Response of Low Gain Avalanche Detector Prototypes to Gamma Radiation

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ATLAS EXPERIMENT

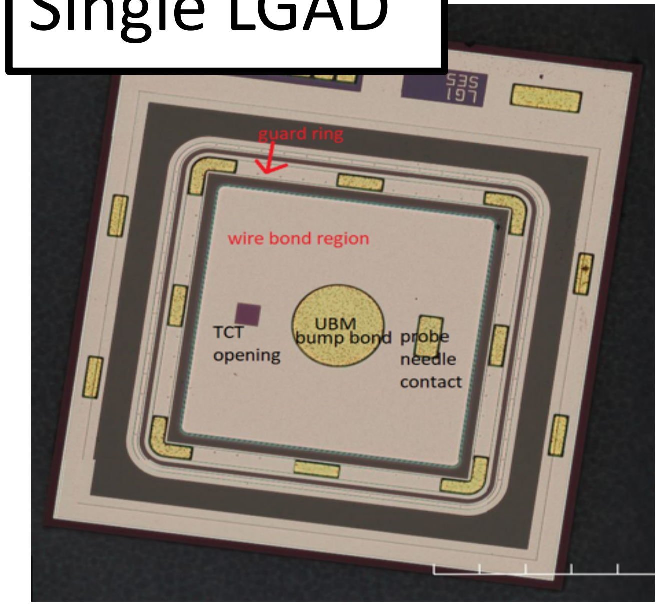
Motivation

- Gamma rays produce surface damage affecting the resistance between the guard rings and pads by creating a large number of trapped positive charges at the Si - SiO_2 interface.
- Gamma rays cause damage in silicon sensors through Compton electrons and photoelectrons which cause point (displacement) defects.
- This damage needs to be characterized before Low Gain Avalanche Detectors (LGADs) are used in the High Granularity Timing Detector (HGTD) in ATLAS, and the Endcap Timing Layer (ETL) of CMS.
- I will report observations of bulk damage and decrease in surface resistivity of LGADs due to gamma irradiation.

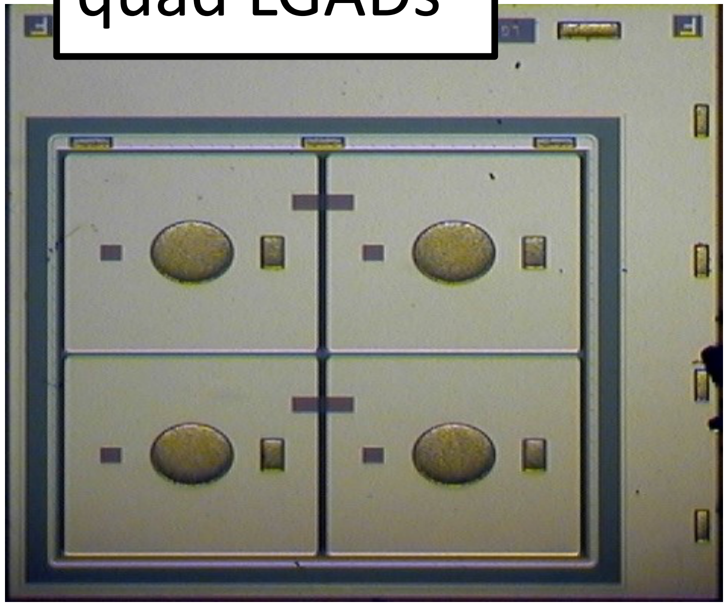
Sensors

- Single LGADs, quad LGADs, and PINs were produced by Hamamatsu Photonics K.K. (HPK)
- Sensors produced on wafers whose implants represent a variety of dopant concentrations
- 2x2 arrays of LGADs (quad LGADs) were produced with a single guard ring
- Sensors of each type were sent to UNM for irradiation and characterization

Single LGAD



quad LGADs



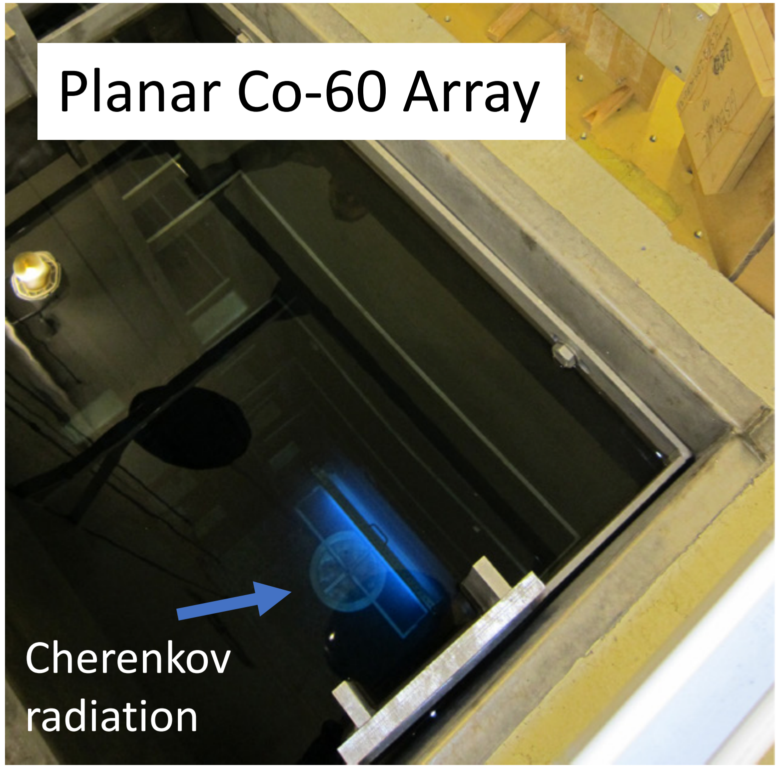
Wafer Properties

Wafer #	Inter-electrode separation in the quad sensors (μm)
25	30, 40, 50, 70
31	30, 40, 50, 70
36	30
42	30

- PIN sensors (lacking gain layer but otherwise identical to the LGADs) were produced and irradiated.

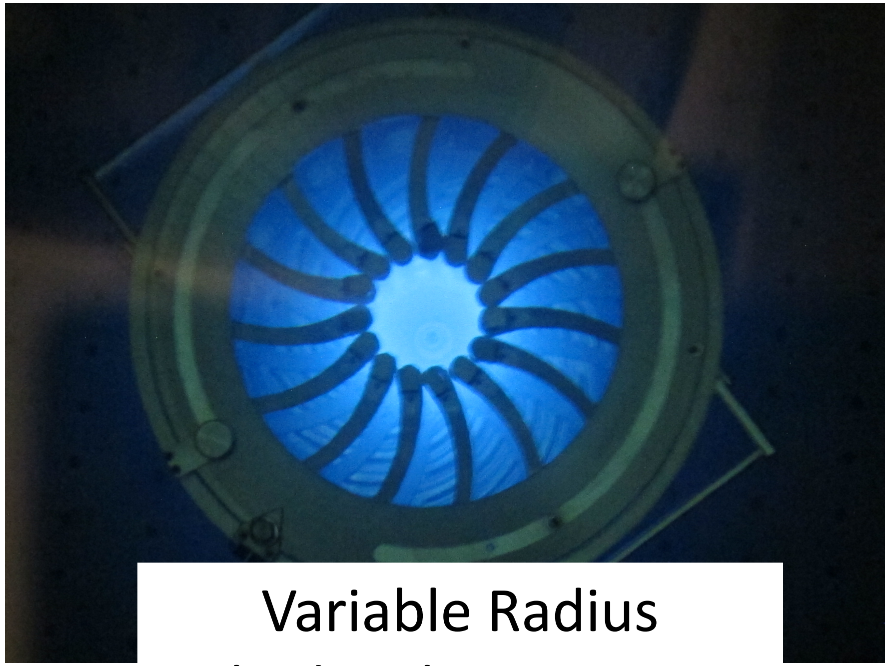
Sandia National Laboratories (SNL) Gamma Irradiation Facility (GIF)

- The GIF uses Co-60 pins to irradiate samples
- 3 test cells with 2 m concrete walls and elevator shafts into a 6 m deep pool
- Experiments are set up and then the Co-60 pins are elevated into the cell
- Different Co-60 pin alignments are used to control dose rate and dose direction



Planar Co-60 Array


Fixed Cylindrical Radius Co-60 Array


Variable Radius Cylindrical Co-60 Array

Our samples at the GIF

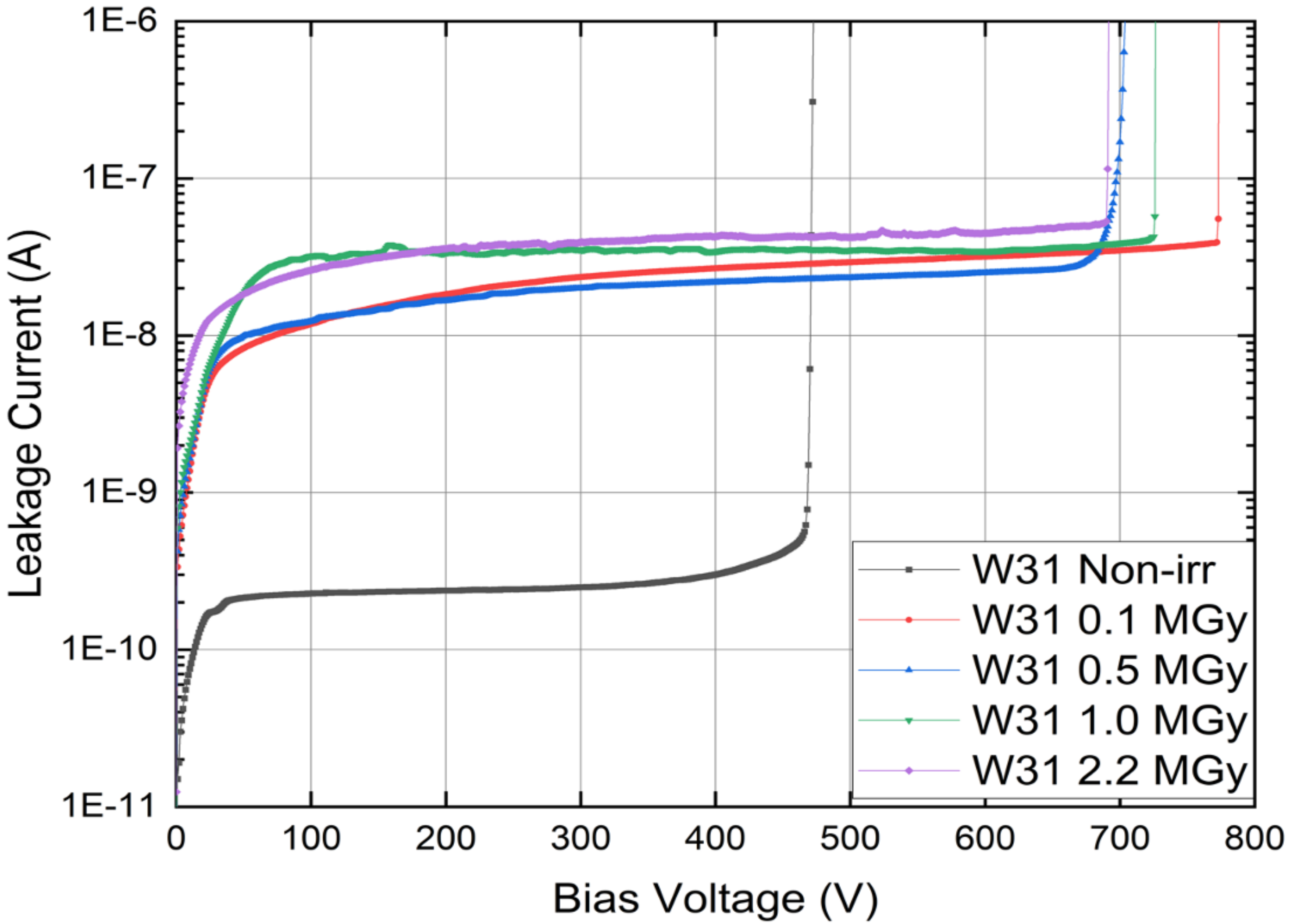
- Samples of every sensor prototype are delivered to SNL, and identical sensors are retained unirradiated for reference.
  - The fixed Cylindrical Radius Co-60 Array was used for the irradiation
  - A 4.16 Gy/s dose rate is achieved in this alignment (~6 day irradiation)

- Single LGADs were subjected to 0.1, 0.5, 1.0, and 2.2 MGy

- Quad LGADs were subjected to 0.5, 1.0 and 2.2 MGy

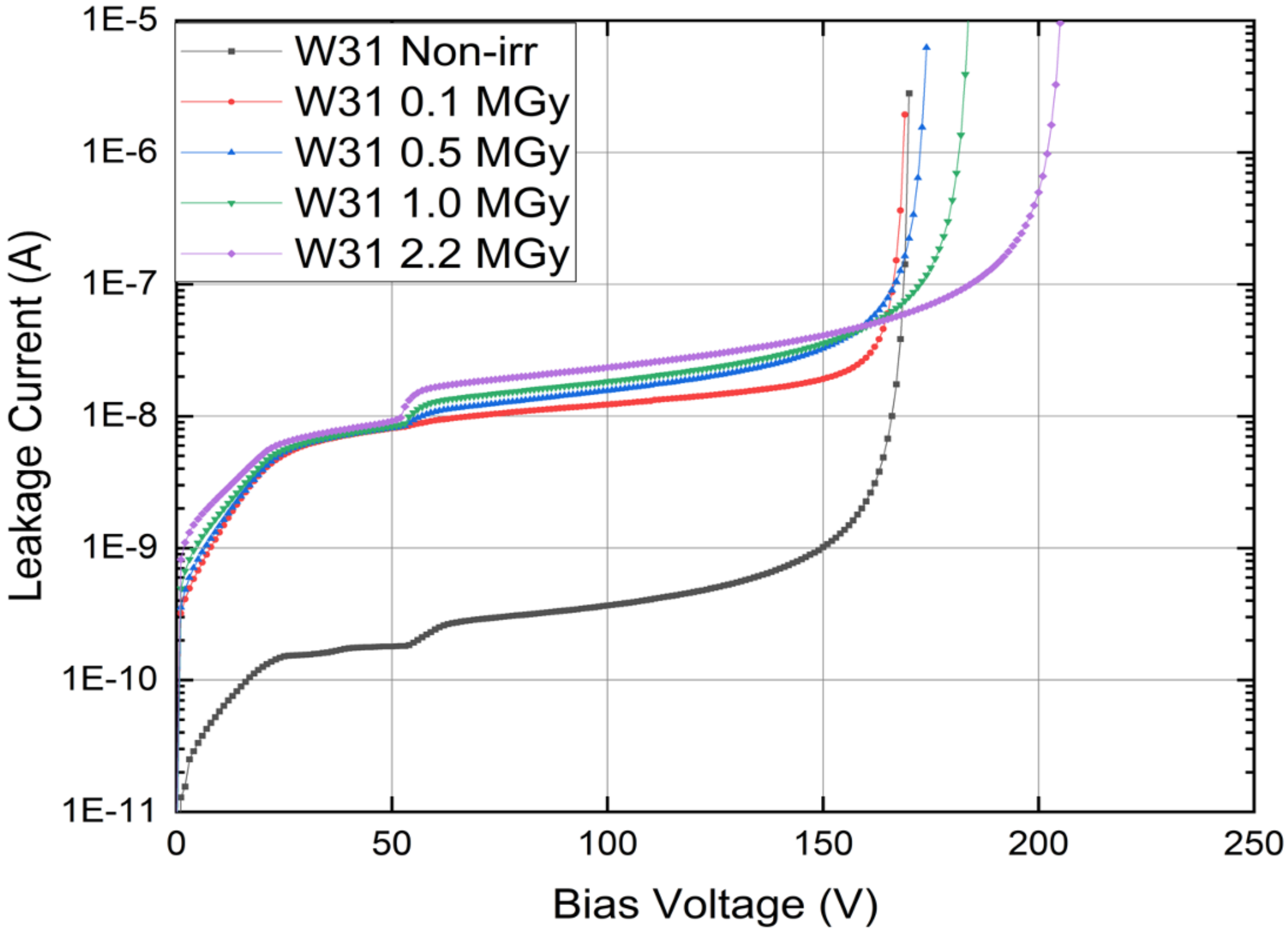
- PIN sensors were also subject to to 0.1, 0.5, 1.0, and 2.2 MGy

PIN response to gamma irradiation



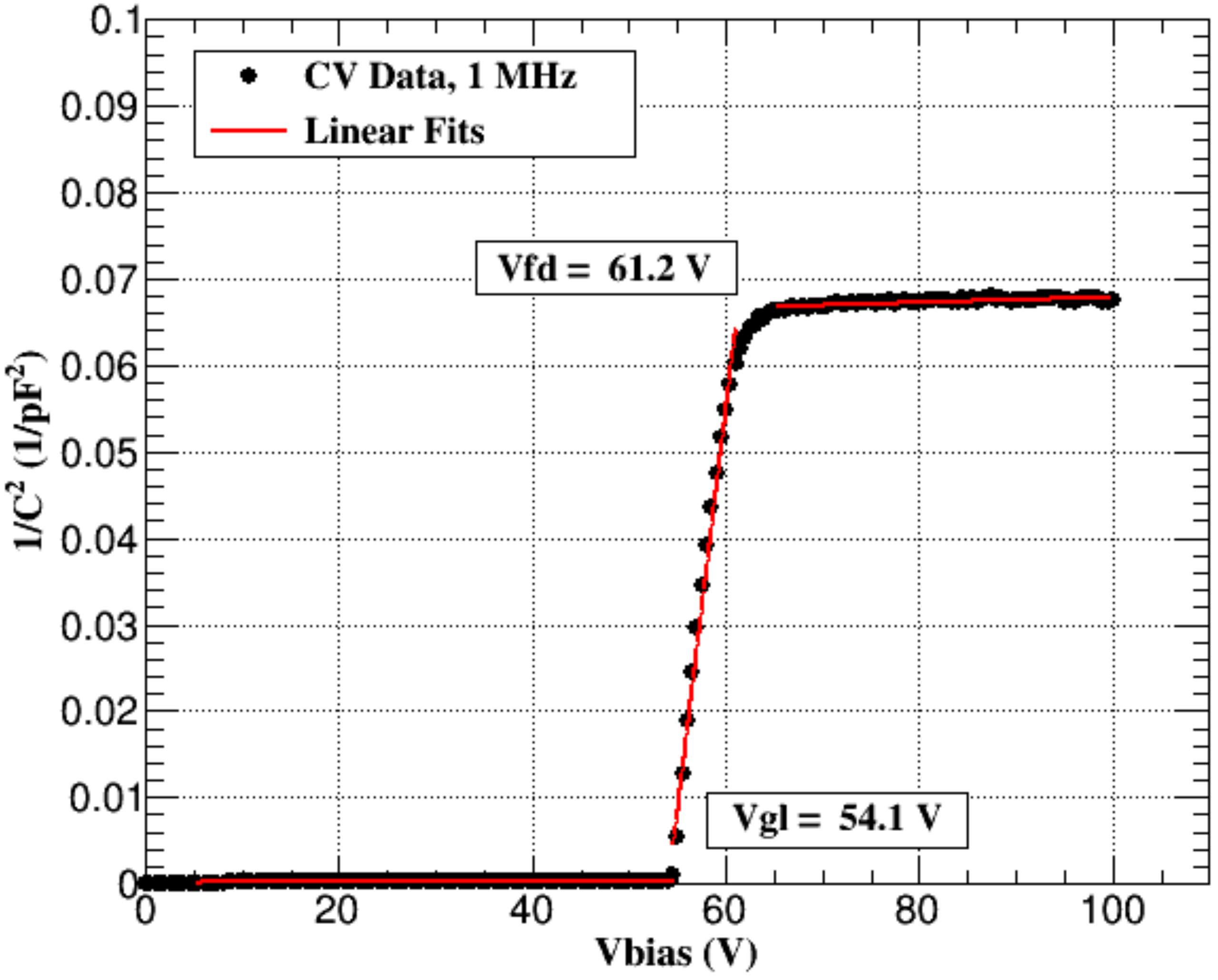
- The PINs are used to verify the silicon bulk breakdown voltage.
- Here is a PIN sensor response to gamma dose.
- There is a rise in leakage current by an order of magnitude after 0.1 MGy.
- The leakage current is approximately constant until just before breakdown.
- The breakdown voltage increases by nearly 300 V after 0.1 MGy.

Single LGAD Current-Voltage (I-V) response to gamma irradiation



- Here is a single LGAD's response to gamma dose. The characteristics are representative of all the wafers studied.
- There is an order of magnitude rise in leakage current after 0.1 MGy. The leakage current increases steadily.
- The knee at ~52 V indicates the gain layer depletion.
- Increase of current by ~5x above 160 V indicates the gain.
- The breakdown voltage increases with gamma dose.

Capacitance-Voltage (CV) Measurement of LGADs



- Here is a representative CV measurement on a single LGAD
- At 54.1 V, the gain layer is depleted (V_{gl}) and the capacitance subsequently drops.
- At 61.2 V, the bulk is fully depleted (V_{fd}) and the capacitance stops increasing with further bias.
- V_{fd}-V_{gl} is proportional to the effective dopant concentration (N_{eff})

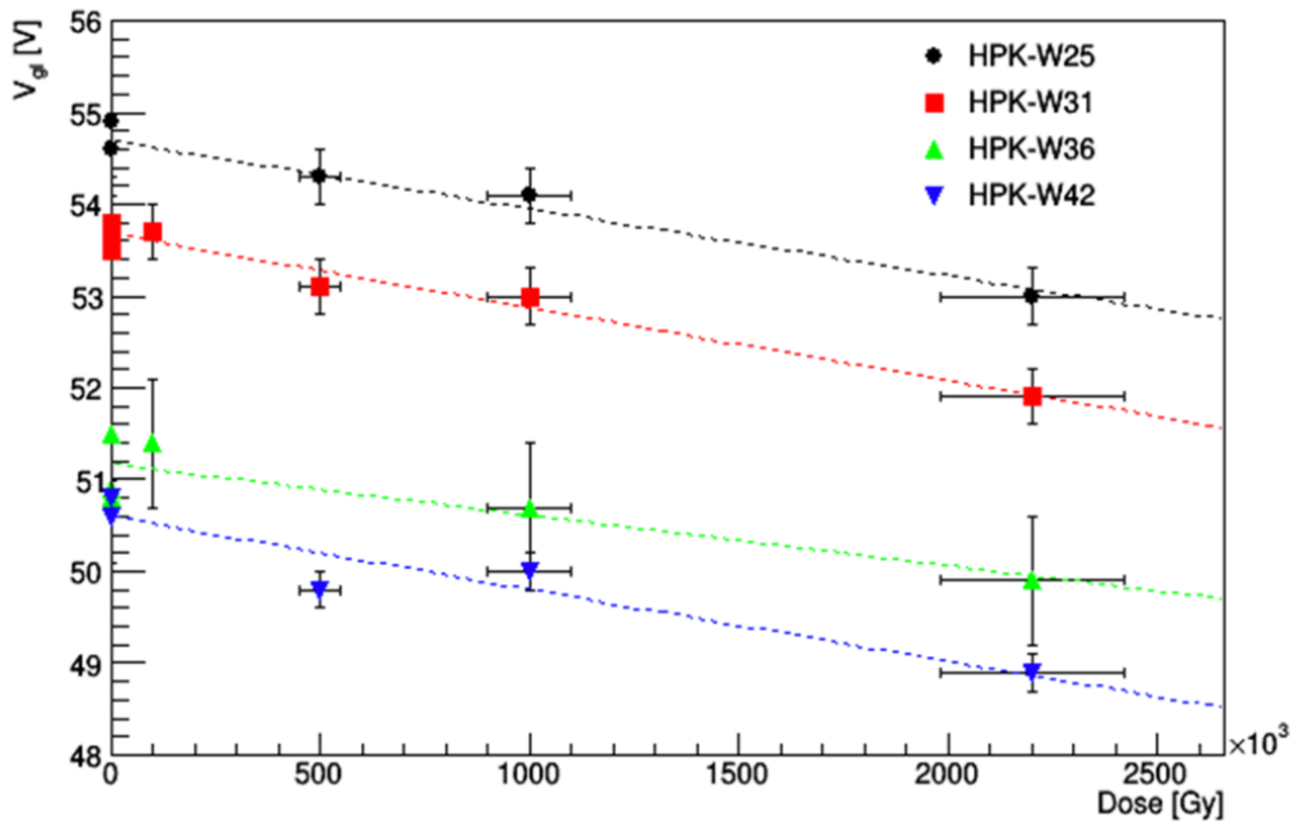
Electron charge — Dopant Concentration

$$V_{fd} - V_{gl} = \frac{qN_{eff}w^2}{2\epsilon}$$

Permittivity of Silicon — Sensor Active Width

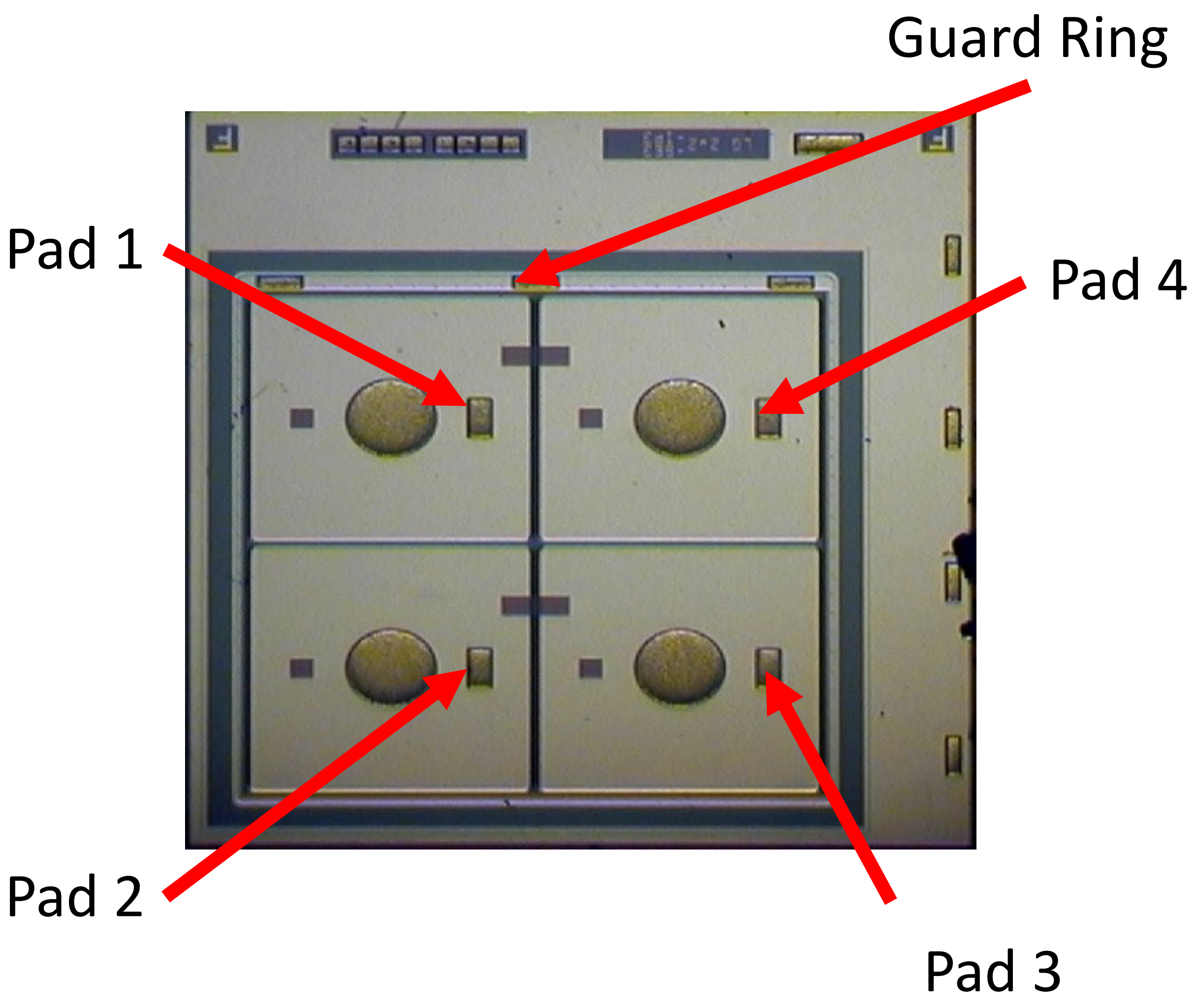
Acceptor removal in the gain layer

- The gain layer depletion voltage (V_{gl}) is found using a capacitance vs voltage measurement.
- Fitting the drop in V_{gl} by $V_{gl} = V_{gl,0} e^{-c\varphi}$ gives the acceptor removal constant, c, for each wafer.
- The acceptor removal constant reflects sensitivity to gain layer damage initiated by gammas



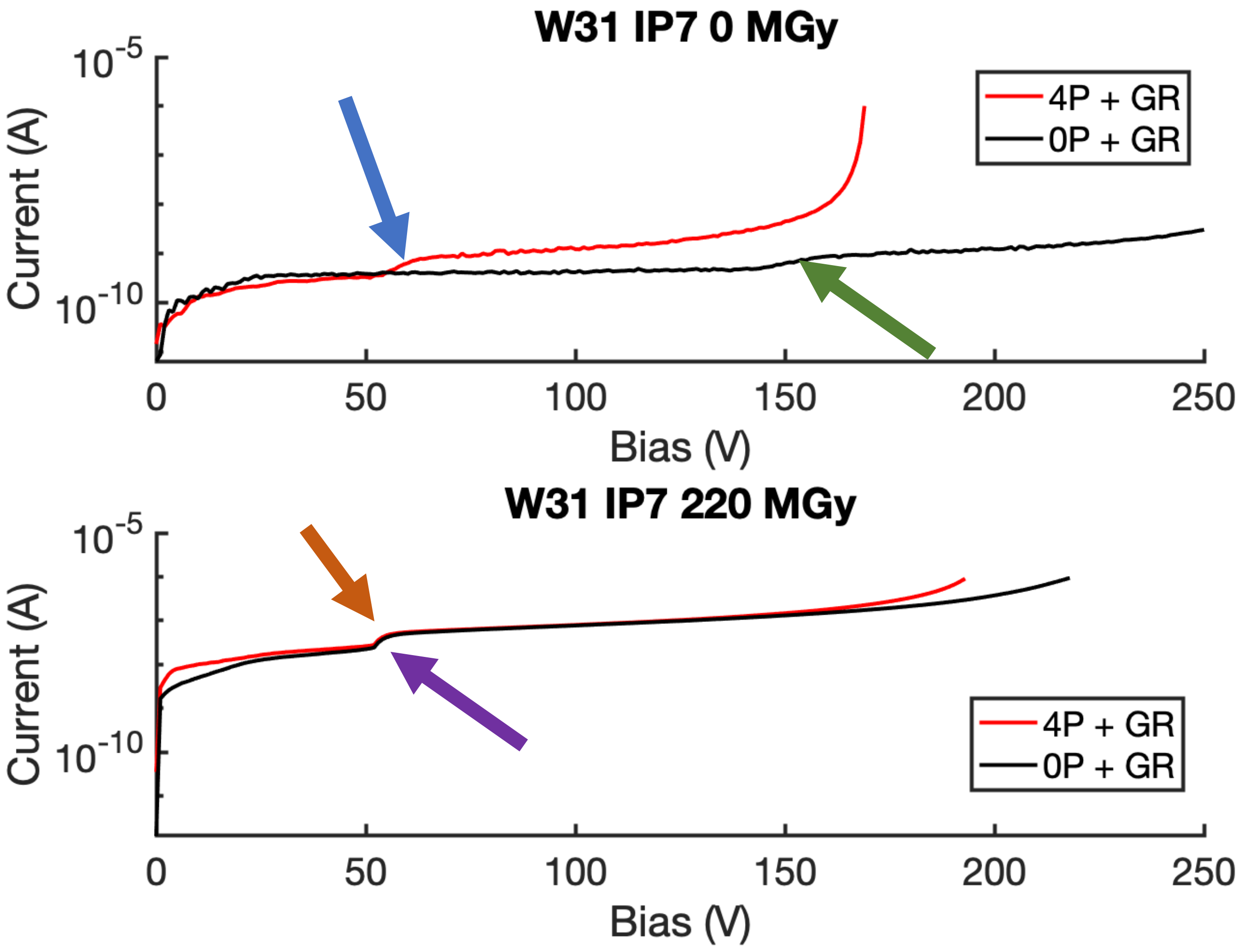
Wafer #	$V_{gl,0}$ (V)	Inter-electrode separation in the quad sensors (μm)	c [x 10^{-8}/Gy] after exposure to 2.2 MGy
25	54	30, 40, 50, 70	1.36
31	53	30, 40, 50, 70	1.51
36	51	30	1.10
42	50	30	1.58

Quad LGAD Current-Voltage (I-V) Response



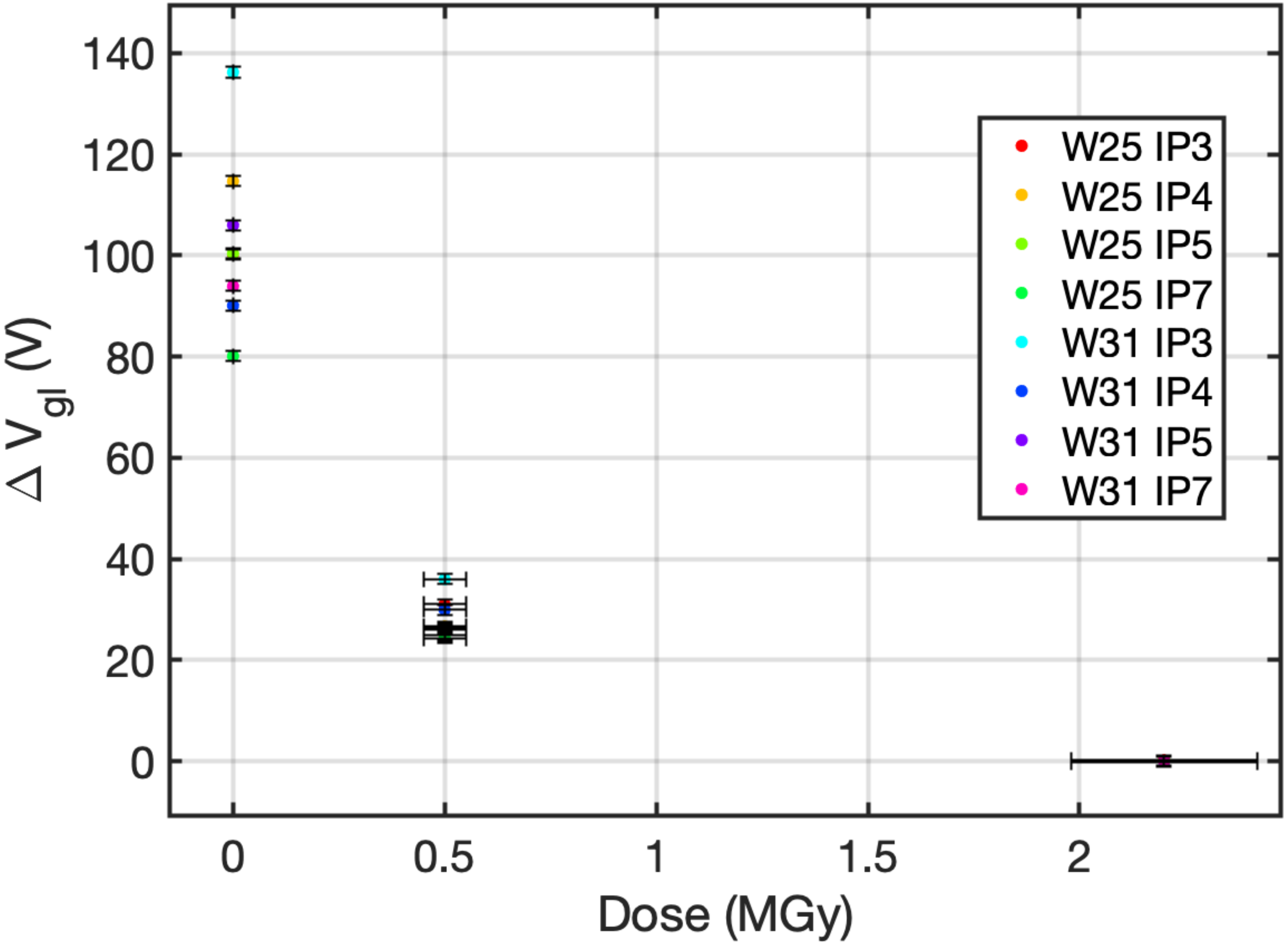
- Quad LGADS were produced with four different inter-pad spacings (30um – 70 um)
- How does gamma irradiation affect the punch-through voltage of the adjacent sensors when one or more pads are floating?
- I-V measurements were performed with contacts on the Guard Ring (GR), the GR and 1 Pad (P), GR and 2 P, GR and 3 P, and with the GR and all 4 P.
- We characterized the punch-though by the difference between the gain layer depletion voltage with only the guard ring connected (0P + GR) and all the pads connected (4P + GR) for different levels of gamma dose.

Quad LGAD I-V Response



- When all pads are biased, we observe the LGADs' characteristic bump in leakage current around 50 V
- When only the GR is biased, the gain layers are not biased until after 150 V
- After gamma irradiation, with all pads biased, the gain layer depletion is still at ~50 V.
- After gamma irradiation, with only the GR biased, the gain layers deplete at ~50 V (indistinguishable from all pads biased)
- We call the difference in the gain layer depletion voltage between all pads biased and only the GR biased ΔV_{gl}

Quad LGAD I-V Response



- Punch-through between the guard ring and the pads occurs at ~100-140 V before irradiation and decreases to near 0 V at 2.2 MGy.
- This indicates a drop of surface resistivity in the region between the guard ring and pads
- The gain implants are still well isolated for fast signals

Summary

(1) The effect of gamma irradiation on single LGADs was characterized.

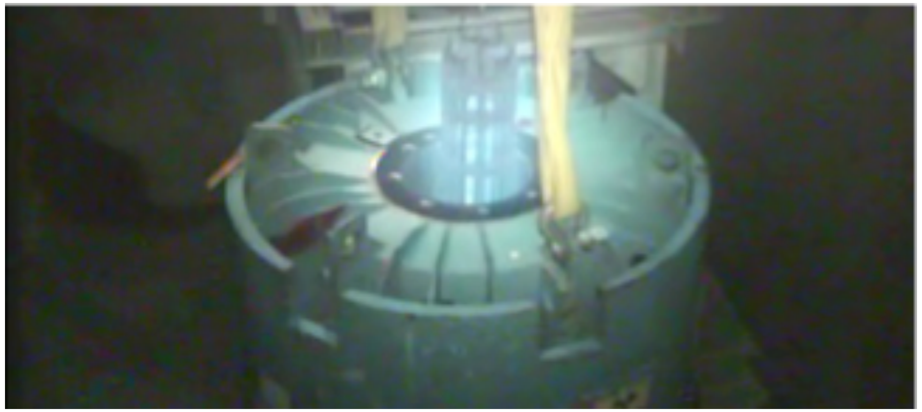
- Leakage current increased by an order of magnitude with 0.1 MGy and doesn’t rise substantially with greater dose.
- Breakdown voltage increased by 30 V, and V_{gl} decreases with 2.2 MGy.

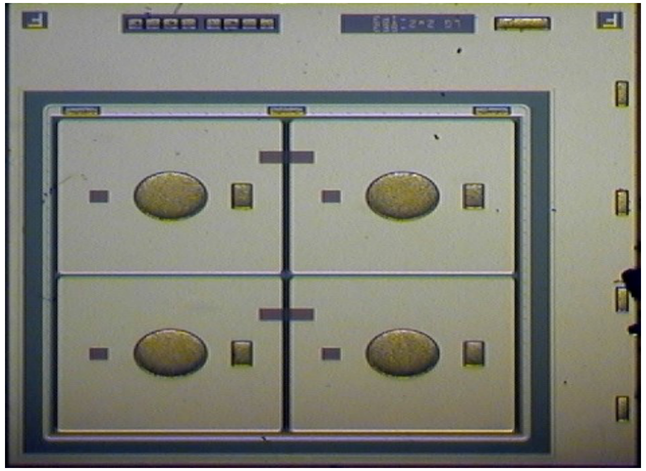
(2) Quad LGADs were used to characterize the loss of resistivity between the guard ring and pads.

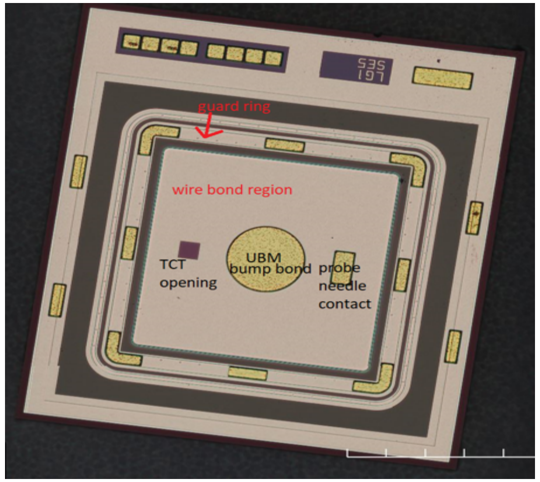
- Punch-though voltage decreased to 0 V with 2.2 MGy indicating loss in surface resistivity between the guard ring and pads.

(3) Now that the LGADs’ leakage current and capacitance response to gamma irradiation have been characterized, the next step is irradiating the detectors at Fermilab ITA with protons.

- **How will proton fluence change the sensors’ leakage current, breakdown voltage, and gain layer depletion voltage?**

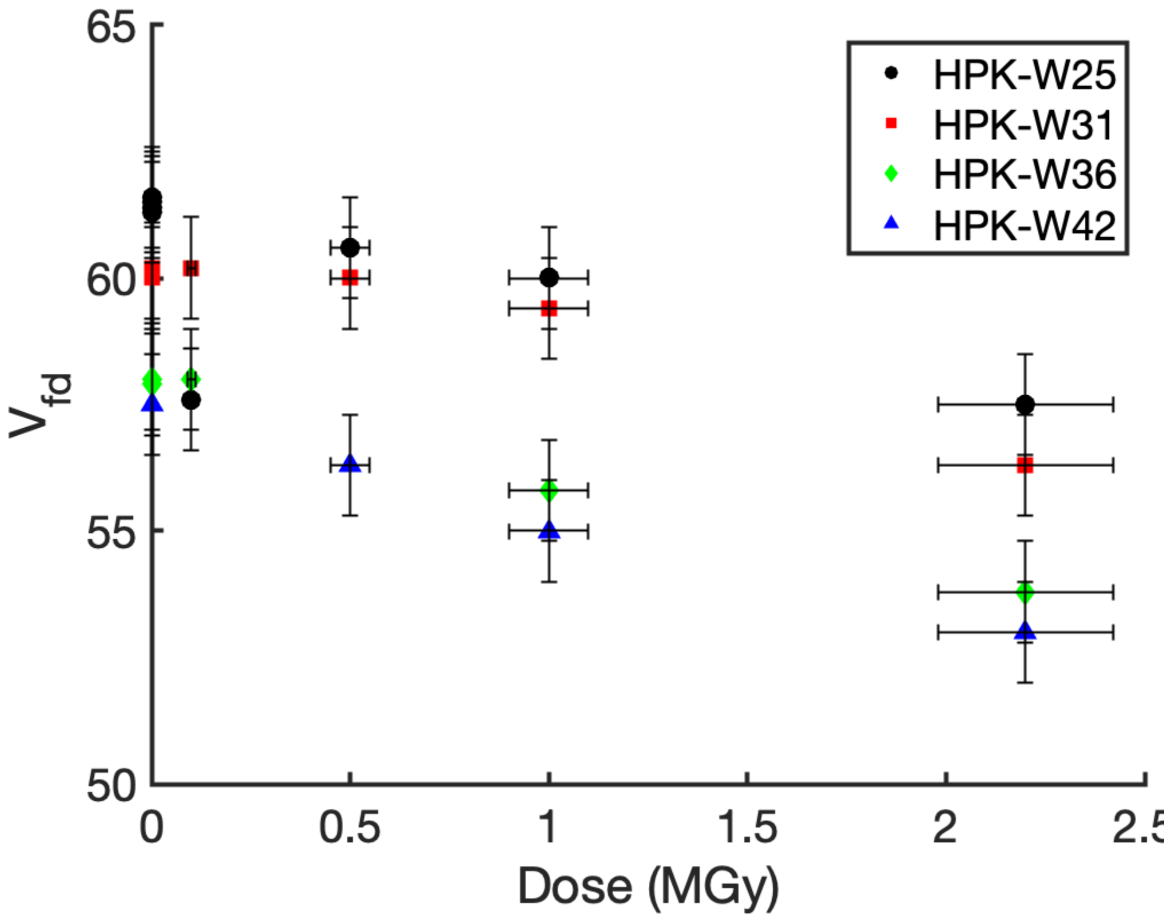


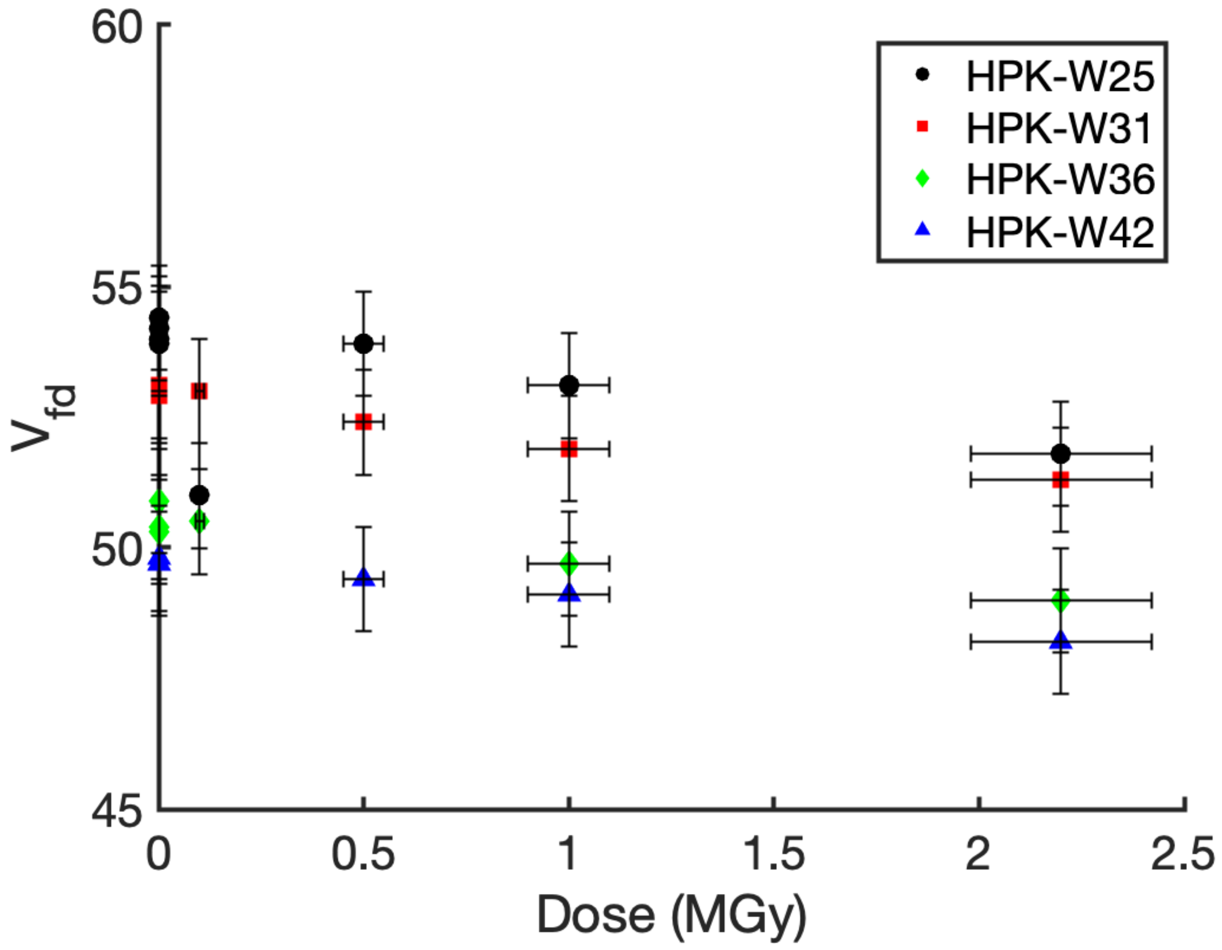




Backup

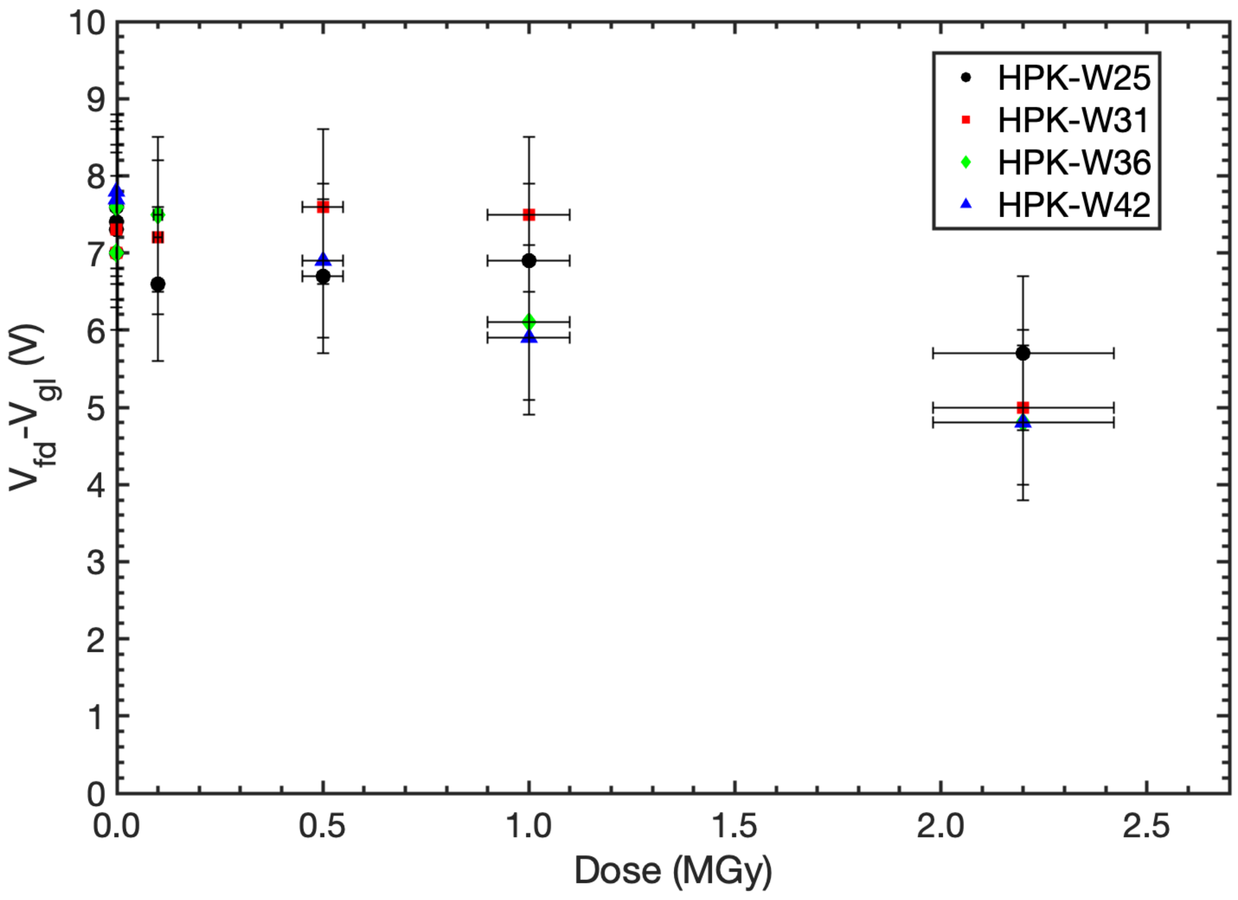
V_gl and V_fd Reference





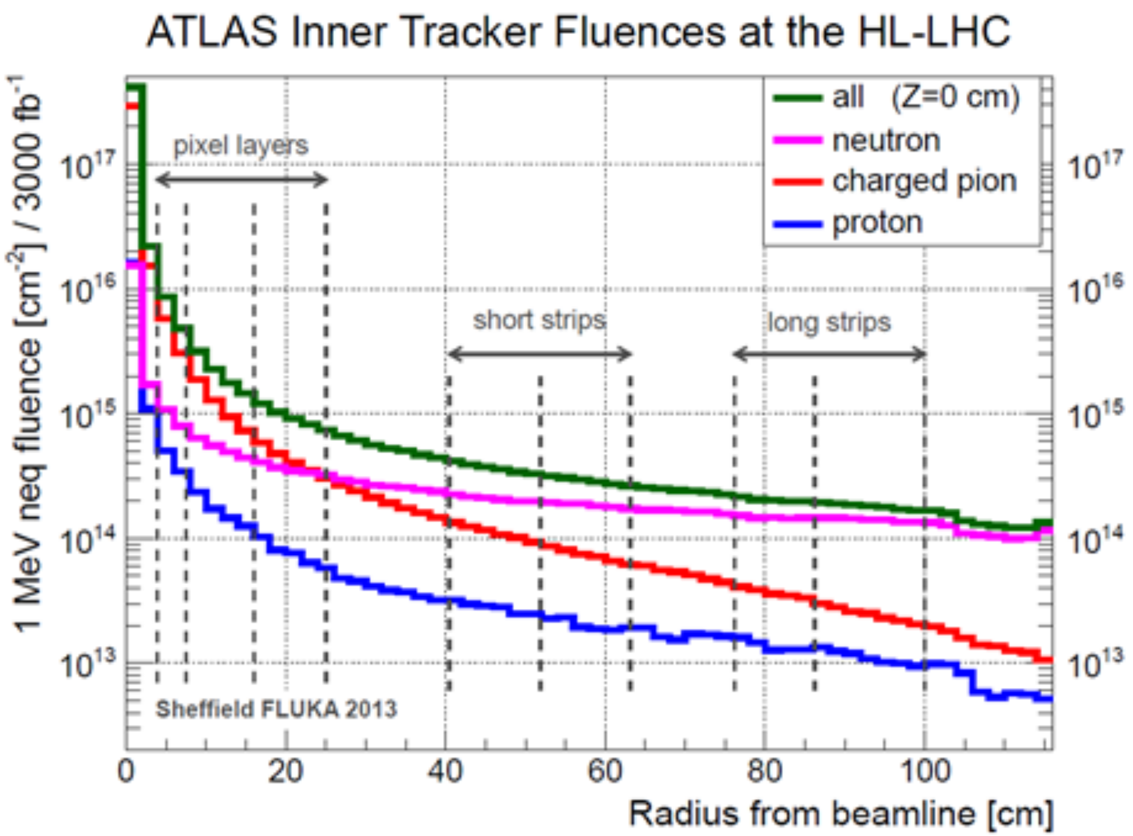
Bulk damage initiated by gammas in single LGADs

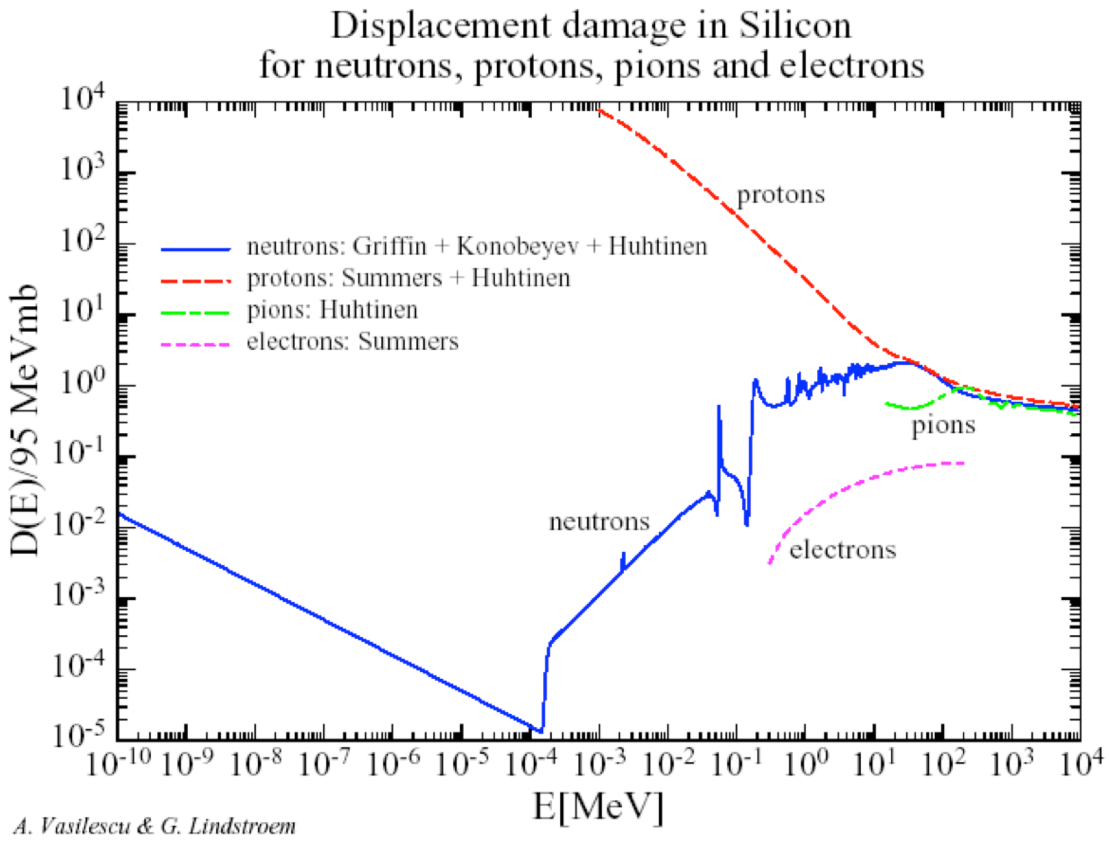
- The difference between the gain layer depletion voltage (V_{gl}) and the full depletion voltage (V_{fd}) versus gamma dose is shown in the plot
- The decrease in V_{fd}- V_{gl} ($\propto N_{eff}$) with increasing dose is indicative of small bulk damage in the crystal.
- The decline in V_{fd}-V_{gl} is due to the decline in dopant concentration from bulk damage. This was fitted to a decaying exponential to yield the acceptor removal constant c



Non-Ionizing Energy Loss (NEIL) scaling hypothesis

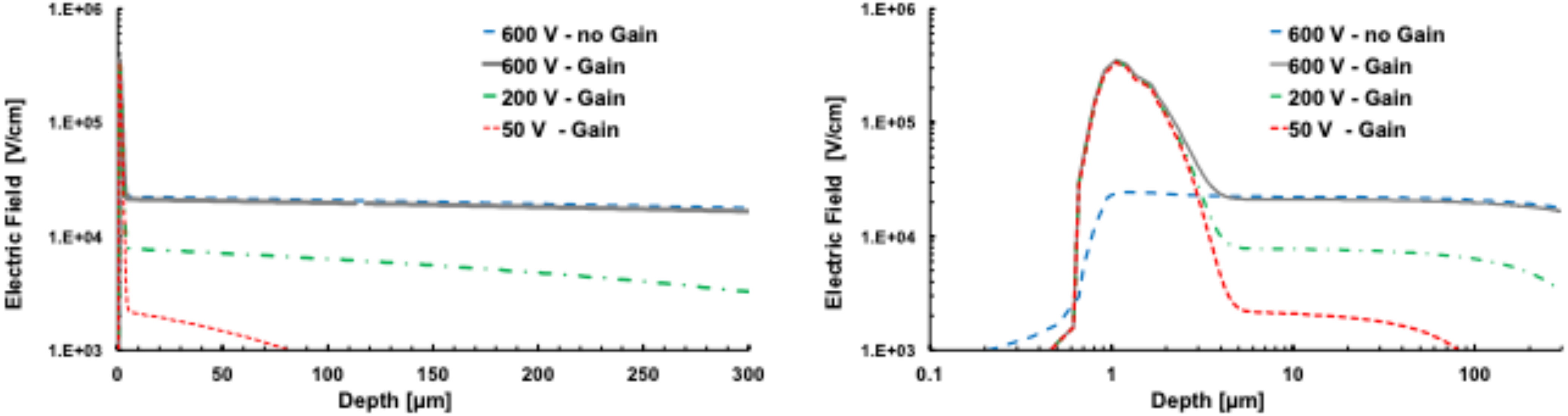
- Most of the charged particle flux at the LHC will be pions with energy around 1 GeV
- The NIEL scaling hypothesis allows us to normalize displacement damage in Silicon between many different charged particles
- In order to simulate this type of fluence, we can use 800 MeV protons from the Los Alamos Neutron Science Center (LANSCE). The scaling factor between these protons and the protons the LGAD will operate under, is ~0.7.





More on the electric field amplification

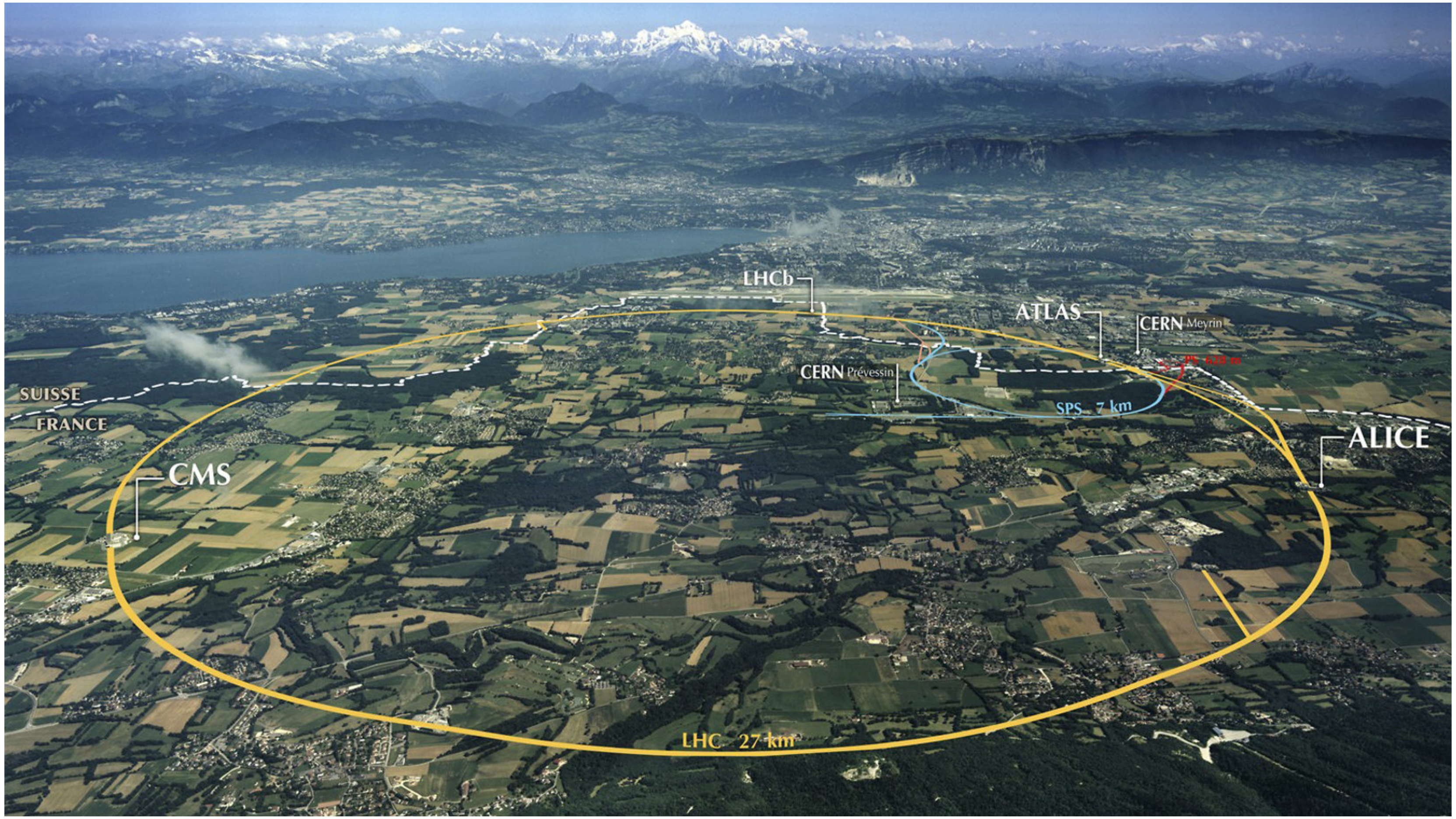
Figure borrowed from **H. F. W. Sadrozinski et al., Ultra-fast silicon detectors (UFSD), Nucl. Instrum. Meth. A831 (2016).**

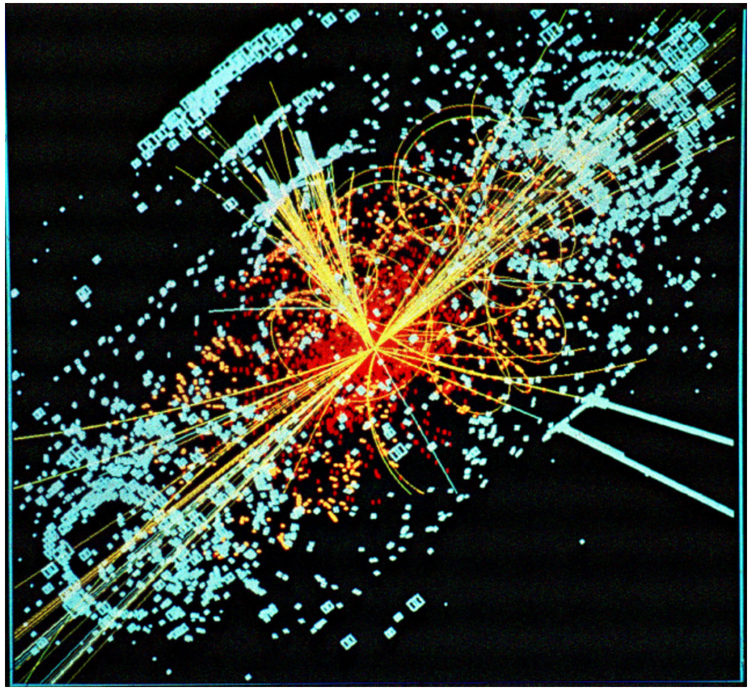


11 Figure 7 The electric field of a 300 µm thick LGAD at different bias voltages compared to a PiN (no gain) Si sensor in linear (left) and logarithmic (right) scale.

Reference: The Large Hadron Collider (LHC)

- The LHC is the largest particle accelerator in the world; with a circumference of 27 km, and providing collisions with enough energy to probe the structure of matter to 10^{-18} m
- Famous for discovering the Higgs Boson

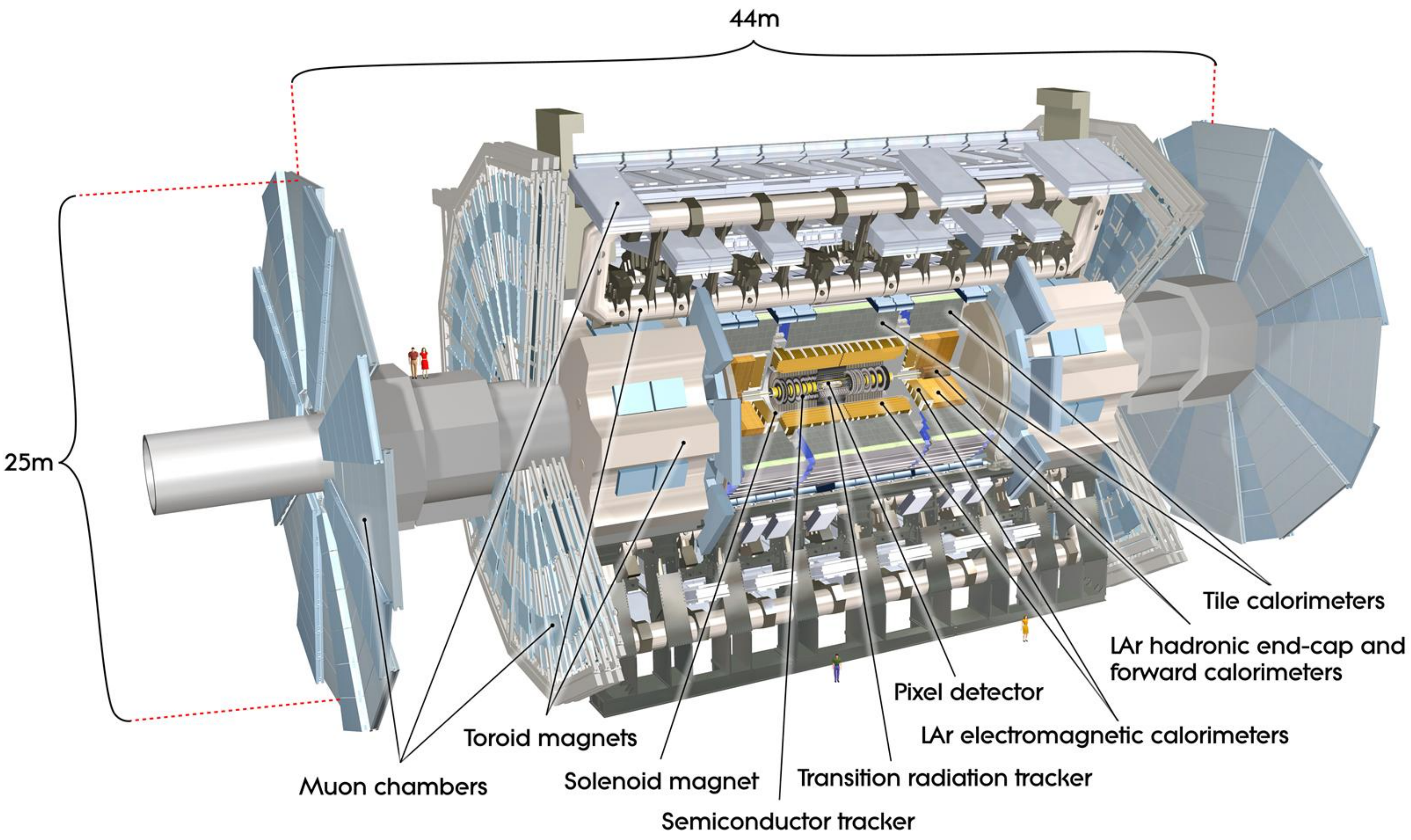




- Four particle detectors are positioned around the accelerator; ALICE, CMS, LHCb, and ATLAS
- A high luminosity upgrade (HL-LHC) is scheduled to finish in 2027, which will increase the luminosity by a factor of 10*

*G. Apollinari et al., High Luminosity Large Hadron Collider HL-LHC, CERN Yellow Reports, 2015

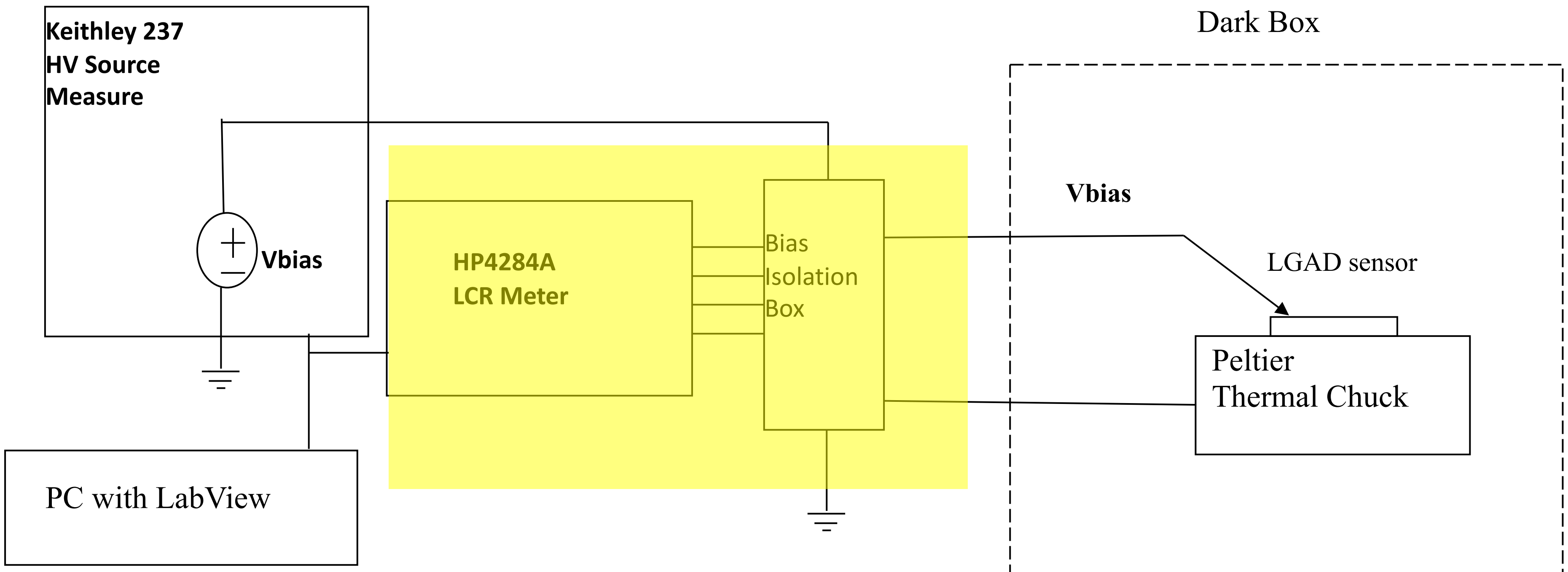
Reference: ATLAS Detector at the LHC



- ATLAS contains six detection subsystems for measuring trajectory, momentum, and energy.
- **Low Gain Avalanche Detectors (LGADs)** are candidates to be installed near the interior of the detector during the HL-LHC upgrade.
  - LGADs will provide better timing resolution than the current pixel detectors
  - LGADs need to be radiation hard to operate after exposure to fluences of 10^{15} neq cm^{-2}

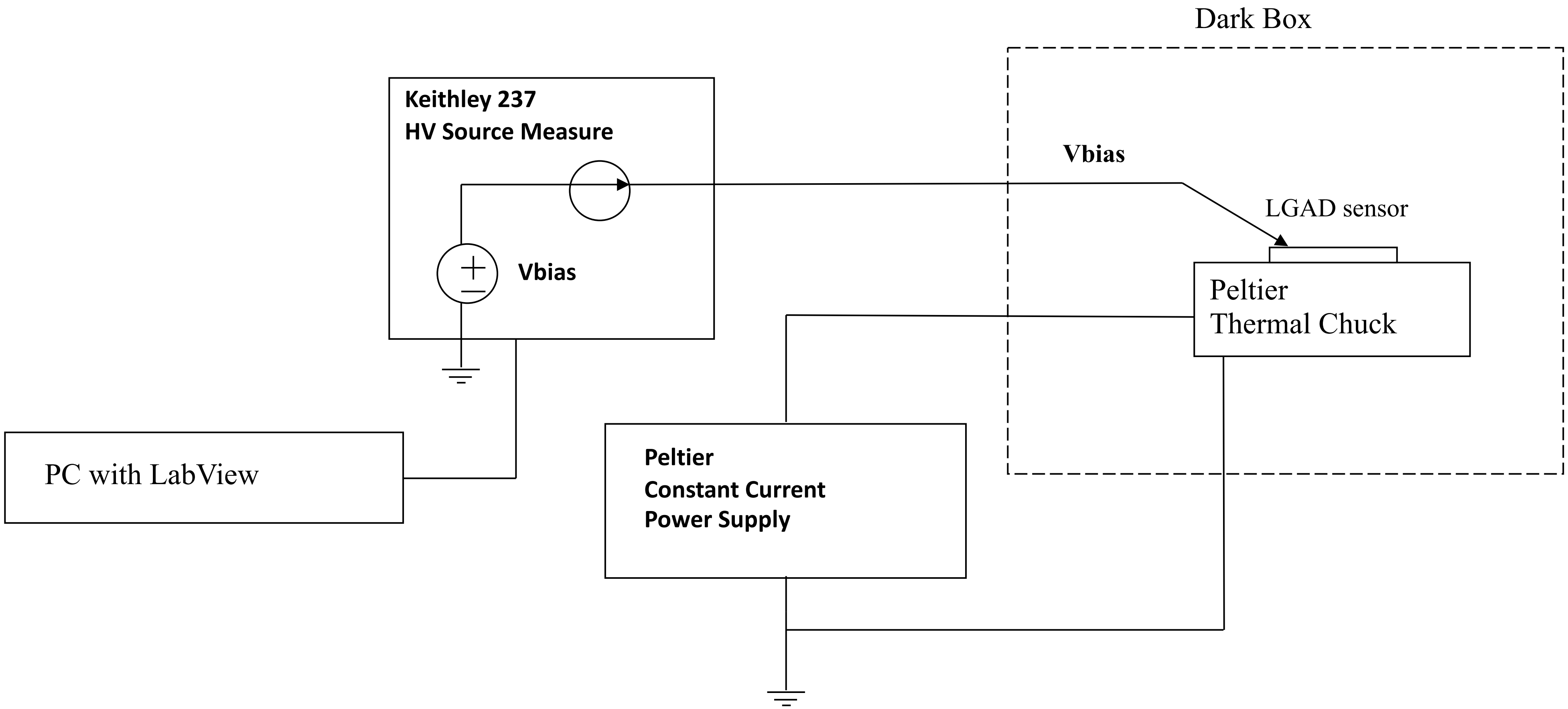
BACKUP: Capacitance vs. Voltage (CV) Measurement

- CV measurements are used to infer the gain layer depletion voltage
- Apply reverse voltage bias with the K237 V-source
- Measure sensor capacitance with the LCR meter at 10kHz, 100Khz, 1MHz frequencies



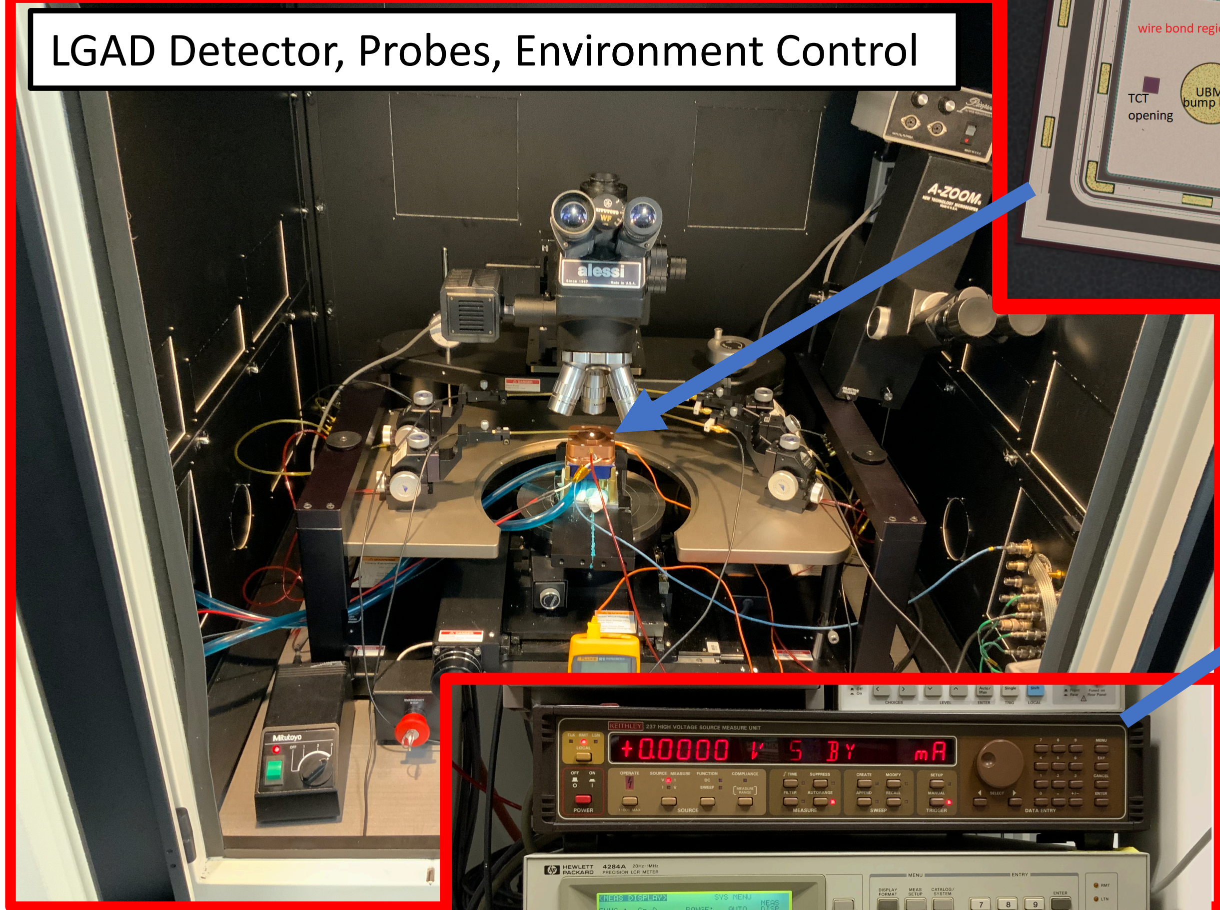
Backup: Current vs. Voltage (IV) Measurement

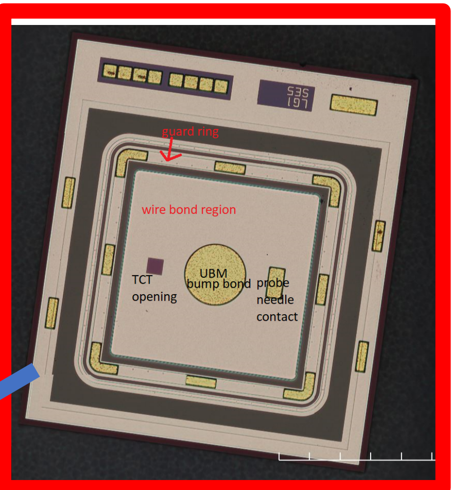
- IV measurements are used to infer depletion and breakdown conditions
- Apply reverse voltage bias with the K237 V-source
- Measure leakage current with the K237



Experiment Setup

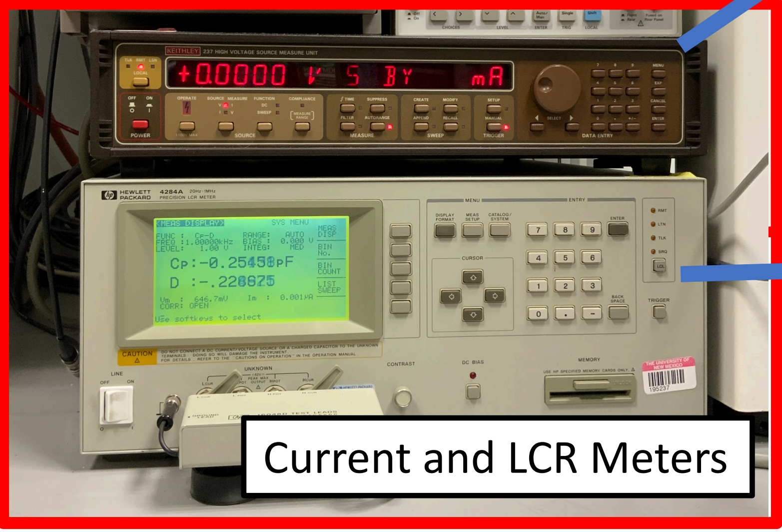
LGAD Detector, Probes, Environment Control





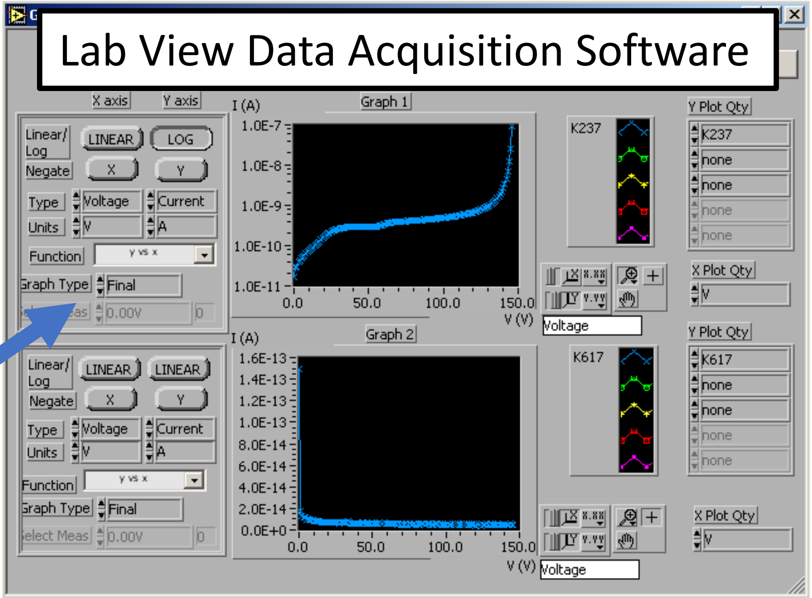
Current vs Voltage

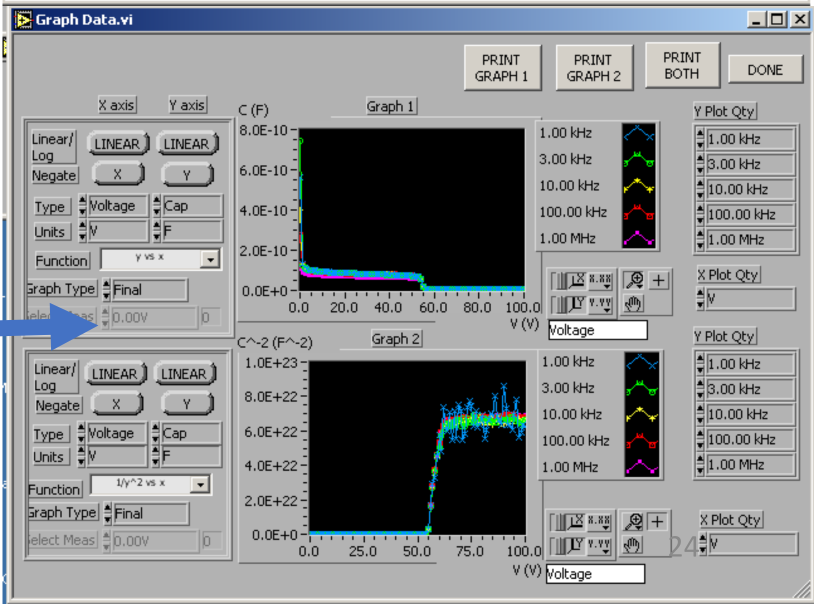
Capacitance vs Voltage



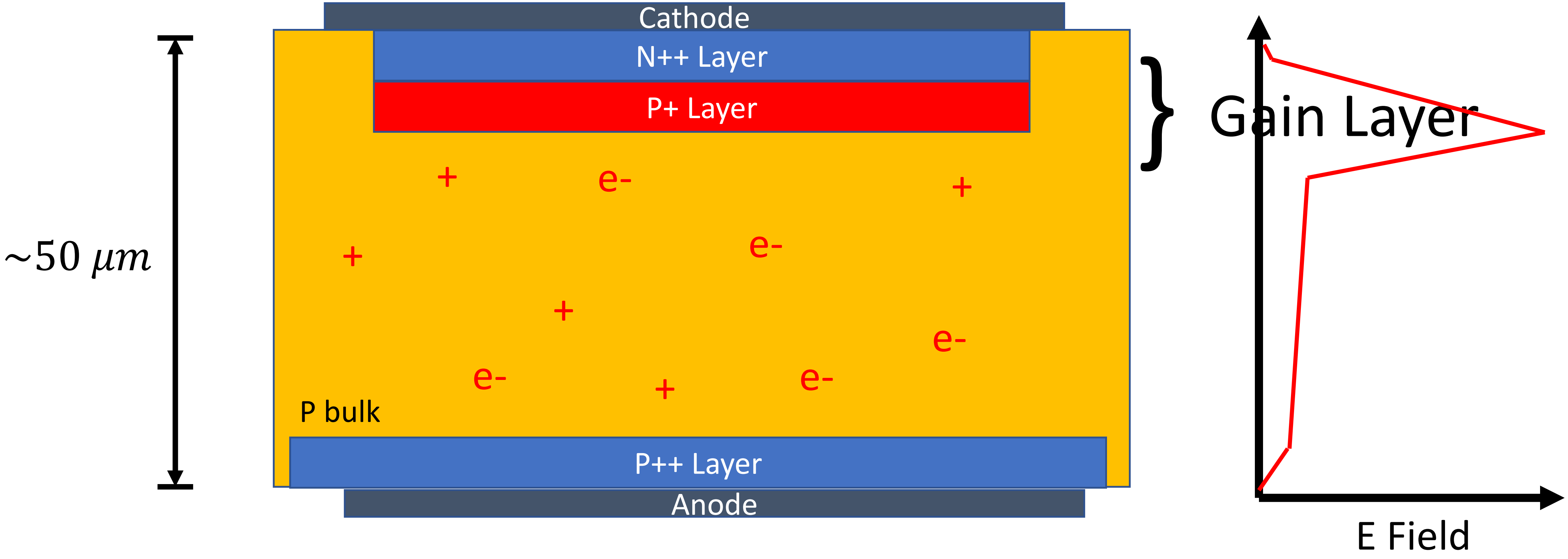
Current and LCR Meters

Lab View Data Acquisition Software



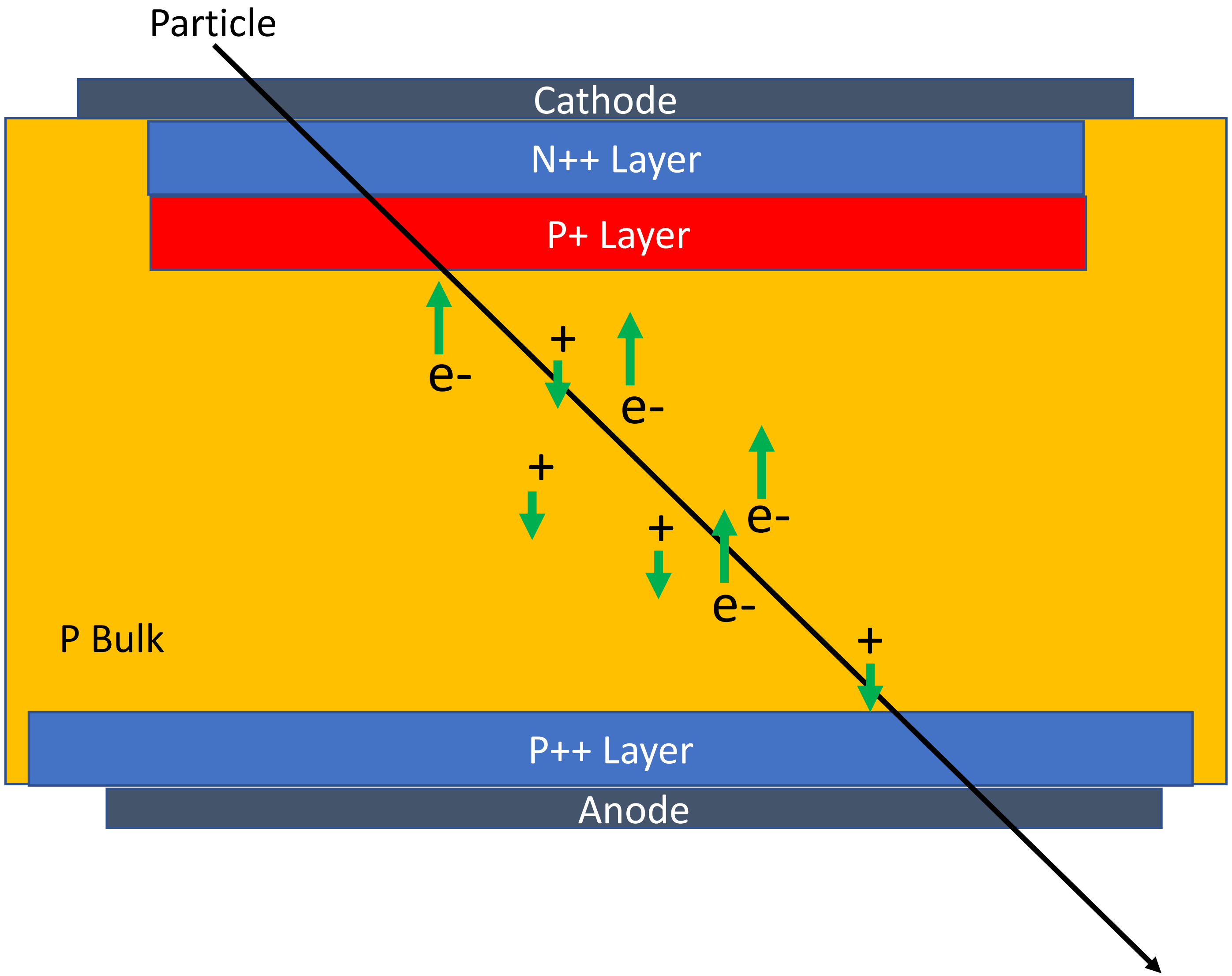


How do LGADs work?



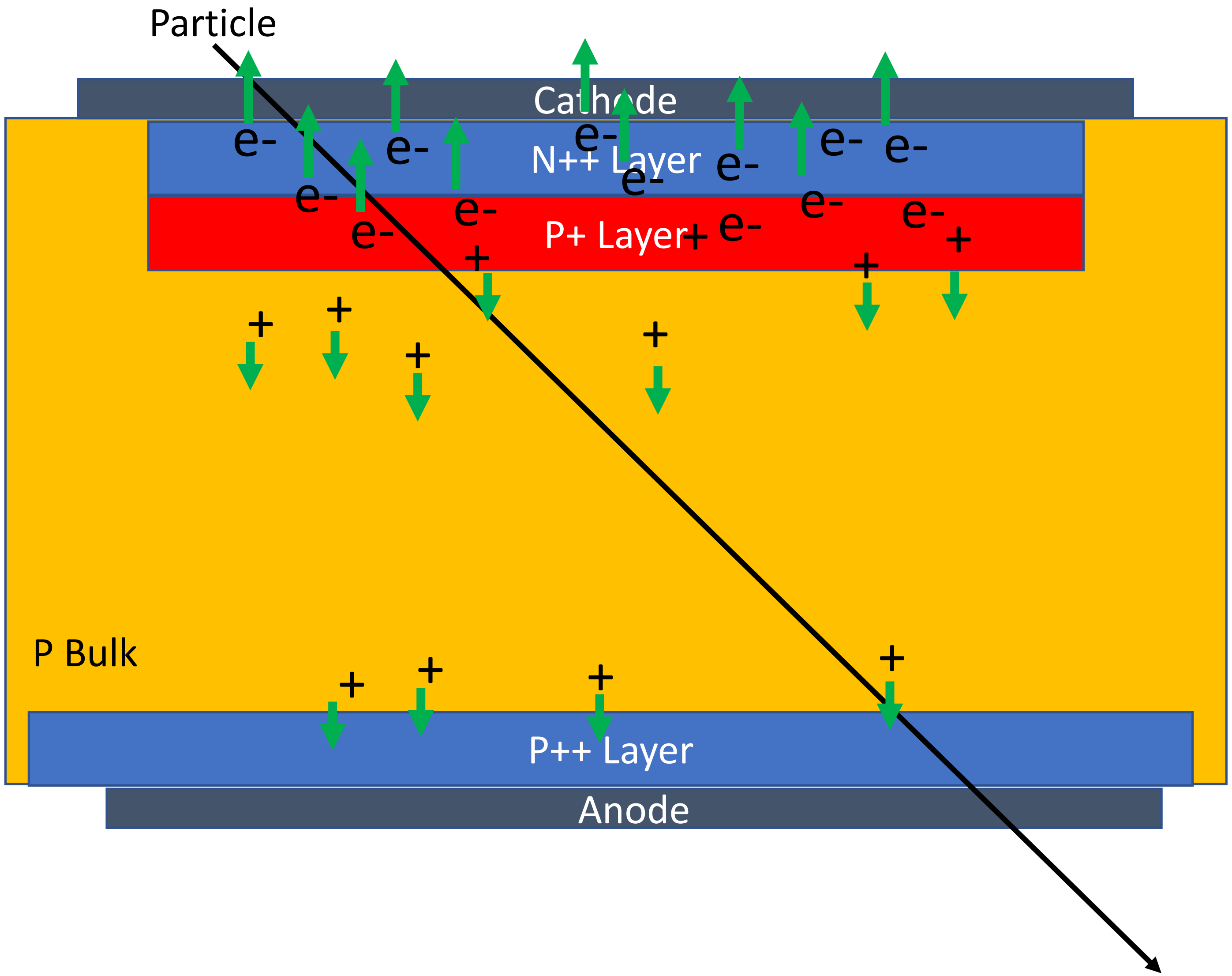
- There are thermally generated electron-hole pairs at temperatures above 0K which can be amplified and contribute to noise. These are swept out by reverse biasing the detector.
- Reverse biasing the detector gives rise to a very large electric field across the N++ and P+ layer, due to the large difference in their doping concentration.

How do LGADs work?



- A charged particle from the interaction point will pass through the detector causing electron ionization. The free electrons and holes will migrate towards the cathode and anode respectively.
- Electrons will drift towards the gain layer

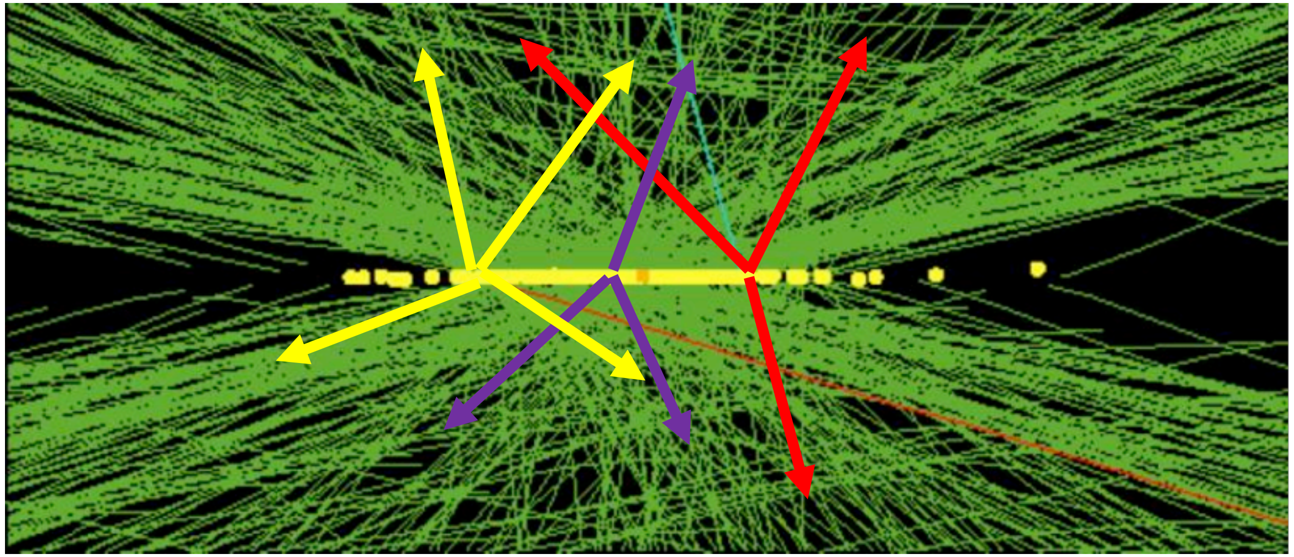
How do LGADs work?



- Electrons that pass through the gain layer will be accelerated by the high electric field.
- With higher momentum, the electrons will generate more free electrons when colliding with silicon atoms in the crystal lattice. This amplification mechanism is impact ionization.
- The sensors' internal gain is ~5-70.

Reference: Why are LGADs being considered?

- Fast timing
  - Proton bunches collide in the detector every 25 ns. This causes pile up, in which particles from different collisions can be attributed to the same collision. At least 50 ps timing resolution will be needed to distinguish different vertices.
  - Thinning detectors can improve timing resolution (quicker charge collection) but reduces the signal (lower charge deposition by ionizing particles)
  - By having some internal signal amplification, the detectors can be made thinner while maintaining adequate signal to noise ratio.



1 ns frame of simulated particle tracks. One bunch crossing will consist of 150-200 events[1].

[1]H. F. W. Sadrozinski et al., Ultra-fast silicon detectors (UFSD), Nucl. Instrum. Meth. A831 (2016) 18–23.

More on the importance of sensor timing

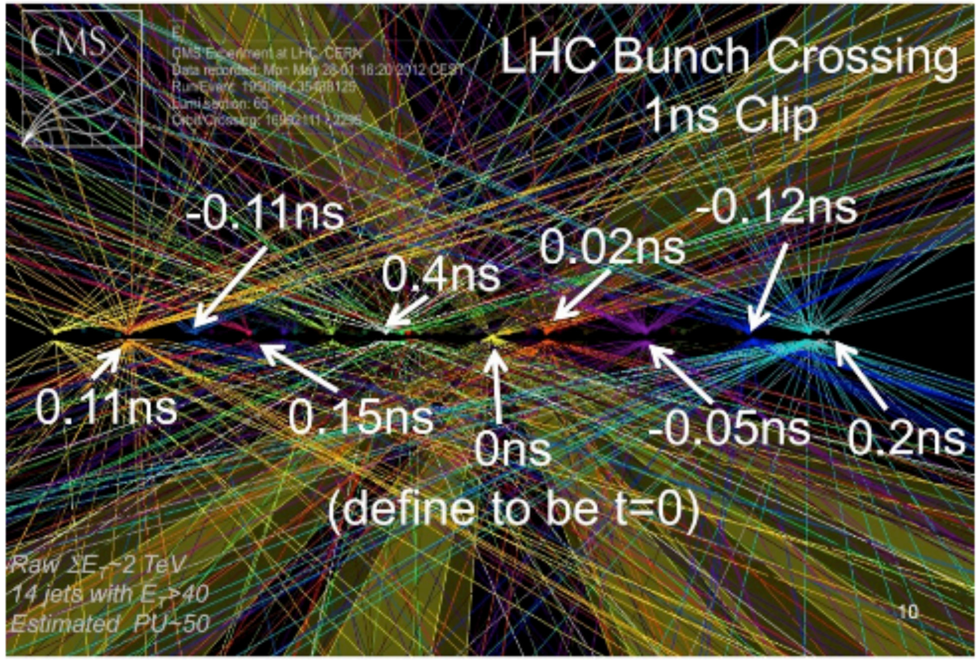


Figure 1 Interaction time of many proton-proton vertexes happening in the same bunch crossing
the case of ~ 50 overlapping events. The vertexes are spaced 10's of pico seconds apart.

Figures borrowed from **H. F. W. Sadrozinski et al., Ultra-fast silicon detectors (UFSD), Nucl. Instrum. Meth. A831 (2016).**

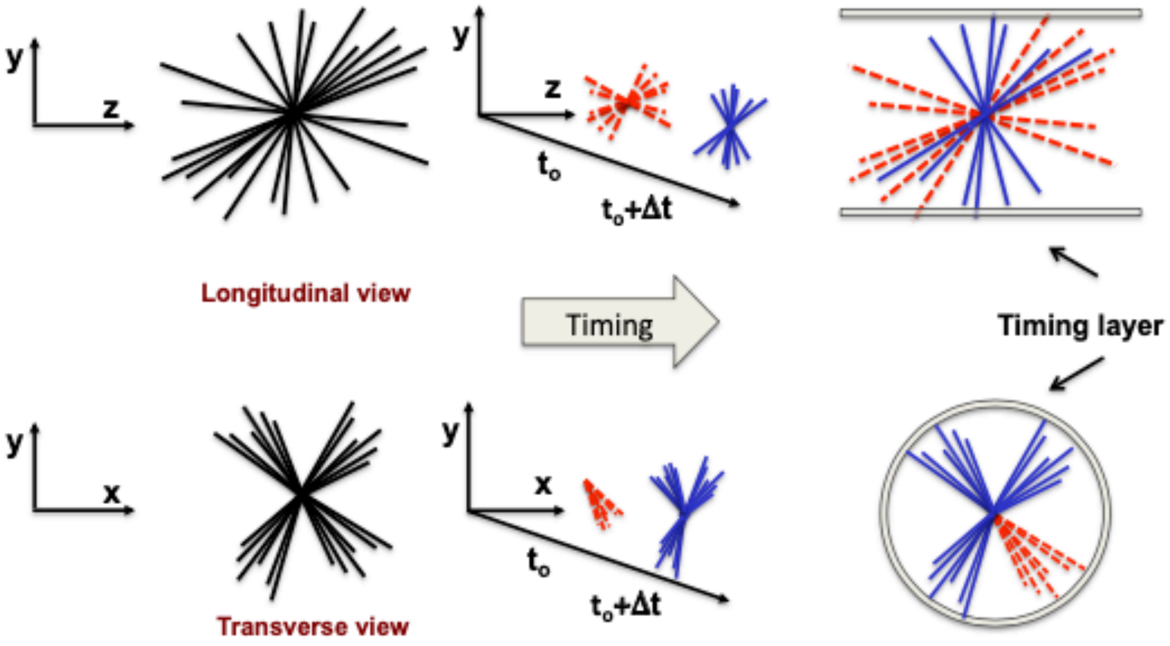
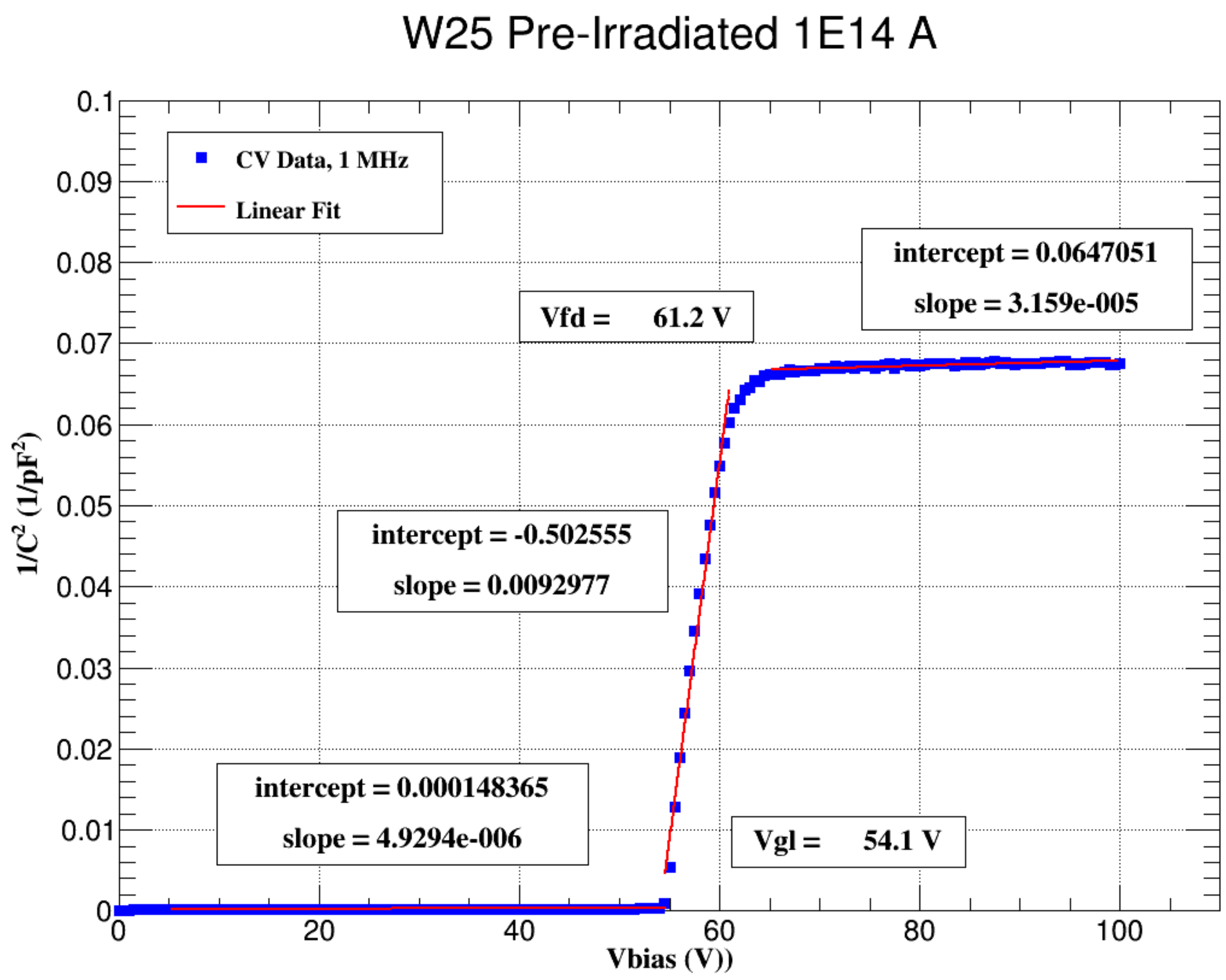
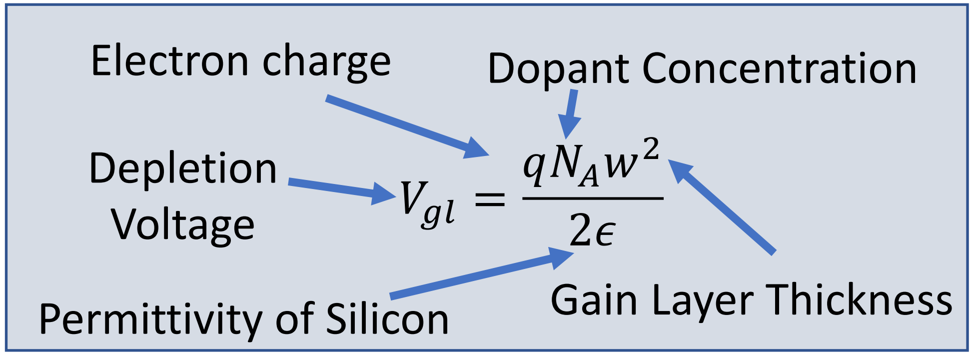


Figure 4 Schematic representation of the power of timing information in distinguishing overlapping events using a timing layer.

Capacitance vs. Voltage Measurement



- The LGAD is reverse biased to sweep the charge from the detector's bulk.
- At 54.1 V, there is a sharp decrease in the LGAD's capacitance (increase in $1/C^2$) when the gain layer finishes depleting.
- At ~61.2 V, the LGAD is fully depleted. The smaller capacitance is due to the lack of free charges after being depleted.



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