. 3 kHz was chosen for better overall feature clarity and noise performance.



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

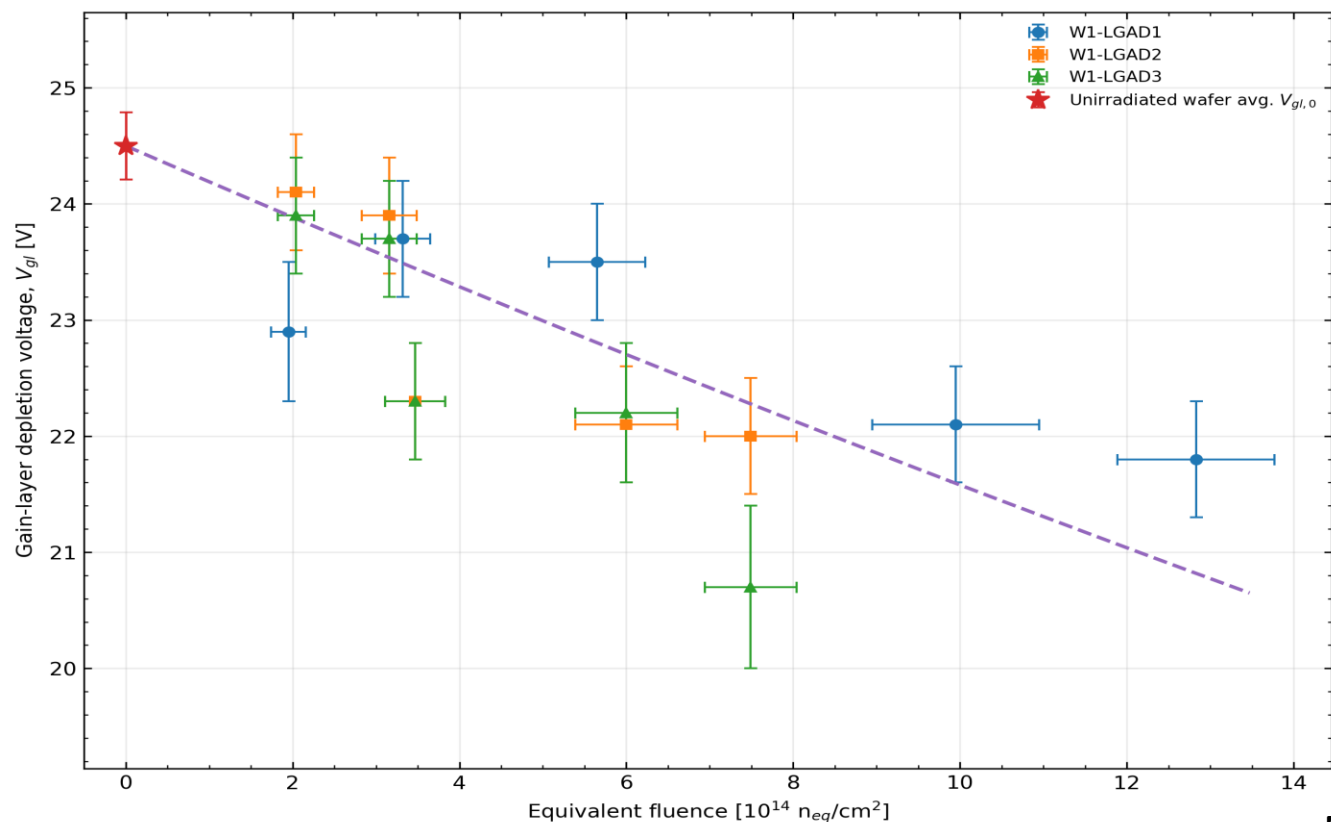


Fluence causes a decrease in the gain layer depletion voltage: $V_{gl}(\phi) = V_{gl,0} \cdot e^{-c \cdot \phi}$.

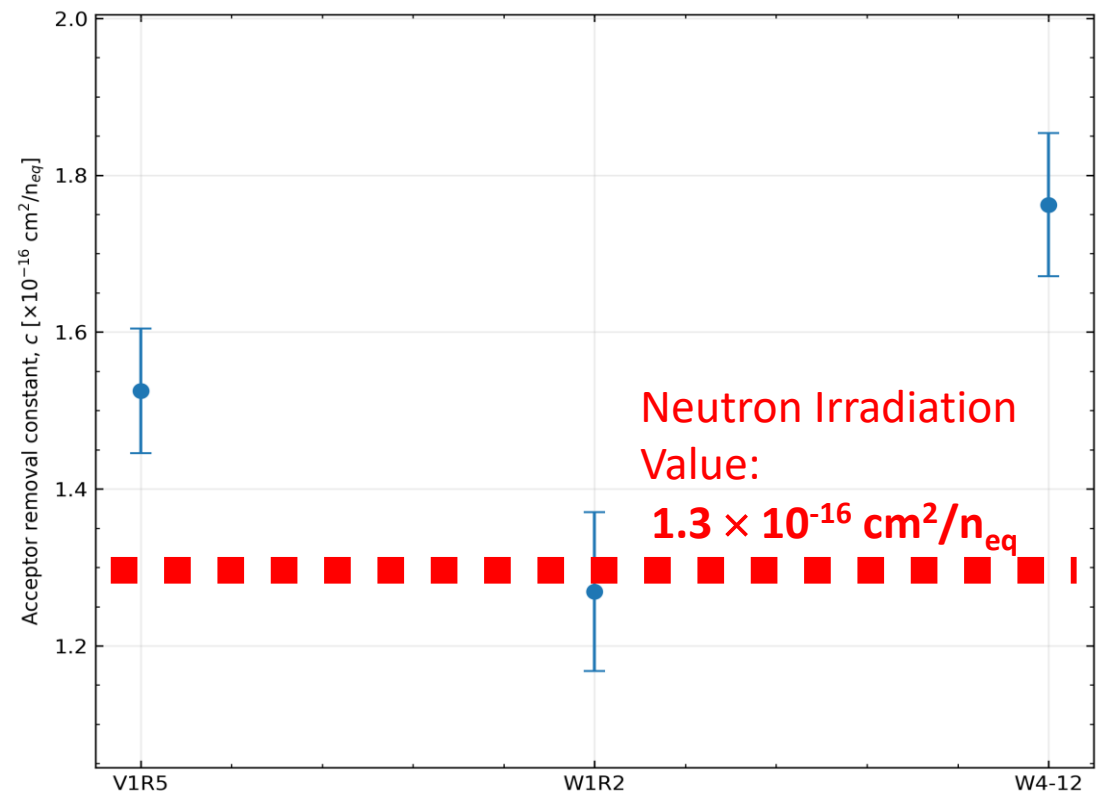
$$V_{gl} = \frac{q N_A w^2}{2\epsilon} \left(1 + 2 \frac{d}{w}\right) \quad [2]$$

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

Our initial results show that the acceptor removal coefficients are $1.3 \text{ to } 1.8 \times 10^{-16} \text{ cm}^2/n_{eq}$, similar to those of neutron irradiation.



V1	$(1.525 \pm 0.079) \times 10^{-16} \text{ cm}^2/n_{eq}$
W1	$(1.269 \pm 0.101) \times 10^{-16} \text{ cm}^2/n_{eq}$
W4	$(1.762 \pm 0.092) \times 10^{-16} \text{ cm}^2/n_{eq}$



Neutron irradiation Acceptor Removal Constant value is from I. Velkovska, et al. TCT-based monitoring of LGAD radiation hardness for ATLAS-HGTD production, Nucl. Instrum. Methods Phys. Res., Sect. A v1084 (2026)



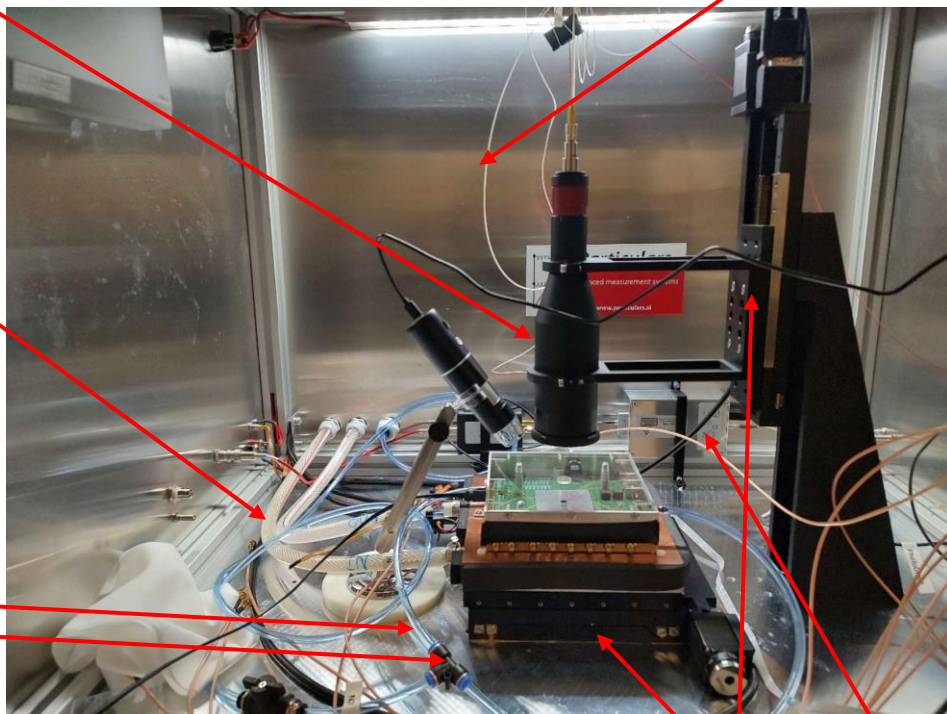
Future plan

Beam
Expander

Fibers

Cooling
water
hoses

Nitrogen
hoses



Enclosure for readout board

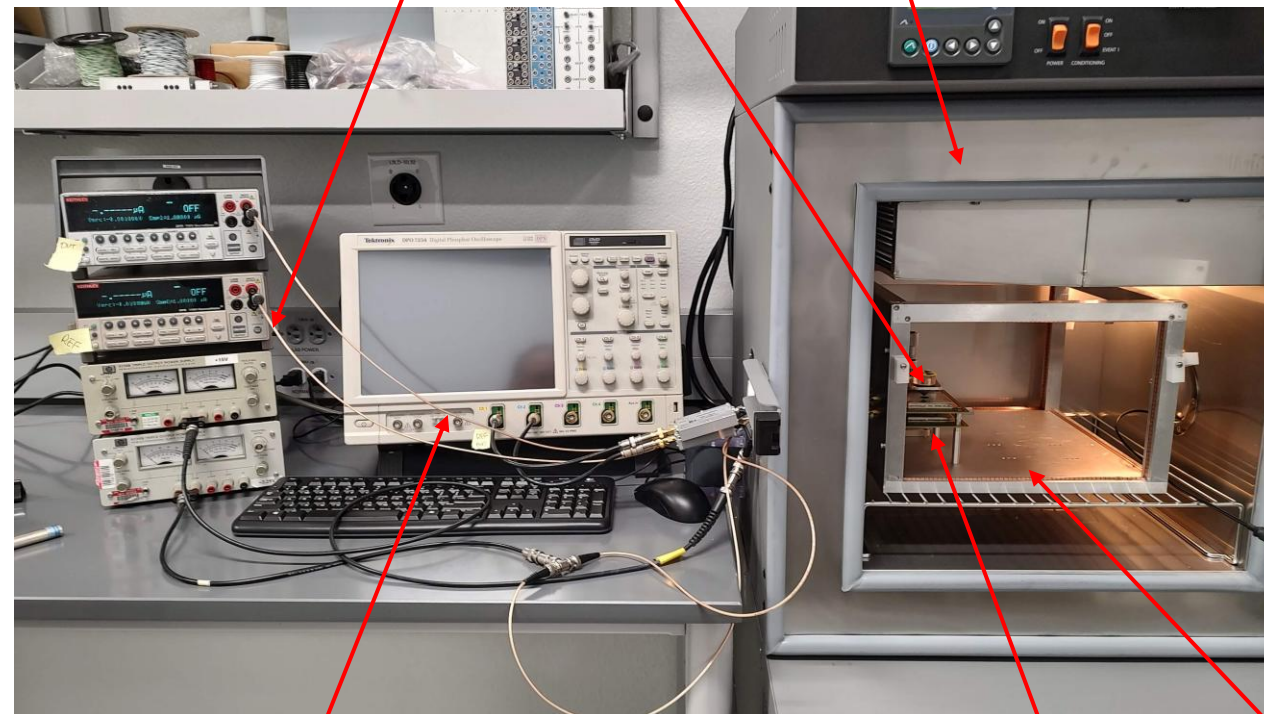
Stages

Laser source

Sr-90 source

Power supplies

Temperature chamber



Oscilloscope

Test stand
Single-channel readout boards

We plan to use the Transient Current Technique (TCT) and the β -source setup to study the LGADs' charge-collection and timing performance.

Summary

- 15 IHEP-IME PIN/LGAD test structures were irradiated at Fermilab ITA, with $0.5 \times 0.5 \text{ cm}^2$ Al foils attached to track the actual received fluences.
- Measurements of IV and CV have been made:
 - PIN IV measurements show that the damage constants are around $3 \times 10^{-17} \text{ A/cm}$.
 - LGAD IV measurements show that the breakdown voltage increases from 150V to 375V as received fluences increase up to $1.6 \times 10^{15} \text{ Neq/cm}^2$.
 - CV measurements show that the acceptor removal coefficients are from 1.3 to $1.8 \times 10^{-16} \text{ cm}^2/n_{\text{eq}}$, comparable to those of neutron irradiation.
- Timing/charge collection measurement is being set up.

Acknowledgments

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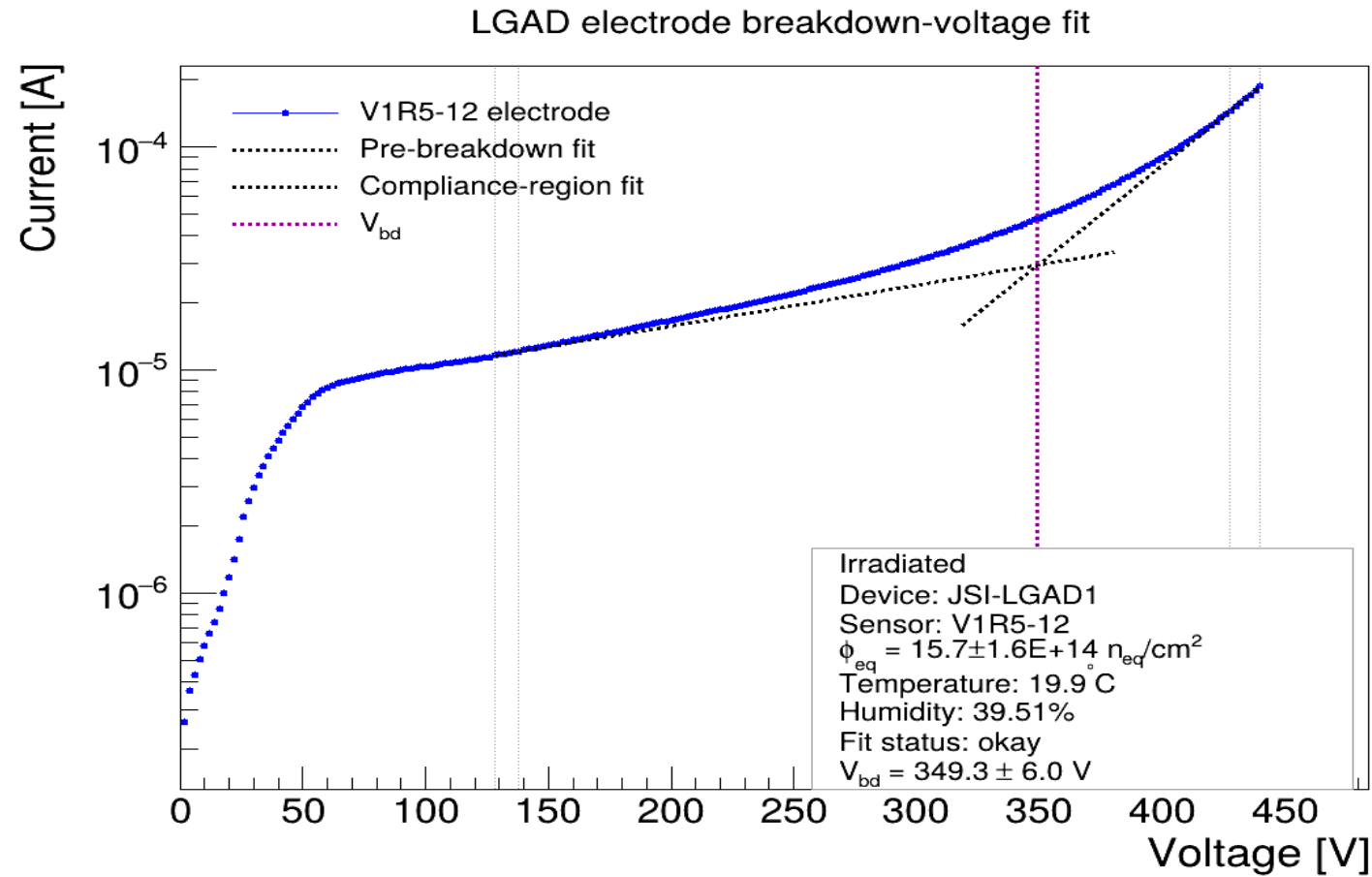
We are grateful to the staff at the Fermilab Irradiation Test Area, especially Evan Niner, for their outstanding support. Thanks are due as well to Carl Willis of the University of New Mexico Department of Nuclear Engineering for assistance with dosimetry.



Thank You!

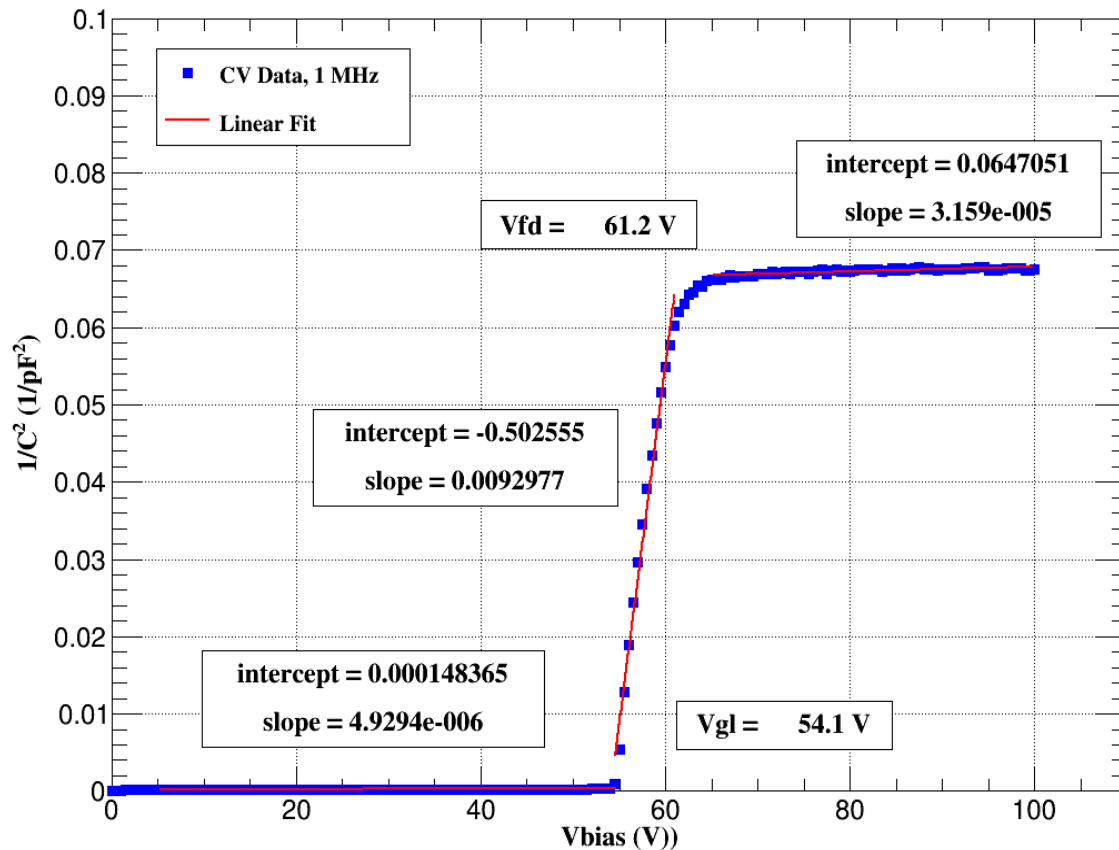
Backup Slides

Breakdown Voltage fitting



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

W25 Pre-Irradiated 1E14 A



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

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

Annotations for the equation:

- Electron charge (q)
- Dopant Concentration (N_A)
- Gain Layer depth (d)
- Gain layer depletion voltage (V_{gl})
- Permittivity of Silicon (ϵ)
- Gain Layer Thickness (w)