Timing and CCE Performance of the LGAD from Teledyne e2v

Philip Patrick Allport[5], Daniela Bortoletto[3], Laura Gonella[5], Martin Gazi[3], Daniel Hynds[3], Douglas Jordan[4], Ioannis Kopsalis[6], Jonathan Mulvey[5], Steve Mcmahon[1], Richard Plackett[3], Konstantin Stefanov[7], E. Giulio Villani[1,3], Trevor Vickey[2], Dengfeng Zhang[2]

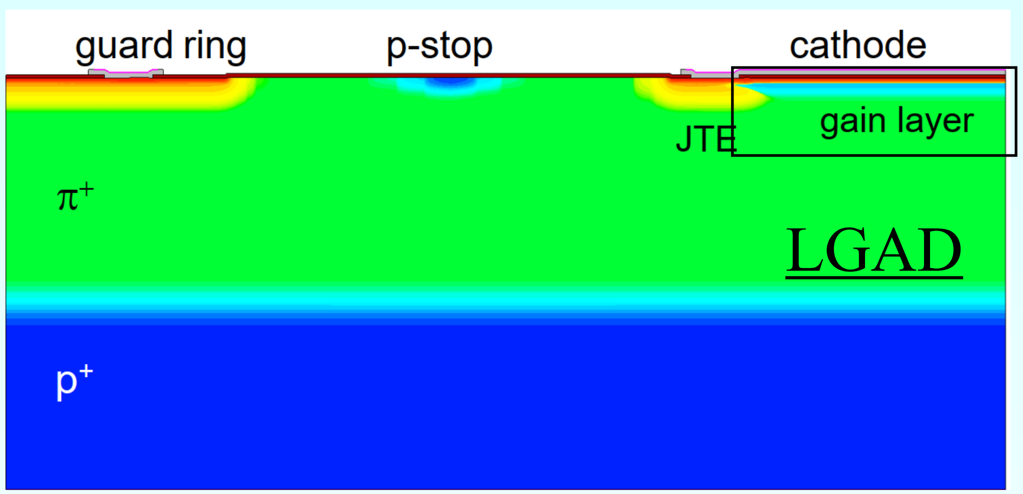
[1]STFC-RAL, [2]University of Sheffield, [3]University of Oxford, [4]Teledyne e2v, [5]University of Birmingham, [6]National Technical University of Athens, [7]The Open University

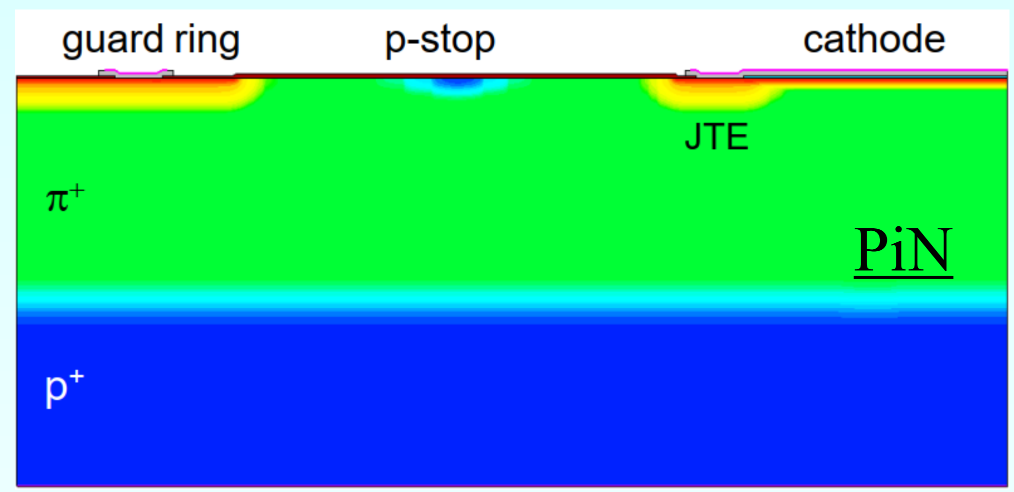
Dec. 04, 2024

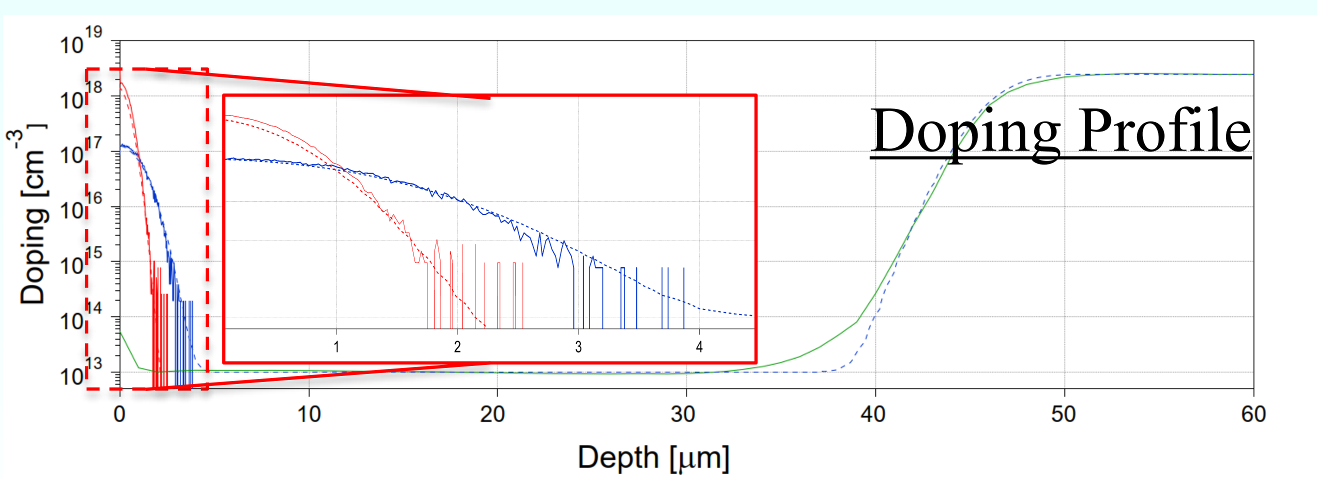
The 2nd DRD3 Week on Solid State Detectors R&D@CERN

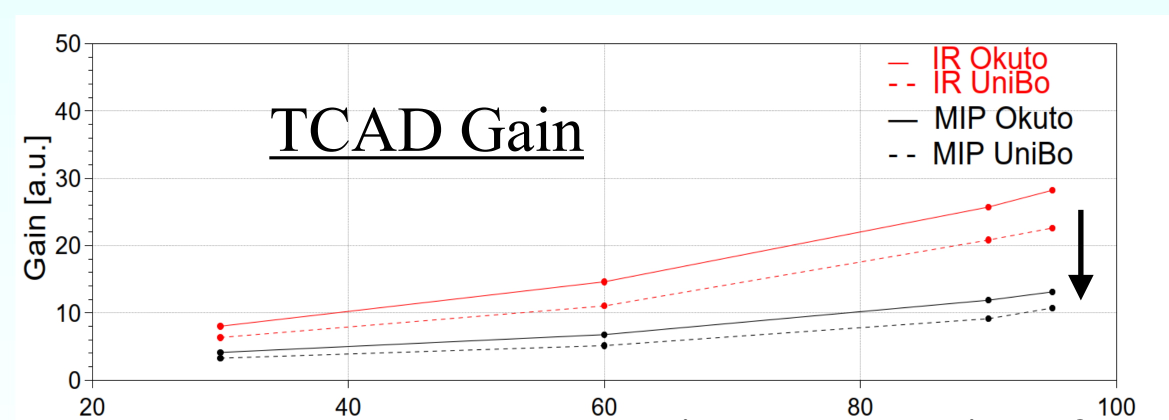
LGAD Design

- Designed at PPD of Rutherford Appleton Laboratory,
  - 50 µm thick high resistivity epitaxial layer (1e13 cm^{-3}) on Cz substrate,
  - Gain: 10-50,
  - Target for the time resolution of 30-50 ps or better.
- TCAD simulation completed for the doping, breakdown, gain, etc.





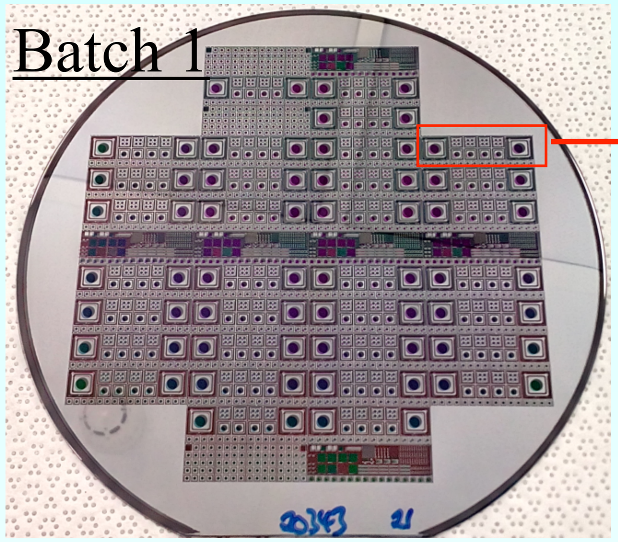


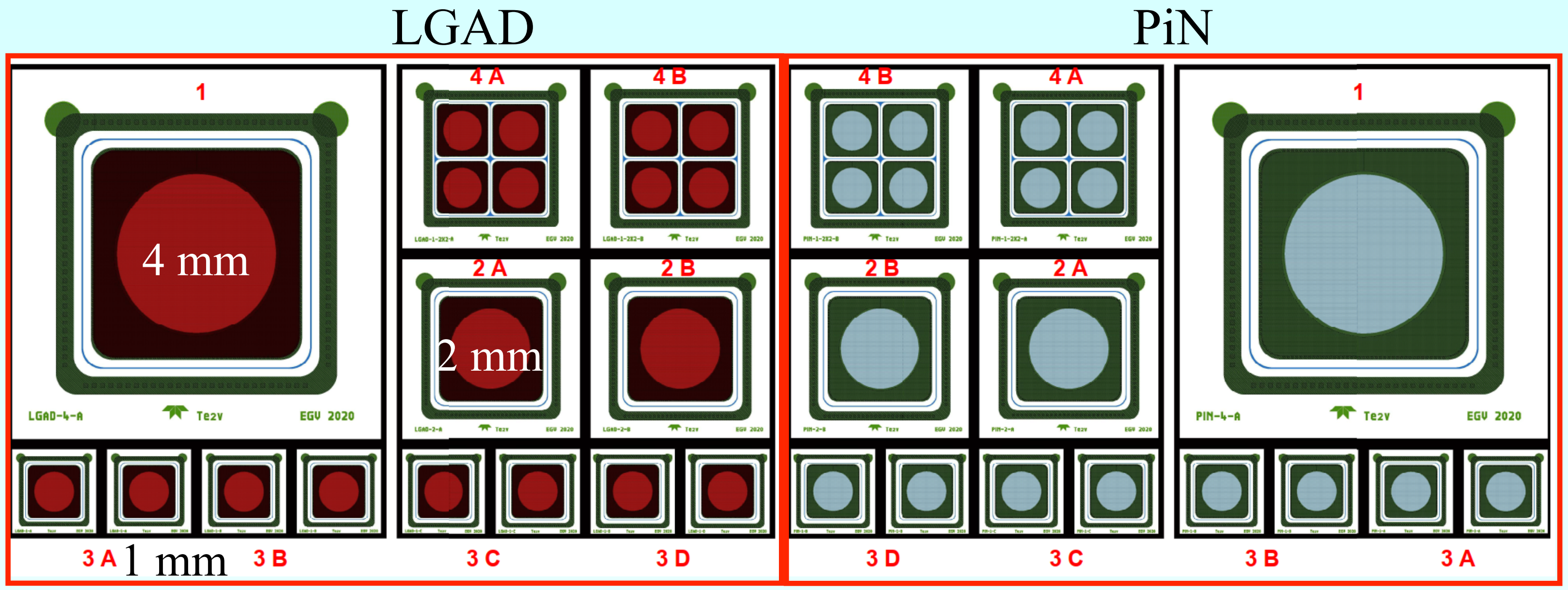


gain suppression for MIP

LGAD from Teledyne e2v

- Fabricated on 6" Wafer at Teledyne e2v, UK,
- Two batches have been fabricated with different implant doses and energies:
  - Batch 1: LGAD and PiN (1,2, 4 and 2×2 of 1×1 mm^2 cells):



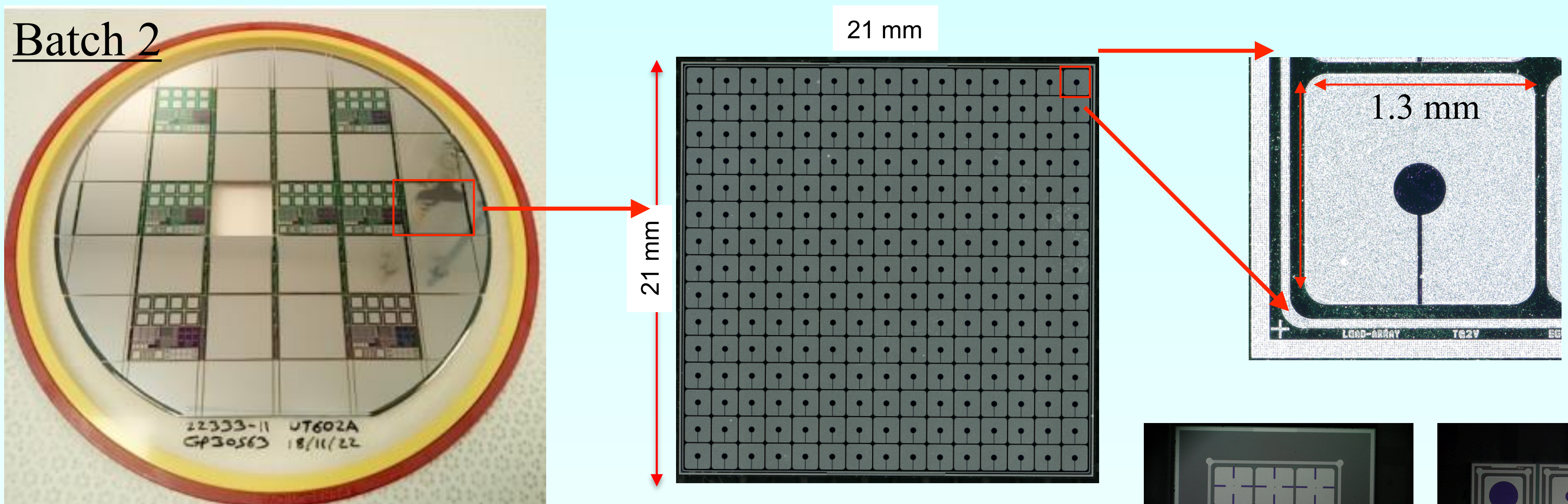


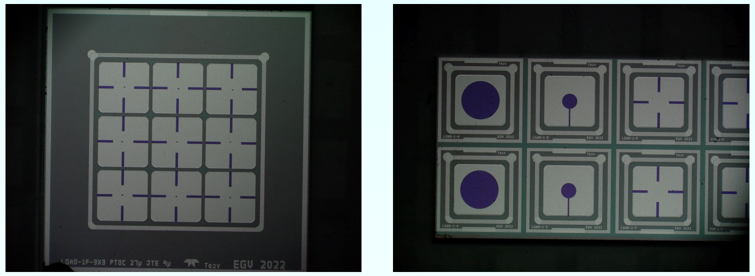
Wafer	GL dose	GL energy
19,20,21	1.00	1.00
17,18	1.07	1.00
15,16	0.92	1.05
12,13,14	1.00	1.05
9,10,11	1.07	1.05
7,8	1.15	1.05
4,5,6	1.00	1.11
2,3,24	1.07	1.11

Cell layout	Cathode diameter [μm]	Laser hole diameter [μm]	Cathode to p-stop [μm]	p-stop width [μm]	p-stop to Guard Ring [μm]	Guard ring width [μm]
1	4000	3020	156	6	152	332
2	2000	1510	78	6	76/96	166
3	1000	755	39	6	38/48/58/68	83
4	1000	755	39	6	38/68	166

LGAD from Teledyne e2v

- Fabricated on 6” Wafer at Teledyne e2v, UK,
- Two batches have been fabricated with different implant doses and energies:
  - ✦ Batch 2: Add the LGAD Array (15×15 cells of 1.3×1.3 mm^2)





Wafer	GL dose	GL energy
1	1.00	1.00
2	0.95	1.07
3	1.00	1.07
4	1.00	0.93

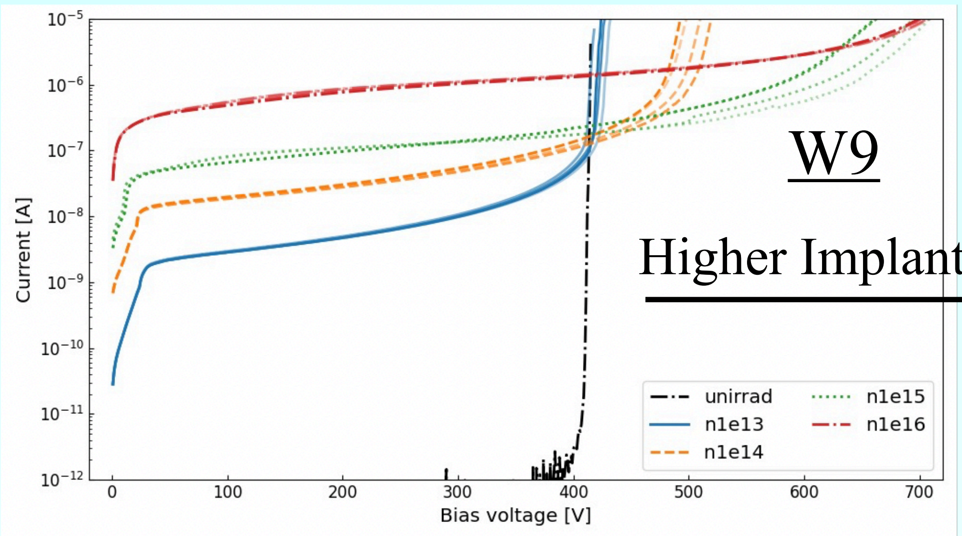
Cathode diameter [μm]	Cathode to GR [μm]	Cathode to p-stop [μm]	p-stop width[μm]	Cathode to Cathode [μm]	GL to GL [μm]
1300	83	30	6	66	86

LGAD Leakage Current after neutron irradiation

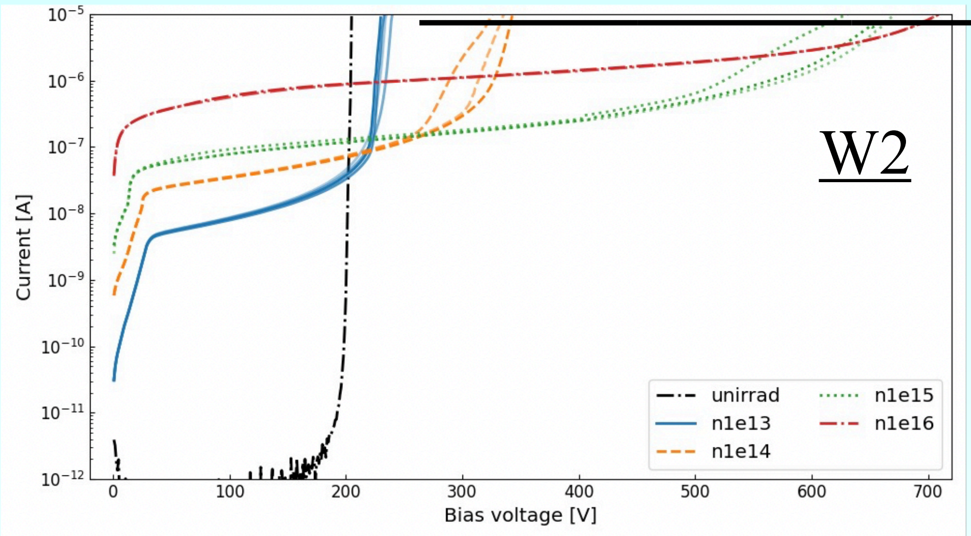
University of Sheffield

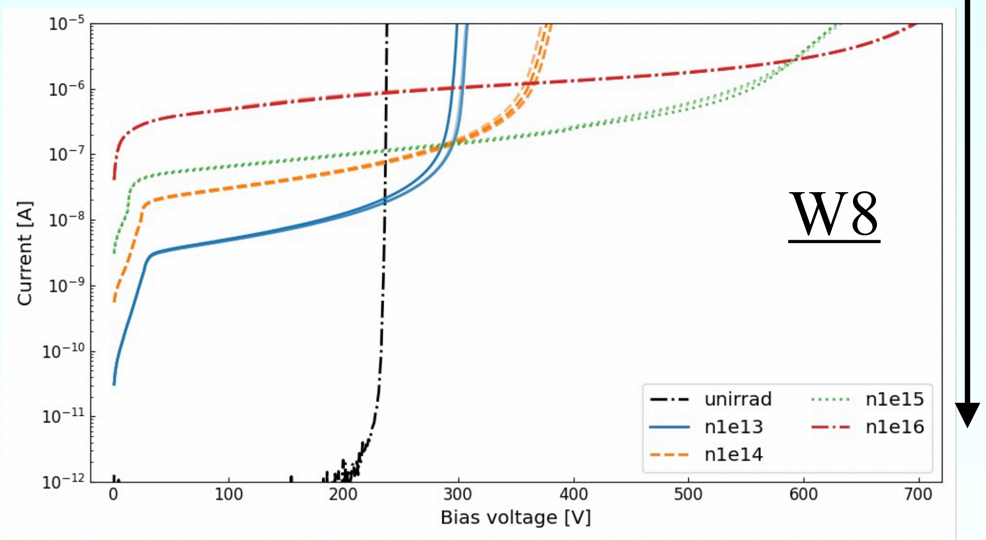
- 1 mm LGAD device from Wafer 2/8/9, measured at -20 °C,
- Neutron irradiation performed at Jozef Stefan Institute in Ljubljana:
  - neutron fluence: 1×10^{13}-1×10^{16} 1 MeV n_{eq}/cm^2
  - annealed at 60°C for 80 min

Wafer	GL dose	GL energy
9	1.07	1.05
8	1.15	1.05
2	1.07	1.11



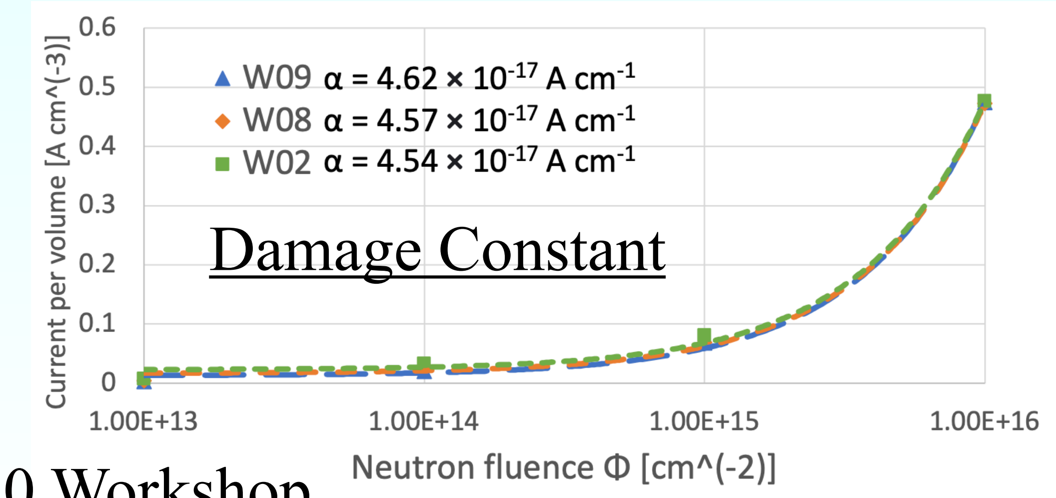
Higher Implant Energy →





Higher Implant Dose ↓

$$\Delta I = I(\Phi) - I(\Phi = 0) = \alpha \cdot \Phi$$



More results in M. Gazi's talk at 41st RD50 Workshop

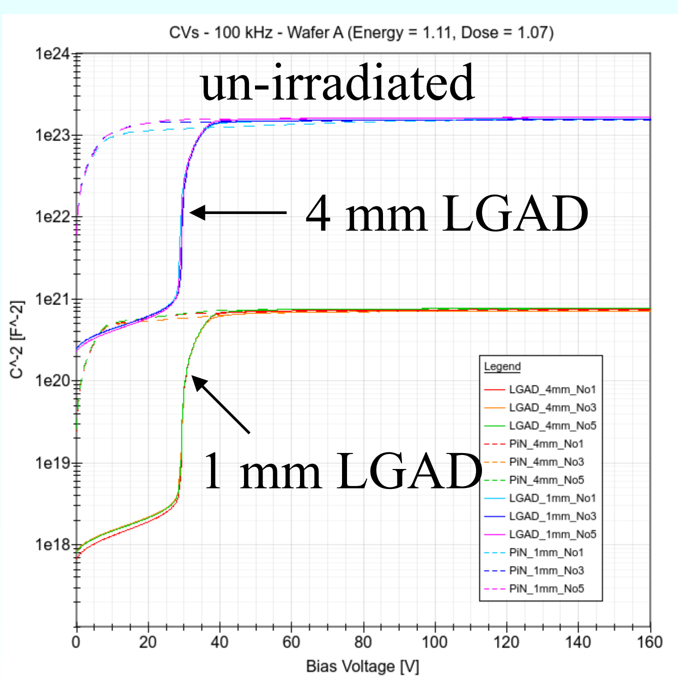
LGAD Capacitance after neutron irradiation

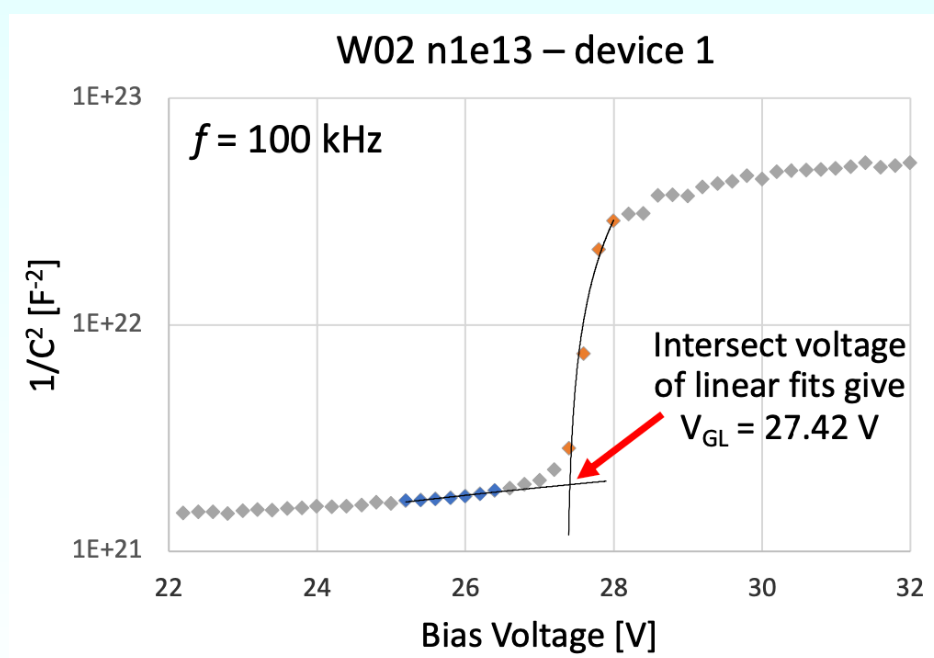
University of Sheffield

- LGAD device from Wafer 2/8/9, measured at -20 °C,
- Neutron irradiation performed at Jozef Stefan Institute in Ljubljana:
  - neutron fluence: 1×10^{13}-1×10^{16} 1 MeV n_{eq}/cm^2
  - annealed at 60 °C for 80 min

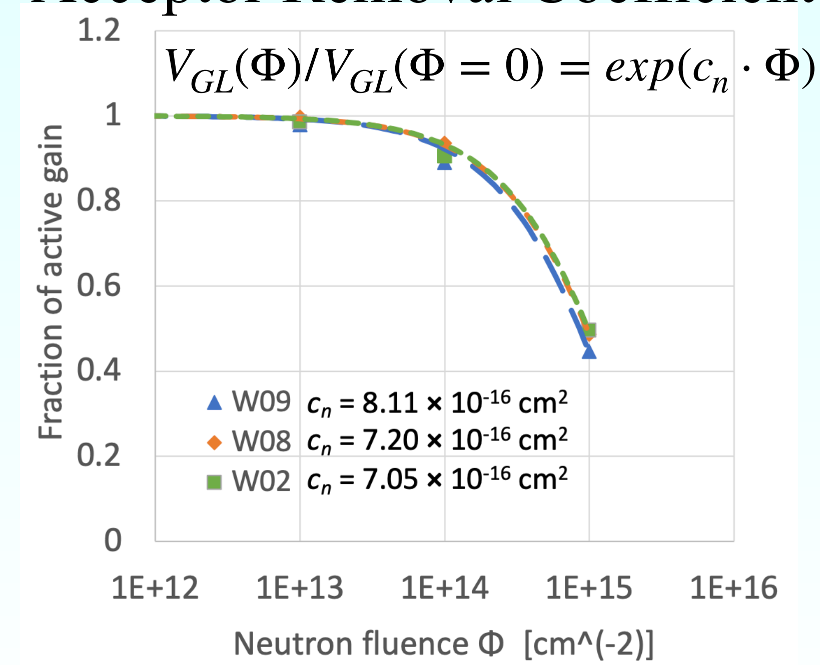
Wafer	GL dose	GL energy
9	1.07	1.05
8	1.15	1.05
2	1.07	1.11

- Gain Layer depletion voltage is 20-30 V and the fully depleted voltage is 30-40 V before irradiation.





Acceptor Removal Coefficient:

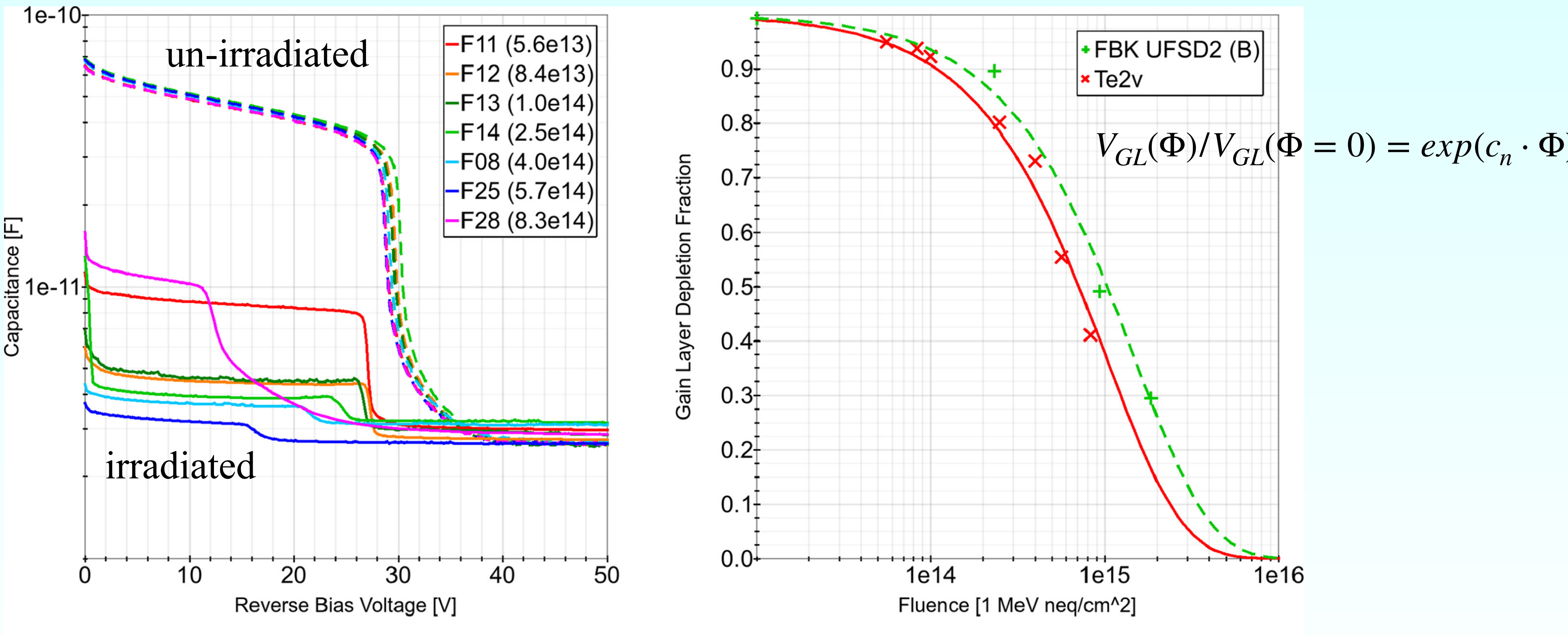


LGAD Capacitance after proton irradiation

University of Sheffield

Wafer	GL dose	GL energy
2	1.07	1.11

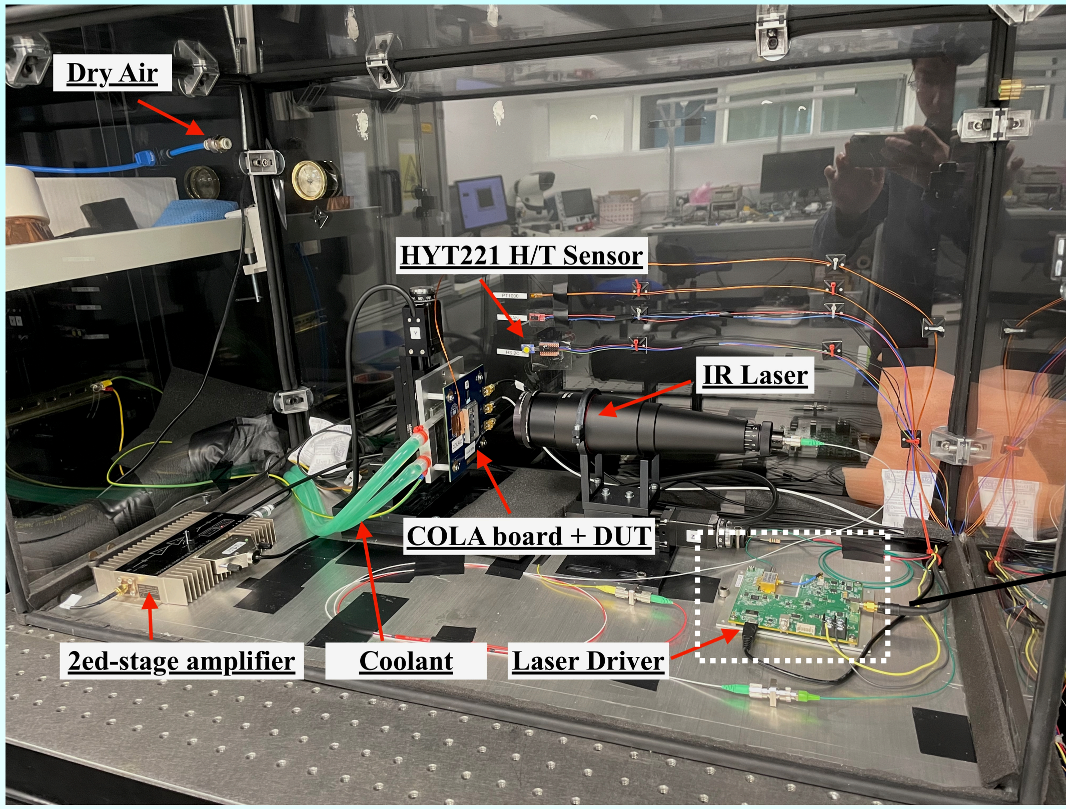
- LGAD device from Wafer 2, measured at -20 °C,
- Proton irradiation performed at MC40 cyclotron with 27 MeV protons in Birmingham.
- Acceptor Removal Coefficient: $9.7\pm0.5\times10^{-16}$ cm^2, similar with the value derived from neutron irradiated devices, but slightly higher,
- More results in M. Gazi's talk at the 41st RD50 Workshop and J. Mulvey's talk at the 38th RD50 Workshop.

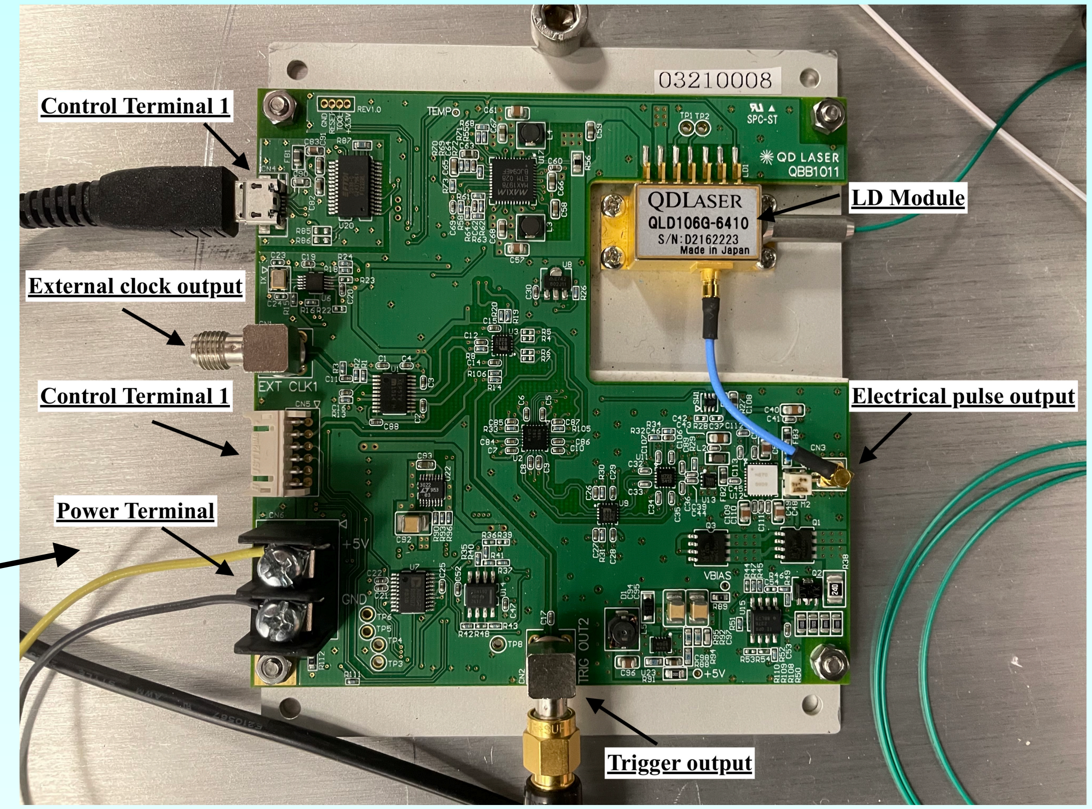


(a) (b)

TCT Setup for LGAD

- Modified TCT setup at PPD of RAL, another twin setup at OPMD (Oxford):





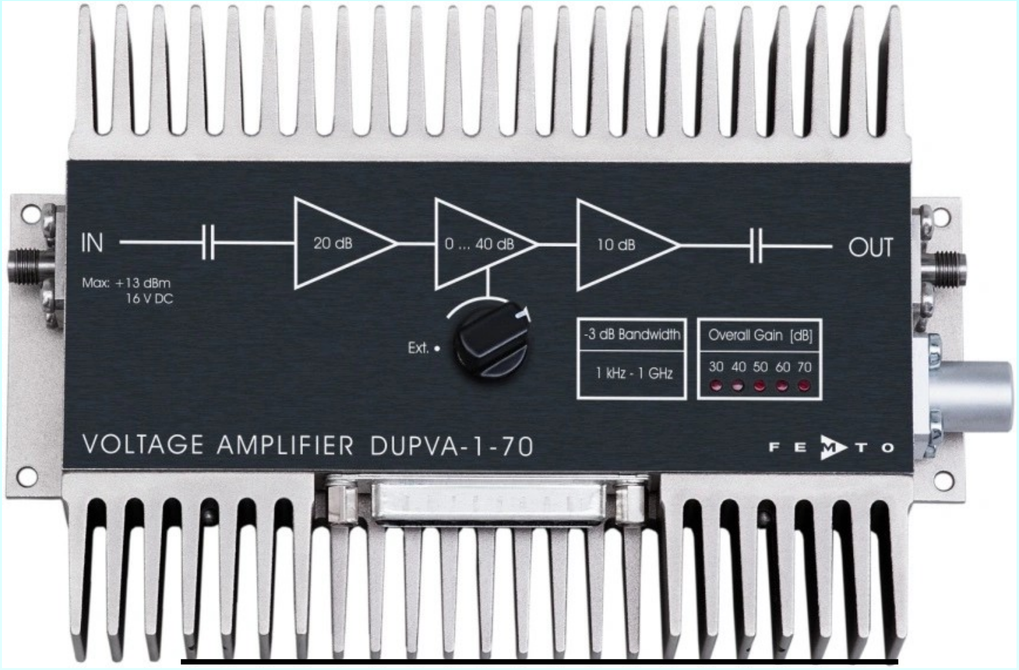
- Stage for DUT and telescope movement,
- Chiller to lower the temperature (-20 °C) for test irradiated sensors,
- Infrared Laser (1064 nm -15 ps) for charge injection,
- Two-stage amplifier for signal amplification $\Longrightarrow$ Next Page
- Signal is readout by fast oscilloscope (Tektronix Oscilloscope: 33 GHz, 100 GS/s).

TCT Setup for LGAD

University of Sheffield

- The output signals from the LGAD are conditioned by a two stage amplifier:

Spficatoins	Values
Supply Voltage [V]	2.25
Gain [dB]	50
Bandwidth [GHz]	1.2
Slew Rate [GV s^{-1}]	0.92
RMS Noise [µV]	155
Jitter [ps]	1.6



Spficatoins	Values
Supply Voltage [V]	±15
Gain [dB]	20-60
Bandwidth [GHz]	1.2
Slew Rate [GV s^{-1}]	2.67
RMS Noise [µV]	977
Jitter [ps]	3

- COLA (Compact OPMD LGAD Amplifier) designed at Oxford-OPMD with a gain of 50 dB and bandwidth > 1 GHz,
- The second stage is a commercial voltage amplifier with variable gain (set to 30 dB in our measurement).

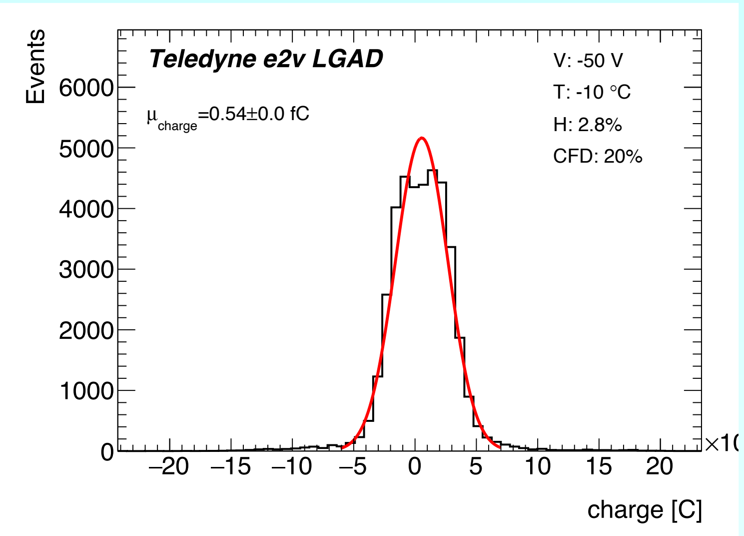
LGAD CCE and Gain after neutron irradiation

University of Sheffield

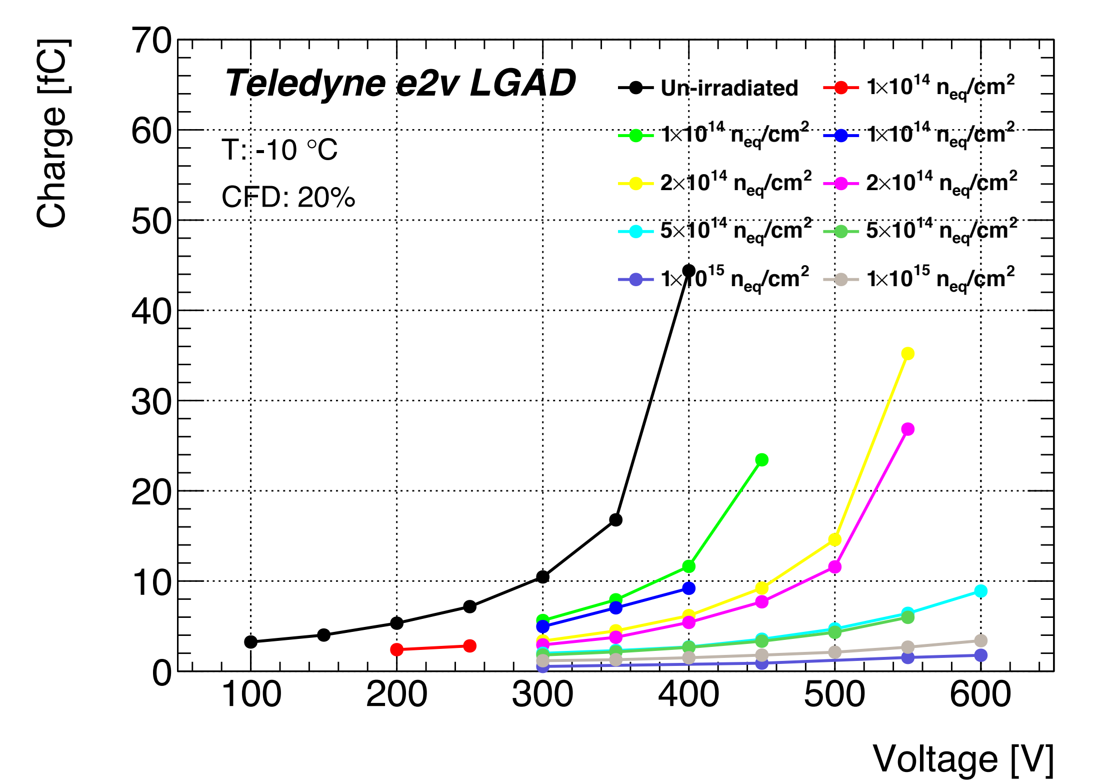
- 1 mm LGAD from Wafer 9 with a typical breakdown voltage of ~450 V before irradiation, measured at -10 °C,

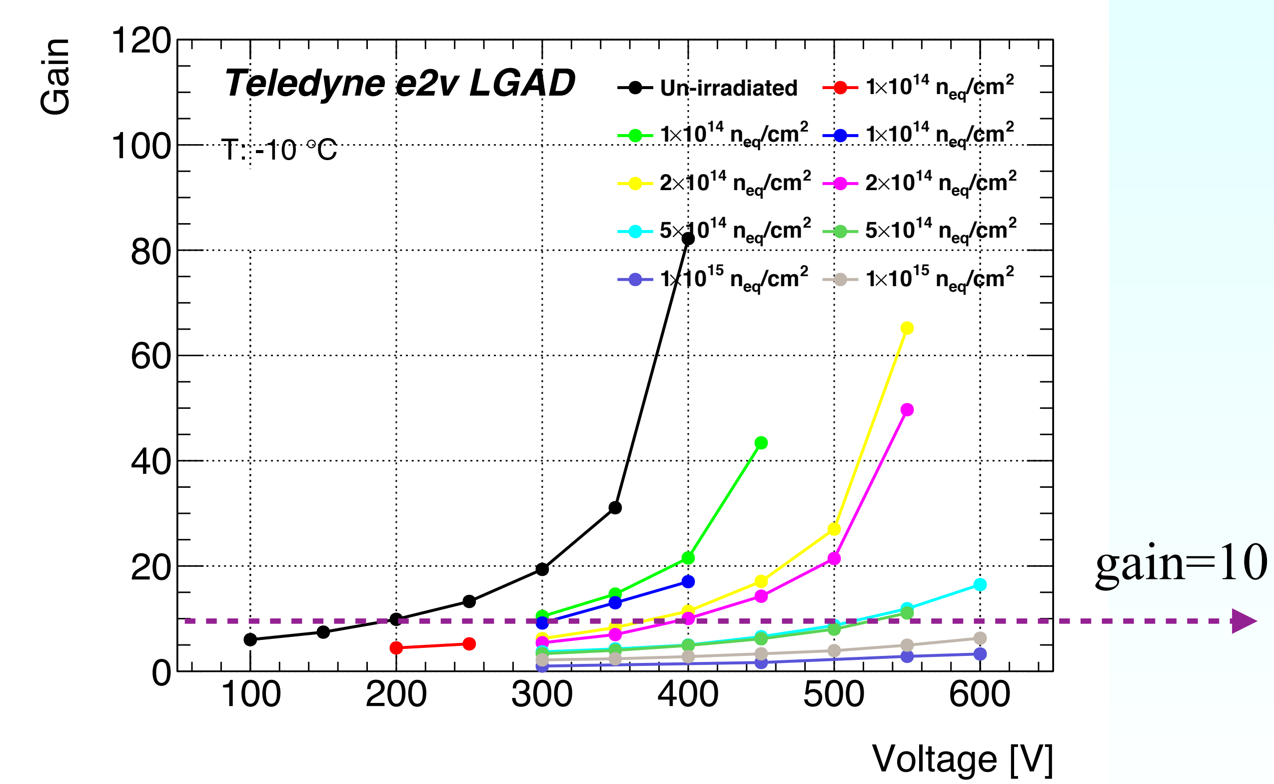
Wafer	GL dose	GL energy
9	1.07	1.05

- The injected charge was calibrated using PiN: 0.54 fC,



- Neutron irradiation performed at JSI:
  - neutron fluence: 1×10^{14}-2×10^{15} 1MeV n_{eq}/cm^2
- LGAD after neutron irradiation of 5×10^{14} n_{eq}/cm^2 can still provide a gain of ~10 at 550 V





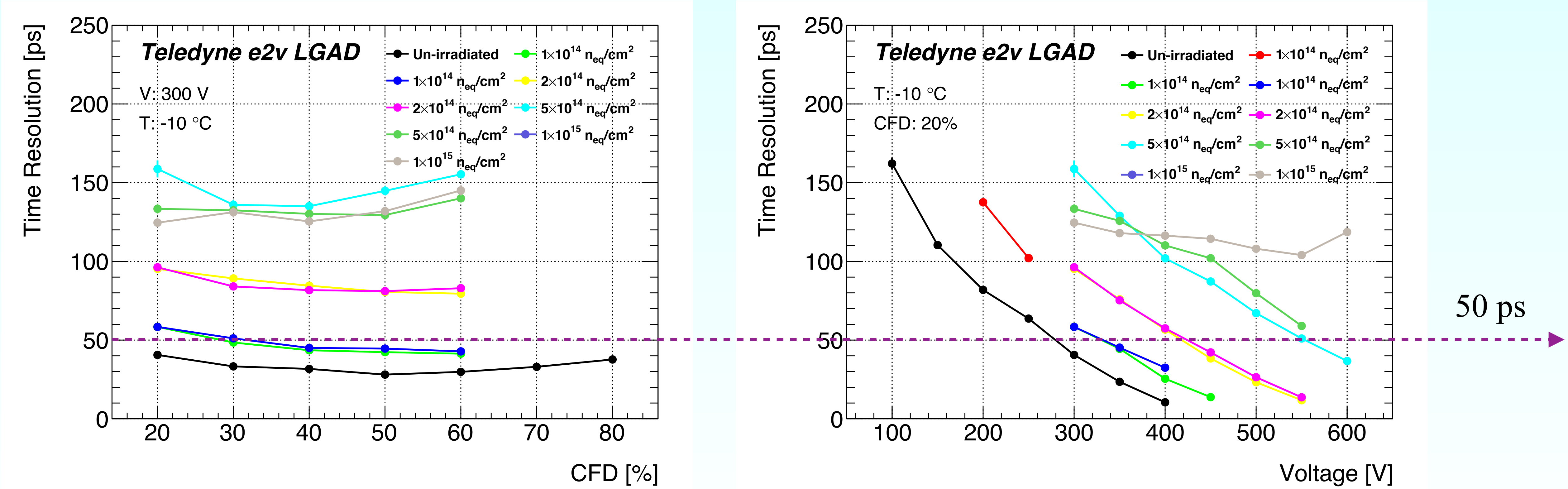
LGAD Time Resolution after neutron irradiation

University of Sheffield

- The time resolution was measured using the Split Delay and Recombine technique with various CFD thresholds:
  - CFD threshold ranging from 20% to 60%

Wafer	GL dose	GL energy
9	1.07	1.05

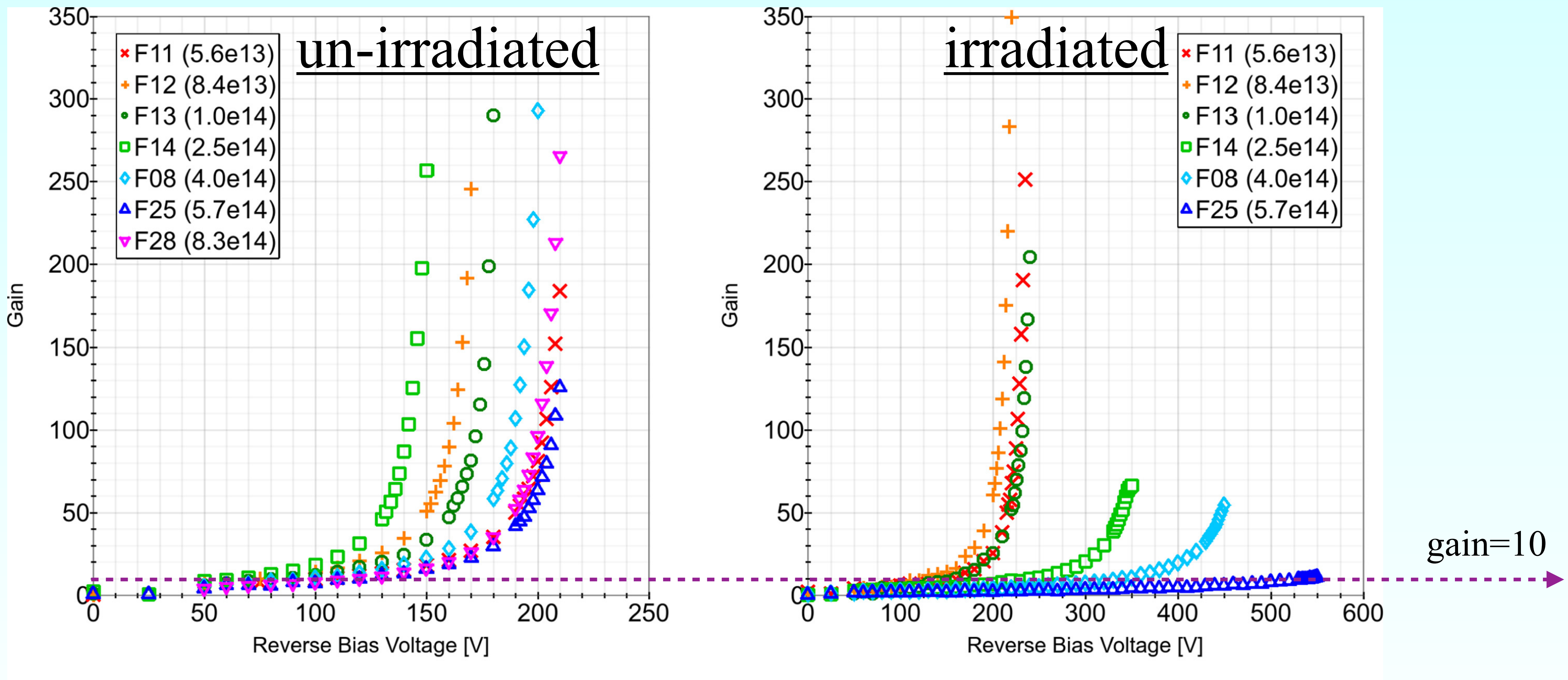
- Un-irradiated LGAD provides a time resolution (jitter) of <50 ps at 300 V,
- LGAD after irradiation of 5×10^{14} n_{eq}/cm^2 can still provide a time resolution of 70-80 ps at 500 V,
- CFD threshold also has slight effect on time resolution.



LGAD Gain after proton irradiation

- Proton irradiation performed at MC40 cyclotron with 27 MeV protons in Birmingham, UK
- Gain measured using TCT technique at -20 °C at Birmingham,
- LGAD after irradiation of 5.7×10^{14} n_{eq}/cm^2 can still provide a gain of ~10 at 550 V, similar with the performances of neutron-irradiated devices.

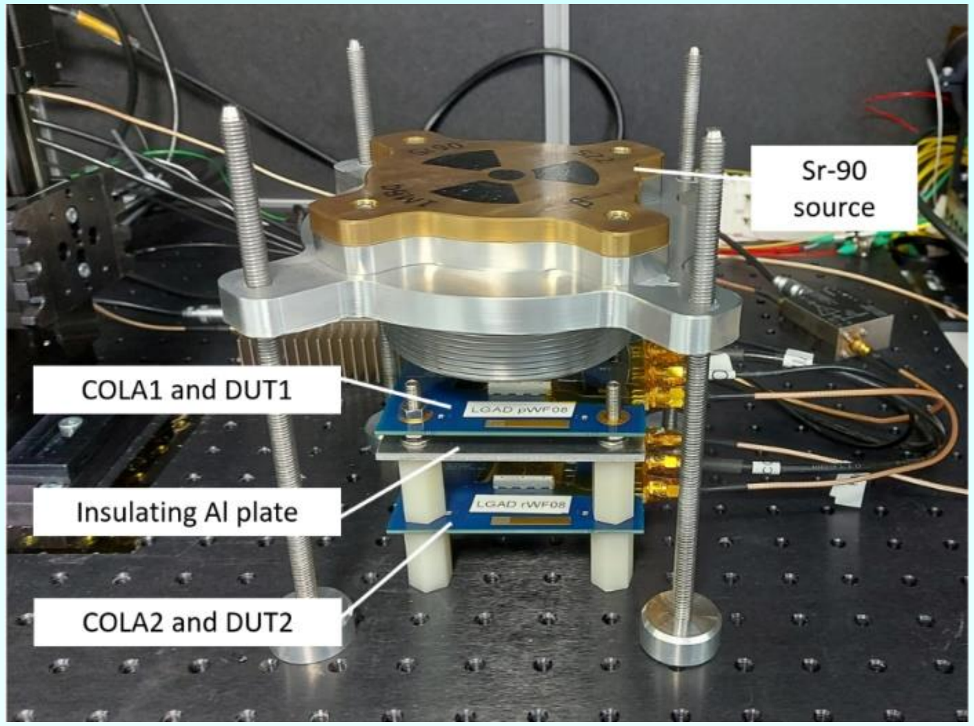
Wafer	GL dose	GL energy
2	1.07	1.11



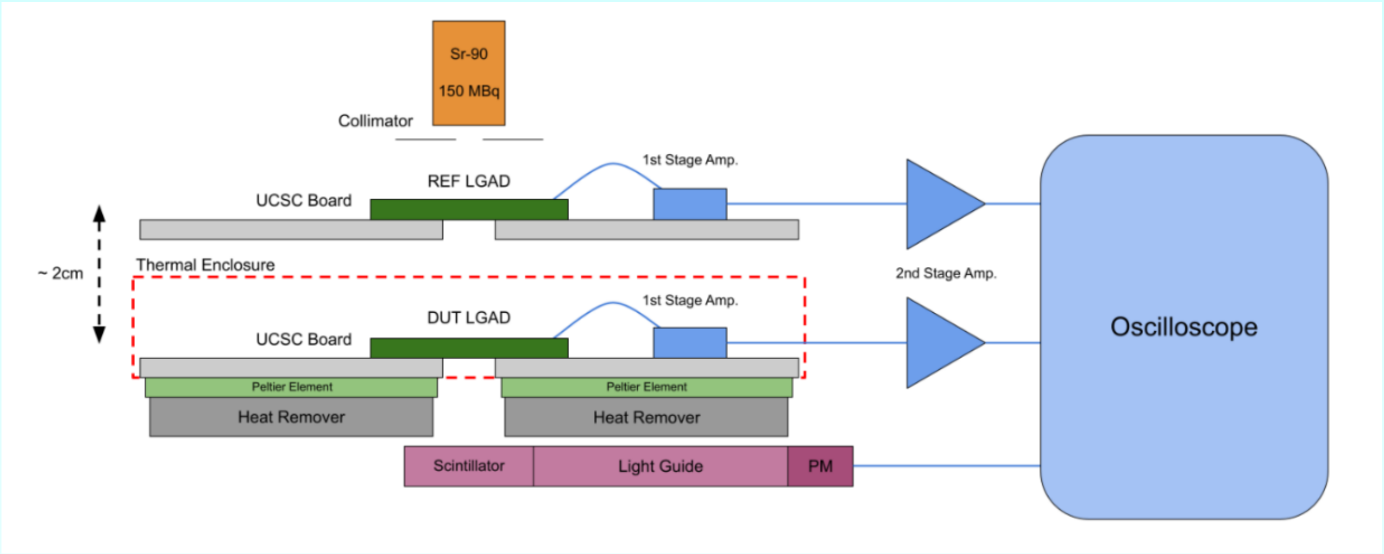
(a) (b)

Beta source setup for LGAD

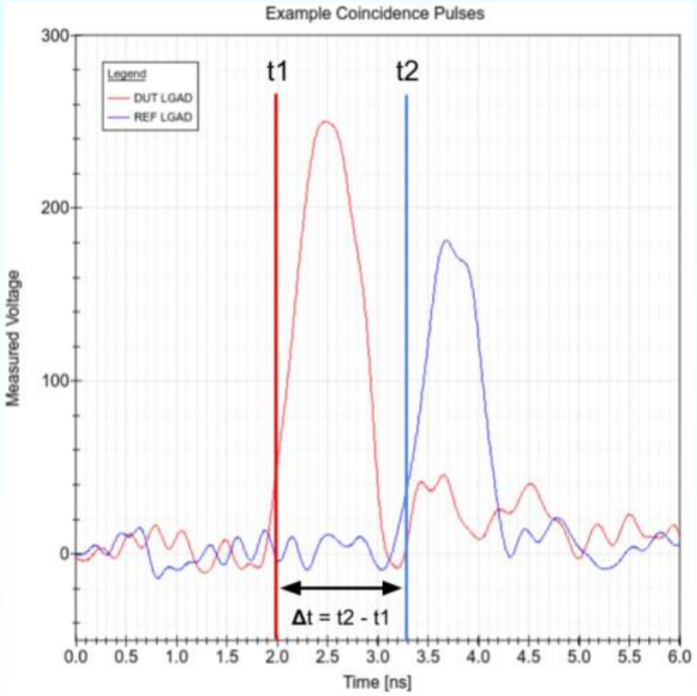
- Timing test were performed using a beta source (^{90}Sr),
- A second LGAD with know time resolution was used as reference.



Setup at OPMD



Setup at Birmingham



- Time resolution was derived from the time difference between two LGADs.

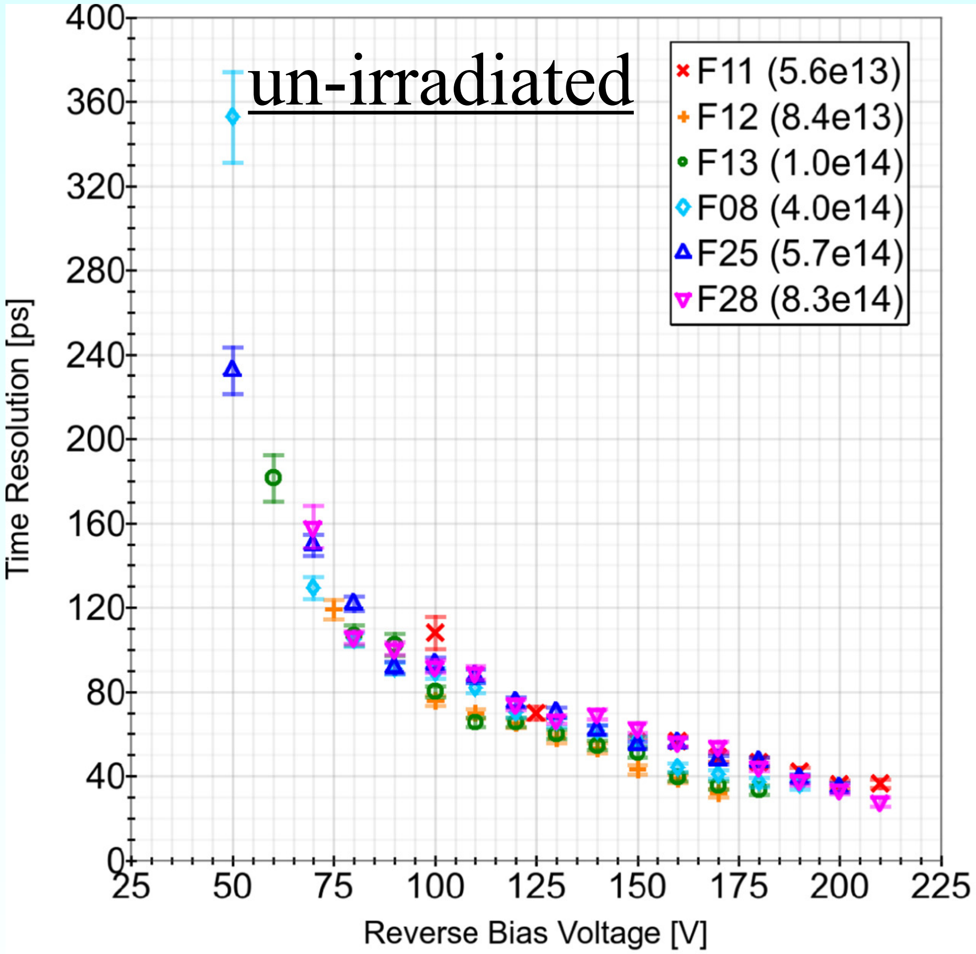
LGAD Time Resolution after proton irradiation

University of Sheffield

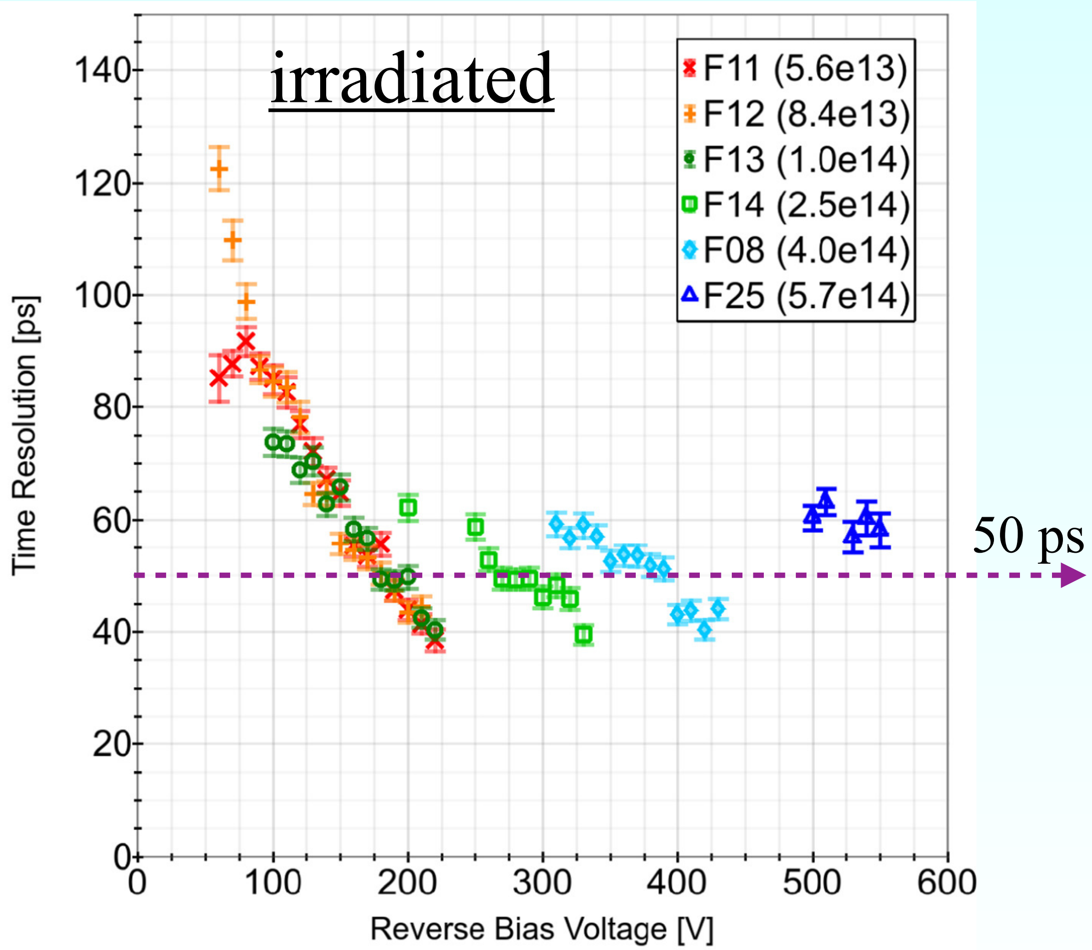
- Proton irradiation performed at MC40 cyclotron with 27 MeV protons in Birmingham, UK

Wafer	GL dose	GL energy
2	1.07	1.11

- Time resolution was obtained from measurement using the the beta source,
- LGAD after irradiation of 5.7×10^{14} n_{eq}/cm^2 can still provide a time resolution of ~60 ps at 550 V and CFD threshold of 20%.



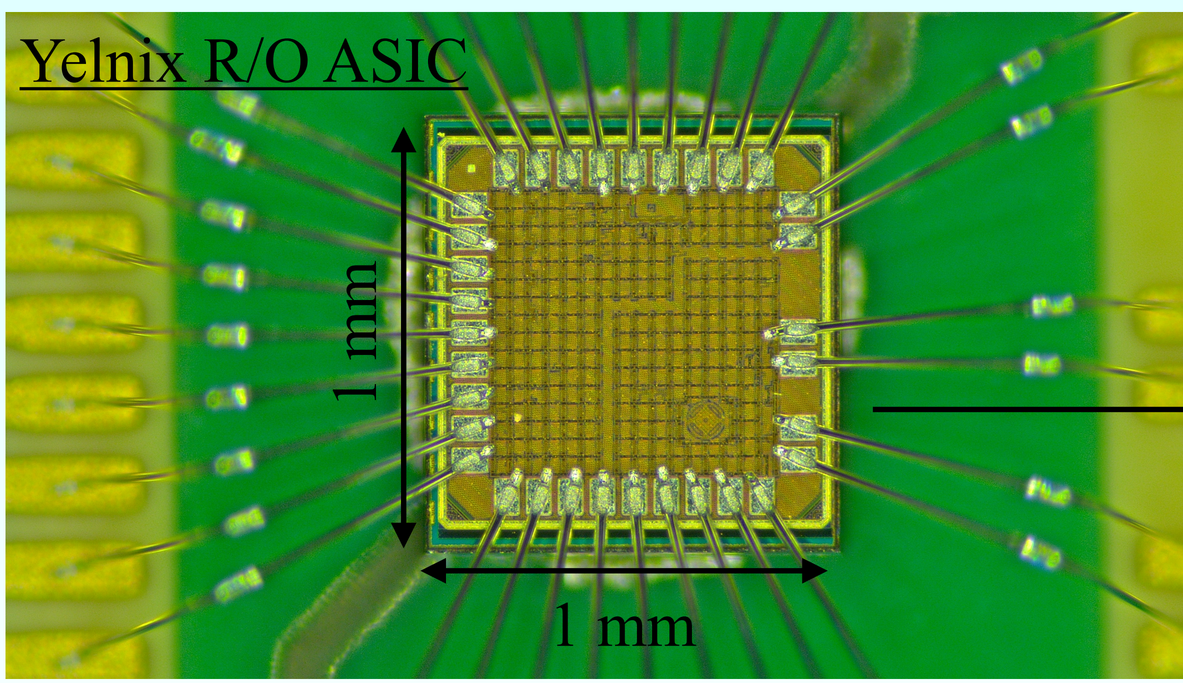
(a)

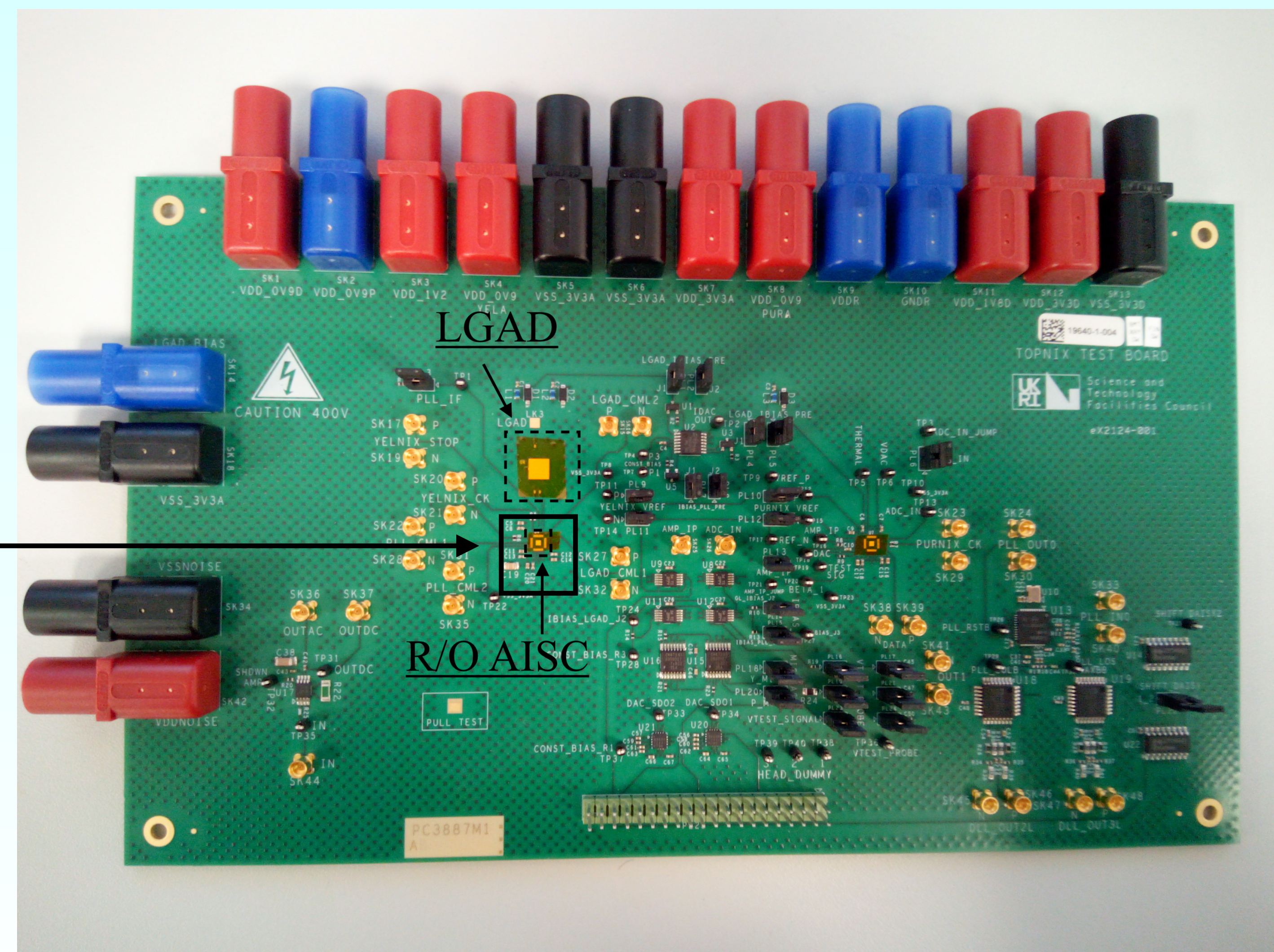


(b)

R/O ASIC for LGAD: Yelnix

- Yelnix: R/O ASIC using 28 nm CMOS technology was designed at RAL for LGAD read out:
  - The ASICs have been successfully fabricated and tests are underway at RAL,
  - Target rms-jitter of <20 ps, ToA and ToT measurements,
- Test board has also been designed and is also ready for LGAD test.

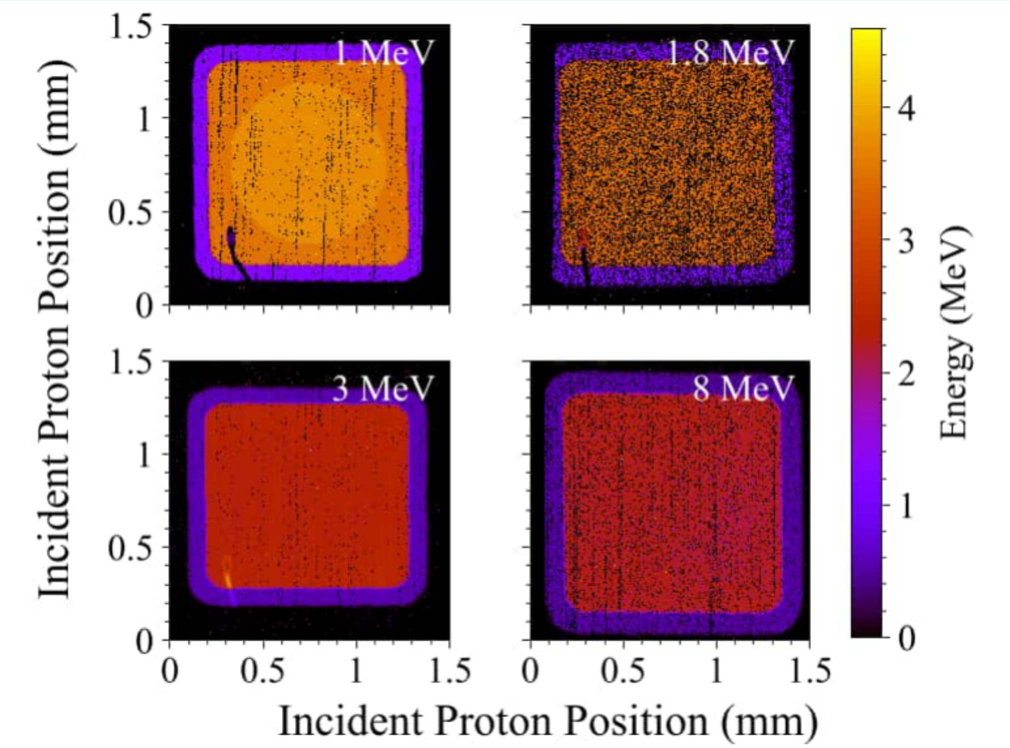


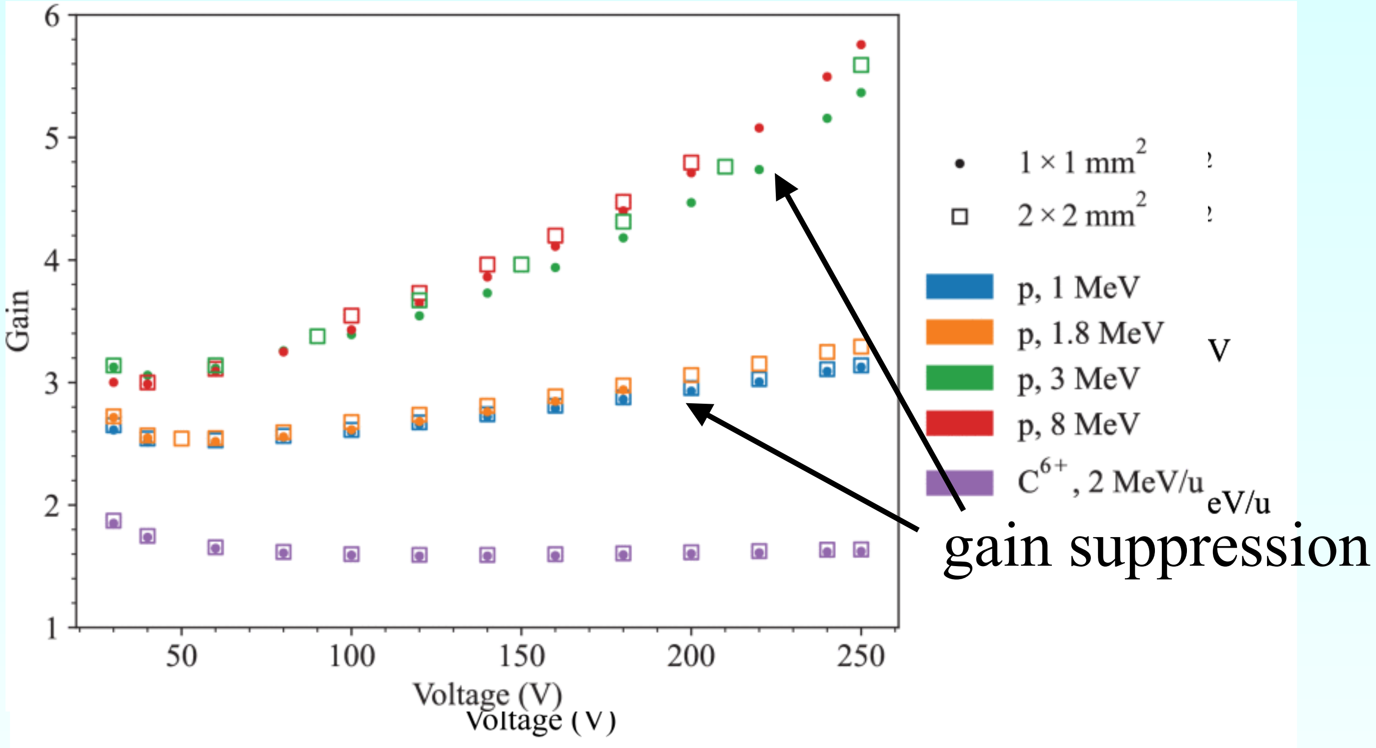


LGAD for Low-LET dosimetry

University of Sheffield

- The intrinsic gain of LGAD devices is a possible solution to improve the signal to noise ratio for low LET dosimetry application:
  - microdosimetry in proton therapy, heavy ion therapy, and space radiation.
- LGAD gain obtained using ion beam induced charge (IBIC) of proton and carbon at Australian Nuclear Science and Technology Organization (ANSTO):





Measured median energy deposition maps for protons of varying energies on the Type 4 LGAD from WF2 and the gain as a function of bias voltage.

J. W. Archer et al., "A Two-Dimensional Characterization of Low-Gain Avalanche Diodes for Low-LET Microdosimetry," in IEEE Transactions on Nuclear Science, vol. 71, no. 3, pp. 342-351, March 2024

TI-LGAD from Micro

- New batch of Trench-Isolated LGAD has been fabricated at Micron Semiconductor Limited,
- Test using TCT setup at RAL is underway,
- More detailed and the initial test results can been found in Fasih's talk at the 1st DRD3 Week.

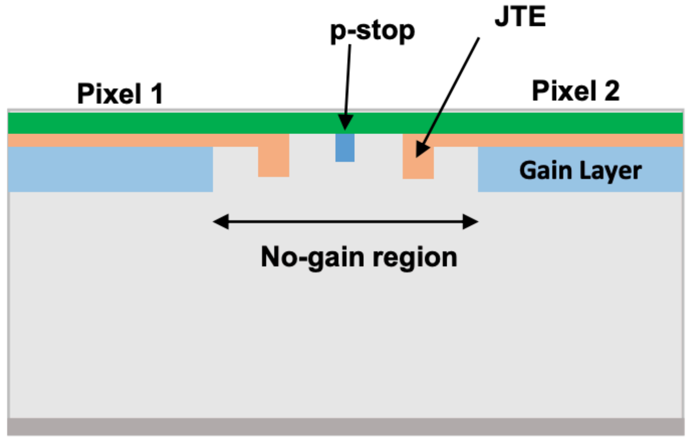


Fig 1(a): Standard LGAD

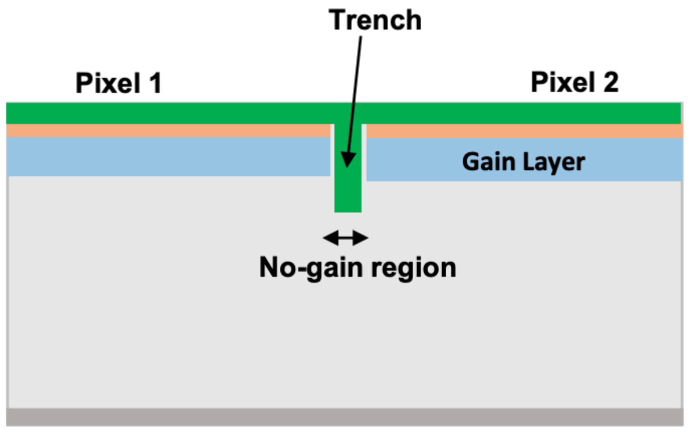
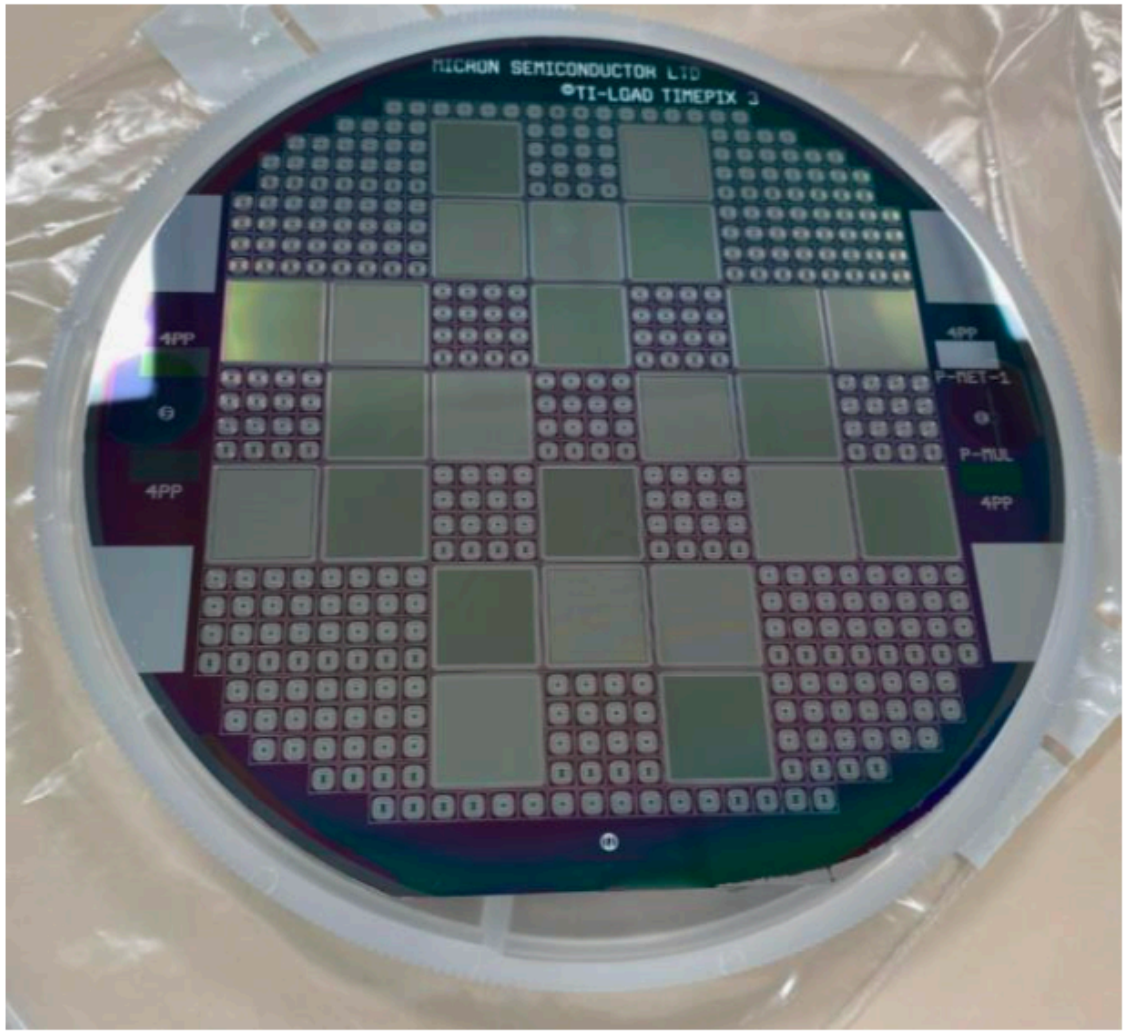


Fig 1(b): Trench-isolated LGAD



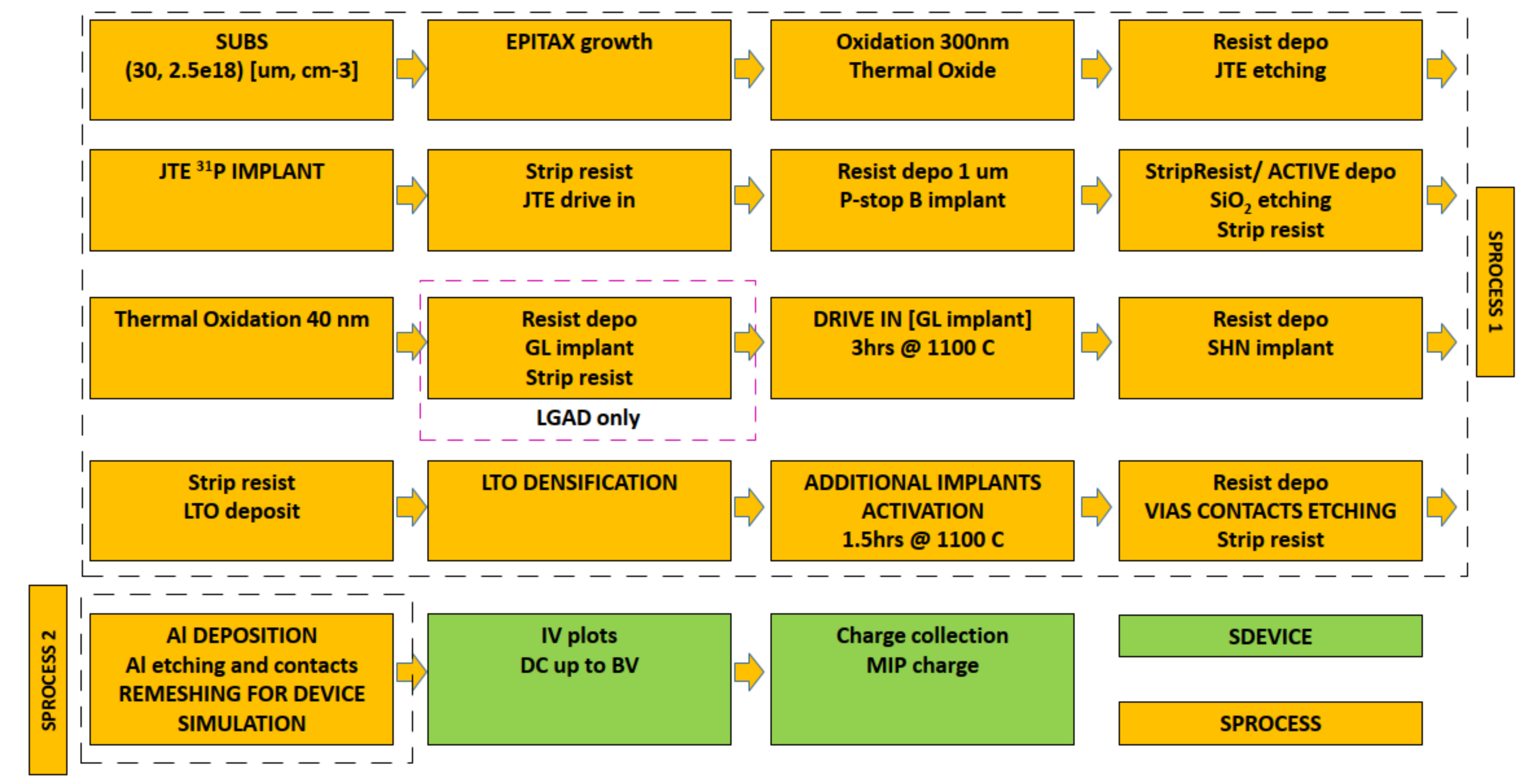
Summary and Future Plans

- Two batches of LGAD have been fabricated at Teledyne e2v,
- LGAD Devices have been measured before and after neutron/ proton irradiation:
  - damage constant and the acceptor remove coefficient have been extracted,
  - gain and time resolution have been measured using either a TCT or beta source setup.
- LGAD application in Low-LET dosimetry has been investigated,
- New 28 nm R/O ASIC has been fabricated and will be used to perform multi channel R/O of Teledyne e2v LGAD,
- Tests on TI-LGAD from Micron Semiconductor is underway,
- Deep gain layer LGAD with deep trench isolation is under investigation.

Thanks

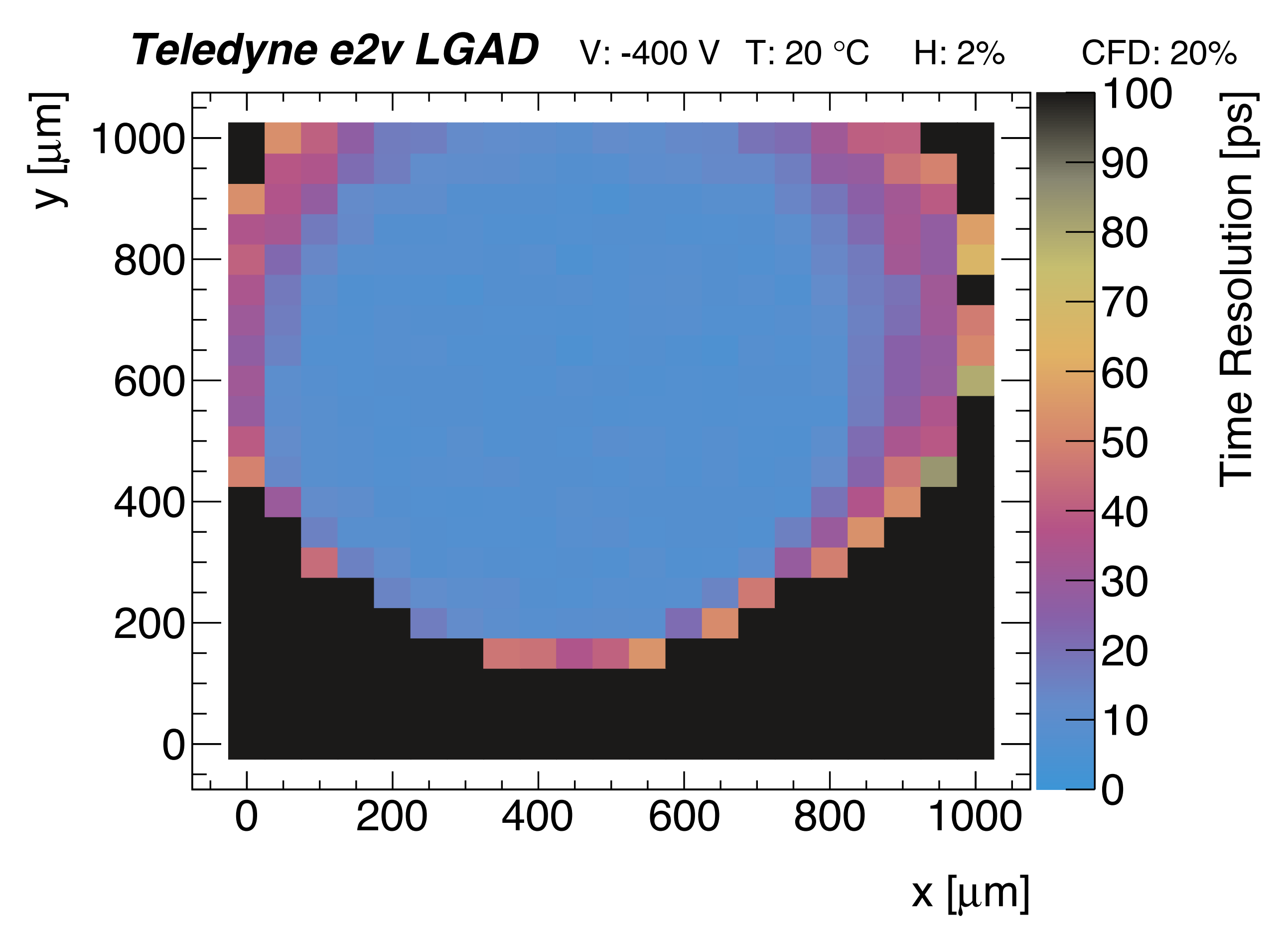
Backup

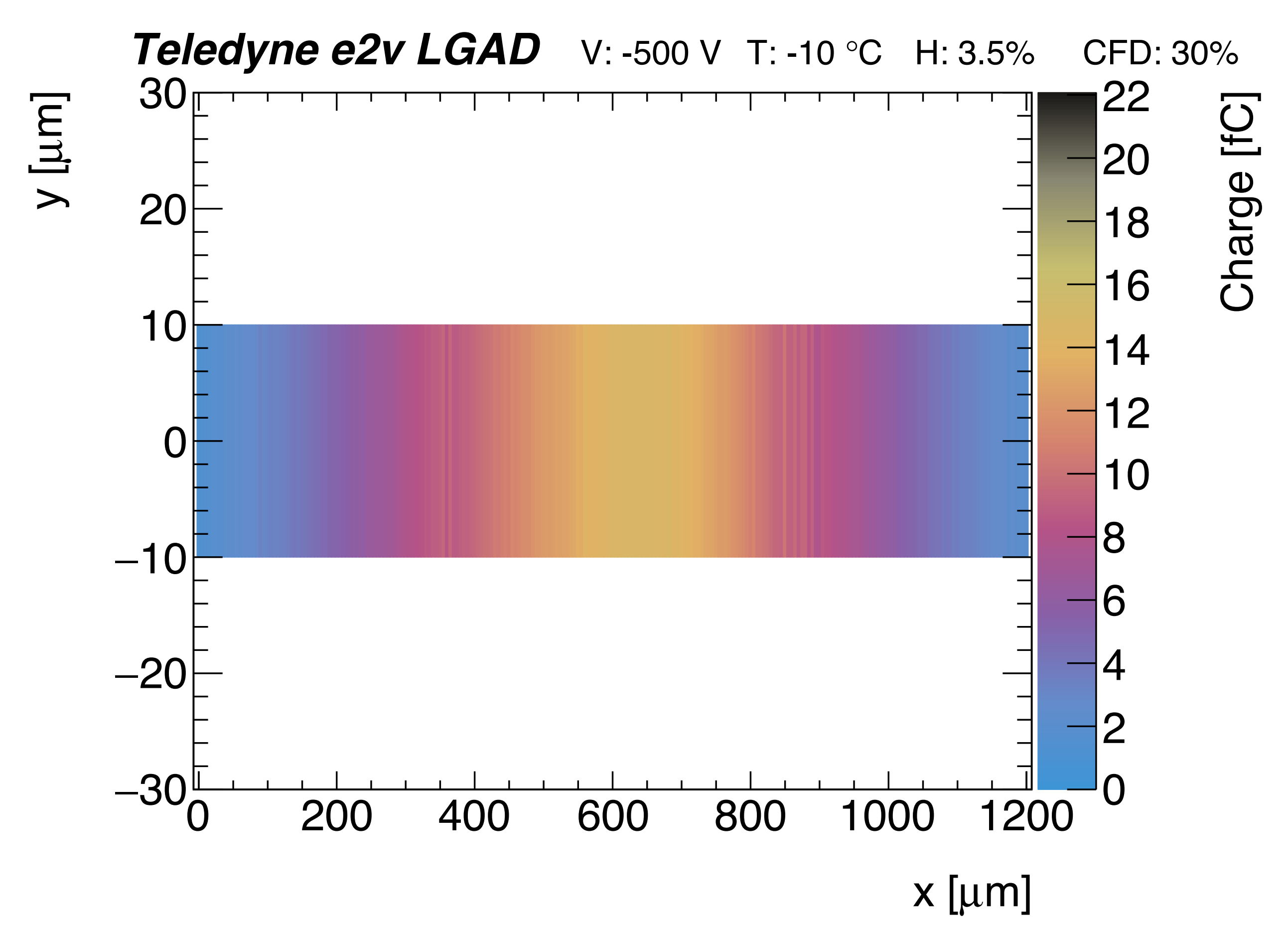
LGAD Simulation



2D/1D Scan of the TCT

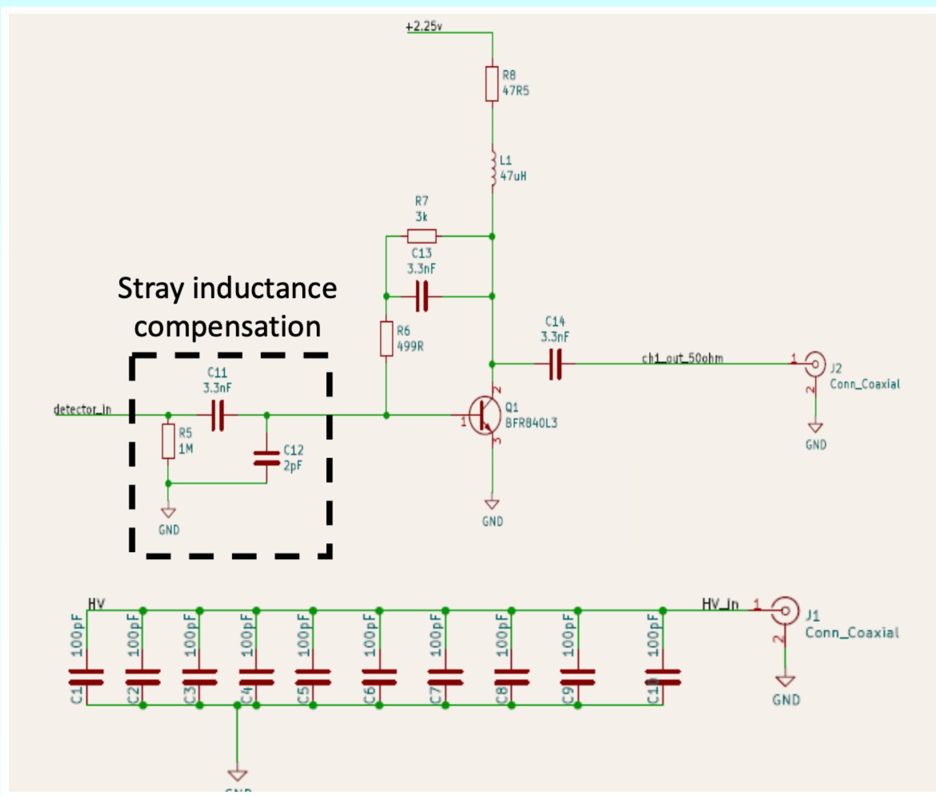
- 1D/2D scan can be performed using the current TCT setup:

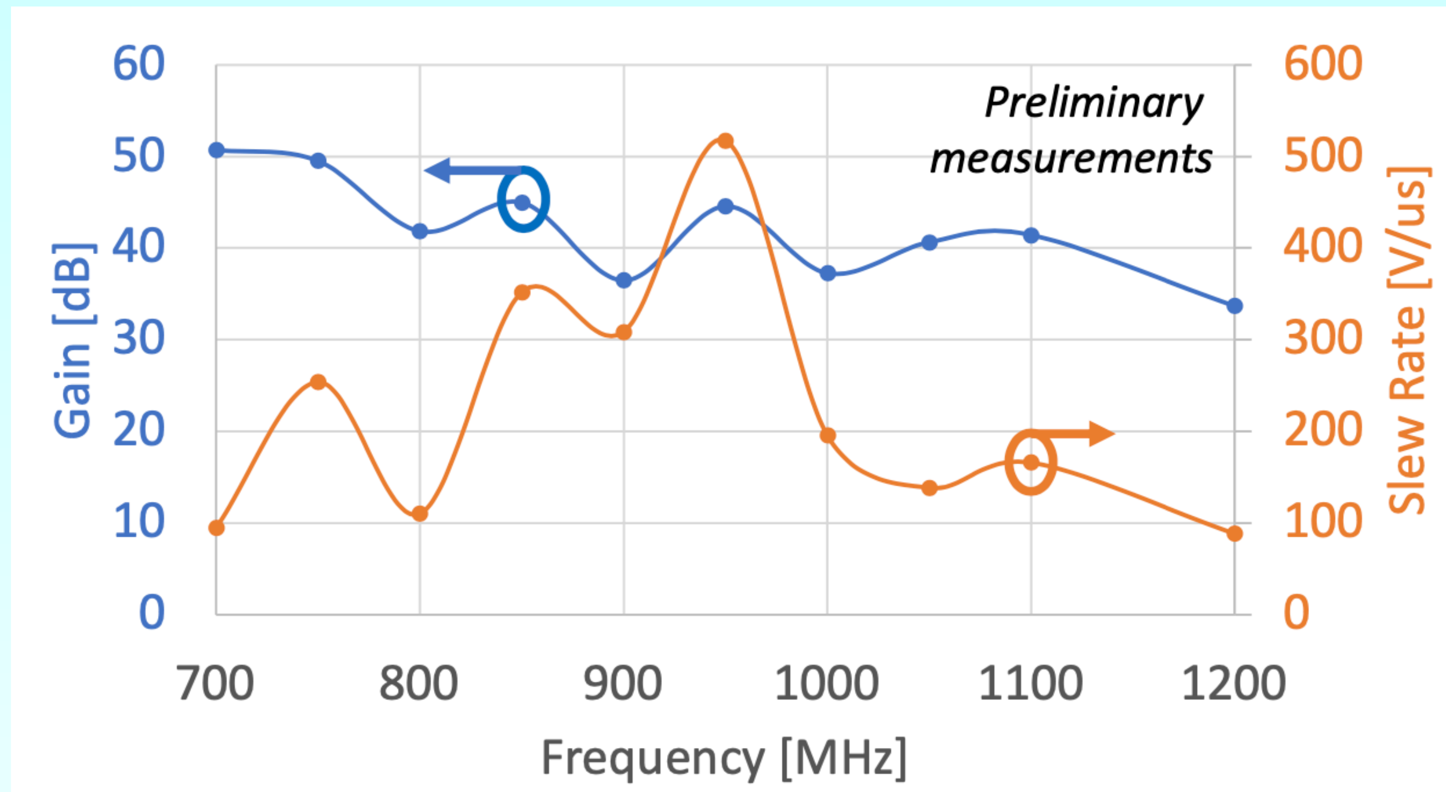




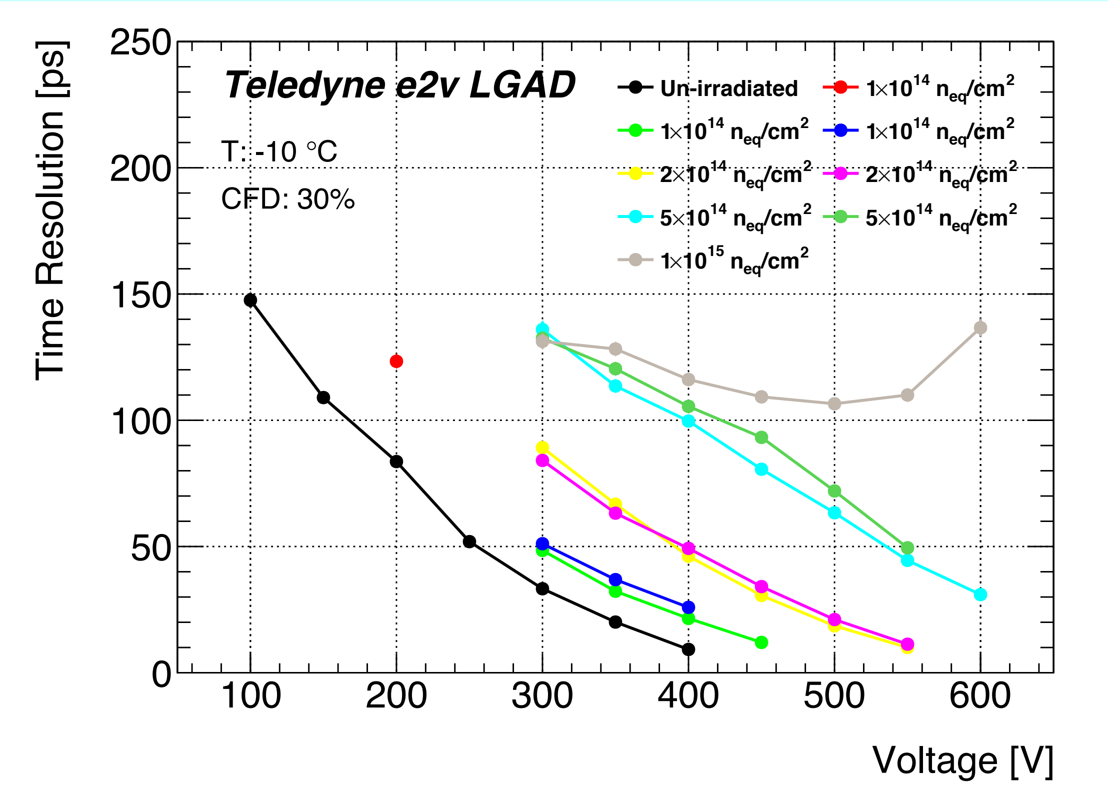
Compact OPMD LGAD Amplifier (COLA)

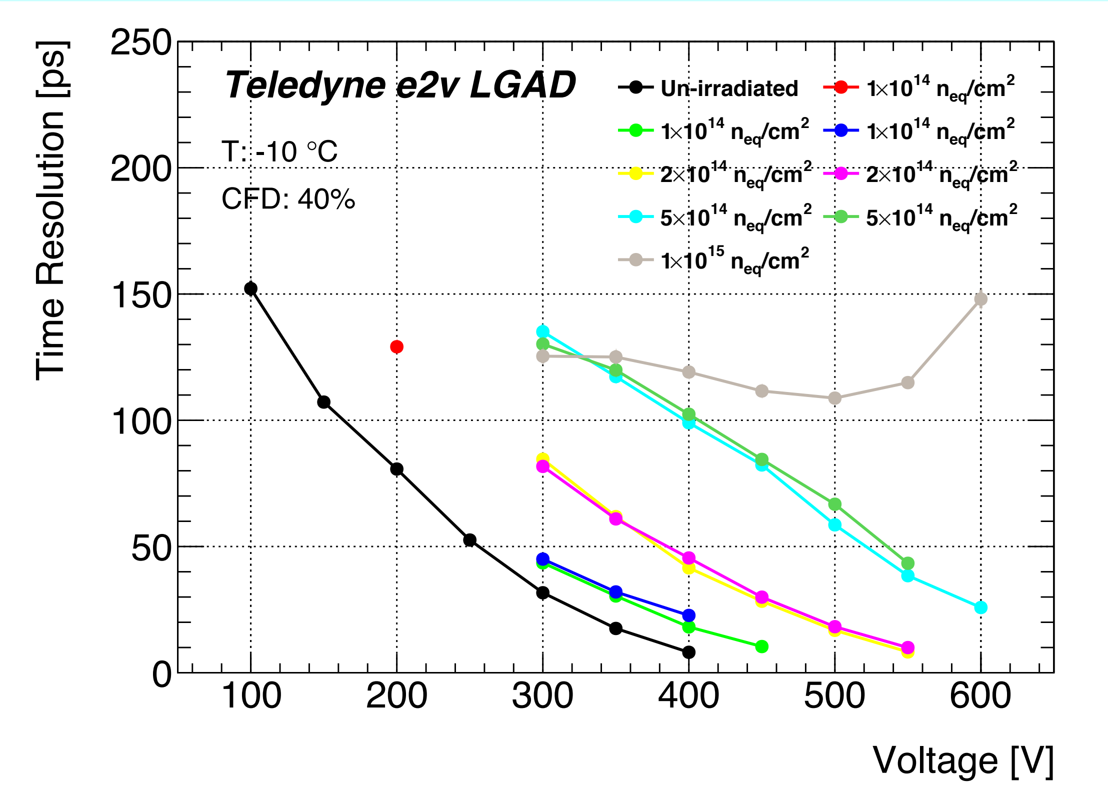
- A Trans-Impedance Amplifier (TIA) board designed by OPMD of the University of Oxford:

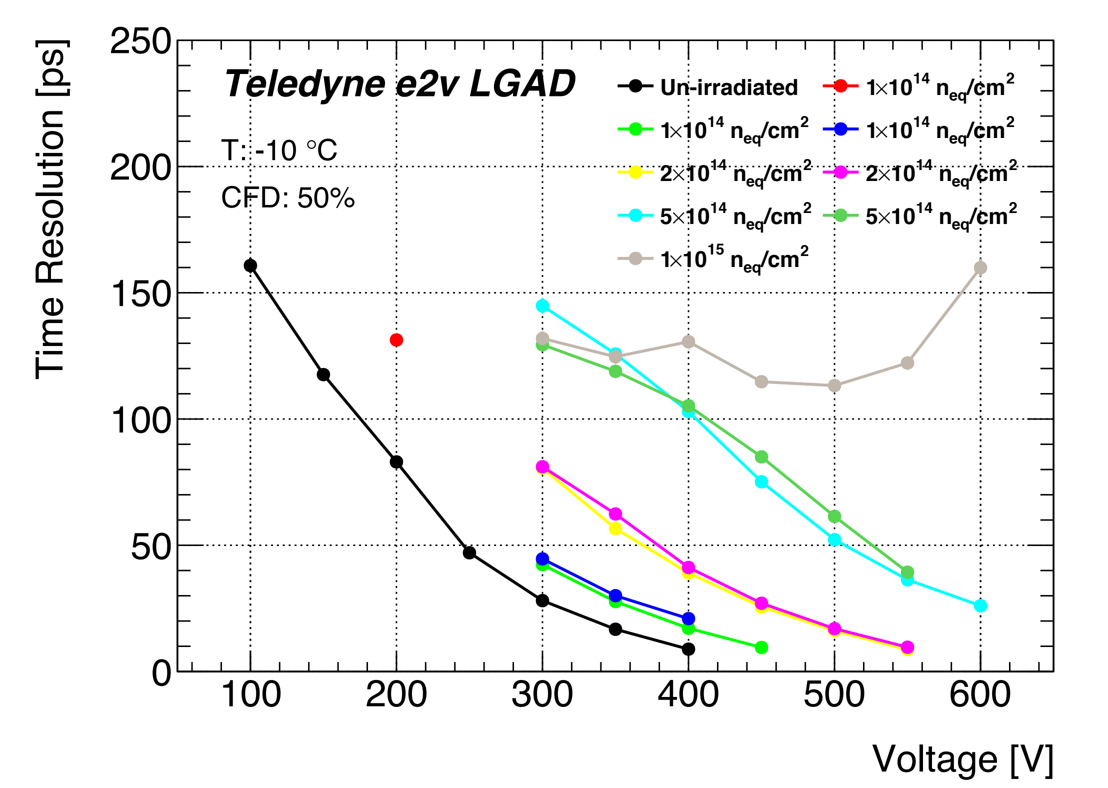


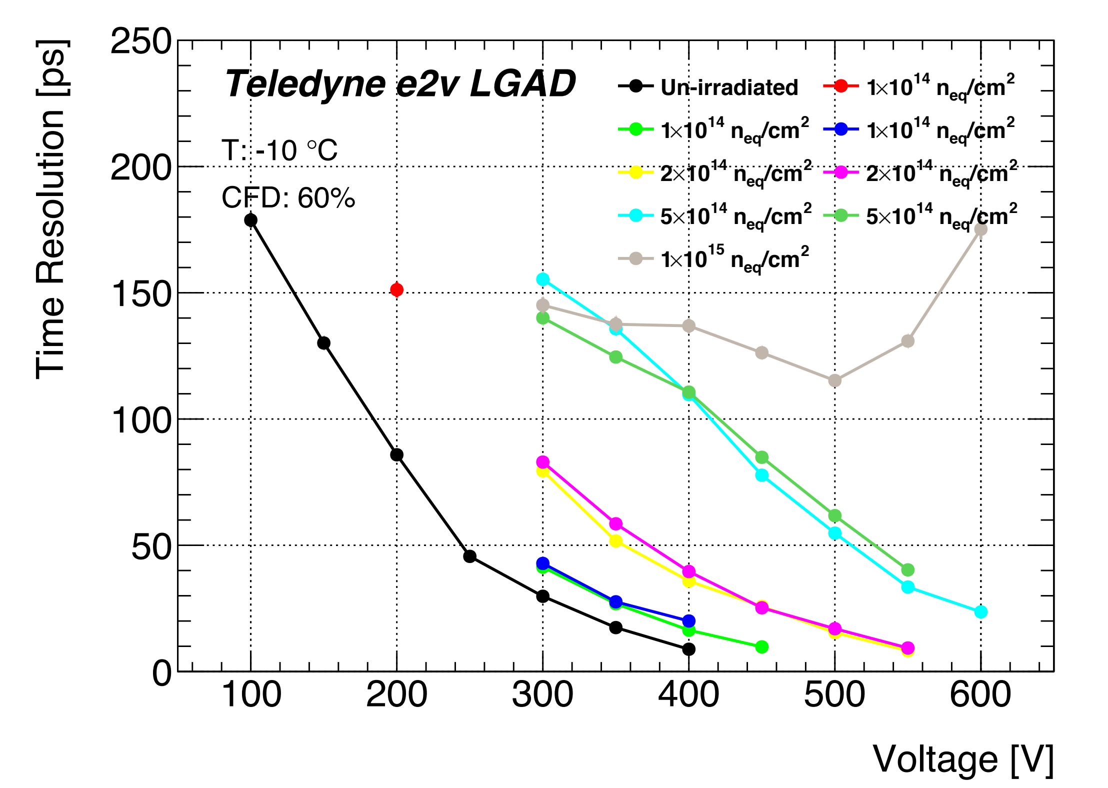


Time Resolution after neutron irradiation



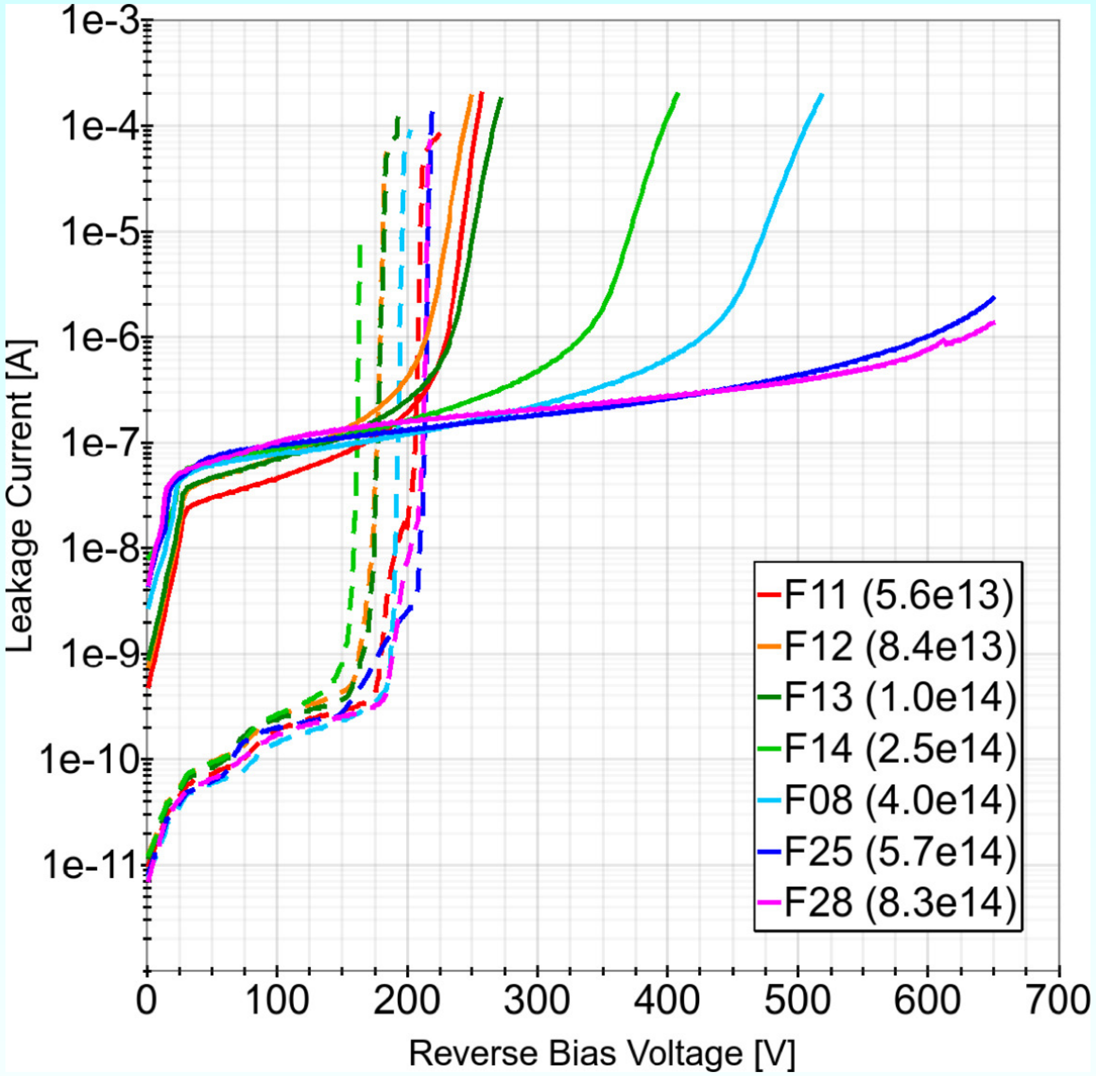






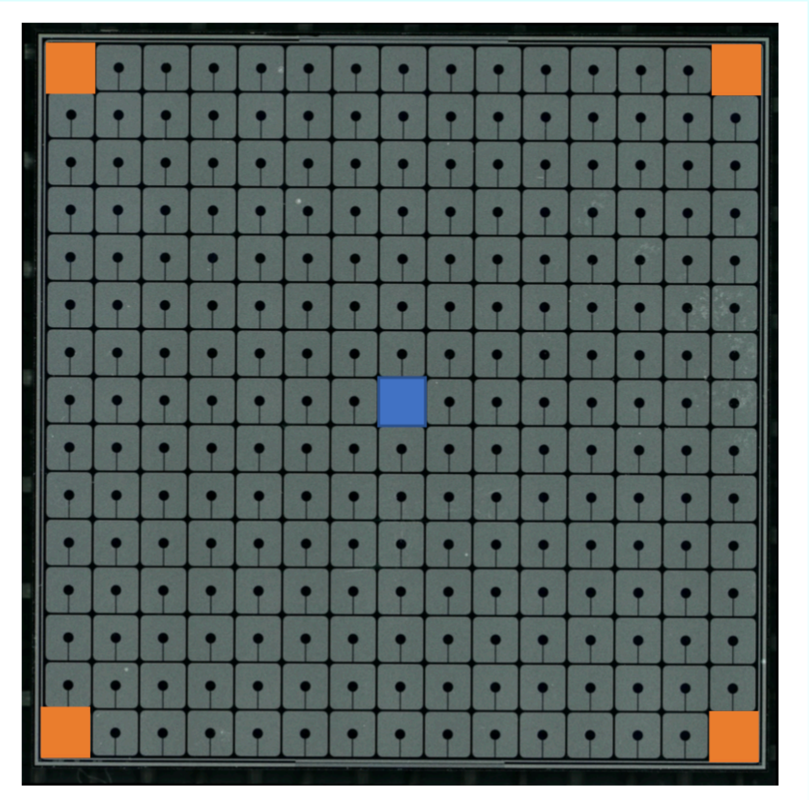
Leakage Current of the LGAD

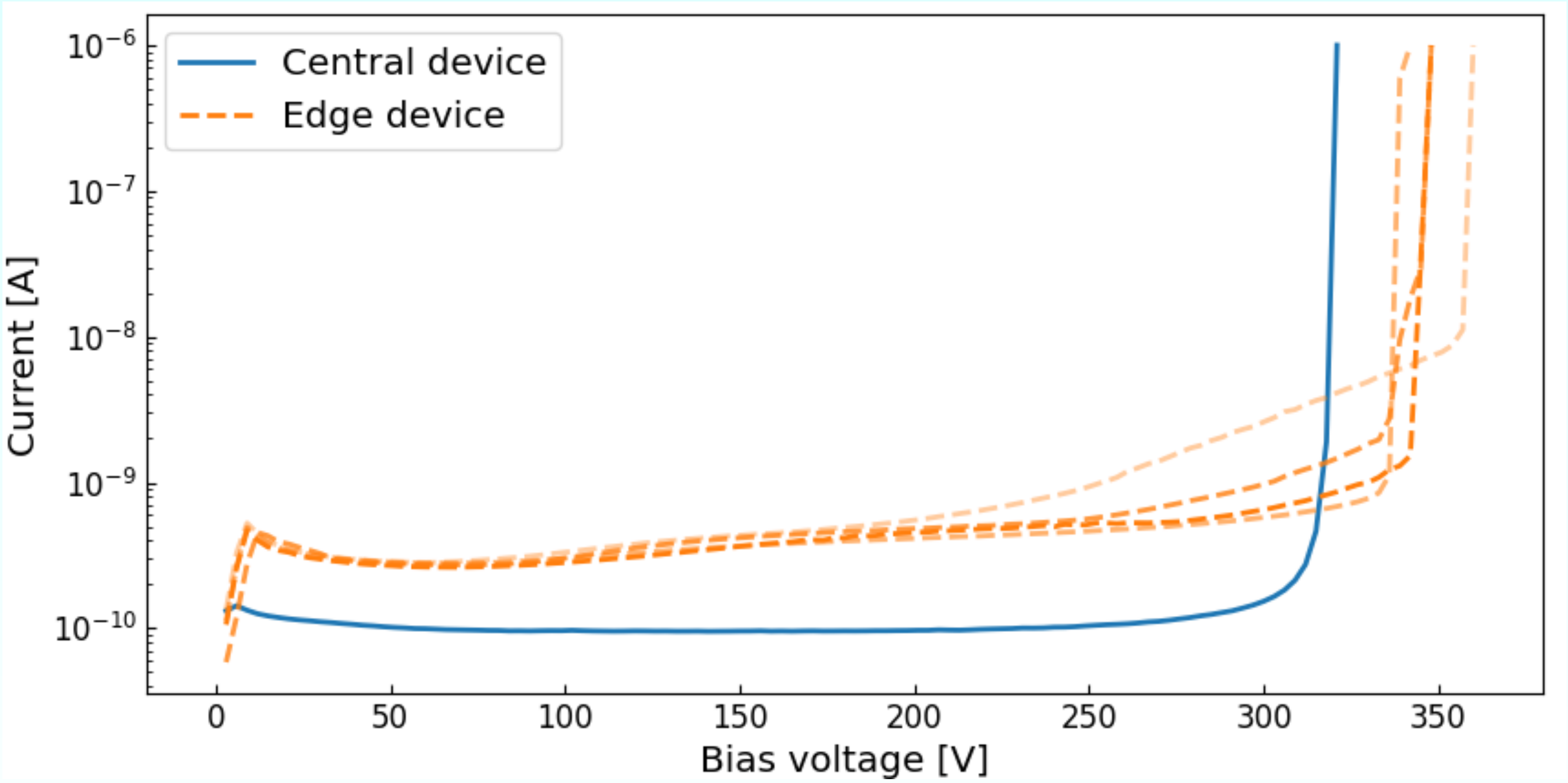
- 1 mm LGAD device from Wafer 2, measured at -20 °C,
- Proton irradiation performed at MC40 cyclotron with 27 MeV protons in Birmingham.



Second batch of LGAD from Teledyne

- Wider range of layouts and arrangements
  - Single devices 1×1 mm^2 (variation of design parameters)
  - 2×2 arrays of 1×1 mm^2 devices
  - 3×3 arrays of 1x1 mm^2 devices
  - 15×15 array of 1.3×1.3 mm^2 LGAD





Teledyne e2v LGAD: IV

- Different areas on the wafer to investigate uniformity of characteristics.