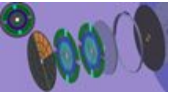

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Research
Agency
arrs

Development and Characterization of Sensors and Electronics for the ATLAS High-Granularity Timing Detector

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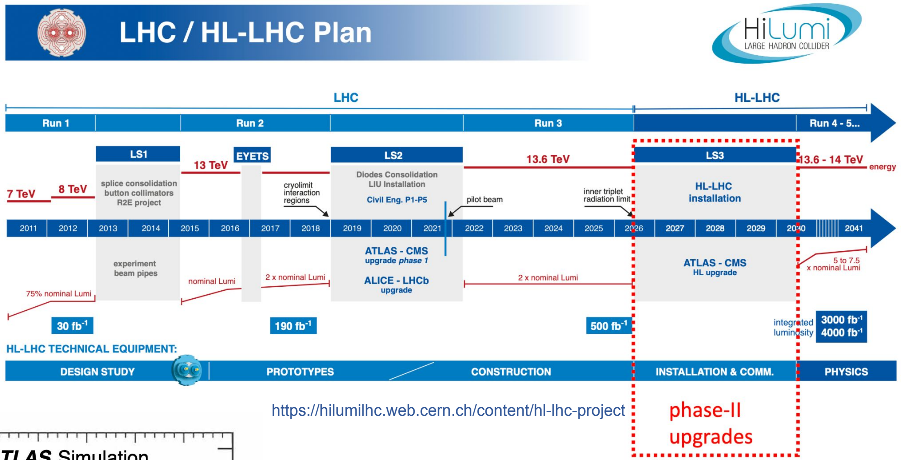
Iskra Velkovska

On behalf of ATLAS HGTD Collaboration

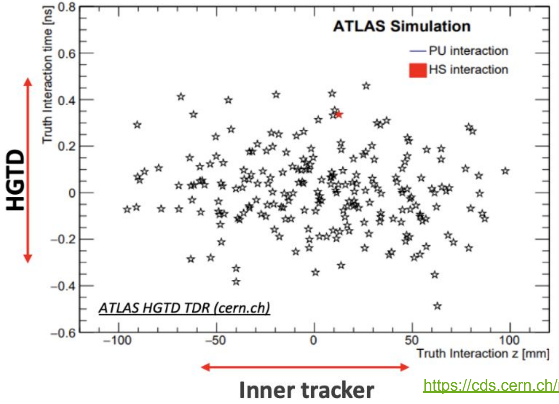
27th International Workshop on Radiation Imaging Detectors, Ghent, Belgium

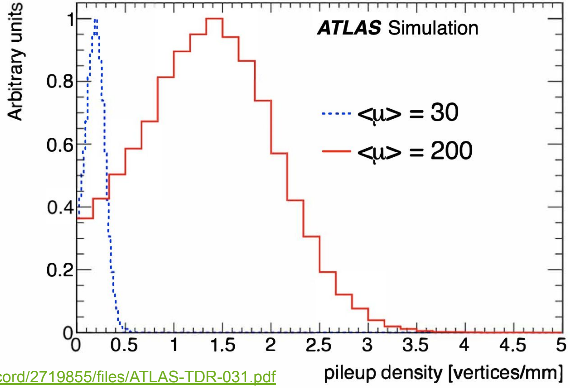
High Luminosity LHC

- **LHC upgrade**: higher beam intensity, improved beam quality and tighter focusing at the collision point
    - Instantaneous luminosity will increase by a factor of ~4, reaching 7.5×10^{34} cm^{-2}s^{-1}
- Creates harsher experimental conditions: **higher event pile-up** and **increased radiation damage**
- HL-LHC installation and upgrades of the LHC detectors during long shutdown **2026-2030**
- Higher pile-up conditions => from <μ>=60 up to **<μ>=200**



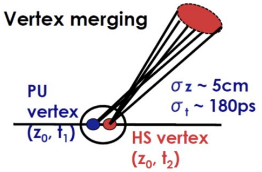
https://hilumilhc.web.cern.ch/content/hl-lhc-project

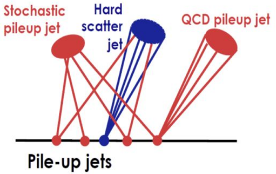




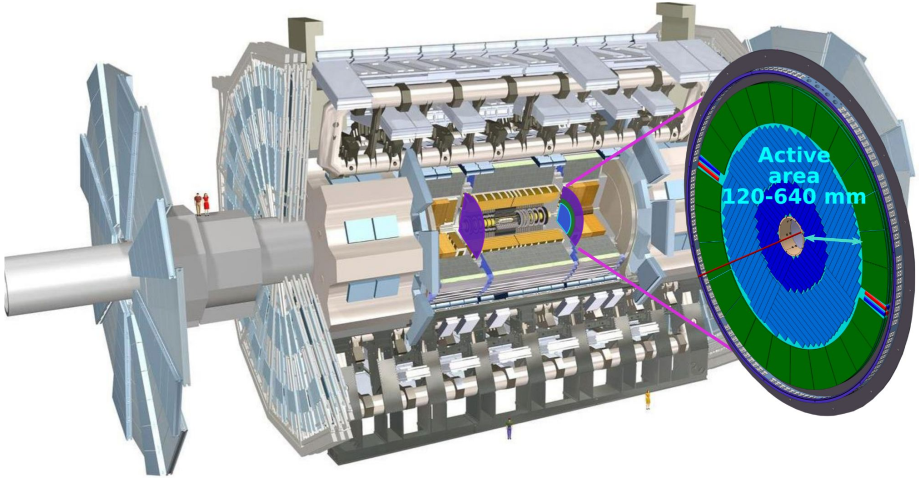
https://cds.cern.ch/record/2719855/files/ATLAS-TDR-031.pdf

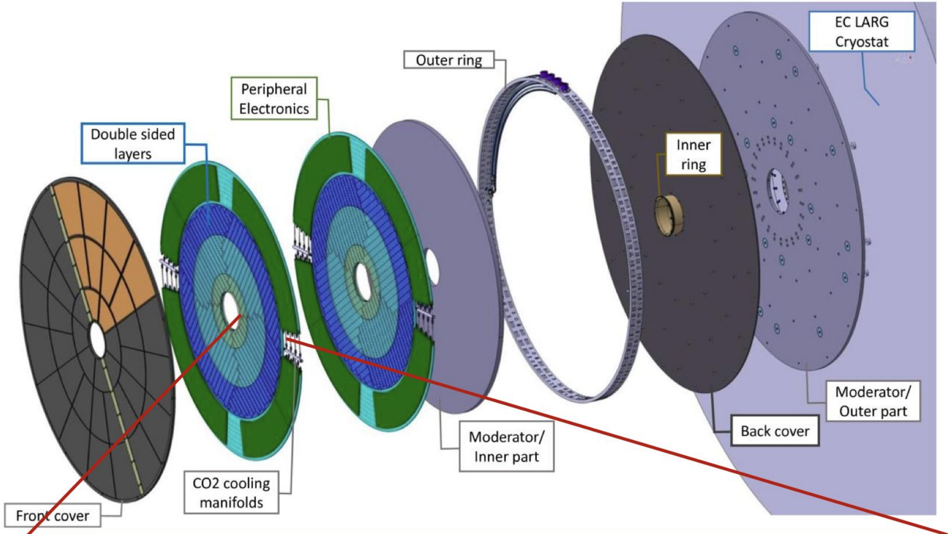
- Vertices distributed (Gaussian) with: σ_z=5 cm & σ_t=180 ps
- Tracking detectors provide resolution of primary vertices in forward region typically >1 mm, which leads to merging of several collision vertices

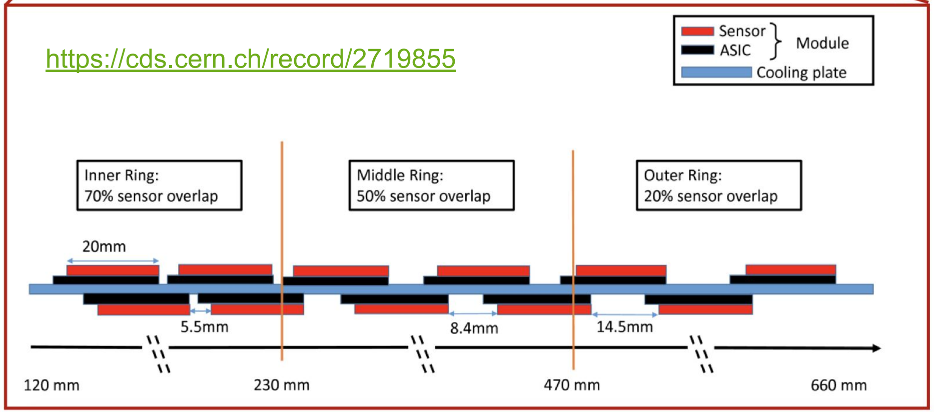




High Granularity Timing Detector (HGTD)





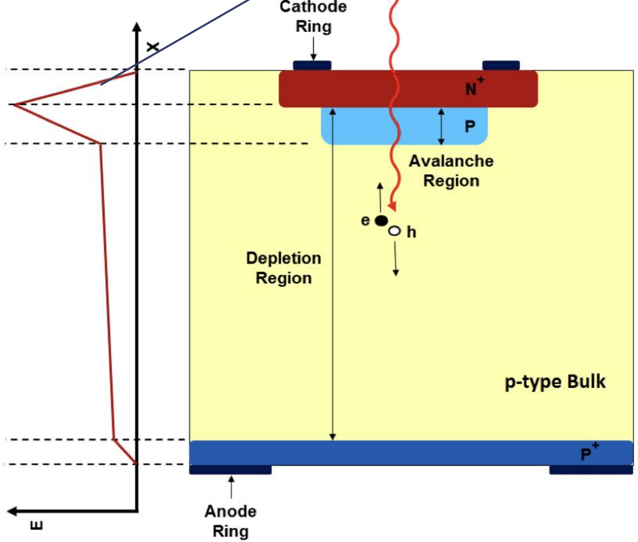

https://cds.cern.ch/record/2719855

- Located between barrel and end cap calorimeters ($|z|=3.5$ m)
- Two instrumented double-sided layers
- provides timing information to tracks in the region of $2.4<|\eta|<4.0$
- Design based on **1.3×1.3 mm^2 silicon pixels, 8032 modules**
- **3.6 million channels** operating at -30°C (6.4 m^2 of Si)
- Radiation damage up to 5.1×10^{15} n_{eq} /cm^2 and 4.7 MGy
- integrated luminosity of 4000 fb^{-1}

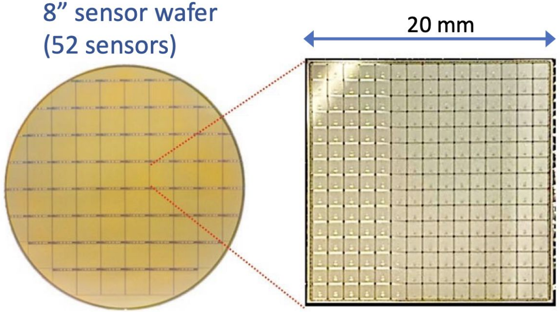
HGTD sensors: Low Gain Avalanche Detectors (LGADs)

- Excellent time resolution requires high S/N ratio -> charge multiplication ir into sensor ->LGADs
- n-on-p silicon sensor with additional **p+ Gain Layer**
- Charge multiplication by impact ionization → improved S/N
- Sensors from two vendors: **IHEP-IME** and **USTC-IME**
-

High E field in the gain layer allows impact ionization



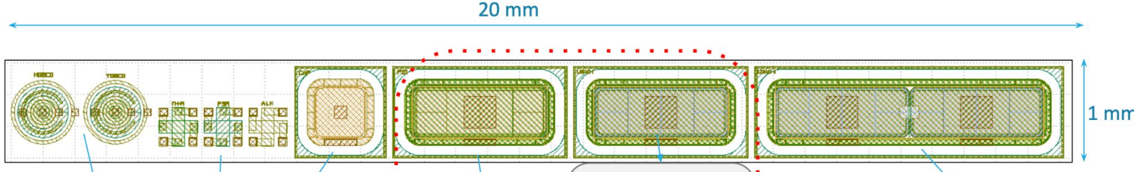
8” sensor wafer
(52 sensors)



-> active sensor thickness **50 um**

-> physical thickness o silicon **300 um**

Quality Control Test Structure (QC-TS)



Gate controlled diodes

Van der Pauw structures
Implant resistivity measurements

MOS Capacitor
SiO_2 thickness monitoring

PIN diode
Bulk properties, dosimetry

1 × 1 LGAD
Charge collection, time resolution, acceptor removal

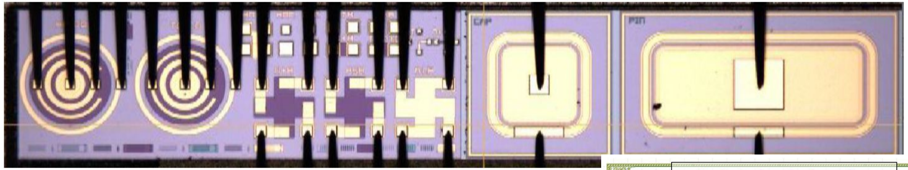
1 × 2 LGAD
Same + interpad region

Main test structure for QC-IT

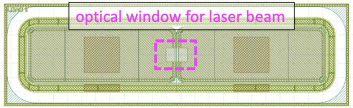
PIN and LGADs have the size of 2.1 mm × 0.65 mm and have the same area (geometric capacitance) as pads on the main sensor

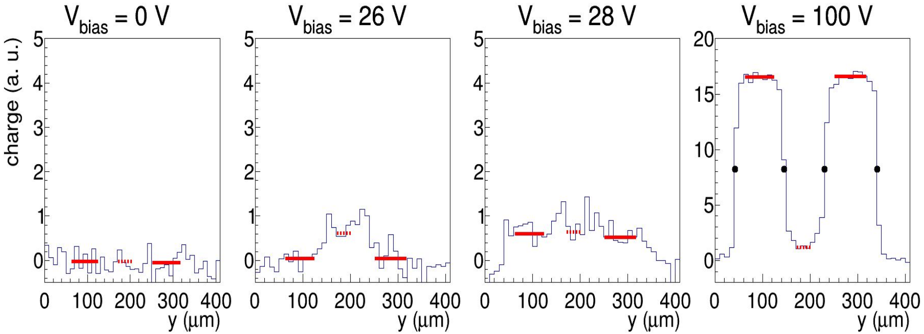
Process Quality Control & Radiation Hardness Monitoring

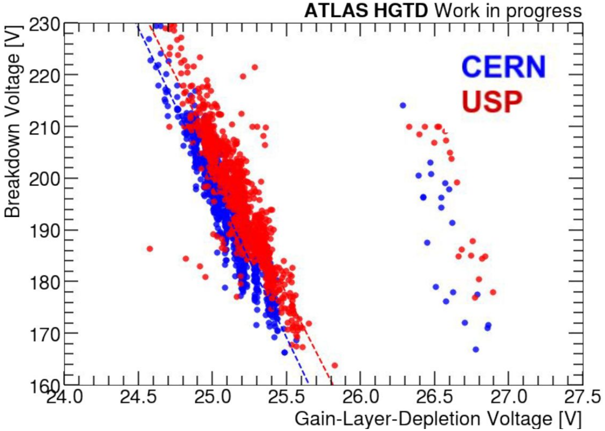
- QC test structures (GCD, VDP, MOS, PIN, LGAD) fabricated alongside every sensor wafer, probing doping profiles, oxide integrity, and gain layer uniformity at two production sites
- Wafer acceptance based on gain layer depletion voltage spread: **RMS(V_{gl}) / Mean(V_{gl}) < 2%**

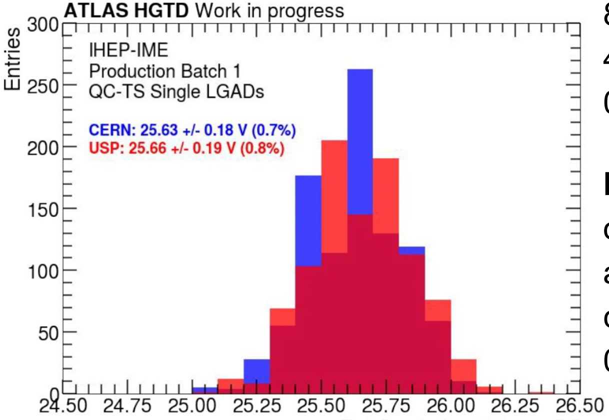


Transient Current Technique -> focused IR laser scanned across the LGAD/PIN









PQC_results_production

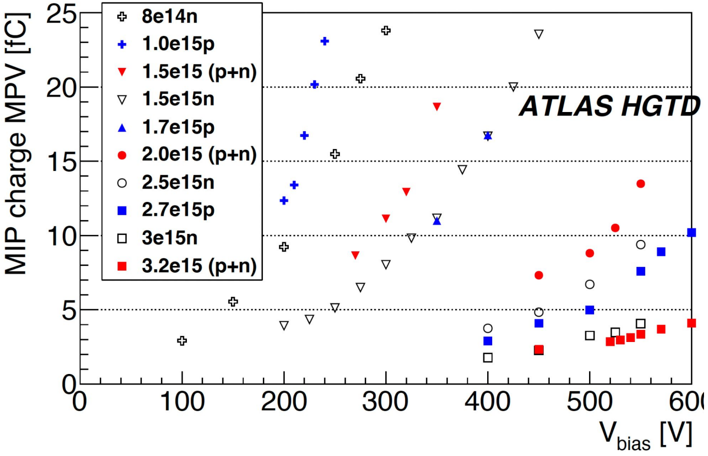
Strong V_{bd}– V_{gl} correlation confirms process uniformity across both sites

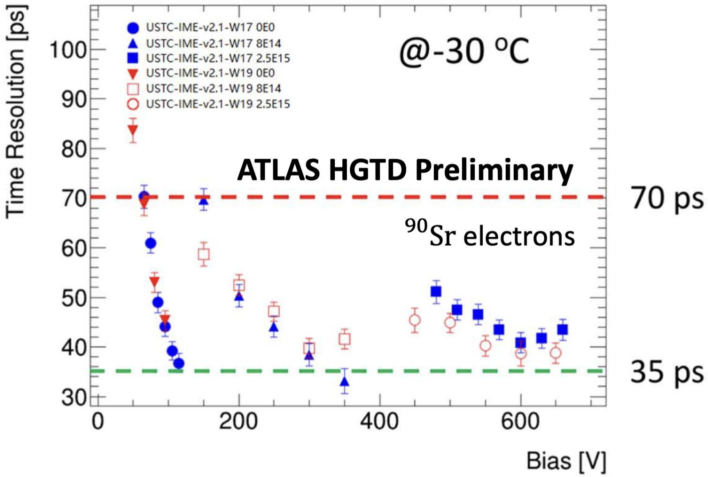
Pre-production validated all parameters within spec V_{bd} spread < 8%, V_{fd} < 30 V, C < 4.5 pF, n+ spread < 0.3%

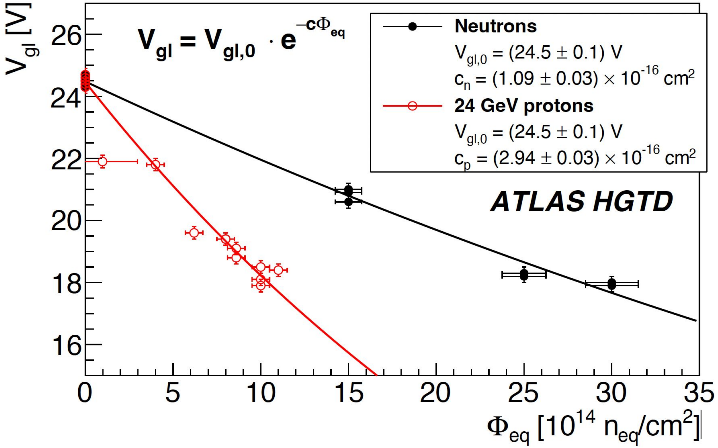
Production Batch 1 ongoing -> CERN and USP sites are consistent within 0.1V

HGTD LGAD Radiation Effects

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots







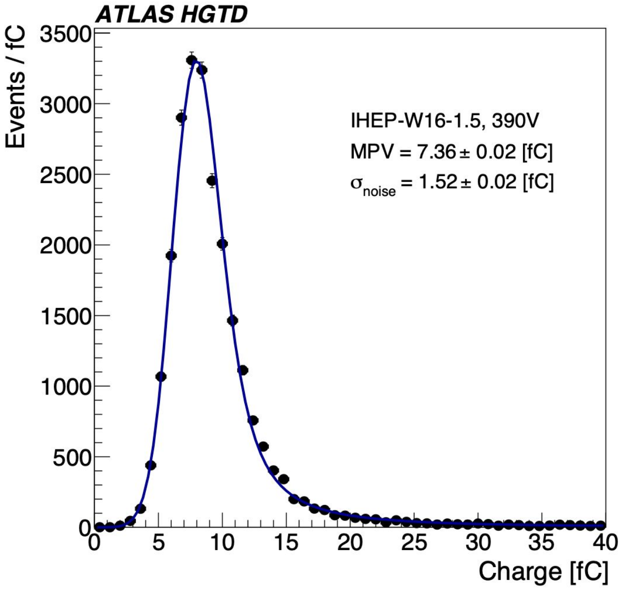
- LGAD performance degrades with radiation exposure due to a loss of gain
  - Recovered by increasing the bias
  - Limit imposed by ***Single Event Burnout*** **(SEB)** effect (local breakdown of electric field) -> Vmax~550 V for 50 μm thickness
  - Carbon-enriched gain layer: lower operating voltage, better radiation hardness
- Collected charge recoverable by increasing bias-> sensors meet 5 fC requirement up to ~2×10^{15} n_{eq}/cm² (End-of-Lifetime fluence)
- "Protons remove acceptors ~2.7× faster than neutrons, validating the mixed-field damage factor.

Contributions to timing accuracy

- Energy deposition along the particle track fluctuates randomly (Landau distribution) causing hit-to-hit variations in signal shape and arrival time
    - mitigated by thin 50 µm active layer and operation at saturated drift velocity → $\sigma_{\text{Landau}} \gtrsim$ **25 ps**

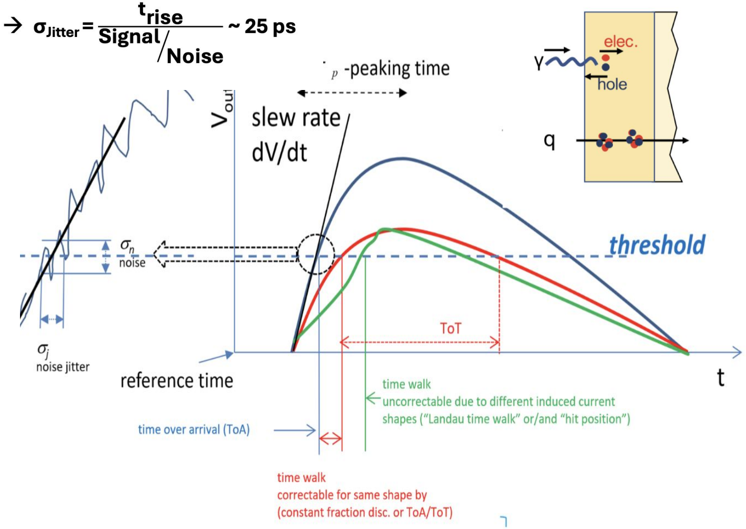
- Collected charge extracted from Landau-Gaussian fits to beam-test charge distributions -> MPV used as the figure of merit
- Higher SNR → lower jitter → better timing

$$\sigma^2_{\text{total}} = \overbrace{\sigma^2_{\text{Landau}}}^{\textbf{sensor}} + \overbrace{\sigma^2_{\text{Timewalk}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{TDC}} + \sigma^2_{\text{Clock}}}^{\textbf{read-out electronics}}$$



Jitter:
Due to electronics noise in the signal shape

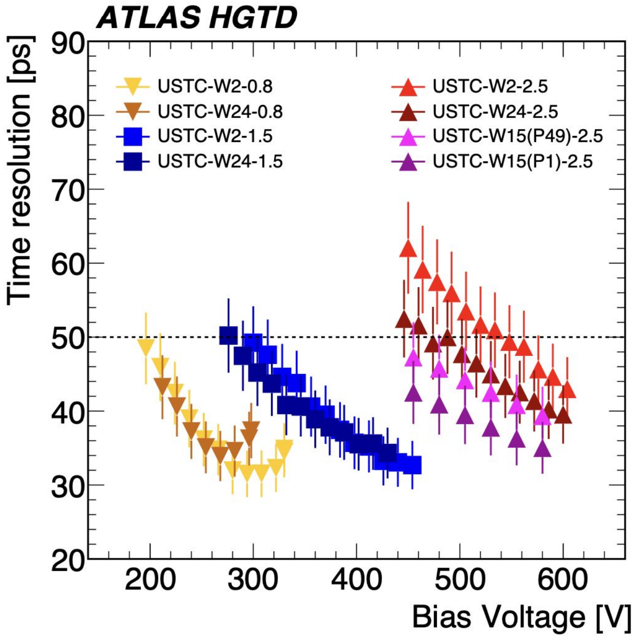
→ $\sigma_{\text{Jitter}} = \frac{t_{\text{rise}}}{\text{Signal}/\text{Noise}}$ ~ 25 ps



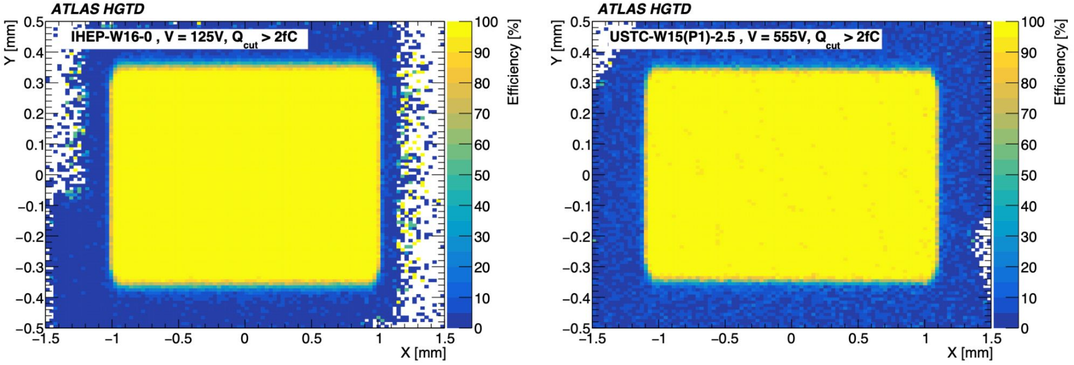
$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

- **Timewalk effect:**
  Time-Of-Arrival (TOA) depends on signal amplitude
  → $\sigma_{\text{Landau}} = \left.\frac{V_{\text{th}}}{\text{Signal}/t_{\text{rise}}}\right|_{\text{RMS}}$
  → Can be corrected based on ToT
- **TDC:**
  From TDC binning / non-linearity
  → $\sigma_{\text{TDC}} \geq \text{LSB}/\sqrt{12}$ = **6 ps**
- **Clock:**
  Jitter of the 40 MHz clock
  → σ_{Clock} < **10 ps**

Beam-test Performance of Pre-production LGADs



-> The blue (black) dashed line at **40 ps (50 ps)** represents the sensor-only per-hit time resolution requirements for unirradiated (irradiated) sensors



-> Efficiency within the active area remains uniform and exceeds 95%

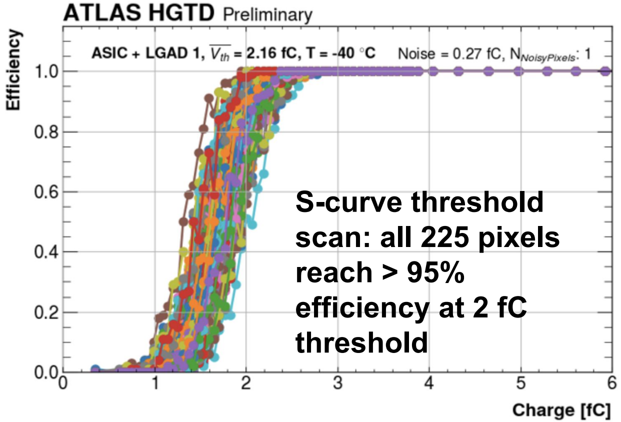
https://iopscience.iop.org/article/10.1088/1748-0221/21/03/P03021/pdf

@ CERN SPS with 120 GeV pions

@ DESY with 5 GeV electrons

The ALTIROC readout ASIC

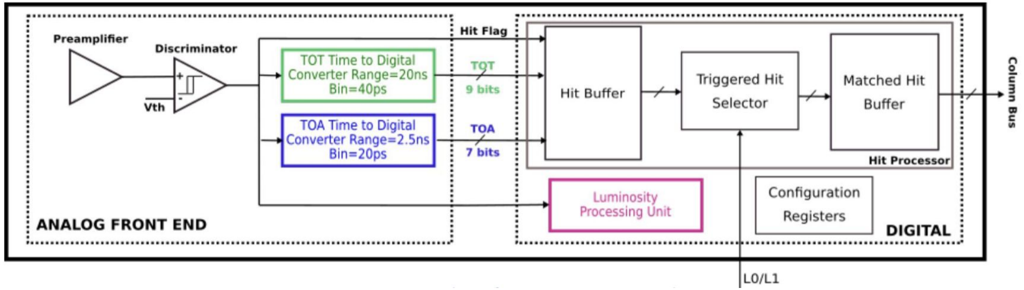
- **A**TLAS **L**GAD **T**iming **I**ntegrated **R**ead-**O**ut **C**hip
- 225 channels (15×15) matching LGAD sensor pixels -> 1.3×1.3 mm² pad size
- 130 nm CMOS from TSMC -> radiation hard to 200 Mrad TID
- Jitter < 25 ps at 10 fC (< 65 ps at 4 fC), threshold < 2 fC, power <4.5 mW/channel
- Measures TOA w.r.t. 40 MHz LHC clock + TOT for time-walk correction



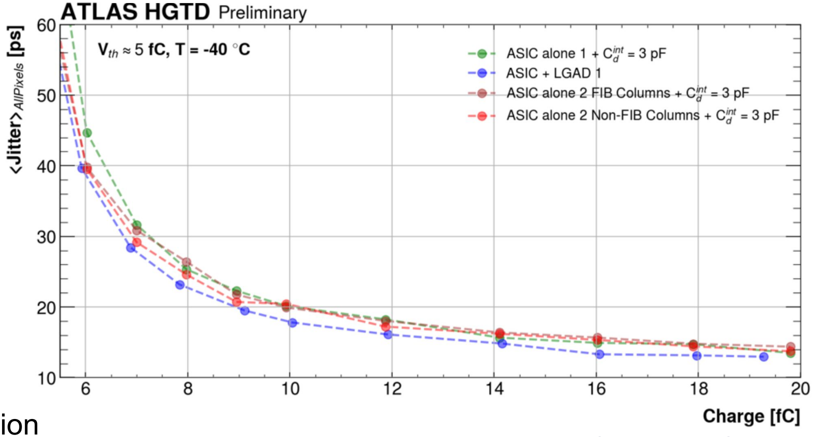
S-curve threshold scan: all 225 pixels reach > 95% efficiency at 2 fC threshold

https://cds.cern.ch/record/2719855/

ALTIROC architecture



- Discriminator threshold >= **2 fC**
- TDC with 20 ps binning
- Provides Time-Of-Arrival (**TOA)** and Time-Over-Threshold (**TOT)** information
- Final version: **ALTIROC-A** (under test)
- Radiation hard up to 200 Mrad

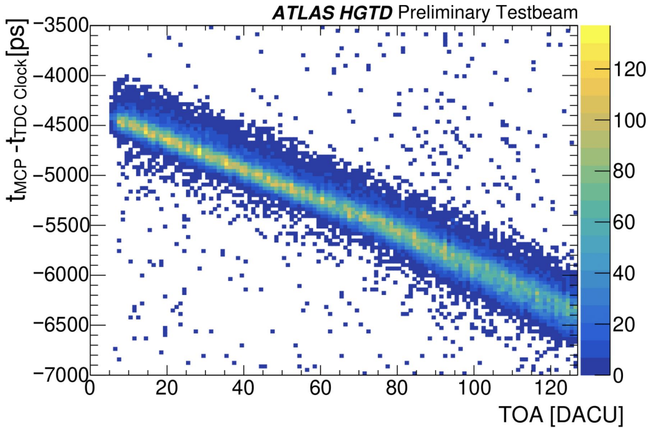


Mean jitter across all channels as function of charge with a threshold of ~5 fC for different chips of ALTIROC3

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

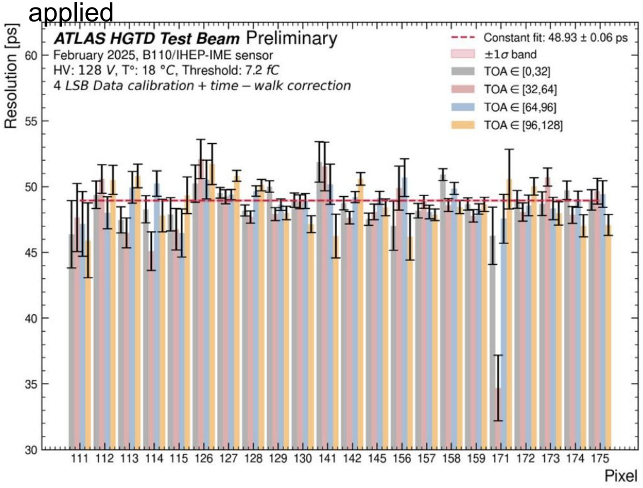
Hybrid test beam results

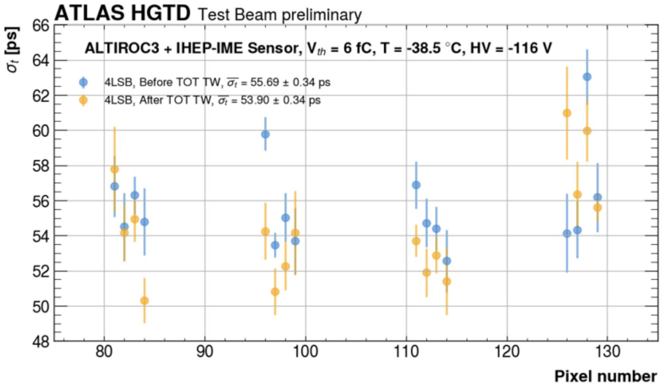
- Time resolution extracted from TOA residuals w.r.t. MCP-PMT reference
  - improved significantly by data-driven LSB and time-walk calibration accounting for TDC non-linearity
  - Best achieved: **49 ps** at room temperature (full calibration)
  - At operating temperature (-38°C): **54 ps** -> meets HGTD irradiated requirement



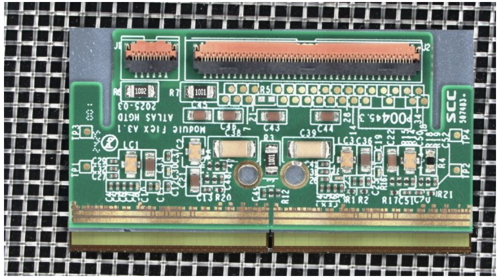
TOA measured by ALTIROC3 vs MCP-PMT reference — strong linear correlation confirms correct TDC functionality (DESY testbeam, November 2023)

Time resolution per pixel -> full calibration applied



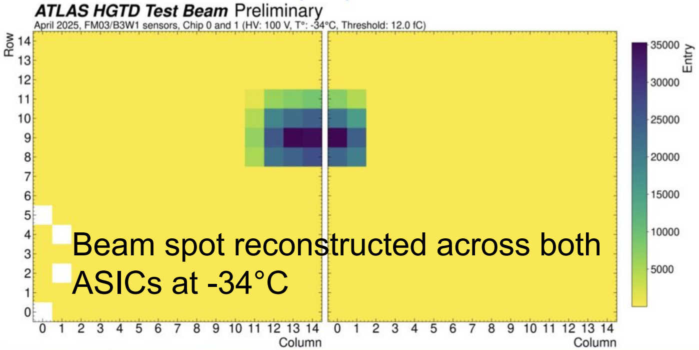


Module assembly

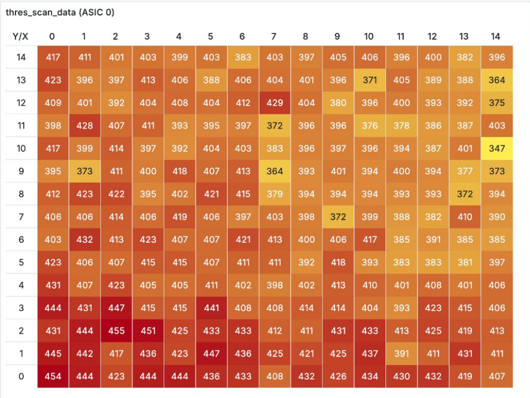


- 8032 modules required -> each module: 2 ASICs + 2 LGAD sensors on a flex PCB
- <50 ps timing achieved in test beam after full calibration -> meeting HGTD irradiated requirement
- Residual ~4 ps contribution from test bench clock jitter -> HL-LHC 40 MHz clock expected negligible

Module-occupancy in test beam

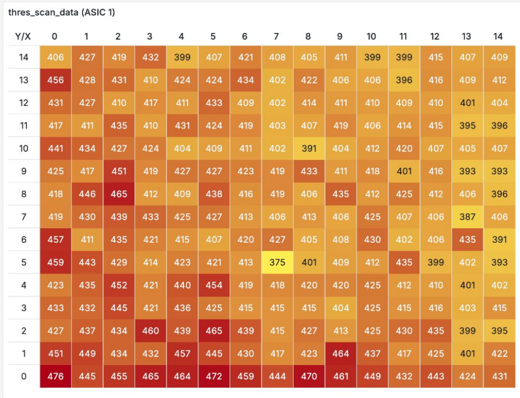


Beam spot reconstructed across both ASICs at -34°C



thres_scan_data (ASIC 0)

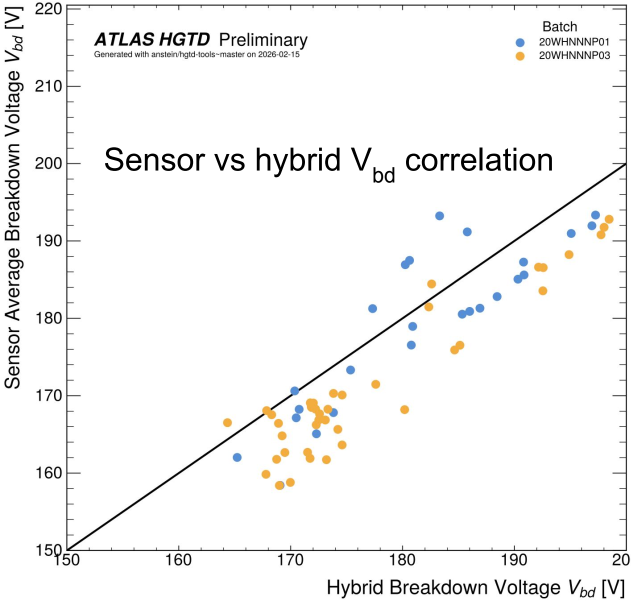
Y/X	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
14	417	411	401	403	399	403	383	403	397	405	406	396	400	382	396
13	423	396	397	413	406	388	406	404	401	396	371	405	389	388	364
12	409	401	392	404	408	404	412	429	404	380	396	400	393	392	375
11	398	428	407	411	393	395	397	372	396	396	376	378	386	387	403
10	417	399	414	397	392	404	403	383	396	397	396	394	387	401	347
9	395	373	411	400	418	407	413	364	393	401	394	400	394	377	373
8	412	423	422	395	402	421	415	379	394	394	394	393	393	372	394
7	406	406	414	406	419	406	397	403	398	372	399	388	382	410	390
6	403	432	413	423	407	407	421	413	400	406	417	385	391	385	385
5	423	406	407	415	415	407	411	411	392	418	393	383	383	381	397
4	431	407	423	405	405	411	402	398	402	413	410	401	408	401	406
3	444	431	447	415	415	441	408	408	414	414	404	393	423	415	406
2	431	444	455	451	425	433	433	412	411	431	433	413	425	419	413
1	445	442	417	436	423	447	436	425	421	425	437	391	411	431	411
0	454	444	423	444	444	436	433	408	432	426	434	430	432	419	407



thres_scan_data (ASIC 1)

Y/X	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
14	406	427	419	432	399	407	421	408	405	411	399	399	415	407	409
13	456	428	431	410	424	424	434	402	422	406	406	396	416	409	412
12	431	427	410	417	411	433	409	402	414	411	410	409	410	401	404
11	417	411	435	410	431	424	419	403	407	419	406	414	415	395	396
10	441	434	427	424	404	409	411	402	391	404	412	420	407	405	407
9	425	417	451	419	427	427	423	419	433	411	418	401	416	393	393
8	418	446	465	412	409	438	416	419	406	435	412	425	412	406	396
7	419	430	439	433	425	427	413	406	413	406	425	407	406	387	406
6	457	411	435	421	415	407	420	427	405	408	430	402	406	435	391
5	459	443	429	414	423	421	413	375	401	409	412	435	399	402	393
4	423	435	452	421	440	454	419	418	420	420	425	412	410	401	402
3	433	432	445	421	436	425	415	415	415	404	425	415	416	403	415
2	427	437	434	460	439	465	439	415	427	413	425	430	435	399	395
1	451	449	434	432	457	445	430	417	423	464	437	417	425	401	422
0	476	445	455	465	464	472	459	444	470	461	449	432	443	424	431

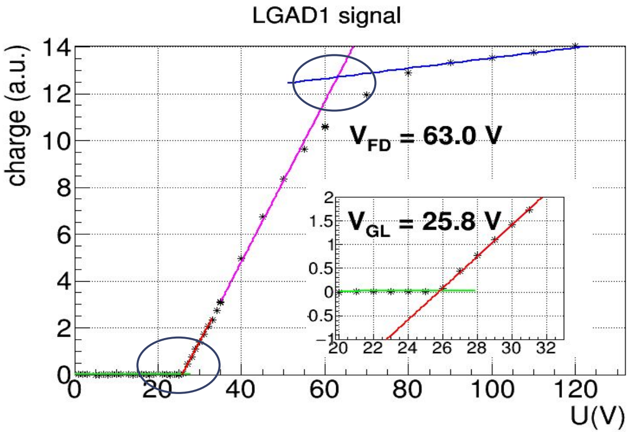
Threshold scan -> uniform response across 225 pixels per ASIC

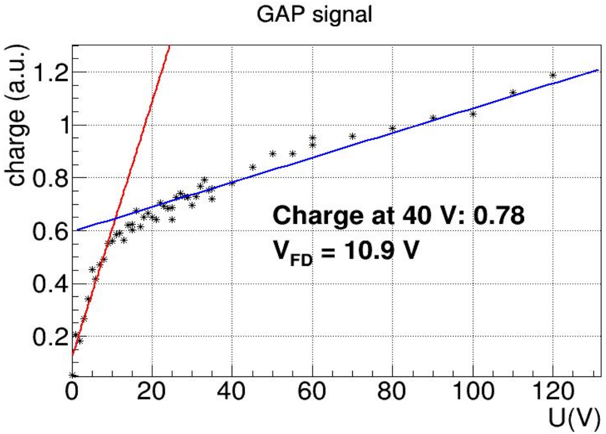


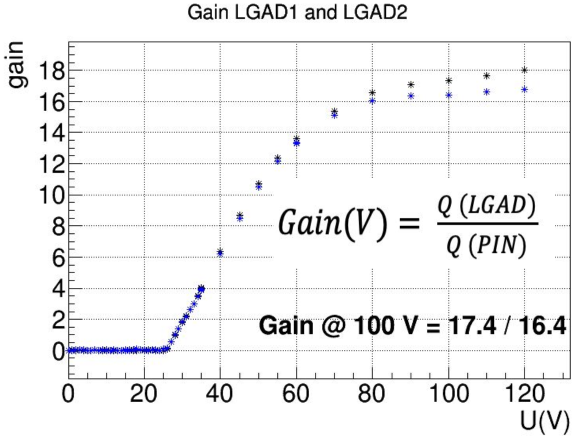
Sensor vs hybrid V_{bd} correlation

Summary

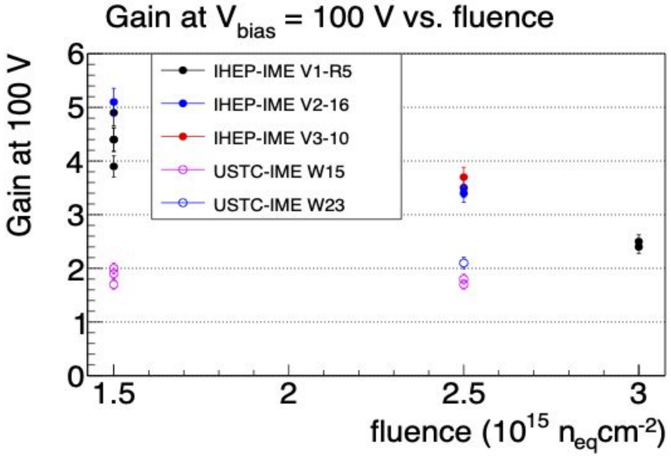
BACKUP

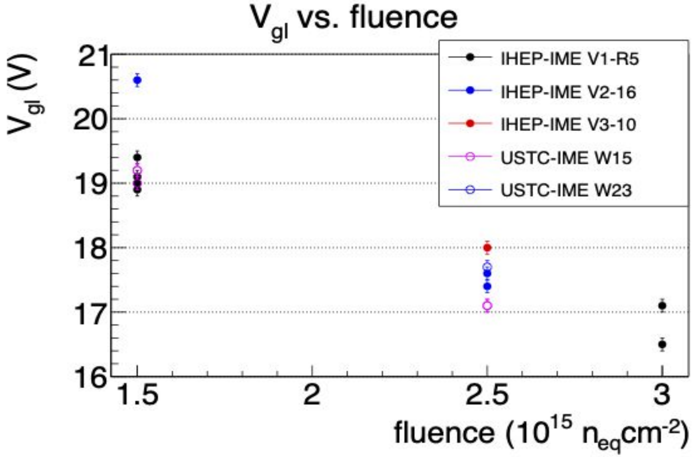






$$Gain(V) = \frac{Q\ (LGAD)}{Q\ (PIN)}$$

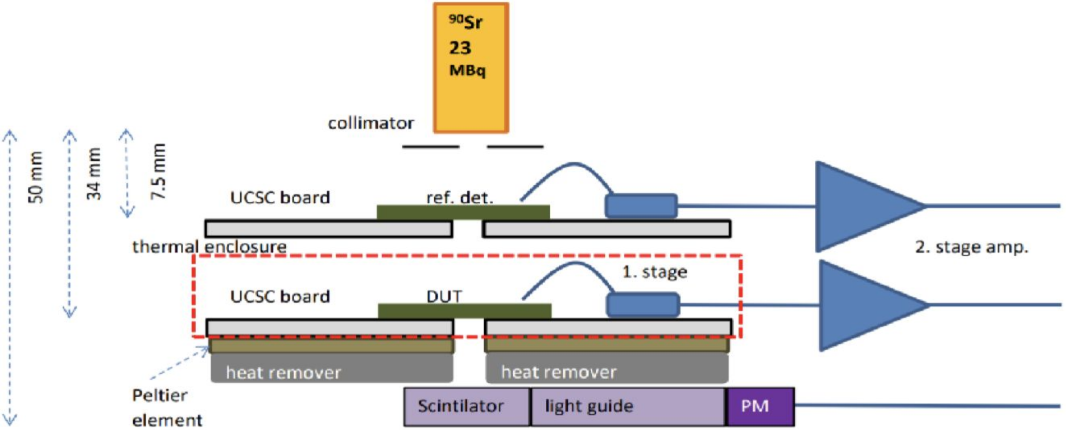


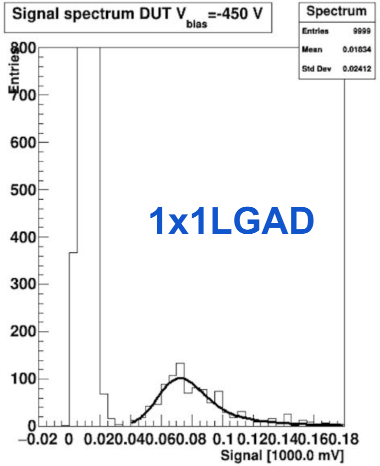


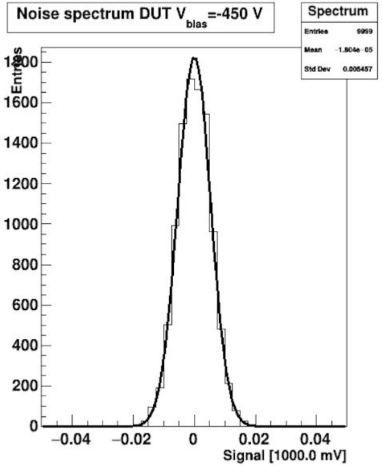
- ***V_{gl}*** ->falling consistently with fluence
- ***Gain***-> falling consistently with fluence (due to smaller V_{gl})

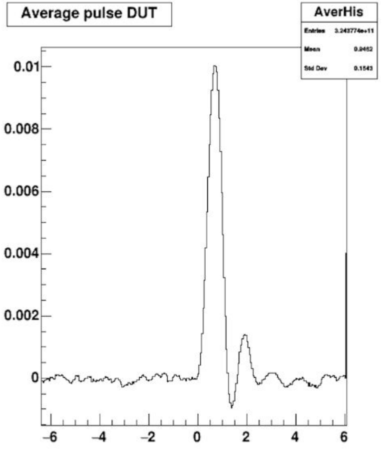
β-^{90}Sr Timing/Collected charge Irradiation Tests

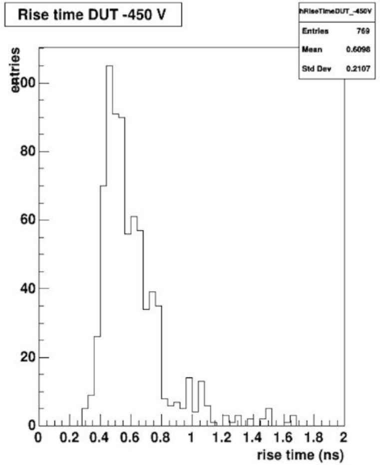
- CV-IV does not directly measure **MIP charge** and **time resolution**
  - **Sr90 is a pure β emitter – laboratory MIP source**
    - deposit 10 % more MPV charge than MIPs
    - multiple scattering in material (10 % more charge)
    - bias due to noise in waveforms ~ 1 fC
- Setup with two LGADs (HPK time reference and Device Under Test (DUT))
- DUT cooled to -27°C
- **Coincidence trigger on PMT + reference LGAD** -> DUT doesn't take part in trigger!

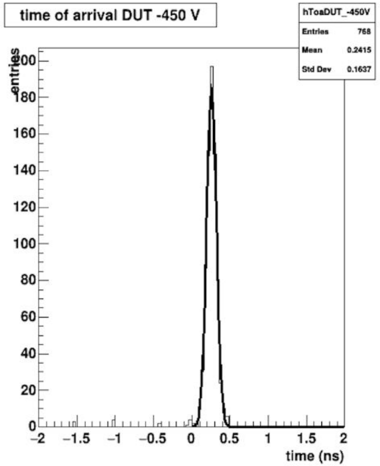


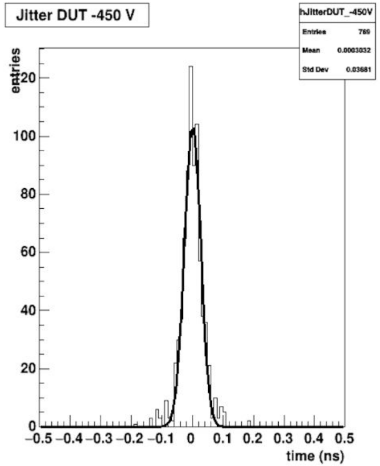


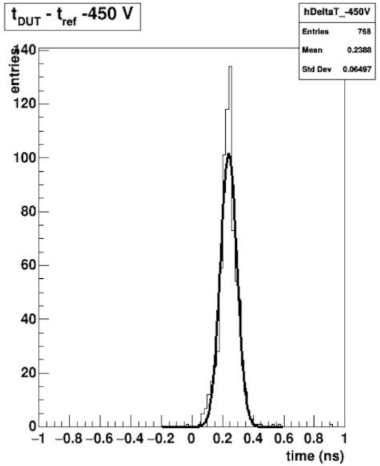






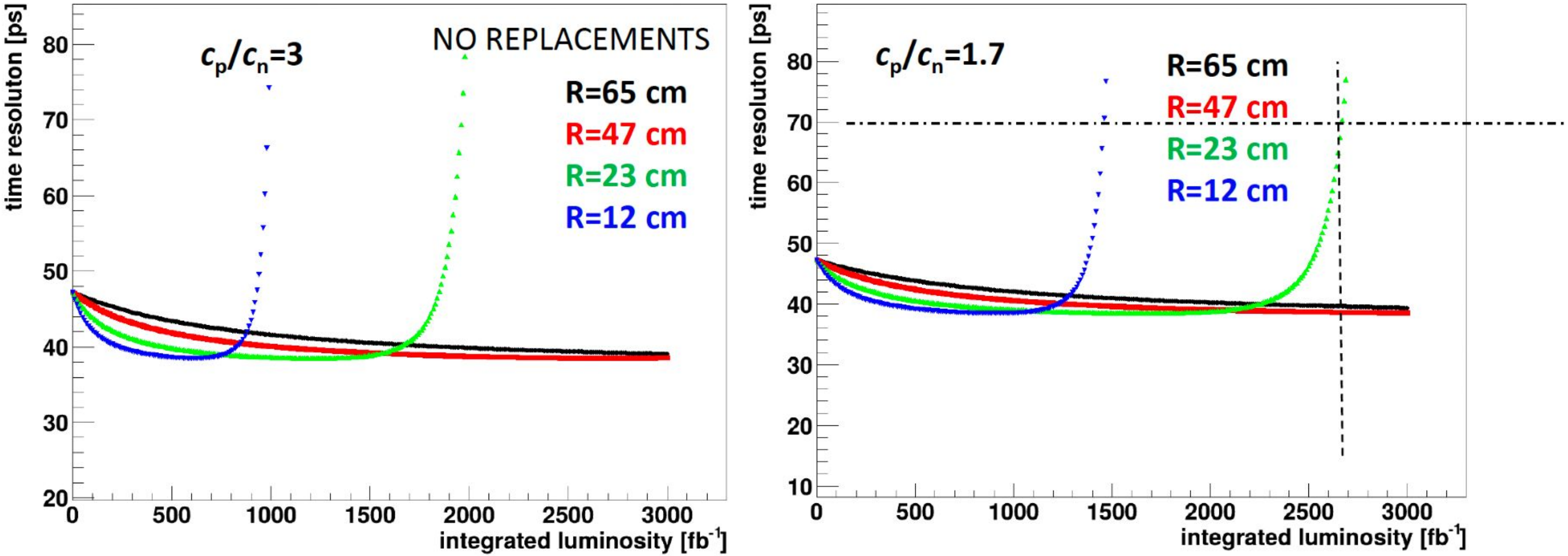




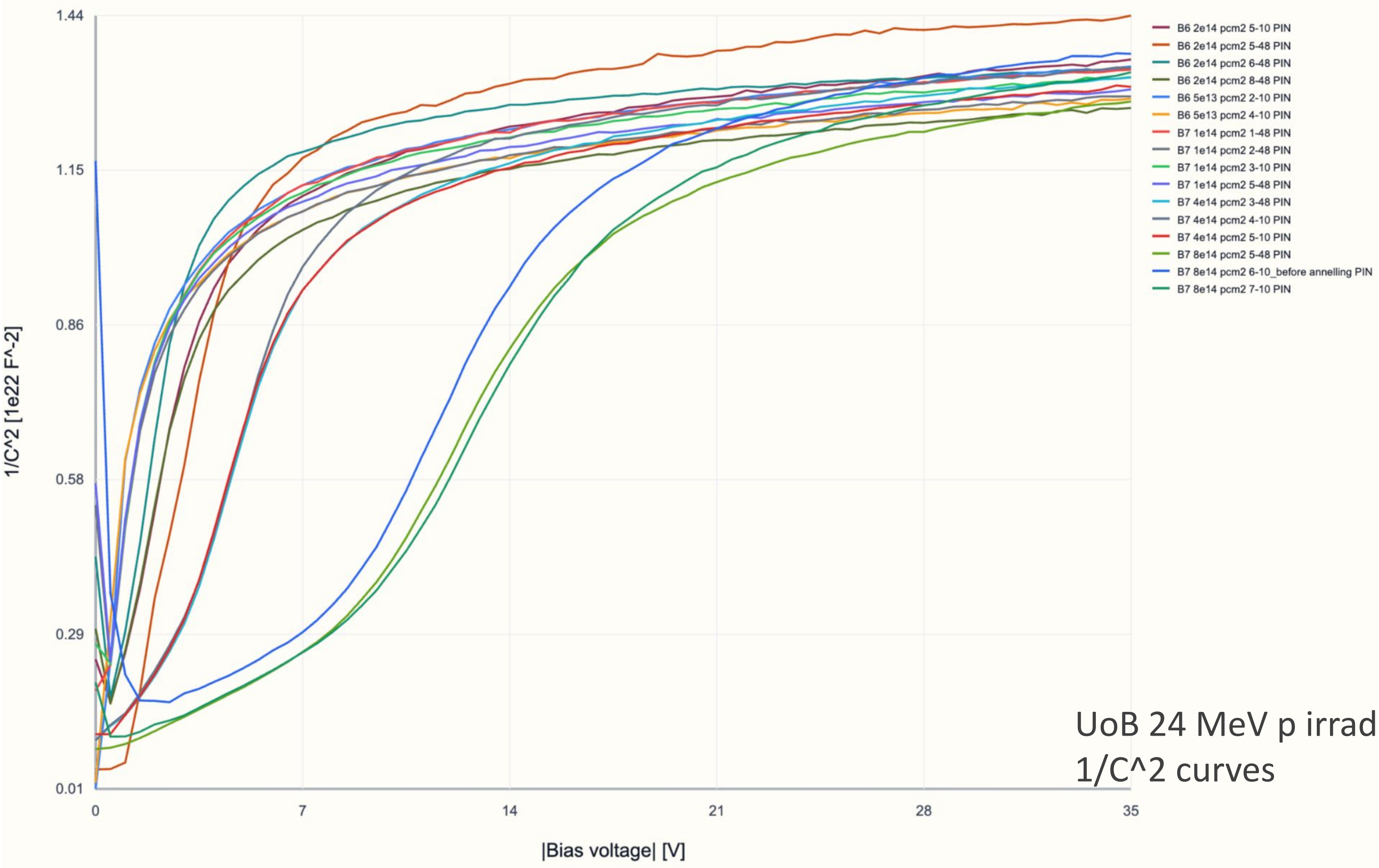


10.8×10^{14} n_{eq}/cm²
Batch 7
Wafer 6, Position 10

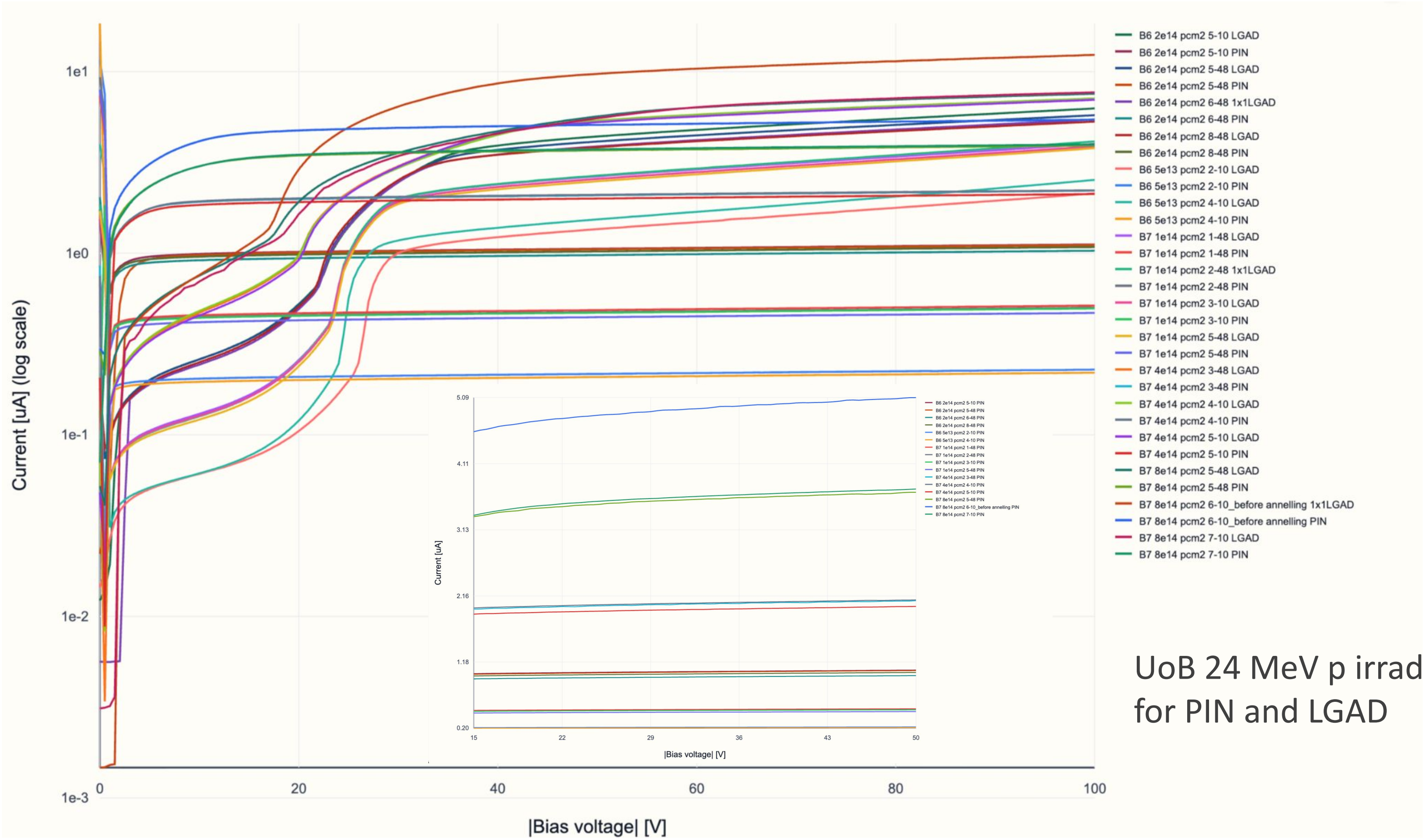
Estimated HGTD performance over the lifetime (3000 fb^{-1})



- HGTD performance simulation using particle composition at HL-LHC
- Significant dependence on charged hadron damage factor c_p/c_n
- The 3000 fb^{-1} scenario (including safety factor 1.5) is evaluated assuming the default replacement plan: 1 replacement for the middle ring and 3 replacements for the inner ring.



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



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