

The ATLAS High Granularity Timing Detector: Results from Hybrids in Test Beam and Test Bench Studies

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on behalf of the ATLAS HGTD Group

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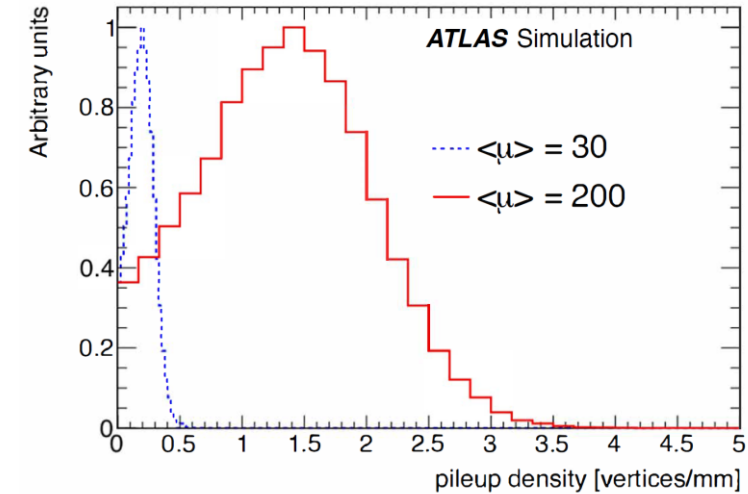
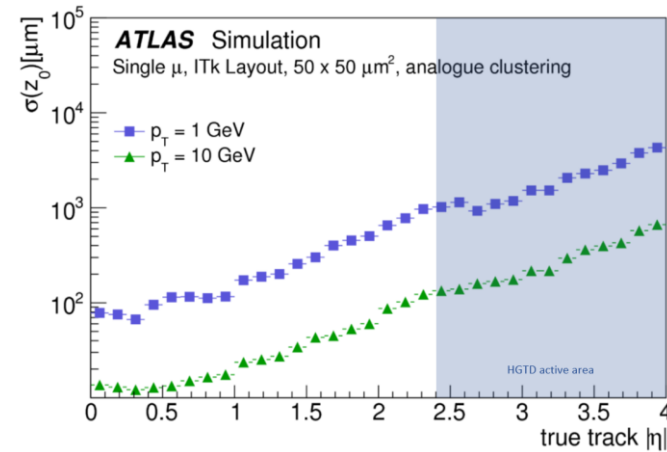
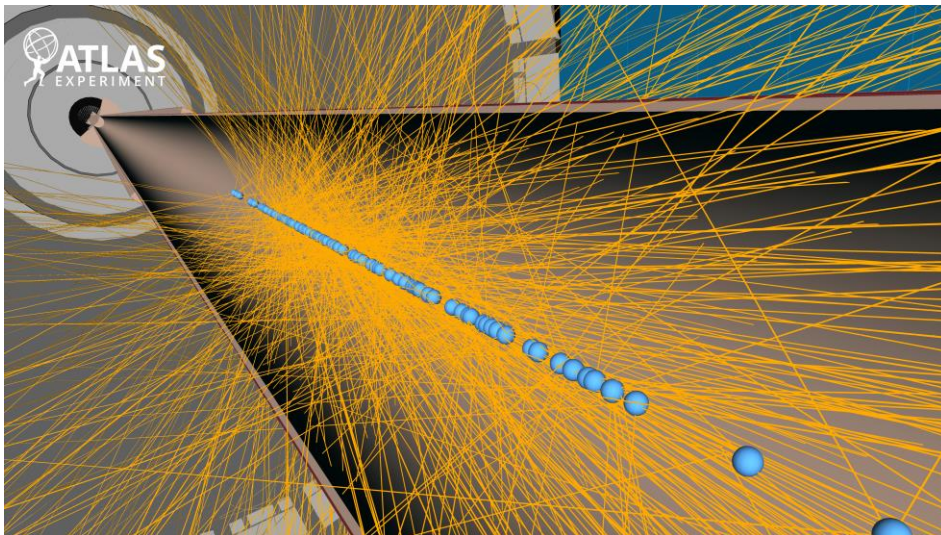


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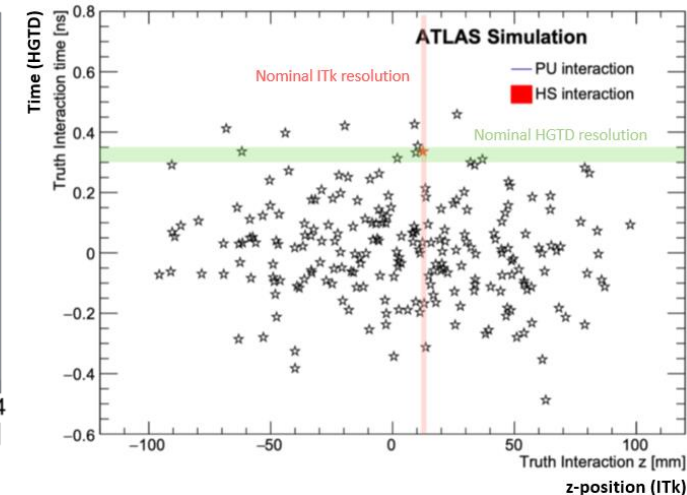
High Luminosity LHC

High Luminosity LHC (HL-LHC):

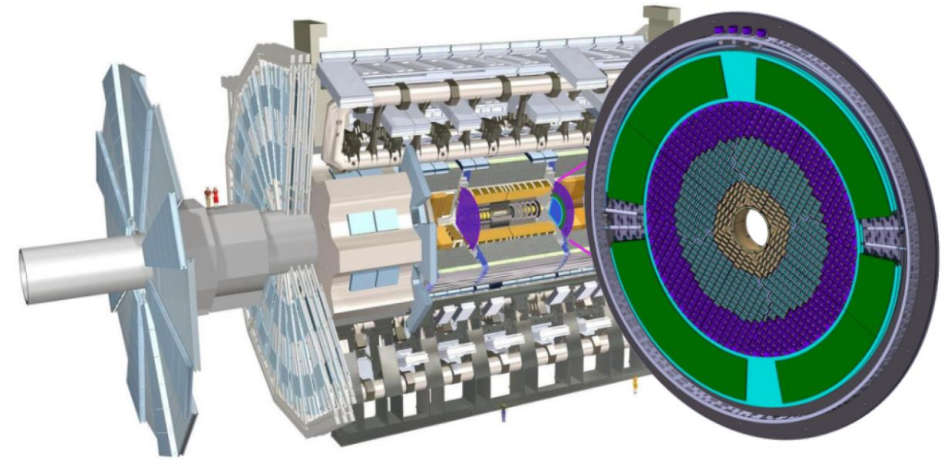
- Operational from 2030
 - Instantaneous luminosities up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - Pile-up $\langle \mu \rangle = 200$ interactions per bunch crossing (on average 1.6 vertices/mm)
- Resolution in longitudinal direction limited in the forward region: correct assignment of tracks to vertices becomes challenging for the ATLAS detector
- Adding timing information in the end-cap region improves pile-up rejection and vertex reconstruction



Images: HGTD Technical Design Report (2020)

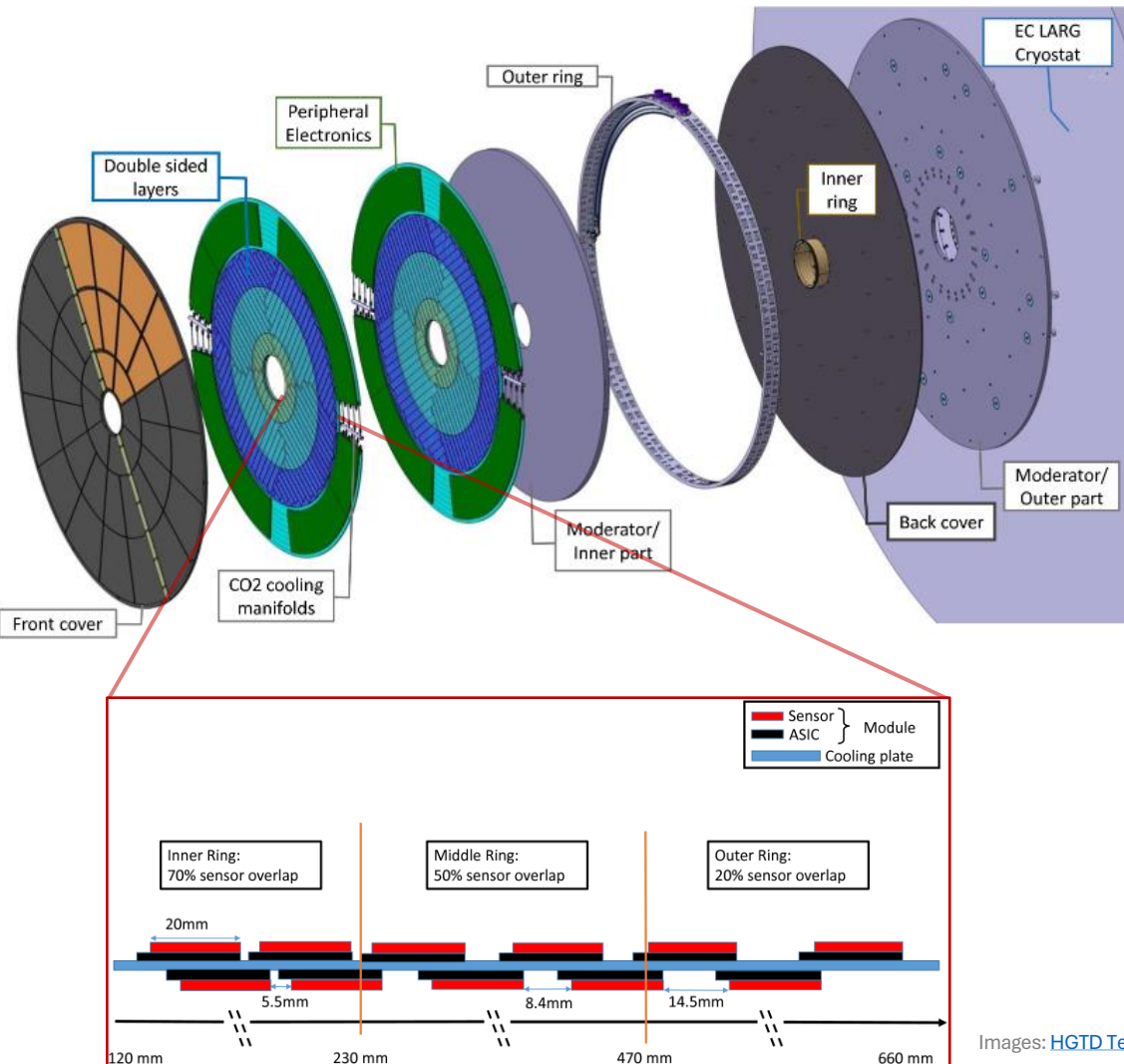


High Granularity Timing Detector



High Granularity Timing Detector (HGTD):

- Placed between the updated Inner Tracker (ITk) and the Liquid Argon Calorimeter
- Active area coverage: $2.4 < |\eta| < 4.0$
- Consists of **16064** hybrids (**8032** modules)
- **Maximum fluence** $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ with replacements of the inner and middle rings
- Operating temperature **-30°C** (CO₂ dual phase cooling)
- Two instrumented double layers per side
- Overlap between modules on all rings

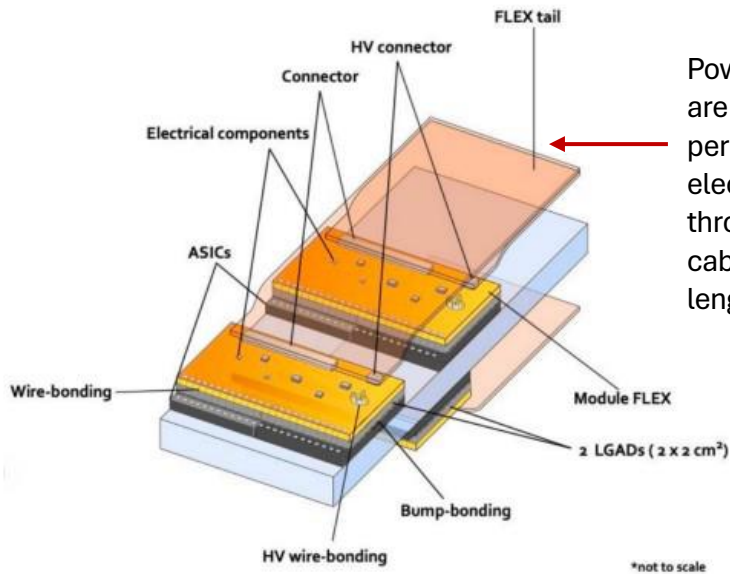


Images: [HGTD Technical Design Report \(2020\)](#)

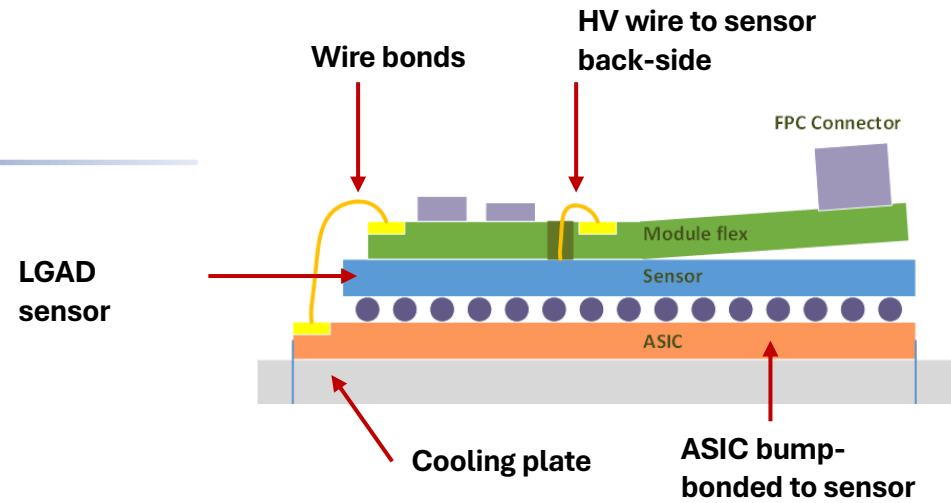
The HGTD Modules

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**

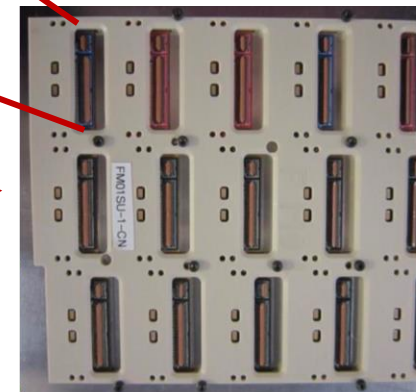


Power and signal are routed to the peripheral electronics through flexible cables of different lengths (flex tail)



Module

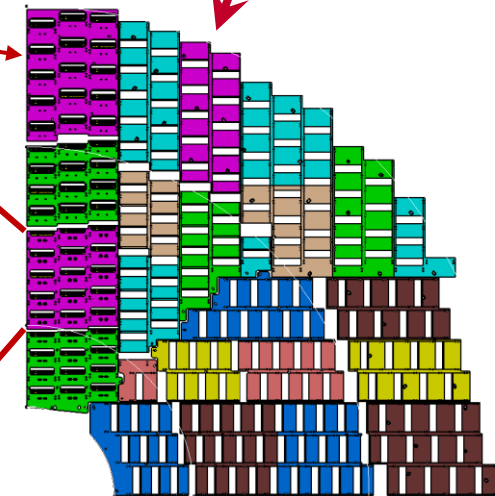
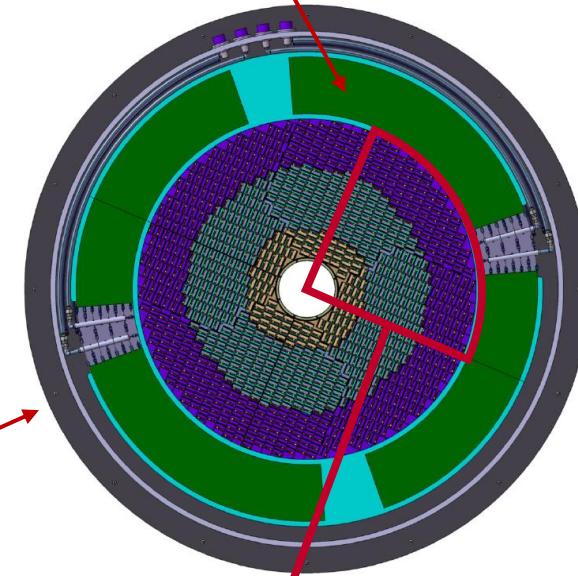
Detector Unit (DU)



An HGTD disk

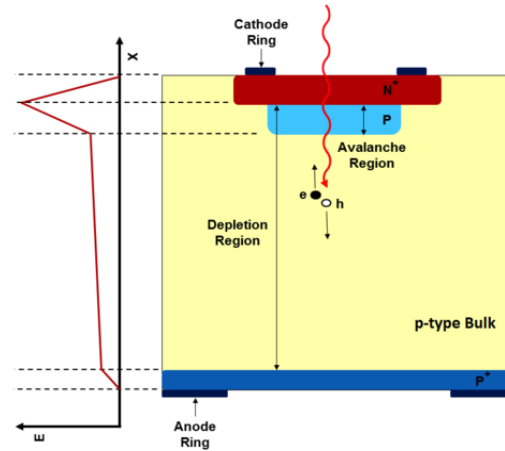
Disk quadrant of the HGTD active region (24DUs)

Peripheral Electronics Board (PEB)



The HGTD 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
- Active thickness: **50 μm**
- **Carbon-enriched gain-layer** for radiation hardness

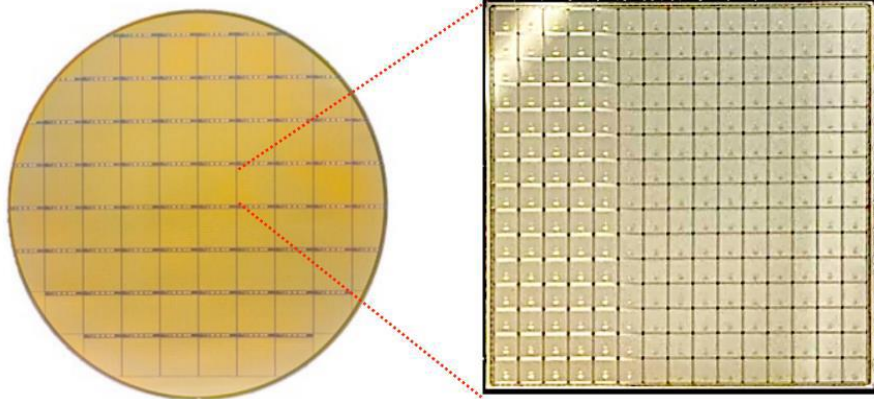


LGAD Technology:

- N-in-P diode structure with extra p-type gain-layer
 - Moderate gain: 10 – 20
 - Extra gain layer: Fast **rise time** and larger **signal-to-noise** ratio
- Excellent time resolution

8'' wafer
52 sensors

15×15 LGAD pads
2×2 cm² sensor



LGAD sensors requirements:

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

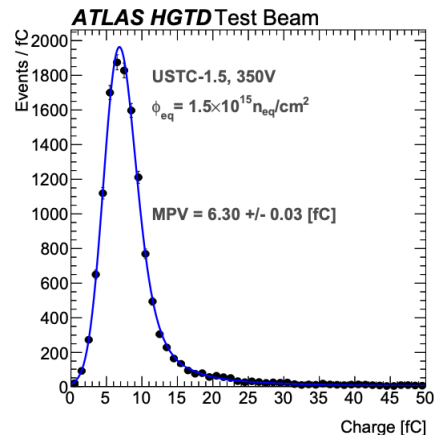
$$\sigma_{\text{per-track}} = \frac{\sigma_{\text{per-hit}}}{\sqrt{N_{\text{hits}}}}$$

- Outer region: $\langle N_{\text{hits}} \rangle = 2$ / Inner Region: $\langle N_{\text{hits}} \rangle = 3$

Timing Components

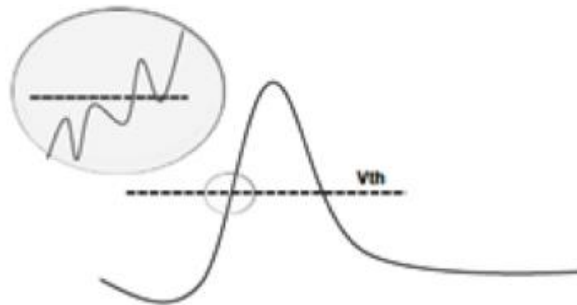
$$\sigma_{\text{Total}}^2 = \sigma_{\text{Landau}}^2 + \underbrace{\sigma_{\text{Jitter}}^2 + \sigma_{\text{Timewalk}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Clock}}^2}_{\text{read-out electronics}}$$

- **Landau Contribution:**
Non-uniform energy deposition distribution in the sensor
→ Mitigation: Small sensor active thickness (50 μm)
→ $\sigma_{\text{Landau}} \sim 30 \text{ ps}$



S. Ali et al 2023 JINST
18 P05005

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



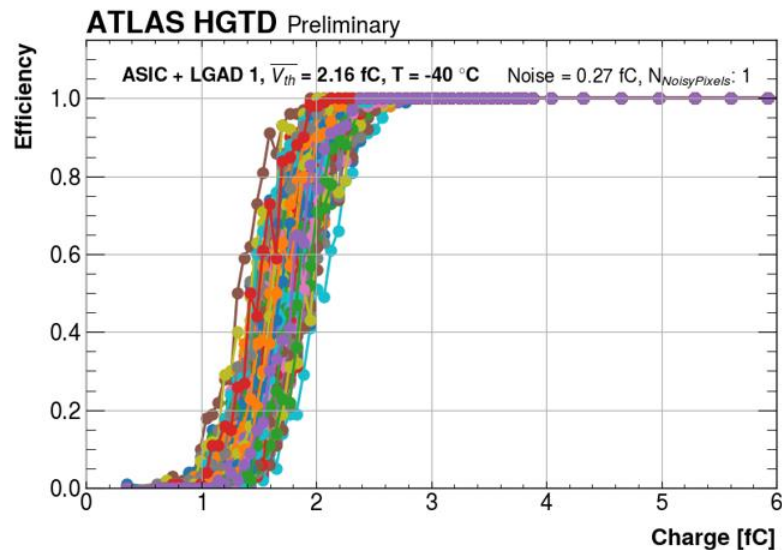
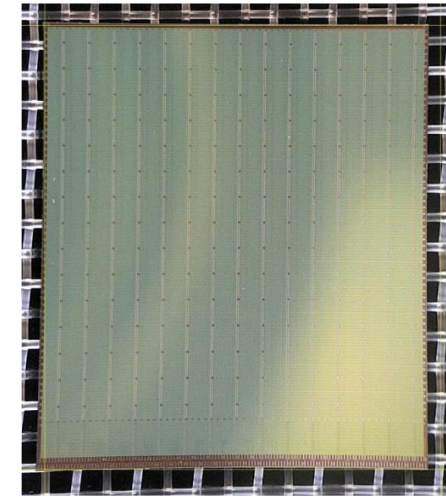
Source: [1704.08666](#)

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

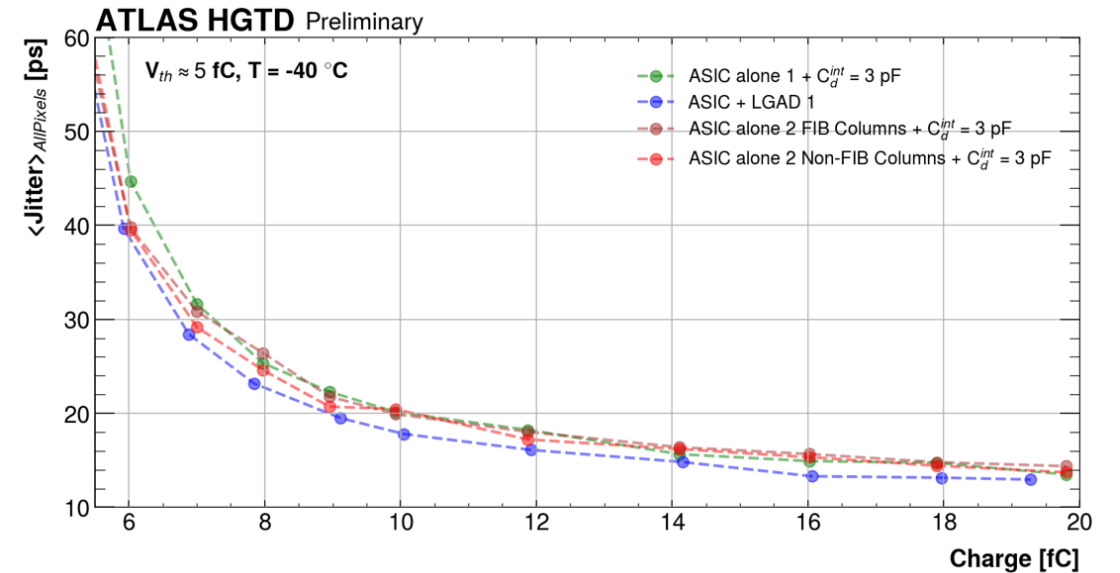
Front-End Read-Out: ASIC

- ATLAS LGAD Timing Integrated Read-Out Chip (**ALTIROC**)
- 130 nm **CMOS** from TSMC
- Jitter: < 25 ps at 10 fC (< 65 ps at 4 fC)
- Radiation hard up to 2 MGy

- Discriminator threshold minimum: 2 fC
- Provides Time-Of-Arrival (**TOA**) and Time-Over-Threshold (**TOT**) information
- **TDC** for timing information
- Final version: **ALTIROC-A** (under test)



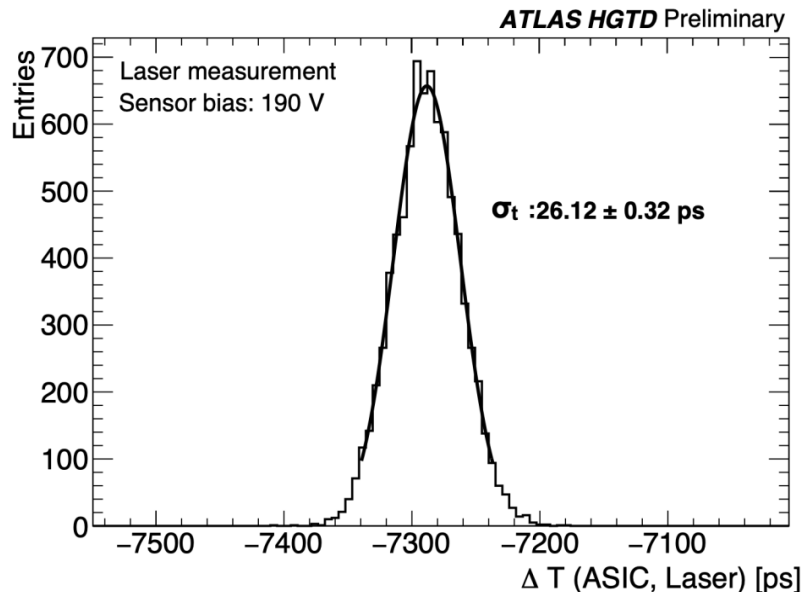
S-Curves of ALTIROC3 + LGAD sensor tuned at 2fC



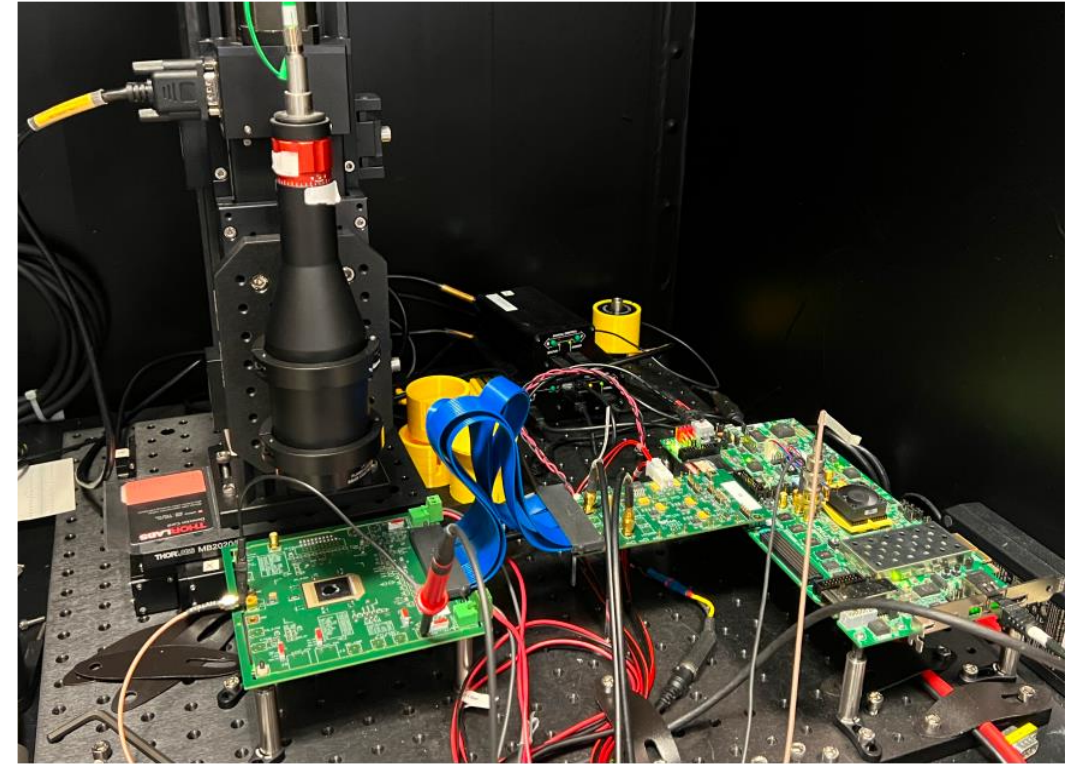
Jitter over charge for ALTIROC-A. The chips are tuned to 5 fC.

Jitter Measurements

- Infrared laser ($\lambda = 1064$ nm, sub-mm focus) to determine jitter
- Photons deposit their energy in the same depth in the sensor
→ Landau and Timewalk contributions negligible
- Time reference: precise signal (3 ps jitter) from laser driver
- Jitter measured to be ~ 23 ps
→ Correction for TDC (10 ps) and clock (8 ps) contributions
→ Consistent with ASIC test-bench measurements

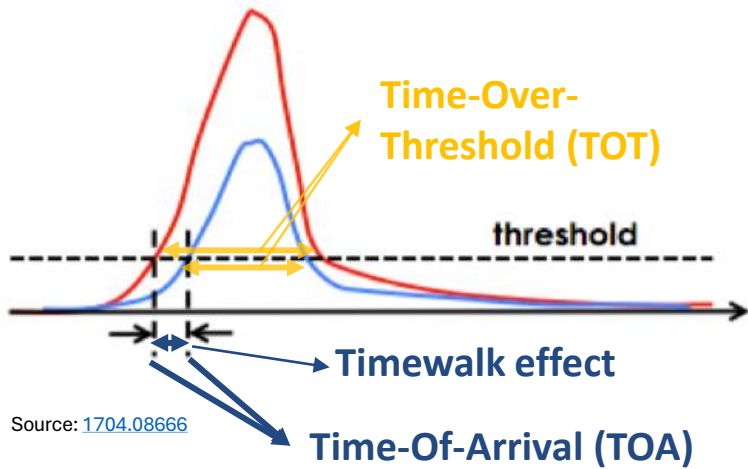


$$\sigma_{\text{total}}^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{Timewalk}}^2 + \underbrace{\sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Clock}}^2}_{\text{read-out electronics}}$$

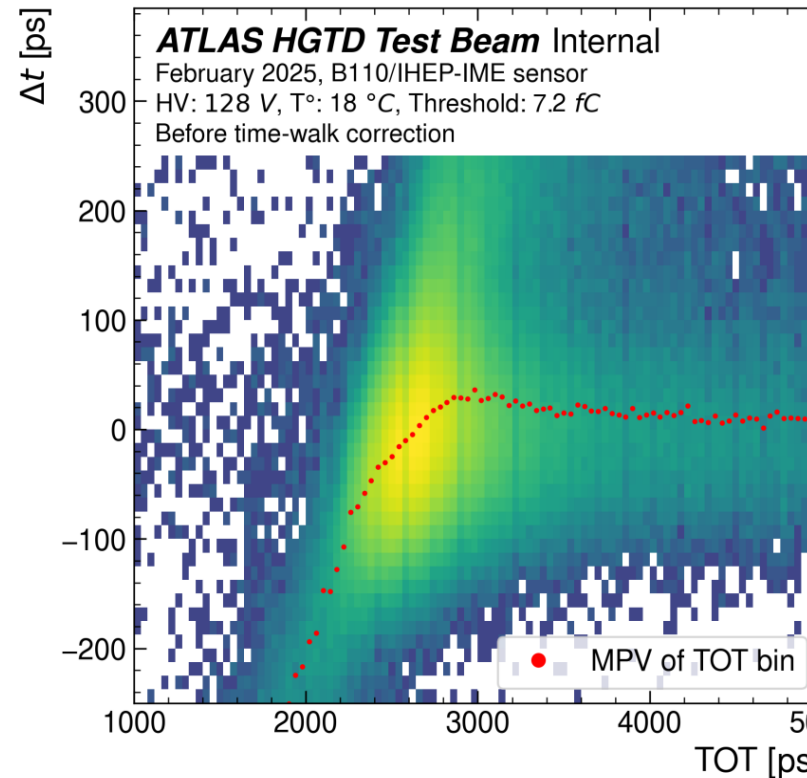


Timewalk Correction

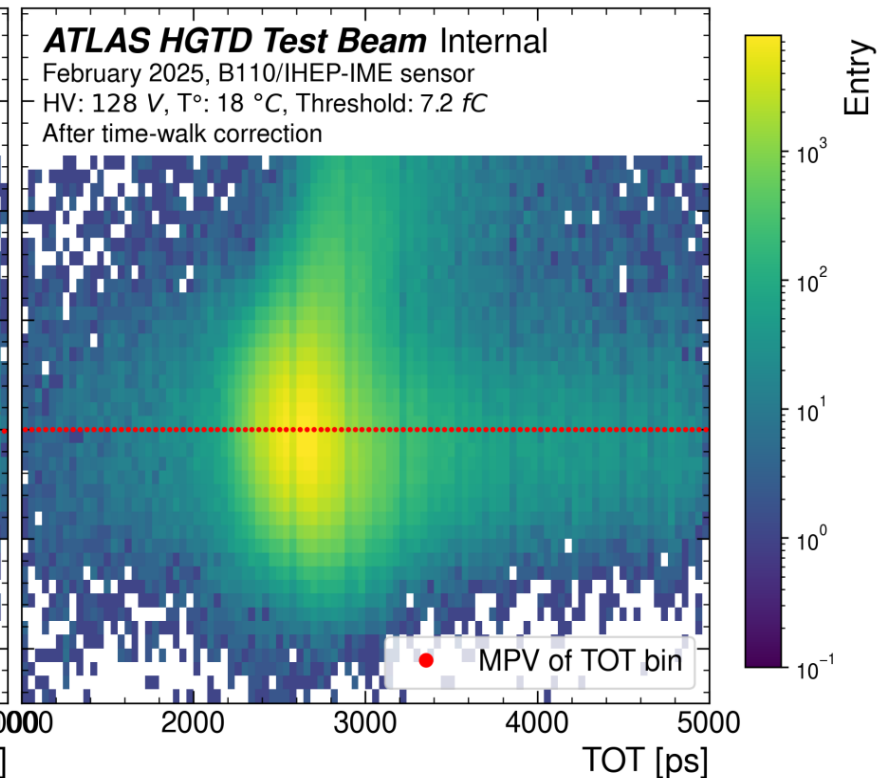
- Timewalk effect: TOA depends on signal amplitude (at constant threshold)
- TOA and TOT are strongly correlated
- Use the correlation to correct for timewalk effect
- Timewalk effect largely reduced after correction



Before TW correction

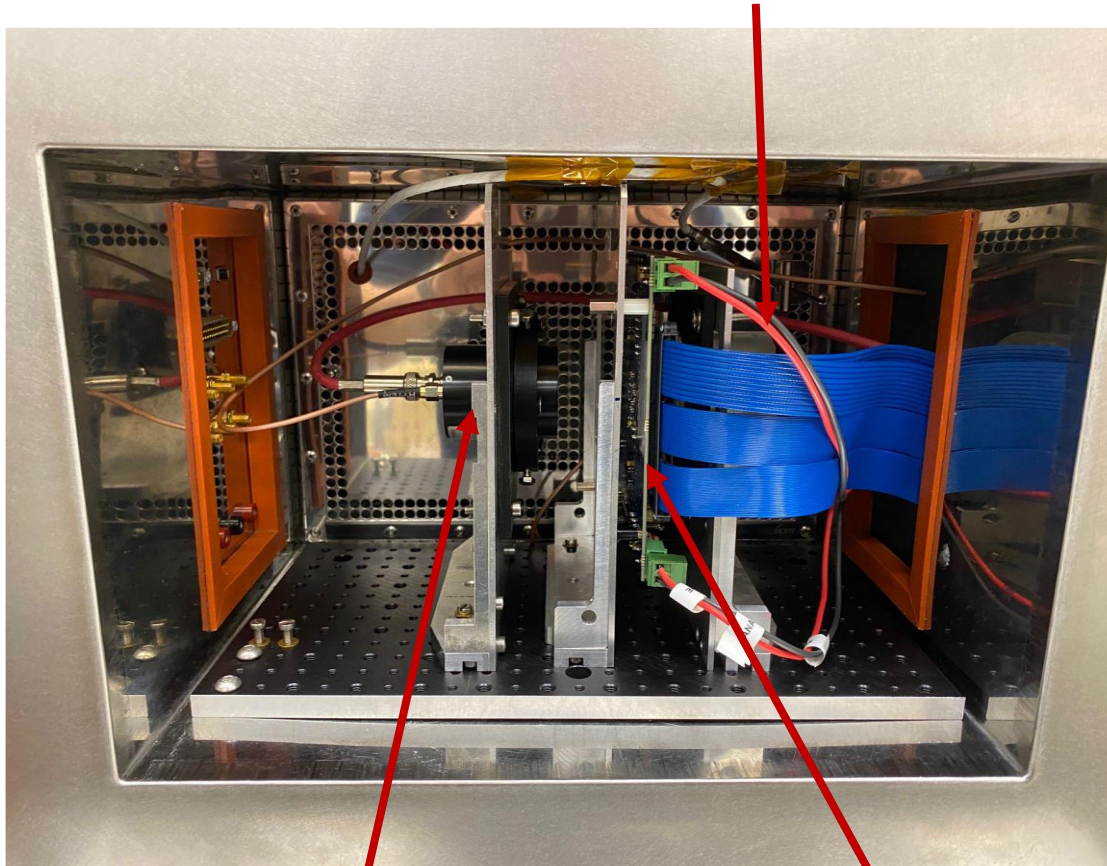


After TW correction



Sr-90 Setup for Hybrids

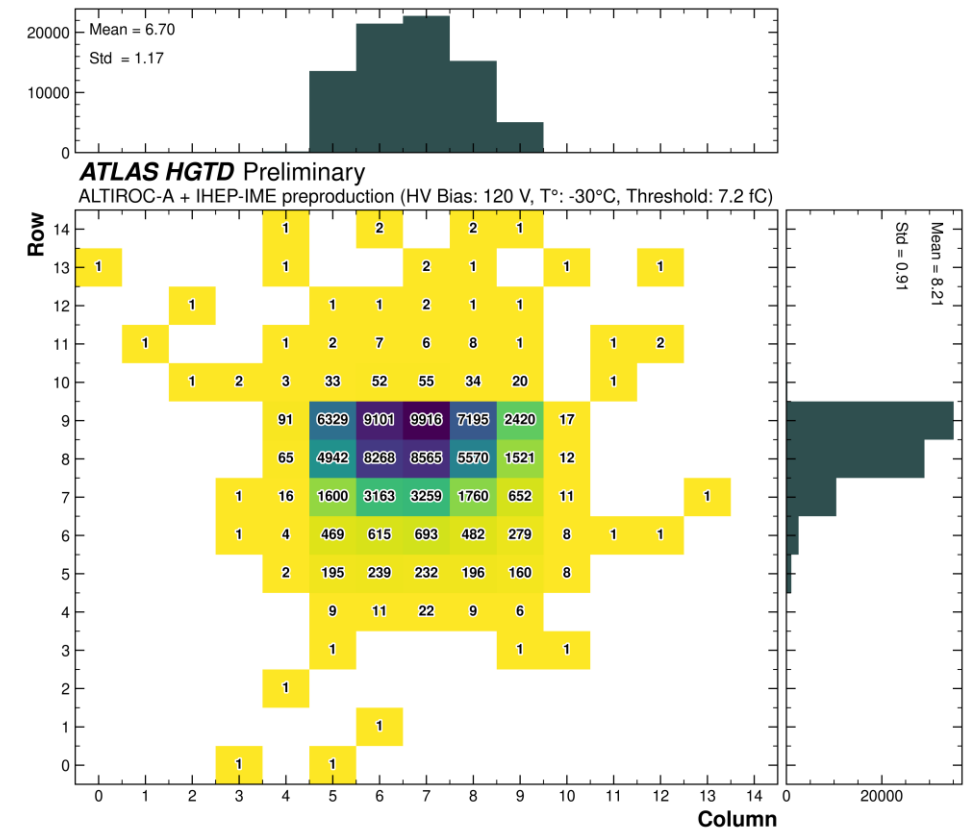
Sr-90 source (~ 30 MBq)



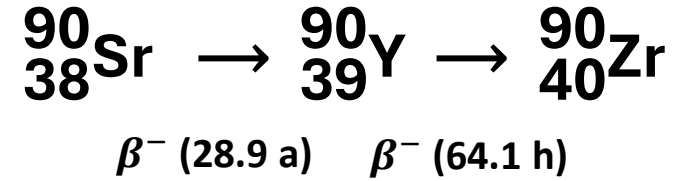
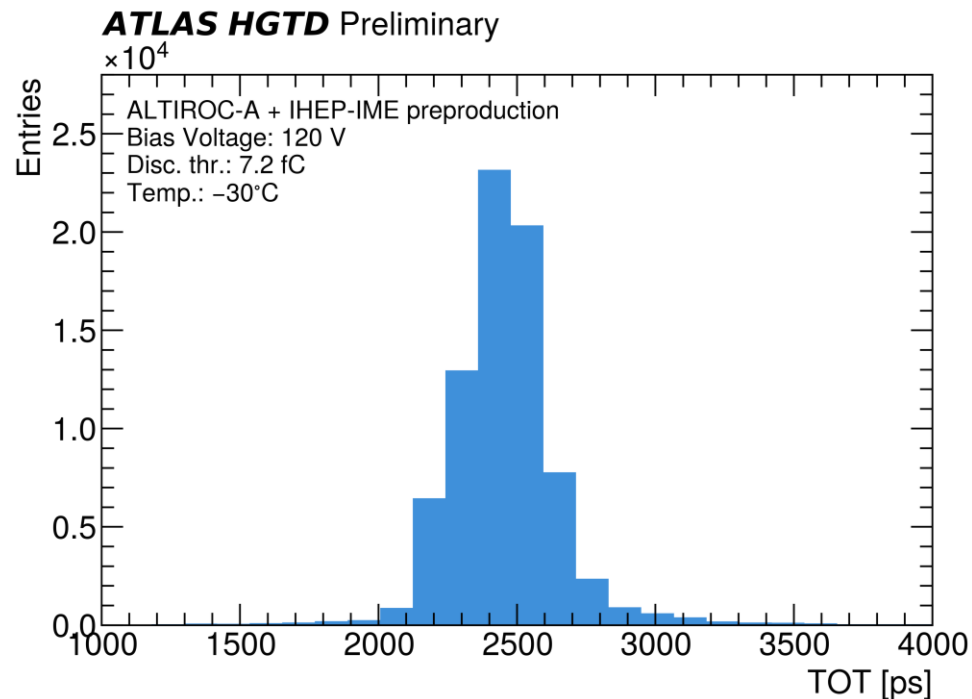
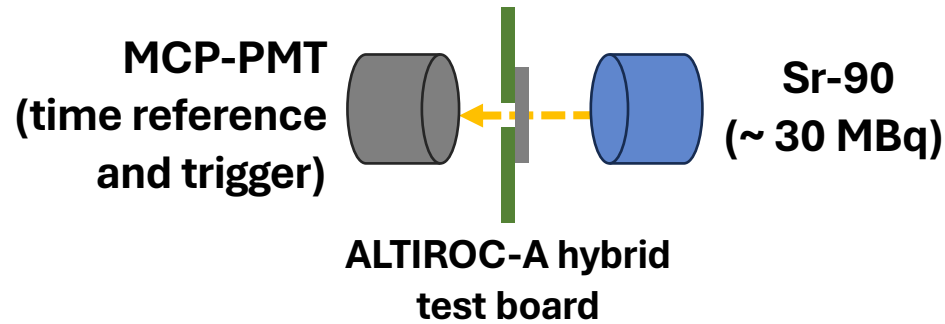
MCP (time reference)

ALTIROC-A test board

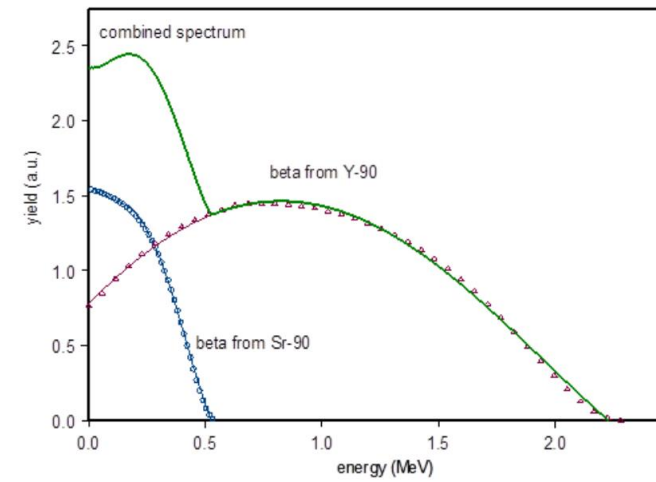
- Test **time resolution** of HGTD Hybrids
- Climate chamber up to -30°C
- Verify test beam results, prepare for test beam
- Pros: Can be used anytime, not only during test beams
- Cons: Slow rate, scan over whole chip not possible, no tracking information



Sr-90 Setup for Hybrids



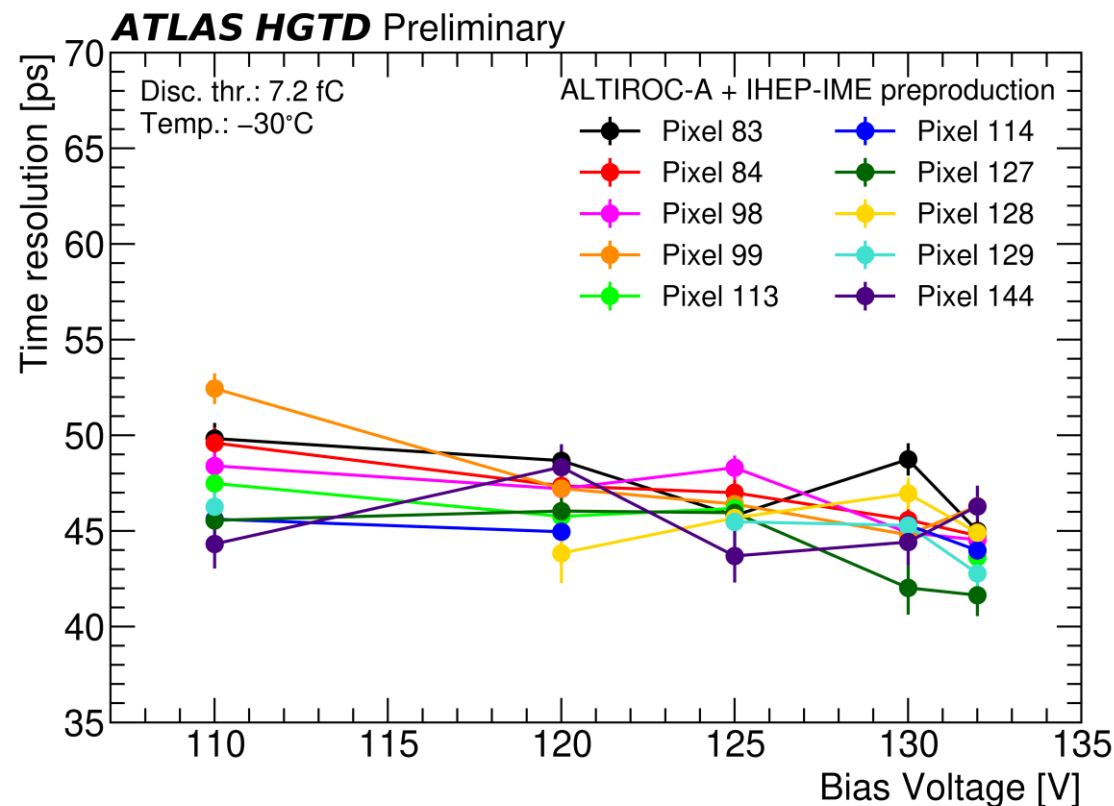
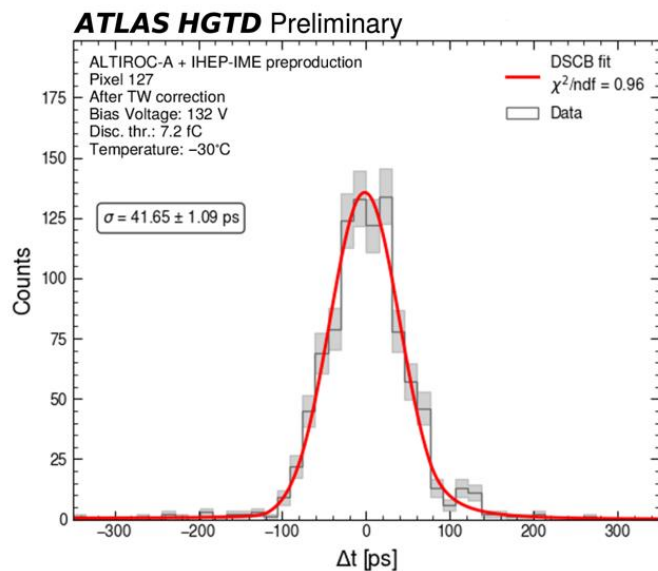
- We see almost exclusively the **Yttrium** decay
 - Only electrons from the high-energy-tail of the decay make it to the trigger (through the hybrid)
 - Those particles are **MIP-alike**
- **TOT distribution** at Sr-90 setup **similar to the one in the test beam** (120 GeV pions at SPS)



Source: <https://cds.cern.ch/record/2013995/files/PH-EP-Tech-Note-2015-003.pdf>

Sr-90 Setup for Hybrids: Timing Results

- Time resolution: Standard deviation on the Gaussian fit of $TOA_{DUT} - TOA_{MCP}$
- TOA_{DUT} : $TOA(DACU) \times LSB$
- Least Significant Bit (LSB) calibrated to 20 ps
- TOA_{MCP} : Determined by CFD-50% method and subtracted by the internal 40 MHz clock of the chip

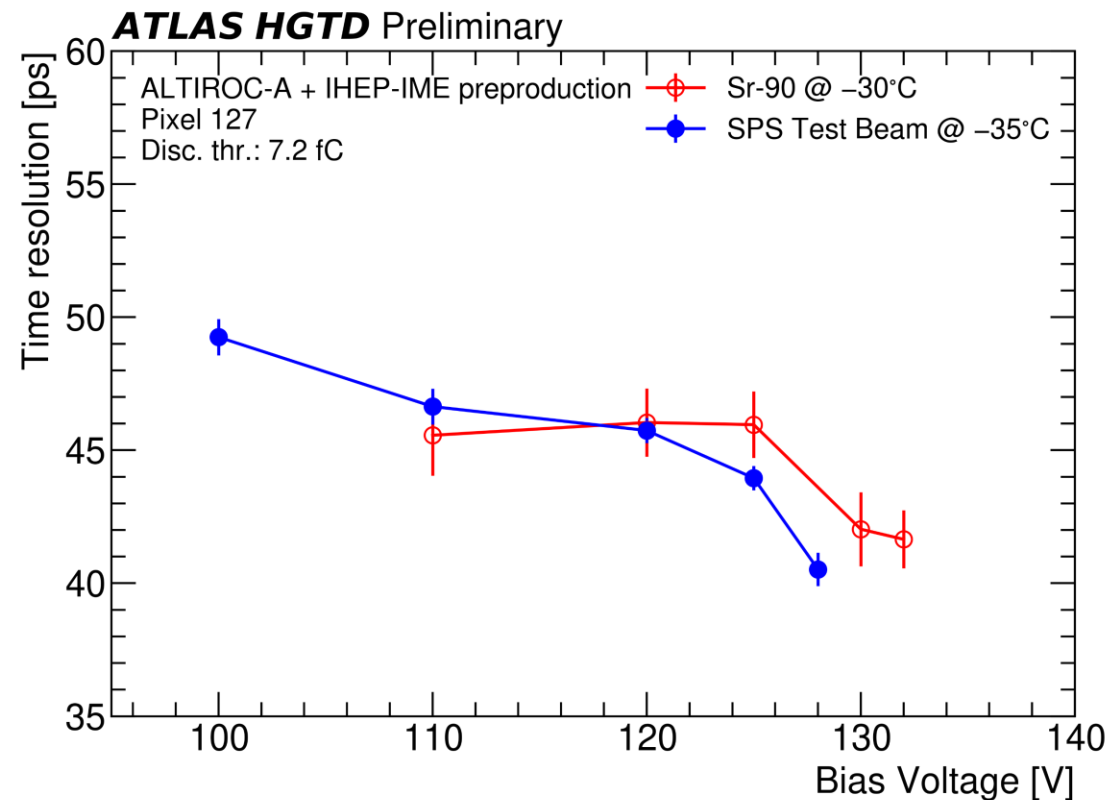
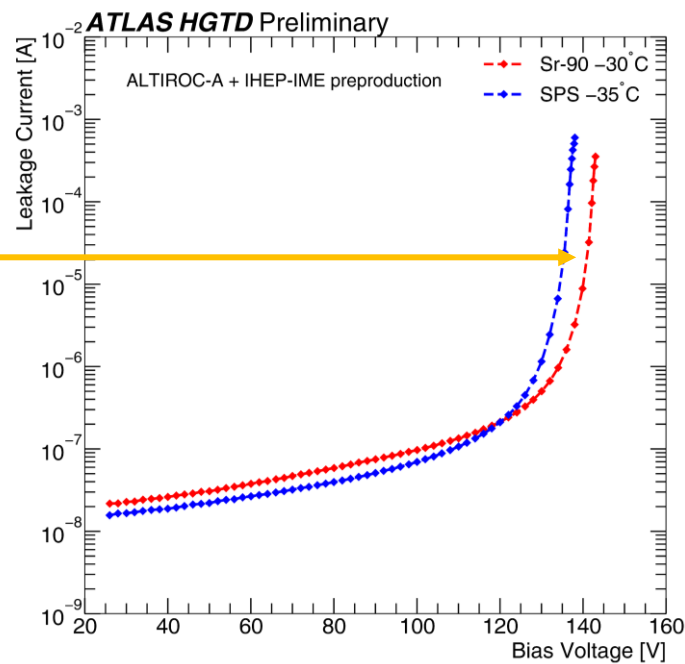


- Here: time resolution after TW correction
- Time resolution ~ 45 ps
- Uniform behavior for all pixels
- Mild dependency upon HV bias (due to time-walk correction)

Sr-90 Setup for Hybrids: Comparison with Test Beam

- Comparison of test beam and Sr-90 results for same pixel
- Test beam and Sr-90 data compatible
- Slight differences can be explained by slightly different environmental conditions

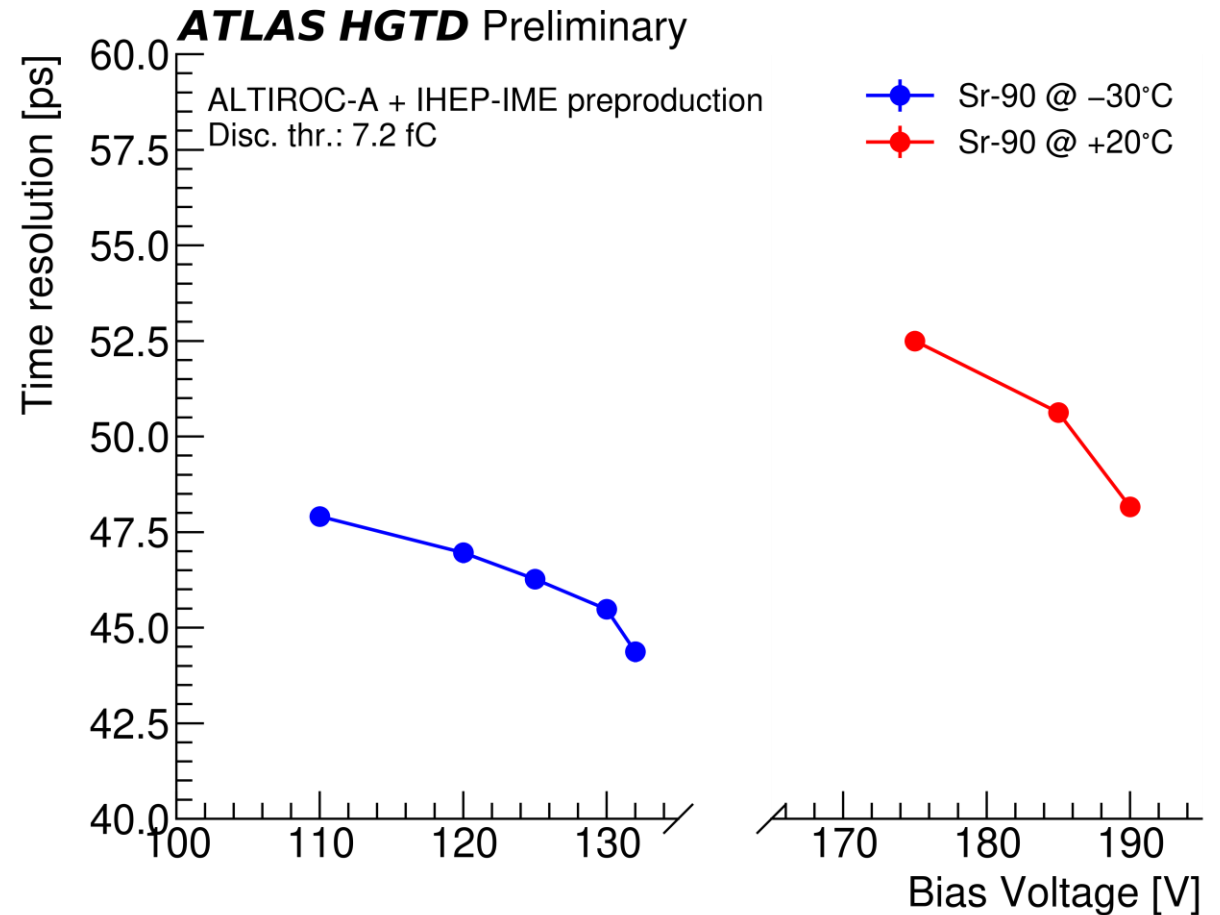
5 K temperature difference results in ~ 5.5 V difference in break-down voltage
→ 1.1 V/K



HGTD Test Beam Campaigns: See talk by Arthur Lafarge tomorrow at 16.30!

Sr-90 Setup for Hybrids: Temperature Dependency

- Timing performance depends on temperature
- At -30°C time resolution 4 ps – 5 ps better w.r.t. $+20^{\circ}\text{C}$
- Expected behavior due to reduced jitter (lower leakage current)



Summary & Outlook

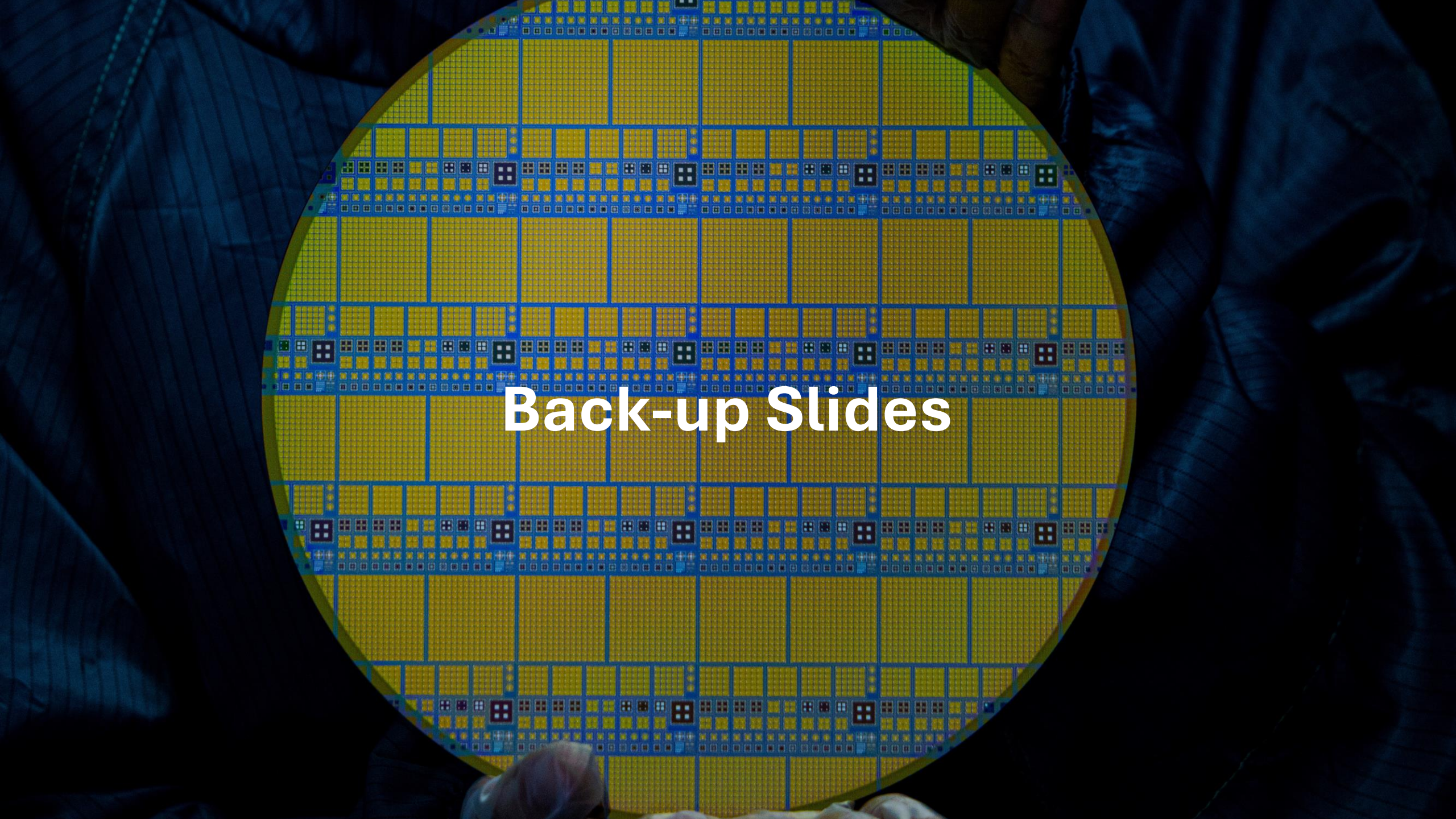


[Link to HGTD Public Plots](#)

- HGTD will be deployed to mitigate pile-up effects at HL-LHC
- HGTD performed extensive LGAD and hybrid testing at test beams and test bench
- Hybrid show good performance in terms of noise and jitter
- Sr-90 timing results promising, per-hit resolution down to 45 ps, close to requirements
- First studies with full modules ongoing

Stay tuned: Detailed test beam results with HGTD hybrids/modules tomorrow at 16.30 by Arthur Lafarge!

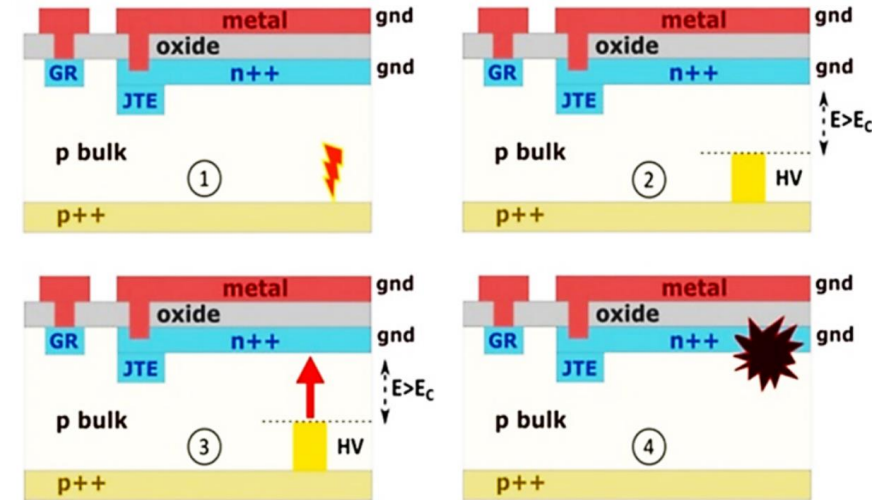
Thank you for your attention!



Back-up Slides

Single Event Burnout (SEB)

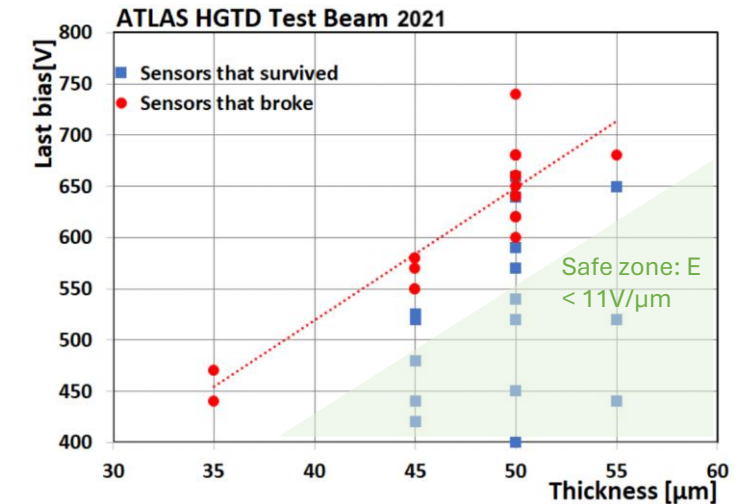
- **Irreversible breakdown** triggered by a large charge deposition at high operation voltages
 - Triggered by a **single particle**
 - Large energy deposits: **electric field collapse in presence of high concentration of free carriers**
 - Observed in several test beam campaigns
 - Common effort of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



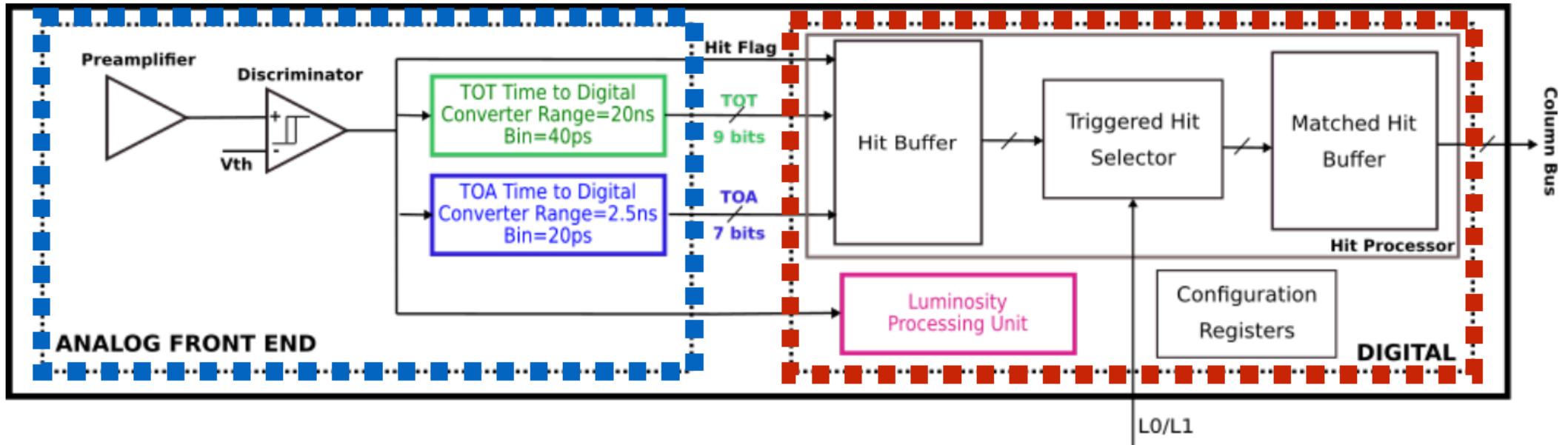
Source: L.A. Beresford et al. JINST 18 P07030



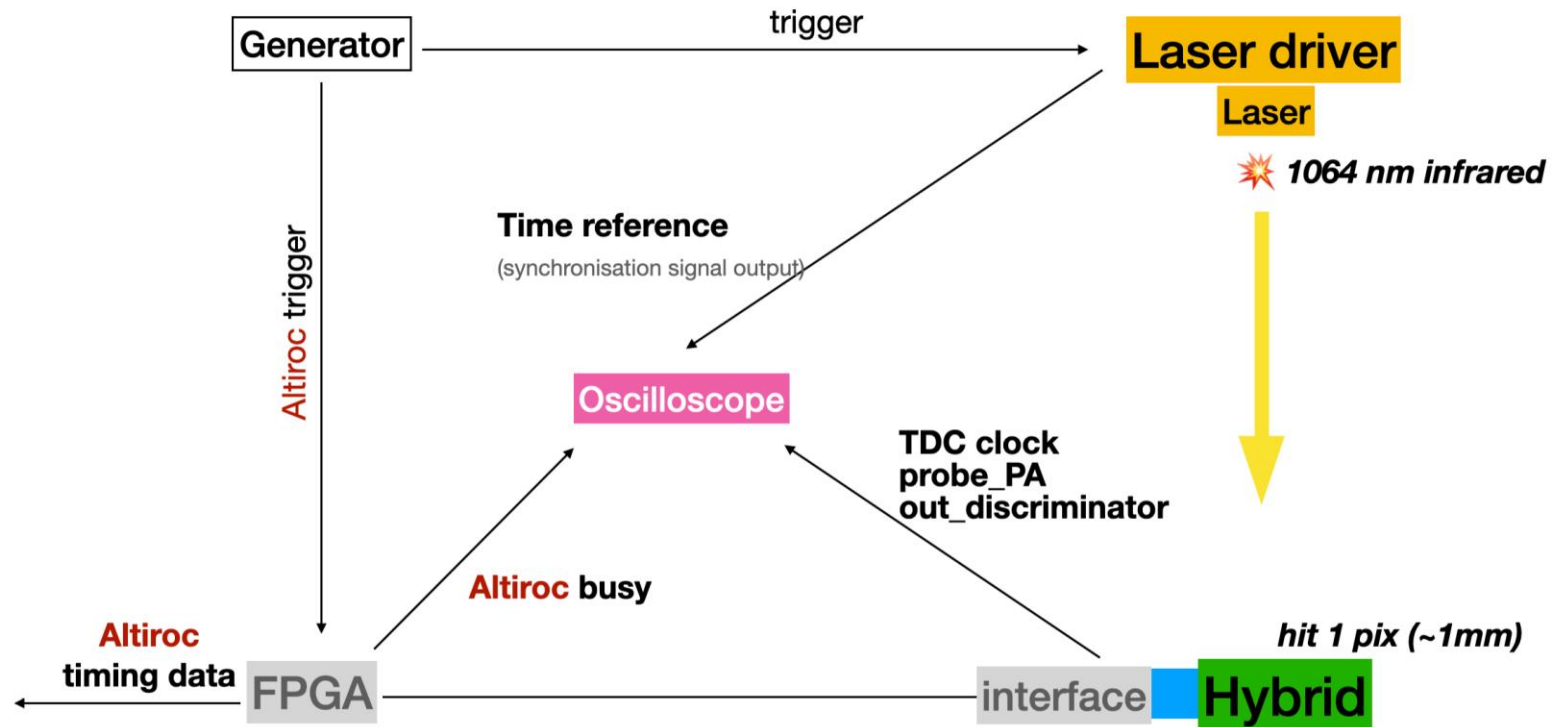
burn mark in the CNM sensor after ATLAS TB in 2018 after the test beam – dimensions are few tens μm (crater photo taken by CNM)



ASIC Architecture



Laser Setup: Read-Out



Sr-90 Setup: Read-Out

