Characterization of neutron- and proton-irradiated LGADs from Teledyne e2v

41st RD50 Workshop, 1st December 2022

P. Allport, D. Bortoletto, M. Gazi, L. Gonella, D. Hynds, D. Jordan, I. Kopsalis, S. McMahon, J. Mulvey, R. Plackett, K. Stefanov, E. G. Villani

UNIVERSITY OF OXFORD

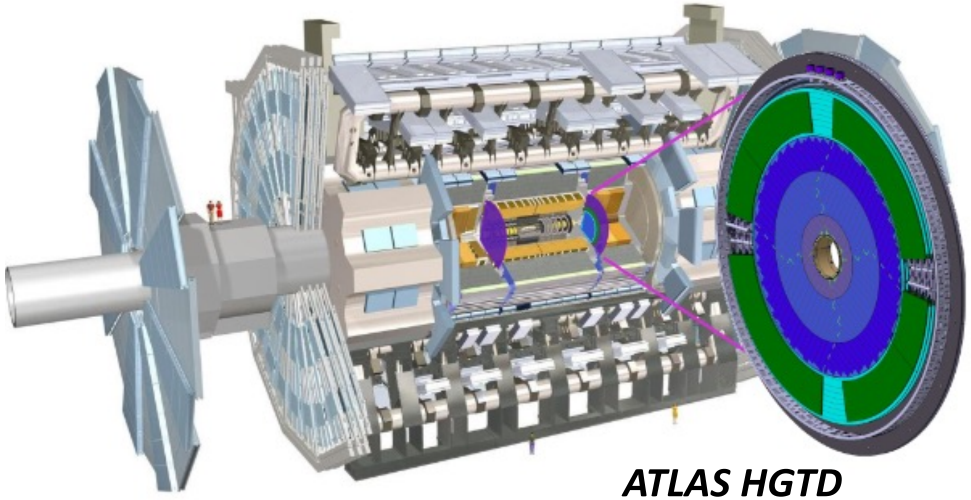
Science & Technology Facilities Council Rutherford Appleton Laboratory

UNIVERSITY OF BIRMINGHAM

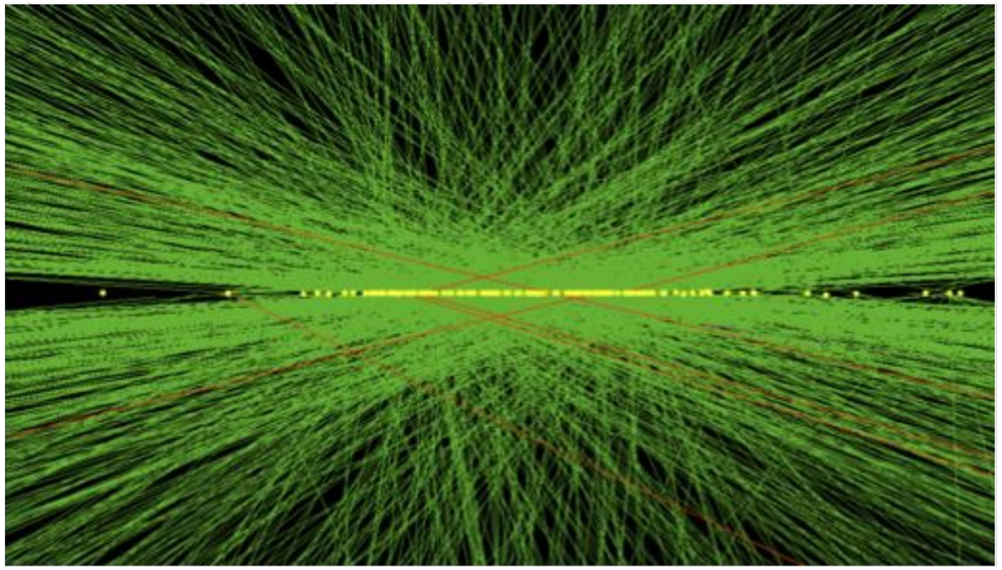
The Open University

TELEDYNE e2v Everywhereyoulook™

The need for Ultra Fast Silicon Detectors



ATLAS HGTD



z-vertex distribution for a single bunch crossing at HL-LHC

- Pile-up is one of the major challenges for tracking at the HL-LHC
- Timing information used to disentangle overlapping events
- ATLAS High-Granularity Timing Detector placed outside the ITk

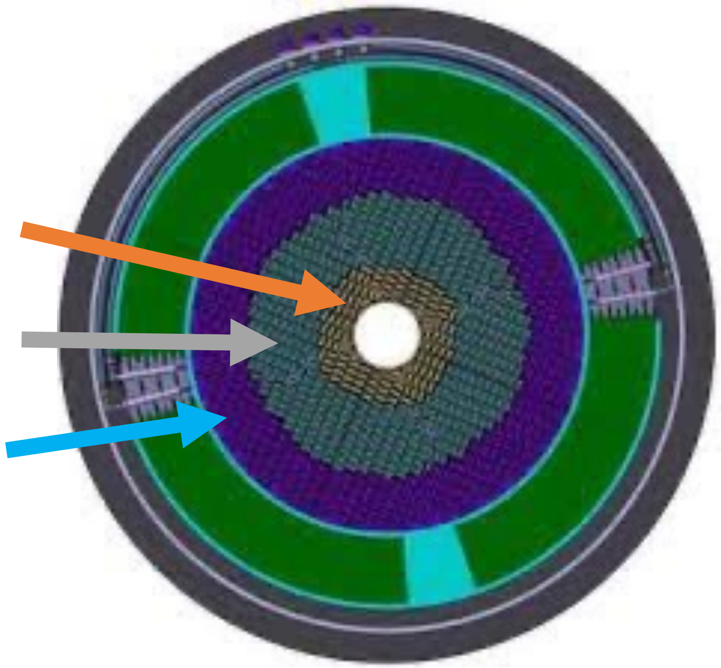
High Granularity Timing Detector

- Replacement of sensors and ASICs needed to maintain a sufficiently precise timing resolution
- Maximum fluence that the sensors have to sustain is 2.5×10^{15} n_{eq} cm^{-2} (including a safe factor of 1.5)
- Excellent understanding of radiation hardness of the sensors needed

Inner ring (120 mm < R < 230 mm) replaced every 2 000/fb

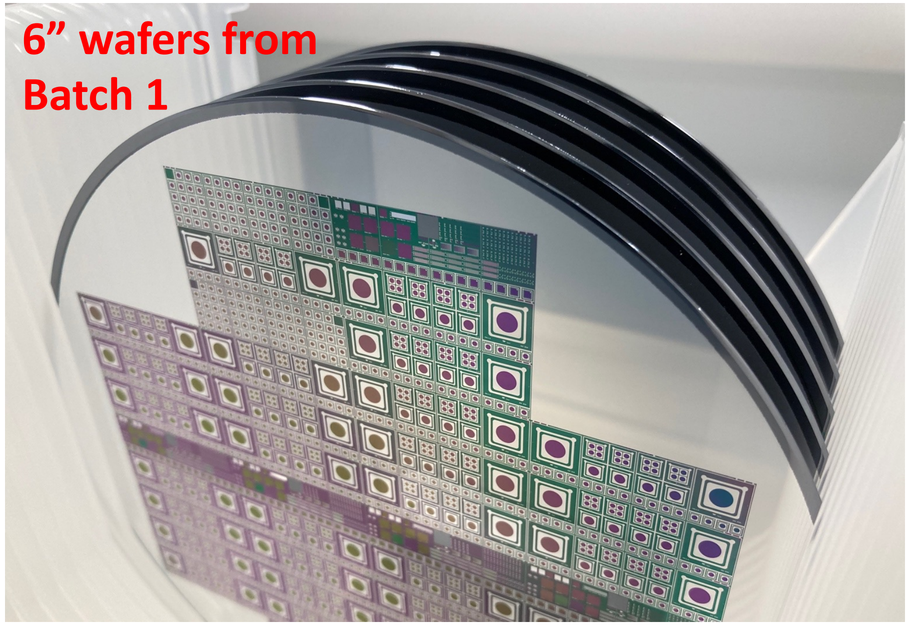
Middle ring (230 mm < R < 470 mm) replaced every 1 000/fb

Outer ring (470 mm < R) not replaced

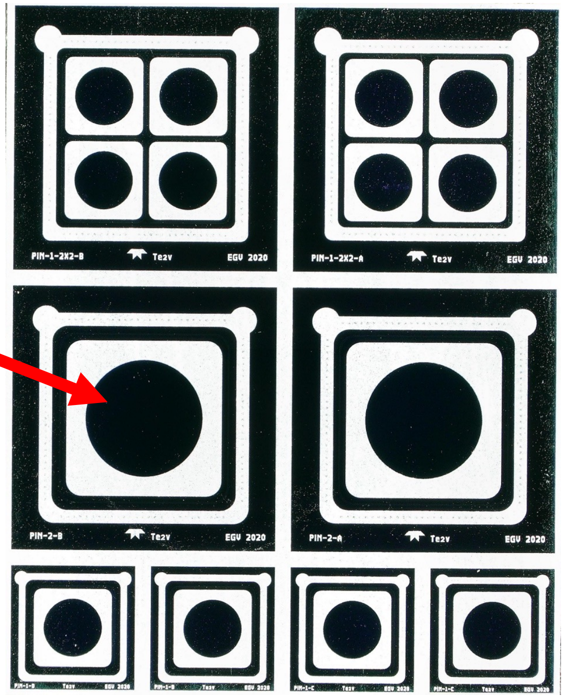


Teledyne e2v LGAD project

- Targeting track timing resolution of approx. 30-50 ps over detector lifetime
  - Time resolution benefits from high slew rate -> increased by introducing internal gain
  - Impact ionization in gain layer -> boron implantation
  - Pre-manufacture simulation done in TCAD
- Batch 1: LGADs and PiN diodes of the same layout



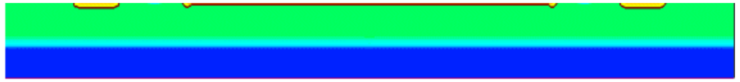
Gap in the surface metallisation for TCT laser injection



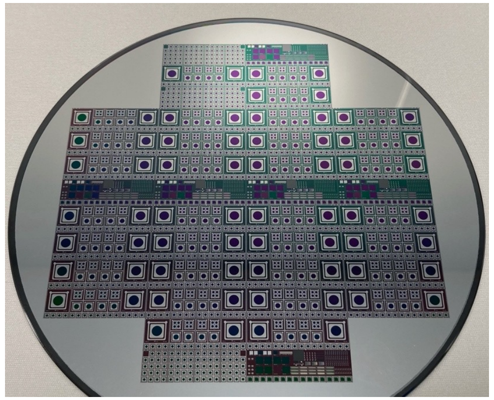
(also features 4x4 mm^2 devices which are not shown)

Teledyne e2v LGAD project - timeline

early 2020 — TCAD simulation



late 2020 — Batch 1 produced

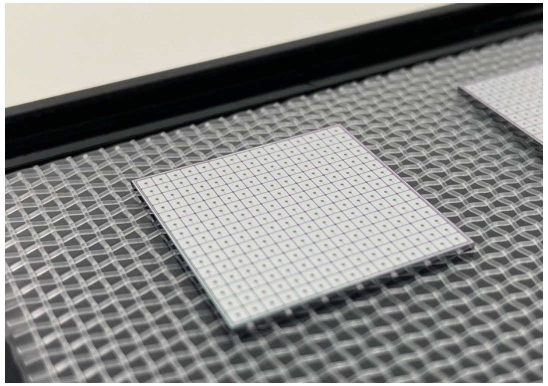


early 2021

late 2021 — simulation and submission of Batch 2

early 2022 — Neutron irradiation of Batch 1

late 2022 — Batch 2 produced



Batch 2 testing

Teledyne e2v LGAD project - devices

- LGAD epitaxial layer: 50 um thick, high resistivity
- 8 different combinations of manufacturing parameters in Batch 1 (4 presented)

Wafer Number	Normalised Dose (D)	Normalised Energy (E)
19,20,21	1.00	1.00
17,18	1.07	1.00
15,16	0.92	1.05
12,13,14	1.00	1.05
9,10,11	1.07	1.05
7,8	1.15	1.05
4,5,6	1.00	1.11
2,3,24	1.07	1.11

- Neutron irradiation performed at the TRIGA reactor at the Jozef Stefan institute in Ljubljana, Slovenia
- Proton irradiation performed at MC40 cyclotron with 27 MeV protons in Birmingham, UK

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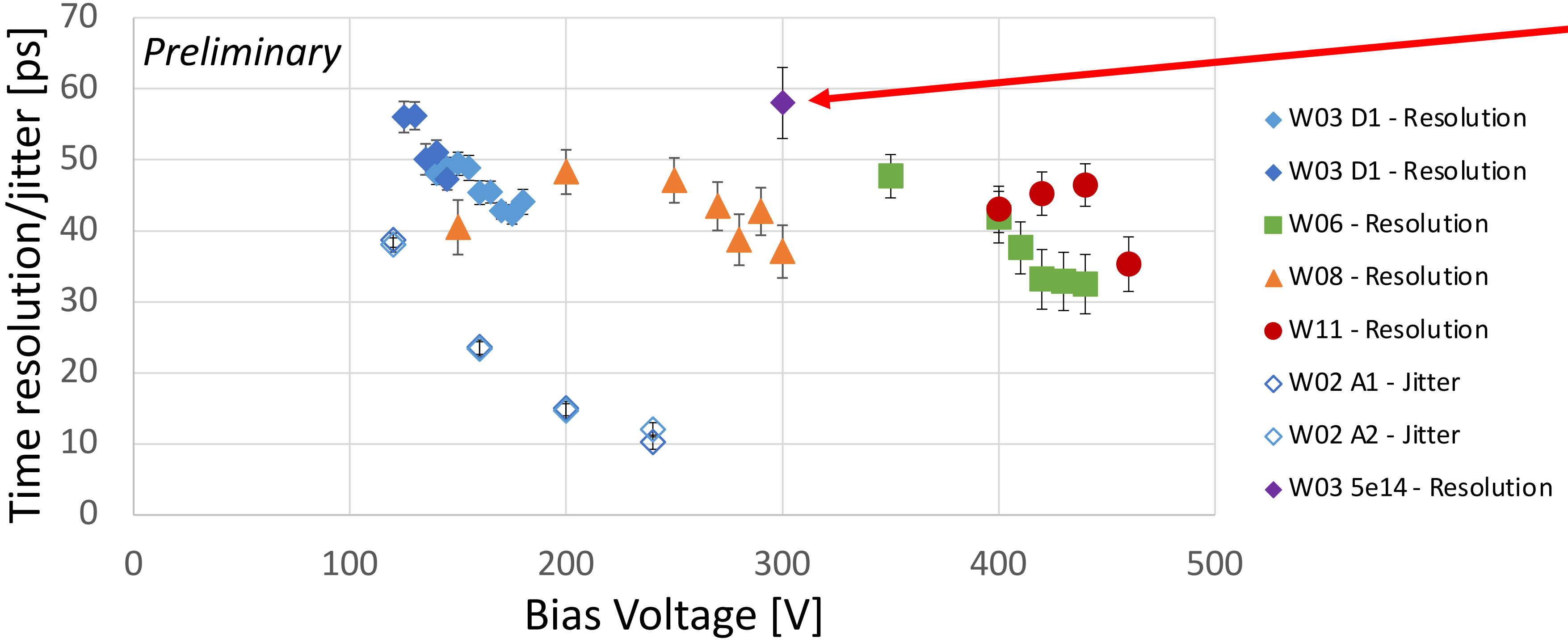
Wafer Number	Normalised Dose	Normalised Energy
9, 11	1.07	1.05
8	1.15	1.05
6	1.00	1.11
2, 3	1.07	1.11

Timing performance 1x1 mm^2 LGADs

- Jitter measurements performed using a transient current technique (TCT)
  - Room temperature measurement, CFD set to 50%
- Timing resolution calculated from coincidence signals from beta particles (Sr90)
  - Room temperature (or -20°C for irrad. sensor), CFD set to 20%



Time resolution of a proton-irradiated LGAD at $5x10^{14}$ 1 MeV n_{eq} cm^{-2}

Wafer Number	Normalised Dose	Normalised Energy
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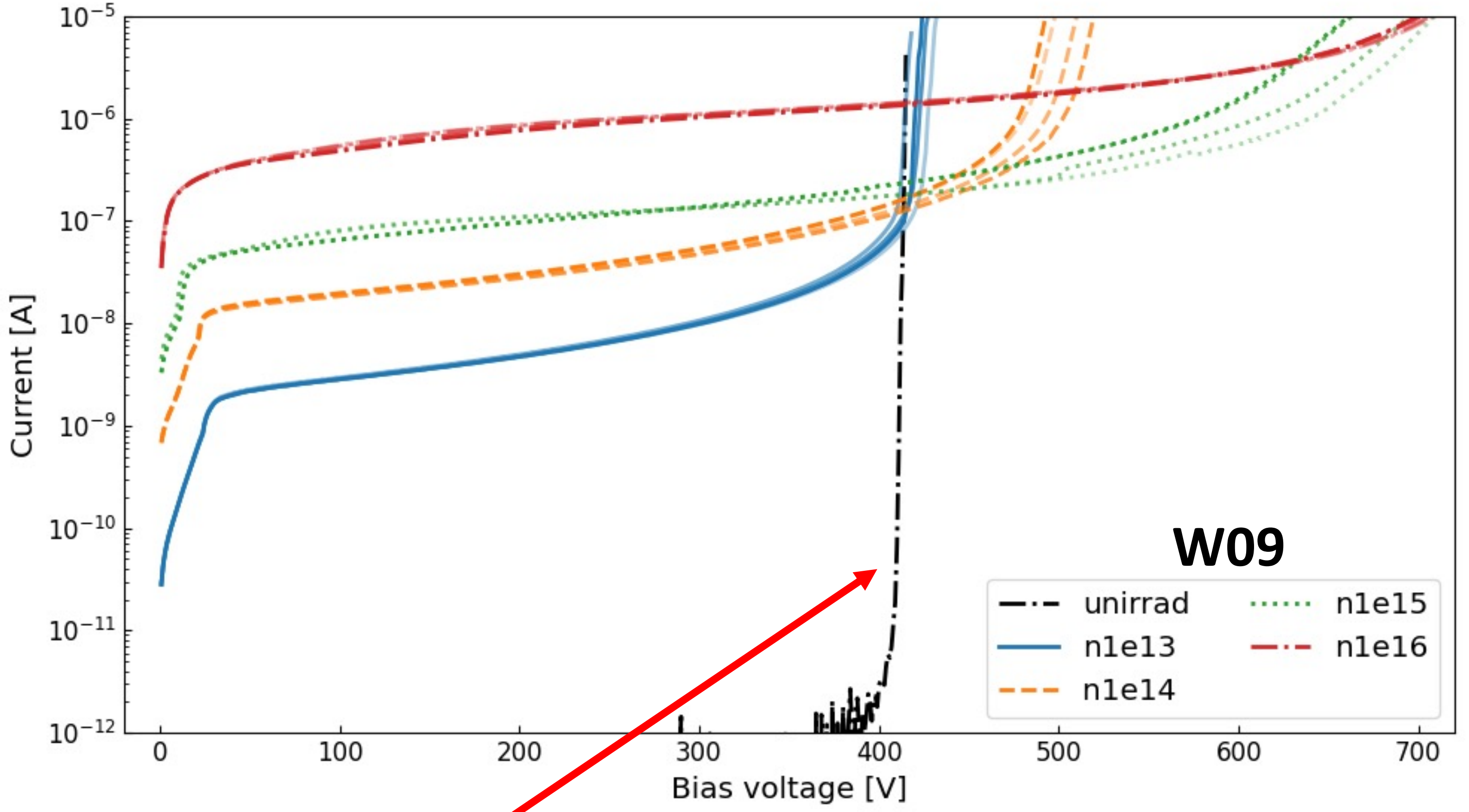
8	1.15	1.05
2	1.07	1.11

Neutron irradiation – leakage current



Current of unirrad. at -20°C below sensitivity!
Curve shown to illustrate BV of unirrad.

- Leakage current for single 1x1 mm^2 devices
- Up to 4 devices measured per wafer per neutron dose
- Devices annealed at 60°C for 80 min.
- All measurements performed at -20°C

Wafer Number	Normalised Dose	Normalised Energy
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8	1.15	1.05
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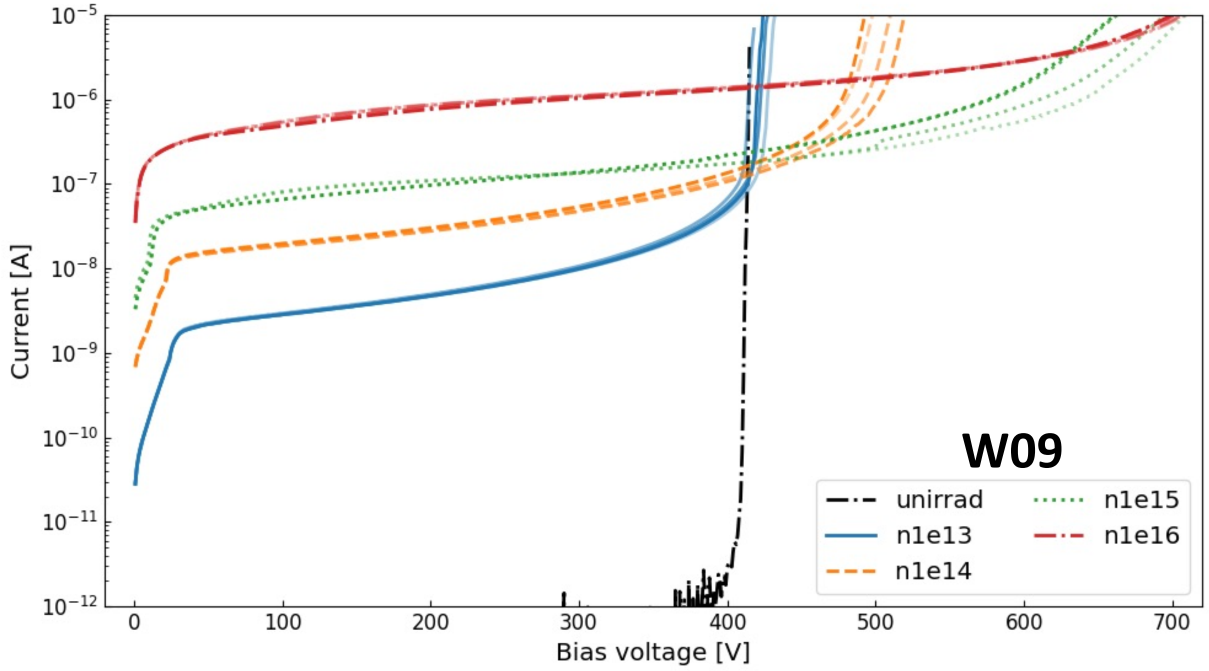

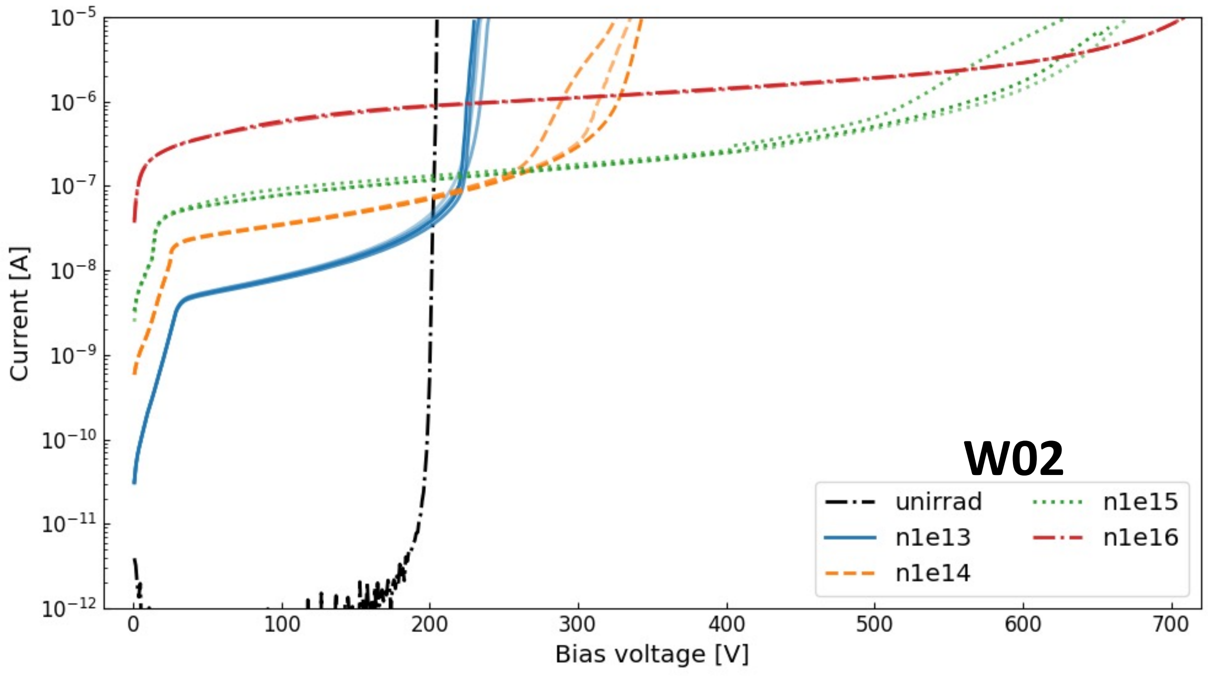

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Curve shown to illustrate BV of unirrad.

T = -20°C

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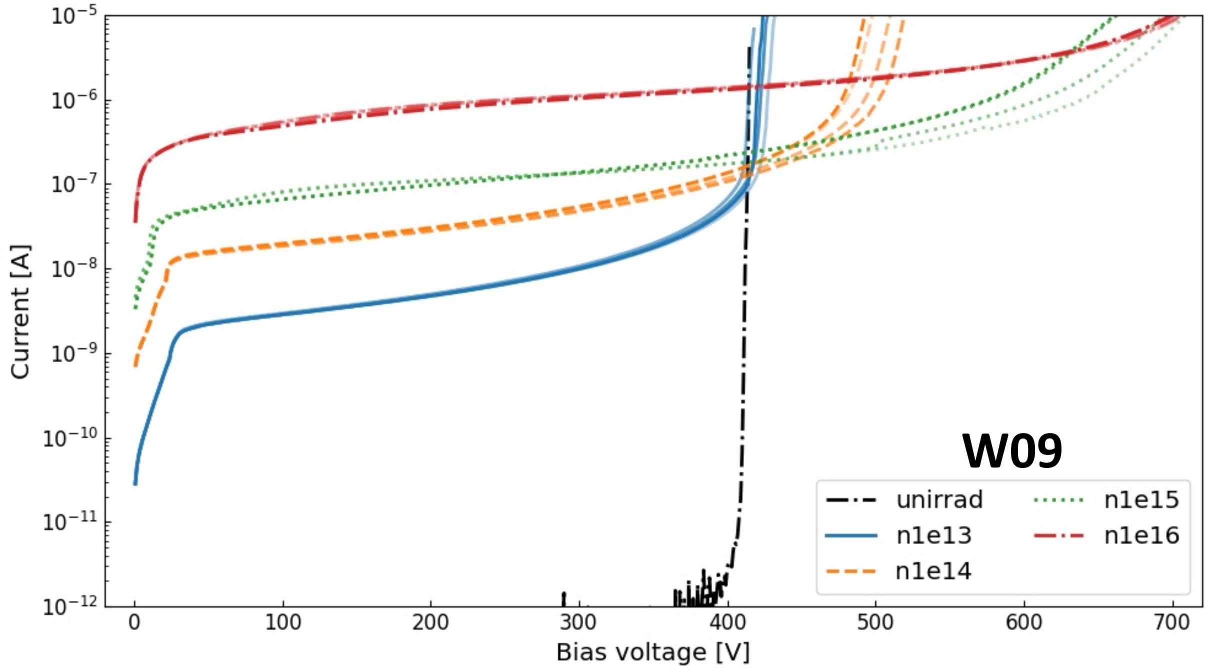

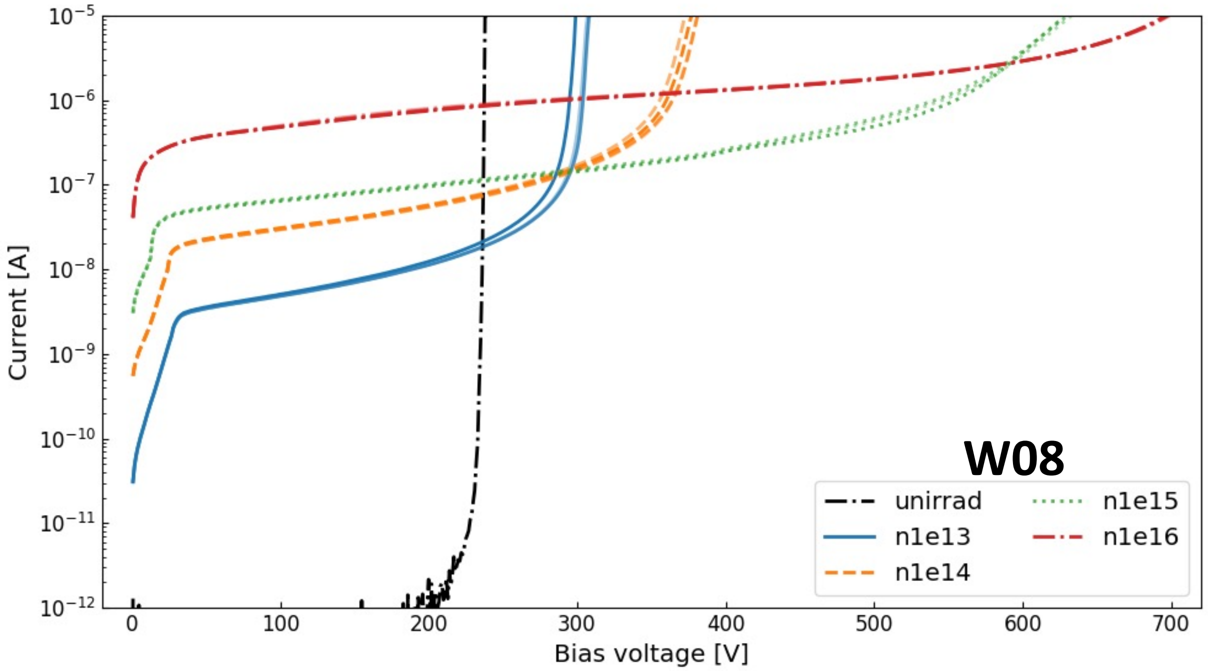

Increasing implant dose

Current of unirrad. at -20°C below sensitivity!
Curve shown to illustrate BV of unirrad.

T = -20°C

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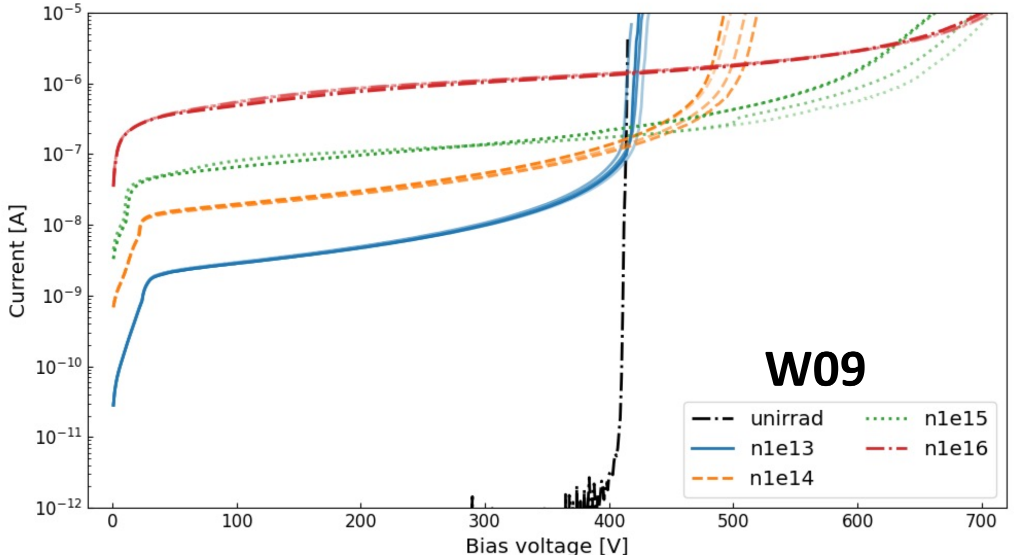
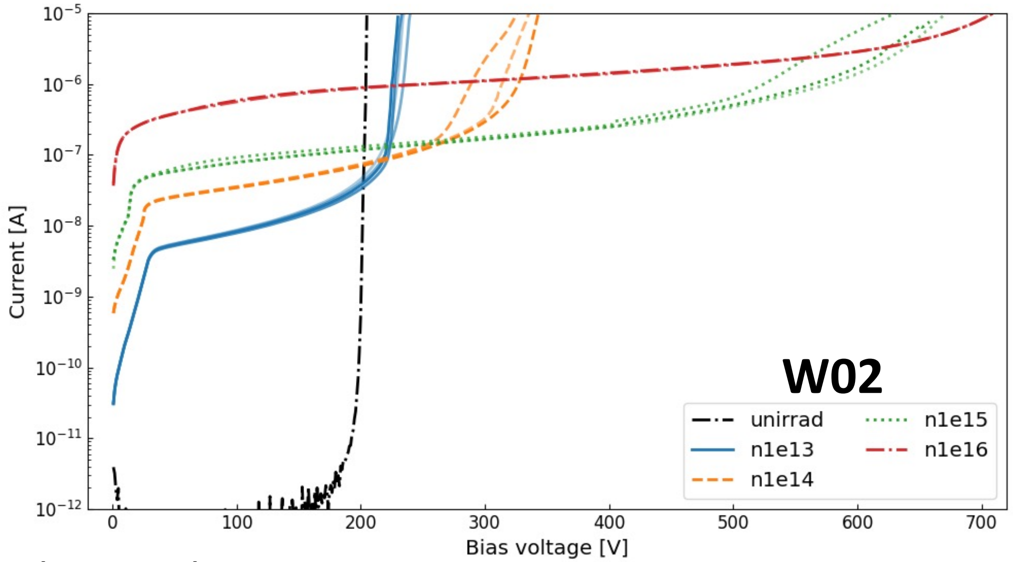
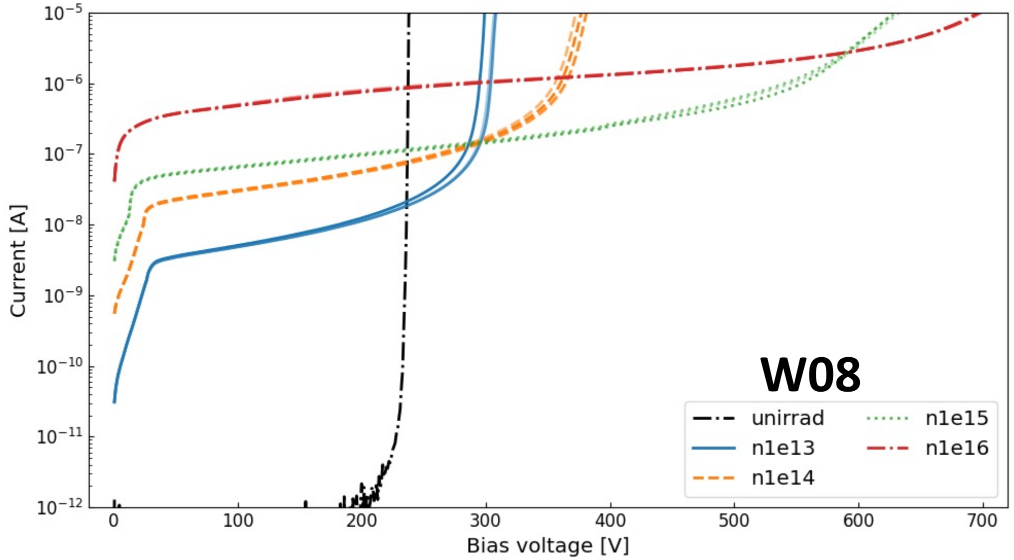
Neutron irradiation – leakage current





Higher implant energy



Higher mplant dose

T = -20°C

Wafer Number	Normalised Dose	Normalised Energy
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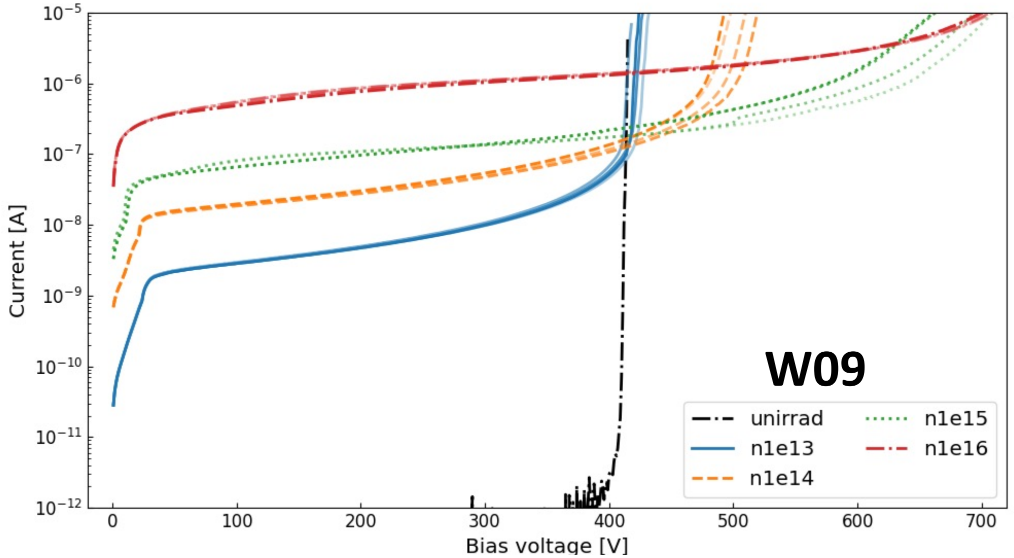
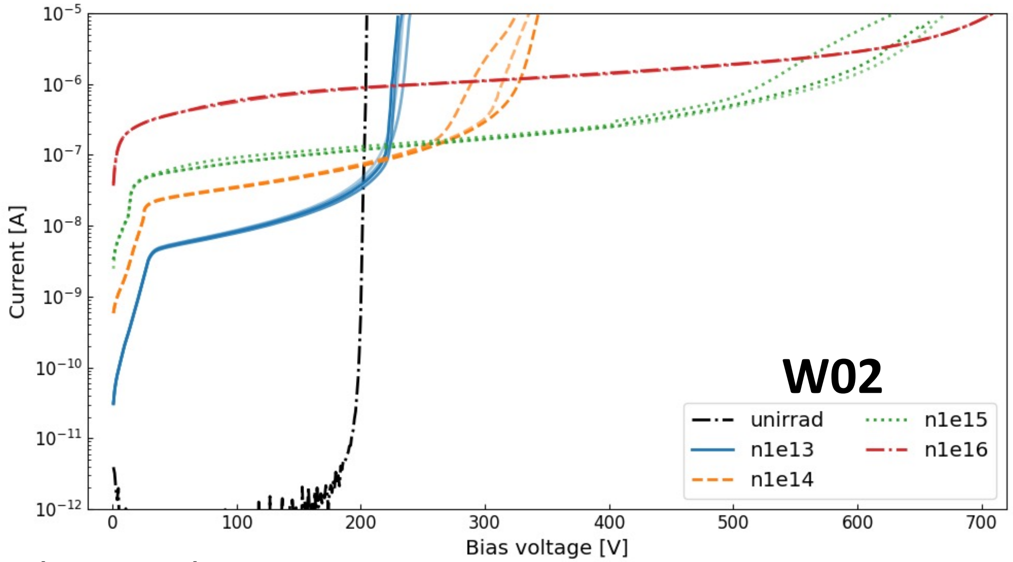
Neutron irradiation – leakage current





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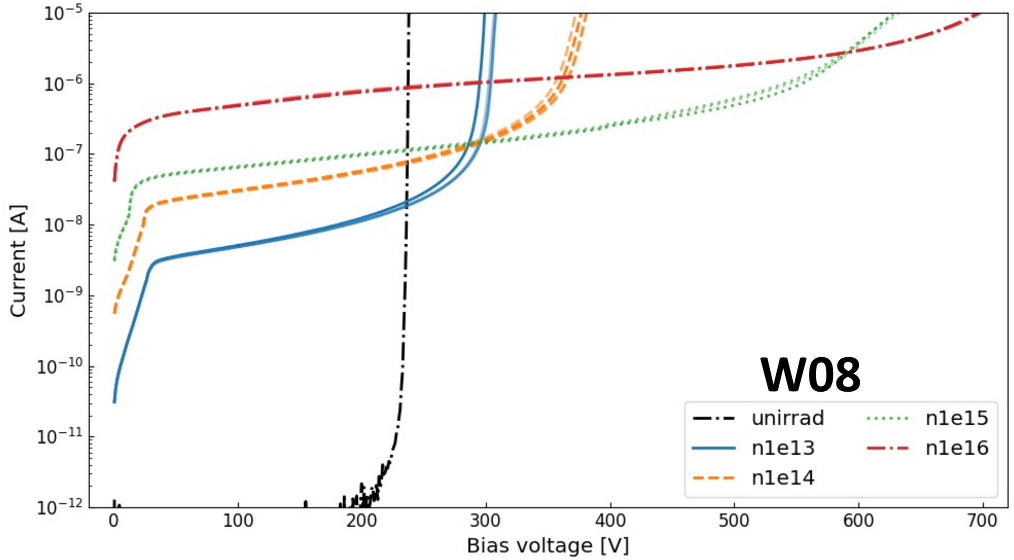

Higher mplant dose

Nominal leakage current at 40 V bias voltage (at -20°C)

Dose	10^{13} cm^{-2}	10^{14} cm^{-2}	10^{15} cm^{-2}	10^{16} cm^{-2}
W09	2×10^{-9} A	1×10^{-8} A	5×10^{-8} A	3×10^{-7} A
W08	3×10^{-9} A	2×10^{-8} A	5×10^{-8} A	3×10^{-7} A
W02	5×10^{-9} A	2×10^{-8} A	6×10^{-8} A	3×10^{-7} A

T = -20°C

Wafer Number	Normalised Dose	Normalised Energy
9	1.07	1.05
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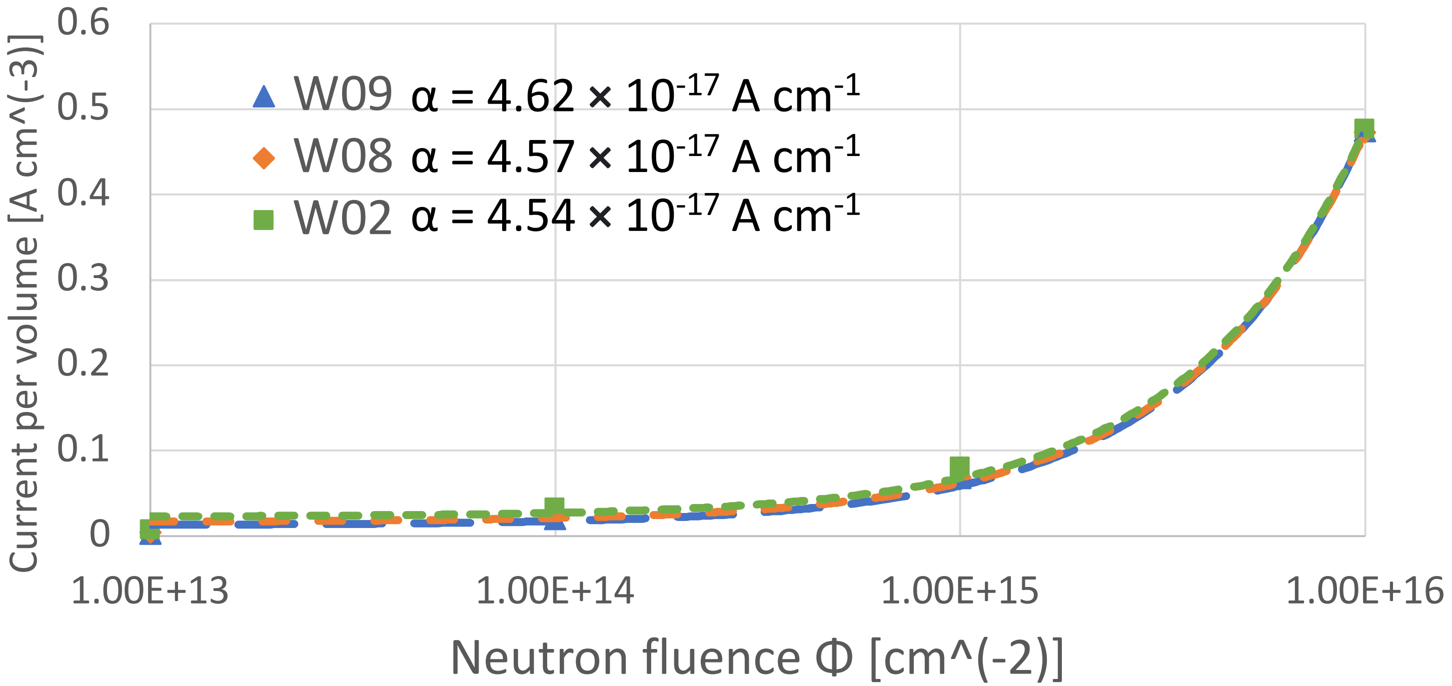
Reverse current damage constant α

$$\Delta I_{Vol} = I_{vol}(\Phi) - I_{vol}(\Phi = 0) = \alpha \cdot \Phi$$

- Diode reverse current per unit volume at full depletion I_{vol}
  - using current at 40 V bias, corrected to 20°C



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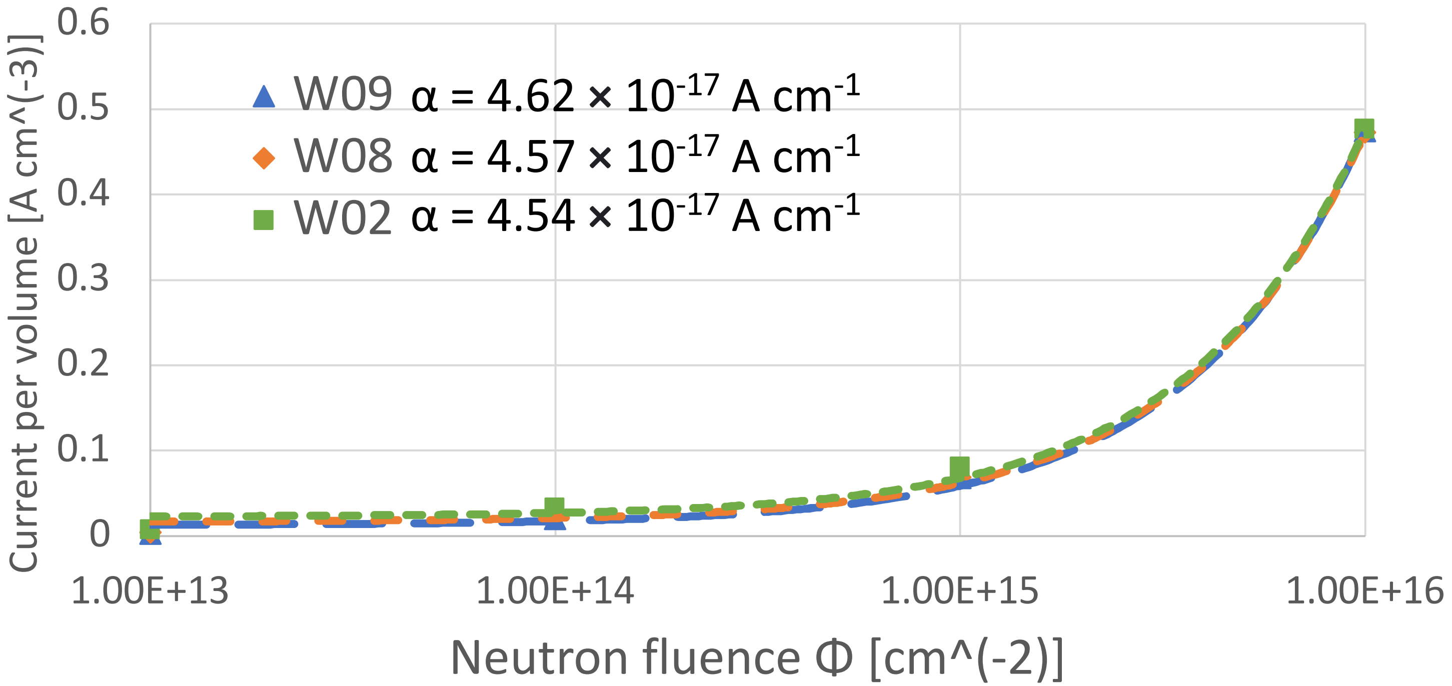
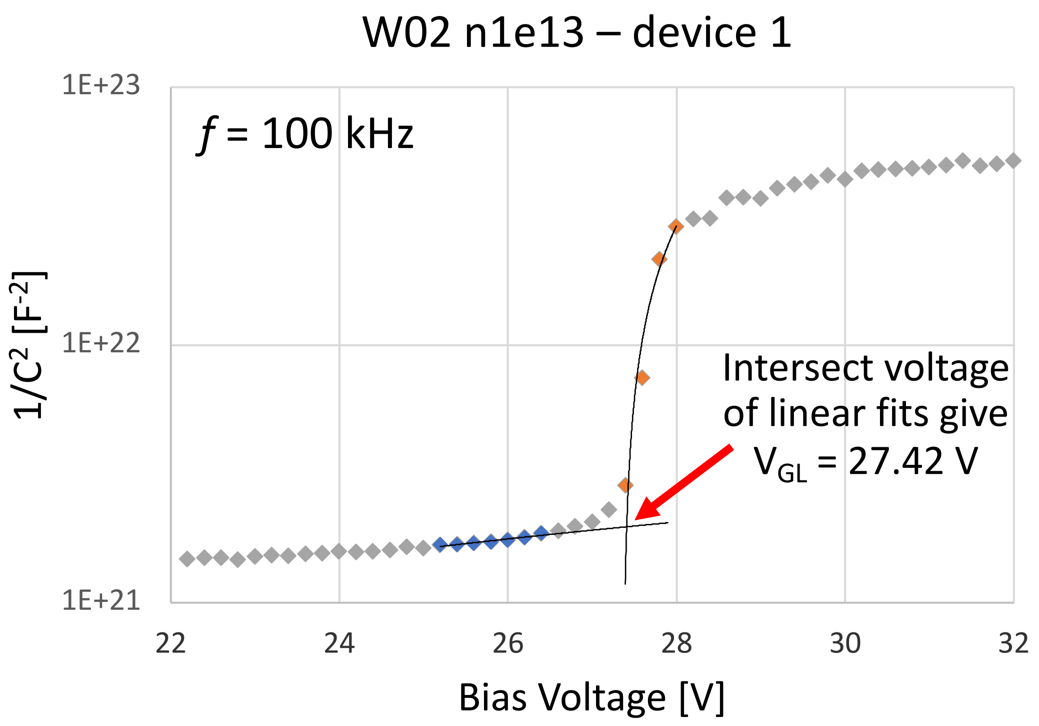


Reports of LGADs with reverse current damage constant of the order 9-15 × 10^{-17} A cm^{-1} (although irradiation type and devices differ)

Study of the radiation-induced damage mechanism in proton irradiated low gain avalanche detectors and its thermal annealing dependence
NIMA 968 (2021) 164814

Gain Layer depletion voltage V_{GL} extraction

For unirradiated and low irradiation sensors extracted from CV (linear fit)



Note that semi-log scale makes linear fit lines bend

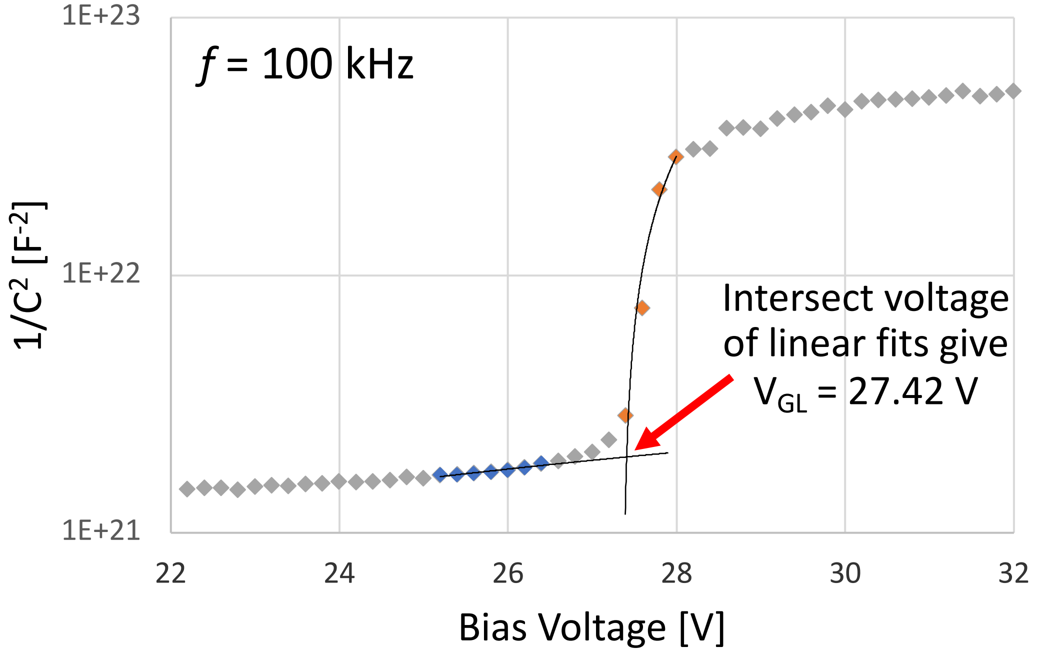
T = -20°C

Gain Layer depletion voltage V_{GL} extraction

For unirradiated and low irradiation sensors extracted from CV (linear fit)

For highly irradiated sensors extracted from IV knee (linear fit)

<u>the same device</u>



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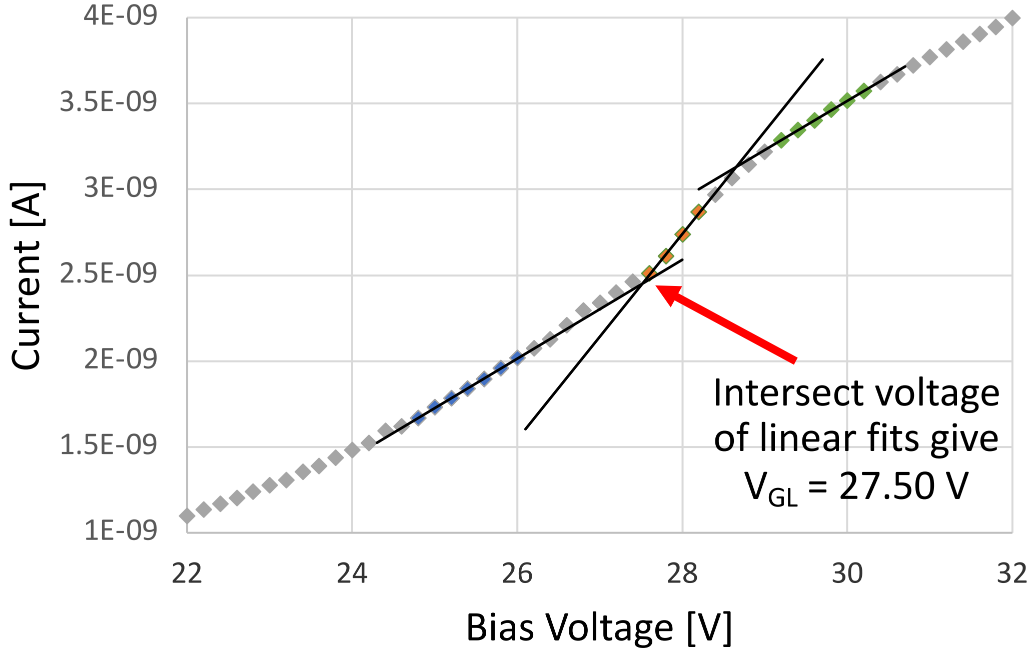


Effect more pronounced at higher fluences (higher current)

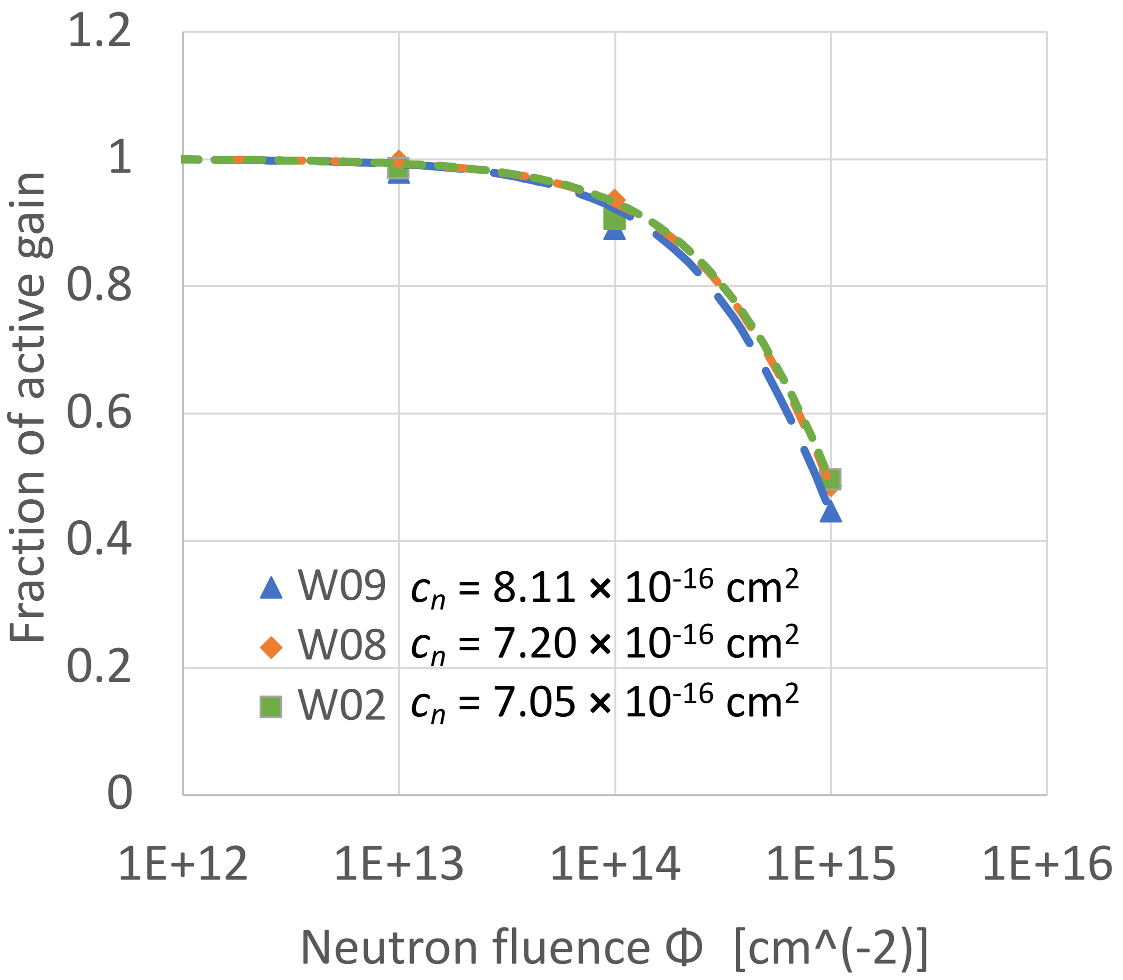
T = -20°C

Wafer Number	Normalised Dose	Normalised Energy
9	1.07	1.05
8	1.15	1.05
2	1.07	1.11

Acceptor Removal Coefficient

$$\underbrace{V_{GL}(\Phi) / V_{GL}(\Phi = 0)}_{\textit{Fraction of active gain}} = exp(-c_n\Phi)$$

- The gain layer depletion voltage at a given fluence is related to the acceptor removal coefficient c_n
- All measurements performed at -20 °C
- Not possible to extract any gain layer depletion voltage from devices irradiated to 10^{16} cm^{-2} neutron fluence



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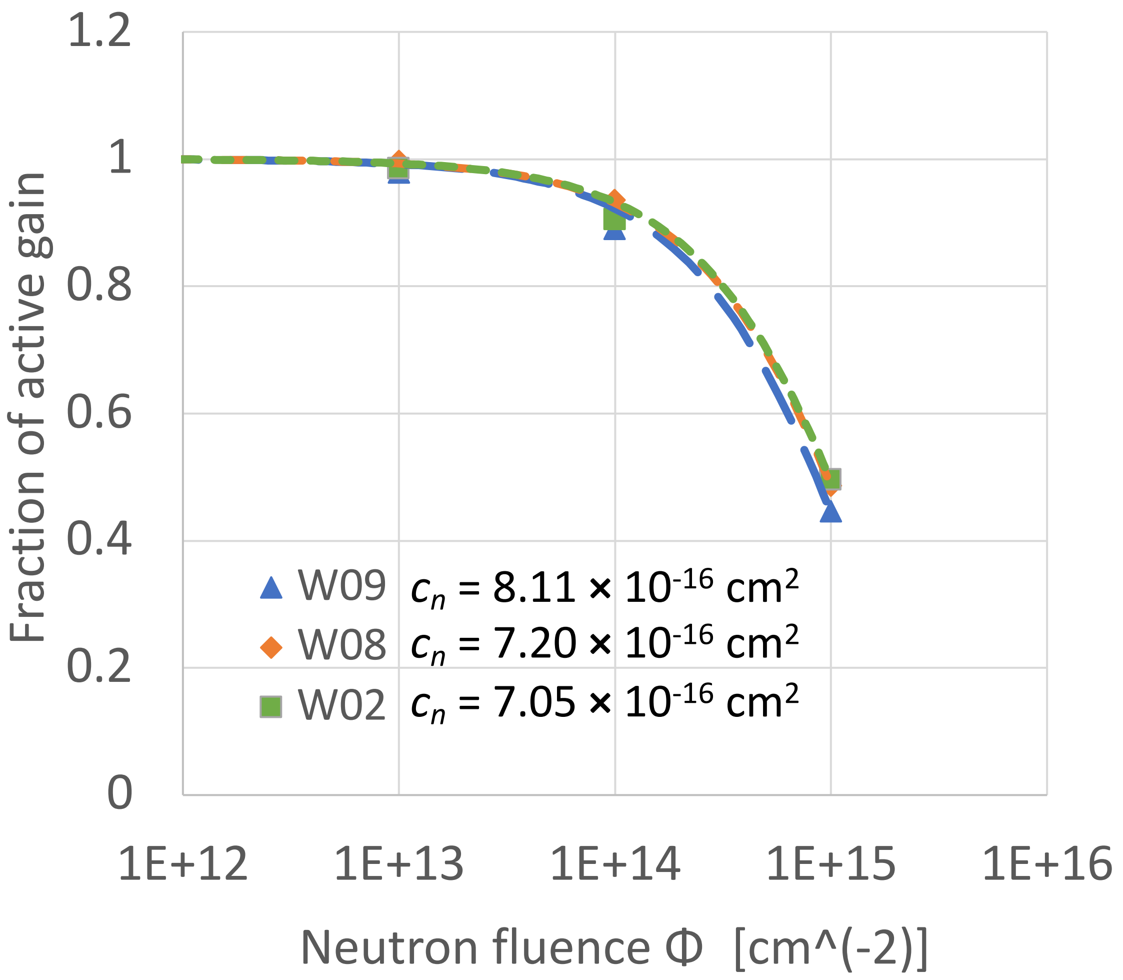
- All measurements performed at -20 °C
- Not possible to extract any gain layer depletion voltage from devices irradiated to 10^{16} cm^{-2} neutron fluence
- Depending on exact gain layer parameters, literature values 4-9 × 10^{-16} cm^2, values below 4 × 10^{-16} cm^2 with carbon implant



M. Ferrero, R. Arcidiacono, M. Mandurrino, V. Sola, N. Cartiglia. Ultra-fast silicon detectors : design, tests, and performances (CRC Press, 2021)

Wafer Number	Normalised Dose	Normalised Energy
8	1.15	1.05
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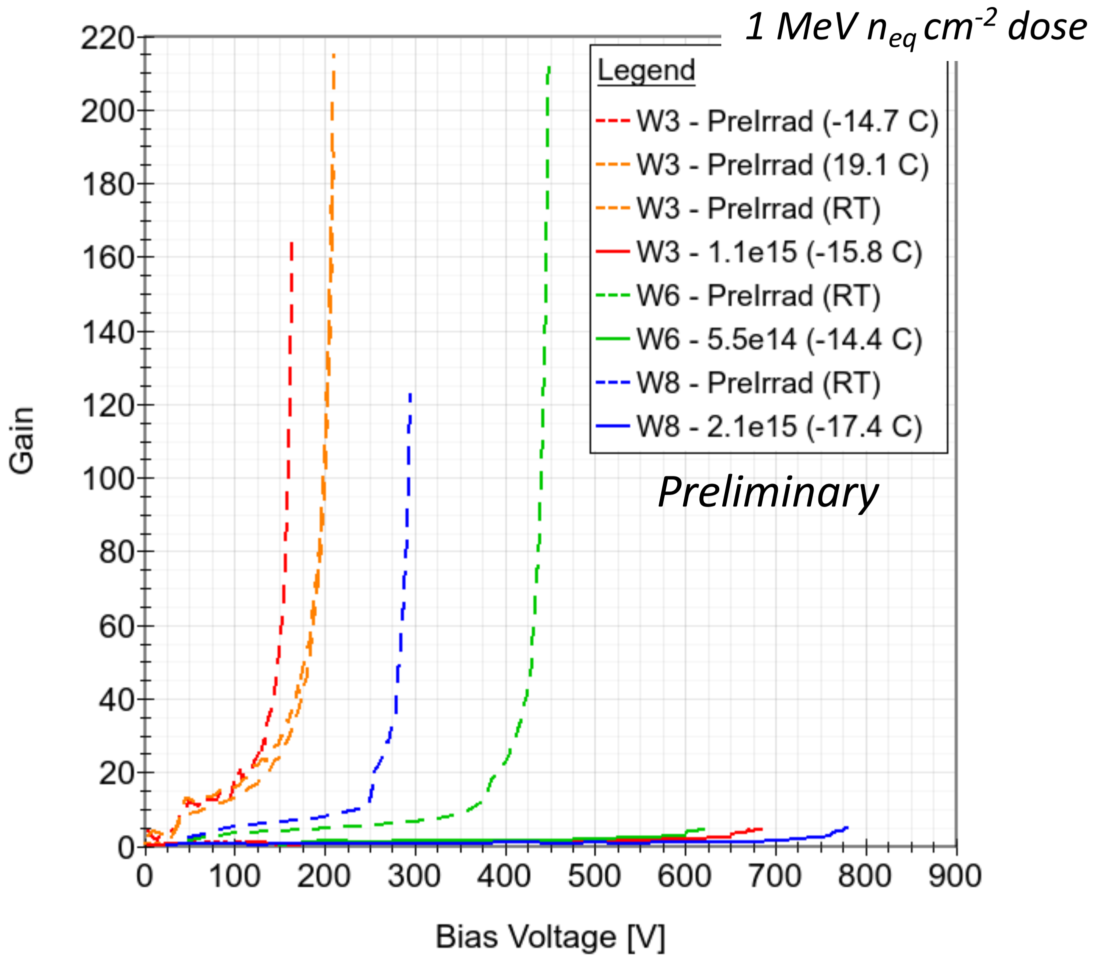
Gain of proton irradiated LGADs

- Devices proton irradiated at MC40 cyclotron with 27 MeV protons at Birmingham
- Gain measurement using TCT, comparing measured signal to a reference
- Showing single 1x1 mm^2 LGADs with quoted dose as equivalent 1 MeV n_{eq} cm^{-2}
- After irradiation, gain is significantly lowered and is achieved at bias voltage of several hundred volts
- Encountered issues with temperature readings, so gain can potentially go higher
- Data to be treated as preliminary for now



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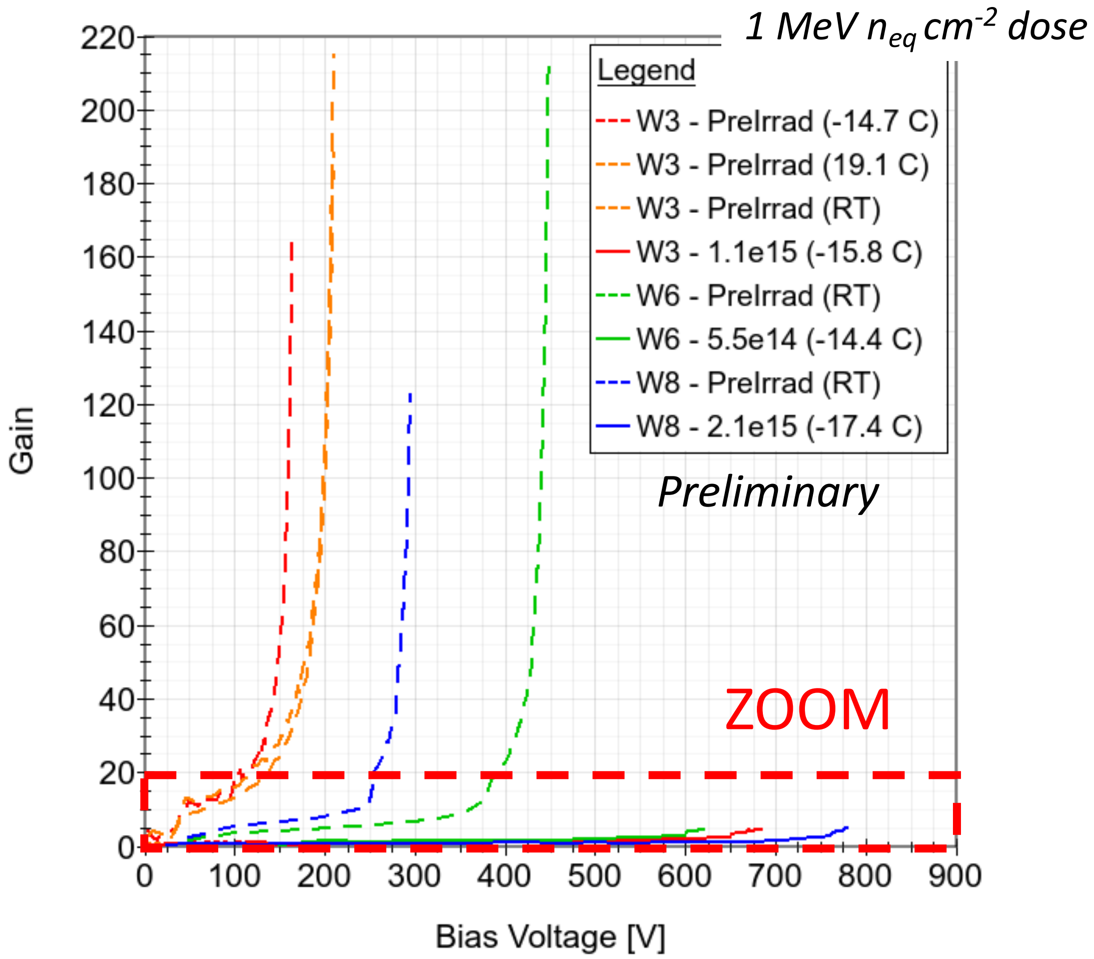

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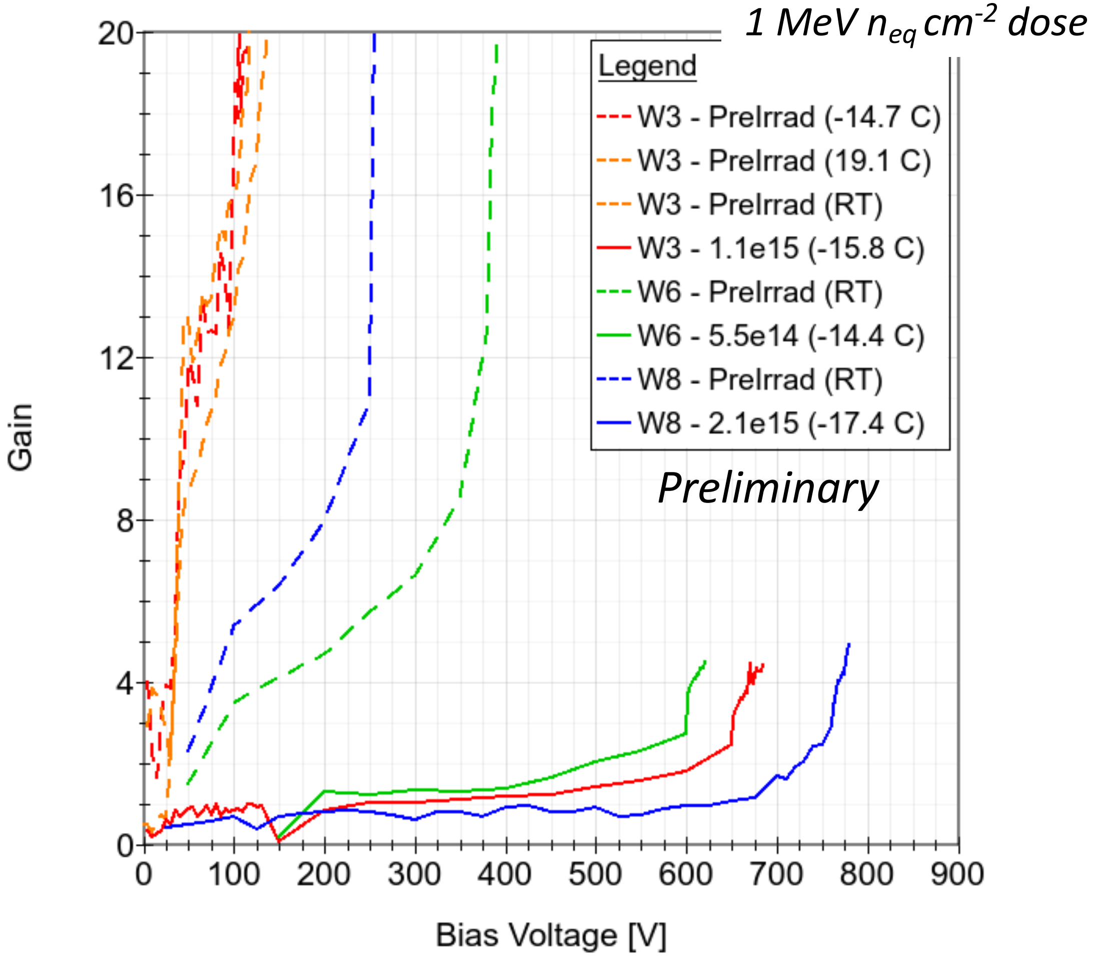

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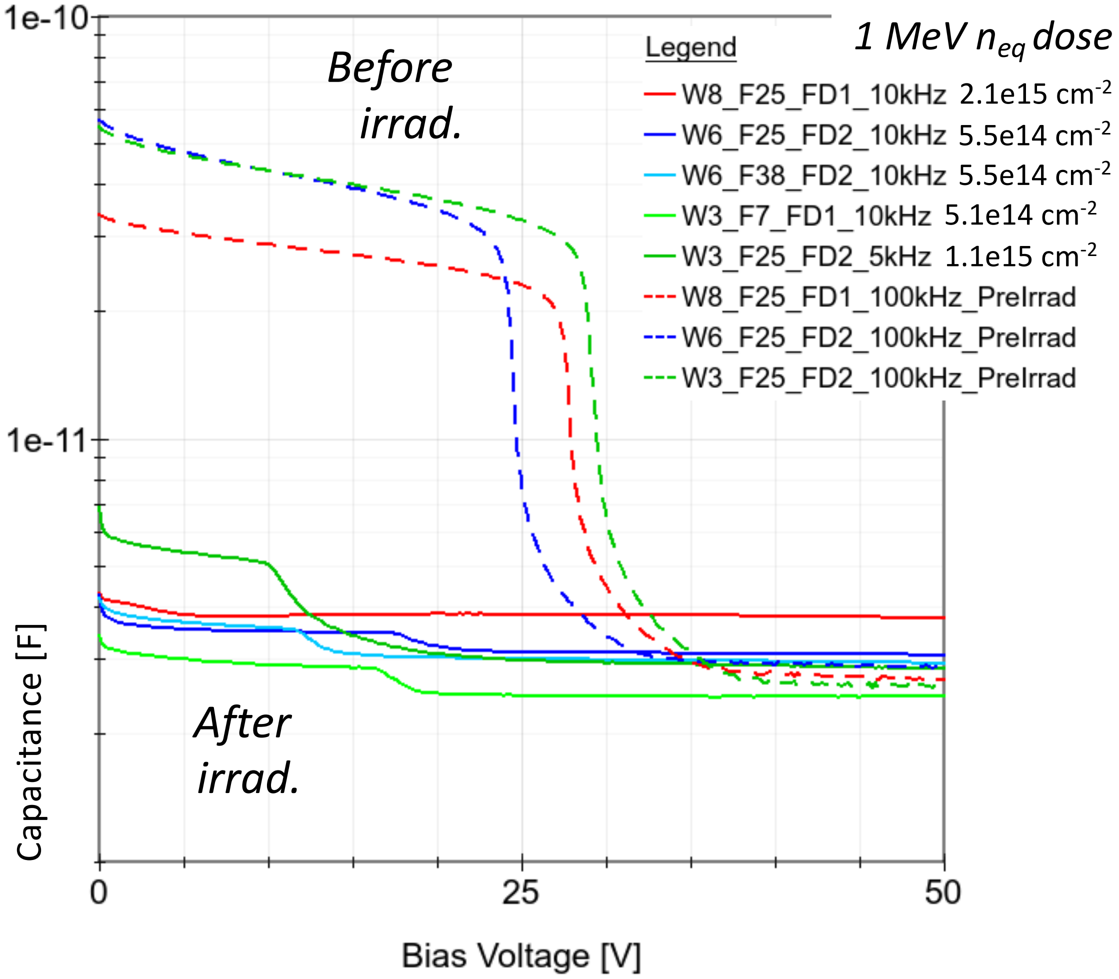
Capacitance of proton irradiated LGADs

- Devices proton irradiated at MC40 cyclotron with 27 MeV protons at Birmingham
- Frequency of the measurement adjusted after proton irradiation to measure CV
  - 100 kHz for un-irradiated devices
  - 5-10 kHz for proton irradiated devices
- Capacitance lower and gain layer depletion voltage decreases after irrad.
- Future plans: expand the range and extract acceptor removal from 27 MeV p^+



Wafer Number	Normalised Dose	Normalised Energy
2, 3, 24	1.07	1.11

LGAD Proton micro-beam measurements

- Measurements using a 8 MeV proton microbeam (1.5 um^2) performed by IBIC at the Australian Nuclear Science and Technology Organisation (ANSTO)
- Motivated by use of LGADs in applications in low-LET (Linear energy transfer) microdosimetry
- Credits for the measurements goes to Jay Archer, Abdelrahman Hani, Vladimir Pan, Thuy Linh Tran, Anatoly Rozenfeld
- Using 1x1 mm^2 LGAD from W24 (same implant as W02 and W03)

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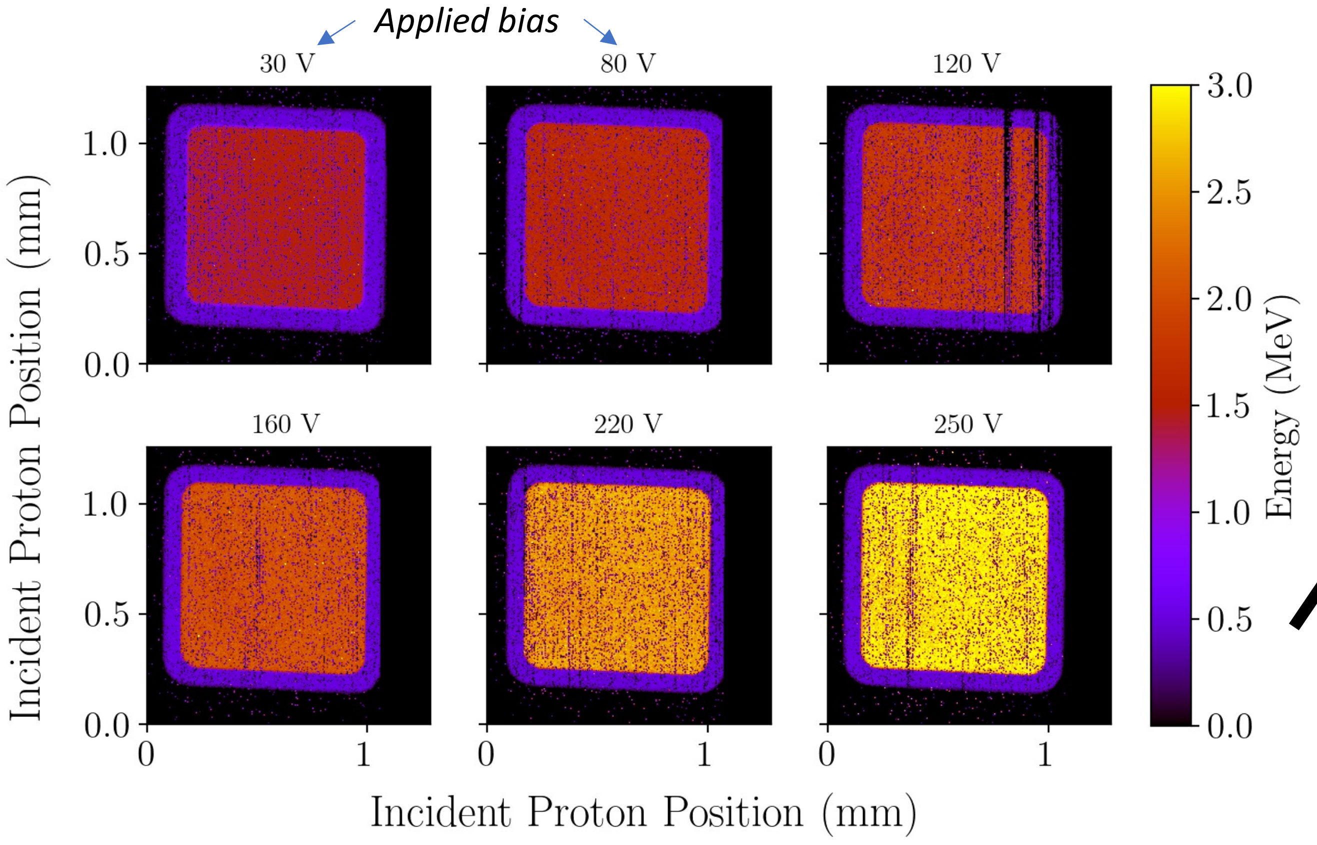
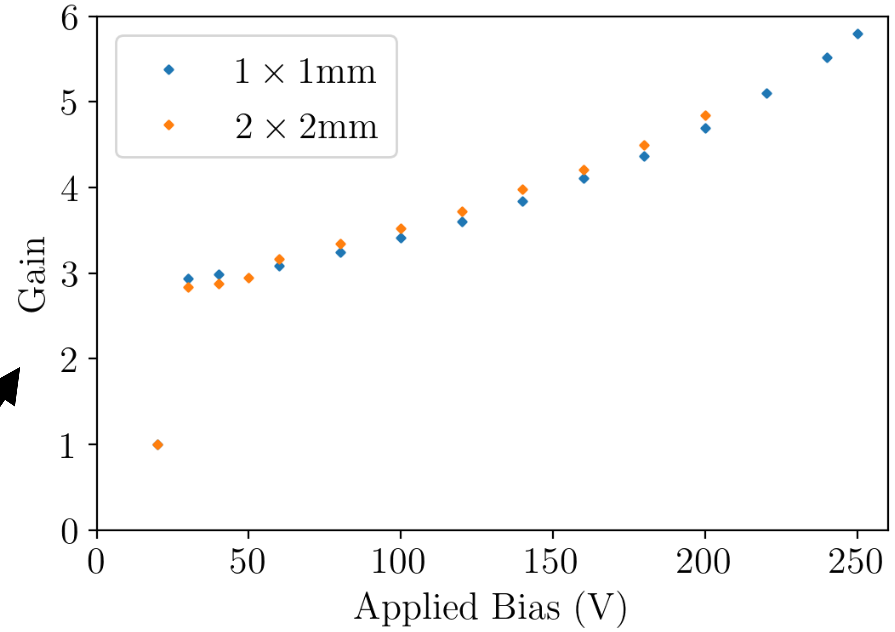
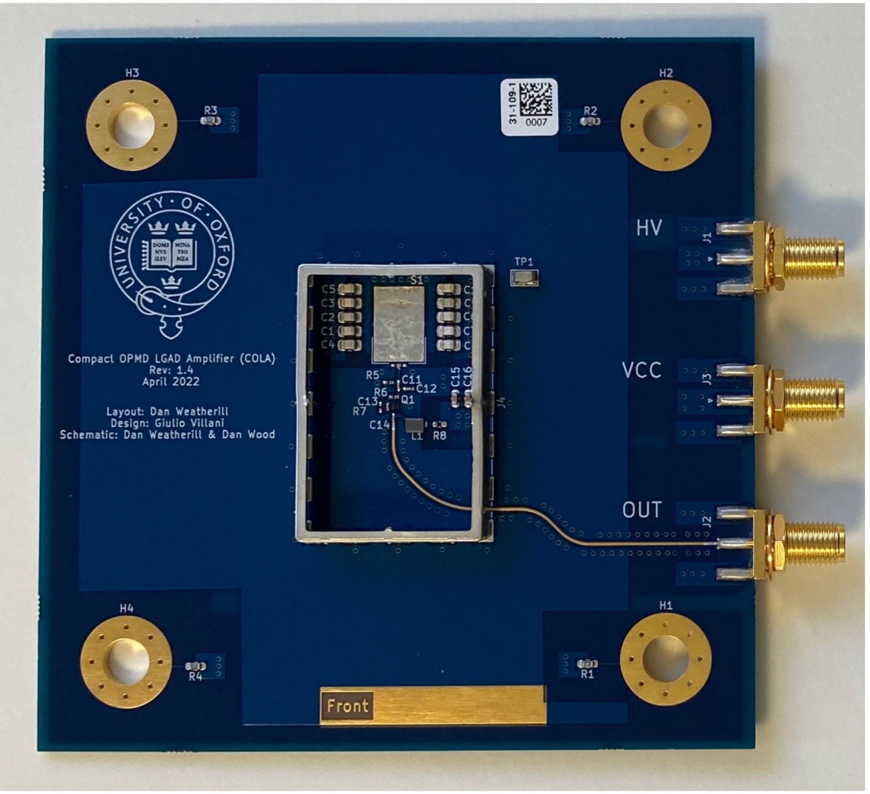


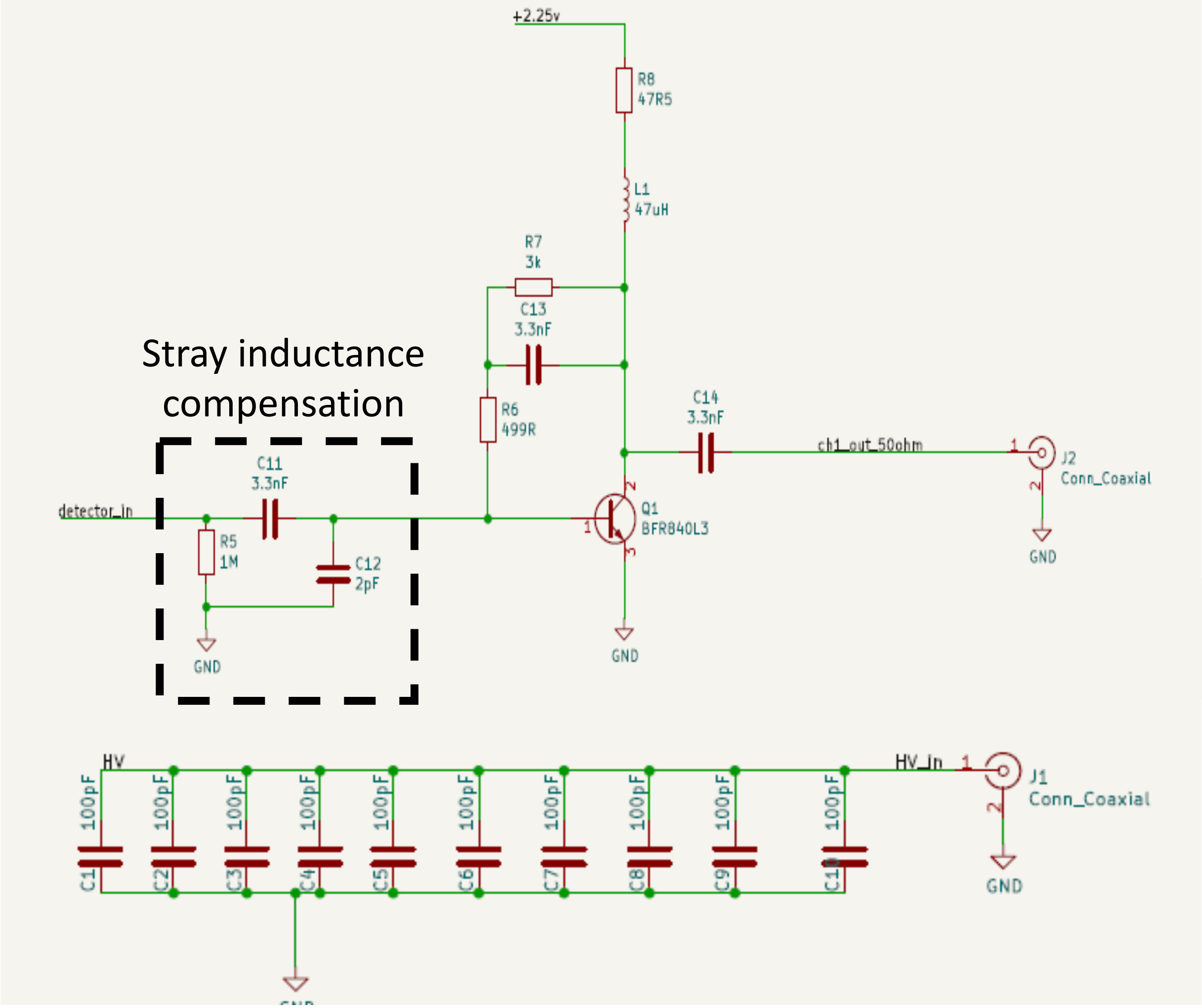


Get gain by taking the ratio of the measured “deposited energy” of gain and no-gain regions. Gain lower compared to TCT.

Compact OPMD LGAD Amplifier (COLA)

- Designed by OPMD at Oxford
- Transimpedance amplifier used as first stage amplifier for LGADs





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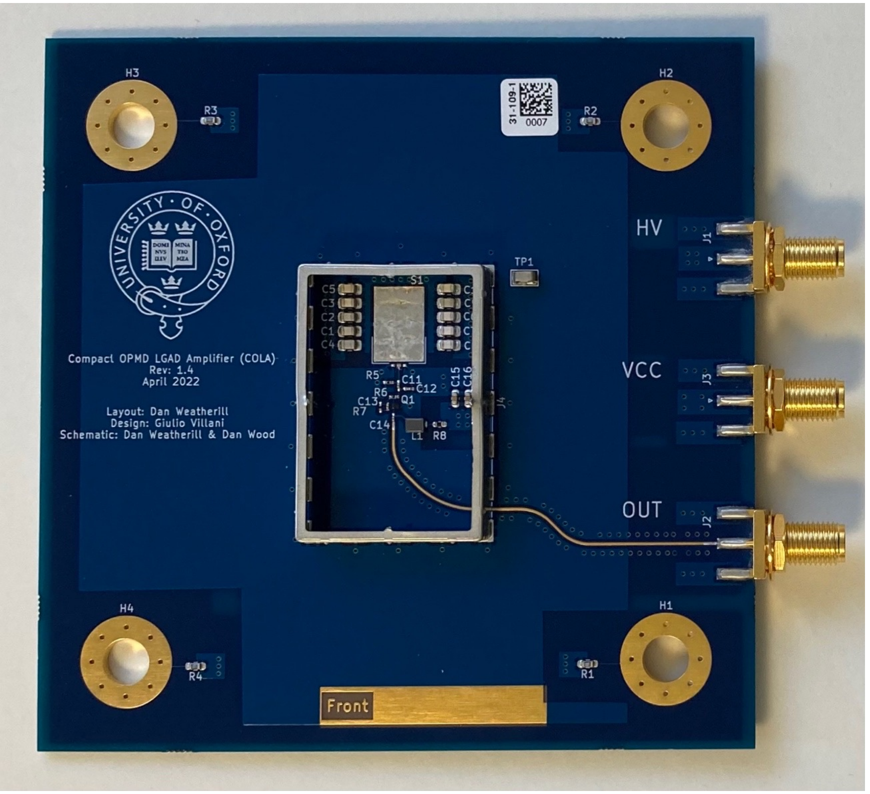
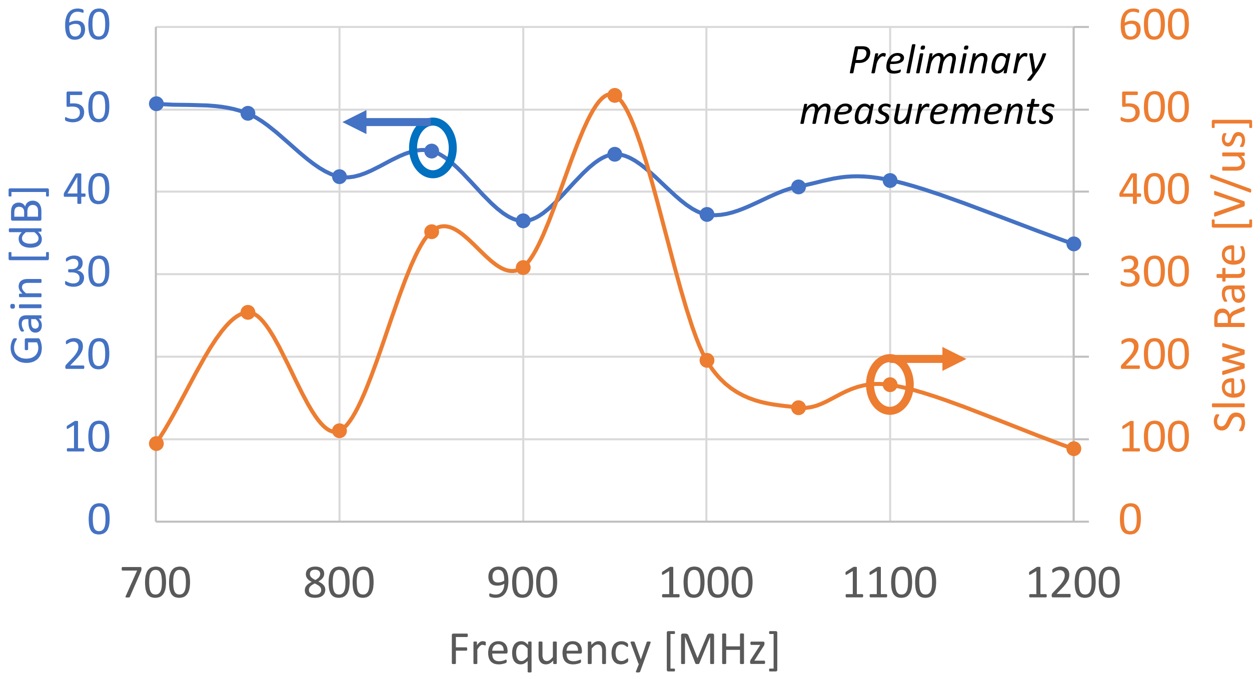
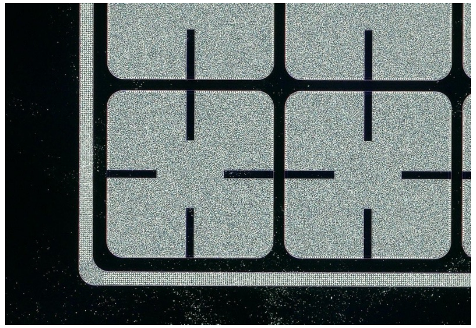




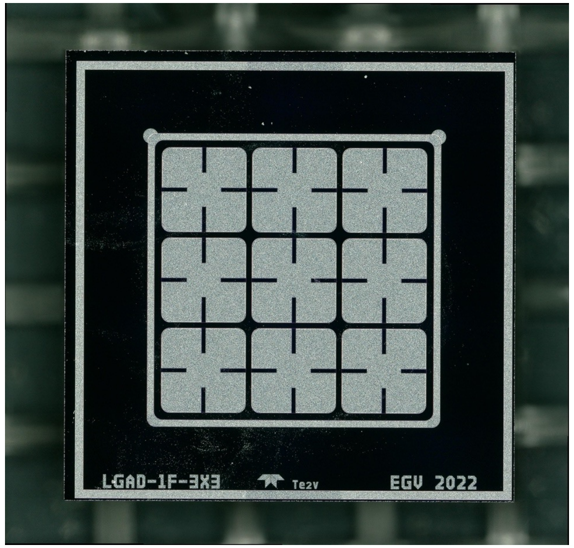
- SPICE simulated gain of approx. 54 dB in the range 0.7-1.2 GHz
- Slew rate sufficient to guarantee low jitter contribution
- Multi-channel version planned for 2023

Second batch of Te2v LGADs

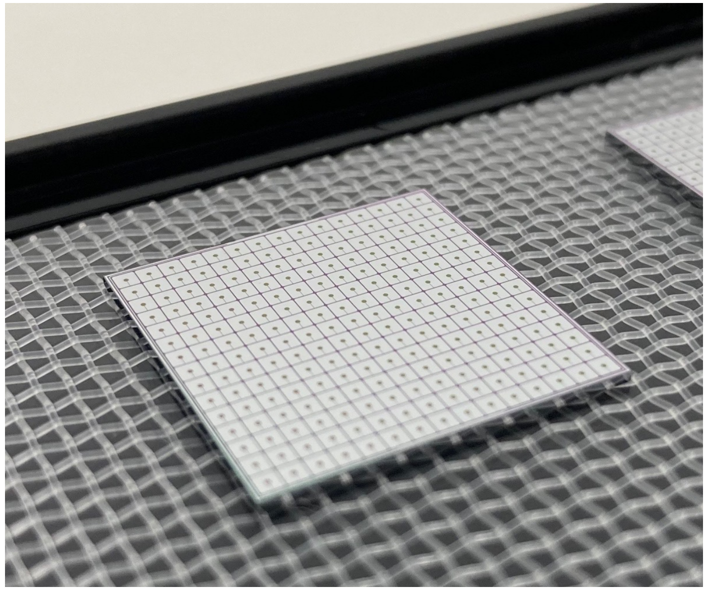
- Second batch of LGAD wafers produced by Teledyne e2v in the second half of 2022
- 4 different combinations of manufacturing parameters (guided by Batch 1 results)
- Wider range of layouts and arrangements
  - Single devices 1x1 mm^2 (variation of design parameters)
  - 2x2 arrays of 1x1 mm^2 devices
  - 3x3 arrays of 1x1 mm^2 devices
  - 15x15 array of 1.3x1.3 mm^2 LGADs



Adjusted surface metallisation for edge-effect measurements with TCT



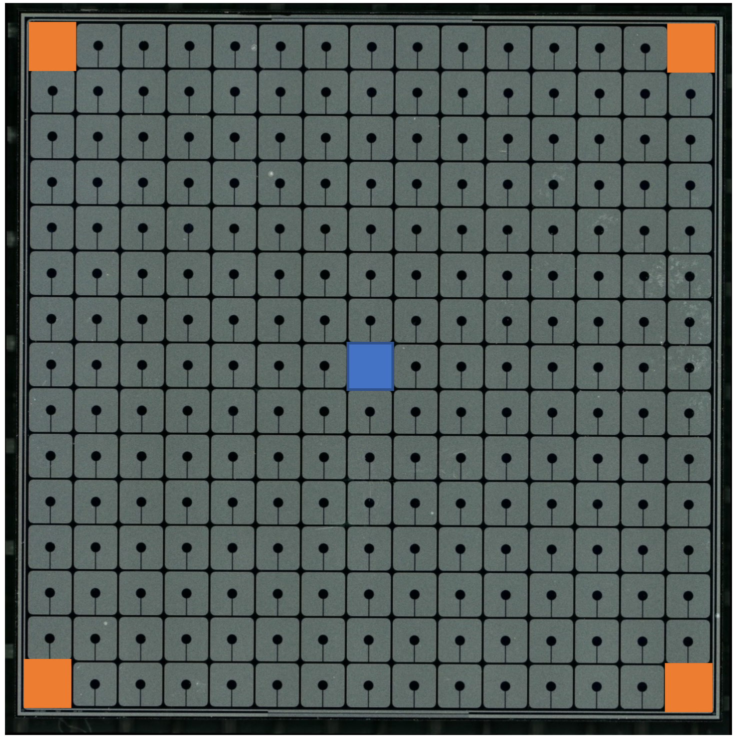
3x3 array for device cross-talk measurements

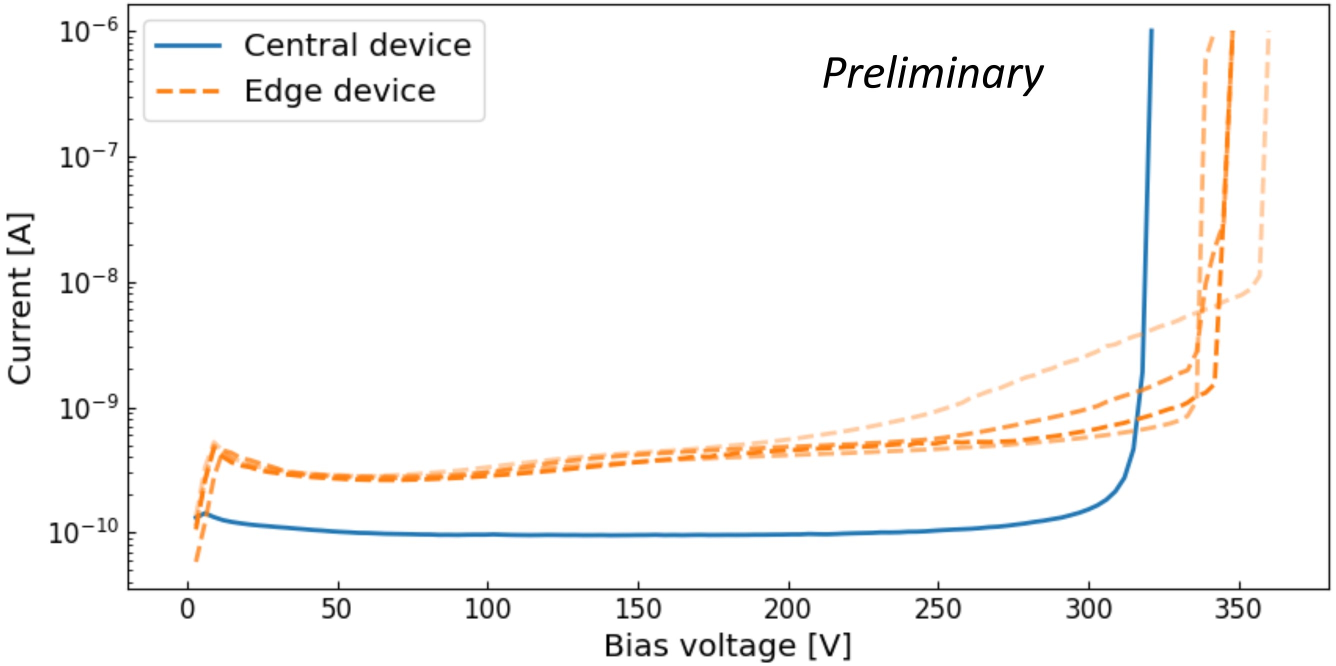


full scale 15x15 array with 1.3x1.3 mm^2 devices

Second batch of Te2v LGADs – first results

- First results from Wafer 20 of Batch 2 (W20B2), should be treated as preliminary
- Leakage current lower for central devices as reported by other collaborations
- Full-array current mapping procedure under development

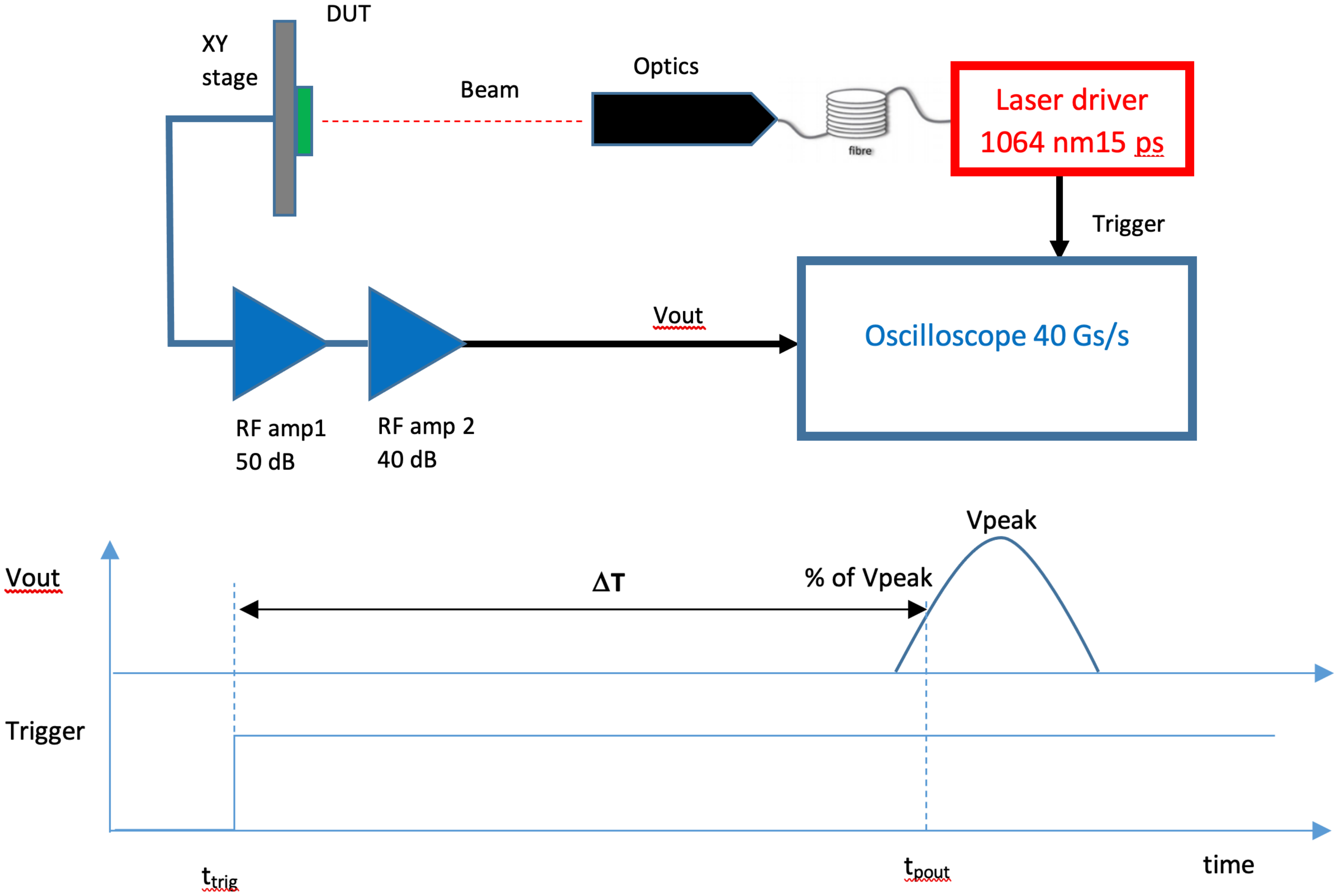




Summary

- Timing performance of unirradiated and proton-irradiated Te2v LGADs
- Characterisation of neutron irradiated Te2v LGADs up to fluence of 10^{16} n cm^{-2}
- Reverse current damage constant measured to be around 4.5×10^{-17} A cm^{-1}
  - Order comparable with other measurements ($9\text{-}15 \times 10^{-17}$ A cm^{-1})
- Acceptor removal coefficient after neutron irradiation $c_n \approx 7 - 8 \times 10^{-16}$ cm^2
  - Order comparable with other measurements ($4\text{-}9 \times 10^{-16}$ cm^2), towards the higher end
- Preliminary measurement of gain of proton-irradiated devices
- Proton microbeam gain measurements
- LGAD readout board COLA with order 50 dB gain
- Batch 2 of LGADs by Te2v produced and in testing with preliminary results shown

TCT jitter measurement setup



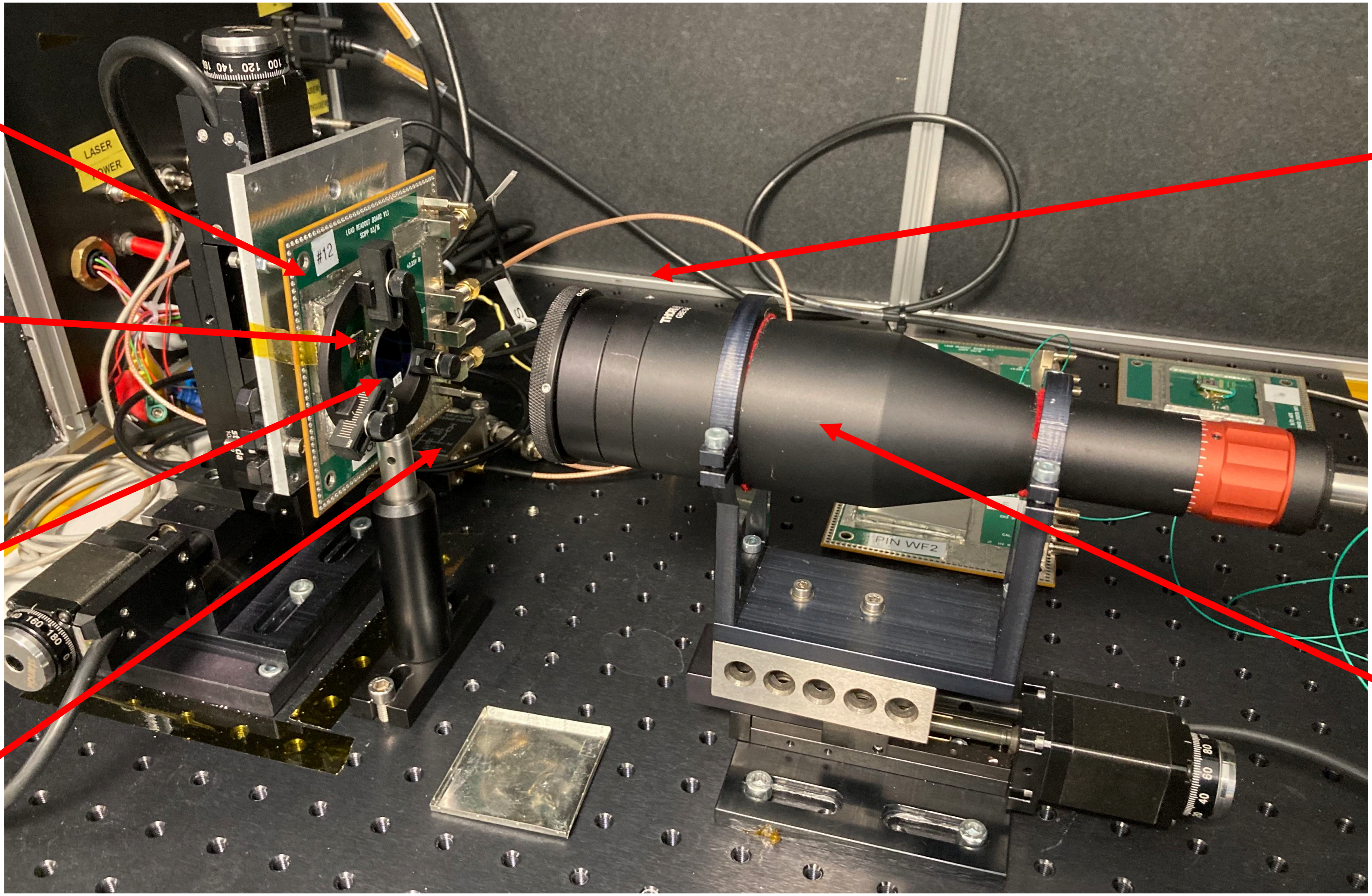
TCT jitter measurement setup

Santa Cruz v1.1
(1st stage amp)

LGAD/PiN
device

ND filter

FEMTO 40dB
(2nd stage amp)



QD Laser
1064 nm
(behind)

Laser Optics

Timing Measurement uncertainties

$$\sigma^2_{\Delta t} = \sigma^2_{trig} + \sigma^2_{Laser} + \sigma^2_{DUT} + \underbrace{\sigma^2_{Amp1} + \sigma^2_{Amp2}}_{\text{Jitter of the amplifiers}} + \sigma^2_{TW} + \sigma^2_{TDC}$$

Jitter term of trigger output

Jitter term due to the laser pulse fluctuations

Intrinsic jitter of the DUT (+ distortion and Landau)

Time-walk term

Time quantization noise of the scope

Timing Measurement uncertainties

Negligible according to the data sheet

$$\sigma^2_{\Delta t} = \sigma^2_{trig} + \sigma^2_{Laser} + \sigma^2_{DUT} + \underbrace{\sigma^2_{Amp1} + \cancel{\sigma^2_{Amp2}}}_{\text{Jitter of the amplifiers}} + \sigma^2_{TW} + \cancel{\sigma^2_{TDC}}$$

Jitter term of trigger output

$\approx (1.5\ ps)^2$

Jitter term due to the laser pulse fluctuations

$\approx (3.1\ ps)^2$

Intrinsic jitter of the DUT ~~(+ distortion and Landau)~~

Negligible for TCT

- Firing on the same spot
- Using a monochromatic laser

Jitter of the amplifiers

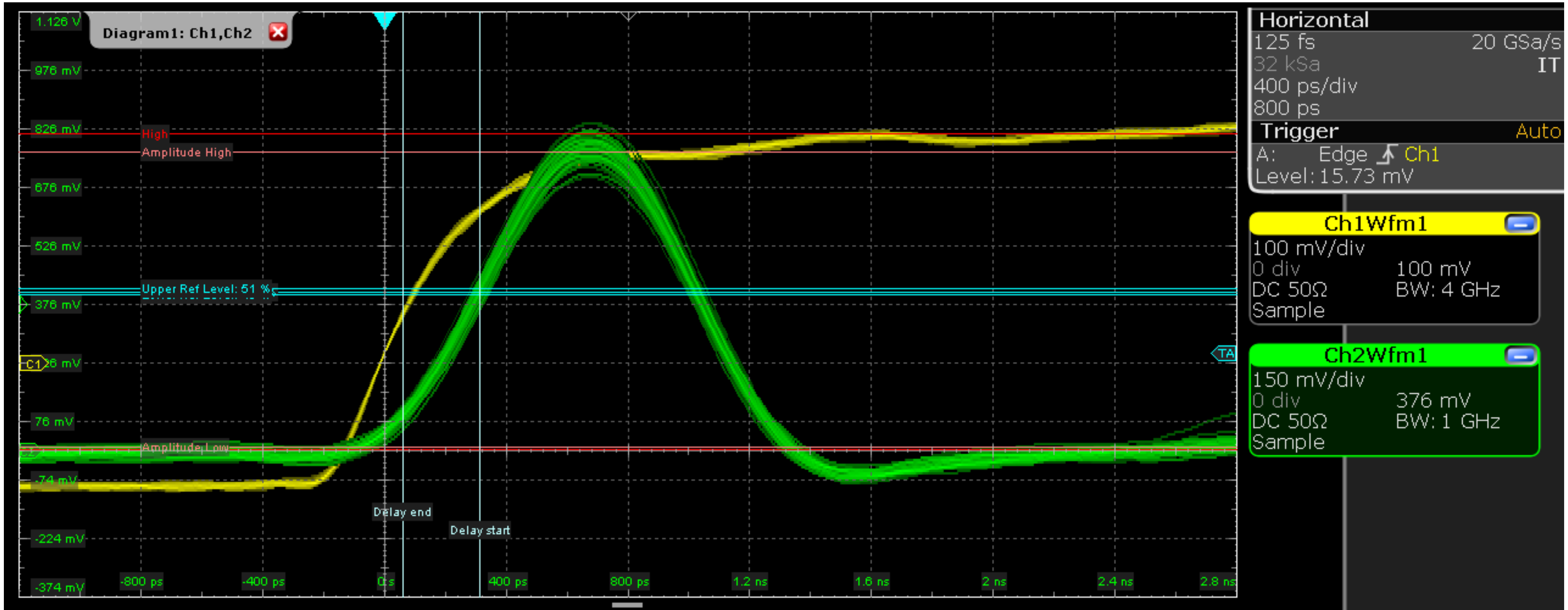
First stage negligible

Second stage negligible

Time-walk term

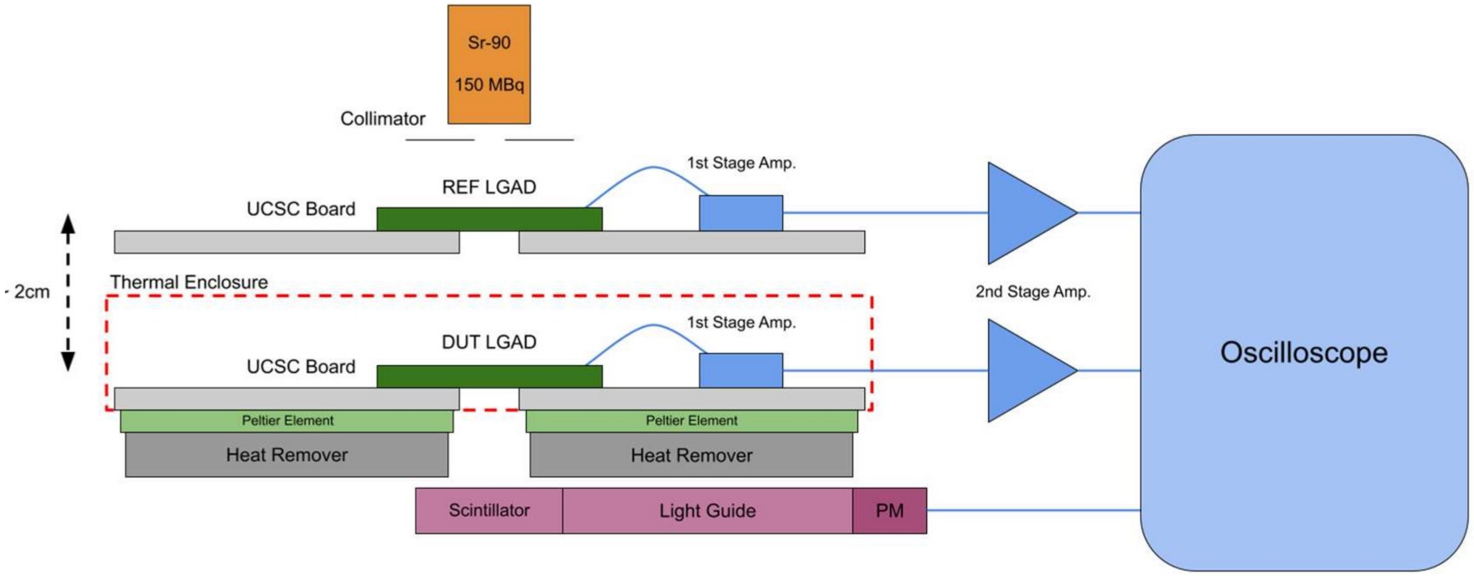
Time quantization noise of the scope

1mm LGAD array W02 signal – 240 V bias



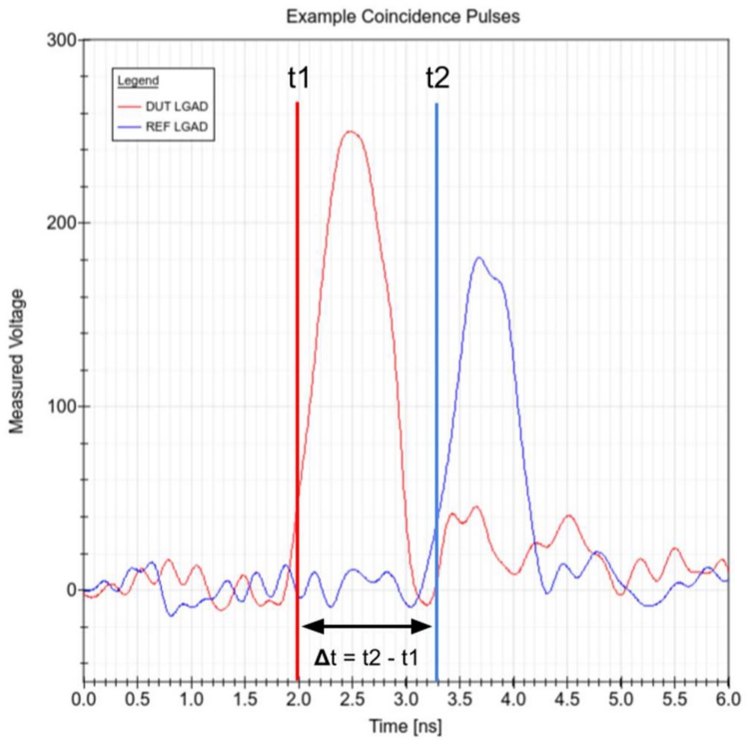
	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1								
Delay	-253.25 ps	-56.337 ps	-273.76 ps	-232.57 ps	232.79 ps	10.087 ps	30458	30458
Meas Group 2								
Low	9.8933 mV	137.36 mV	-76.075 mV	-6.4623 mV	10.271 mV	7.9831 mV	30458	30458
Amplitude	755.93 mV	975.3 mV	664.03 mV	781.75 mV	782.2 mV	26.727 mV	30458	30458
Area	531.33 pV*s	1.1405 nV*s	444.15 pV*s	548.53 pV*s	549.37 pV*s	30.33 pV*s	30458	30458
Meas Group 3								
Slew rate rising	1.5 V/ns	1.933 V/ns	500.31 V/µs	1.521 V/ns	1.524 V/ns	86.028 V/µs	30458	30458

Sr90 - Timing resolution setup



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

Timing setup from Ljubljana

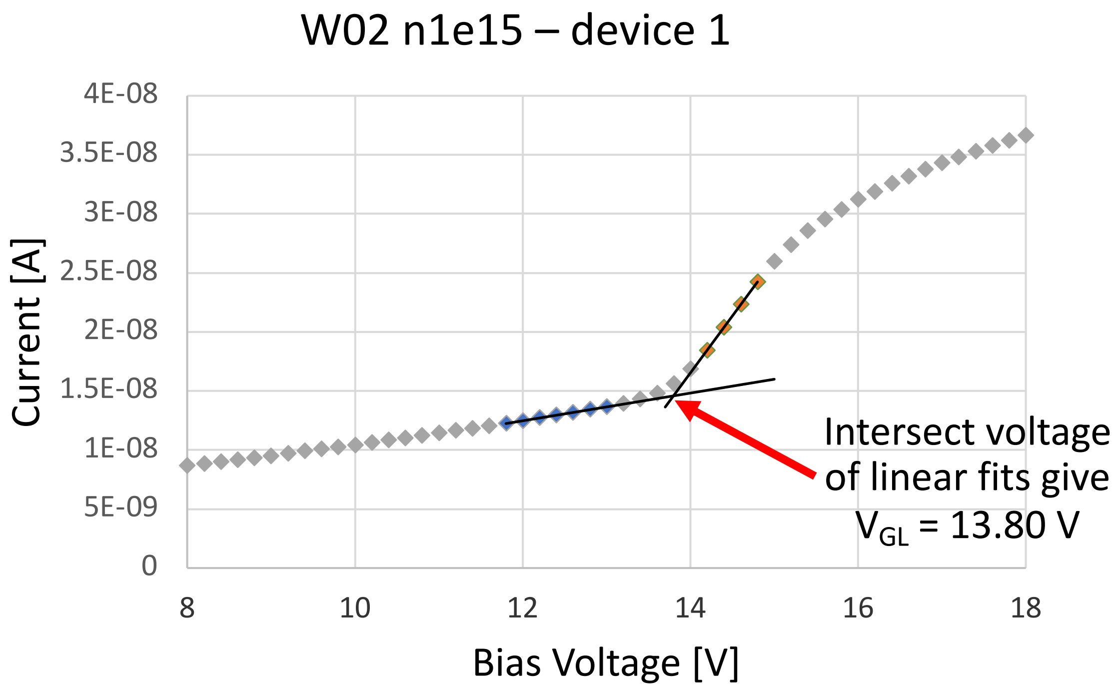


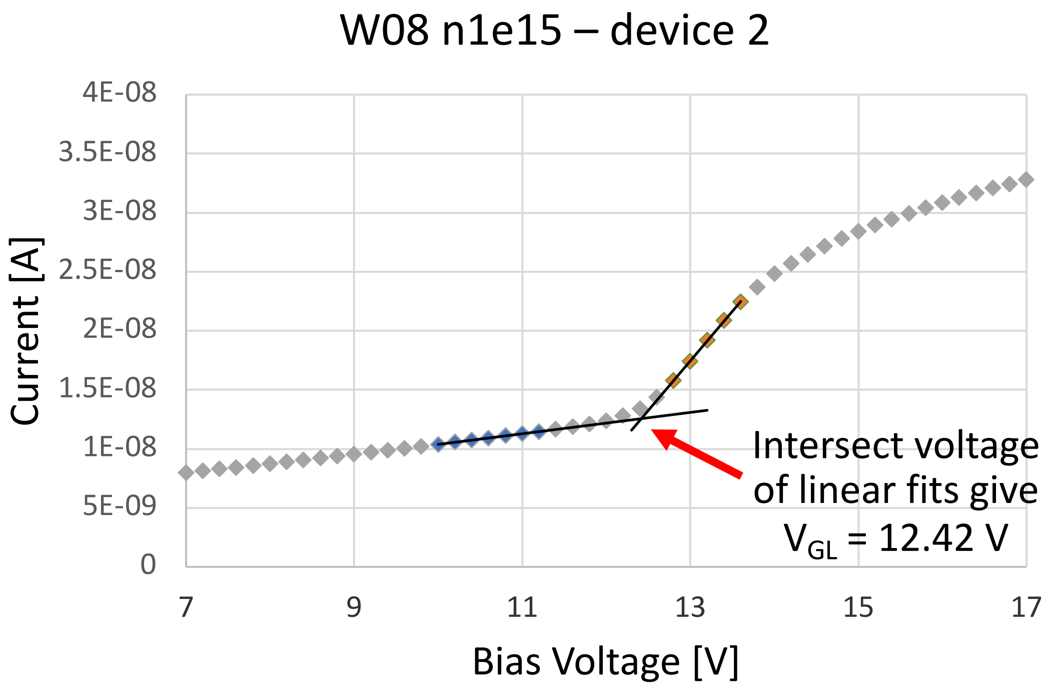
Measurement setup:

- Sr-90 coincidence setup, replica of the one used by colleagues at Ljubljana.
- Trigger is done by the DUT LGAD (scintillator trigger soon to be implemented).
- LGAD on Santa Cruz board, second-stage amp Particulars AM-01B 35dB 2GHz.
- CFD is set at 20%.

Gain Layer depletion voltage V_{GL} extraction – high Φ

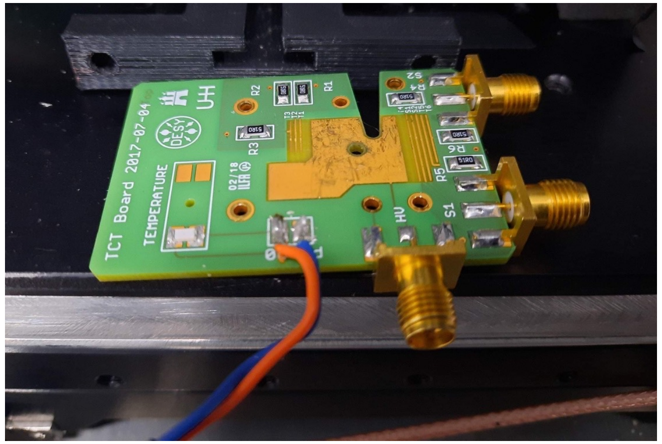
For highly irradiated sensors gain layer depletion voltage extracted from IV knee

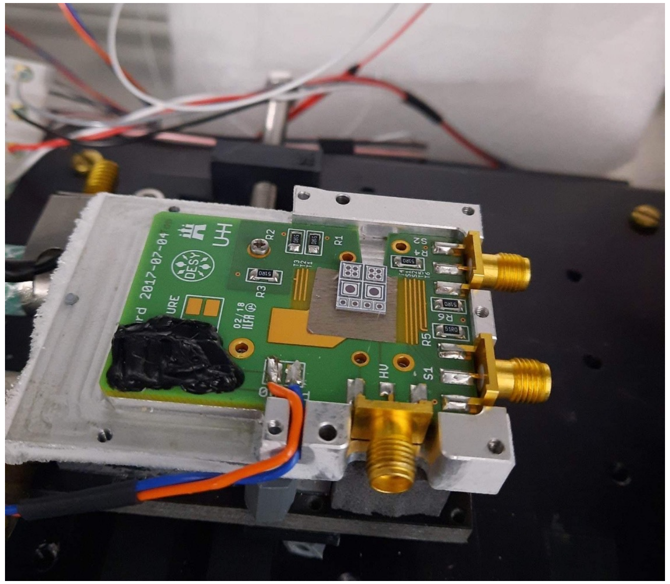




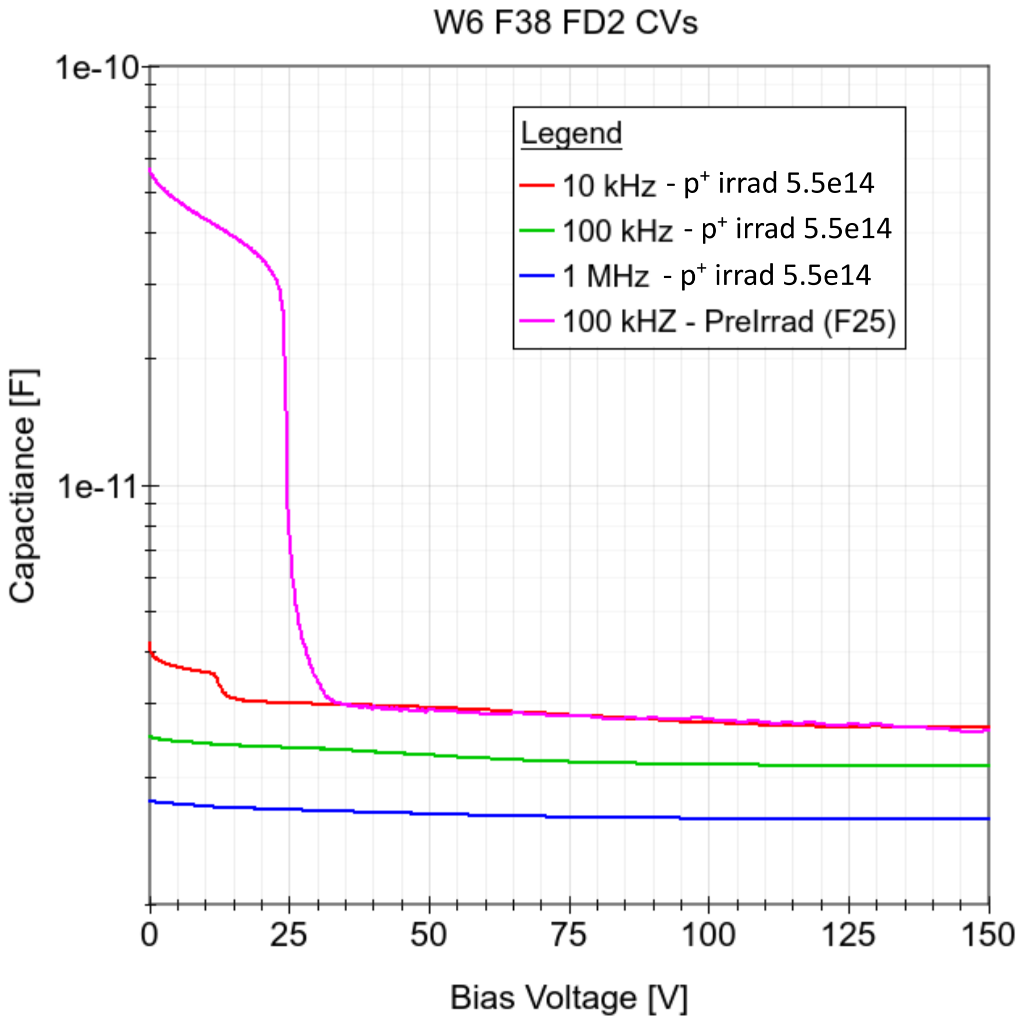
Gain of proton irradiated devices - measurement

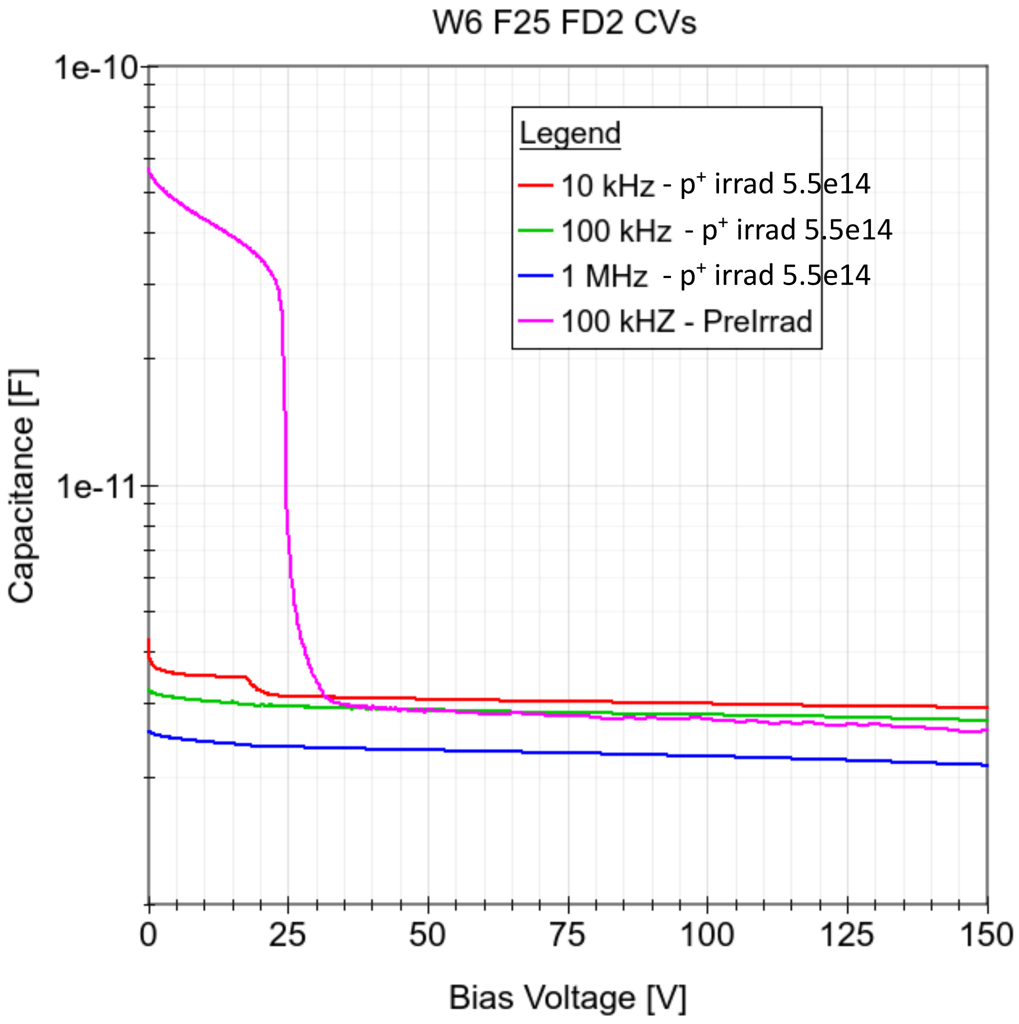
- Some inconsistencies with temperature readings, likely due to the nitrogen used to decrease humidity
- Nitrogen was being fed in at room temperature and we are continuously flushing directly over the sensor.
- Three solutions were enacted:
  - Decrease the nitrogen flow. Helped considerable but humidity started to increase
  - Submerge ~10m of nitrogen tubing in the chiller’s bath
  - Place hot glue over the PT100 temperature sensor so measurements are less effected by the flow of nitrogen
- Effective, however exact temperate of the LGAD still not accurate, hence measurements to be treated as preliminary



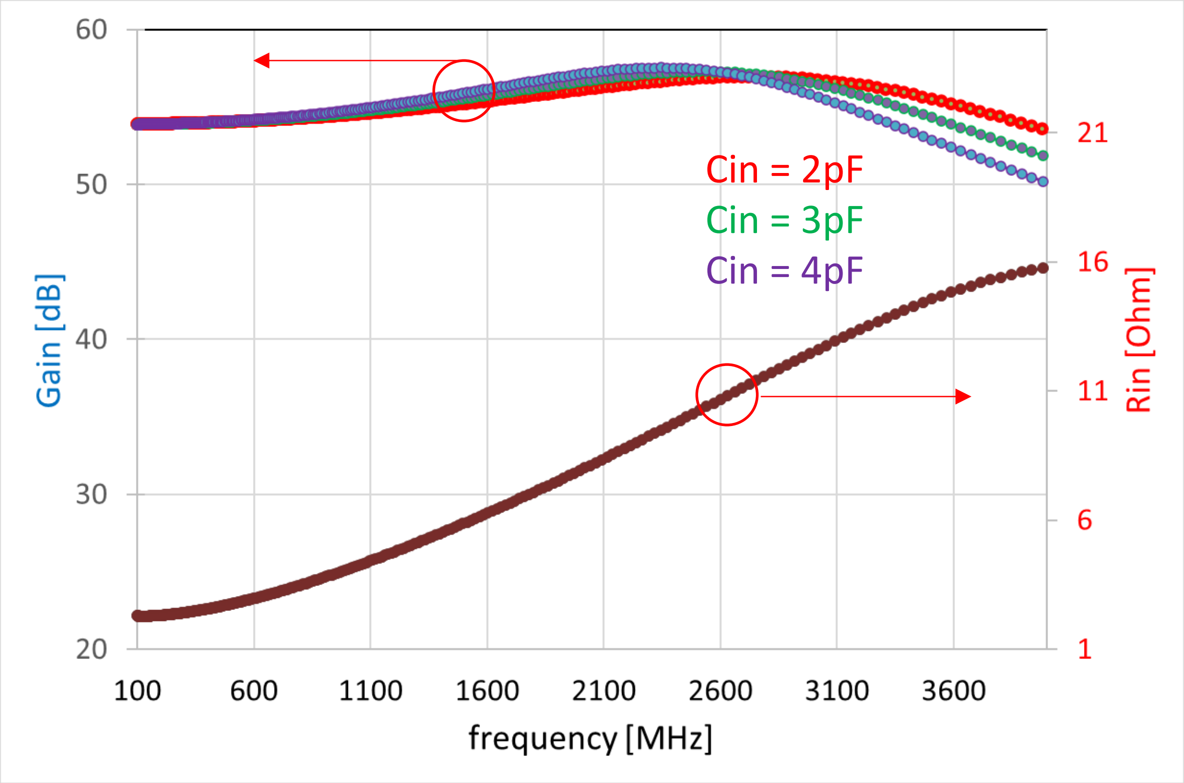


Capacitance of proton irradiated LGADs - frequency

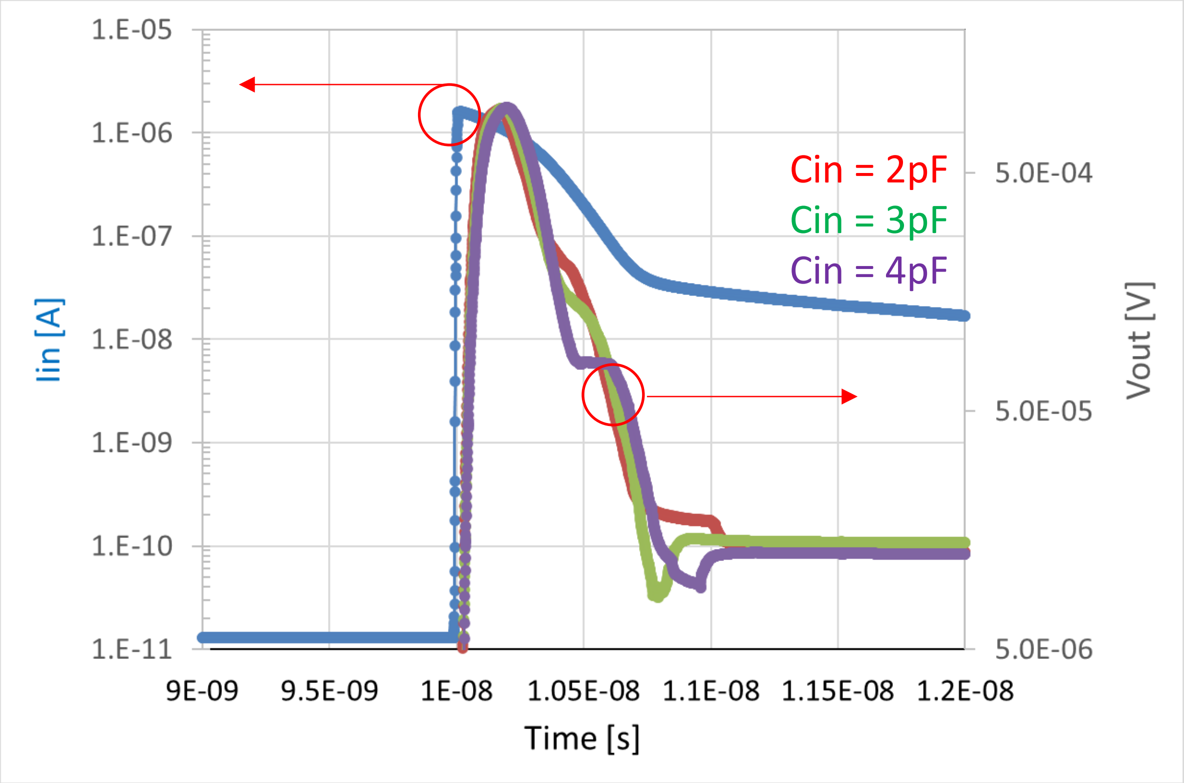




SPICE - Compact OPMD LGAD Amplifier (COLA)



SPICE COLA – AC gain and R_{in} for three different input capacitance values



SPICE COLA – simulated PIN current I_{in} (from TCAD – MIP @ 300 V) and time output