



# The ATLAS High-Granularity Timing Detector for the HL-LHC: project status and results

VERTEX 2025 – 33rd International Workshop on Vertex Detectors

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on behalf of the ATLAS HGTD group

# Outline

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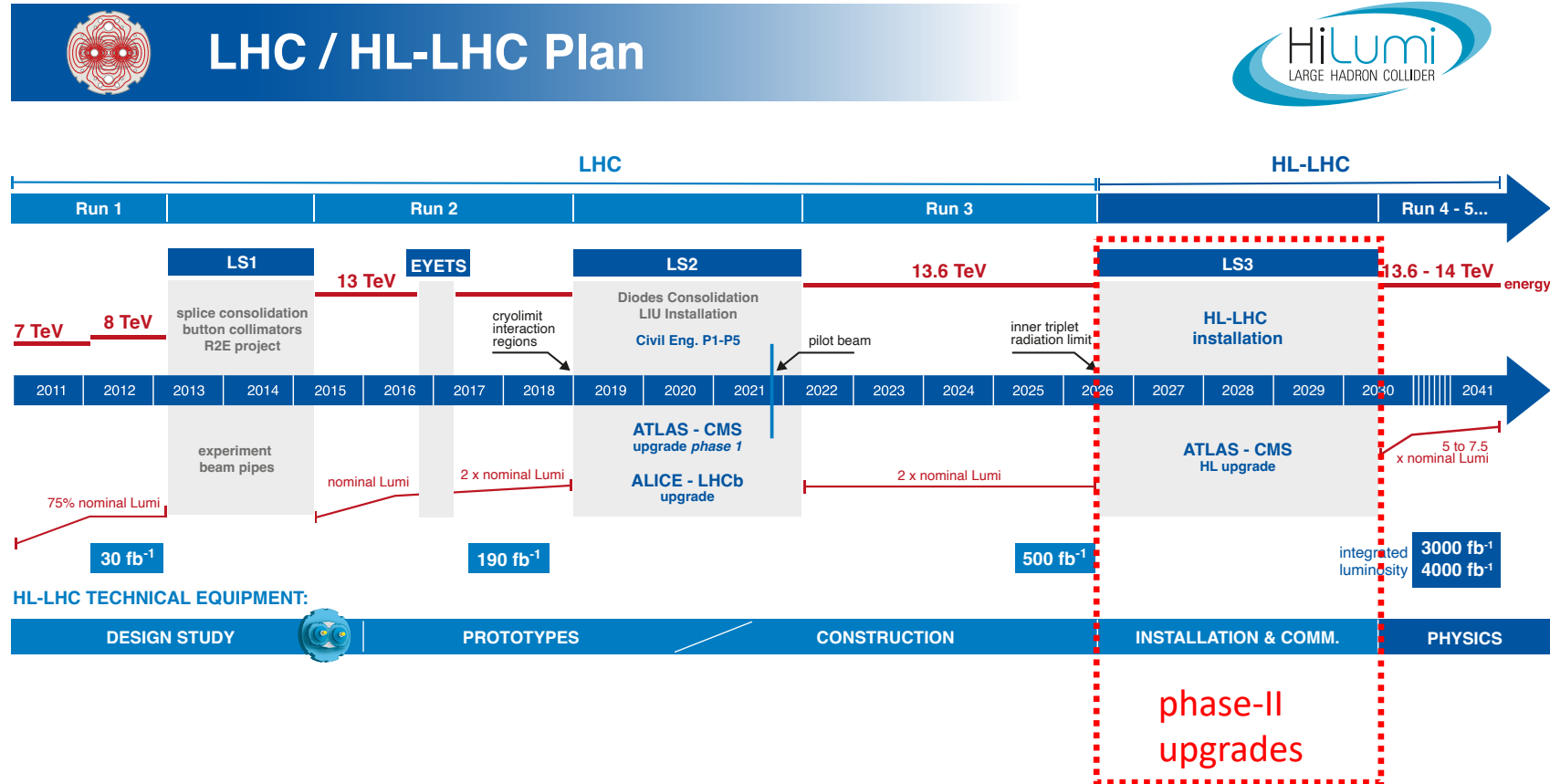
- Motivation for timing in the future ATLAS detector
- HGTD timing-detector concept
- Sensor qualification
- Performance with ASICs
- System-level tests
- Conclusions

# High Luminosity LHC

## High Luminosity LHC (HL-LHC):

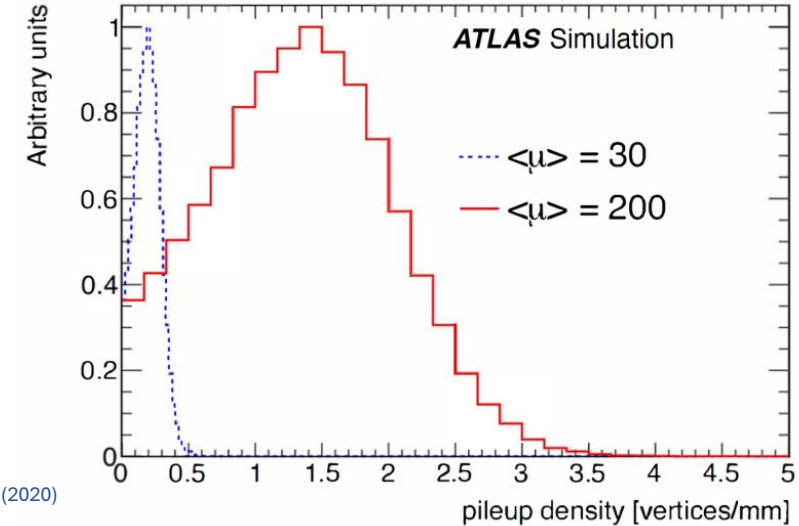
- **Upgrade** of the Large Hadron Collider, enhancing beam intensity, emittance and final focus  
 → increase of the instantaneous luminosity by factor  $\sim 4$  up to  $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Leads to more challenging data-taking conditions for the experiments: **event pile-up, radiation damage**
- HL-LHC installation and upgrades of the LHC detectors during long shutdown **2026-2030**

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

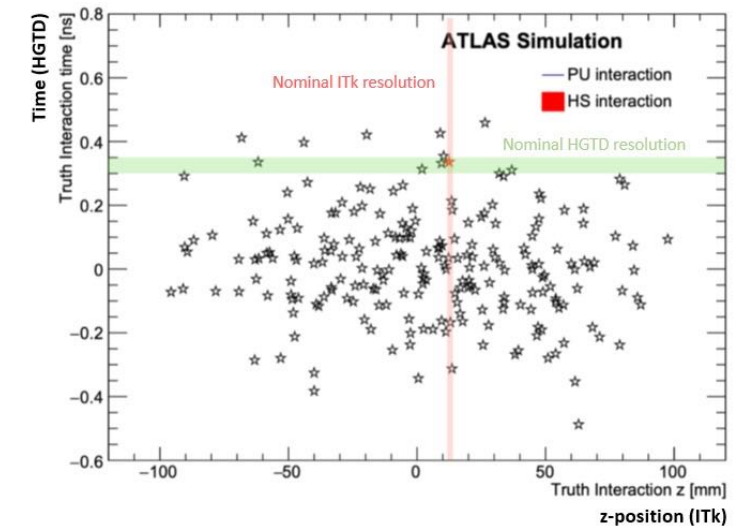
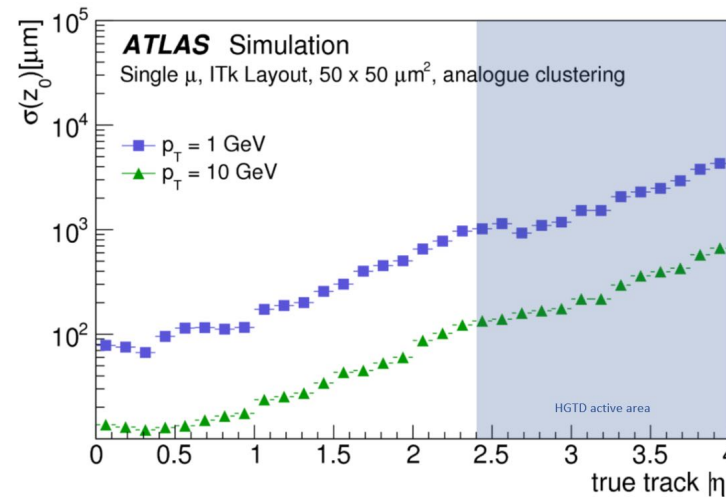
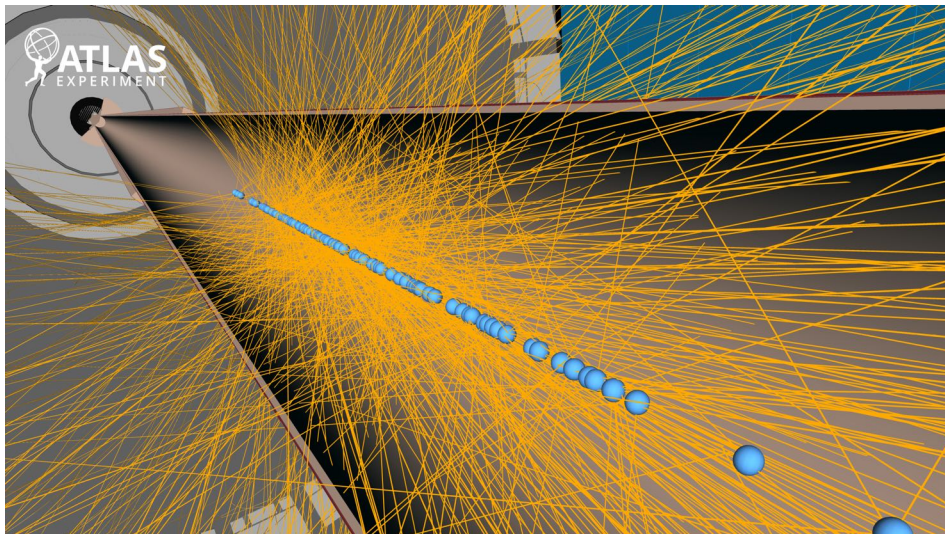


# ATLAS detector challenges at HL-LHC

- Expected **pile-up** in the ATLAS detector:  $\langle \mu \rangle = 200$  interactions per bunch crossing (on average 1.6 vertices/mm)
- Highest rates in **forward detector regions**, where tracker resolution is poorest: correct assignment of tracks to vertices becomes challenging
- Adding **precision-timing information** in the forward regions improves pile-up rejection and vertex reconstruction

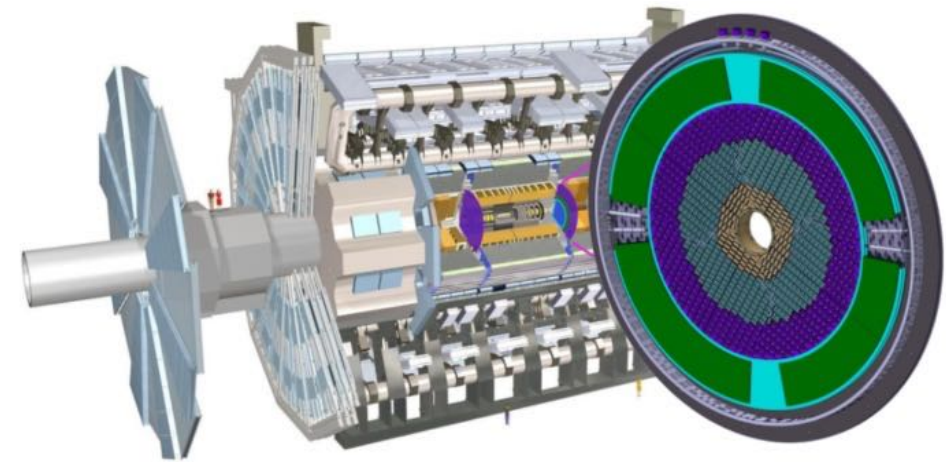
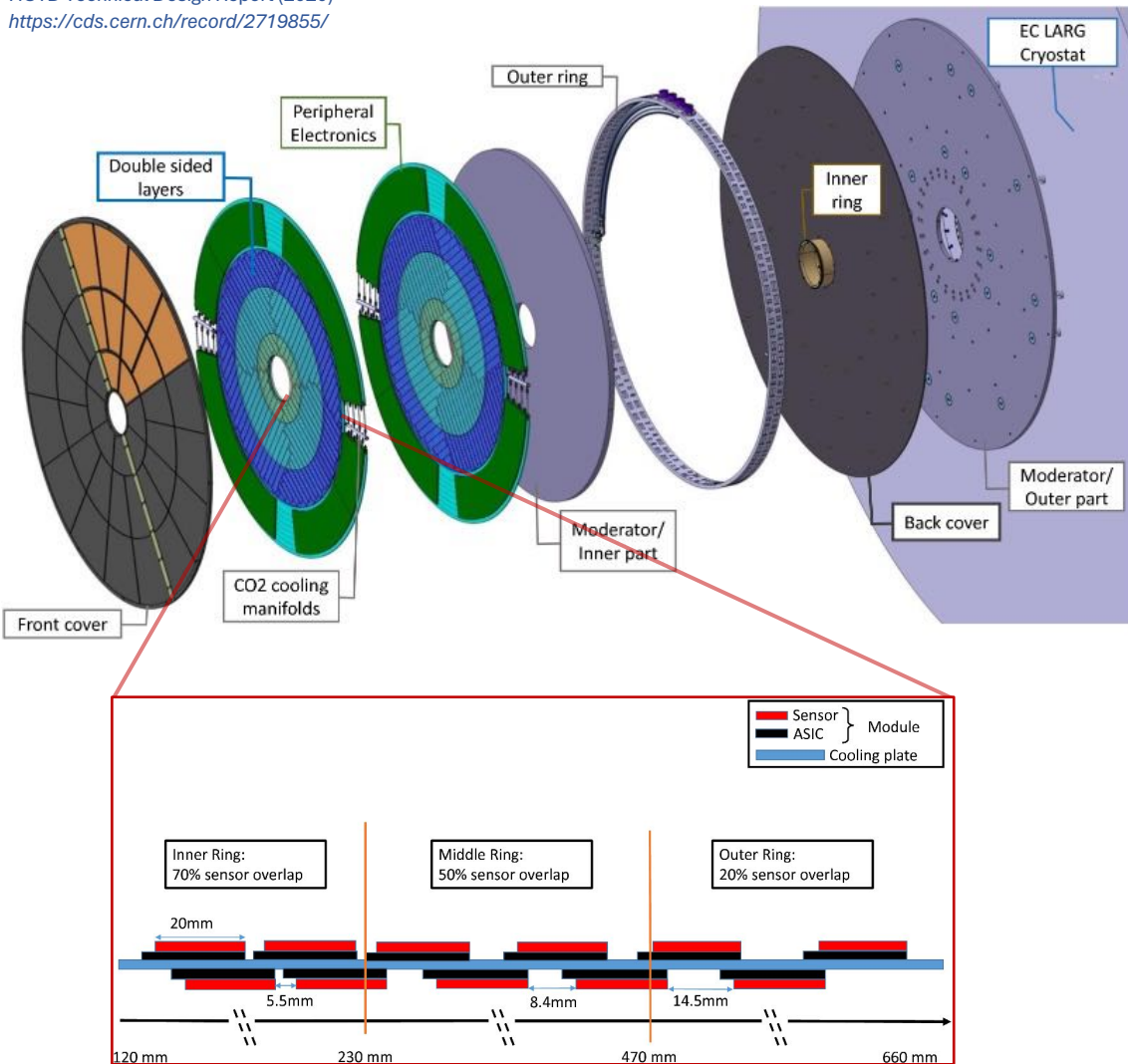


Plots: HGTD Technical Design Report (2020)  
<https://cds.cern.ch/record/2719855/>



# High Granularity Timing Detector

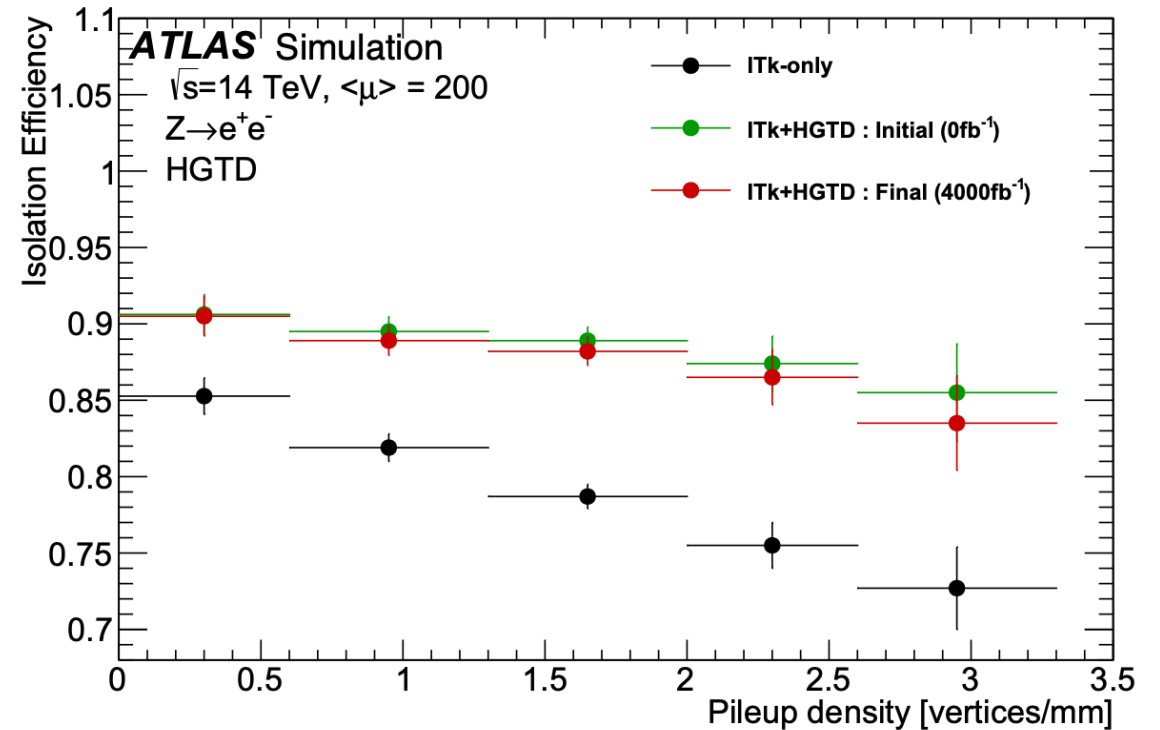
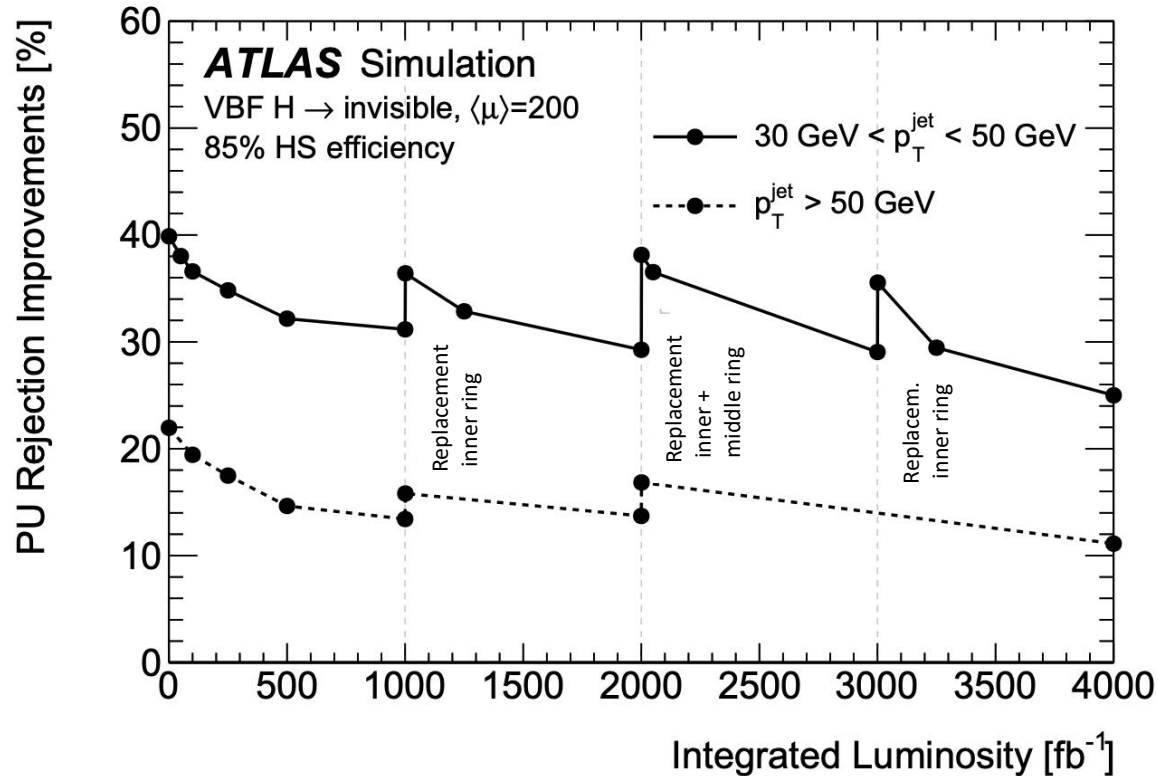
HGTD Technical Design Report (2020)  
<https://cds.cern.ch/record/2719855/>



## High Granularity Timing Detector (HGTD):

- Placed between Inner Tracker (ITk) and Liquid Argon Calorimeter
- Active area coverage:  $2.4 < |\eta| < 4.0$
- Consists of **8032** modules (2 LGAD sensors + 2 r/o ASICs each) **6.4 m<sup>2</sup>** of silicon sensors
- Radiation hardness requirements (with replacements of the inner and middle rings):
  - Maximum fluence:  $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ ; TID: 2 MGy
- Operating temperature **-30°C** (CO<sub>2</sub> dual phase cooling)
- Two instrumented double layers per side
- Overlap between modules on all rings
- Track-time resolution: **35 ps** (start) - **50 ps** (end)

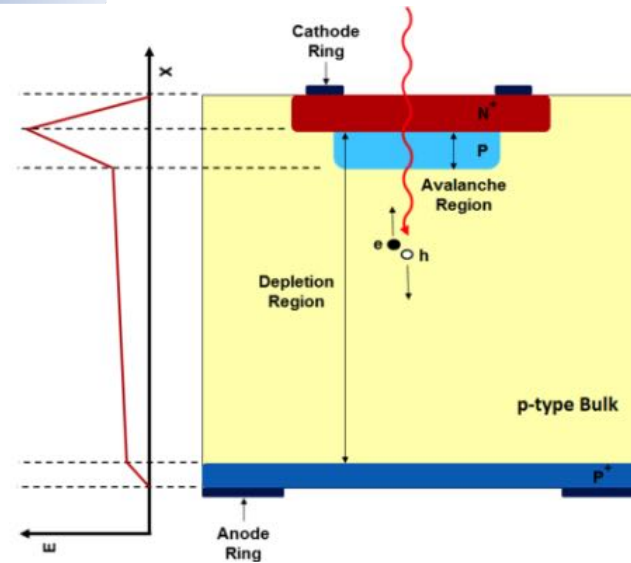
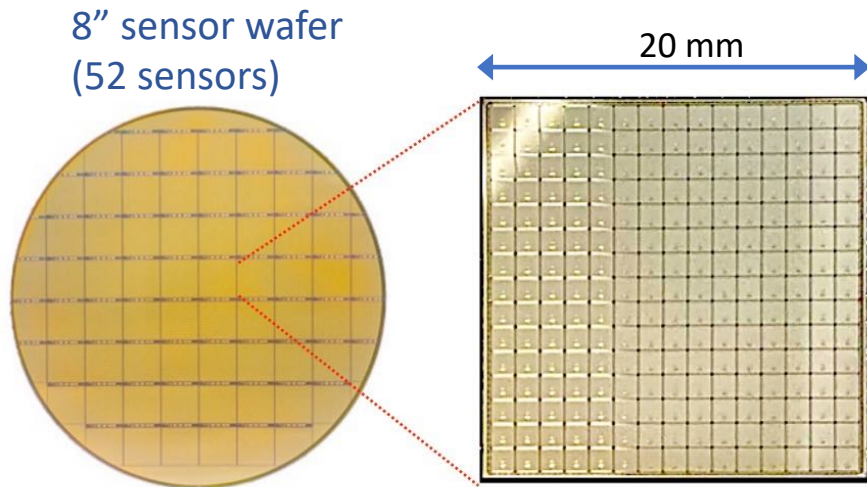
# Performance improvement with HGTD



- Track-timing information from HGTD will allow for recovering the performance in the forward detector regions:
  - Improved rejection of **pile-up**
  - Increased **lepton-isolation** efficiency
- HGTD also allows for measuring the **luminosity** bunch-by-bunch (hit counting at 40 MHz),  $<1\%$  accuracy

# The HGTD LGAD Sensors

- **Low Gain Avalanche Detector (LGAD)** technology utilized for HGTD
- **15×15 pads**
- Pad size: **1.3 mm×1.3 mm**
- **3.6 M** channels
- Physical / active thickness: **775 μm / 50 μm**
- **~22k** sensors to be produced



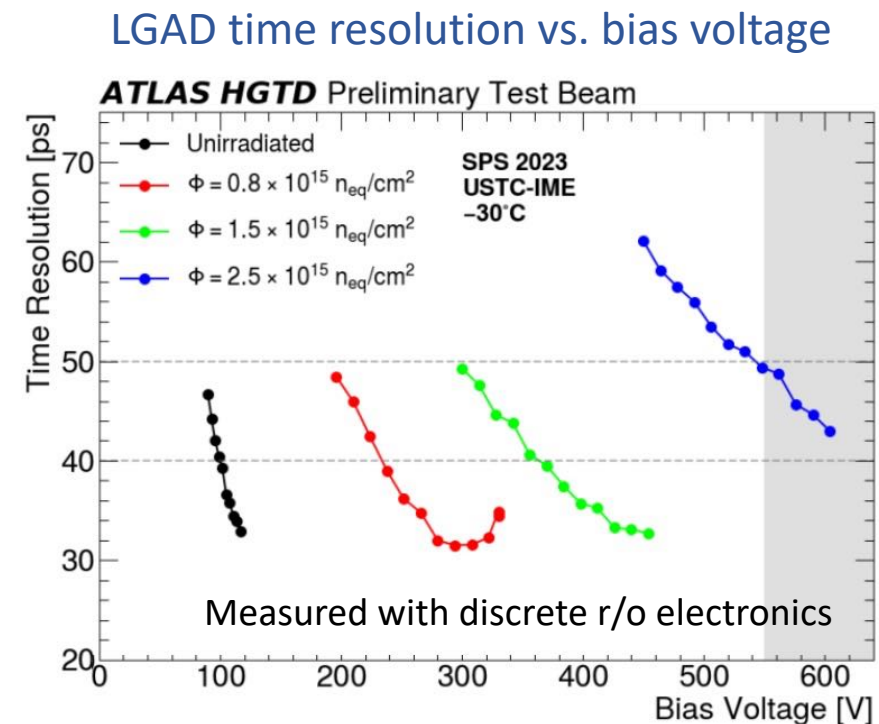
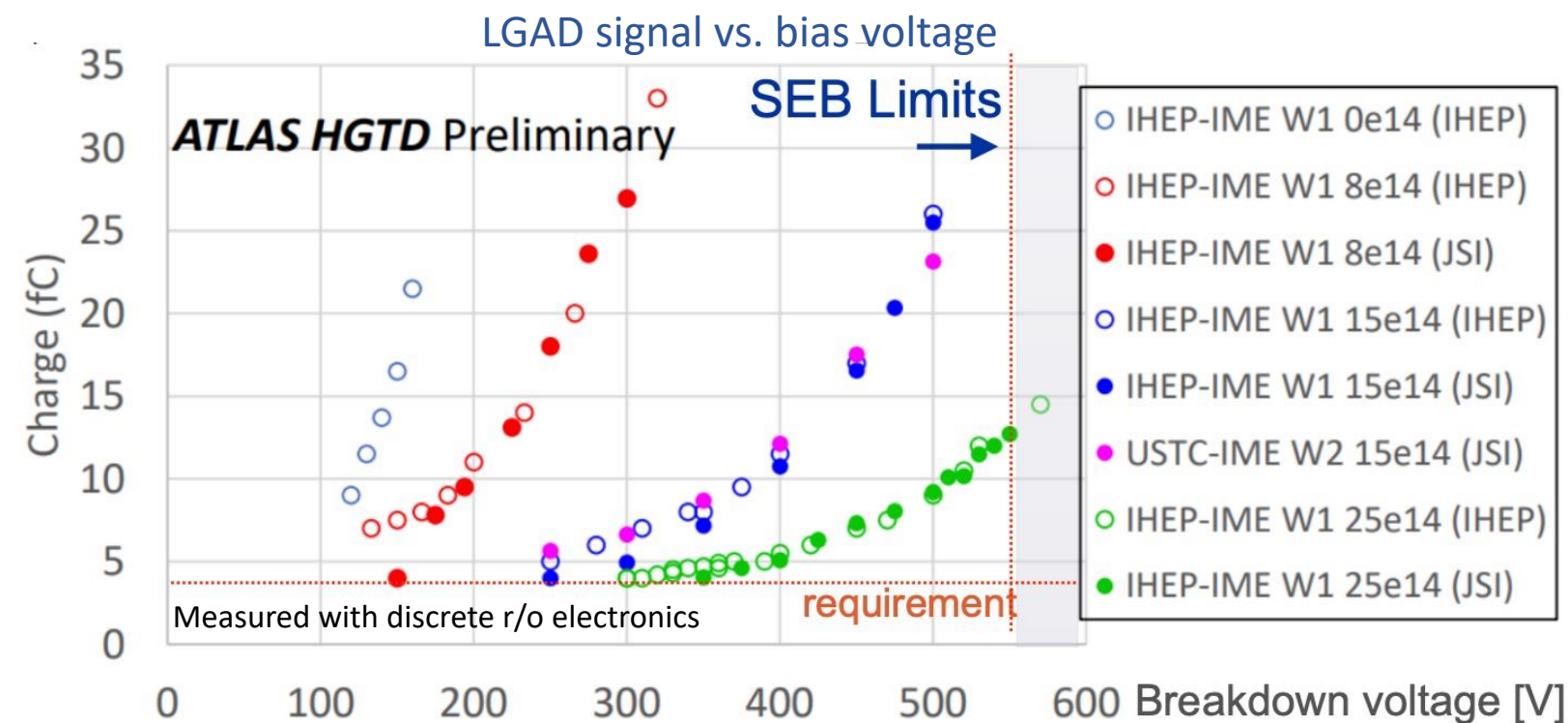
## LGAD Technology:

- N-in-P diode structure
  - extra p-type **gain-layer** for moderate gain 10-40
- Fast **rise time** and larger **signal-to-noise** ratio
- Excellent time resolution

## LGAD sensors requirements:

- Hit-time resolution: **40 ps** (start) - **70 ps** (end)
- Collected charge per hit: **10 fC** (start) - **4 fC** (end)
- Hit efficiency: **97 %** (start) - **95 %** (end)

# LGAD radiation effects



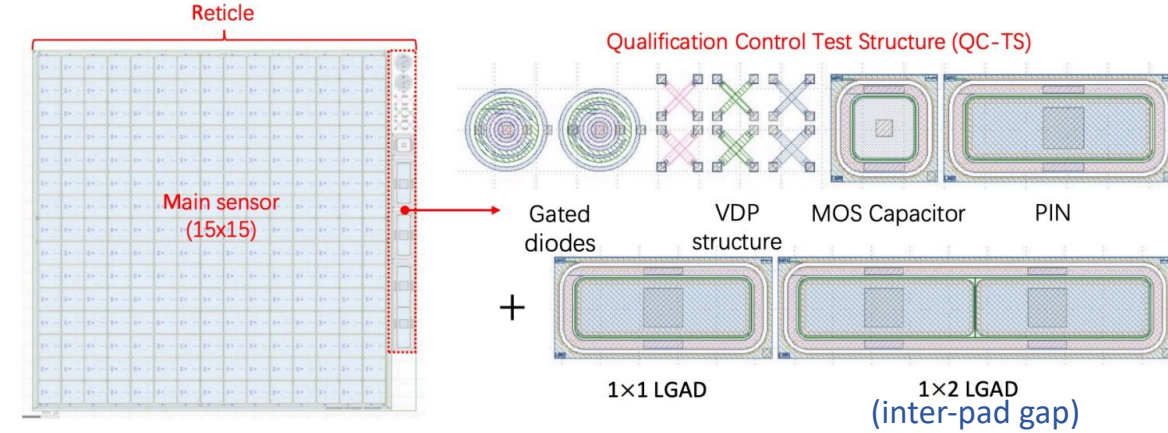
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots>

- 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)  $\rightarrow V_{max} \sim 550$  V for 50  $\mu$ m thickness
- **Carbon enriched gain layer** to reach lower operation voltages and thereby improved radiation hardness.

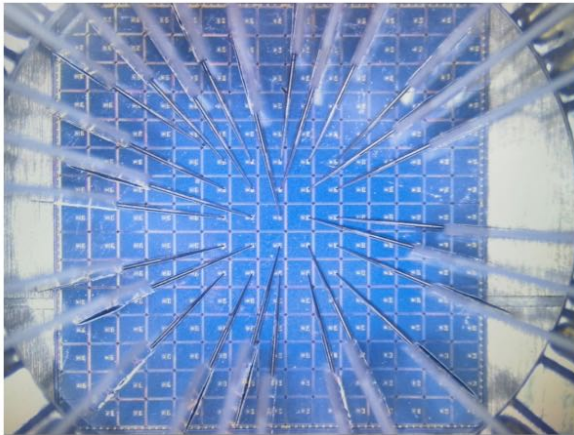
# LGAD sensor production and QC

<https://indico.cern.ch/event/1386009/contributions/6279120/>

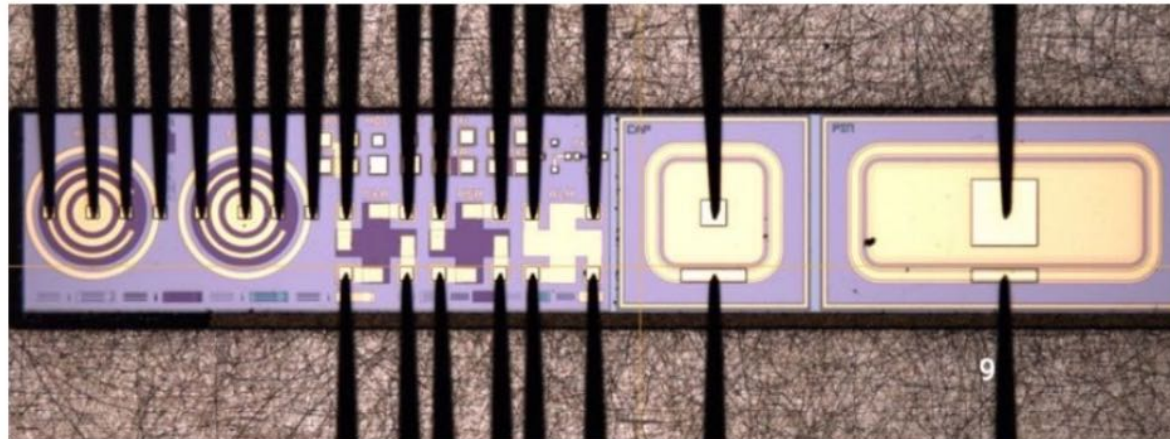
- Pre-series production of a total of **117** wafers (8") (5% of main production, 1100 sensors) recently concluded
- Sensors from two vendors: **IHEP-IME** and **USTC-IME**
- Systematic electrical measurements on all **main sensors** to extract leakage currents and breakdown values
- Electrical measurements on dedicated quality-control test structures (**QC-TS**), to monitor various technological parameters
- **Irradiation tests** on main sensors and QC-TS



Probe-card measurement on main sensor



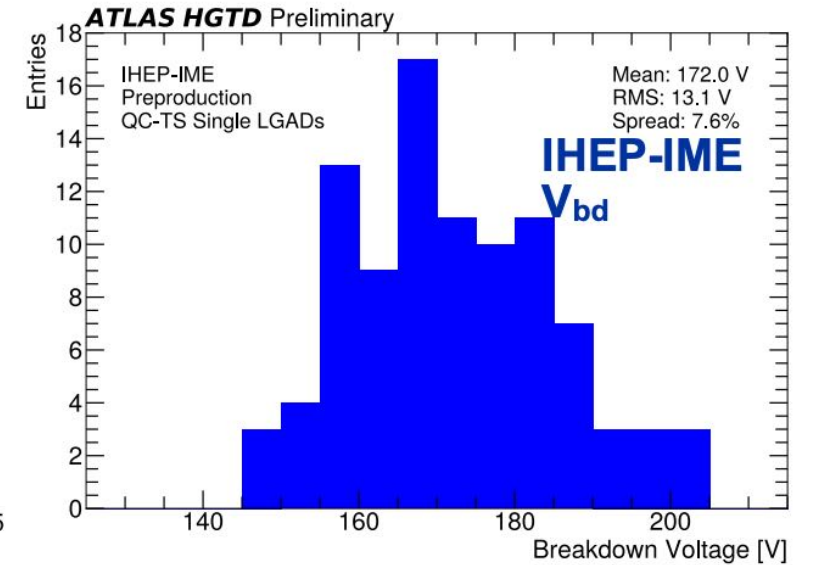
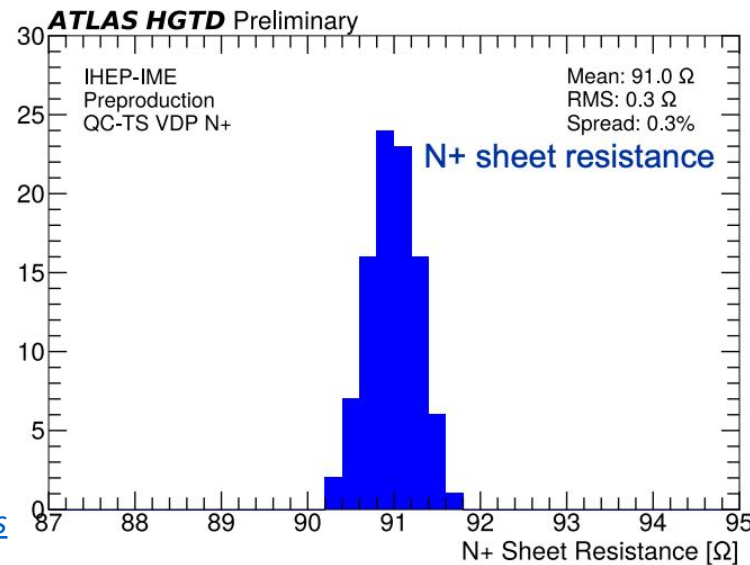
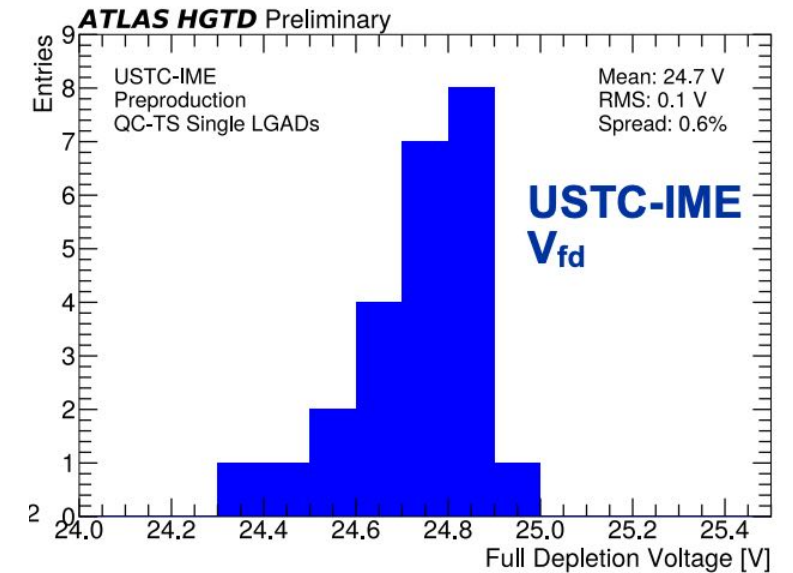
Probe-card measurement on quality-control test structure (QC-TS)



QC Device	Parameter	Description	Technique used
Single LGAD	Vgl	Gain layer depletion voltage	C-V
	Vfd	Full depletion voltage of the device	C-V
	I@Vfd	Current at full depletion voltage	I-V
	Vbd	Device breakdown voltage	I-V
	Cpad	Electrode capacitance	C-V
PIN	Vbd	Breakdown Voltage	I-V
	Ileak	Leakage Current	I-V
MOS	tox	Oxide Thickness	C-V
	Vfb	Flatband Voltage	C-V
VDP NA	R_sheet	Sheet Resistance for N implantation	I-R
VDP PS	R_sheet	Sheet Resistance for P implantation	I-R
VDP AI	R_sheet	Sheet Resistance for Aluminum	I-R

# QC-TS pre-production results

- Measurements on ~10 **QC-TS** per wafer for both vendors
- Results consistent within the specifications / expectations
  - **Break-down voltage:**  $V_{bd}$  spread 5.6% - 7.6% (spec: <8%)
  - **Full-depletion voltage:**  $V_{fd} < 30$  V (spec: <70 V), spread <10%  
→ resistivity >1 kOhm\*cm
  - **Gain-layer depletion voltage:**  $24$  V <  $V_{gl}$  <  $55$  V
  - **Detector capacitance:**  
 $C_{det} \sim 4.2$ - $4.4$  pF (spec: <4.5 pF)
  - **Oxide thickness:**  $\sigma(t_{ox})/t_{ox} < 3\%$
  - **n+ sheet resistance:** <0.3% spread
  - **Inter-pad gap:**  $\lesssim 100$   $\mu$ m



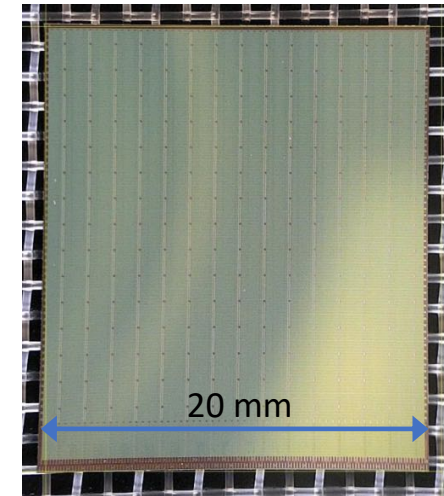
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots>  
<https://indico.cern.ch/event/1386009/contributions/6279120>

# The ALTIROC readout ASIC

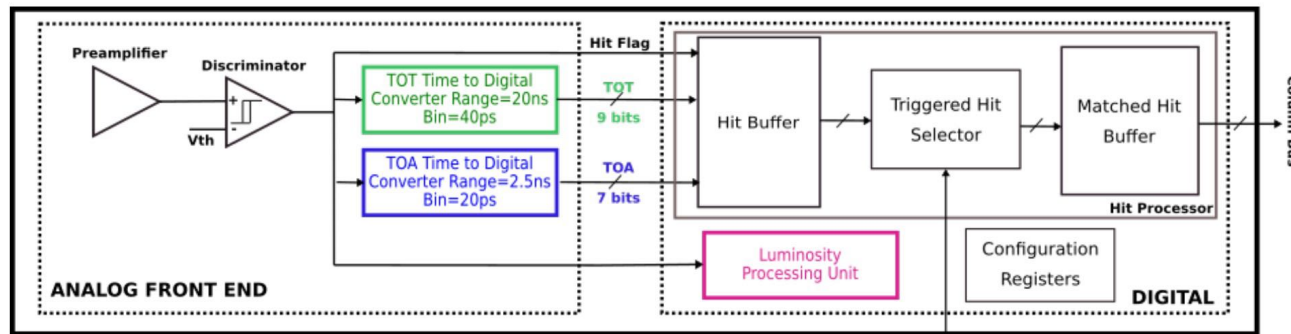
- **ATLAS LGAD Timing Integrated Read-Out Chip (ALTIROC)**
- **225 channels** matching LGAD sensor pixels
- 130 nm **CMOS** from TSMC
- Jitter: < 25 ps at 10 fC (< 65 ps at 4 fC)

- Discriminator threshold  $\geq 2$  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 2 MGy

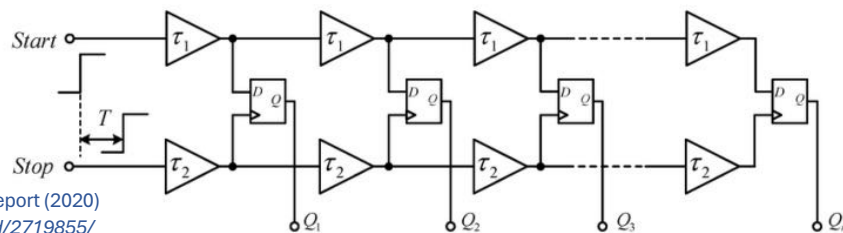
ALTIROC-A



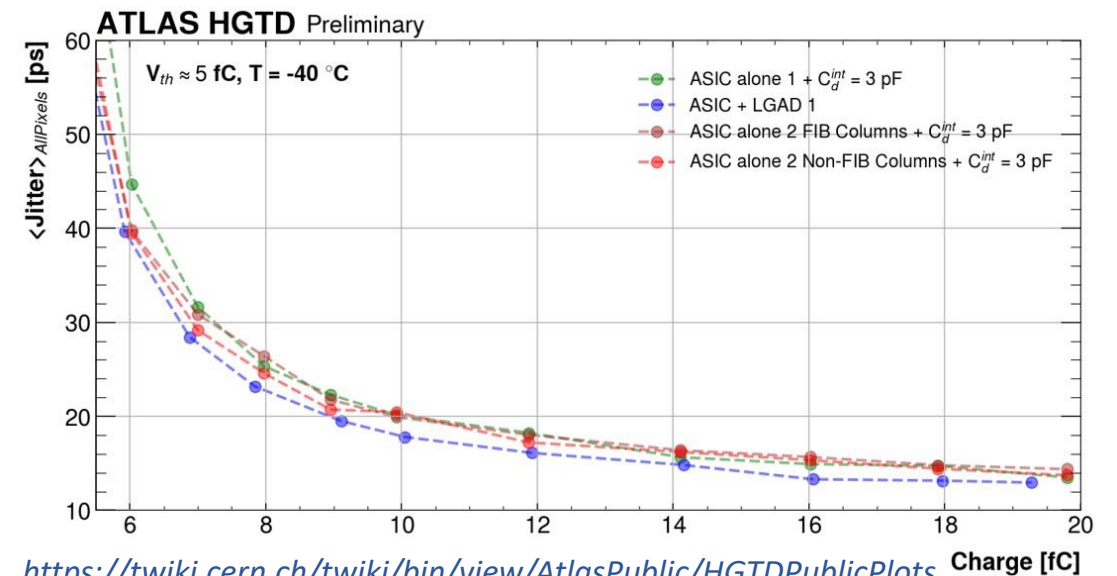
ALTIROC architecture



4 TDC cycles for 32 ToAs each



Jitter vs. charge for ALTIROC-A, detection threshold: 5 fC

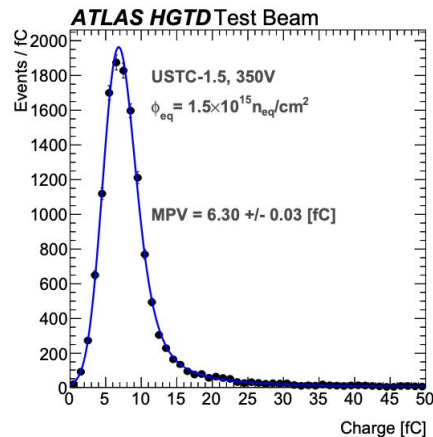


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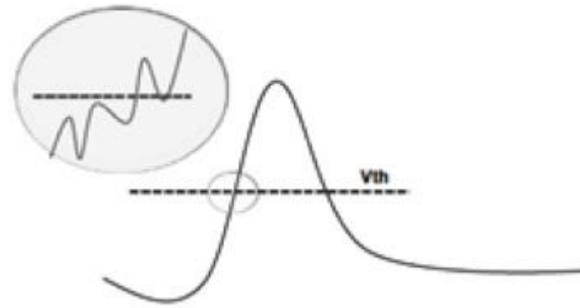
# Contributions to timing accuracy

$$\sigma_{\text{total}}^2 = \sigma_{\text{Landau}}^2 + \underbrace{\sigma_{\text{Timewalk}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Clock}}^2}_{\text{read-out electronics}}$$

- **Landau Contribution:**  
Fluctuations of energy deposition + charge transport in the sensor  
→ Mitigation: Small sensor active thickness (50  $\mu\text{m}$ ), saturated drift velocity  
→  $\sigma_{\text{Landau}} \gtrsim 25 \text{ ps}$



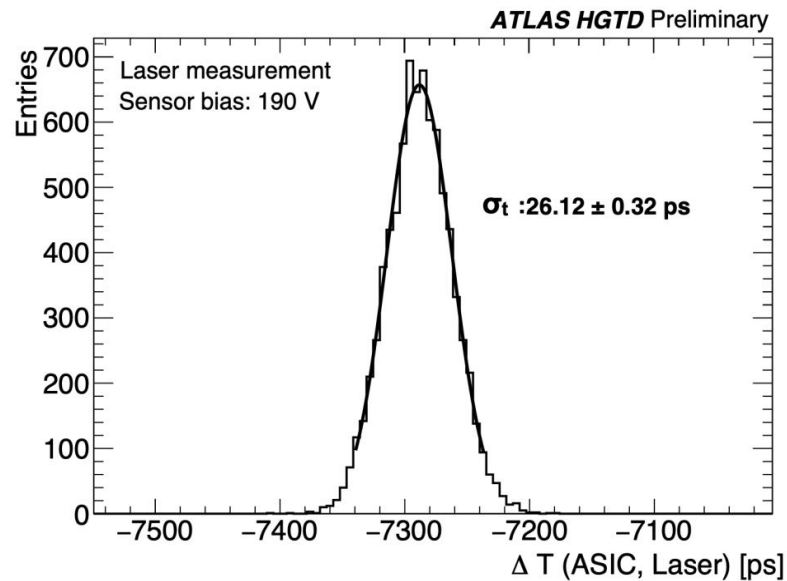
- **Jitter:**  
Due to electronics noise in the signal shape  
→  $\sigma_{\text{Jitter}} = \frac{t_{\text{rise}}}{\text{Signal}/\text{Noise}} \sim 25 \text{ ps}$



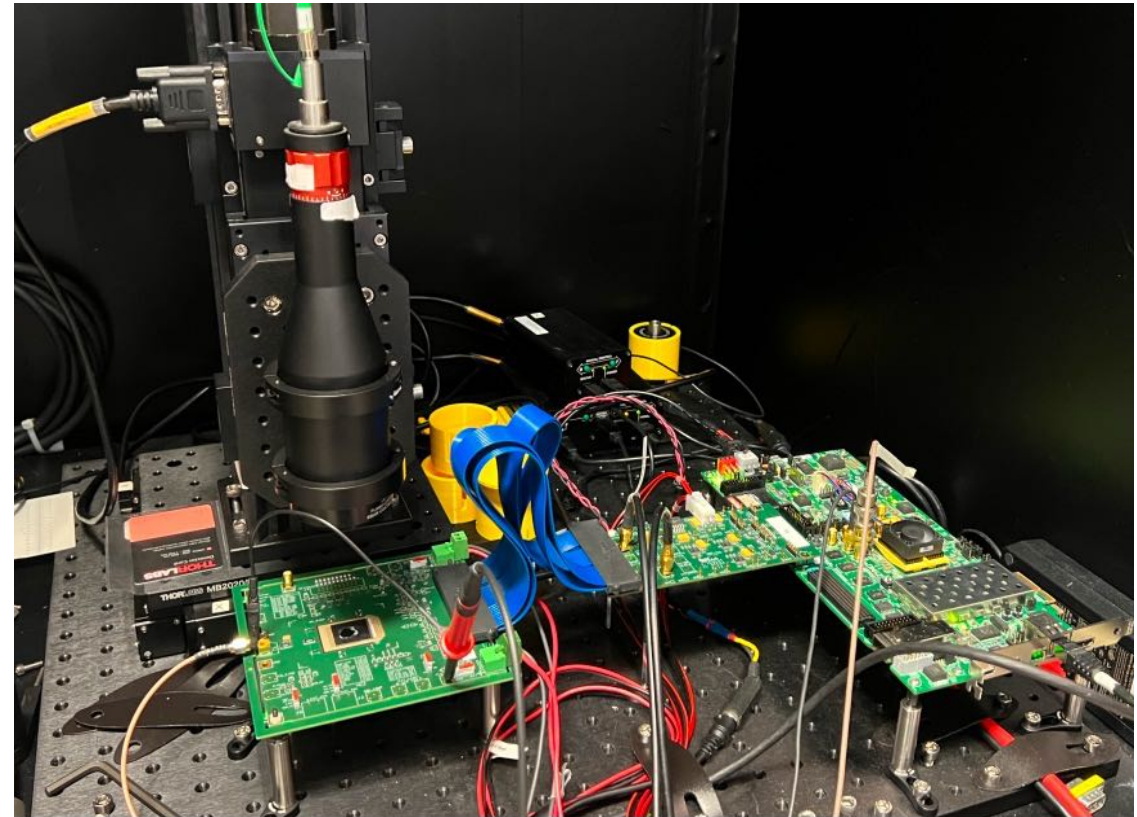
- **Timewalk effect:**  
Time-Of-Arrival (TOA) depends on signal amplitude  
→  $\sigma_{\text{Landau}} = \frac{V_{\text{th}}}{\text{Signal}/t_{\text{rise}} \text{ RMS}}$   
→ Can be corrected based on ToT
- **TDC:**  
From TDC binning / non-linearity  
→  $\sigma_{\text{TDC}} \geq \text{LSB} / \sqrt{12}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

# Jitter Measurements

- **Infrared laser** (1064 nm, sub-mm focus) used to determine jitter
- **Uniform deposition** of constant energy in the sensor
  - Landau and Timewalk contributions negligible
- Time reference: precise signal (3 ps jitter) from laser driver
- Jitter measured to be **~25 ps**
  - Consistent with ASIC test-bench measurements



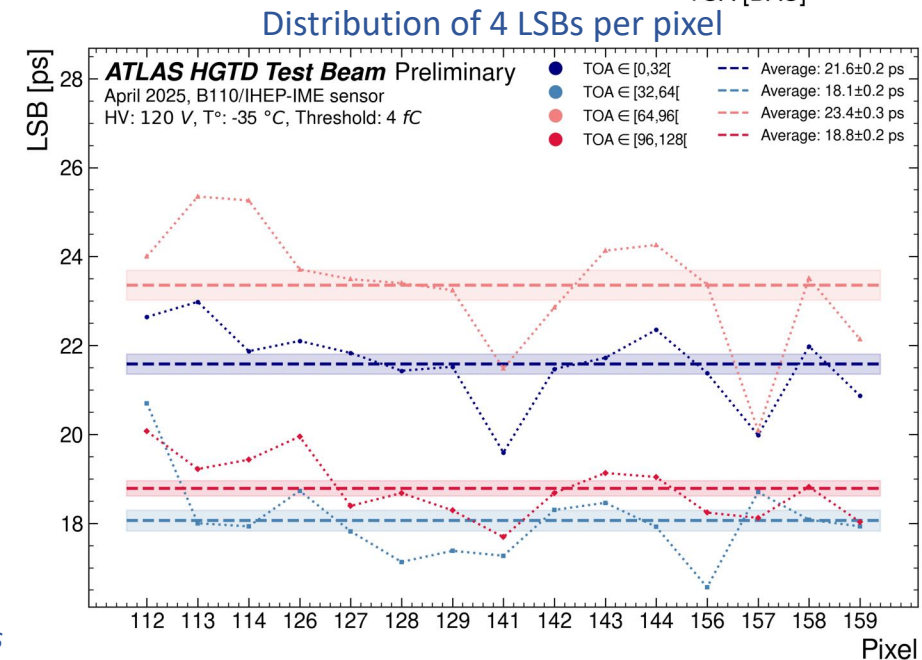
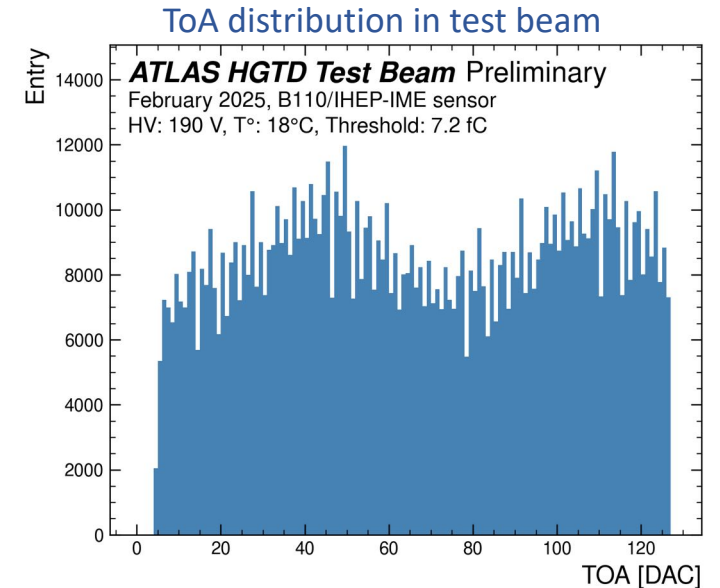
$$\sigma_{\text{total}}^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{Timewalk}}^2 + \underbrace{\sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Clock}}^2}_{\text{read-out electronics}}$$



# TDC bin corrections

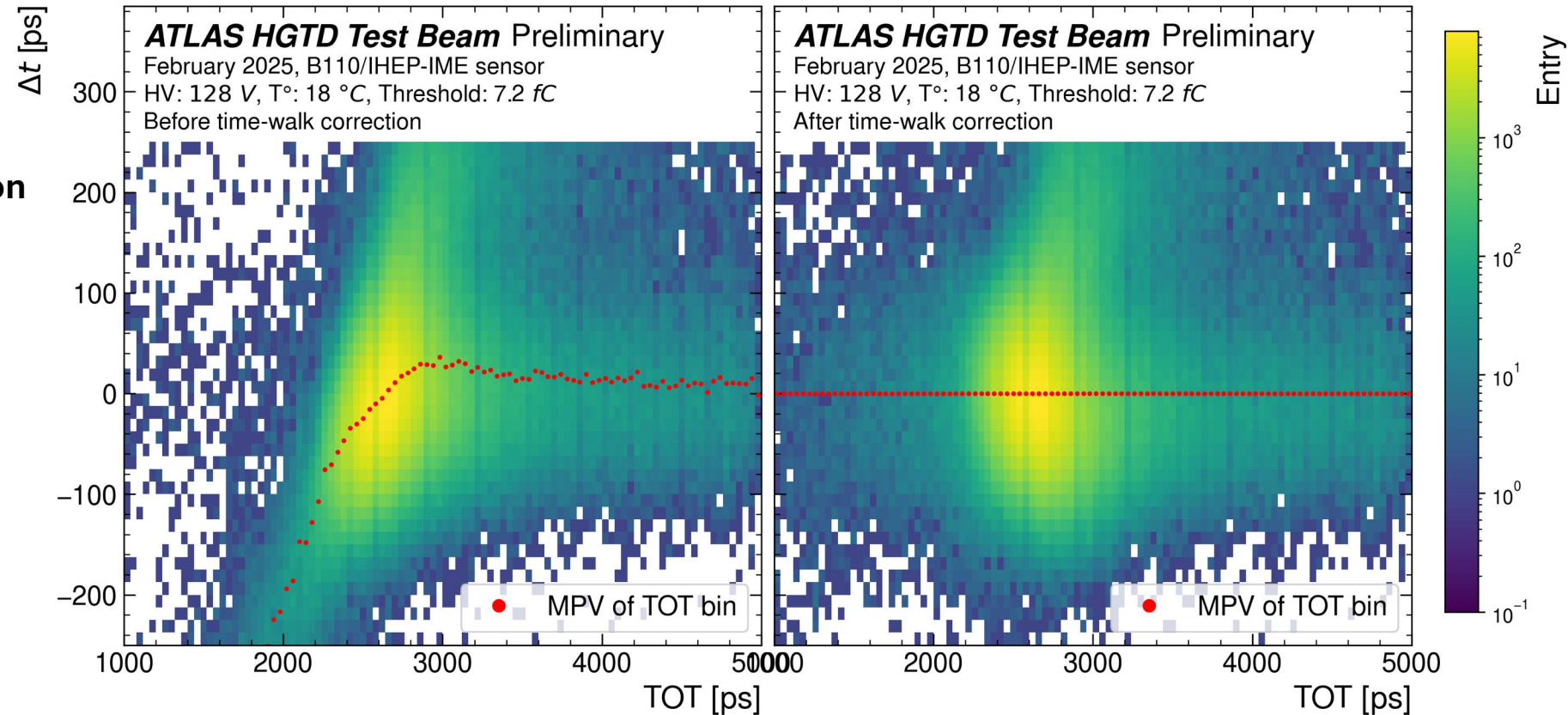
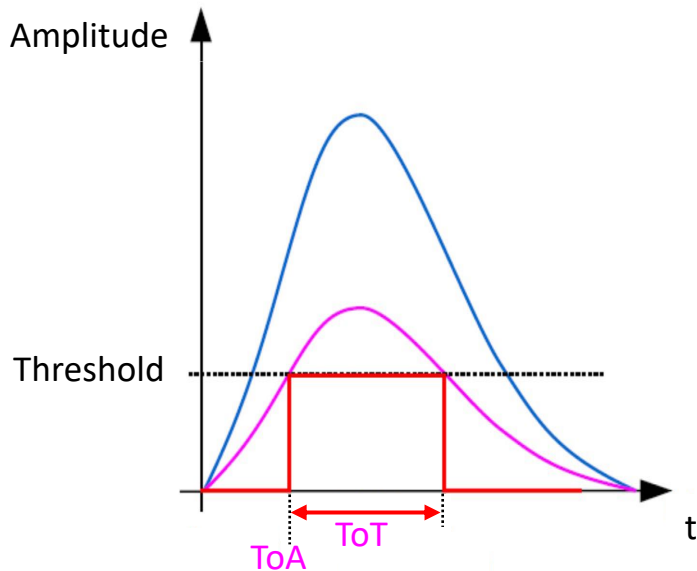
- **ToA** measurement based on Time-to-Digital Converter (**TDC**)
  - Quantization error given by TDC quantization step size (Least Significant Bit = **LSB**)
  - Nominal LSB value: **20 ps**
  - Observed LSB shows variations over the 128 ToA bins from Differential Non Linearity (**DNL**)
  - LSB values depend also on temperature and stability of power supplies
- Several methods developed for **in-situ calibration** of LSBs per-pixel:
- Internal charge injection in ASIC
  - Data-driven calibration from high-statistics test-beam data sets:
    - Either one **global LSB** value per pixel
    - Or one LSB value per group of **32 ToAs**
- gives best results

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



# Timewalk Correction

- **Timewalk** effect: ToA depends on signal amplitude (at constant threshold)
- **ToA** and **ToT** are **correlated**
- Use correlation to obtain **correction**
- Time-walk effect largely reduced after correction

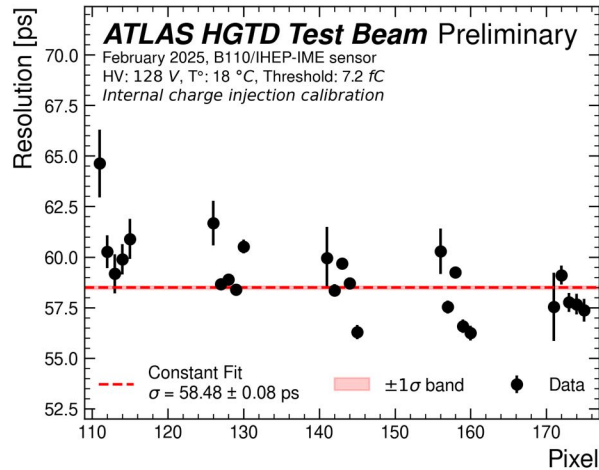


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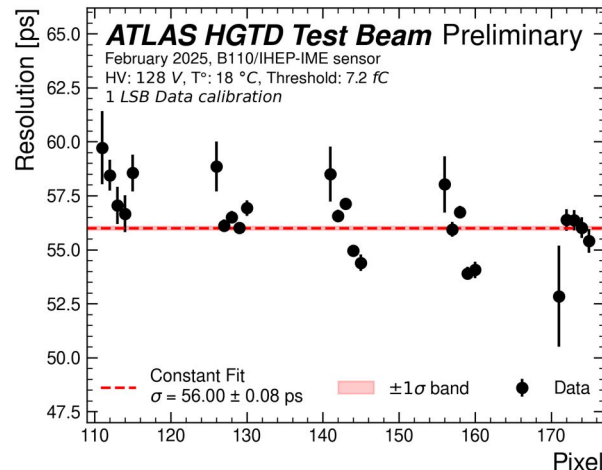
# Hybrid test-beam measurements – ToA calibration

- **Time resolution** is extracted from residuals between ToA measurement and MCP-PMT time reference (tracking not used → sample contains events from the pixel borders)
- ToA values are calibrated:
  - **LSB** of TDC (from charge injection / data-driven)
  - **Time-walk** effects (data-driven)
- Time resolution improves significantly when using data-driven methods and accounting for DNL of TDC

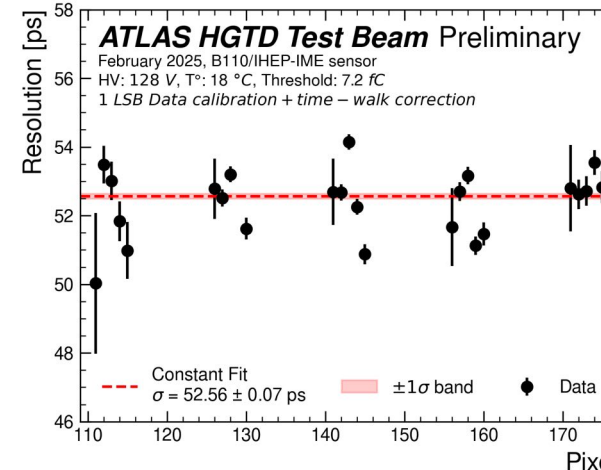
Constant LSB (charge injection), no TWC



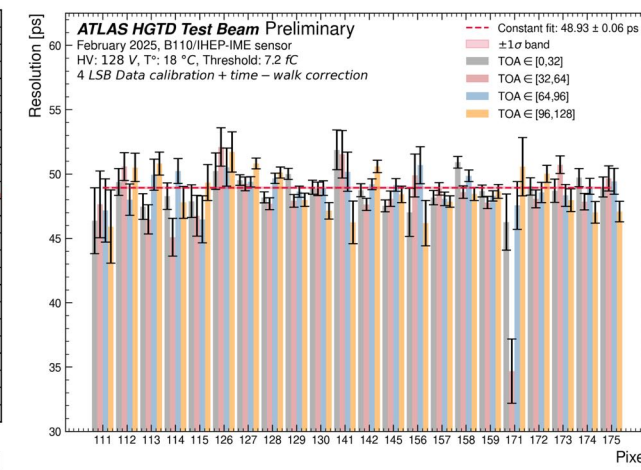
Constant LSB from TB data, no TWC



Constant LSB from TB data, with TWC

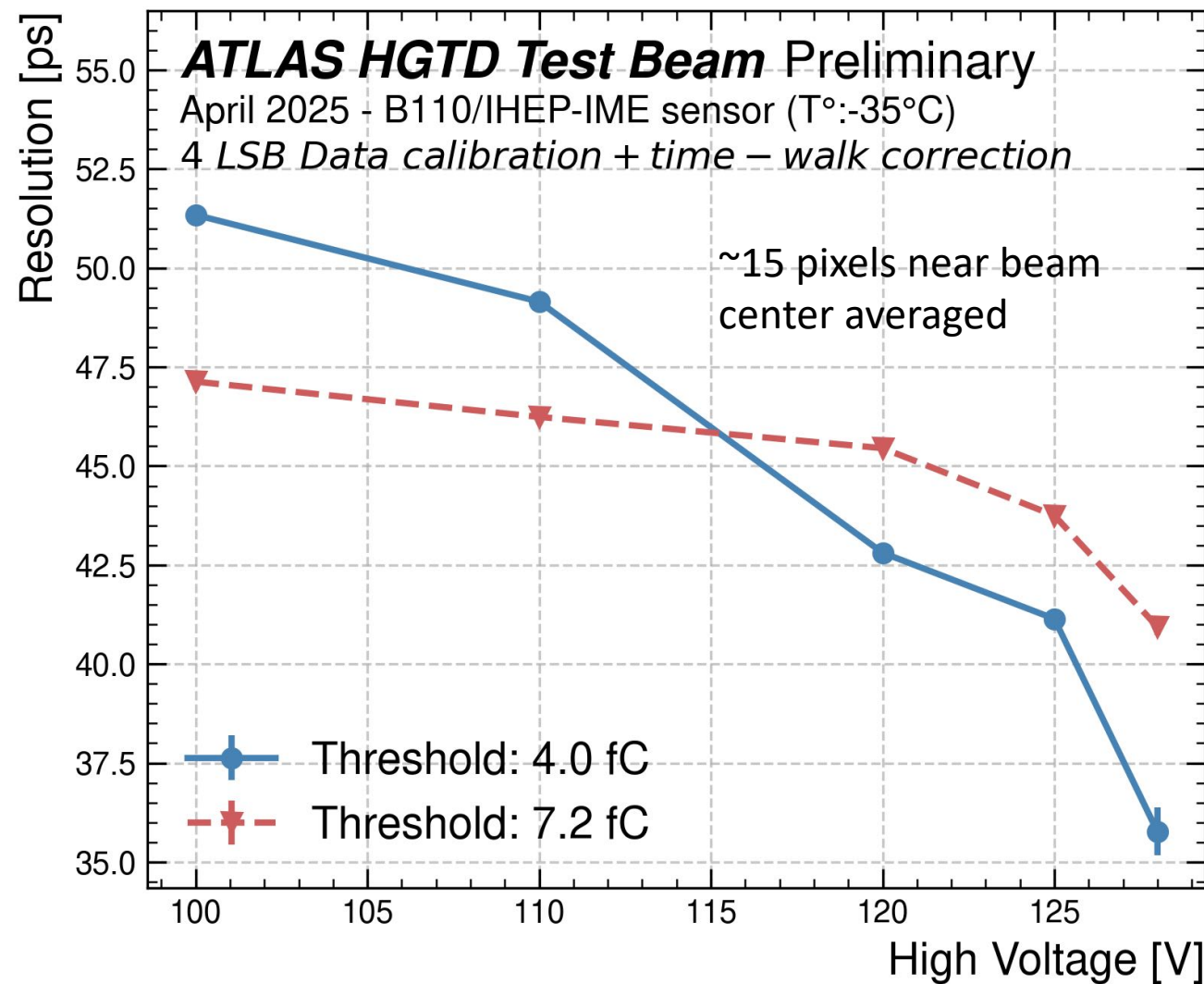
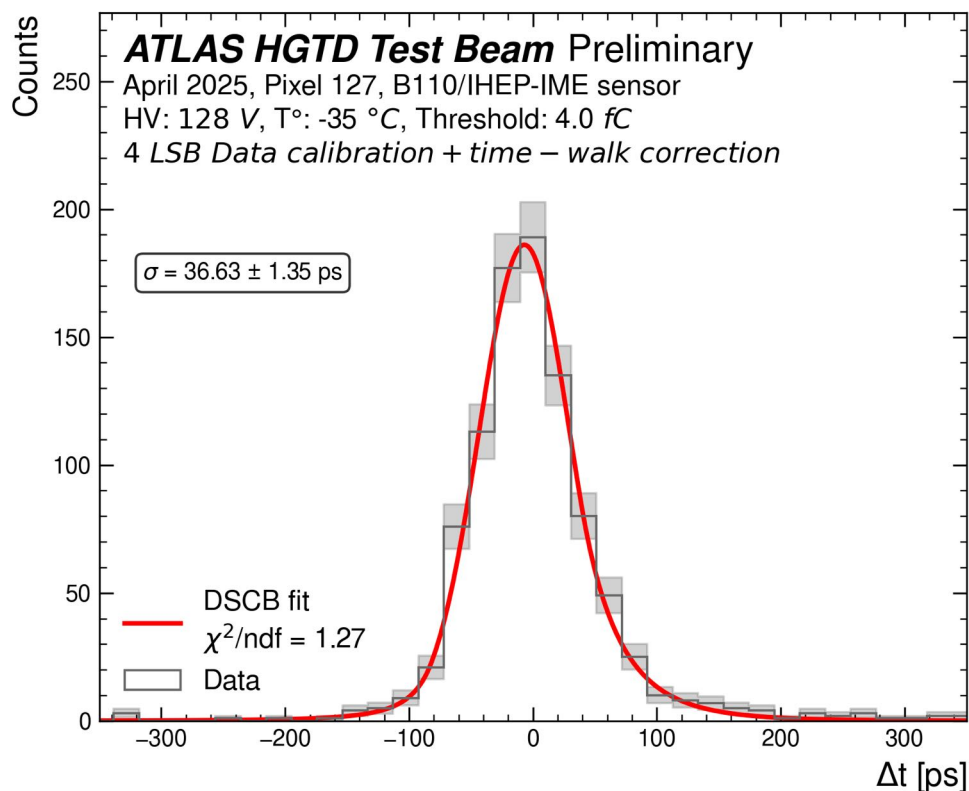


4 LSB from TB data, with TWC

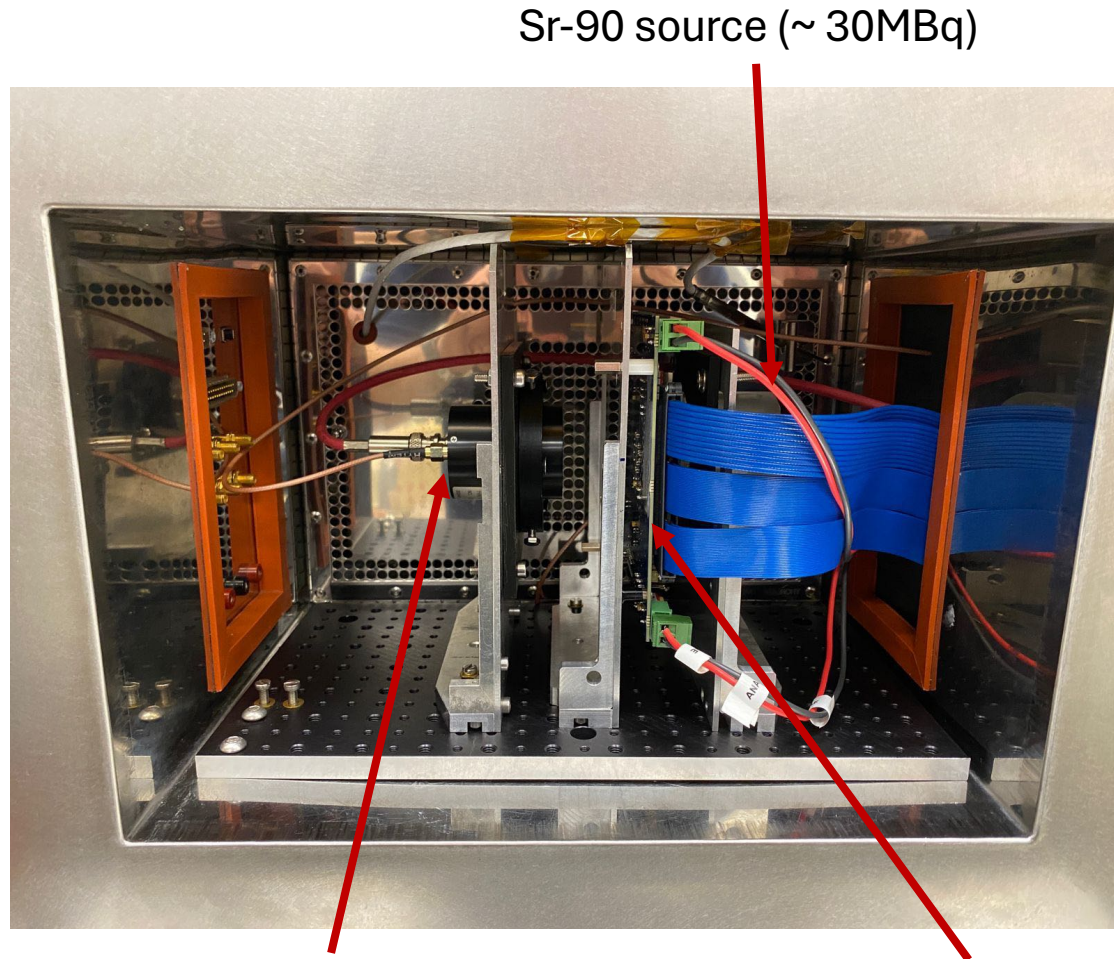


# Hybrid test-beam performance

Performance measurements in **optimal conditions**:  
Low temp. (-35°), high bias voltage (>120 V), low thr. (4 fC)  
→ Timing precision in core of distribution down to **~40 ps**



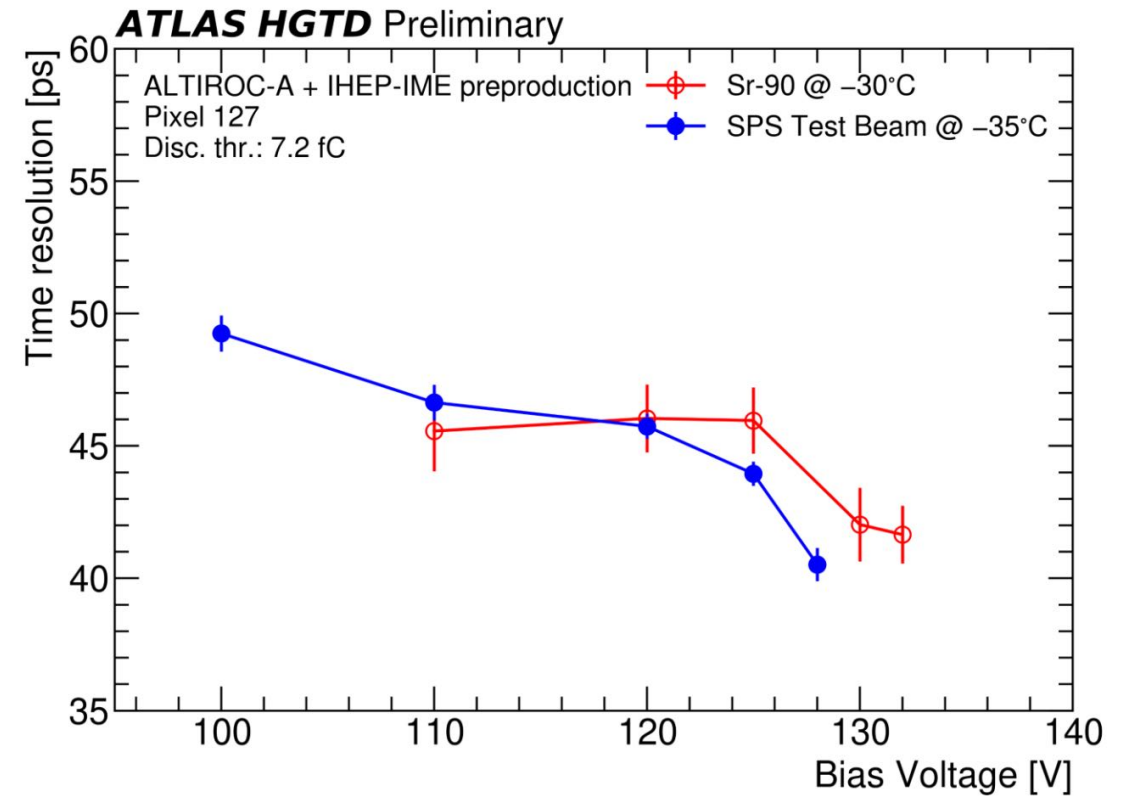
# Hybrid timing measurements with $\beta$ -source



Sr-90 source ( $\sim 30\text{MBq}$ )

MCP-PMT (time reference)

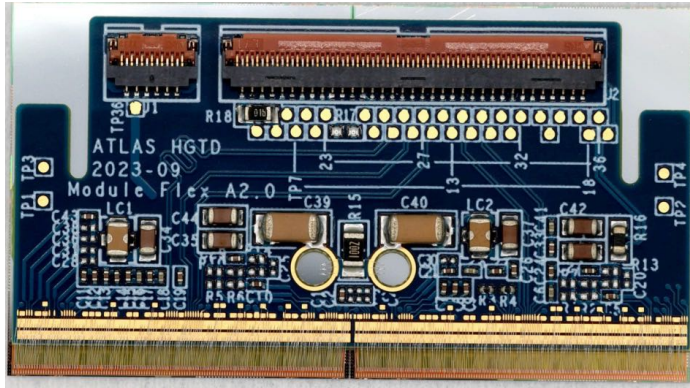
ALTIROC-A + LGAD test board



- Least Significant Bit (**LSB**) calibrated to 20 ps (charge inj.)
- **Time-walk** correction applied for DUT; CFD for MCP-PMT
- Time **resolution**: Std. dev. of Gaussian fit of  $\text{TOA}_{\text{DUT}} - \text{TOA}_{\text{MCP}}$ 
  - **$\sim 45$  ps** achieved for 7 fC threshold, consistent with test-beam results
  - **Uniform** behavior for all pixels

# Module test-beam results

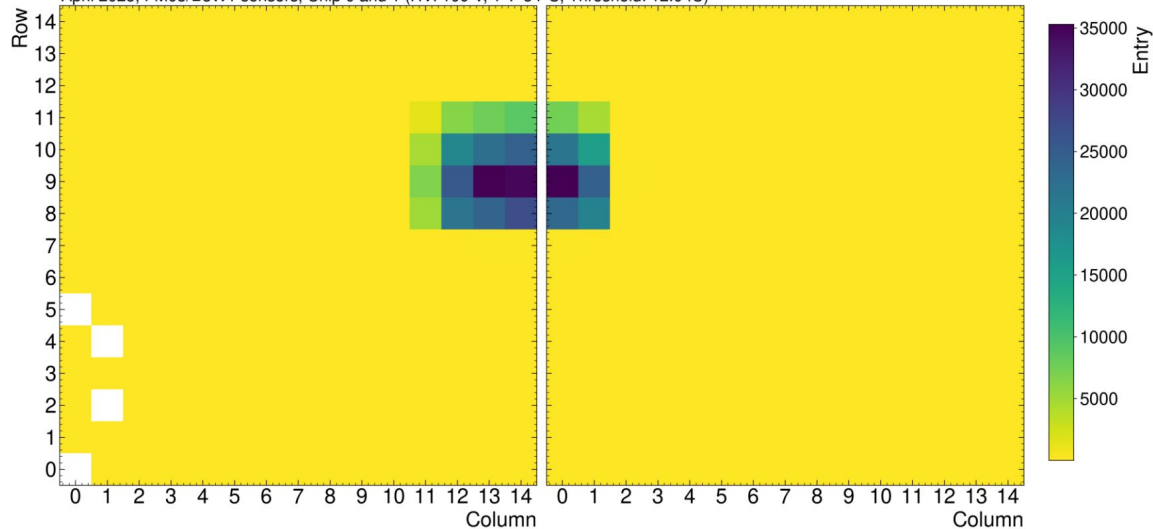
Wire-bonded HGTD module



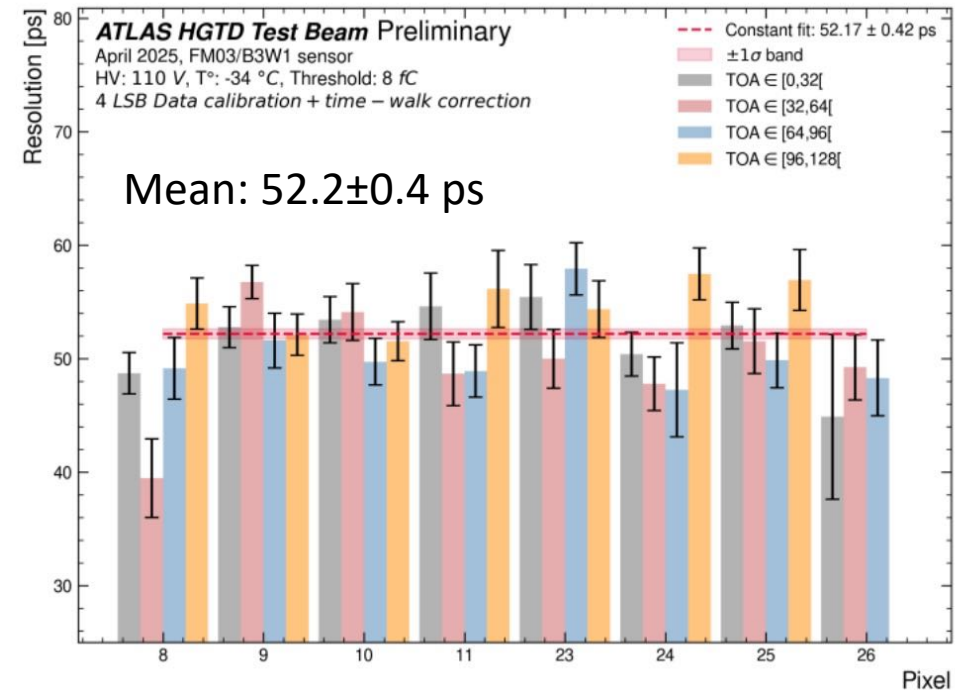
- HGTD made of 8032 modules: 2 ASICs + 2 sensors, sharing one HV bias channel
- Module performance is studied in ongoing lab and test-beam measurements
  - <50 ps timing achieved in test beam, after calibration and time-walk correction
  - HL-LHC 40 MHz clock is expected to have negligible contribution

Module-occupancy in test beam

**ATLAS HGTD Test Beam Preliminary**  
April 2025, FM03/B3W1 sensors, Chip 0 and 1 (HV: 100 V, T°: -34°C, Threshold: 12.0 fC)

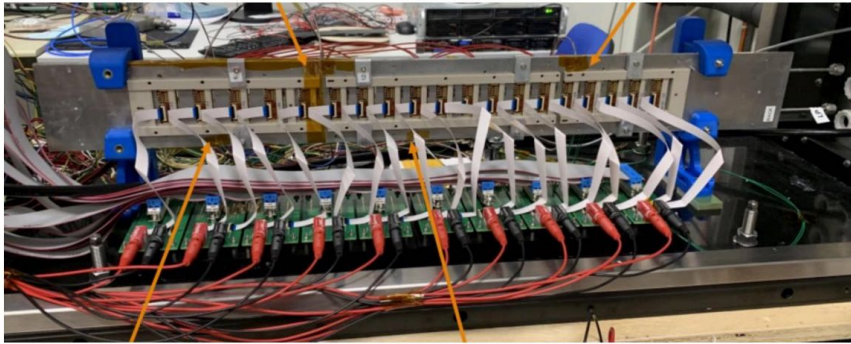


Module test-beam time resolution



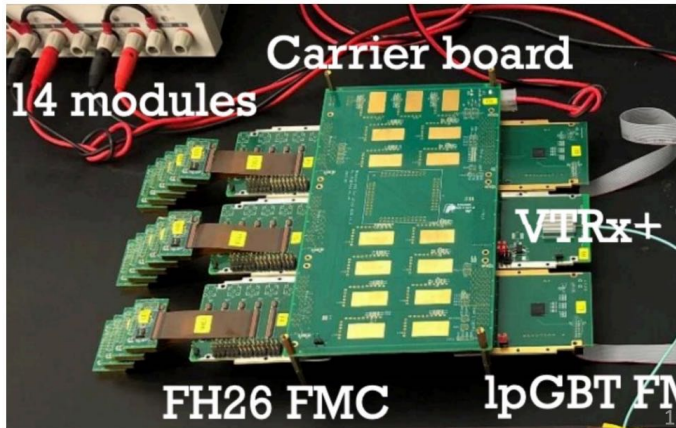
# System-level tests

## Thermal demonstrator



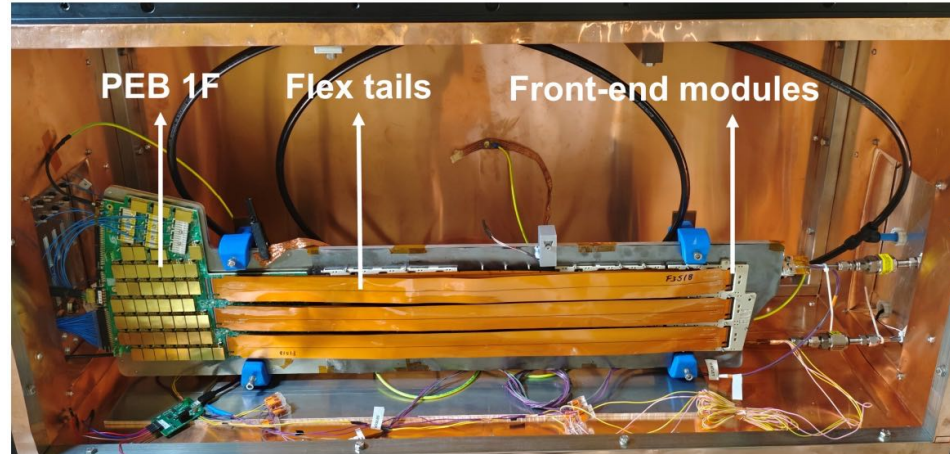
→ CO2 cooling tests with realistic heat load

## DAQ demonstrator

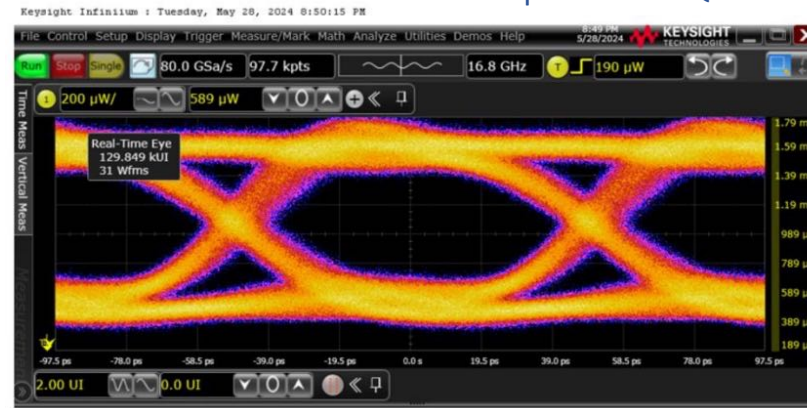


→ Testing readout path from module to FELIX FPGA DAQ cards, using final components of the peripheral electronics boards (PEBs)

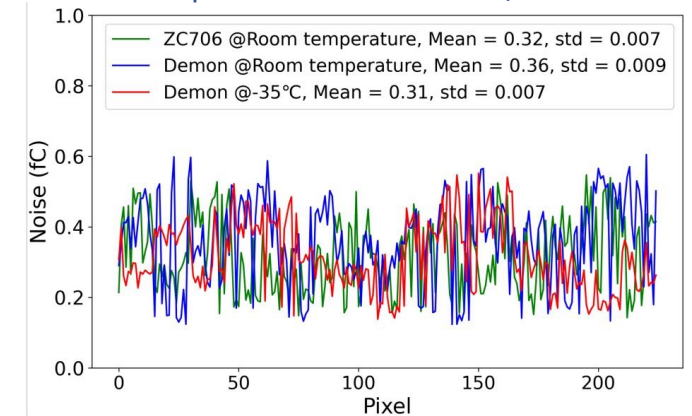
Full demonstrator - 1 peripheral electronics board (PEB) connecting 54 modules on 4 support units + cooling



## Data-transfer test from the lpGBT to DAQ



## Noise comparison demonstrator / test bench

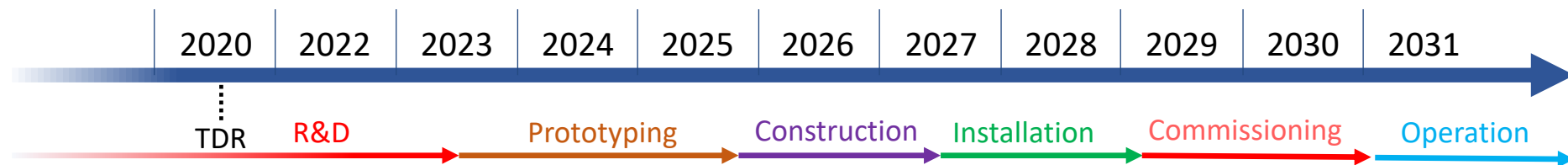


→ Tests of all components on system level, including HV/LV, interlocks

JINST 19 (2024) C12012

# Conclusions

- HGTD under construction, to mitigate pile-up effects at HL-LHC
- QC methods developed and validated for upcoming sensor production
- Extensive testing of LGAD sensors, test structures, hybrids and modules
- Sensors meet requirements for timing, charge, and uniformity
- Hybrids and modules show good performance after calibrations, down to  $\sim 40$  ps
- Moving towards system-level tests and detector construction

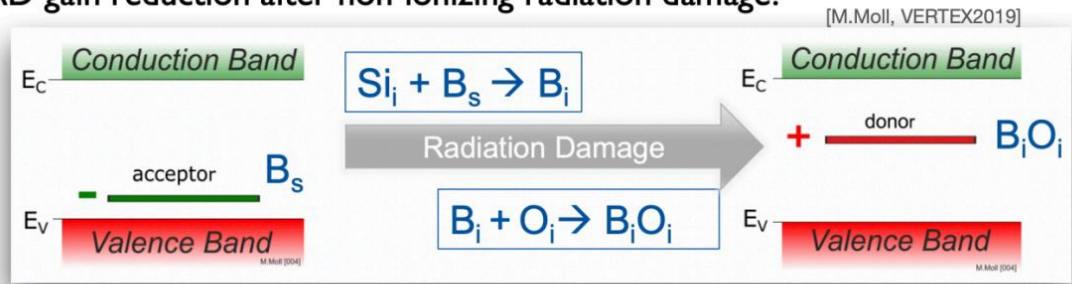


# Additional material

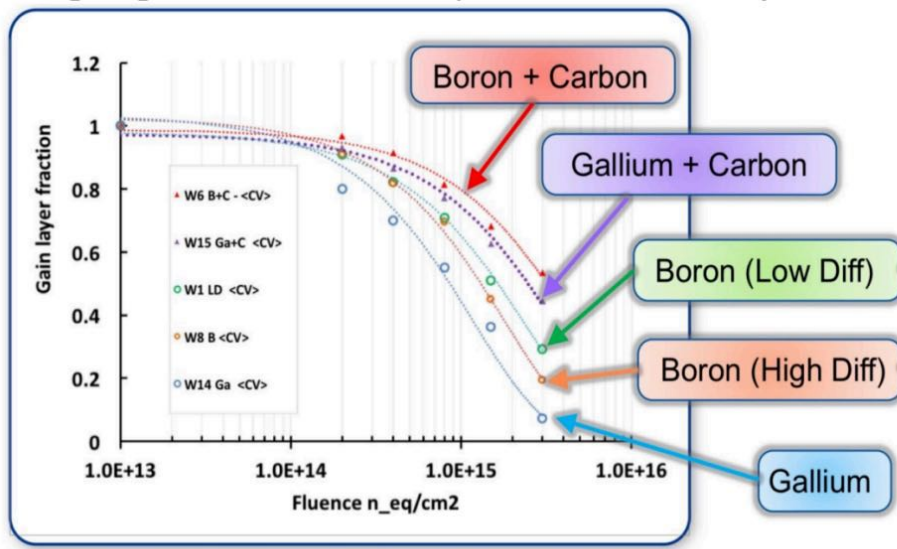
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# Carbon implantation

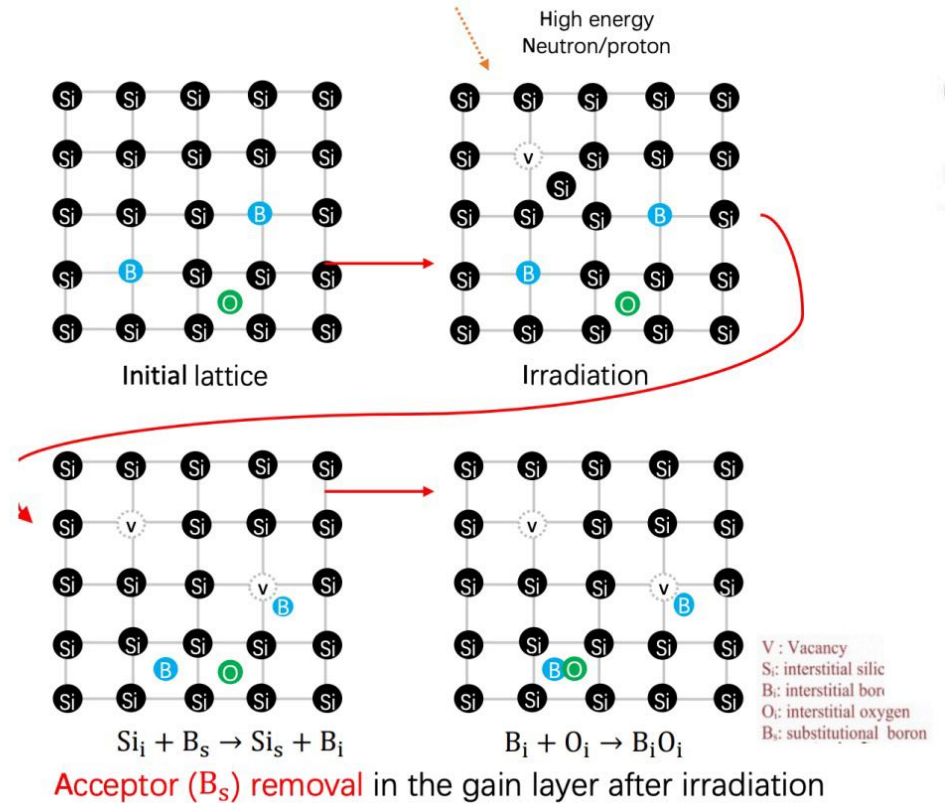
- The reduction of effective doping in the gain layer is caused by the “acceptor removal” process  
→ LGAD gain reduction after non-ionizing radiation damage.



- Explored use of different gain layer designs, doping materials and C-enriched substrates  
→ **B + C** shows largest gain after irradiation ( $C_i + O_i \rightarrow C_i O_i$  competes with  $B_i + O_i \rightarrow B_i O_i$ )



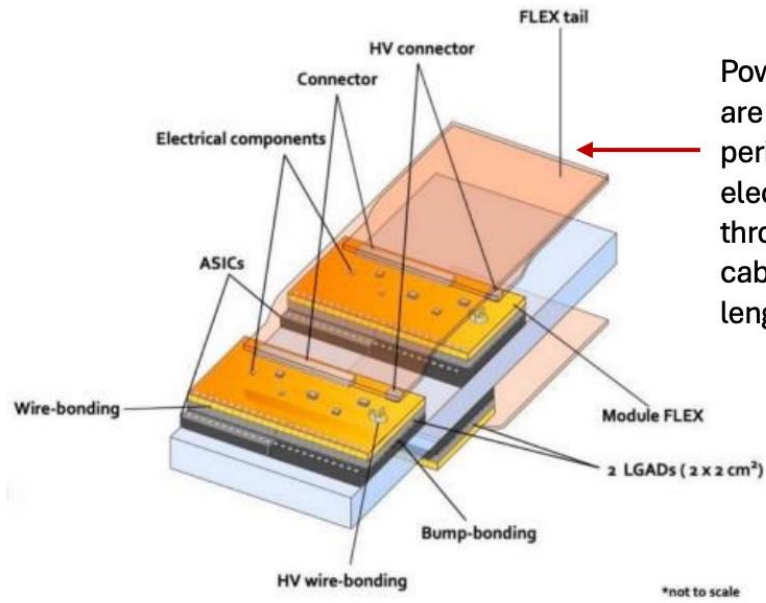
G.Paternoster, TREDI 2019



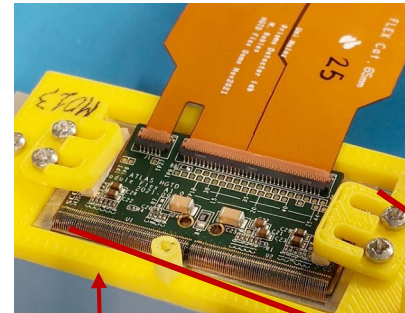
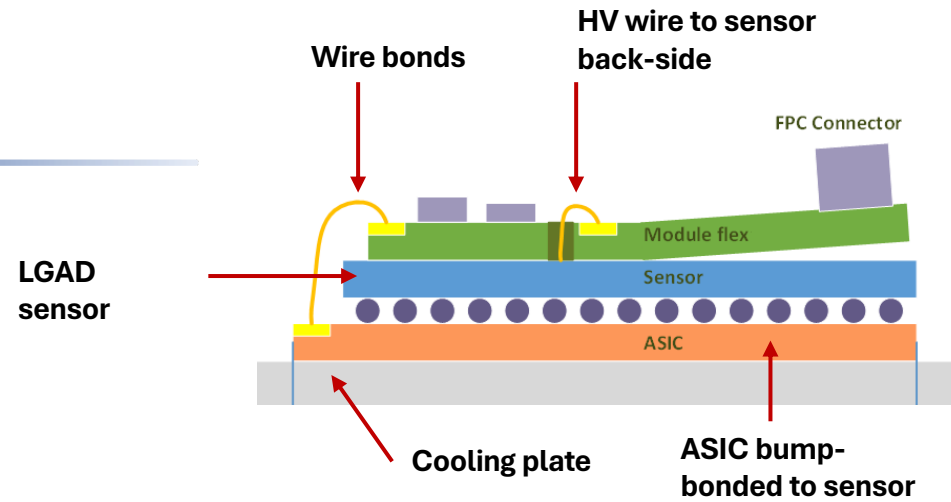
# The HGTD Modules

An **HGTD module** consists of:

- Two **sensors** ( $2\text{ cm} \times 2\text{ cm}$ )
- Two **ALTIROC ASICs** ( $2\text{ cm} \times 2\text{ cm}$ )
- A **module flex**
- A **flex tail**

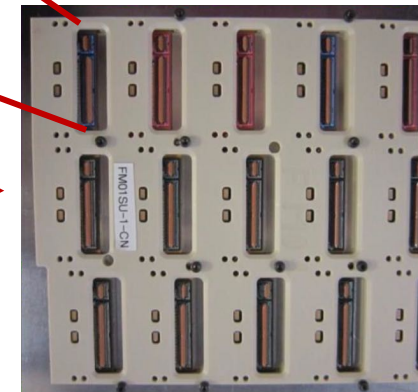


Power and signal are routed to the peripheral electronics through flexible cables of different lengths (flex tail)



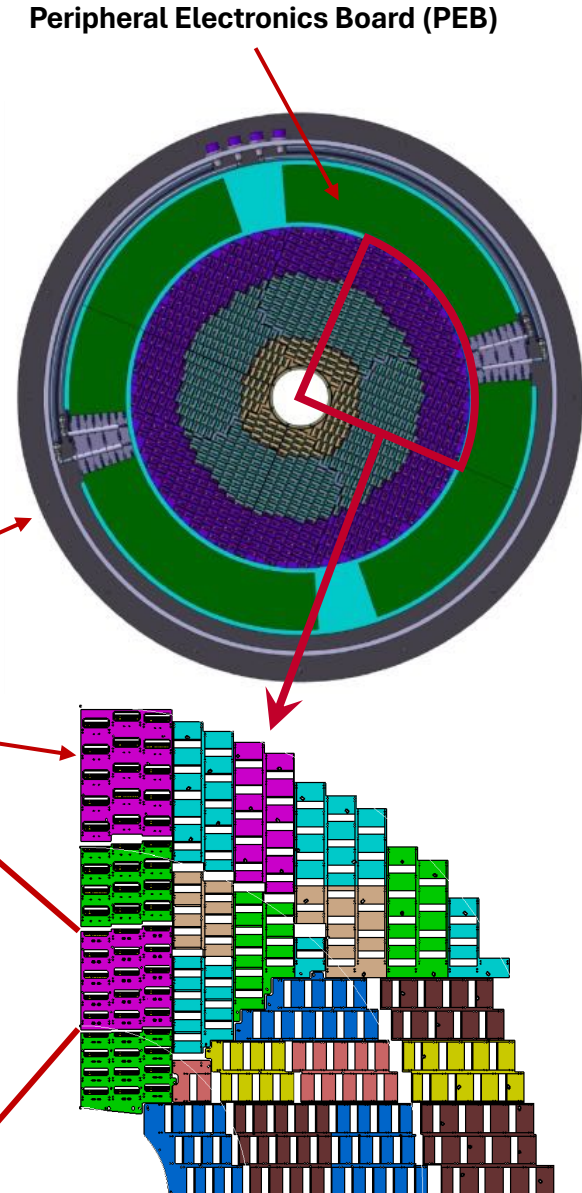
**Module**

**Detector Unit (DU)**



**An HGTD disk**

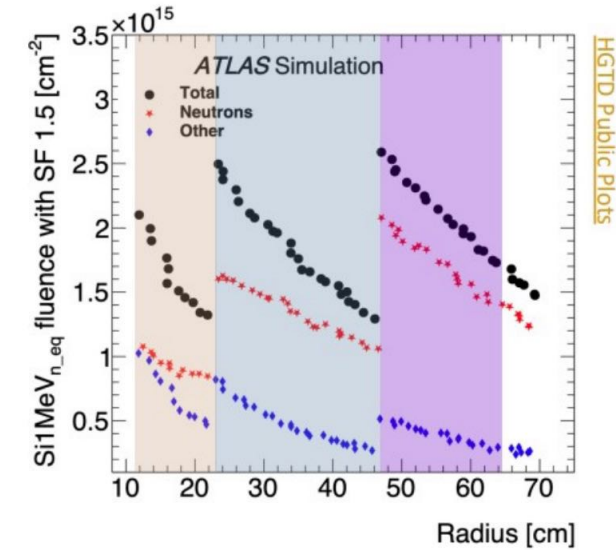
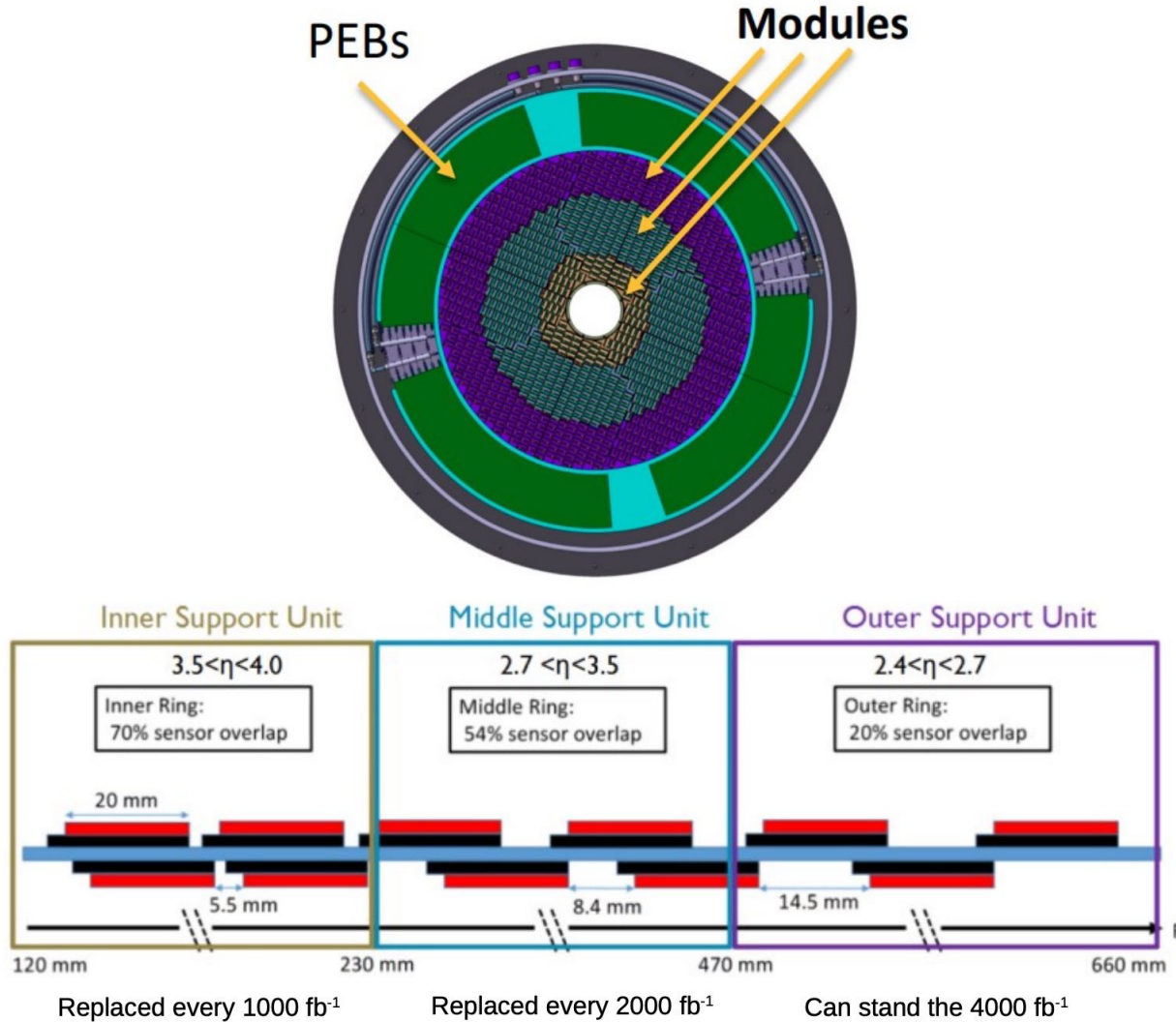
**Disk quadrant of the HGTD active region (24DUs)**



<https://indico.cern.ch/event/1469148/contributions/6460347/>

# HGTD radiation hardness

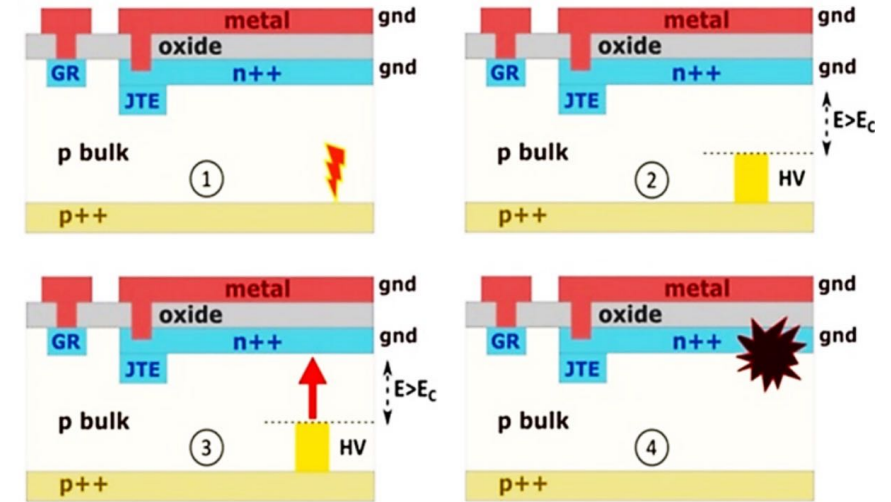
- Detector segmented into three independently replaceable rings:



Maximum fluence  **$2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$**   
and **2 MGy** at the end of HL-LHC  
(after 4000  $\text{fb}^{-1}$ )

# Single Event Burnout (SEB)

- **Irreversible breakdown** triggered by a large charge deposition at high operation voltages
- Triggered by a **single particle**
- Large energy deposits: **electric field collapse in presence of high concentration of free carriers**
- Observed in several test beam campaigns
- Common effort of **ATLAS/CMS/RD50** collaborations: determine a safe operating voltage
- Systematically studied at HGTD test beams
- Safe operating zone: **11V/ $\mu\text{m}$**
- For 50 $\mu\text{m}$  sensor thickness: **550V**



Source: L.A. Beresford et al. JINST 18 P07030

