Timing and Gain Performance of Teledyne e2v's LGADs after Irradiation

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Teledyne e2v LGAD Project

- University of Birmingham, University of Oxford, RAL and the Open University
- **Teledyne e2v is a foundry based in Chelmsford, UK**
- Established in 1947 (as EEV) to become a major producer of semiconductor imaging sensors (CCDs) and RF solutions for space, astronomy, medical and industrial applications
- **Large production volume capacity** for detectors with fast timing capability would be a big asset to the Particle Physics community

https://teledyne-e2v.com/en-us

Outline

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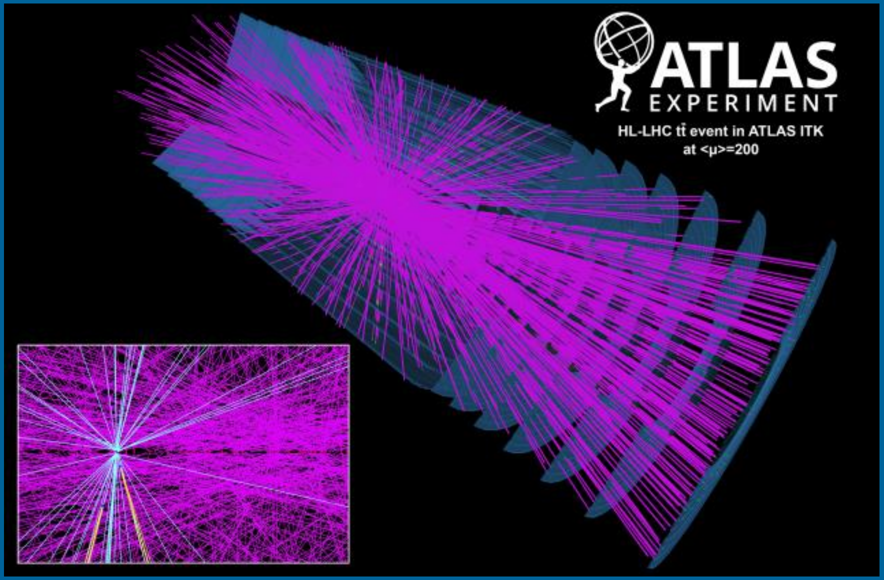
- Introduction to the project
- Sensor design
- Irradiation campaign
- Characterisation before and after irradiation
  - IVs
  - CVs
  - Gain
  - Timing
- Conclusion

Why Timing?

- The LHC's High-Luminosity upgrade will see a large **increase in pile-up**, with up to 200 events per 25 ns bunch crossing.
- Overlapping events make track reconstruction challenging and this limits the ability to correctly associate tracks with their primary vertices.
- ATLAS and CMS plan to use a dedicated **rad-hard timing layers equipped with LGAD**s. These will be installed outside of the trackers to add fine timing information to each track.
- Later upgrades might look towards LGADs as a replacement for the inner tracking, unlocking true 4D tracking.

https://cds.cern.ch/record/2667167



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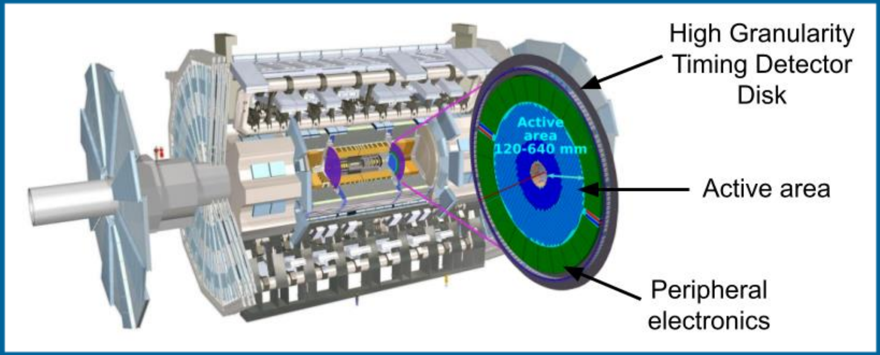

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Low Gain Avalanche Detectors

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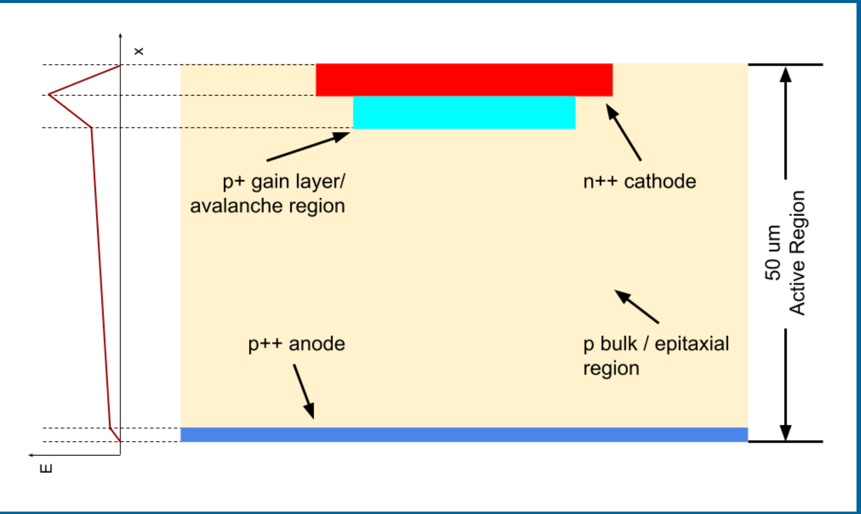
- LGADs consist of a **thin**, planar n-in-p sensor, with a **multiplication layer** tuned to achieve low/moderate gain
- This design achieves **high S/N**, uniform signal, fast rise time
  - Reduced jitter and distortion terms
  - Reaches physical limit: Landau fluctuations (~20 ps)
  - **Excellent time resolution (~35 ps)**



$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{ionization}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$$

https://doi.org/10.1016/j.nima.2020.164664

Te2v 1st Batch

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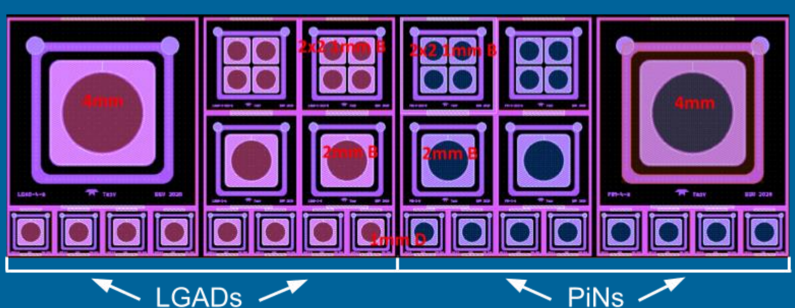
- First batch of 22 wafers was fabricated in late 2020 with eight flavours of varying dose and energy of the **Boron** implant
  - 33 test fields per wafer
  - LGAD size varies from 4mm to **1mm**
  - Fields are mirrored with **PiNs** (identical to the LGADs but **without the Boron implant**)
- Initial characterisation presented at the RD50 workshops and various conferences. Today, we'll be focusing on the **1mm** devices from our **most promising wafer** (A) which has the **highest combined implant energy and dose**



Wafer code	Normalised Implant Dose [D]	Normalised Implant Energy [E]
A	1.07	1.11
B	1.07	1.05
C	1.07	1.00
D	0.92	1.05
E	1.15	1.05
F	1.00	1.00
G	1.00	1.05
H	1.00	1.11

Irradiation Campaign

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- Seven identical devices have been irradiated with **27 MeV protons** at the **MC40 cyclotron at Birmingham**
  - F11-F28 have been irradiated with fluences from **5.6e13 1 MeV neq/cm^2** up to **8.3e14 1 MeV neq/cm^2**
- The aim of the study is to investigate how the timing properties of these devices change with fluence due to **acceptor removal** in the gain layer
- The gain layer implant is Boron, **without carbon enrichment**

Device code	Fluence [1 MeV neq/cm2]
F11	5.6e13
F12	8.4e13
F13	1e14
F14	2.5e14
F08	4e14
F25	5.7e14
F28	8.3e14

IVs

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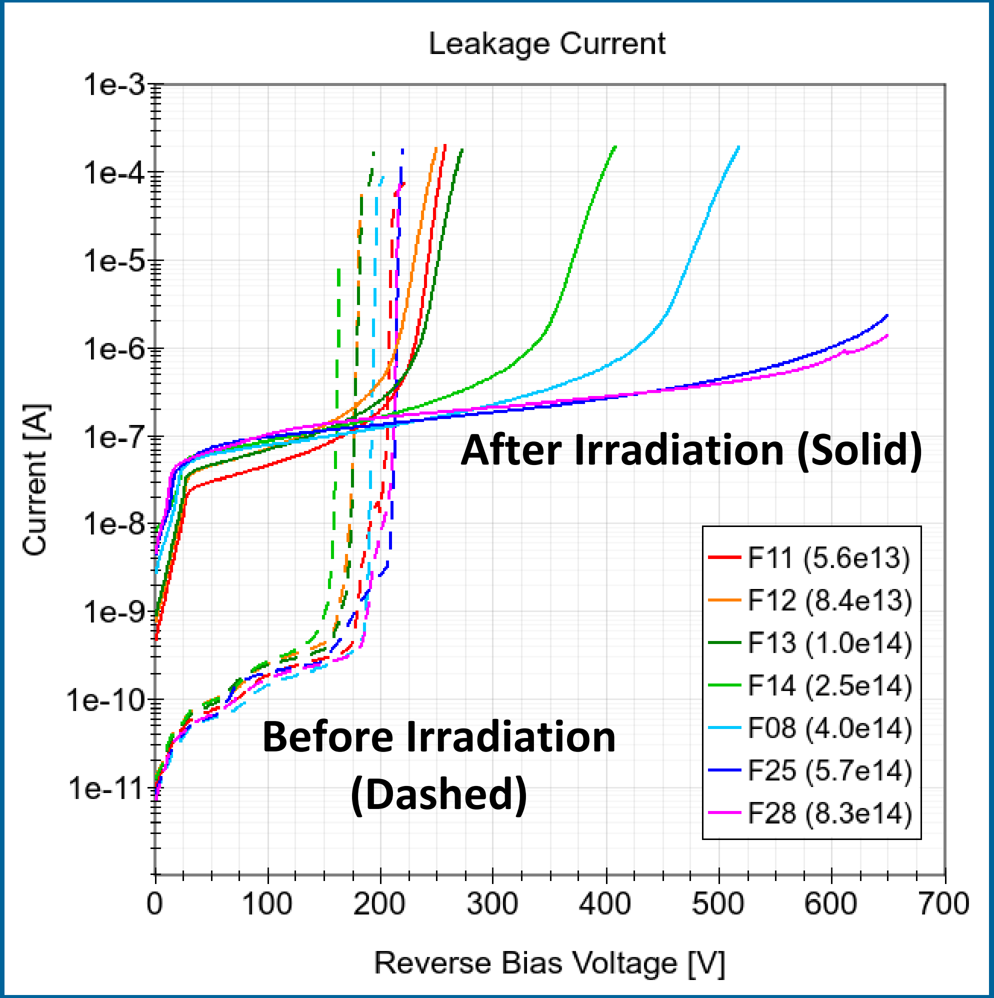
- IV curves are measured to check the highest operating voltage which minimises leakage current
  - Pre-irrad at room temperature
  - Post-irrad at –20 ˚C with low humidity
- **Large variability** (±30 V) in breakdown voltage pre-irradiation
- Change in breakdown voltage increases with fluence **as expected**



CVs

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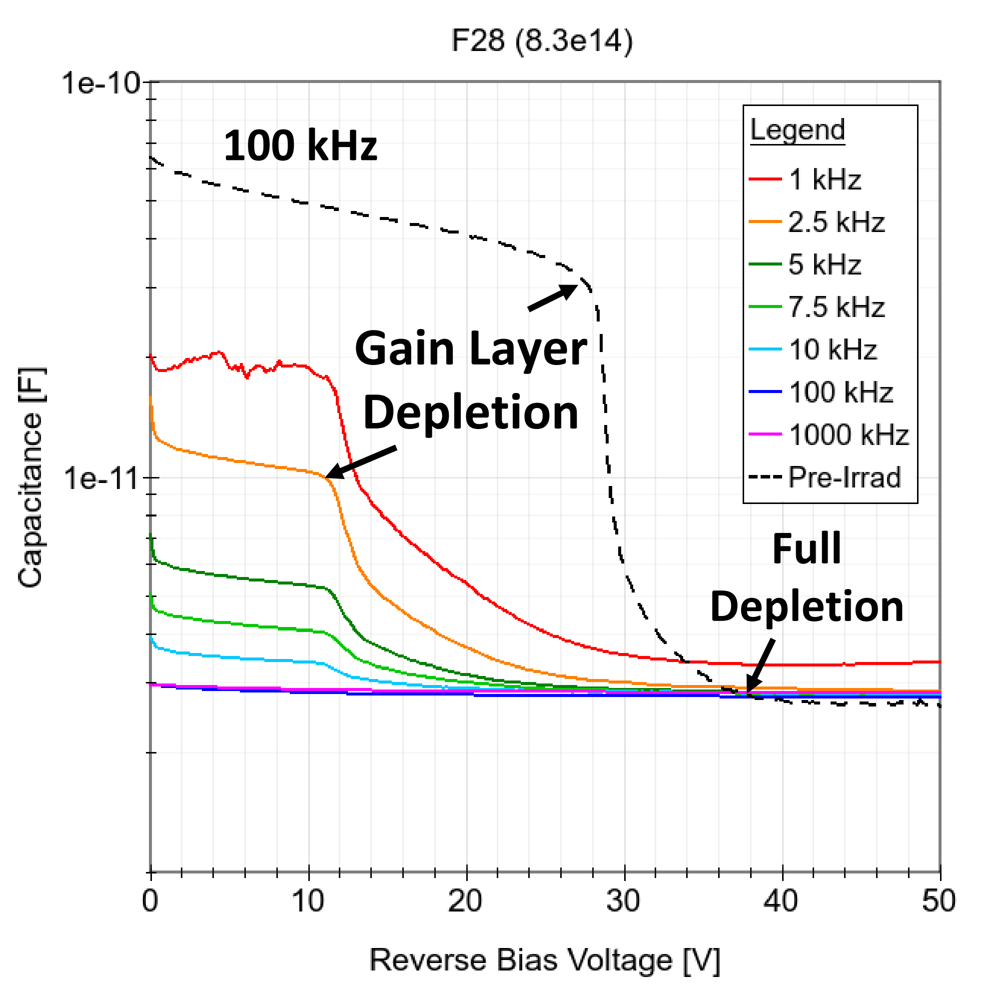
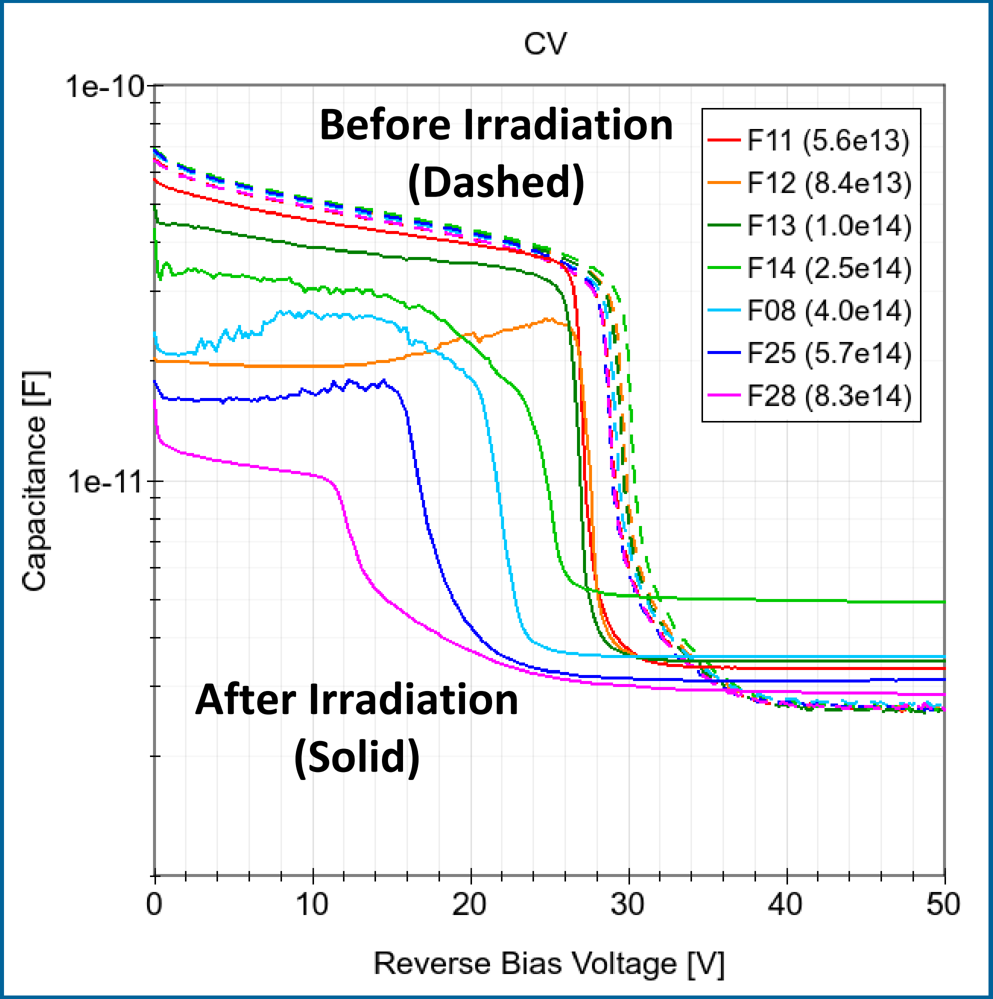
- Determination of gain layer and full **depletion voltage** is done via CV measurements
- For irradiated devices, the **measured capacitance** changes as a function of **frequency**
- At high fluences, full depletion **hard to identify**



CVs

- Pre-irrad - 100kHz
- Post-irrad - 1kHz
- F28 (8.3e14)- 2.5kHz
- Pre-irrad shows very **little variability** in capacitance between devices
- Increasing irradiation fluence results in decreasing depletion voltages



Parameterising CVs

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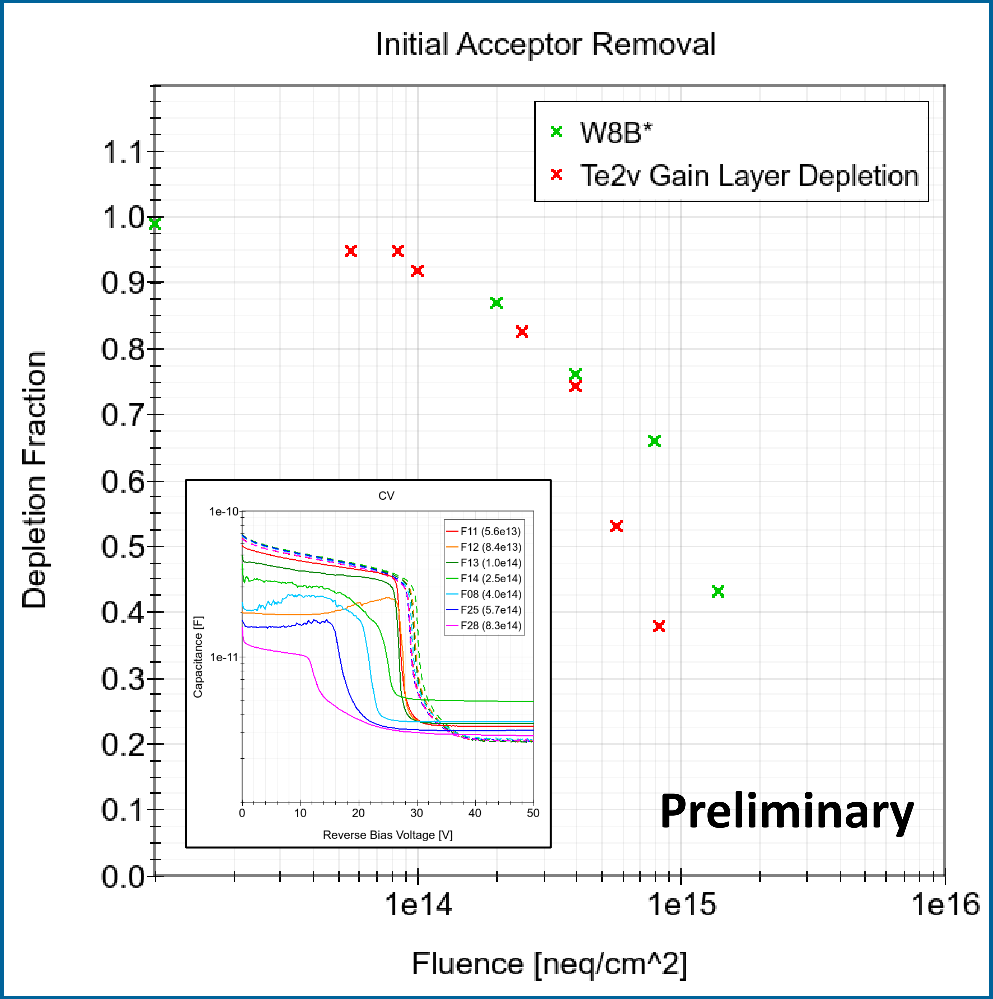
- The change in gain layer depletion voltage can be characterised by plotting the depletion fraction versus fluence
- For low fluences our results are in agreement. However we demonstrate a **worse radiation hardness** for higher fluences (>= 5.7e14 1 MeV neq/cm^2)

*FBK neutron irradiated Boron-implanted LGADs. Ferreroa, M., 2018

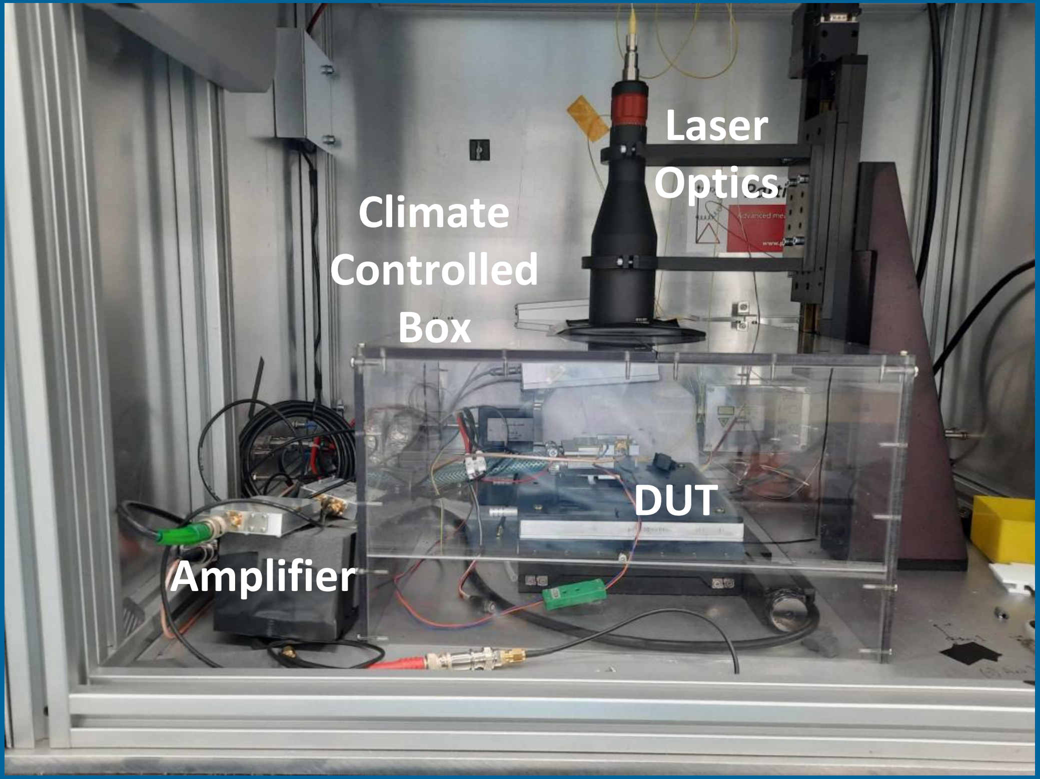
$$\frac{V_{GL}(\phi)}{V_{GL}(0)} = \frac{\rho_A(\phi)}{\rho_A(0)} = e^{-c(\rho_A(0))\phi}.$$

https://arxiv.org/pdf/1802.01745.pdf



Laser Charge Injection

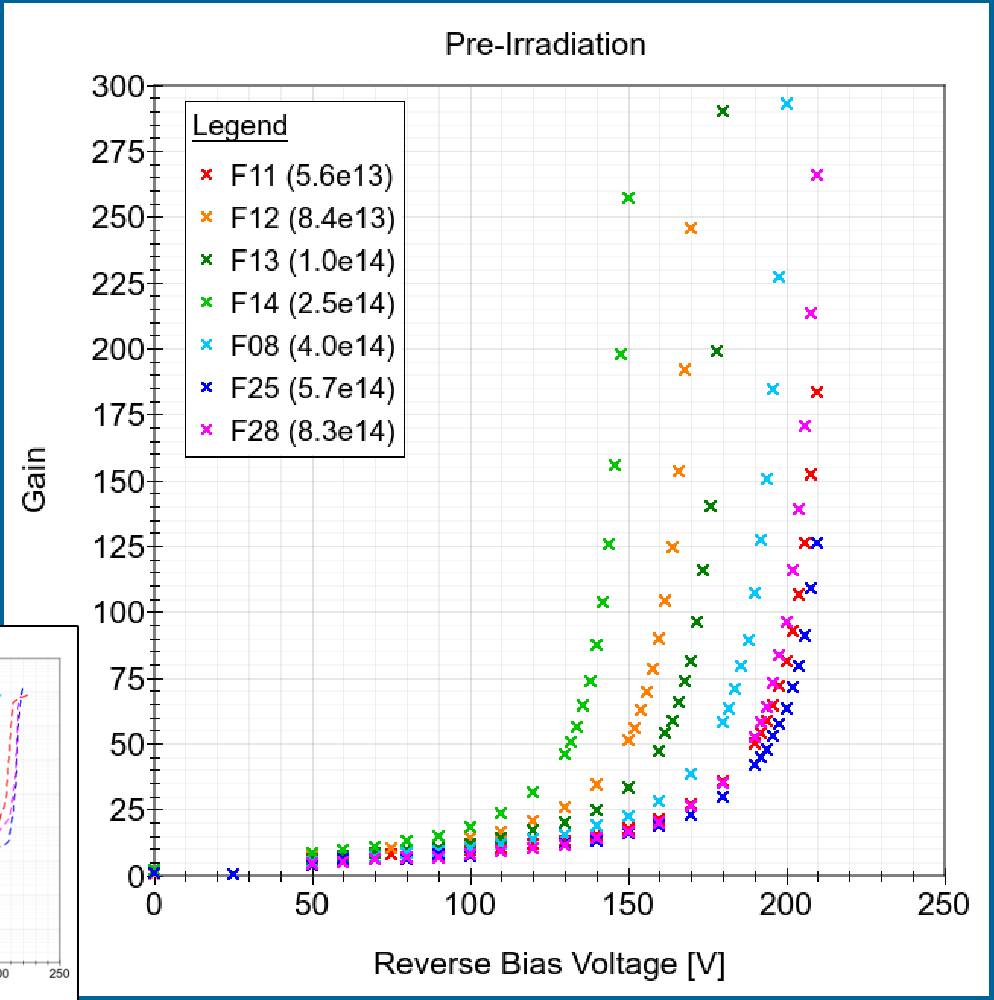
- **1064 nm** laser injects charge into an LGAD and a PiN (LGAD without gain layer)
  - Pulse is integrated and amplified by a Particulars AM-02A
  - Resulting signal is integrated (offline) and the **ratio between the LGAD and the PiN is the gain**
- Laser is convenient but, unlike with charged particles, there is no gain suppression

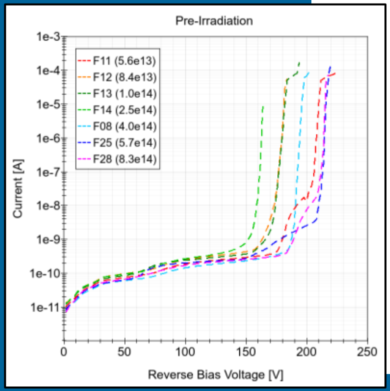


https://www.particulars.si/downloads/ParticularsAmps-Manuals.pdf

Pre-Irrad Gain

- All devices achieve a similar value of gain, but the bias voltage required varies significantly
- This is mirrored in the IV curves which also have a similar variance in breakdown voltage





Post-Irrad Gain

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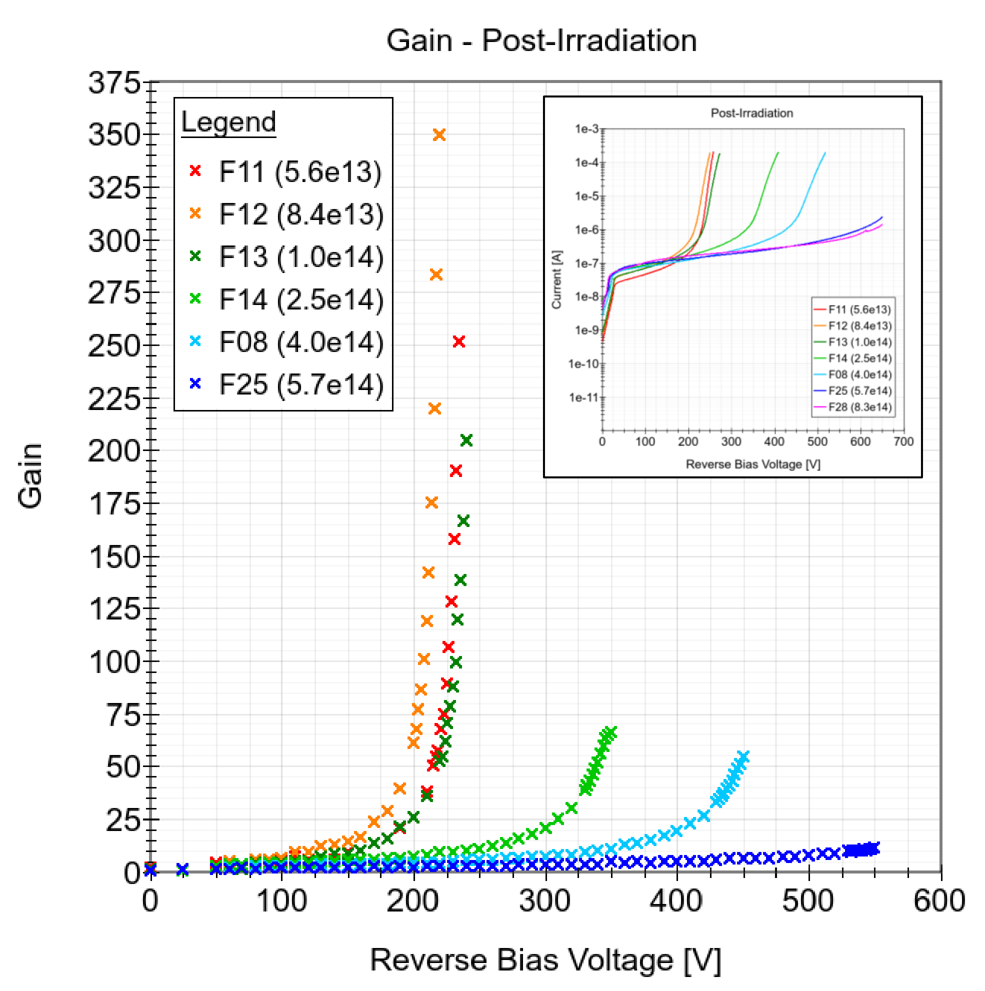
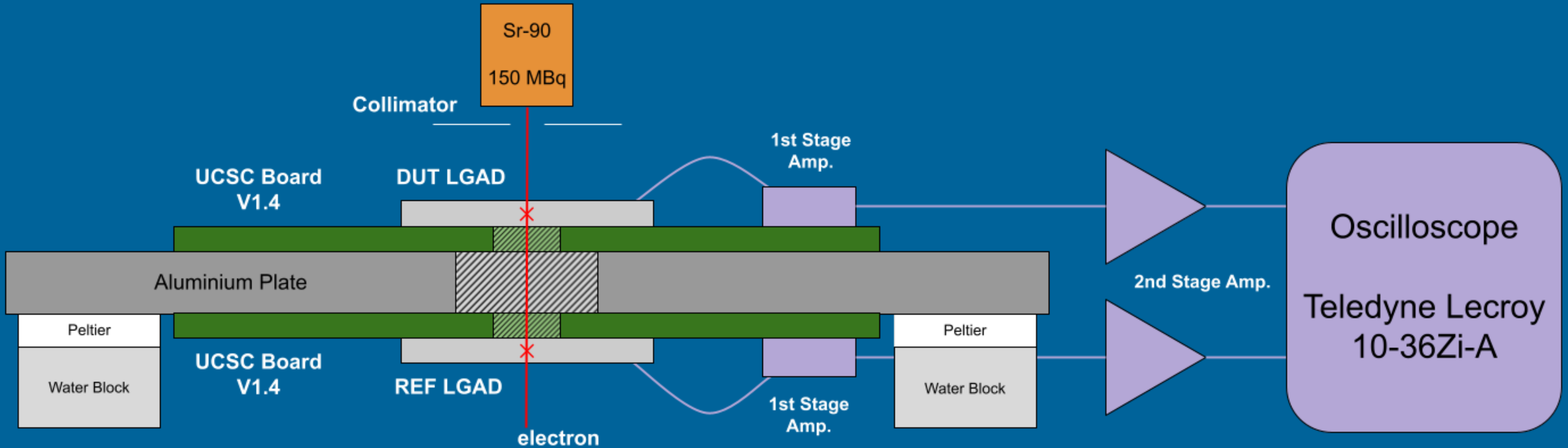
- **Low fluence** devices see **minimal change** aside from a slight change in bias voltage dependence
- With **higher fluences** one is **unable to achieve as high a value of gain**. A higher bias voltage is also needed to see moderate gain



Coincidence Timing Technique

- Strontium-90 beta source injects **charged particles** towards two **coincidently placed LGADs** (DUT and a reference of known time resolution). Oscilloscope triggers on the two LGAD pulses provided they are within 5 ns of each other

- Santa Cruz timing boards initially amplify the signal, followed Particulars AM-01B for 2nd stage amplification. The resulting signal is recorded for offline analysis



https://arxiv.org/pdf/1707.04961.pdf

https://www.particulars.si/downloads/ParticularsAmps-Manuals.pdf

Cold Timing

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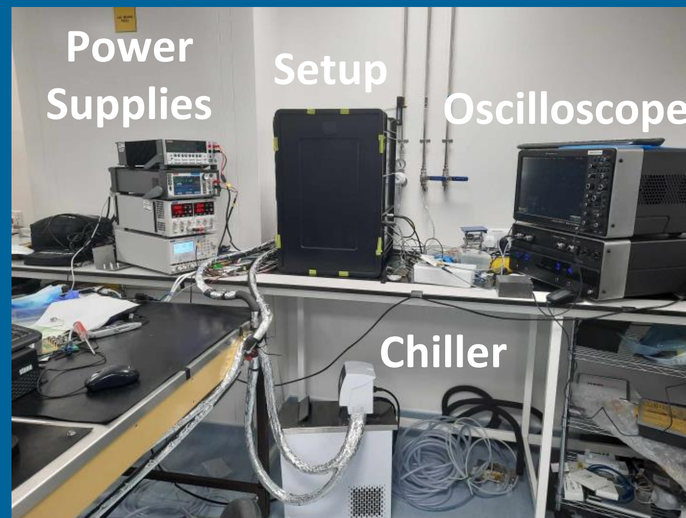
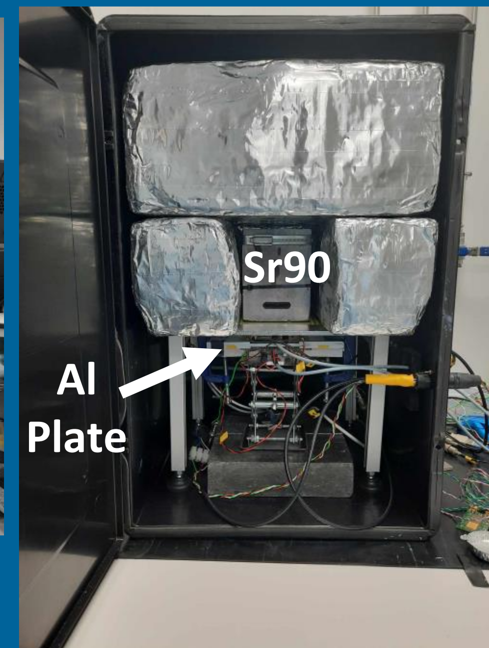
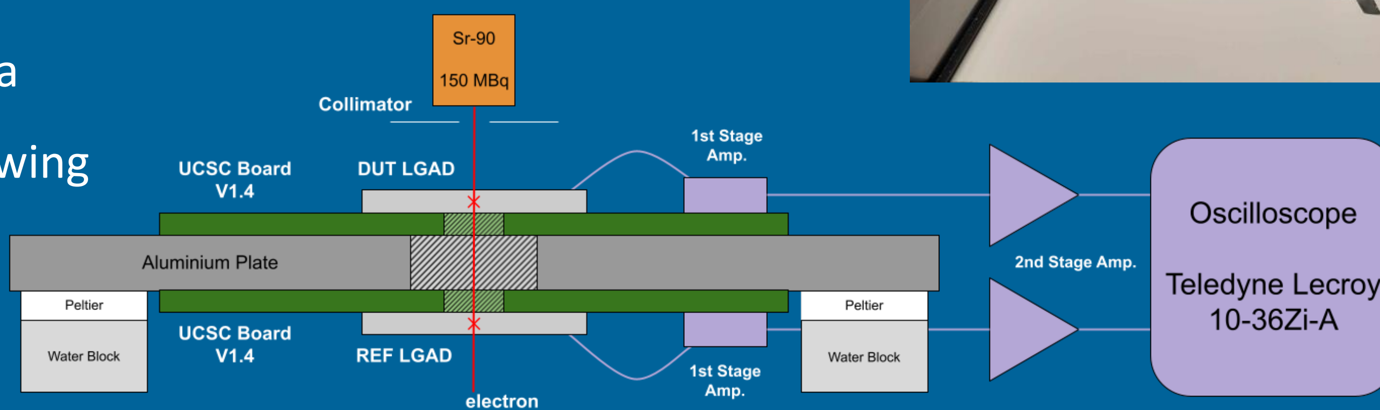
- A pair of peltiers (assisted by a chiller) keep the LGADs at **-20 ˚C** for post-irradiation tests
- Aluminium plate is sandwiched between the LGADs to provide a thermal mass allowing **uniform cooling**







Time of Arrival

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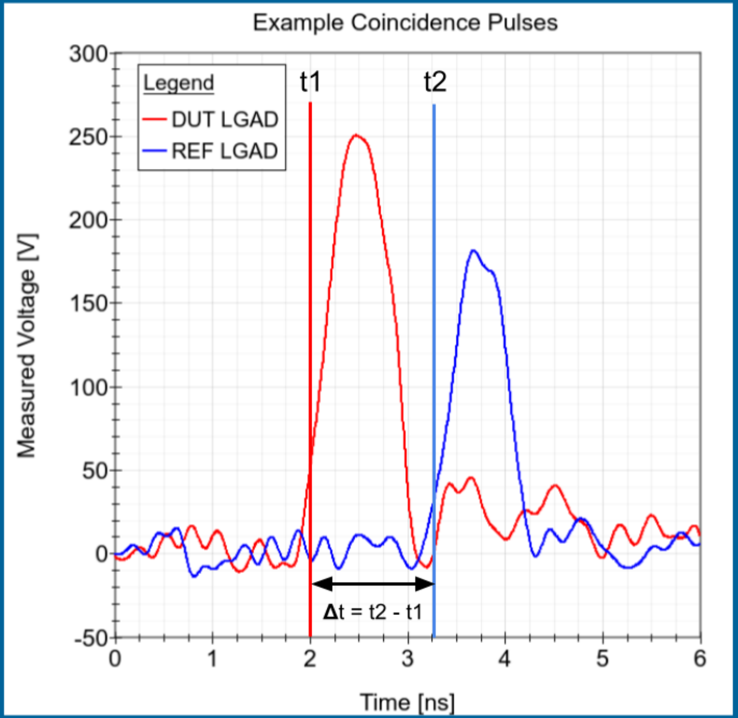
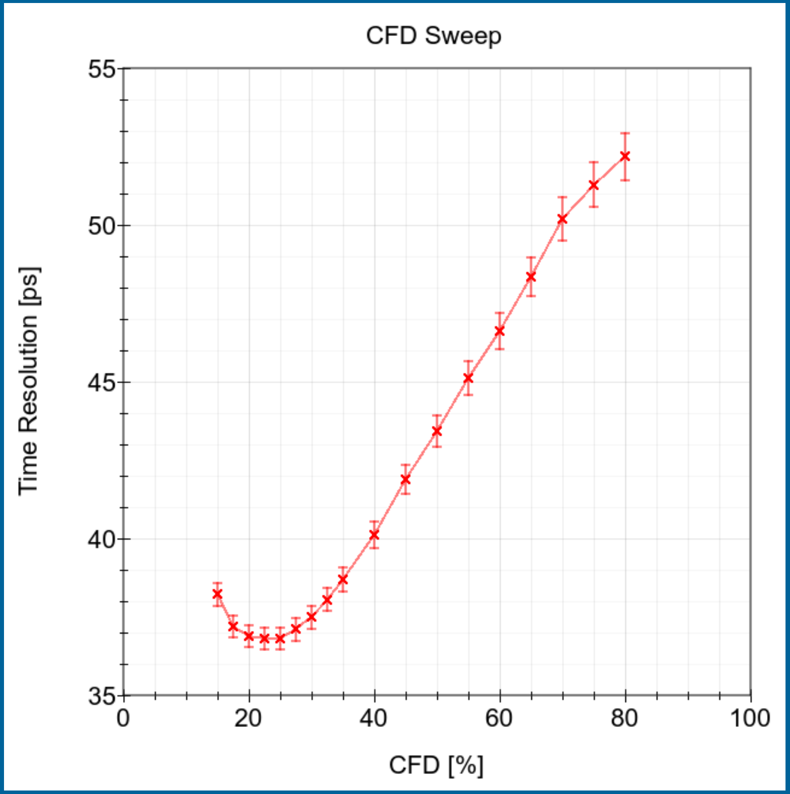
- A single electron triggers both LGADs with an **arbitrary constant time** difference the error of which is dominated by the time resolution of the two LGADs





- Time of arrival is determined with a **20% constant fraction discriminator** (CFD) applied offline to the collected data. This was determined by performing a **CFD sweep** to identify the optimal value

Time Resolution

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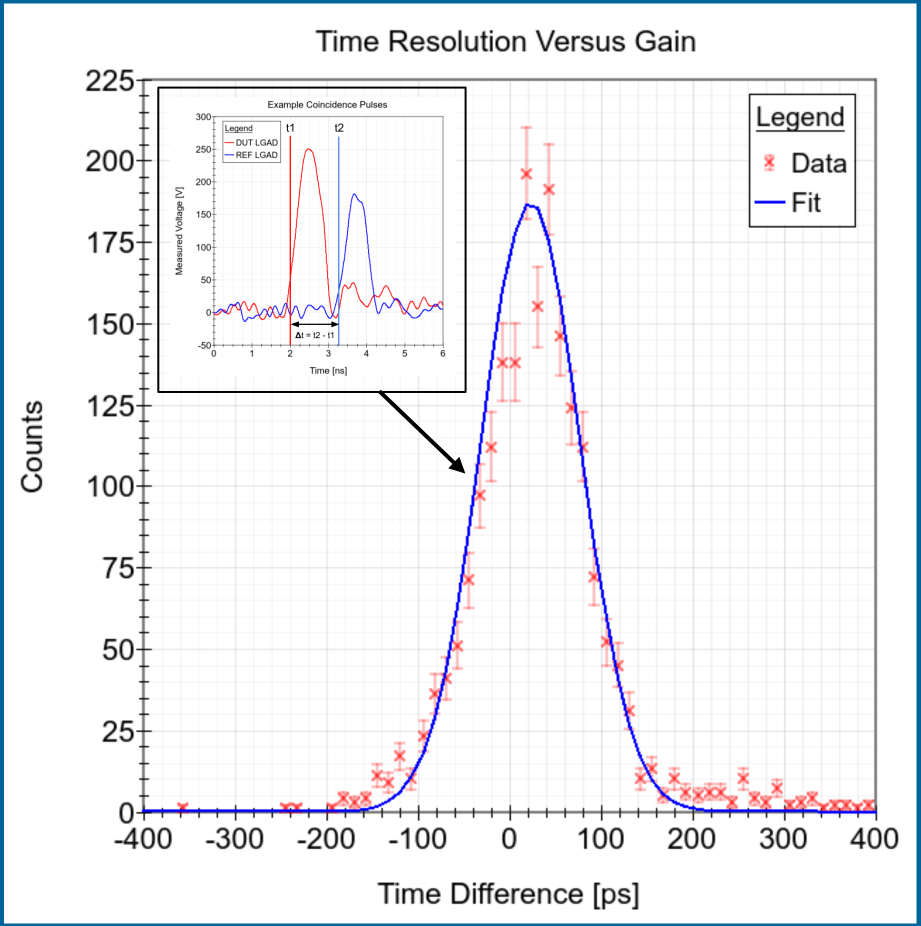
- After ~2000 coincidence events have been collected one can fit a Gaussian distribution (represented visually with a histogram)
- This Gaussian is a product of the two LGAD time resolutions
- Thus the resolution of the reference needs to be subtracted in quadrature from the measured Gaussian's standard deviation

$$\sigma_{MEAS}{}^2 = \sigma_{DUT}{}^2 + \sigma_{REF}{}^2$$



Pre-Irrad Timing

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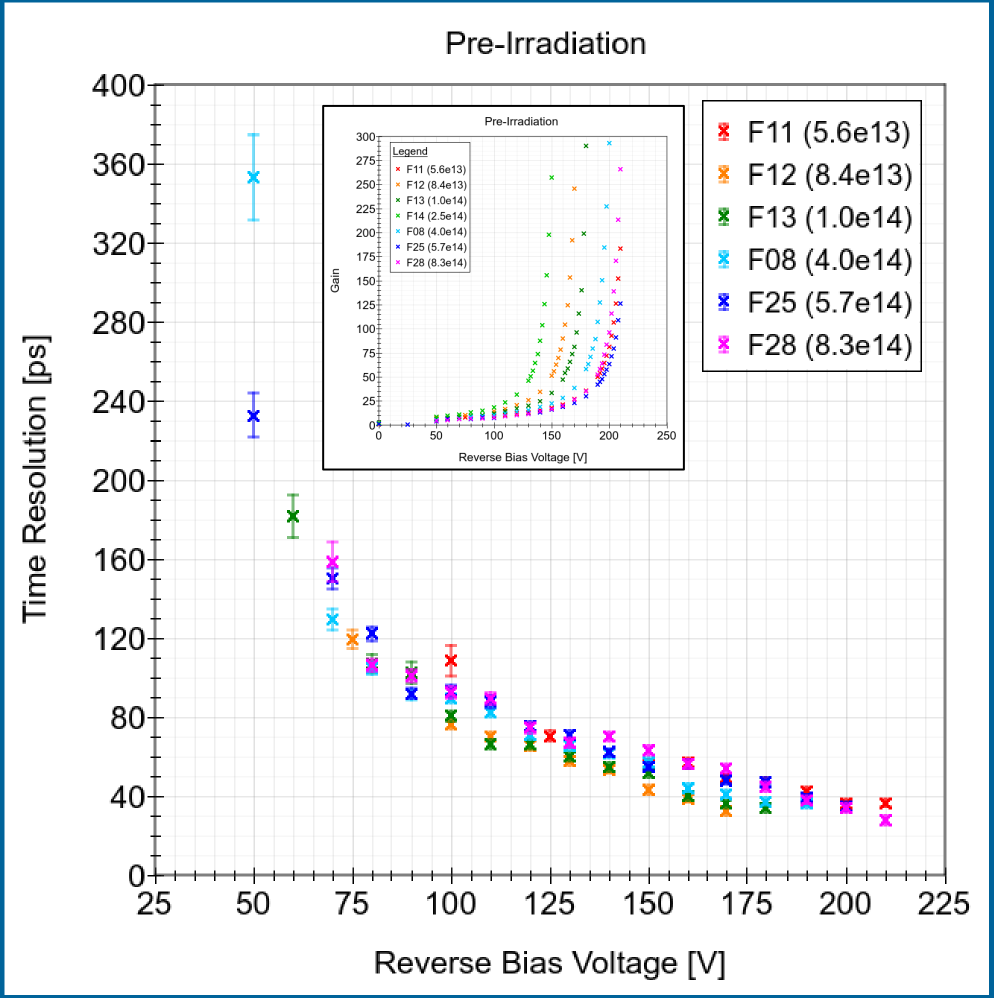
- All 7 devices show a **similar timing performance versus bias voltage**
- Minimal variability corresponds to the **variation in gain** as a function of voltage



Pre-Irrad Timing

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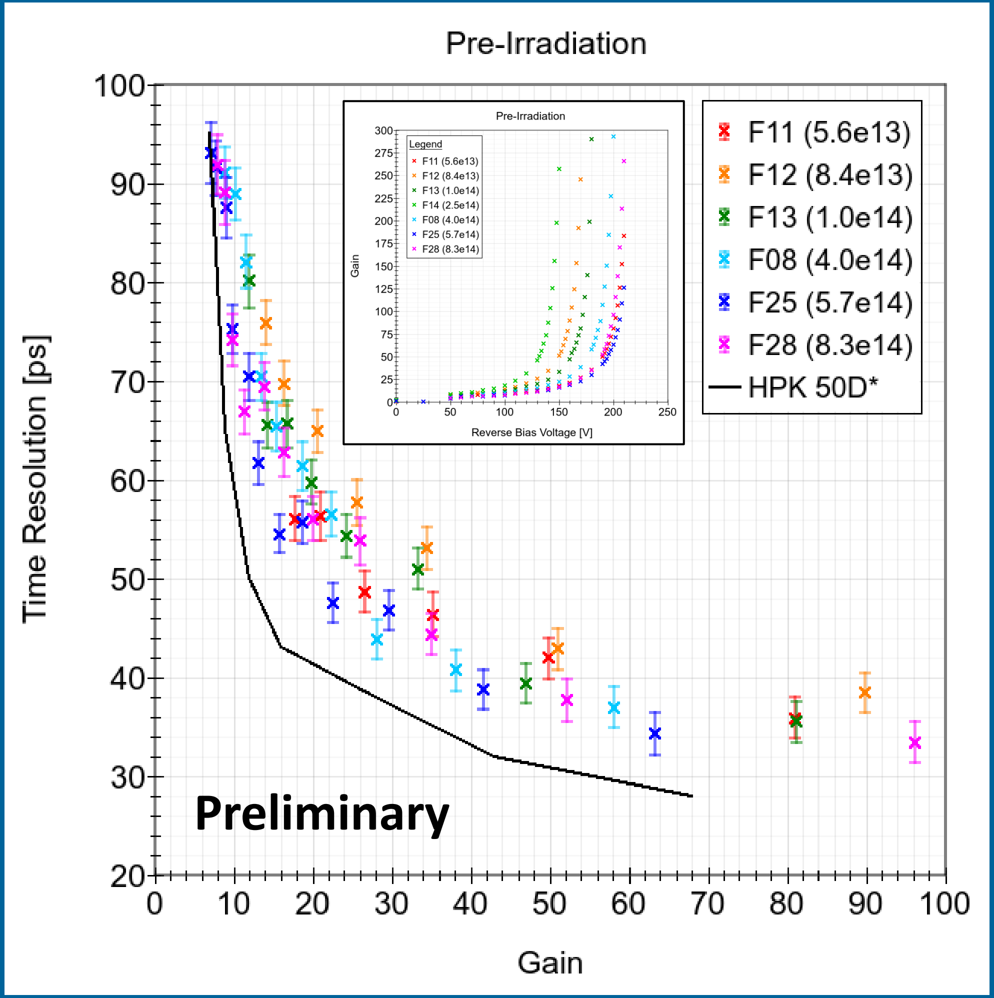
- Time resolution as a function of gain shows a **similar trend** to what we see from other vendors
- While comparable, our **time resolution is slightly worse** than those from HPK (*)
- However, values of gain may be overestimated using laser injection (no gain suppression)



https://indico.cern.ch/event/587631/contributions/2471694

Post-Irrad Timing

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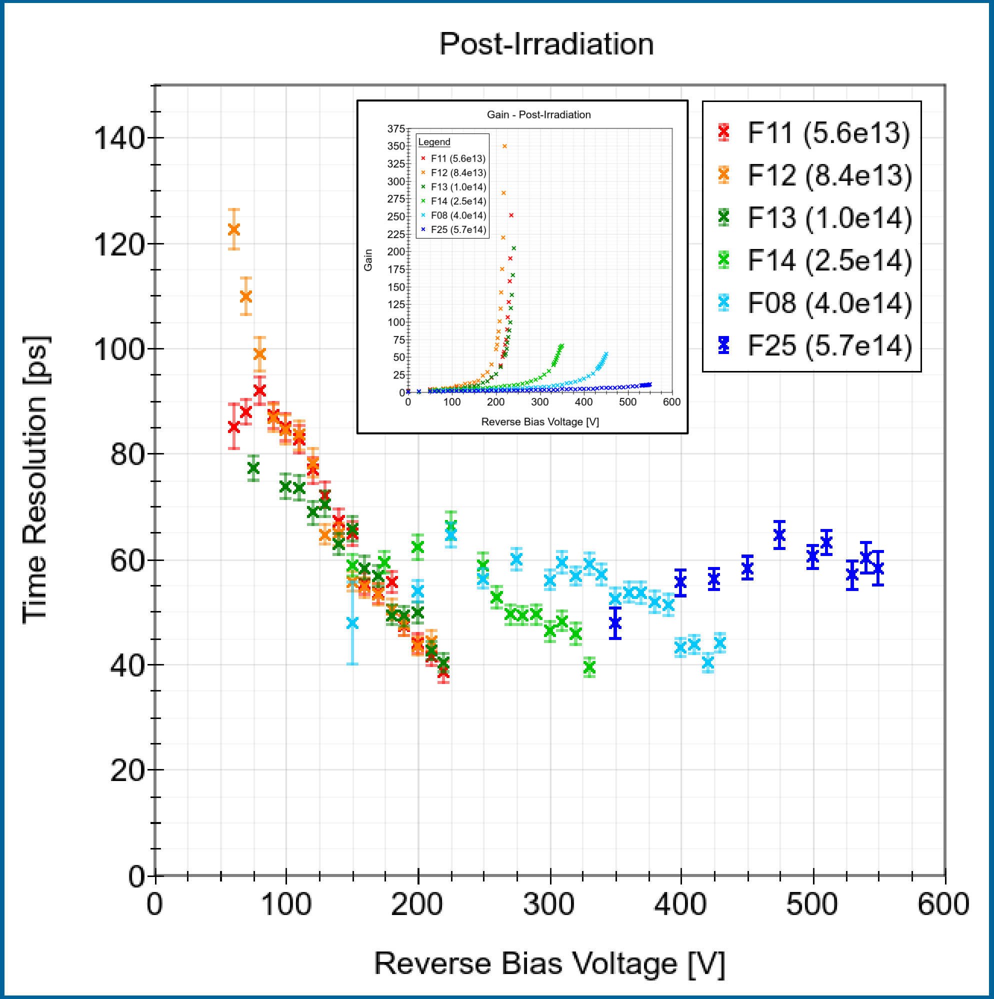
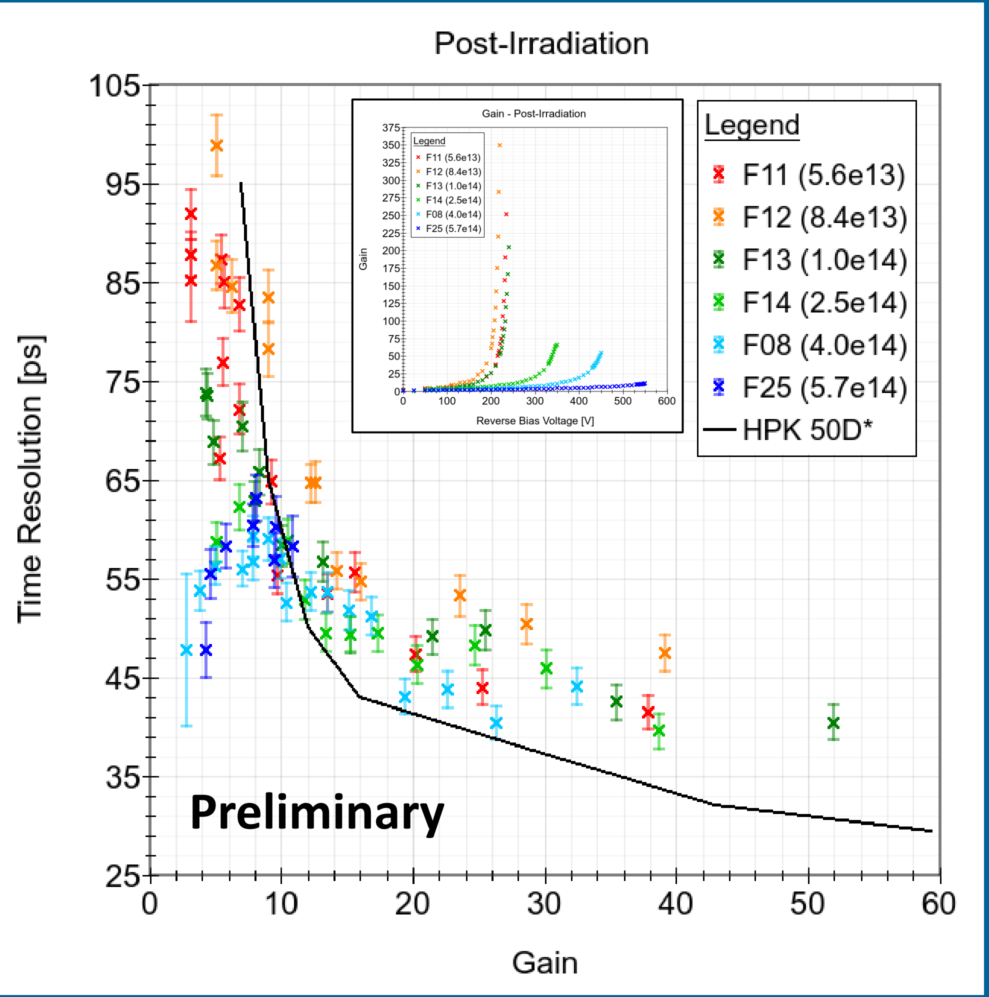
- As seen with gain, a **higher bias is required** to achieve a good time resolution as fluence increases
- **Time resolution is generally worse compared** to pre-irrad (sub 40ps)
- We were unable to test F28 due to unstable current at high bias voltages



Post-Irrad Timing

- Time resolution as a function of gain maintains the **same relationship** after irradiation
- At low values of gain, the time resolution begins to improve. This is due to some signals falling below the oscilloscope's trigger threshold, **biasing the data towards only including the largest signals**. This has been confirmed by lowering the trigger threshold



https://indico.cern.ch/event/587631/contributions/2471694

Conclusions

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- Teledyne e2v is a **new player** for Particle Physics applications, demonstrated with their **first batch** of LGADs
  - **Slightly worse but comparable timing performance**
  - **Radiation hardness needs further investigation and improvement at higher fluences (>= 5.7e14 1 MeV neq/cm^2)**
- Promising results from their first batch establishes them as a potential future vendor for the Particle Physics community
- In addition to the 7 devices shown today, we plan to characterise up to 4 additional wafers to investigate the effect of implant energy and dose

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Thank you for your time

Any questions?

Previous Talks

- 37th RD50 workshop, Nov 2020
  - https://indico.cern.ch/event/896954/contributions/4106308/
- 38th RD50 workshop, June 2021
  - https://indico.cern.ch/event/1029124/contributions/4411263/
  - https://indico.cern.ch/event/1029124/contributions/4411247/
- PSD12, Sept 2021 (+ proceedings)
  - https://indico.cern.ch/event/797047/contributions/4455947/
- Vertex, Sept 2021 (+ proceedings)
  - https://indico.cern.ch/event/1047531/contributions/4520803/
- 39th RD50 workshop, Nov 2021
  - https://indico.cern.ch/event/1074989/contributions/4601996/
  - https://indico.cern.ch/event/1074989/contributions/4602008/
- 17th Trento Workshop, March 2022
  - https://indico.cern.ch/event/1096847/contributions/4743794/

Backup Slides

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Low Gain Avalanche Detectors

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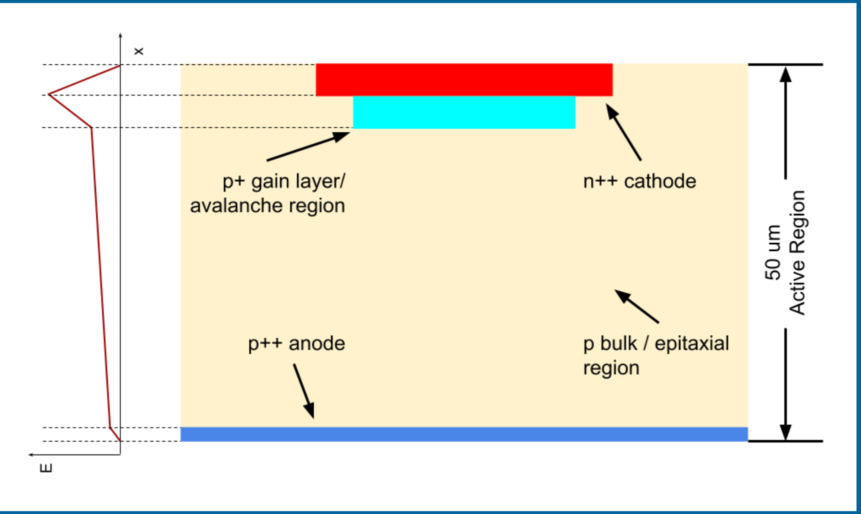
- We study LGADs for their excellent time resolution (~35 ps). This time resolution has a few contributions
- **Distortion** is due non-uniformity in the drift velocity and weighting field. High bias voltage ensures a saturated and uniform drift velocity. Ensuring the gain layer is as large as the pitch of the sensor keeps the weighting field uniform
- **TDC** is due to the readout electronics and is usually small enough to be ignored



$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{ionization}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$$

Low Gain Avalanche Detectors

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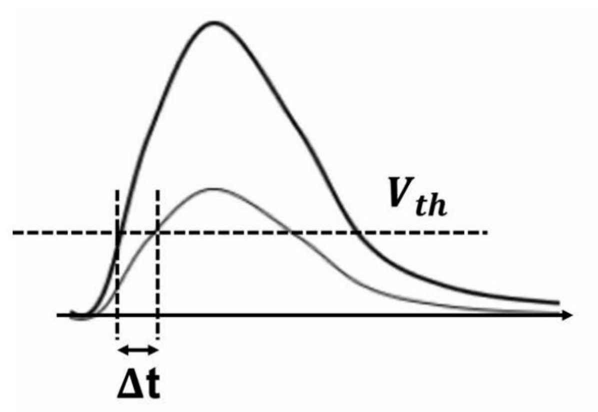
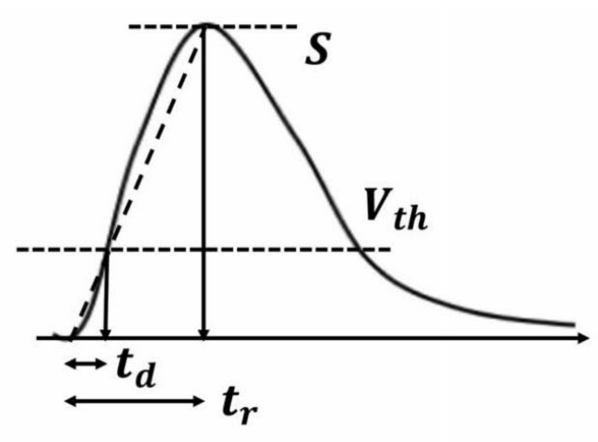
- **Ionisation** is due to the irregularity in the signal shape caused by the discrete nature of e-h pair generation
- The first effect is a change in amplitude which causes timewalk (a larger signal arrives earlier). This can be corrected for using a Constant Fraction Discriminator (CFD)
- The second effect is called Landau Fluctuations and is due to irregularities and noise in the signal shape itself. These fluctuations are unavoidable but can be minimised with thin sensors (~50 um) which bring this intrinsic limit down to ~25 ps

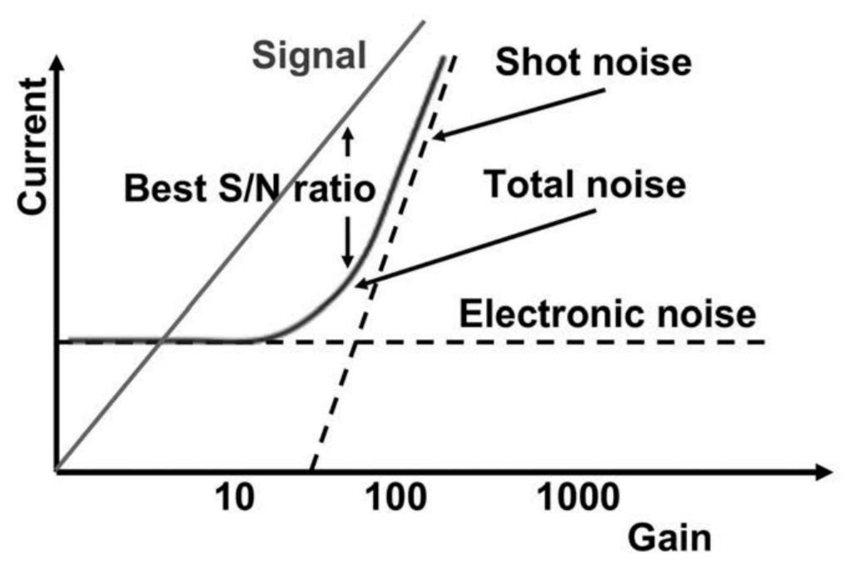




$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{ionization}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$$

Low Gain Avalanche Detectors

- **Jitter** is any additional noise on top of the signal which can cause the signal to appear to arrive earlier or later than it actually does.
- For a constant slope in the rise of the signal, the jitter is approximately proportional to the rise time divided by the SNR.
- A low gain maximises the SNR which therefore minimises the jitter. Hence low gain gives good time resolution.



$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{ionization}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$$

https://arxiv.org/abs/1704.08666

Parameterising CVs

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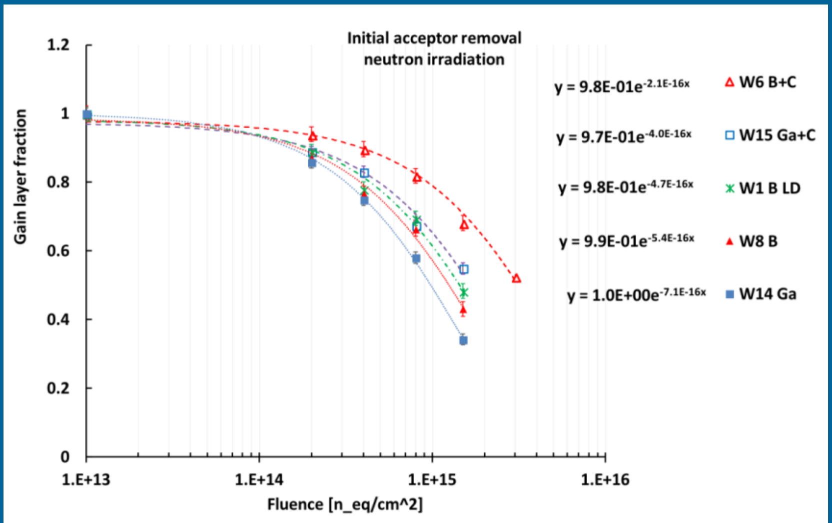

*FBK neutron irradiated Boron-implanted LGADs. Ferreroa, M., 2018

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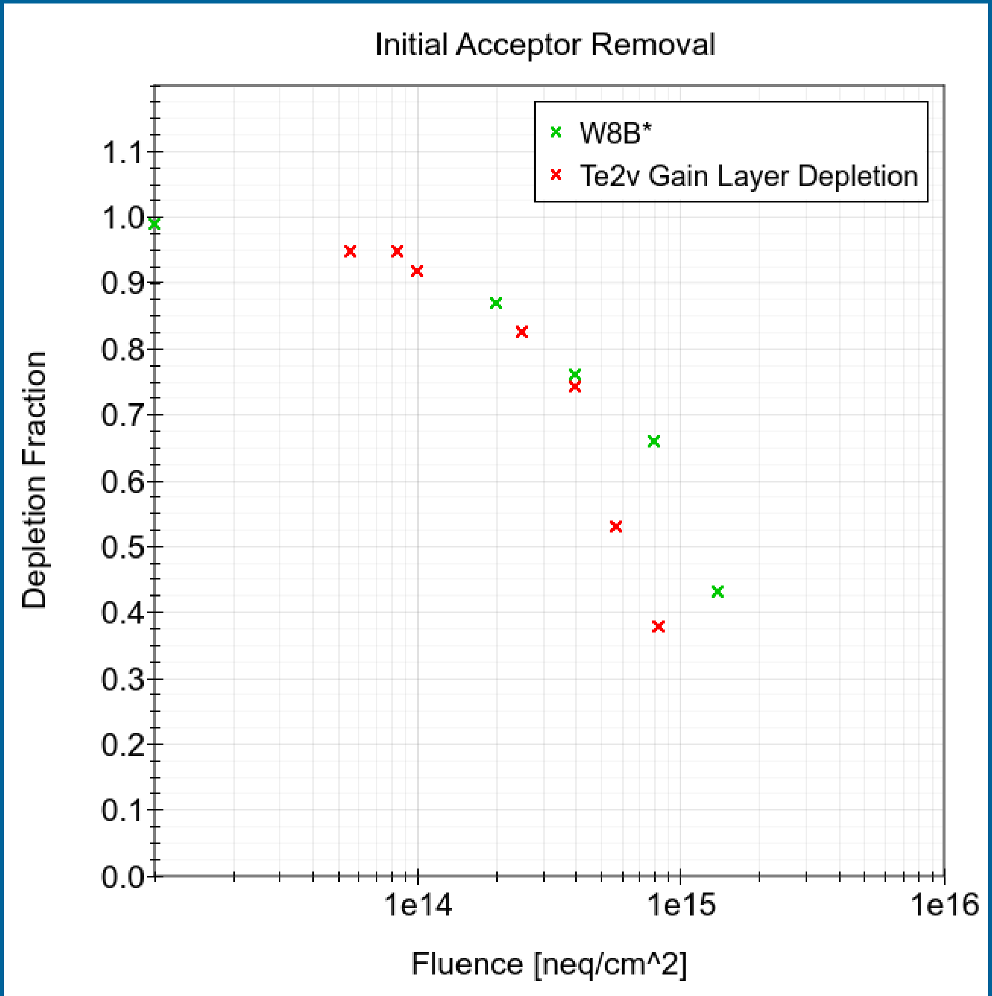


Reference Time Resolution

- If we don't have a device of known time resolution, we have two options:
- The first is to use two identical LGADs and assume their time resolutions are the same. This results in the second equation. This is most likely a reasonable estimate and then gives us a reference device, however we can improve on this method to remove the assumption.
- The second option is to measure 3 LGADs (identical or not) in 3 sets of pairs (third set of equations). Then by combining these in a particular order, we can extract the time resolution of each device.
- Whilst this provides us with a reference device, it currently yields a rather high error which has a knock-on effect with future measurements.

$$\sigma^2_{MEAS} = \sigma^2_{DUT} + \sigma^2_{REF}$$

$$\sigma_{DUT} = \frac{\sigma_{MEAS}}{\sqrt{2}}$$

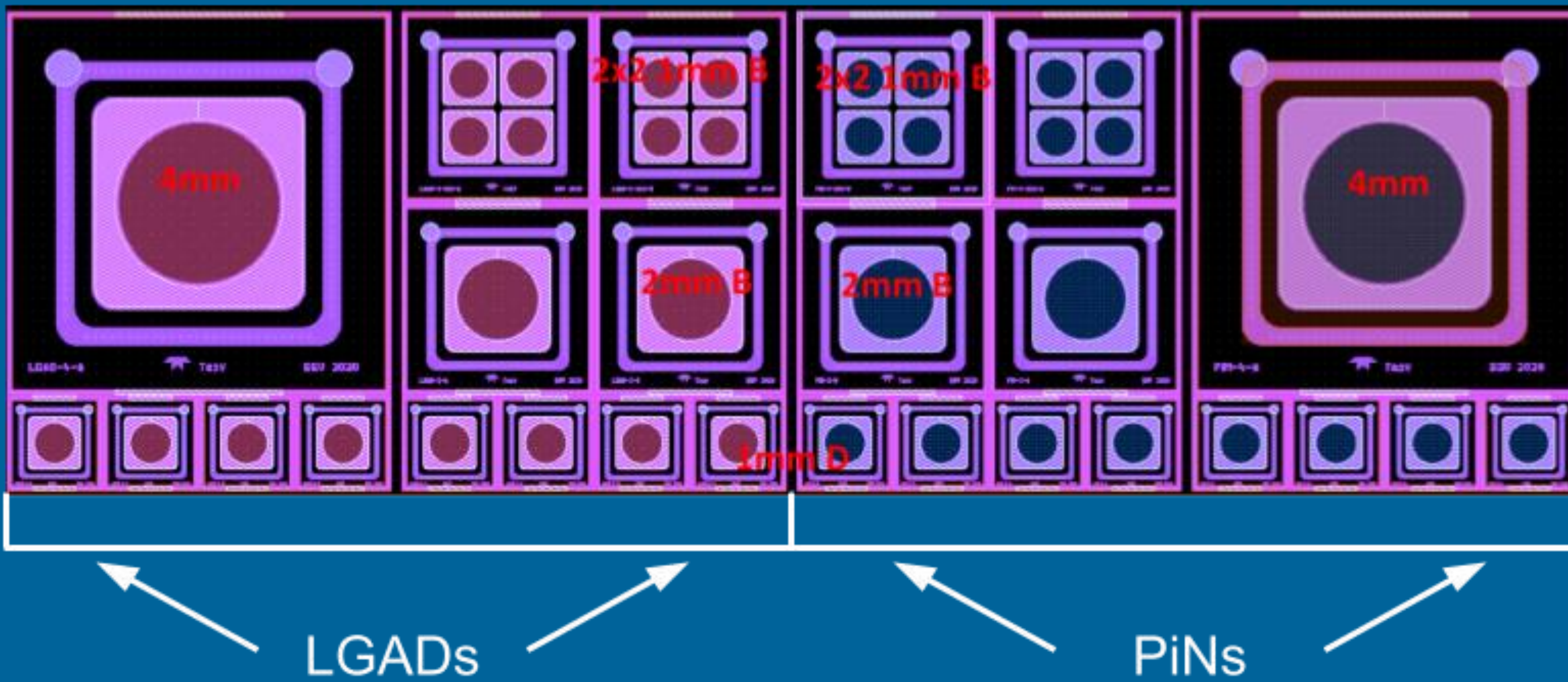
$$\sigma_1^2 = \sigma_A^2 + \sigma_B^2,$$

$$\sigma_2^2 = \sigma_C^2 + \sigma_B^2,$$

$$\sigma_3^2 = \sigma_A^2 + \sigma_C^2,$$

$$\sigma_1^2 + \sigma_2^2 - \sigma_3^2 = 2\sigma_B^2$$

1st Batch



Pre-Irrad Timing

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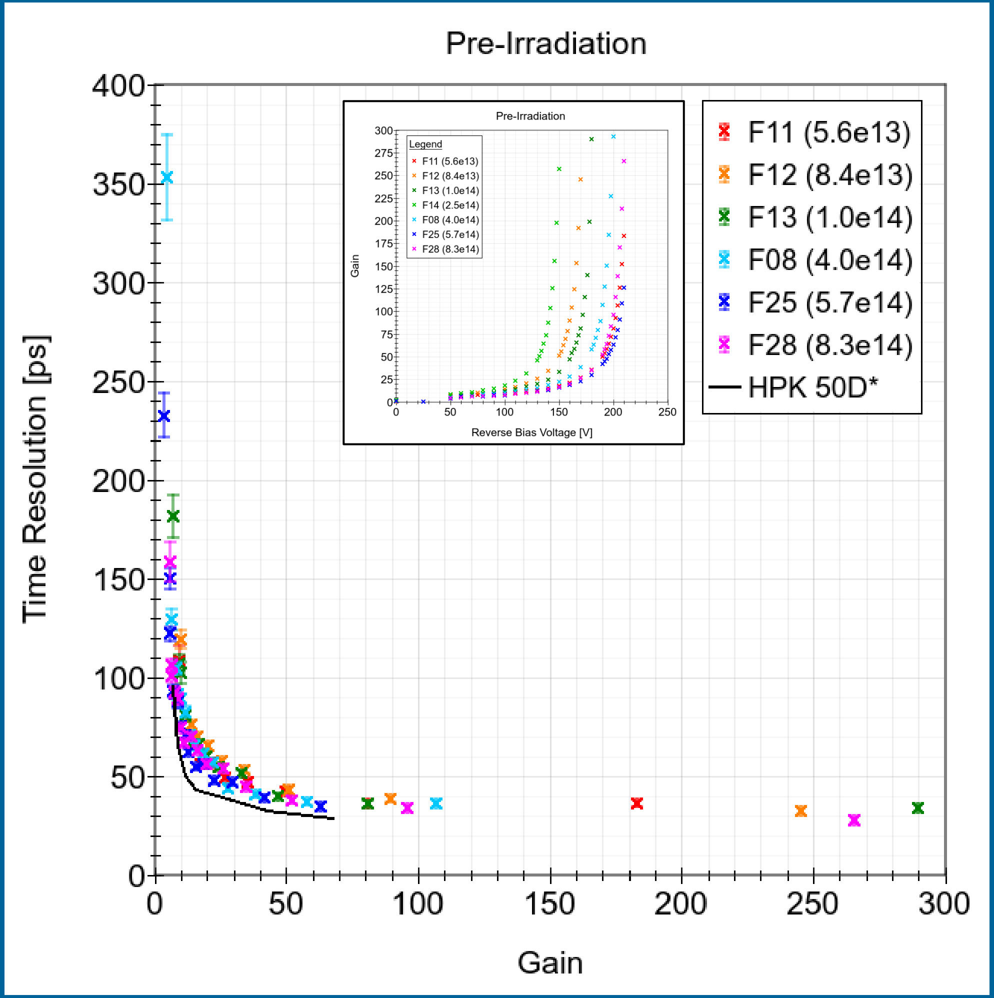

*Sadrozinski, H., Ultra-fast Silicon Detectors, 2017 https://arxiv.org/abs/1704.08666

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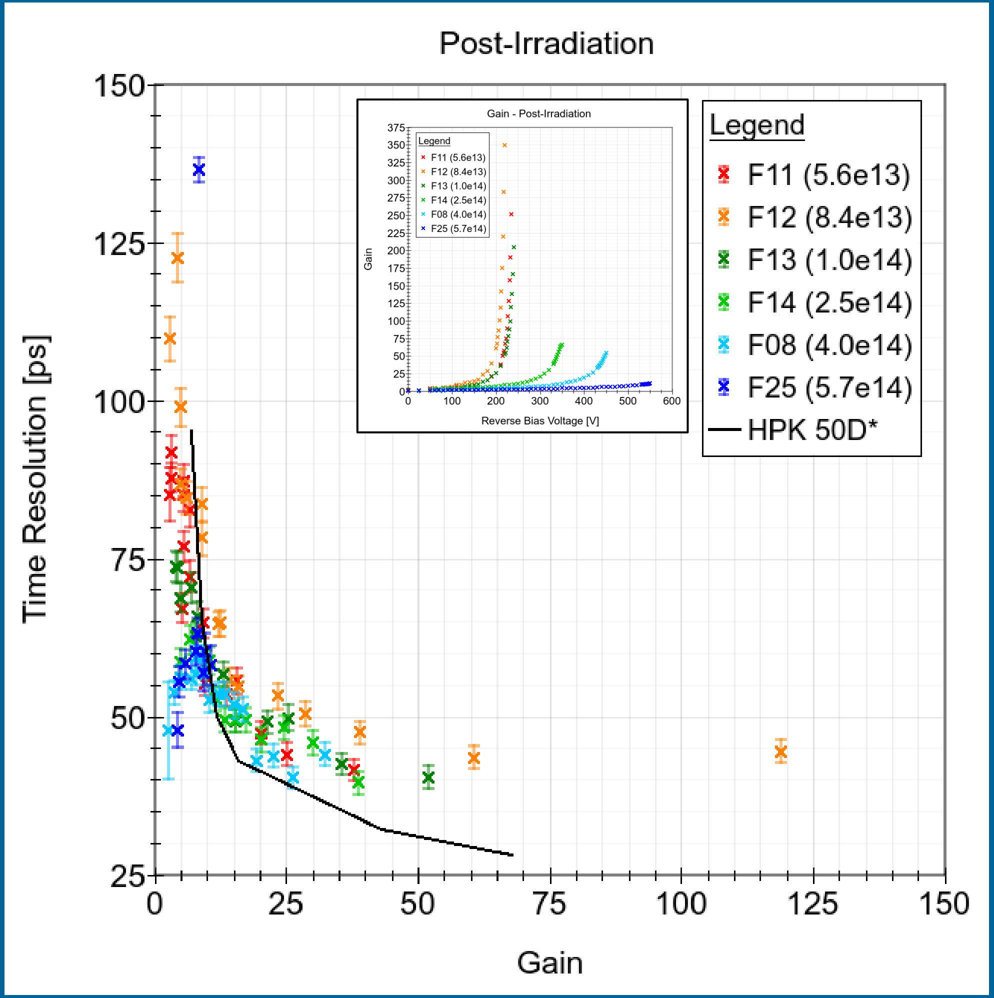
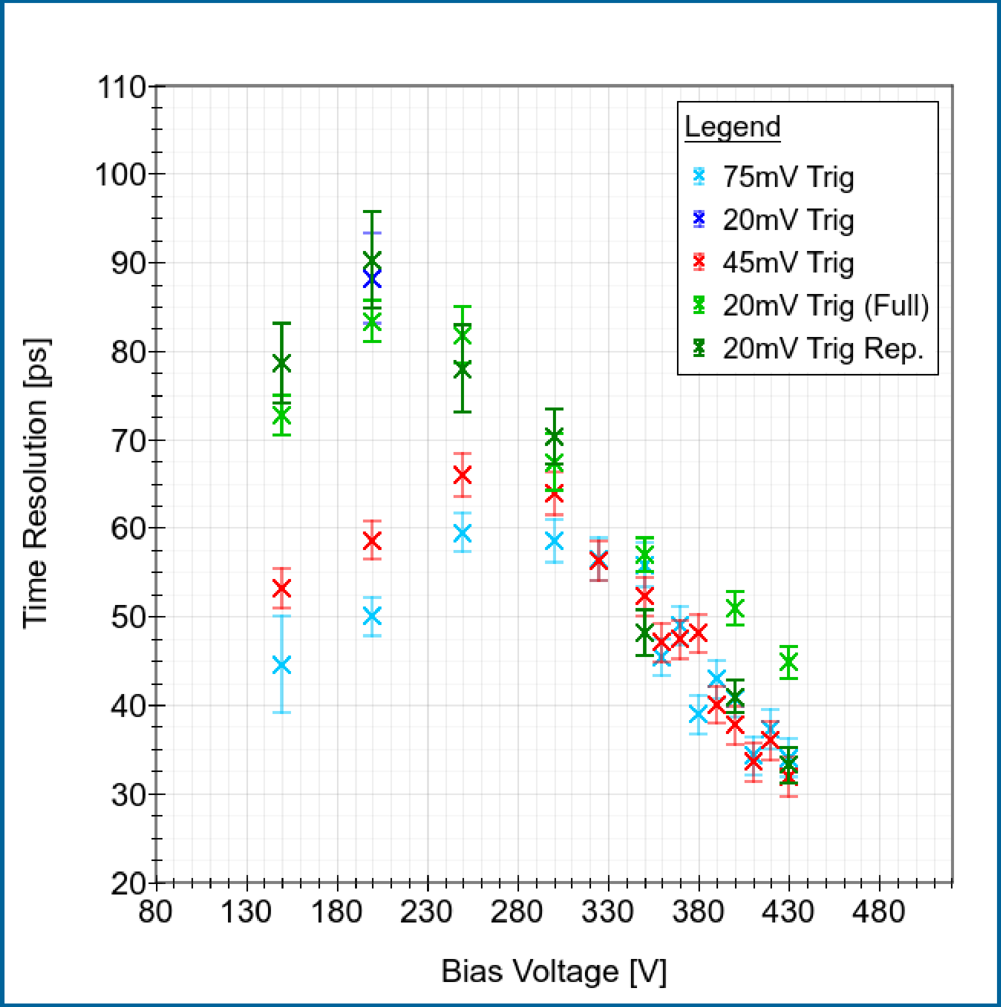


*Sadrozinski, H., Ultra-fast Silicon Detectors, 2017 https://arxiv.org/abs/1704.08666

Landau Cutting

- Bias sweep performed at different trigger thresholds
- Higher thresholds give a better time resolution since only large signals are accepted
- Higher thresholds are sometimes still used to make the measurement speed practical



Landau Cutting

- Signal height for 2000 events are plotted as a histogram. Each curve shows a different trigger threshold. Plot on the left shows high bias and trigger threshold has no effect. Right plot shows low bias and the trigger significantly changes the distribution