Institut "Jožef Stefan", Ljubljana, Slovenija

DRD3 AIDAInnova CERN SPS Test Beam Readiness on FBK TI-LGADs for October 2025

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Overview

DRD3 AIDAInnova Test Beam - October ’25

- Irradiated test structures for October TB are wire-bonded at JSI
- Test structures were checked with a radioactive source to verify signal detection
- Non-irradiated samples will be provided by CERN / Zürich
- Leakage Current Transition (LCT)[1] method applied to TI-LGADs in leakage current-voltage analysis, implemented with a skew-normal + baseline fit
- V_{gl} is defined as the location parameter μ, which generalizes the original LCT peak-based definition (explained in more detail later in the presentation)

[1] Gkougkousis, E. L. (2021). Comprehensive technology study of radiation hard LGADs, CERN. https://cds.cern.ch/record/2790739

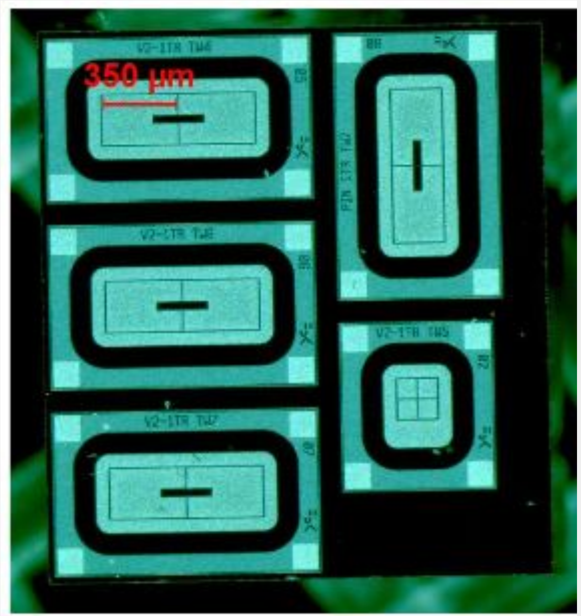
TI-LGAD test structures to be characterized at SPS

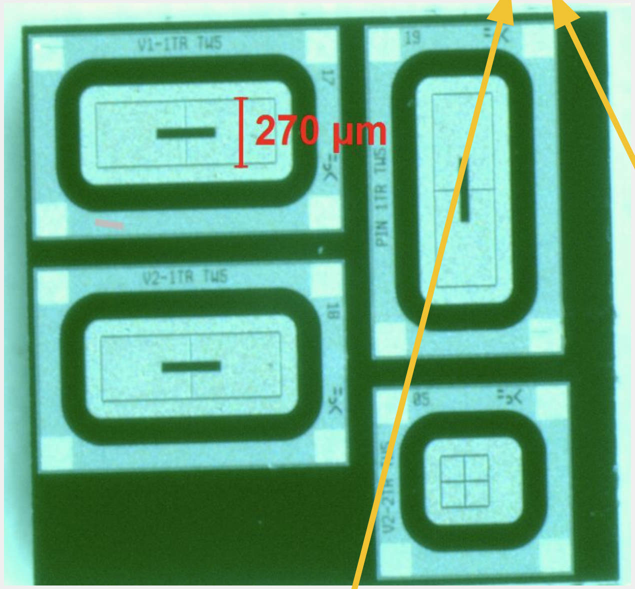
Border version	Number of Trenches
V2	1TR
V1	1TR
V2	1TR
V2	2TR

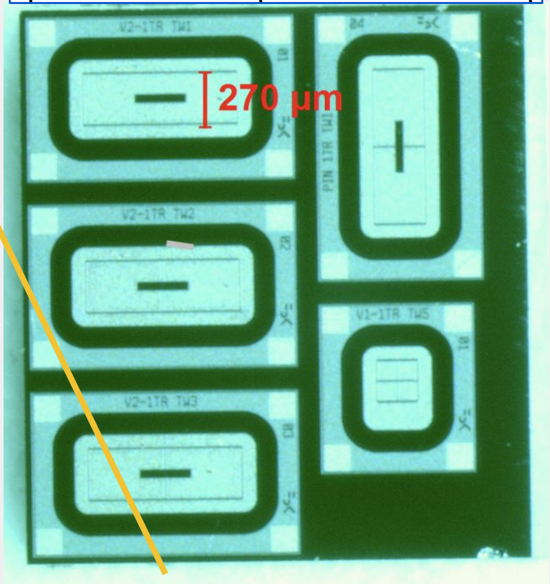
45 µm thick sensors

375 µm × 250 µm pixel pitch

Priority!





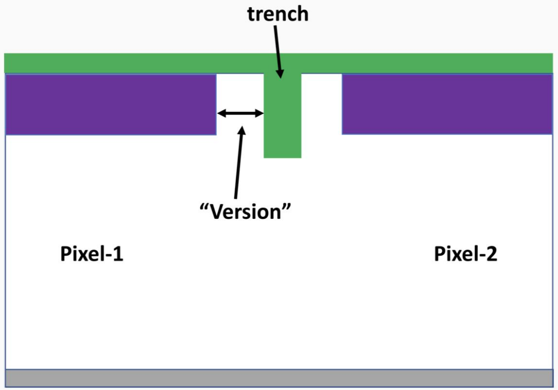


V2 - 1TR- TW 4/6/7

V 1/2 - 1TR- TW 5

V2 - 1TR- TW 1/2/3

Meaning of V1 & V2 Test Structures



[Data Source – FBK](#)

Versions:

- **V1**, V2, V3, and V4
- V1 → Aggressive
- V4 → Safe

V1	TW5
V1	TW5
V1	TW5
V1	TW5
V1	TW5
V1	TW5
V1	TW5
V2	TW 4/6/7
V2	TW 4/6/7
V2	TW 4/6/7
V2	TW 4/6/7
V2	TW 1/2/3
V2	TW 1/2/3
V2	TW 1/2/3
	From previous test beam
V2	TW 1/2/3
V2	TW 1/2/3

Testing V1 TW5 for the first time in October – previously only V2

V parameter refers to the distance that is left between the edge of the gain layer and the center of the trenches structure:

[Comprehensive Characterization of the TI-LGAD Technology](#)

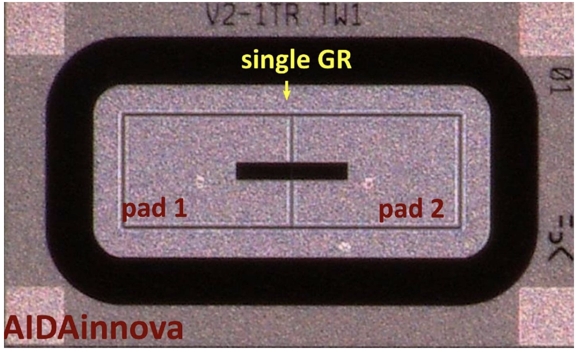
Test structures to be characterized I

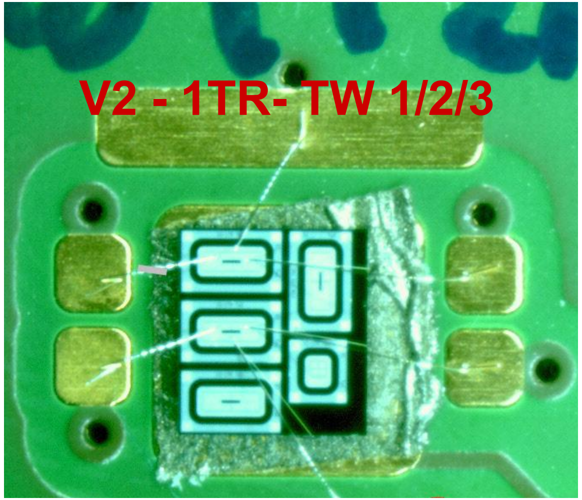
DRD3 AIDAInnova Test Beam October '25 TI-LGADs types

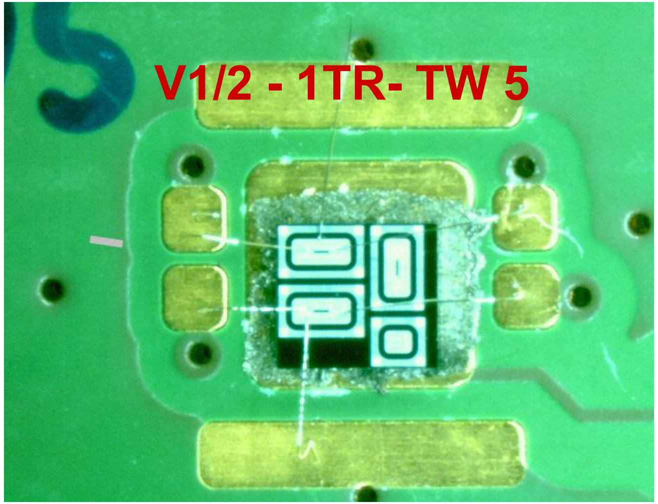
Link to TS:
October_TB_2025

Test structures to be characterized II

DRD3 AIDAInnova Test Beam October ’25 TI-LGADs types





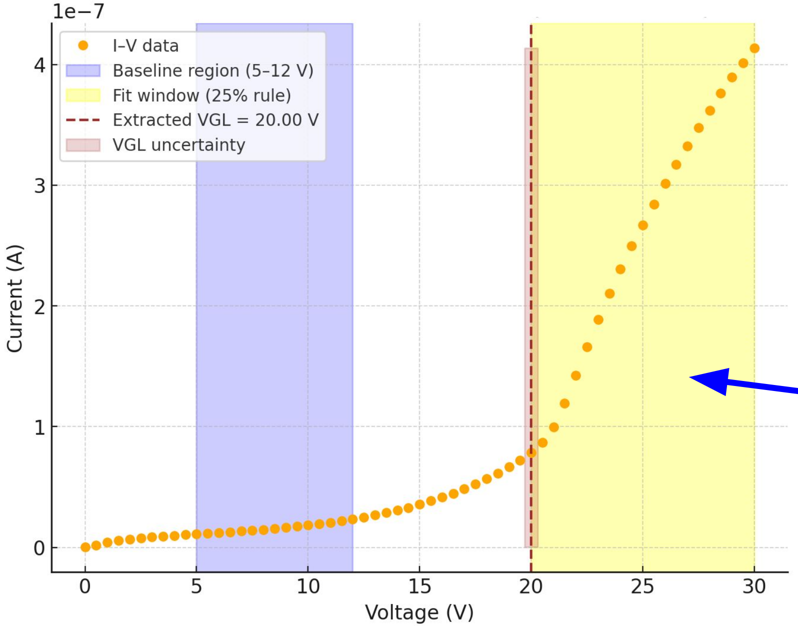


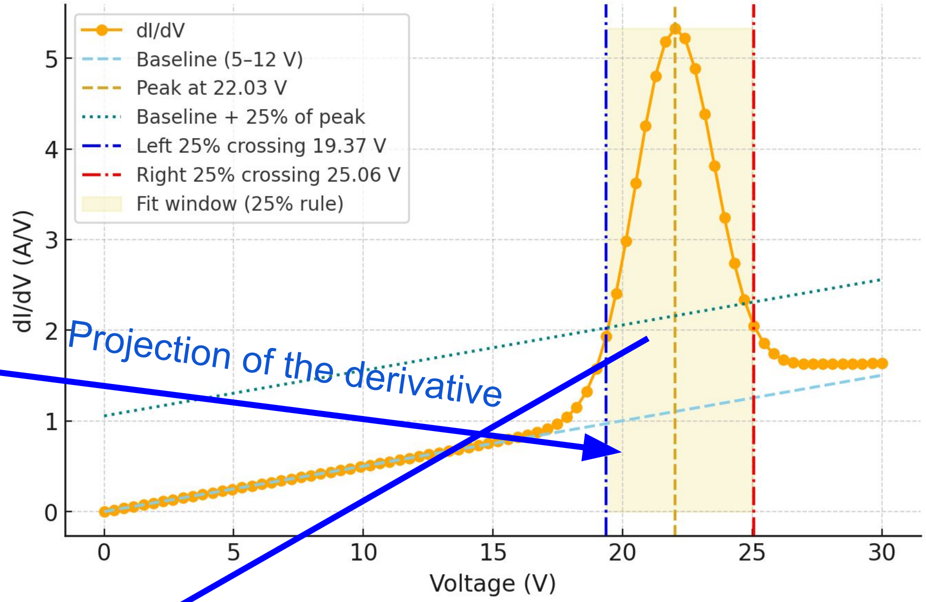
Link to TS:
October_TB_2025

Wire-bonded test structures

Trench Depth	Trench parameter	Fluence (n_{eq}/cm^2)	Devices	Number of daughterboard	Chubut CH1,2	Chubut CH3,4	Batch Number (proposed)
V1	TW5	2.50E+15	V1TW5 / V2TW5	1	V1TW5	V2TW5	1
V1	TW5	2.50E+15	V1TW5 / V2TW5	2	V1TW5	V2TW5	2
V1	TW5	2.50E+15	V1TW5 / V2TW5	3	V1TW5	V2TW5	3
V1	TW5	2.50E+15	V1TW5 / V2TW5	4 @JSI	V1TW5	V2TW5	
					V1TW5	V2TW5	1
V1	TW5	1.50E+15	V1TW5 / V2TW5	5	V1TW5	V2TW5	2
V1	TW5	1.50E+15	V1TW5 / V2TW5	6	V1TW5	V2TW5	
V1	TW5	1.50E+15	V1TW5 / V2TW5	7 @JSI	V1TW5	V2TW5	3
V2	TW 4/6/7	1.50E+15	Standard	8	V2TW4	V2TW6	
V2	TW 4/6/7	1.50E+15	Standard	9 @ JSI	V2TW4	V2TW6	3
V2	TW 4/6/7	2.50E+15	Standard	10	V2TW4	V2TW7	3
V2	TW 4/6/7	2.50E+15	Standard	11	V2TW4	V2TW6	2
V2	TW 1/2/3	1.50E+15	Standard	12	V2TW1	V2TW3	2
V2	TW 1/2/3	2.50E+15	Standard	13	V2TW1	V2TW2	1
V2	TW 1/2/3	2.50E+15	Standard	14	V2TW1	V2TW3	1
	From previous test beam						
V2	TW 1/2/3	8.00E+14	Standard	15	V2TW1	V2TW2	Backup
V2	TW 1/2/3	1.50E+15	Standard	16	V2TW1	V2TW2	Backup

Representation of the model used in the IV analysis I

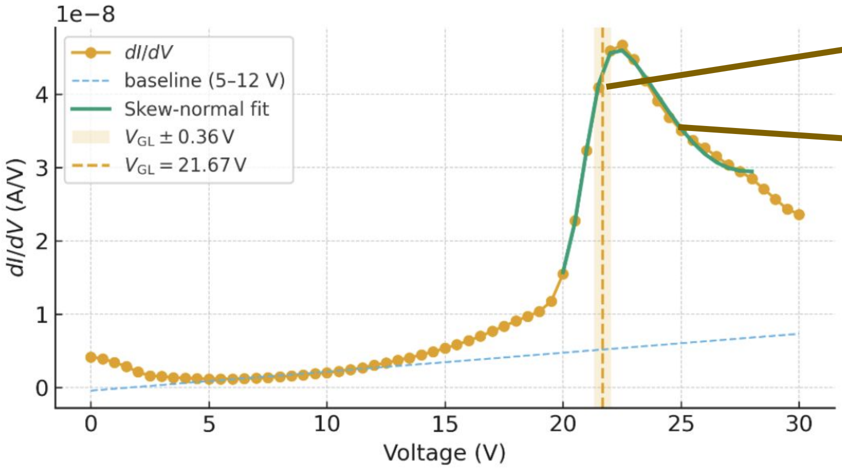




Projection of the derivative

*25% refers to **amplitude in dI/dV**: the window is where dI/dV stays above **baseline + 25% of the peak height***

Representation of the model used in the IV analysis II



The method defines V_{gl} as the fitted location parameter μ of the skew-normal, not the peak maximum -> positive skewness

joint fit = baseline + skew-normal peak to the knee region
Savitzky–Golay smoothing filter was applied to get rid of noisy data

The fitting function is:

$$dI/dV(V) \;=\; A \cdot \mathrm{SkewNormal}(V;\, \mu, \sigma, \alpha) \;+\; (mV + c)$$

We choose μ because it marks the stable center of the transition, while the apex shifts with skewness and slope. This makes V_{gl} unbiased.

*For a **right-skewed** peak, the **mode** lies **to the right** of μ, so the dashed V_{gl} line will appear **slightly left** of the visible peak. That offset is expected and encodes the skewness.*

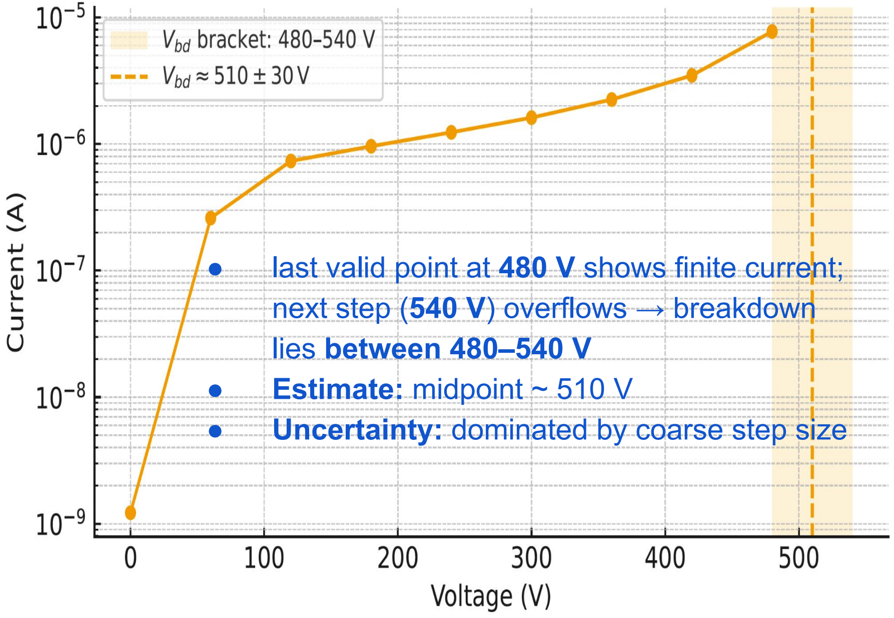
For details on skew-normal distribution and derivation: see in backup

Why use LCT dI/dV fits instead of linear intersections?

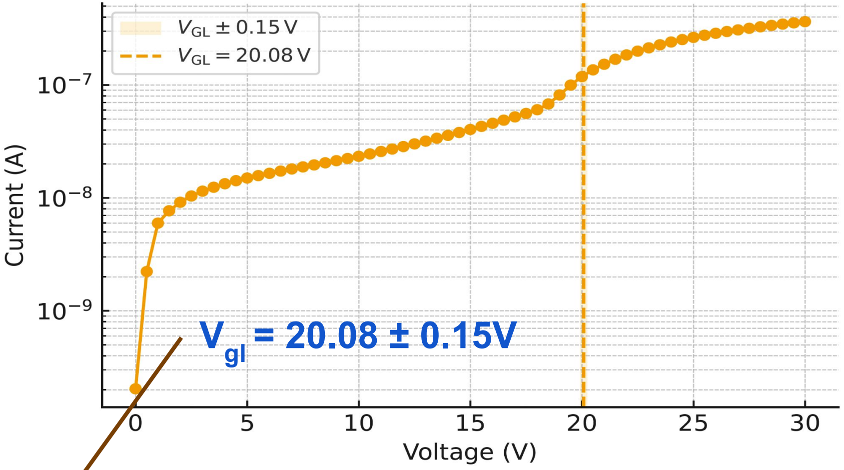
- **Directly probes the transition:** dI/dV shows the knee as a peak → no need to extrapolate lines that don't really hold
- **Baseline bias corrected:** joint fit (baseline + peak) removes slope-induced shifts that would move V_{gl}
- **Provides real shape: skew-normal/**Voigt accounts for asymmetric tails
- **Robust & objective:** window defined by peak fraction (α) → avoids tail bias, less sensitivity to point selection
- We use dI/dV only to pinpoint the knee voltage V_{gl} ; the actual leakage current is then taken from the original I(V) at that voltage.

I–V Curve Validation of V2 TW5 TI-LGAD after $1.5\times10^{15}\ n_{eq}/cm^2$ irradiation

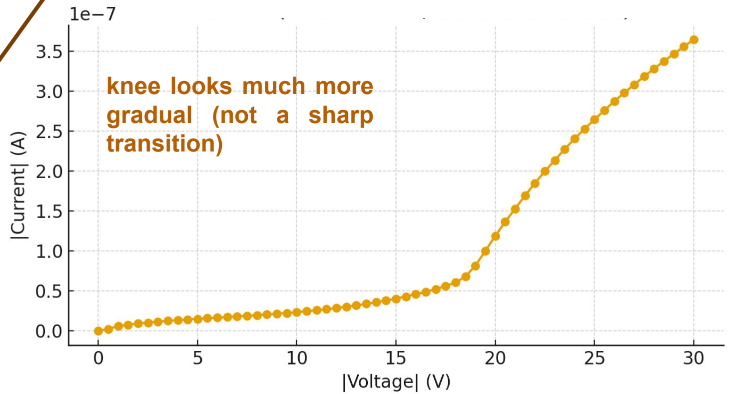
@ 480 V → 7.73 µA



- last valid point at **480 V** shows finite current; next step (**540 V**) overflows → breakdown lies **between 480–540 V**
- **Estimate:** midpoint ~ 510 V
- **Uncertainty:** dominated by coarse step size



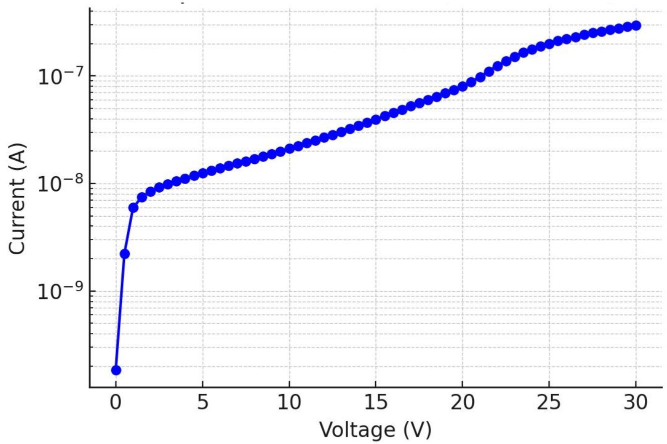
V_{gl} = 20.08 ± 0.15V

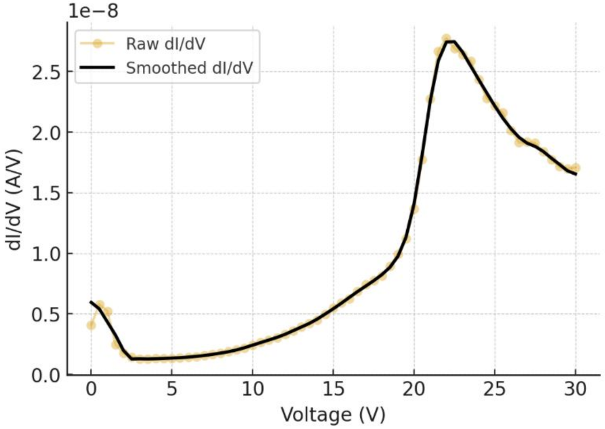


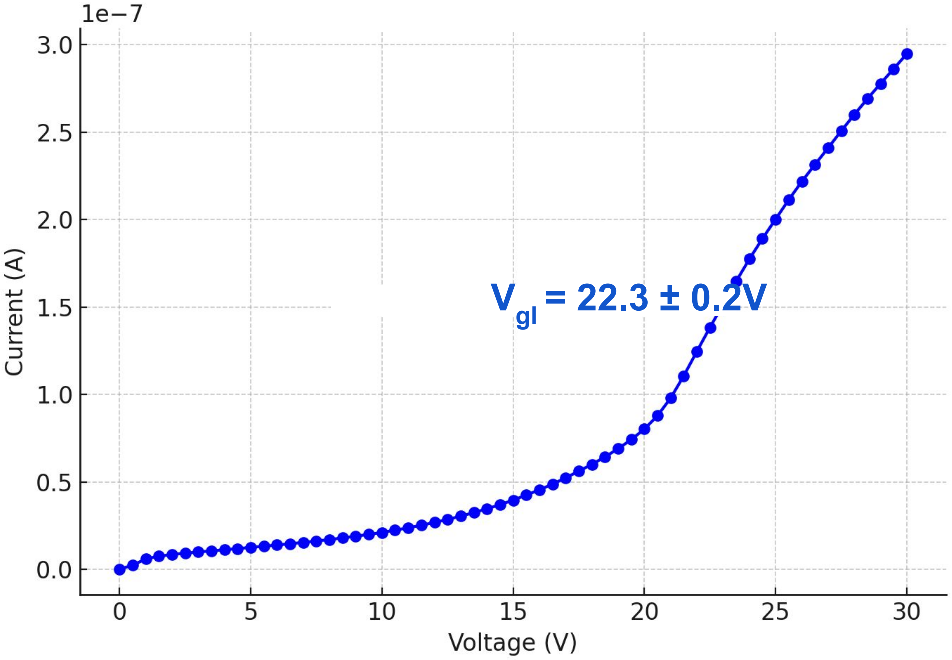
Model used for V_{gl} extraction: LCT with skew-normal fit + baseline;

V_{gl} is defined as the location parameter μ of the fitted peak not the visual apex.

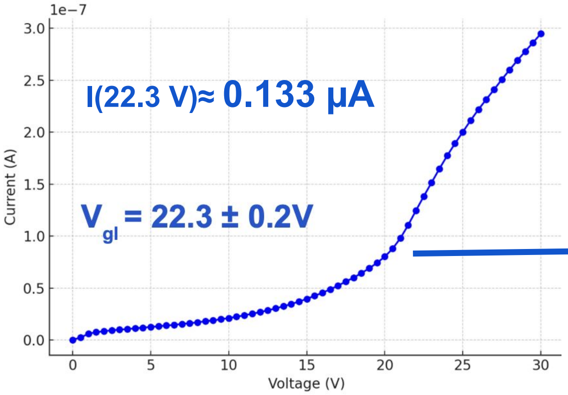
I–V Curve Validation of V1 TW5 TI-LGAD after $1.5\times10^{15}\ n_{eq}/cm^2$ irradiation

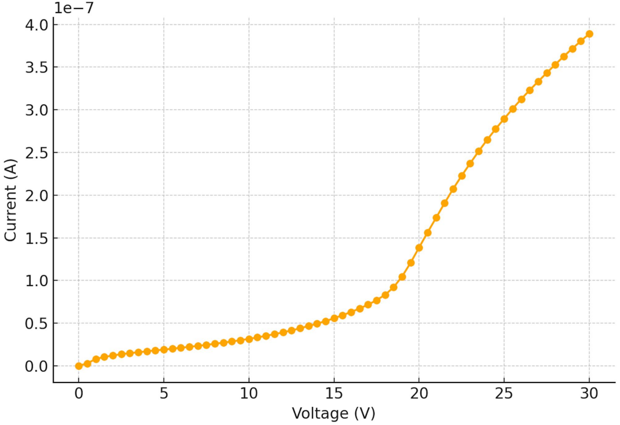


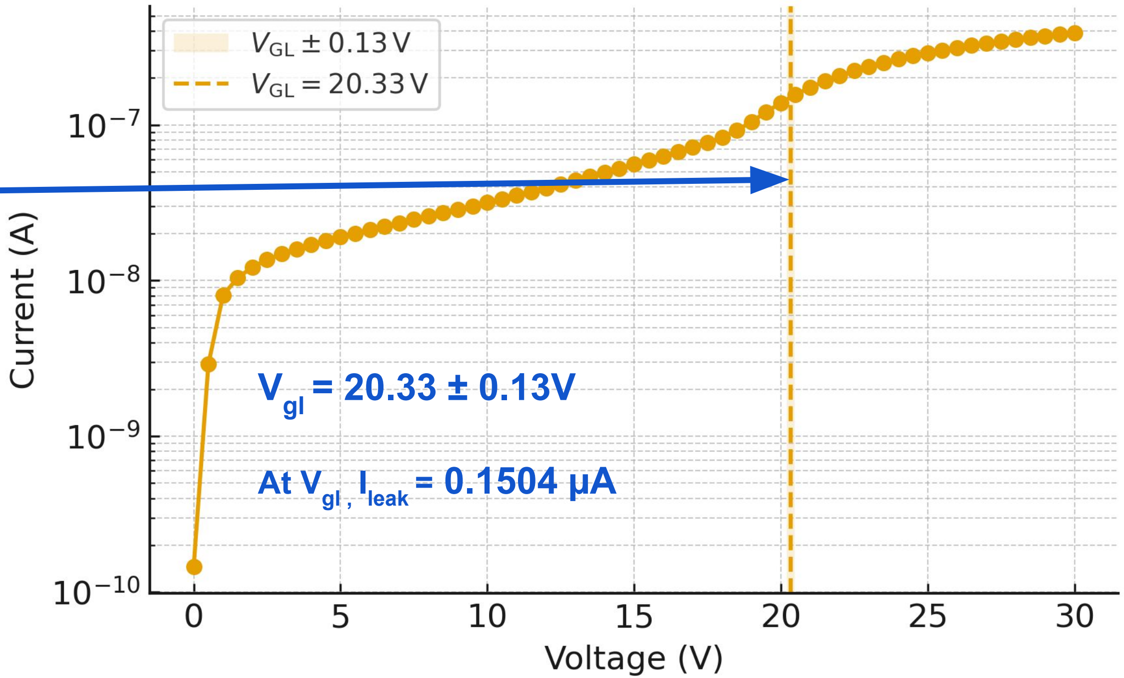




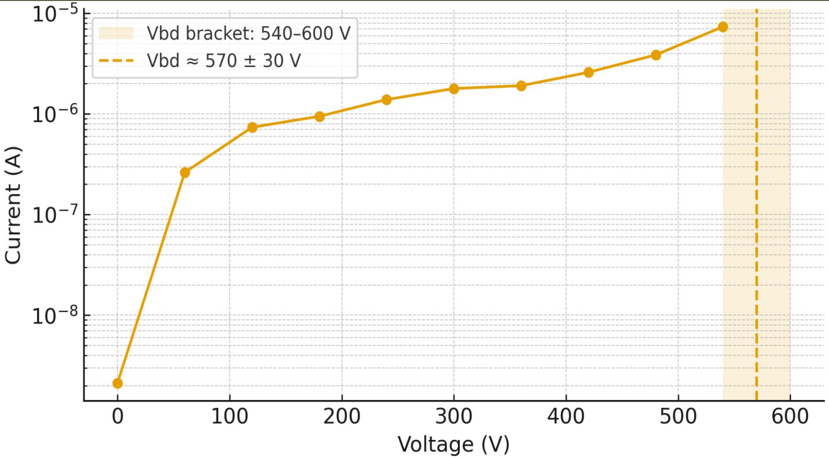
I–V Curve Validation of V1 TW5 TI-LGAD after $2.5\times10^{15}\ n_{eq}/cm^2$ irradiation

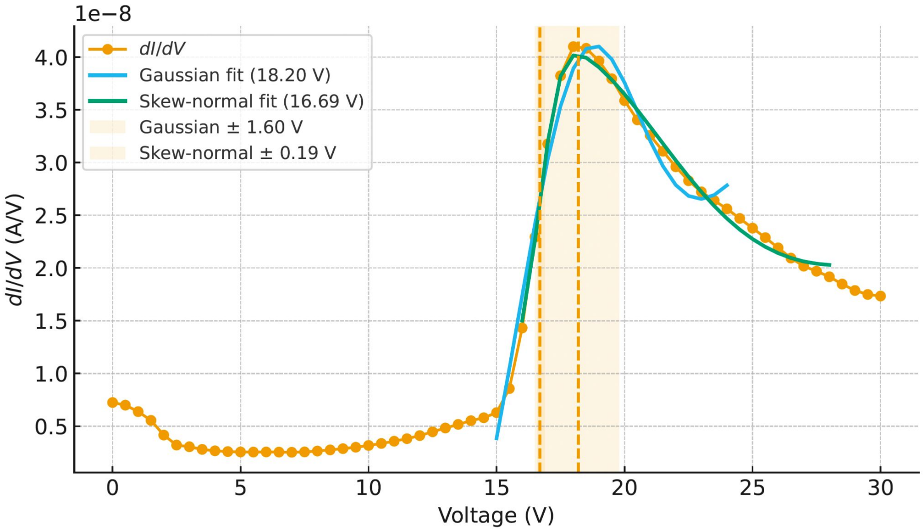


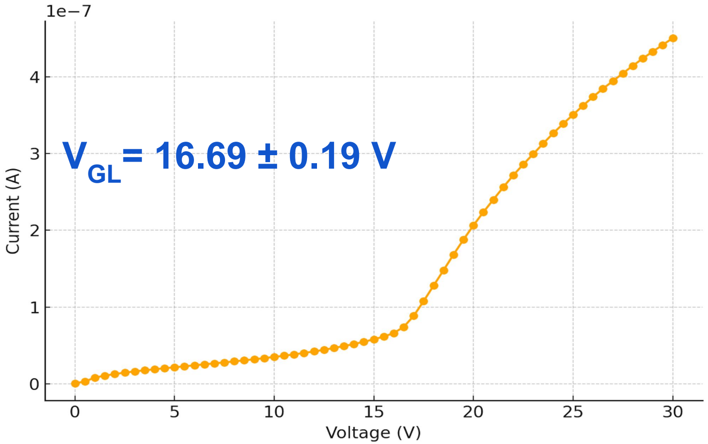




I–V Curve Validation of V2 TW5 TI-LGAD after $2.5\times10^{15}\ n_{eq}/cm^2$ irradiation



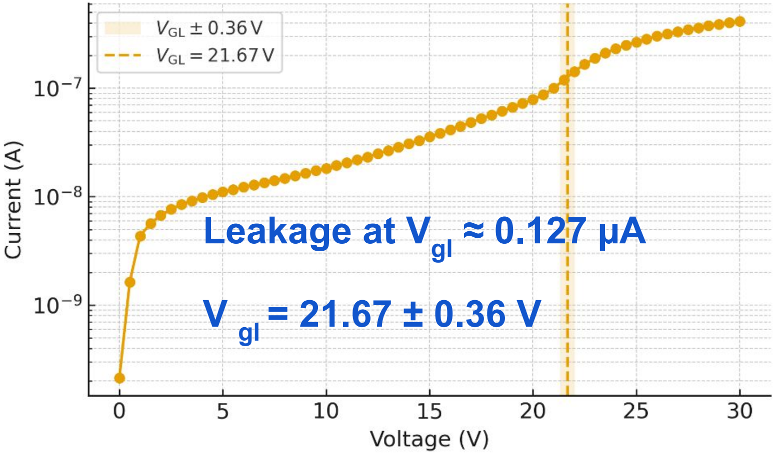




$V_{GL} = 16.69 \pm 0.19$ V

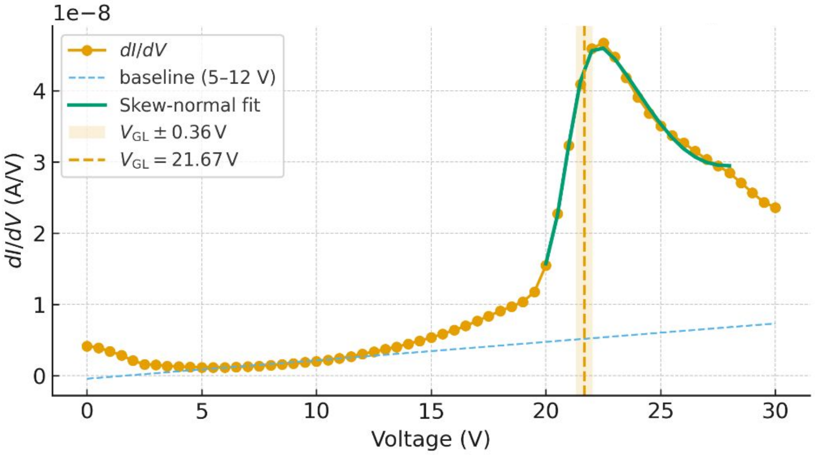
Teal line: **Skew-normal + linear baseline** within **25% objective window**

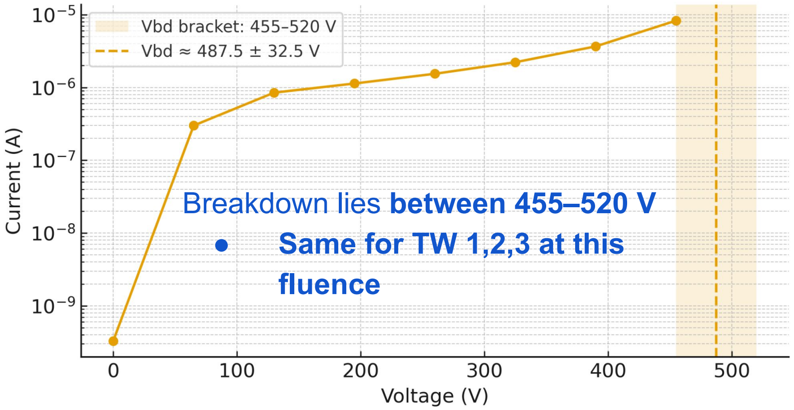
I–V Curve Validation of V2 TW1 TI-LGAD after $1.5\times10^{15}\ n_{eq}/cm^2$ irradiation



Leakage at $V_{gl} \approx 0.127$ μA

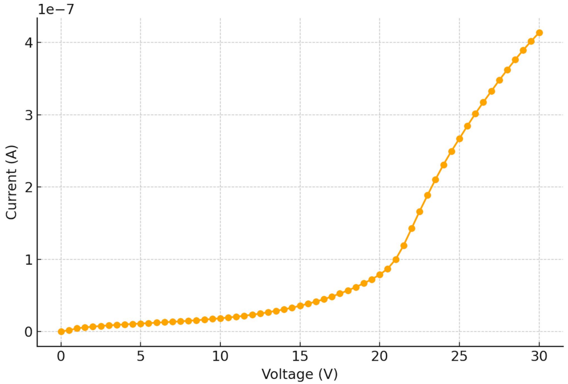
$V_{gl} = 21.67 \pm 0.36$ V



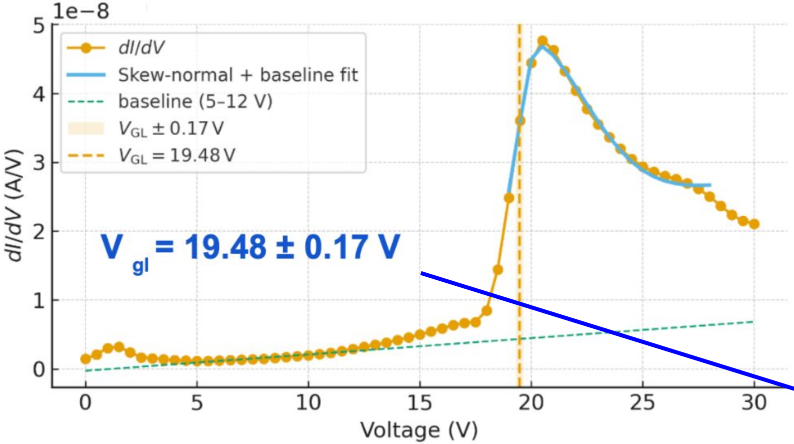


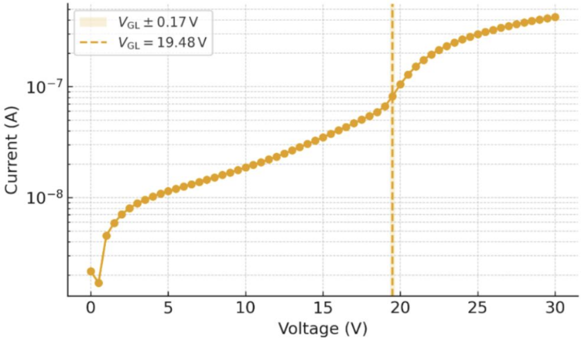
Breakdown lies **between 455–520 V**

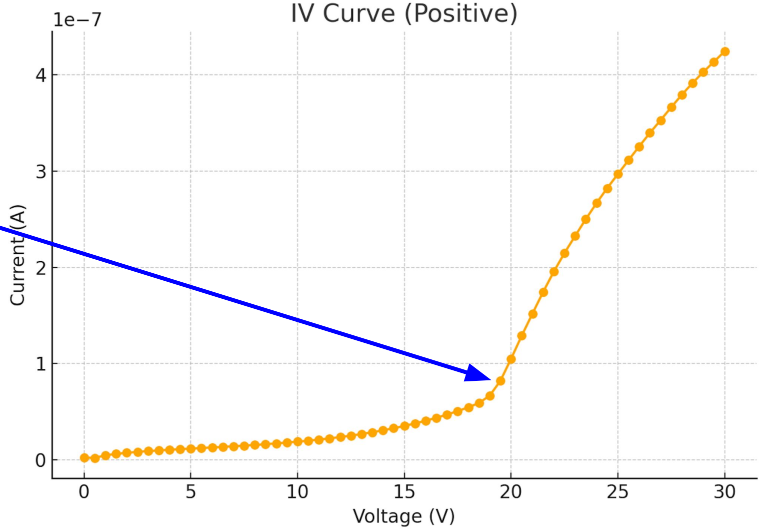
- **Same for TW 1,2,3 at this fluence**



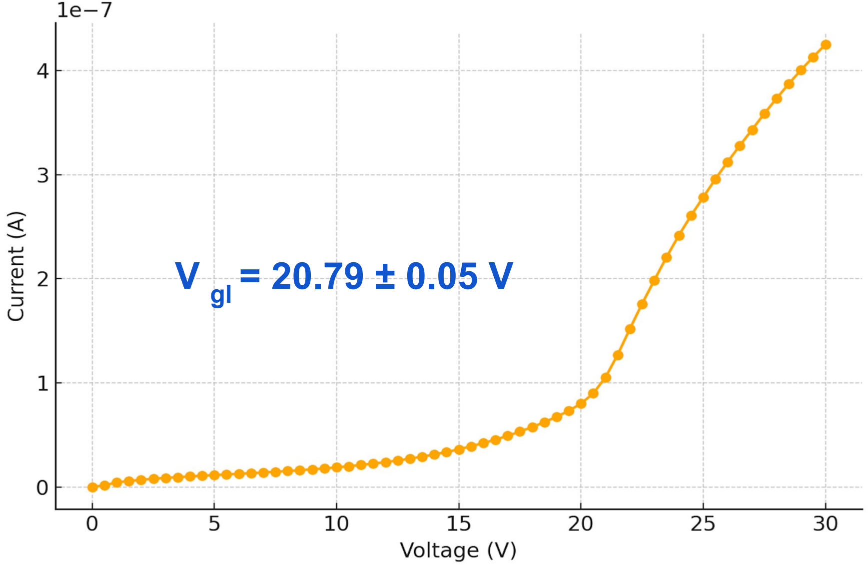
I–V Curve Validation of V2 TW2 TI-LGAD after 1.5×10^{15} n_{eq}/cm^2 irradiation

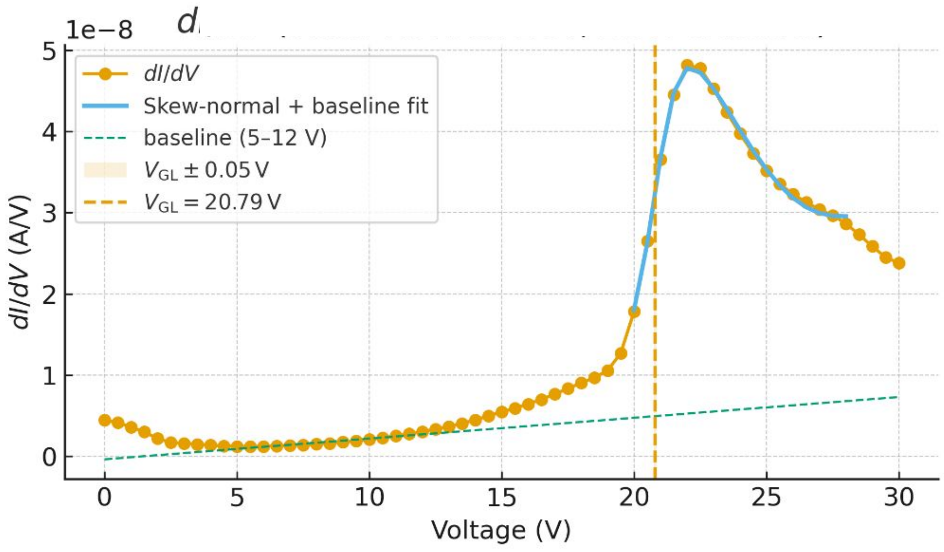






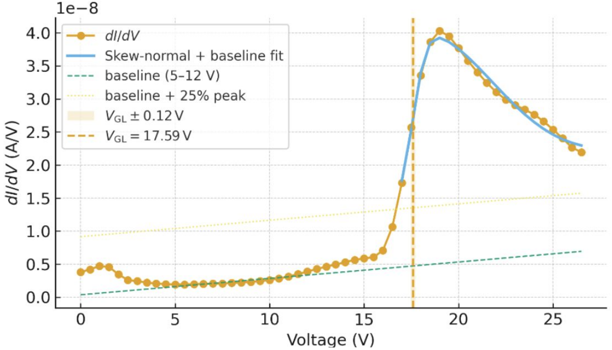
I–V Curve Validation of V2 TW3 TI-LGAD after $1.5\times10^{15}\ n_{eq}/cm^2$ irradiation

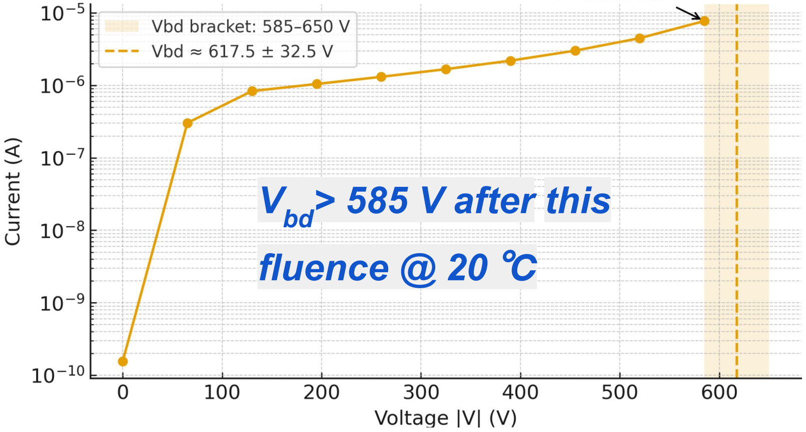




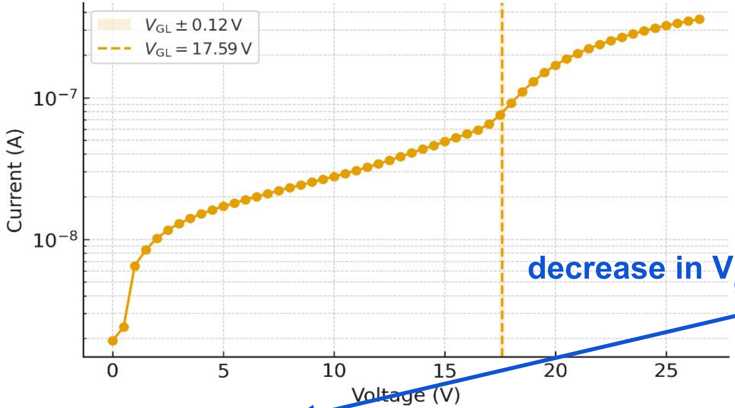
25% window: fit only the **middle of the rise**—keep points where the slope > **25% of its peak**—to avoid tail bias

I–V Curve Validation of V2 TW1 TI-LGAD after $2.5\times10^{15}\ n_{eq}/cm^2$ irradiation

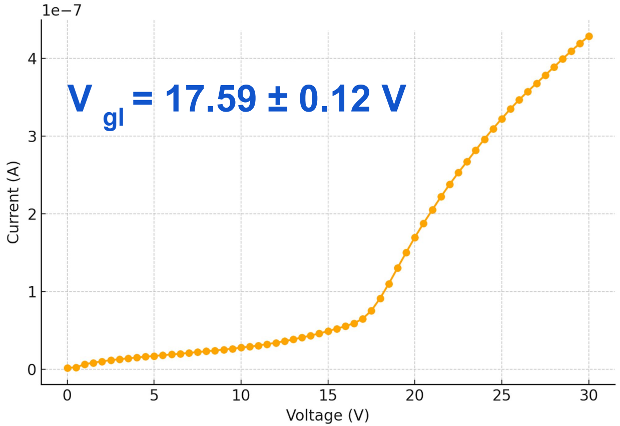




V_{bd} > 585 V after this fluence @ 20 ℃



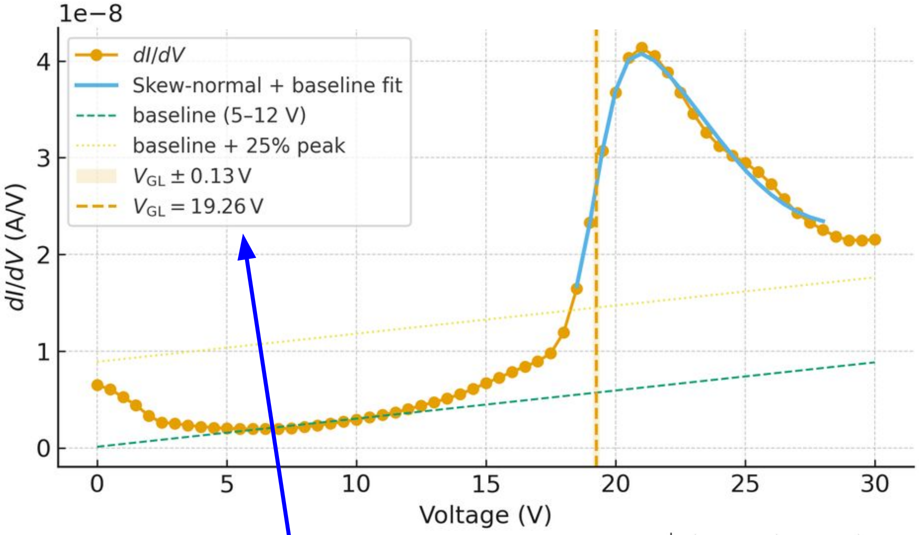
decrease in V_{gl}

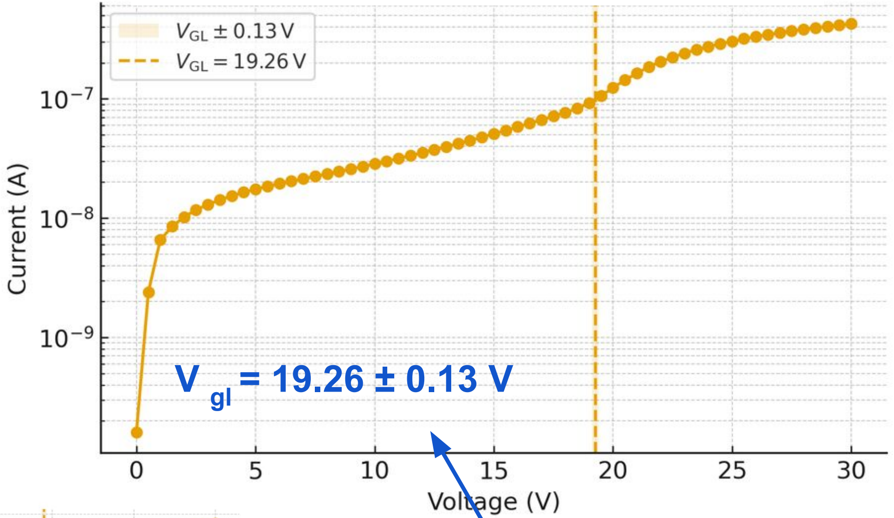


V_{gl} = 17.59 ± 0.12 V

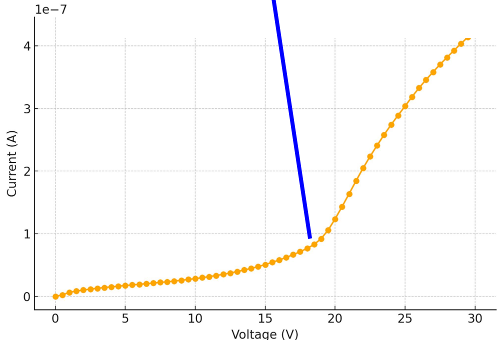
@ $1.5\times10^{15}\ n_{eq}/cm^2$ V_{gl} ~ 21.67 V for TW1

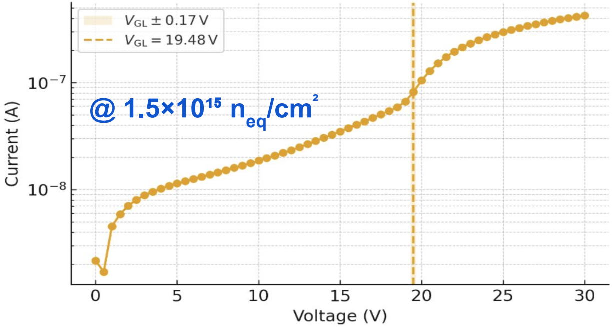
I–V Curve Validation of V2 TW2 TI-LGAD after $2.5\times10^{15}\ n_{eq}/cm^2$ irradiation





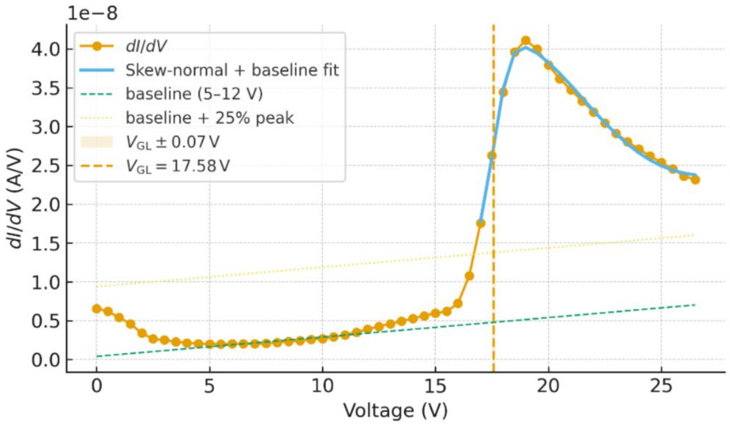
$V_{gl} = 19.26 \pm 0.13$ V

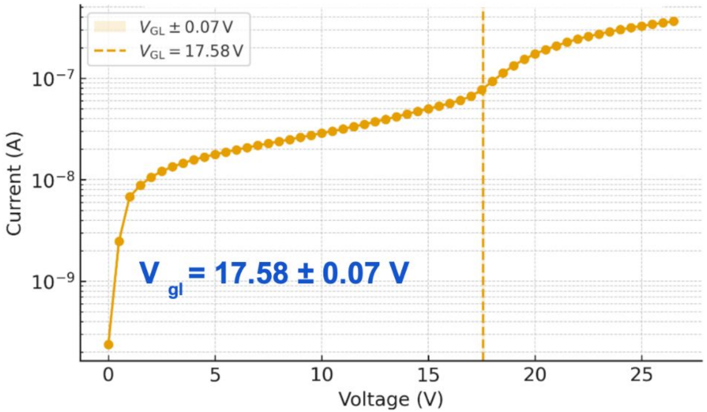


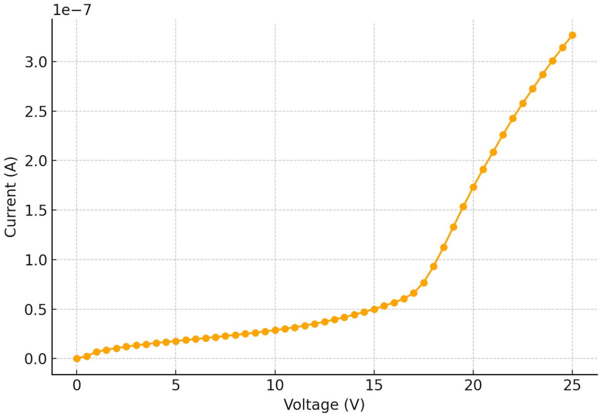


minimal dependence on irradiation for TW 2

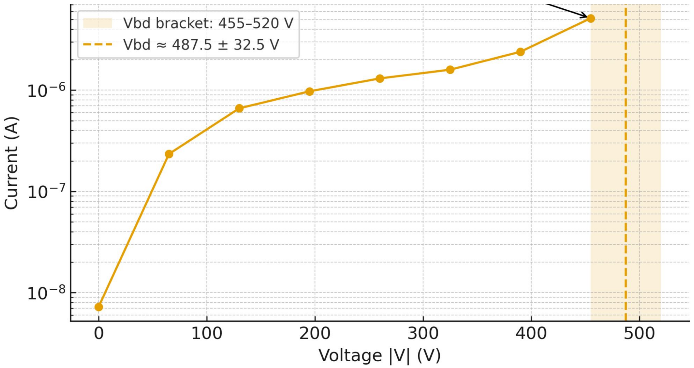
I–V Curve Validation of V2 TW3 TI-LGAD after 2.5×10^{15} n_{eq}/cm^2 irradiation



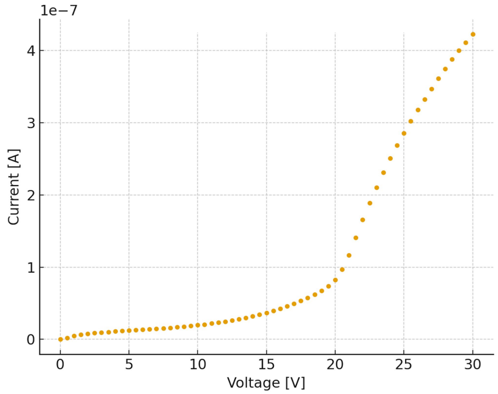


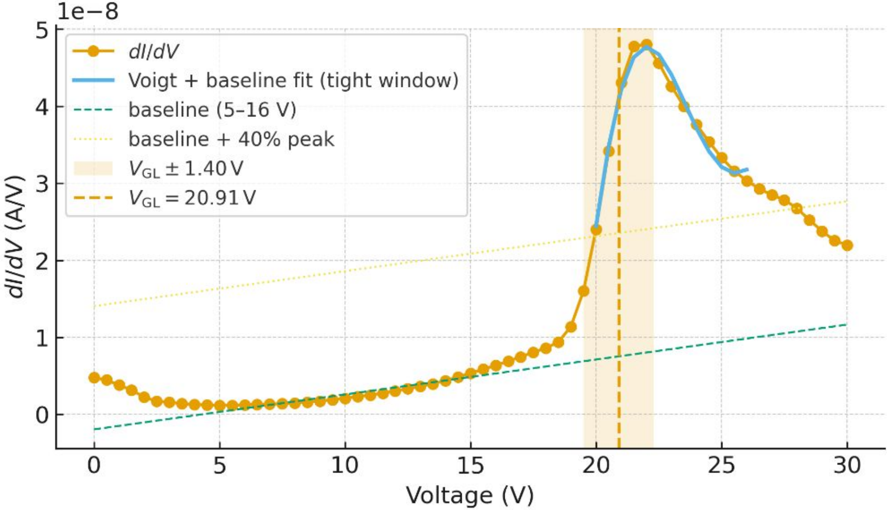


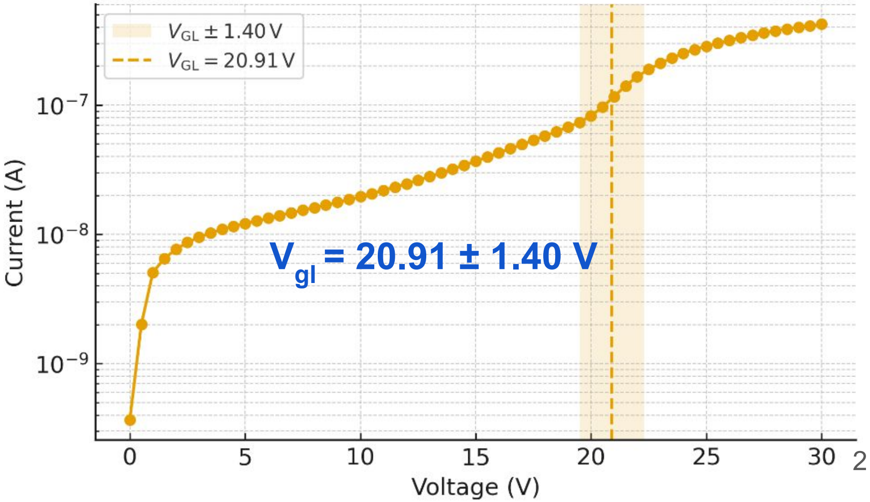
I–V Curve Validation of V2 TW4 TI-LGAD after $1.5\times10^{15}\ n_{eq}/cm^2$ irradiation



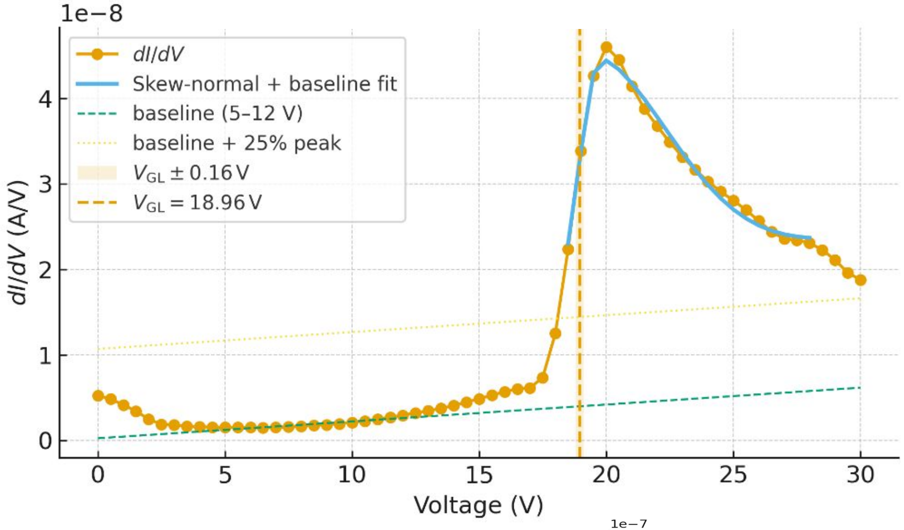
- V_{GL} = 21.3 ± 0.5 V (skew-normal, 25% window)
- Cross-check: Voigt (40% window) gives V_{GL} = 20.9 ± 1.4 V, consistent within 1 σ
- V_{bd} > 455 V @ 20 ℃

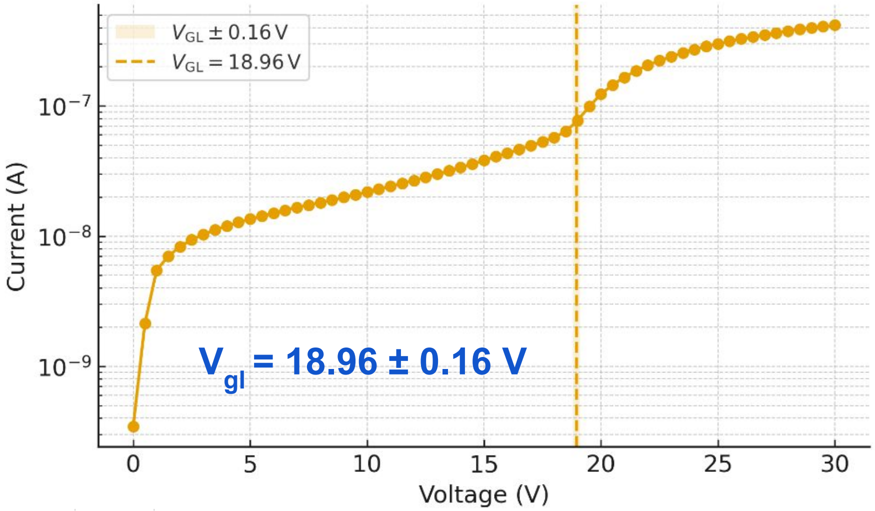




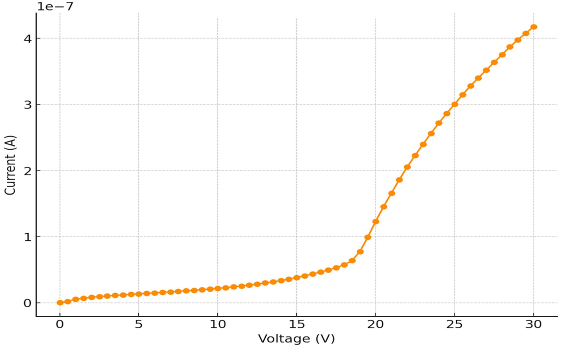


I–V Curve Validation of V2 TW6 TI-LGAD after $1.5\times10^{15}\ n_{eq}/cm^2$ irradiation

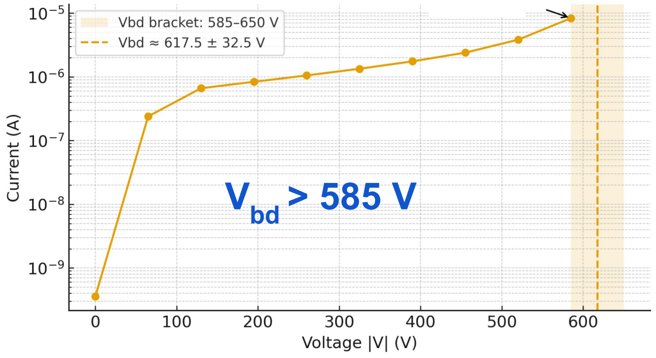


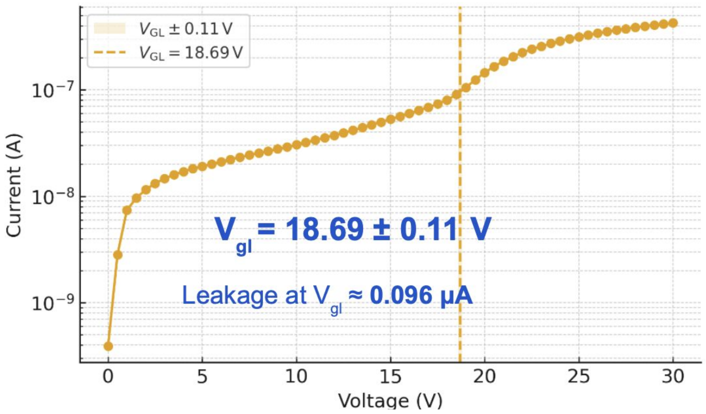


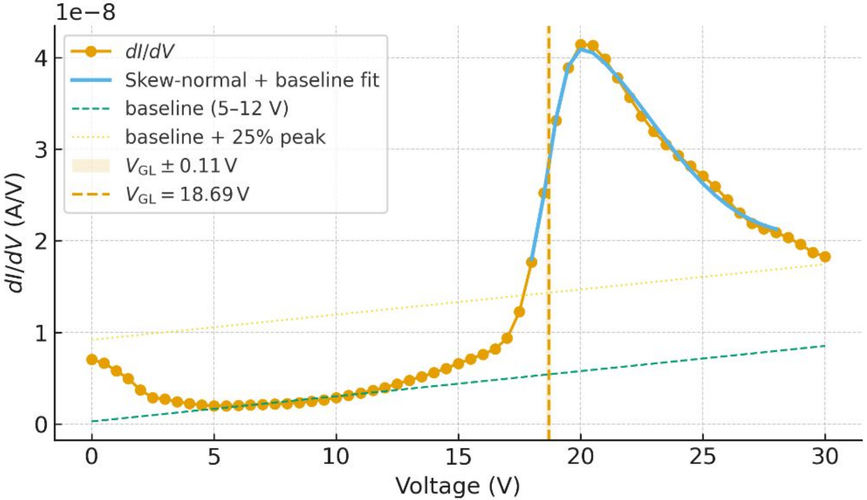
V_{gl} = 18.96 ± 0.16 V

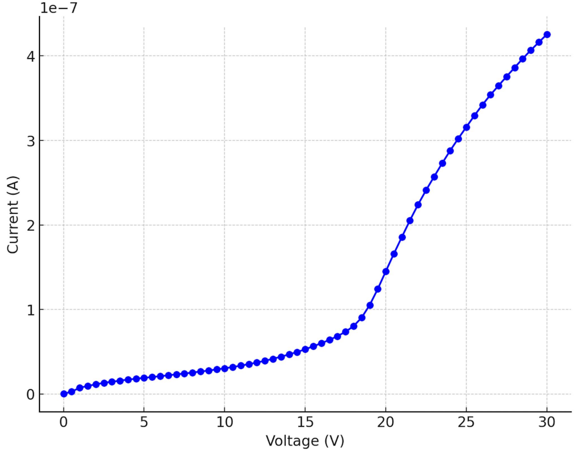


I–V Curve Validation of V2 TW4 TI-LGAD after $2.5\times10^{15}\ n_{eq}/cm^2$ irradiation

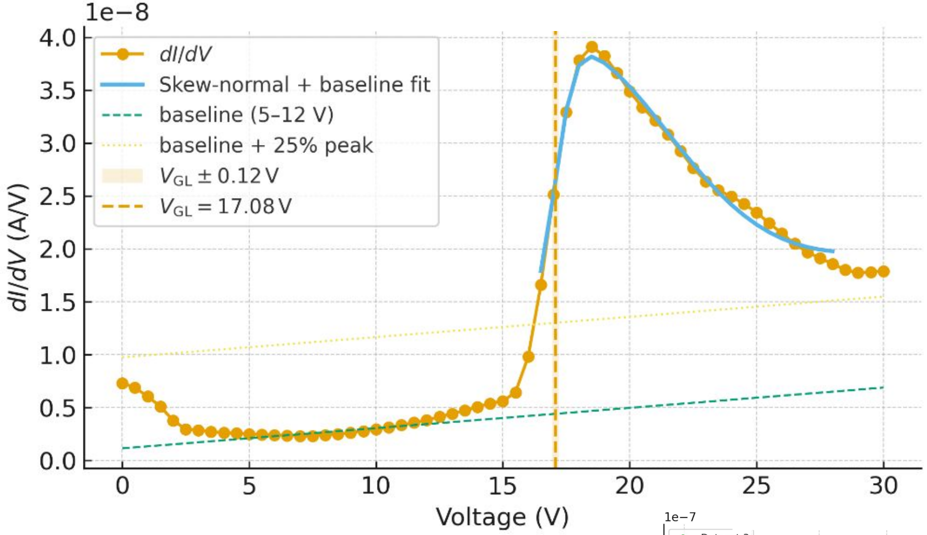


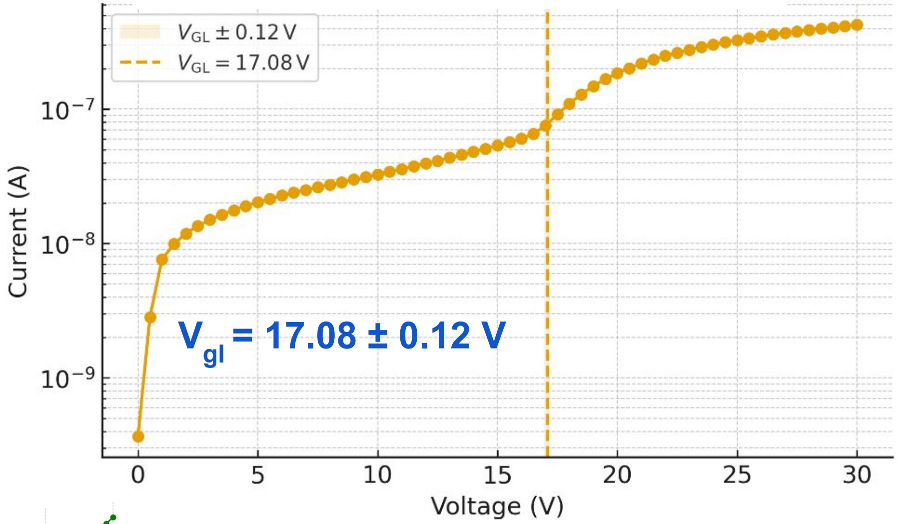


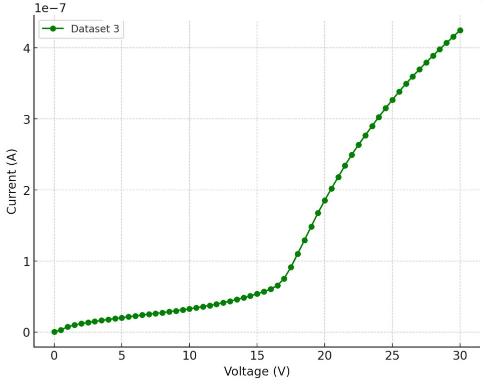




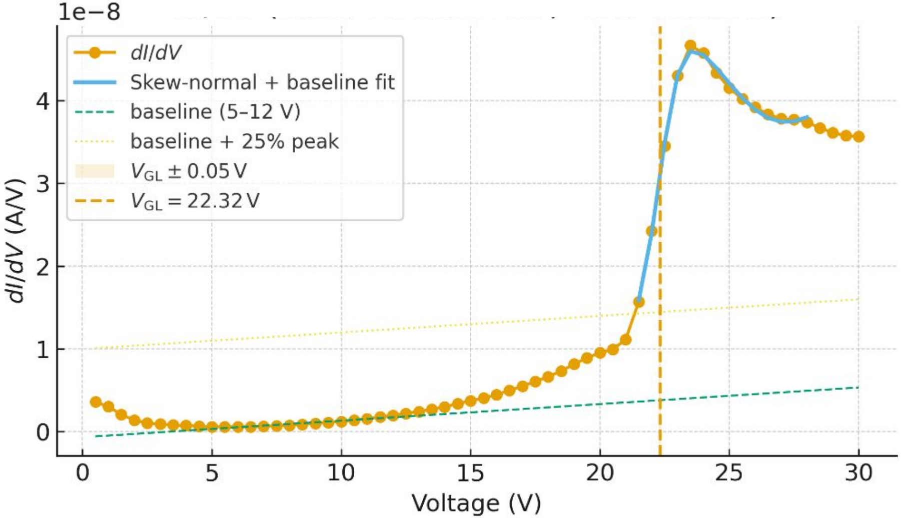
I–V Curve Validation of V2 TW6 TI-LGAD after 2.5×10^{15} n_{eq}/cm^2 irradiation

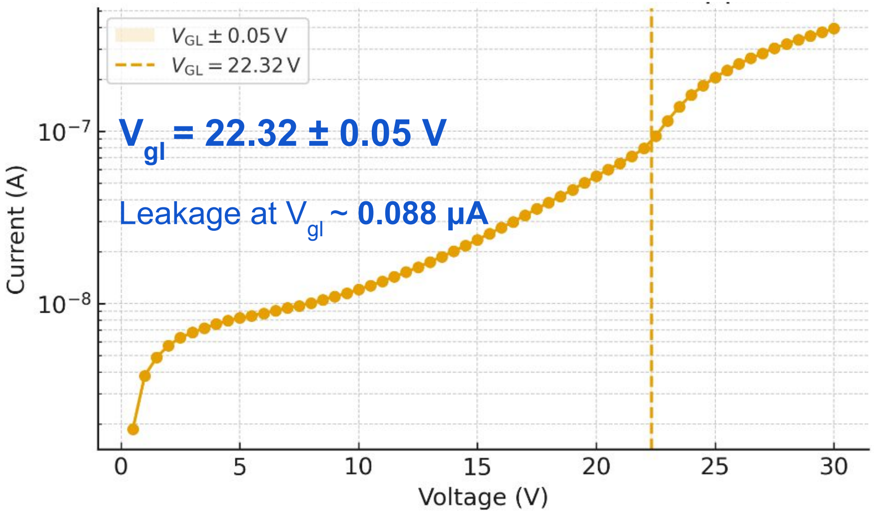




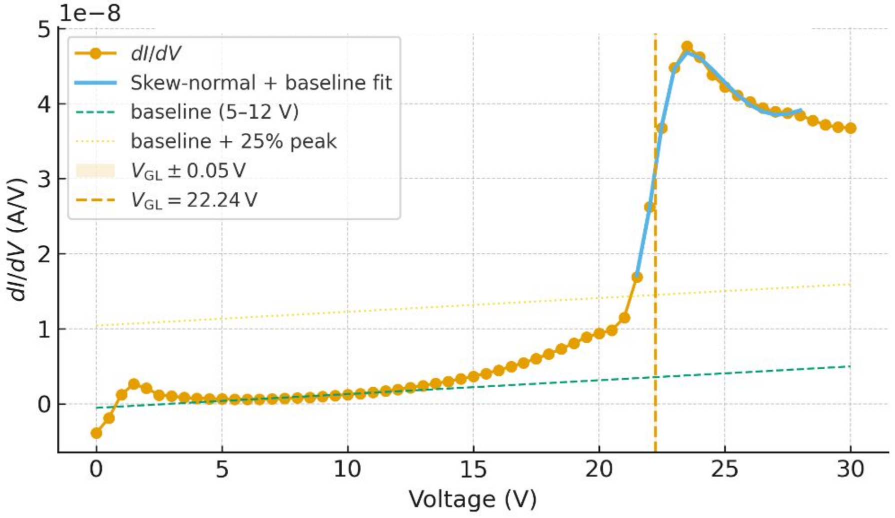


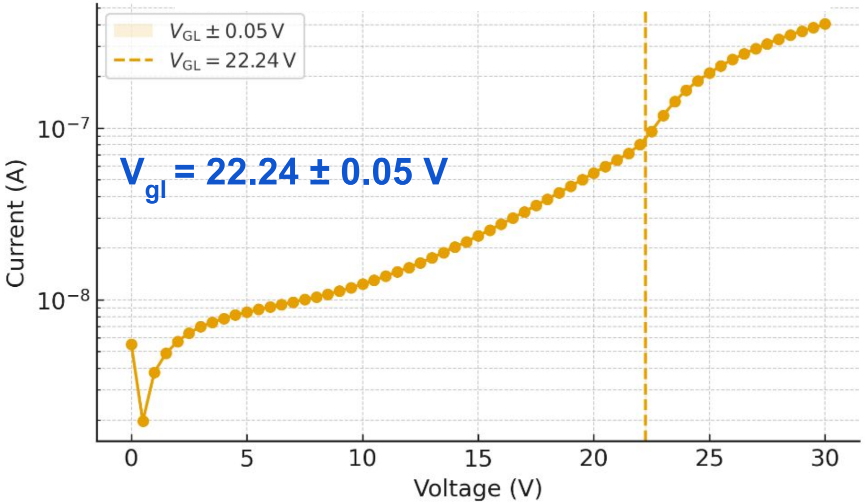
I–V Curve Validation of V2 TW1 TI-LGAD after $0.8\times10^{15}\ n_{eq}/cm^2$ irradiation



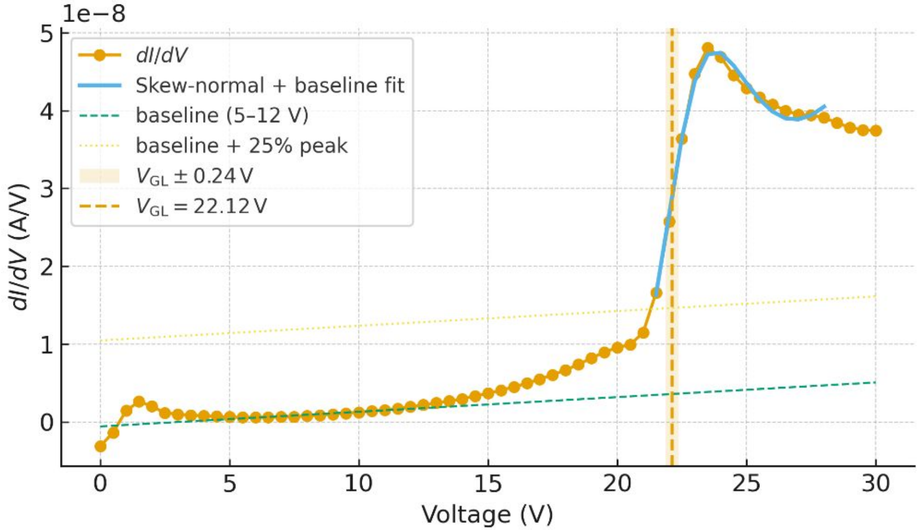


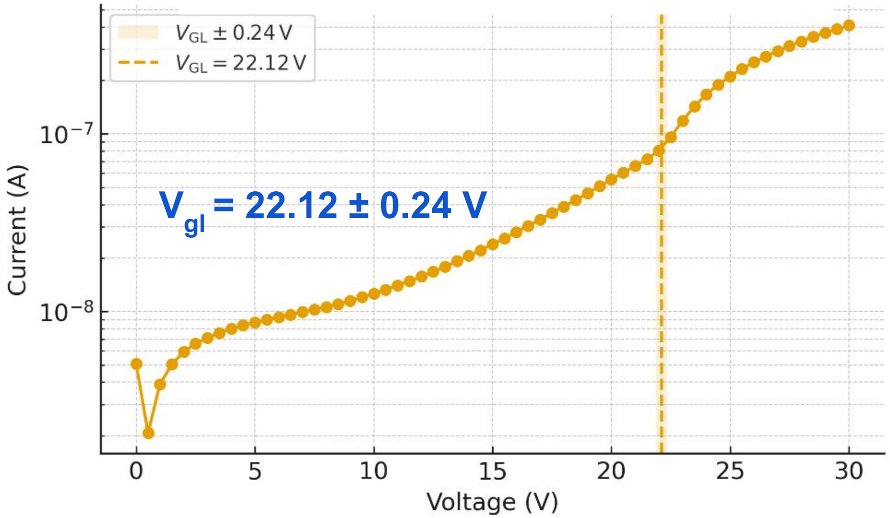
I–V Curve Validation of V2 TW2 TI-LGAD after 0.8×10^{15} n_{eq}/cm^2 irradiation



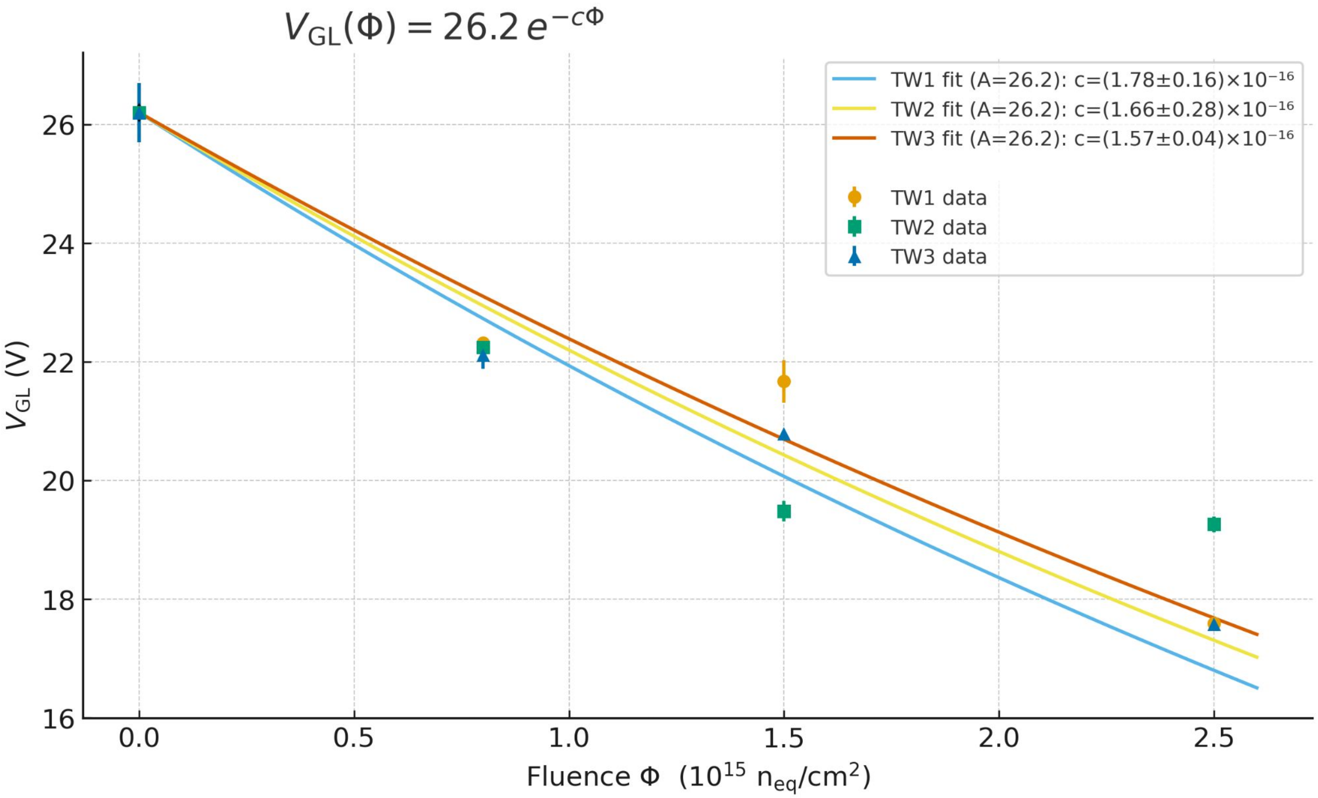


I–V Curve Validation of V2 TW3 TI-LGAD after $0.8\times10^{15}\ n_{eq}/cm^2$ irradiation





Acceptor removal extraction for V2 TW 1/2/3 single trench devices



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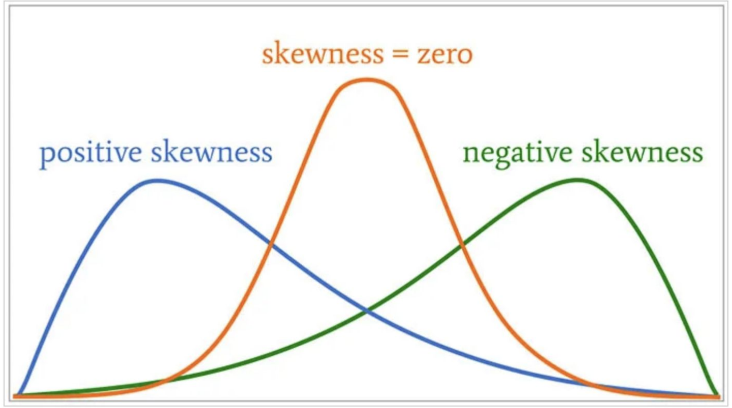
BACKUP

Skew-normal distribution

In a **skew-normal distribution** (the model we are fitting):

- It has a **location parameter** μ
- It also has a **mode** (the apex, where the function reaches its maximum)
- If the peak is **perfectly symmetric** (α=0), then μ = mode
- If the peak is **right-skewed** (α>0), the distribution has a longer tail to the right → the **apex (mode)** shifts **to the right of μ -> positive skewness**
- If it's **left-skewed** (α<0), the apex shifts **to the left of μ -> negative skewness**

$$f(x;\mu,\sigma,\alpha) = \frac{2}{\sigma}\phi\left(\frac{x-\mu}{\sigma}\right)\Phi\left(\alpha\frac{x-\mu}{\sigma}\right)$$



- $\mu \in \mathbb{R}$ = **location parameter** (shifts the distribution along the x-axis),
- $\sigma > 0$ = **scale (width)** parameter,
- $\alpha \in \mathbb{R}$ = **shape (skewness)** parameter,
- $\phi(z) = \frac{1}{\sqrt{2\pi}}e^{-z^2/2}$ = standard normal PDF,
- $\Phi(z) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{z}{\sqrt{2}}\right)\right]$ = standard normal CDF.

Why V_{GL} is defined as the location parameter μ

- The derivative curve dI/dV shows a **transition region ("knee")**
- This region is modeled as:
  dI/dV ≈ Skew-normal peak + linear baseline
- In a skewed distribution: **μ is the location parameter ("center")** of the transition
- **The mode called apex is the highest point**
- If skewness α ≠ 0, then apex is not μ
- Adding a rising baseline pushes the **apex further right**
- The visible peak maximum is biased, but μ remains **stable**
- μ **tracks the intrinsic "onset" of the leakage-current transition, while the apex is distorted by skew and baseline**

IV curves for TI-LGADs and V_{gl} extraction method

- **Input:** I–V on **linear current** (use V if biased negative)
- **(Optional) Smooth:** light Savitzky–Golay (**5–9** pts, poly **2–3**) to tame point-to-point wiggles
- **Differentiate:** compute $\frac{dI}{dV}$
- **Window the peak:** keep **transition region** only (e.g., **15–24 V**); **exclude** > 25–30 **V** tail
- **Fit model:**

$$\frac{dI}{dV}(V) = A\exp\left(-\frac{(V-\mu)^2}{2\sigma^2}\right) + mV + c$$

- **Extract:** $V_{\mathrm{GL}} = \mu$; $\quad \sigma \approx$ dopant-mixing width
- **If asymmetric:** use *skew-normal* or *Voigt*; still take **peak location** as V_{GL}
- **Report:** value $\pm$ fit uncertainty and brief robustness check (window/smoothing insensitivity)

older convention, when skew couldn't be modeled

here skew-normal location parameter μ is used because it coincides with the peak in symmetric cases but remains a stable, unbiased marker of the transition when the peak is asymmetric

IV curves for TI-LGADs and V_{gl} extraction method

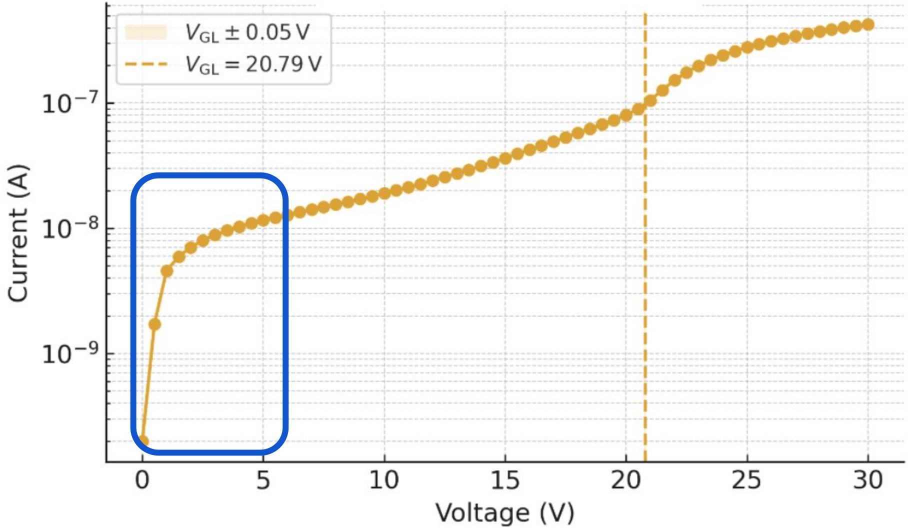
Measured slope is a peak plus a slow pedestal:

$$\frac{dI}{dV}(V) = Ae^{-\frac{(V-\mu)^2}{2\sigma^2}} + (b_0 + b_1 V).$$

Maximizing the raw sum shifts the apex to the right by approximately

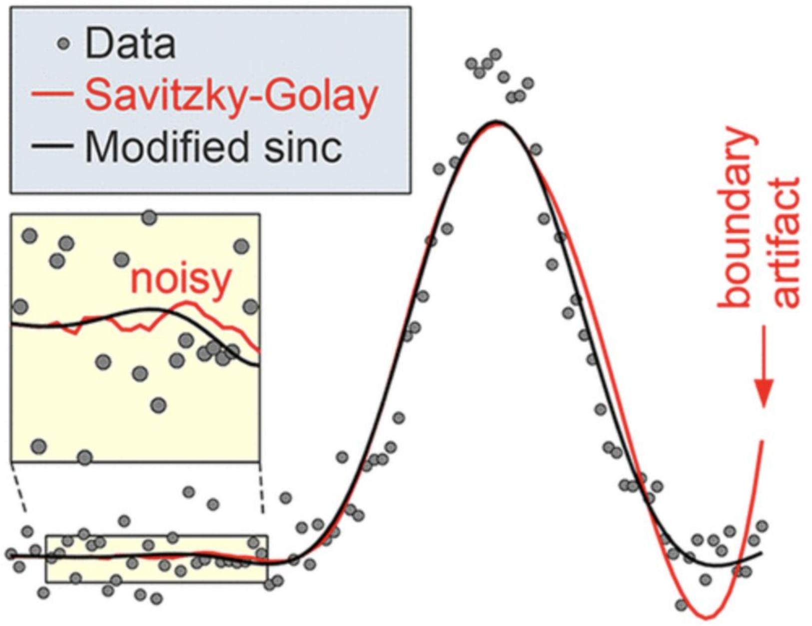
$$\boxed{\Delta V \approx \frac{b_1 \sigma^2}{A}} \quad \text{(for small shifts)},$$

hence a positive baseline slope biases the apparent maximum to higher V. Fitting (or subtracting) the baseline recovers the unbiased center μ.



- **Tiny kink @ ~3 V** on log I–V
- **Not V_{GL}** (we get $V_{GL} \approx 20.8$ V from dI/dV; no sharp peak at 3 V)
- **Likely low-bias effects:** edge/guard-ring turn-on
- **No impact on V_{GL}:** baseline 5–12 V excludes 0–5 V

Savitzky–Golay Filter



The Savitzky-Golay filter is a digital filter that smooths data points by fitting successive sub-sets of adjacent data points with a low-degree polynomial using the method of linear least squares

The Savitzky-Golay filter works by sliding a window of fixed size (one of its hyperparameters) over the data and fitting a polynomial to the points within this window

I–V Curve Validation of V2 TW3 TI-LGAD after 1.5×10^{15} n_{eq}/cm^2 irradiation