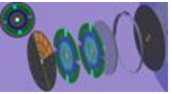

Performance of HGTD QC-TS after proton irradiations

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JOŽEF STEFAN INSTITUTE, LJUBLJANA, SLOVENIA

HGTD Week in Morocco, 18-23 May 2026

Charged-hadron damage in HGTD

- Radiation-damage studies have been so far mainly focused on reactor neutrons
- In HGTD, a significant fraction of the damage is also expected to arise from charged hadrons, in particular pions with energies of a few GeV
- Dedicated proton irradiations at different energies therefore provide useful benchmarks for charged-hadron damage relevant to HGTD operation
- This motivates the present **24 MeV** and **60 MeV** proton-irradiation studies of LGAD acceptor removal and timing performance

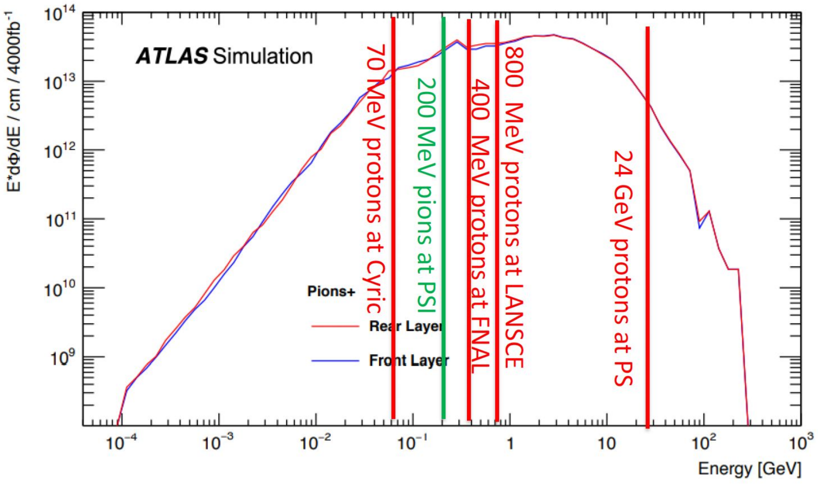
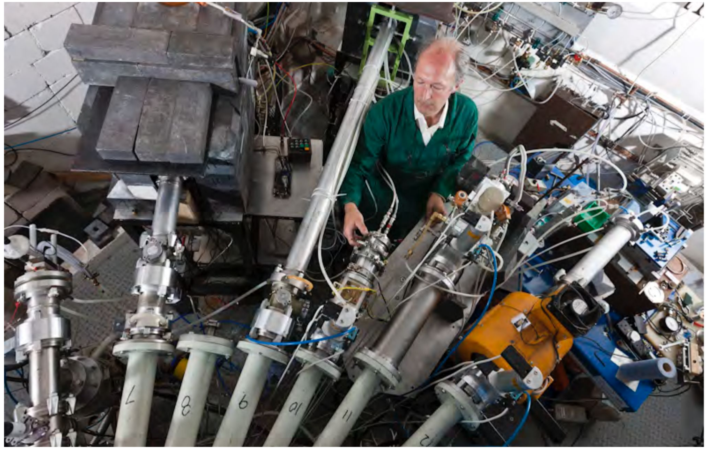


Figure A.3: Pion spectra averaged over the rear (outermost) and front (innermost) silicon layer of the HGTD. The uncertainties are of the order of 5%

ATLAS HGTD

Proton irradiation campaign (University of Birmingham cyclotron)

- Irradiations performed at the **UoB MC40 cyclotron facility**
- **primarily used for the production of radioisotopes for medical applications**
- Low-energy proton irradiations at ~24 MeV (https://arxiv.org/pdf/2408.12410)
- Dosimetry calibration based on Nickel foil activation
- Proton beam current: 200nA
- A collimated square beam spot of 10 mm × 10 mm
- Study motivated by proton-induced acceptor removal
- Target fluences:
  - 5×10^{13}, 1×10^{14}, 2×10^{14}, 4×10^{14}, 8×10^{14} p/cm^2
- Achieved fluences:
  - 5.4×10^{13}, 1×10^{14}, 1.8×10^{14}, 3.9×10^{14}, 7×10^{14} p/cm^2
  - Fluence uncertainty: ~10%
- Uniform beam scanning used for homogeneous irradiation
- Irradiation campaign completed successfully



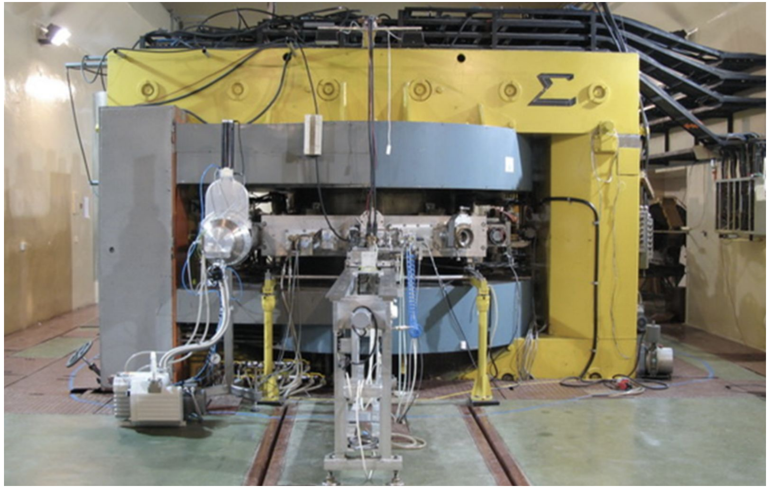
Proton energy	Hardness factor k
10.5 MeV	3.07 ± 0.37
16.4 MeV	2.73 ± 0.27
24.3 MeV	2.19 ± 0.22

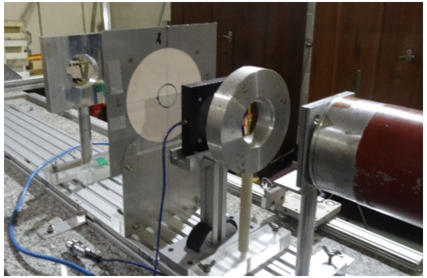
E. Liu et al.
Measurements of proton hardness factors in silicon at energies between 10 MeV and 25 MeV

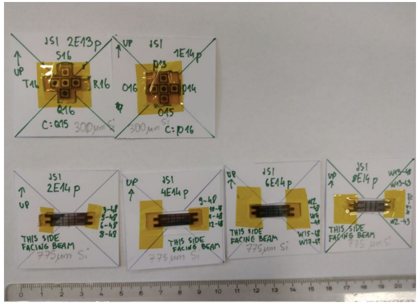
arXiv:2408.12410

→ Post-irradiation characterization results presented here

60 MeV proton irradiation station at the AIC-144 cyclotron facility







- Energy: 60 MeV (10MeV-60MeV)
- Proton beam current: 2nA – 100nA
- Samples were irradiated on the isotope line, 45 degrees against the beam -> hardness factor k = 1.6 ± 0.03
- Spot size: ~ 10mm (1σ, estimated)
- Flatness ≥ 15% (10%)
- The nominal fluences were 5×10^{13}, 2×10^{14}, 4×10^{14}, 8×10^{14}, 1.5×10^{15}, and 8×10^{14} p/cm², while the achieved fluences from the IFJ dosimetry report were 5.93×10^{13}, 2.23×10^{14}, 4.63×10^{14}, 8.82×10^{14}, 1.53×10^{15}, and 8.00×10^{14} p/cm², respectively

→ Post-irradiation characterization results presented here

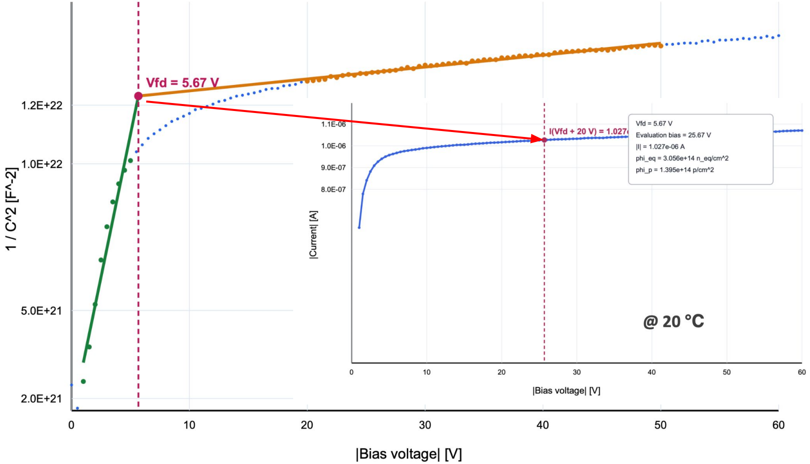
Dosimetry evaluation

- Equivalent fluence in the PIN calculated from the leakage current (NIEL hypothesis)

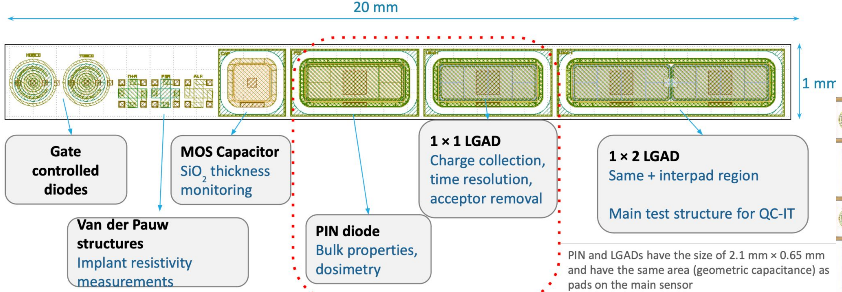
$$\emptyset_{\mathbf{eq}} = \frac{\mathbf{1}}{\underbrace{\boldsymbol{\alpha S d}}_{2.94\text{e-}14\ n_{eq}/\text{cm}^2\ /\mu\text{A}}} \times \boldsymbol{I}\ (\boldsymbol{T} = \mathbf{20°C})$$

$\alpha = 4 \times 10^{-17}\,\text{cm}^{-1}$, $S = 2.1 \times 0.8\ \text{mm}^2$, $d = 50\ \mu\text{m}$

I is the current at $V_{fd} + 20$ V

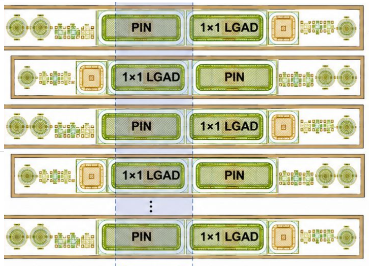


Quality Control Test Structure (QC-TS)



PIN and LGADs have the size of 2.1 mm × 0.65 mm and have the same area (geometric capacitance) as pads on the main sensor

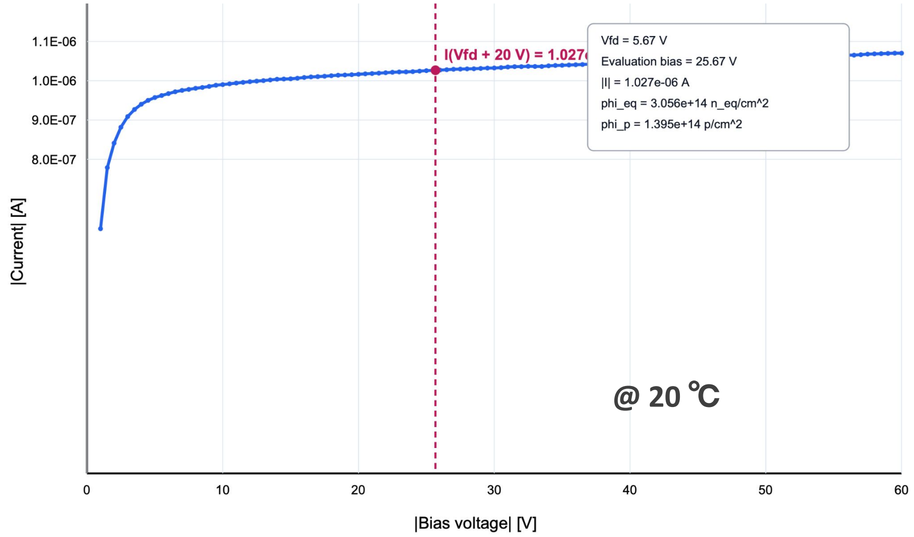
Quality Control Test Structures (QC-TS) main devices in radiation hardness testing

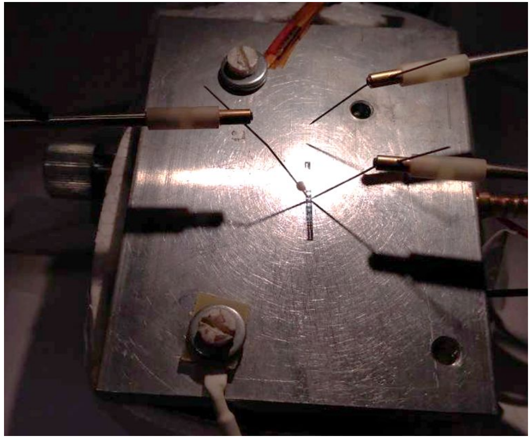


All samples were annealed for 80 min at 60 °C, and the fluence values shown here are based on each sample's own PIN dosimetry

ATLAS HGTD

24 MeV irradiation PIN dosimetry evaluation





Uncertainty calculation:

- UoB reported fluence uncertainty: ~10%
- k = 2.19 ± 0.22
- fit-window systematic on PIN-measured fluence: ~0.2–0.3%
- leakage current also evaluated at -20 °C

- Capacitance-Voltage measurements were performed in Cp-Rp mode with a 0.5 V AC signal at 10 kHz @ 20 °C as well as at 1 kHz @ -19.5 °C, in order to extract Vgl

PIN dosimetry evaluation summary

Reported UoB received fluence vs measured PIN-based fluence, shown in 10^14 n_eq/cm^2

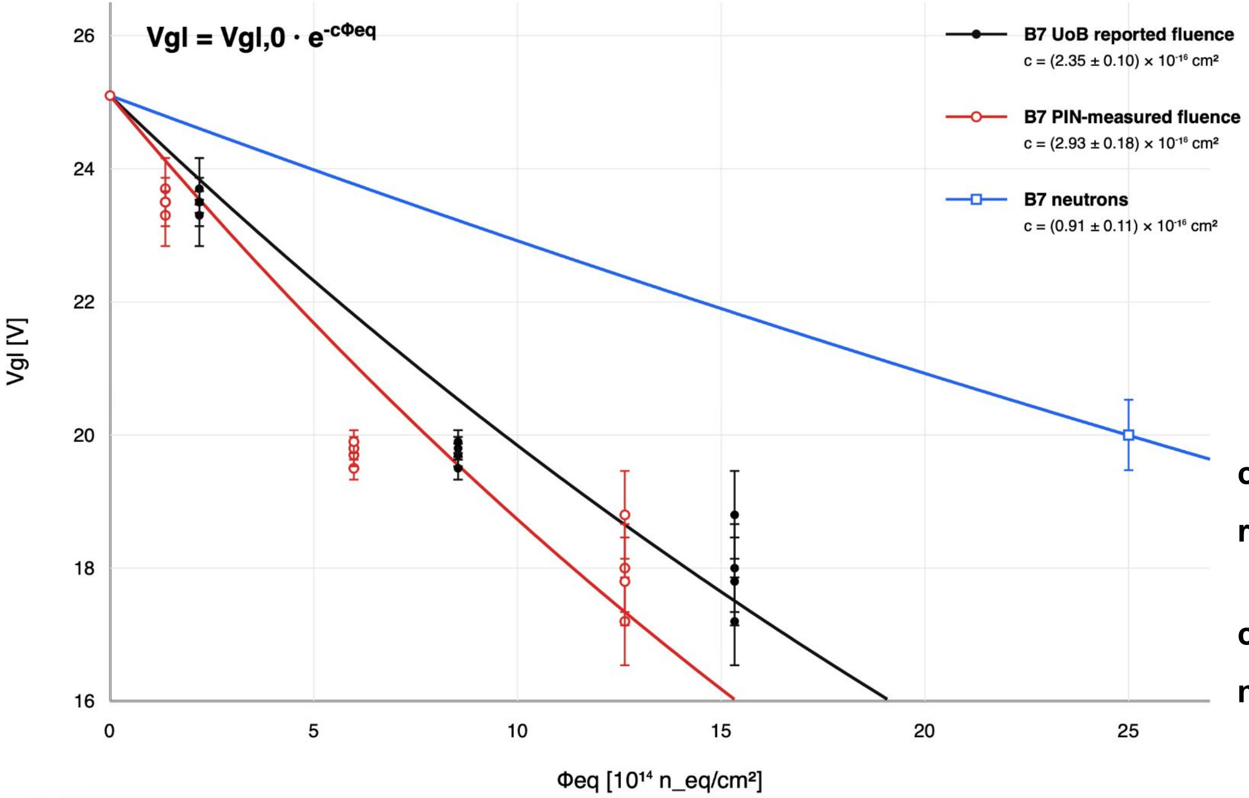
Workflow: Vfd from PIN C-V (1/C^2), then I_PIN taken at Vfd + 20 V

Sample	Reported	Measured	Ratio	Comparison
B6 5e13 2-10	1.2	0.6	0.53	
B6 5e13 4-10	1.2	0.6	0.51	
B6 2e14 5-10	3.9	3.1	0.77	
B6 2e14 5-48	3.9	3.0	0.77	
B6 2e14 6-48	3.9	2.8	0.71	
B6 2e14 8-48	3.9	3.0	0.75	
B7 1e14 1-48	2.2	1.4	0.64	
B7 1e14 2-48	2.2	1.4	0.63	
B7 1e14 3-10	2.2	1.4	0.62	
B7 1e14 5-48	2.2	1.3	0.59	
B7 4e14 3-48	8.5	6.1	0.71	
B7 4e14 4-10	8.5	6.1	0.71	
B7 4e14 5-10	8.5	5.8	0.68	
B7 8e14 5-48	15.3	10.8	0.71	
B7 8e14 6-10_before annelling	15.3	15.7	1.02	
B7 8e14 7-10	15.3	11.4	0.75	

UoB reported fluence uncertainty: ~10%

On average, the PIN-based measured fluence is 0.67 ± 0.08 times the reported fluence, about 33% lower

Acceptor removal studies @ 24 MeV



Note that only Batch 7 is shown in the main acceptor-removal comparison to avoid mixing batch-to-batch variations and to retain the most complete and internally consistent fluence dependence.

c_p / c_n

reported: 2.58 ± 0.32

PIN: 3.22 ± 0.42

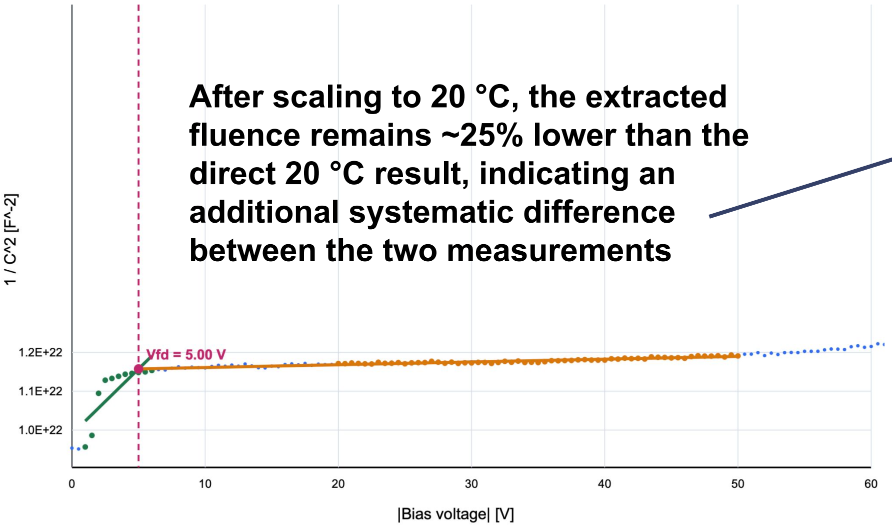
Common reference: Vgl,0 = 25.1 V

c_p = (2.35 ± 0.10) × 10^{-16} cm² with reported fluence by UoB

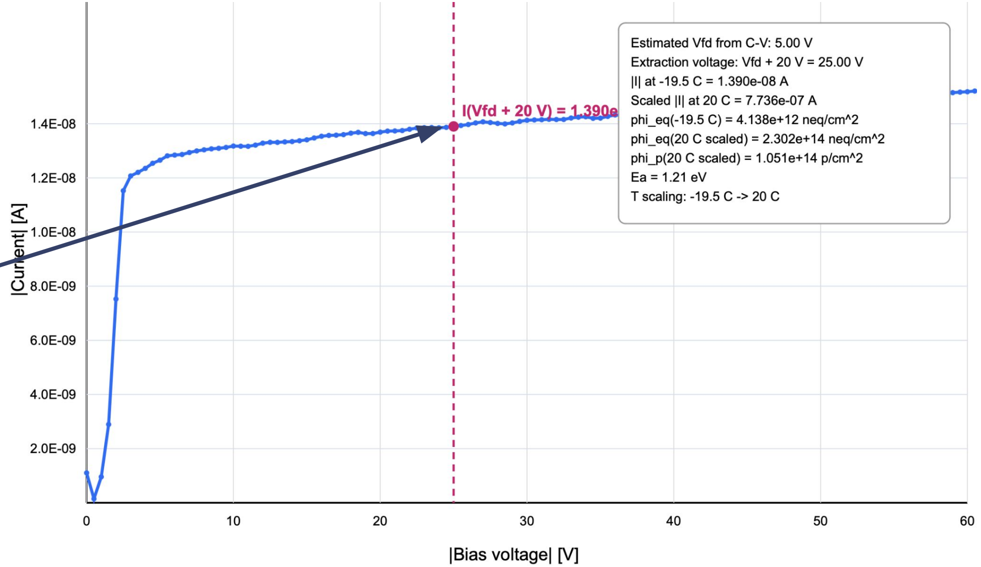
c_p = (2.93 ± 0.18) × 10^{-16} cm² from PIN measurements

24 MeV irradiation PIN dosimetry evaluation @ - 19.5 ℃

QC-TS: Batch 6 Wafer 5, 3.9 x 10^{14} n_{eq}/cm^2



After scaling to 20 °C, the extracted fluence remains ~25% lower than the direct 20 °C result, indicating an additional systematic difference between the two measurements



$$I(T_R) = I(T) \cdot \left(\frac{T_R}{T}\right)^2 \cdot e^{-\frac{E_a}{2k_B}\left(\frac{1}{T_R} - \frac{1}{T}\right)}$$

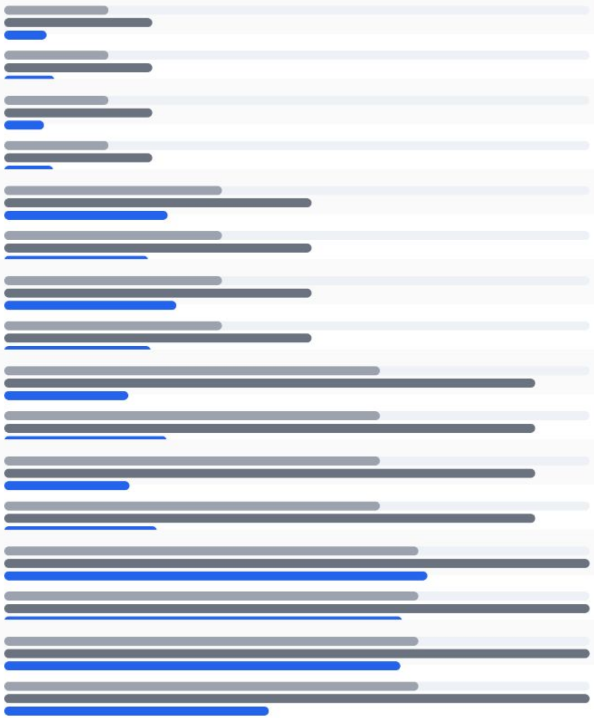
The leakage current measured at -19.5 °C was scaled to 20 °C using the standard silicon temperature-scaling relation with E_a = 1.21 eV. The equivalent fluence was then calculated using α_{eq} = (3.99 ± 0.03) × 10^{-17} A cm^{-1}, quoted for currents referenced to 20 °C.

https://arxiv.org/pdf/2408.12410

PIN dosimetry evaluation summary

IFJ achieved 45° and 90° facility fluence vs measured PIN-based fluence, shown in 10^14 n_eq/cm²

Sample	Group	IFJ 45°	IFJ 90°	PIN measured	45° ratio	90° ratio	Comparison
W3-48	2E14	2.5	3.6	1.0	0.41	0.29	
W5-48	2E14	2.5	3.6	1.2	0.48	0.34	
W6-48	2E14	2.5	3.6	1.0	0.38	0.27	
W8-48	2E14	2.5	3.6	1.2	0.47	0.33	
W9-48	4E14	5.2	7.4	3.9	0.75	0.53	
W10-48	4E14	5.2	7.4	3.5	0.66	0.47	
W11-48	4E14	5.2	7.4	4.2	0.79	0.56	
W12-48	4E14	5.2	7.4	3.5	0.67	0.48	
W2-48	6E14	9.1	12.8	3.0	0.33	0.23	
W4-48	6E14	9.1	12.8	3.9	0.43	0.31	
W15-48	6E14	9.1	12.8	3.0	0.33	0.24	
W17-48	6E14	9.1	12.8	3.7	0.41	0.29	
W13-48	8E14	10.0	14.1	10.2	1.02	0.72	
W13-43	8E14	10.0	14.1	9.6	0.96	0.68	
W9-10	8E14	10.0	14.1	9.6	0.96	0.68	
W2-43	8E14	10.0	14.1	6.4	0.64	0.45	

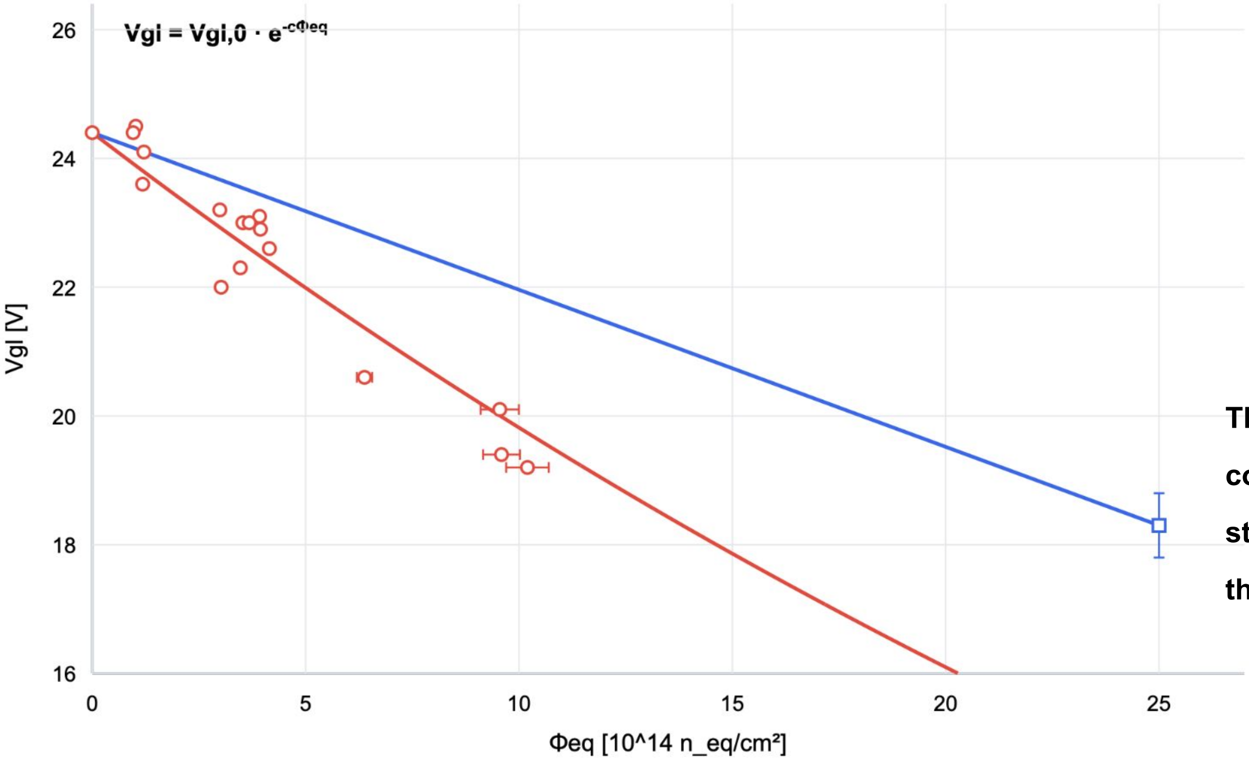


IFJ achieved proton fluences were converted to n_eq/cm² using k = 1.6.

PIN / IFJ 45° = 0.61 ± 0.24; PIN / IFJ 90° = 0.43 ± 0.17

The PIN-based measured fluence is on average about 39% lower than the IFJ 45° reference fluence and about 57% lower than the IFJ 90° reference fluence.

Acceptor removal studies @ 60 MeV



C_p = (2.08 ± 0.65) × 10^{-16} cm²

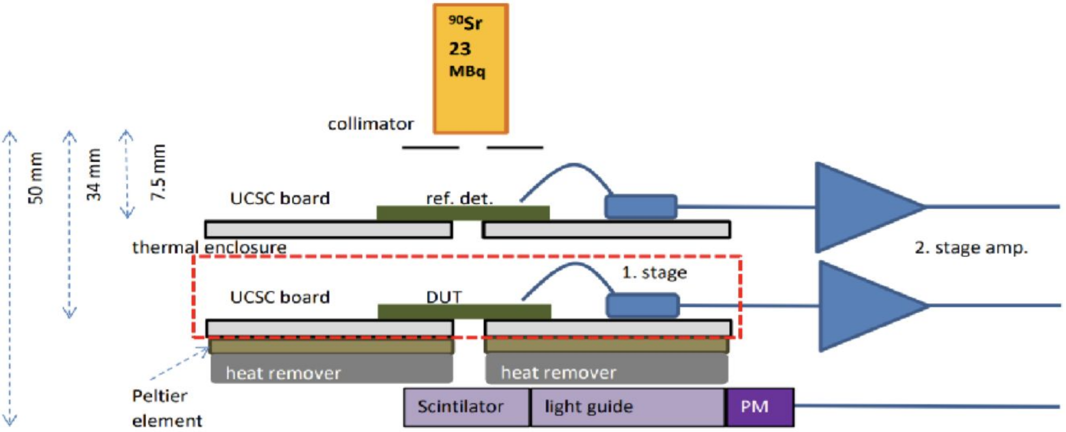
Cn = 1.15 × 10^{-16} cm²

C_p/C_n = 1.81 ± 0.57

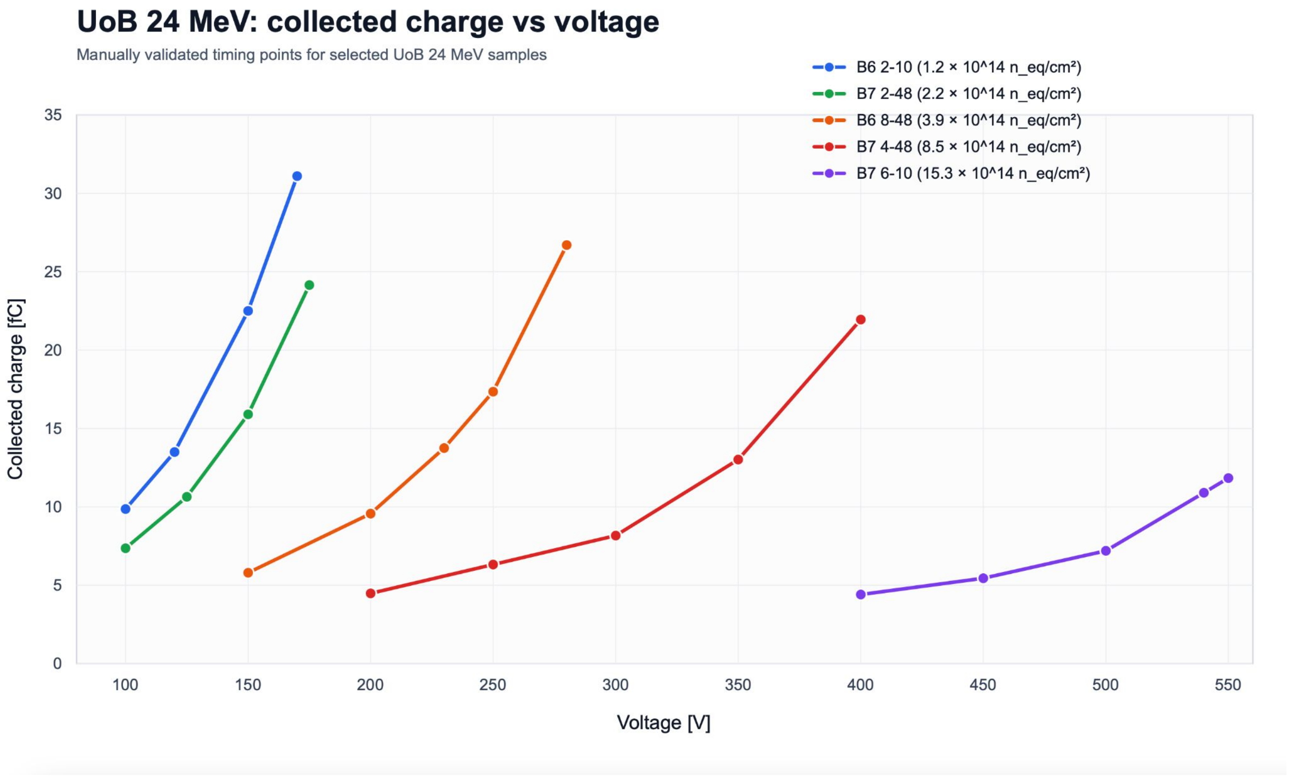
The extracted proton acceptor-removal constant is larger than C_n, indicating stronger acceptor removal for protons than for neutrons.

β-^{90}Sr Timing/Collected charge Irradiation Tests

- TCT not directly measuring **MIP charge** and **time resolution**
  - **Sr90 is a pure β emitter – laboratory MIP source**
    - deposit 10 % more MPV charge than MIPs
    - multiple scattering in material (10 % more charge)
    - bias due to noise in waveforms ~ 1 fC
- Setup with two LGADs (HPK time reference and Device Under Test (DUT))
- DUT cooled to -26°C
- **Coincidence trigger on PMT + reference LGAD** -> DUT doesn't take part in trigger!



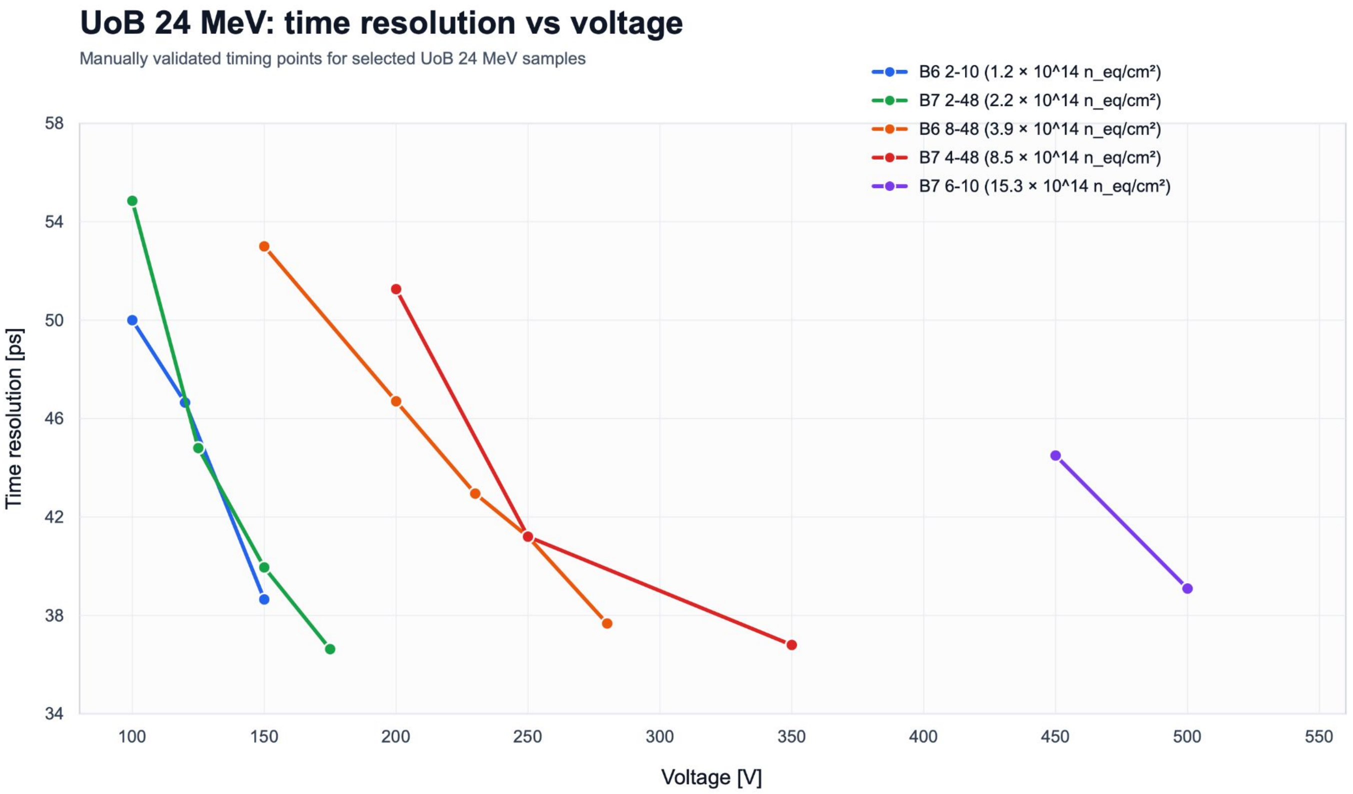
Collected charge after 24 MeV



Collected charge increases with bias for all selected samples, as expected from improved charge collection and stronger gain at higher voltage.

At the highest fluence, measured 10.8 x 10^{14} n_{eq}/cm^2 @ 550 V, collected charge is 11.85 fC

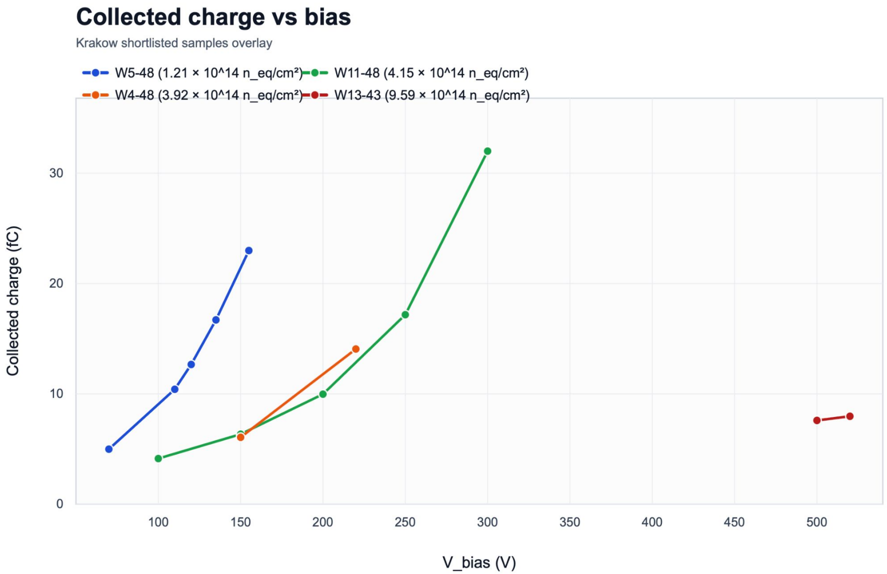
Time resolution after 24 MeV

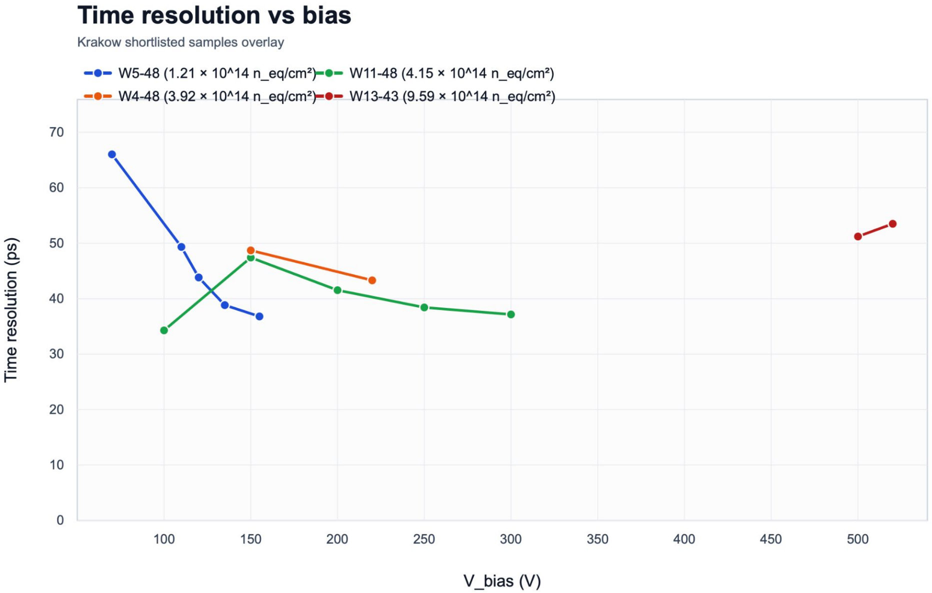


Time resolution generally improves with bias voltage

The slight degradation at the highest voltage is likely related to noise fluctuations.

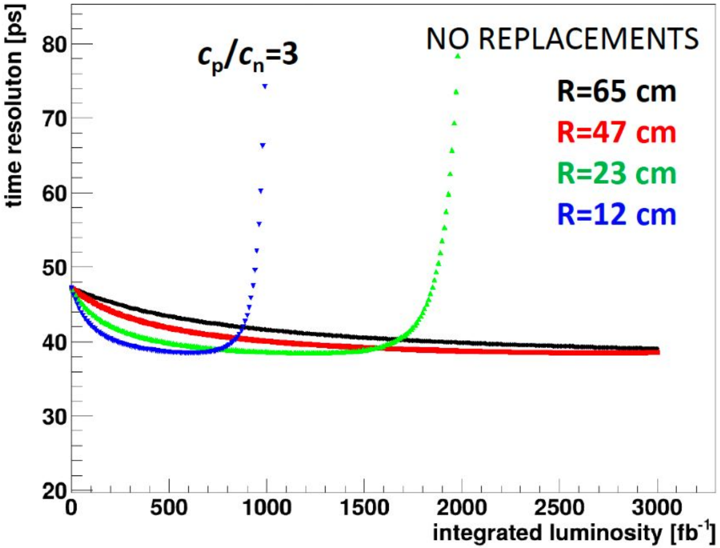
Collected charge and time resolution after 60 MeV

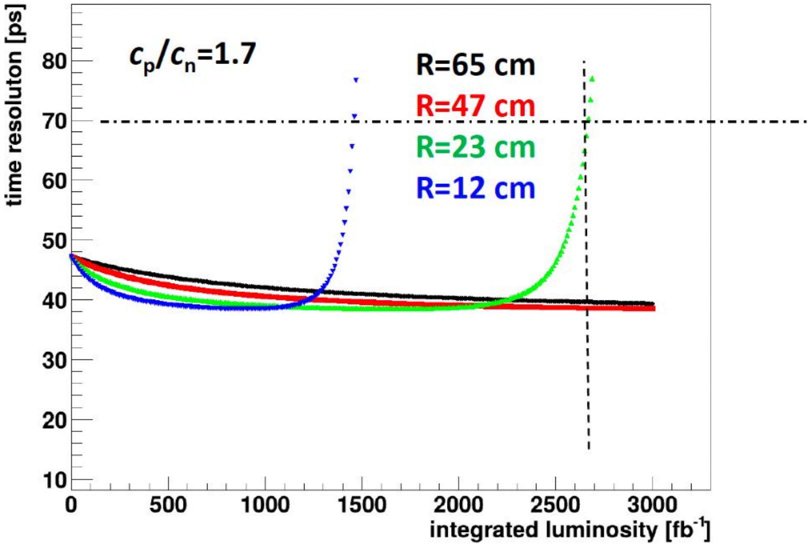




- **Although the full dataset is not yet shown here, the expected trend is already visible: collected charge decreases with increasing fluence, while time resolution improves with increasing bias.**

Estimated HGTD performance over the lifetime (3000 fb^{-1})





- HGTD performance simulation using particle composition at HL-LHC
- Significant dependence on charged hadron damage factor c_p/c_n
- Indication that 3000 fb^{-1} (including safety factor 1.5) can be withstood with 1-2 replacements of the inner part (default plan is two replacements), etc.

Summary

- 24 MeV and 60 MeV proton irradiations were performed for the pilot batch, Batch 6, and Batch 7.
- C-V measurements (Vgl, c) and 90Sr timing measurements were used to extract acceptor removal, collected charge, and time resolution.
- PIN dosimetry: the PIN-based extracted fluence is generally lower than the reference irradiation fluence; for UoB, the average measured/reported ratio is 0.67 ± 0.08, and the PIN-based result should therefore be regarded as conservative.
- Acceptor removal: for UoB, cp = $(2.35 \pm 0.10) \times 10^{-16}$ cm² using reported fluence and cp = $(2.93 \pm 0.18) \times 10^{-16}$ cm² using PIN-based fluence, with cp/cn = 2.58 ± 0.32 and 3.22 ± 0.42, respectively; for the current Krakow 60 MeV analysis, cp = $(2.08 \pm 0.65) \times 10^{-16}$ cm², Cn = 1.15×10^{-16} cm², and cp/Cn = 1.81 ± 0.57.
- Collected charge and time resolution: collected charge increases with bias and decreases with increasing fluence, while time resolution generally improves with increasing bias; the observed timing and charge trends are compatible with the C-V results.

Acknowlegments

I would like to acknowledge the University of Birmingham, in particular Andrew and Amelia, for their help in successfully carrying out the irradiation campaign at the MC40 cyclotron and for their help in clarifying and discussing the fluence-analysis procedure.

I would also like to acknowledge the support provided for the irradiations performed at the 60 MeV proton irradiation station at the AIC-144 cyclotron facility.

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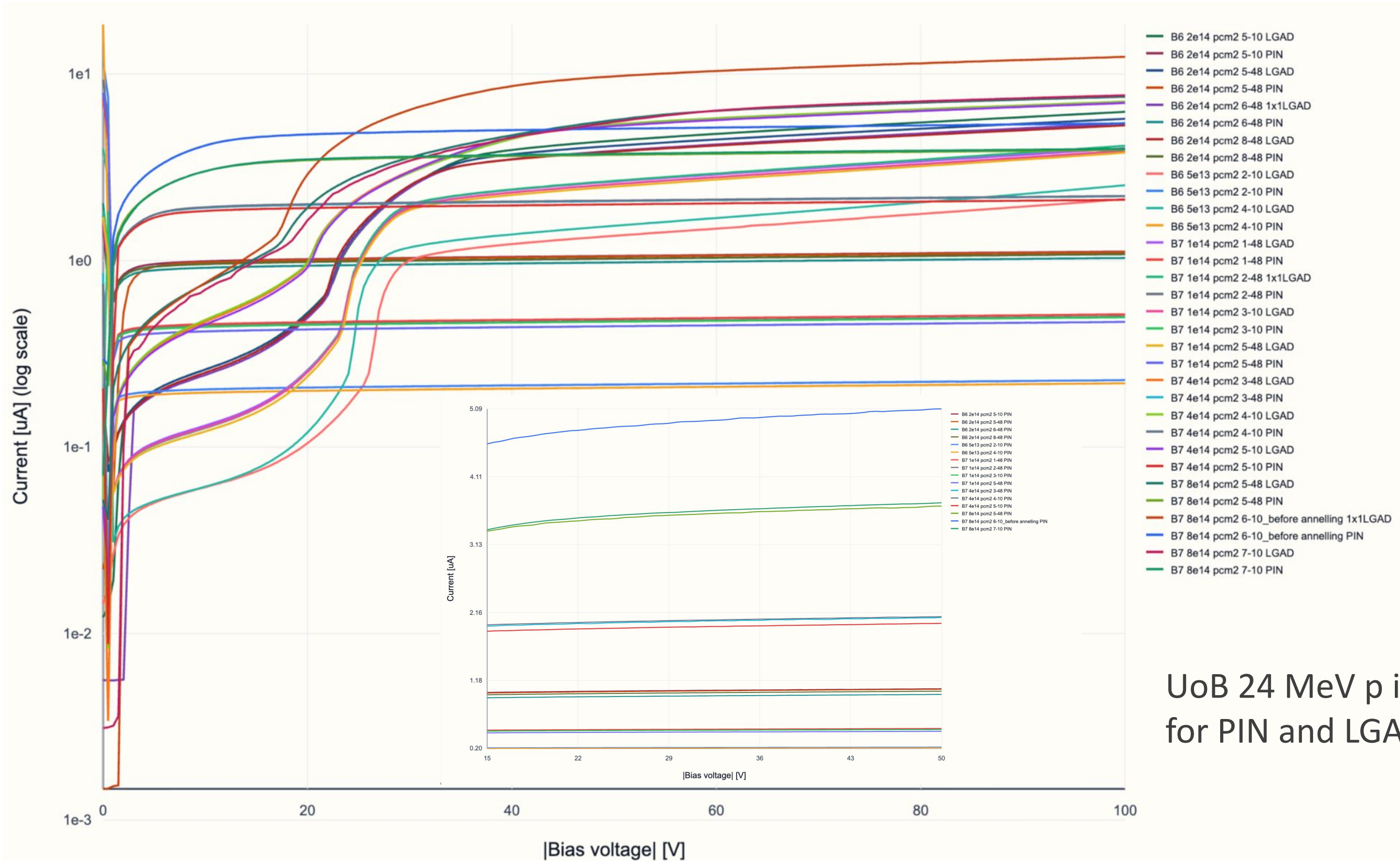
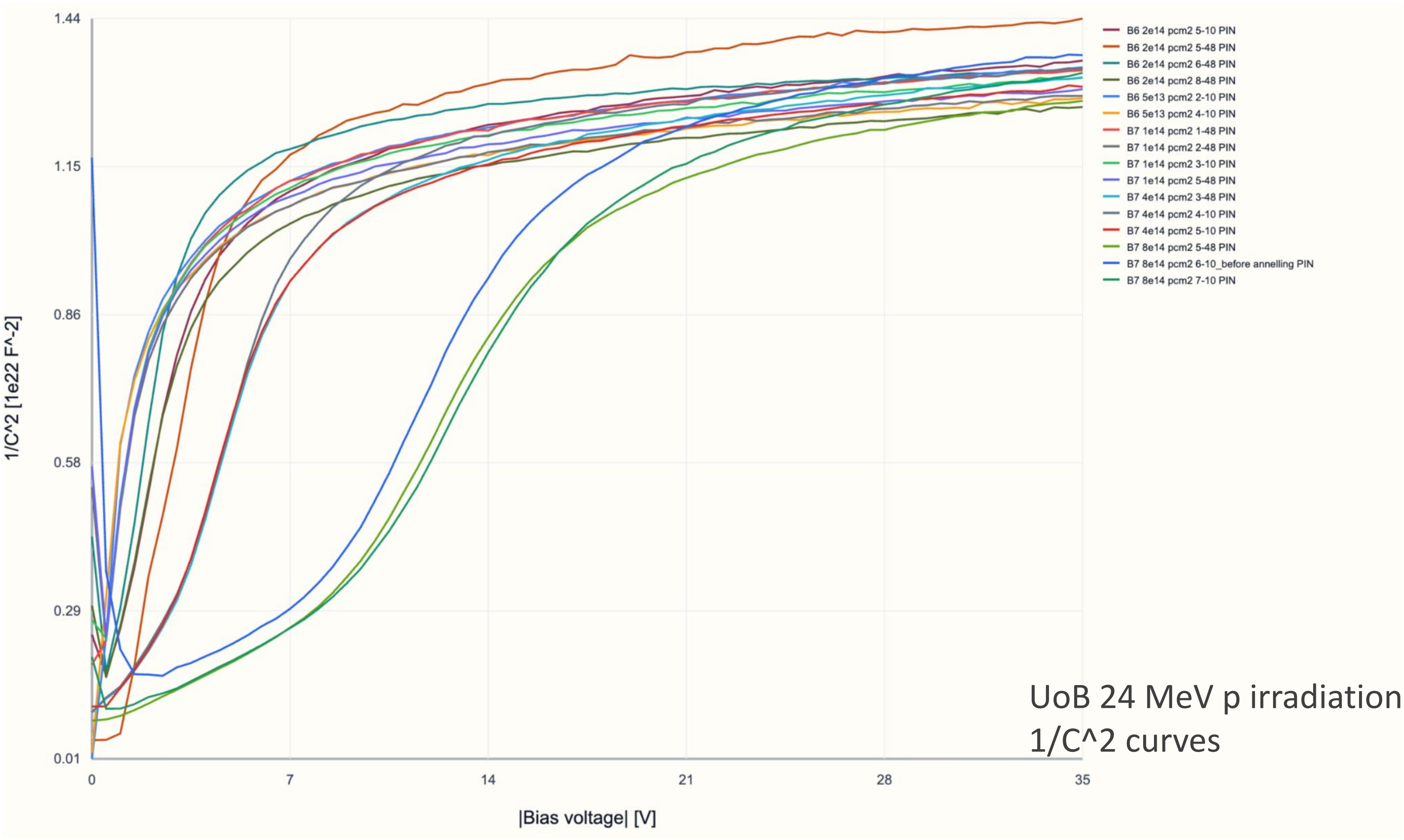
BACKUP



UoB 24 MeV p irradiation IV-curves for PIN and LGAD



UoB 24 MeV p irradiation PIN-only 1/C^2 curves