The ATLAS High Granularity Timing Detector: Test beam campaigns and results

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Introduction and Motivation for HGTD

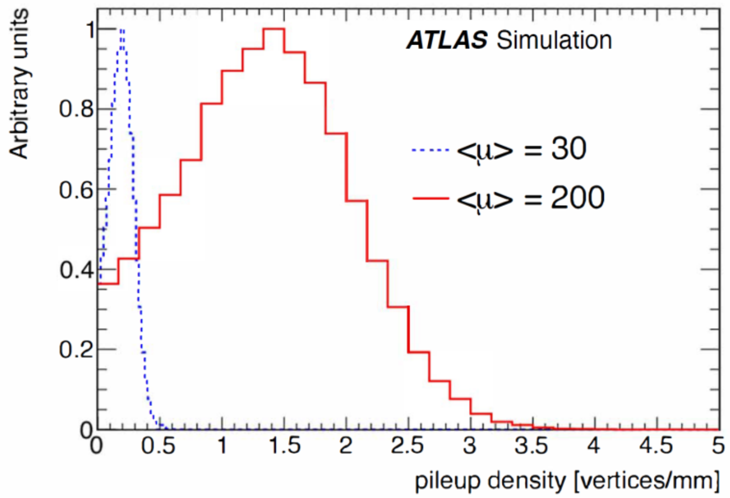
High Luminosity LHC

High Luminosity LHC (HL-LHC):

- Operational from 2029
- Instantaneous luminosities up to 7.5×10^{34} $cm^{-2}s^{-1}$
- Pile-up <μ> = 200 interactions per bunch crossing (on average 1.6 vertices/mm)

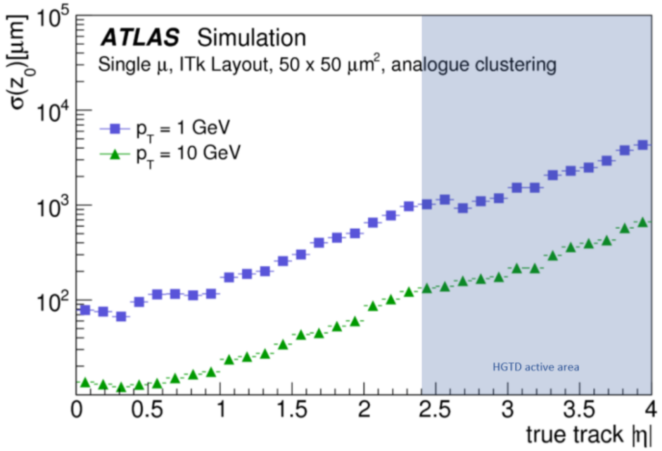
→ **Resolution in longitudinal direction limited in the forward region: correct assignment of tracks to vertices becomes challenging for the ATLAS detector**

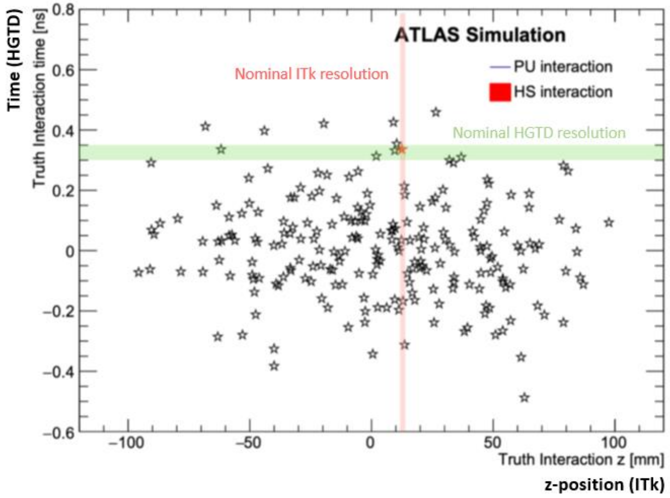
→ **Adding timing information in the end-cap region improves pile-up rejection and vertex reconstruction**



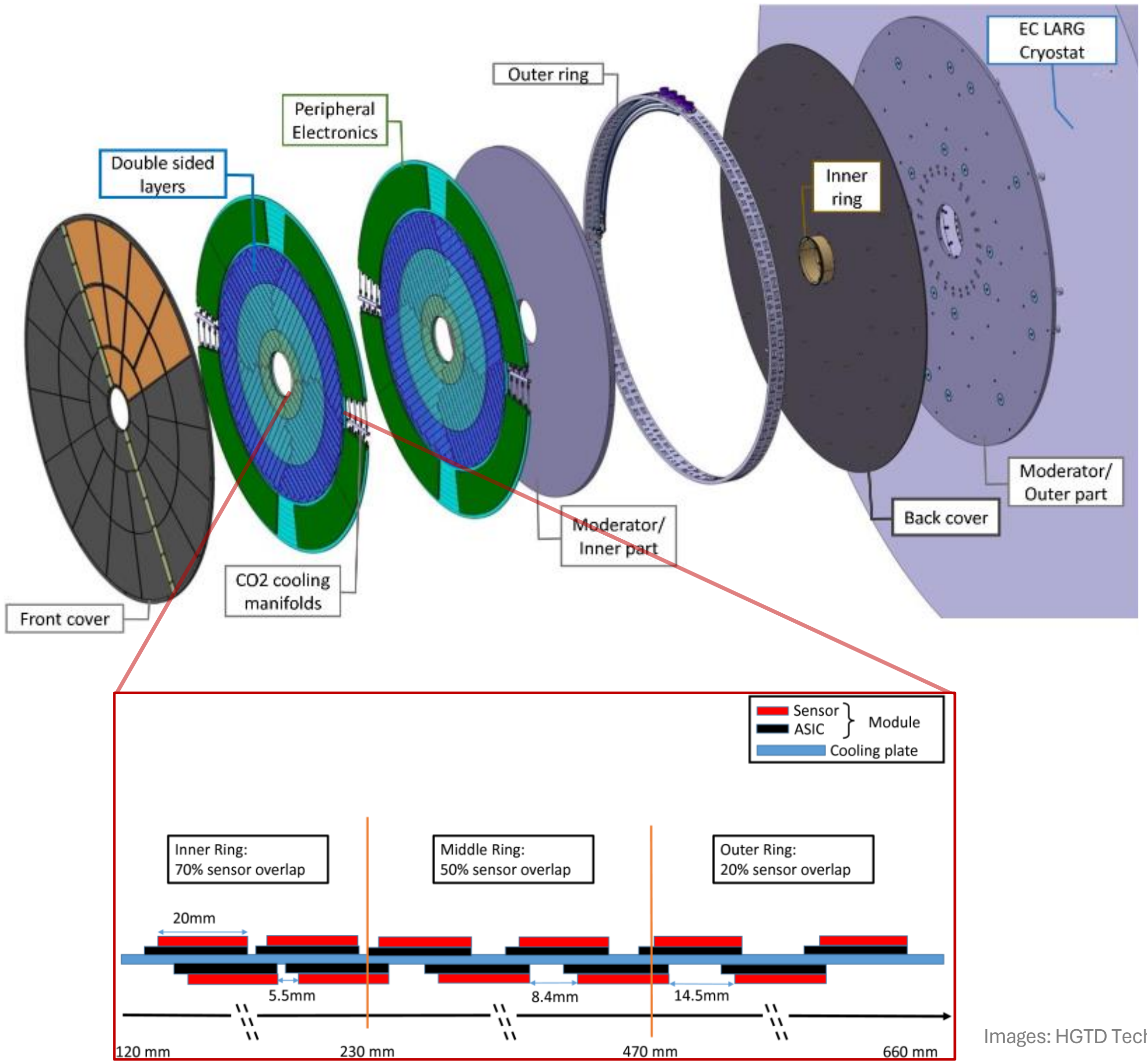
Plots: HGTD Technical Design Report (2020)

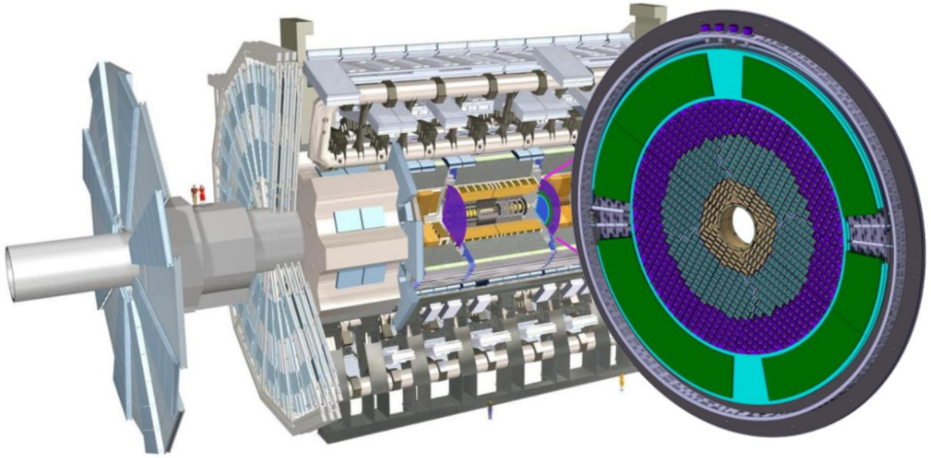
https://hilumilhc.web.cern.ch/article/ls3-schedule-change





High Granularity Timing Detector





High Granularity Timing Detector (HGTD):

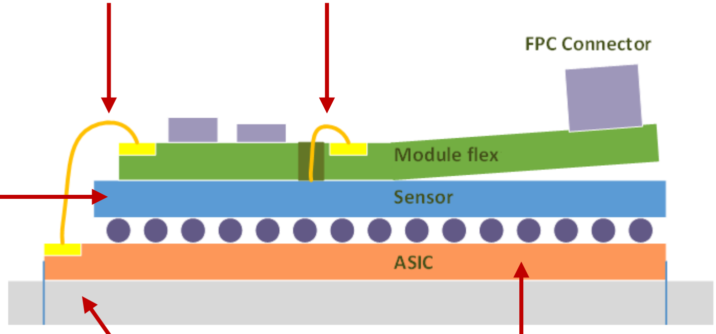
- Placed between the updated Inner Tracker (ITk) and the Liquid Argon Calorimeter
- Active area coverage: **2.4 < |η| < 4.0**
- Consists of **8032** modules
- **Maximum fluence $2.5{\times}10^{15}$ n_{eq}/cm^2** with replacements of the inner (every 1000 fb^{-1}) and middle rings (every 2000 fb^{-1})
- Operating temperature **-30ºC** (CO_2 dual phase cooling)
- Two instrumented double layers per side
- Overlap between modules on all rings

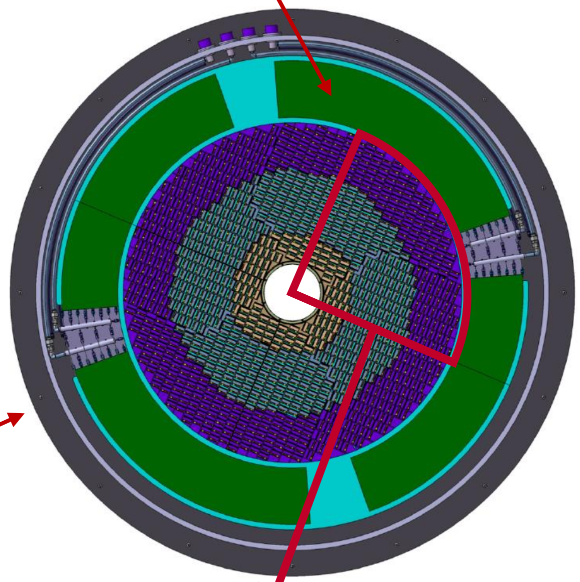
Images: HGTD Technical Design Report (2020)

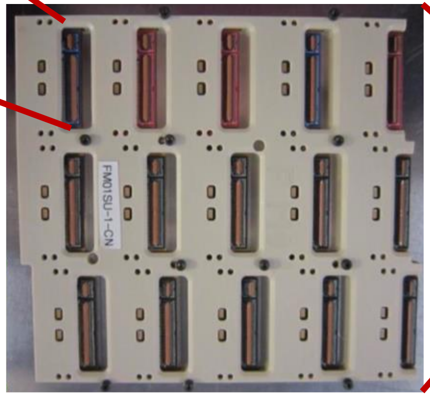
The HGTD Modules

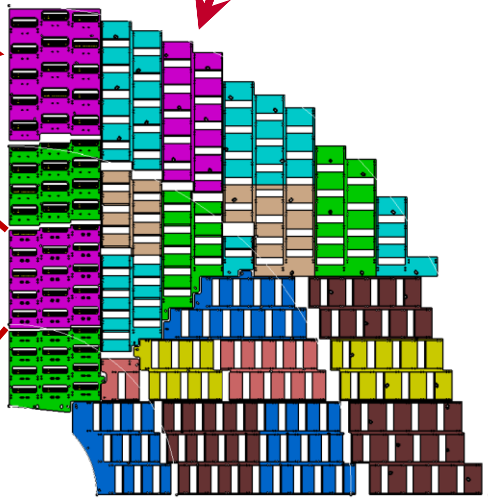
An **HGTD module** consists of:

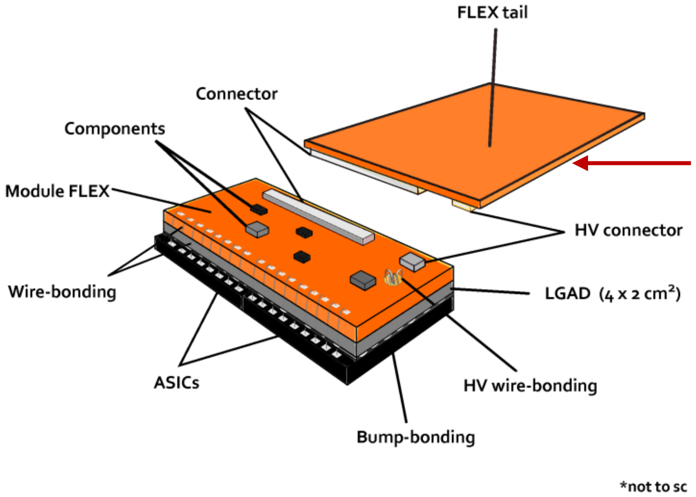
- Two **sensors** (2 cm × 2 cm)
- Two **ALTIROC ASICs** (2 cm × 2 cm)
- A **module flex**
- A **flex tail**







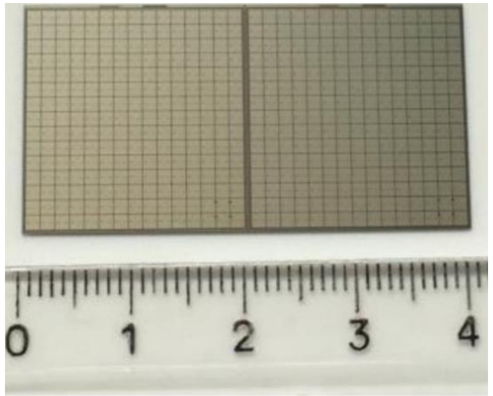


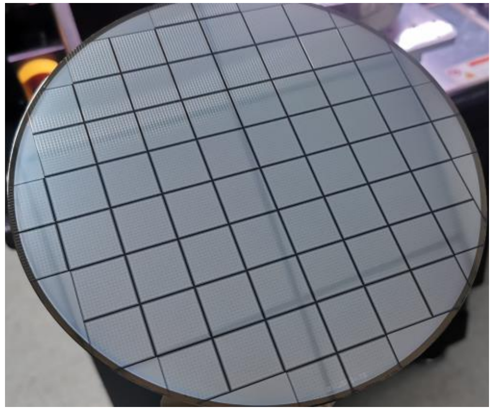


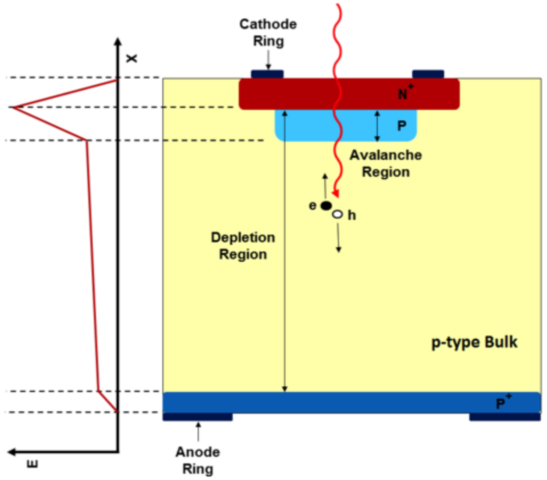
Power and signal are routed to the peripheral electronics through flexible cables of different lengths (flex tail)

The HGTD Sensors

- **Low Gain Avalanche Detector (LGAD)** technology utilized for HGTD
- Each sensor is an array of **15×15 pads**
- Pad size: **1.3 mm×1.3 mm**
- **3.6 M** channels
- Active thickness: **50 µm**
- Vendors: **IHEP-IME** and **USTC-IME**







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

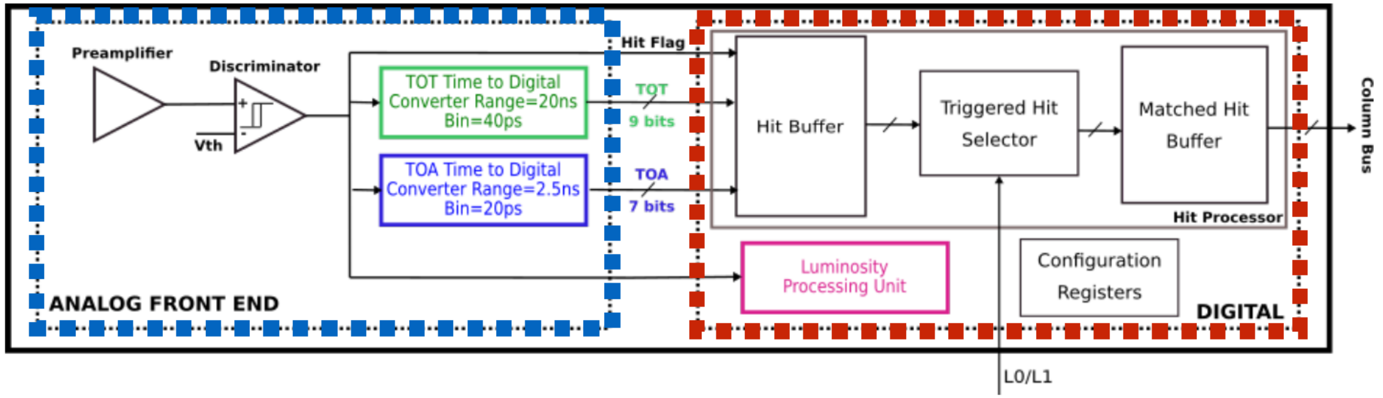
LGAD sensors requirements:

- Time resolution per-hit: **35 ps** (start) - **70 ps** (end)
- Time resolution per-track: **30 ps** (start) - **50 ps** (end)
- Collected charge per hit: **10 fC** (start) - **4 fC** (end)
- Hit efficiency: **97 %** (start) - **95 %** (end)

Sensor Testing:

- LGAD prototypes have been **extensively tested** (test bench and in **test beam** campaigns) with focus on **performance after irradiation**
- **Process Quality Check (PQC)**: Monitor sensor quality and extract wafer parameters during the production

ALTIROC ASIC

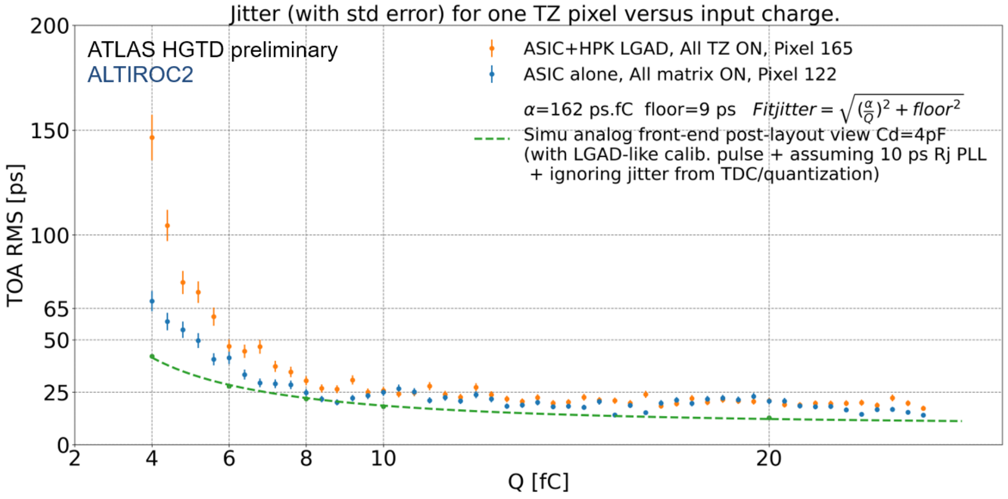


- **A**TLAS **L**GAD **T**iming **I**ntegrated **R**ead-**O**ut **C**hip
- 130 nm **CMOS** from TSMC
- 225 readout channels (15×15)
- Requirements:
  - Radiation-hard (up to 2 MGy)
  - Jitter: < 25 ps at 10 fC (< 65 ps at 4 fC)
  - Discriminator threshold minimum: 2 fC
- Latest version: **ALTIROC3** (under test)

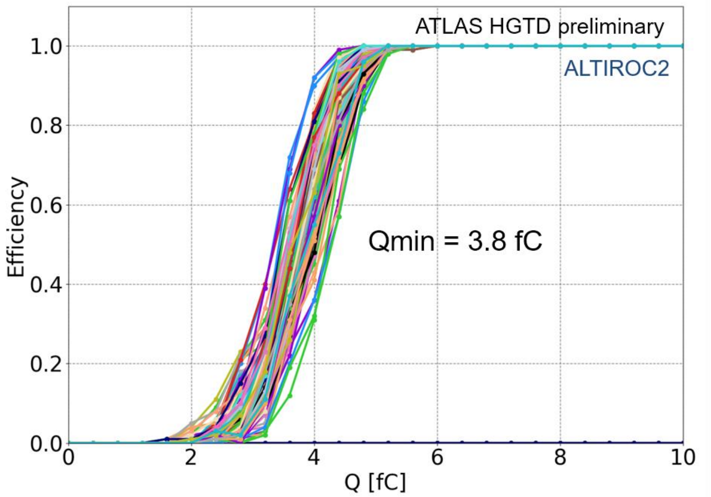
- Each readout channel fits within one sensor pad
- Sensor signal: **preamplifier** and **discriminator**
- Provides **TOA** and **TOT** information
- Provide **luminosity** in hits per ASIC per bunch crossing

ALTIROC performance testing**:**

- Tests with ASIC-only and ASIC + sensor (hybrids)
- Test beam and with Sr90
- ALTIROC3 tests ongoing

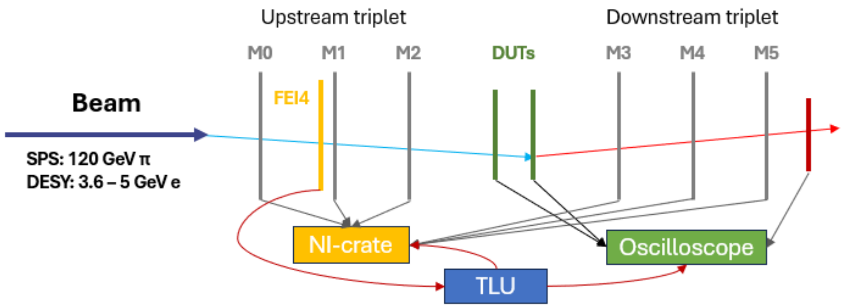


Jitter over charge for ALTIROC2



HGTD Test Beam Campaigns

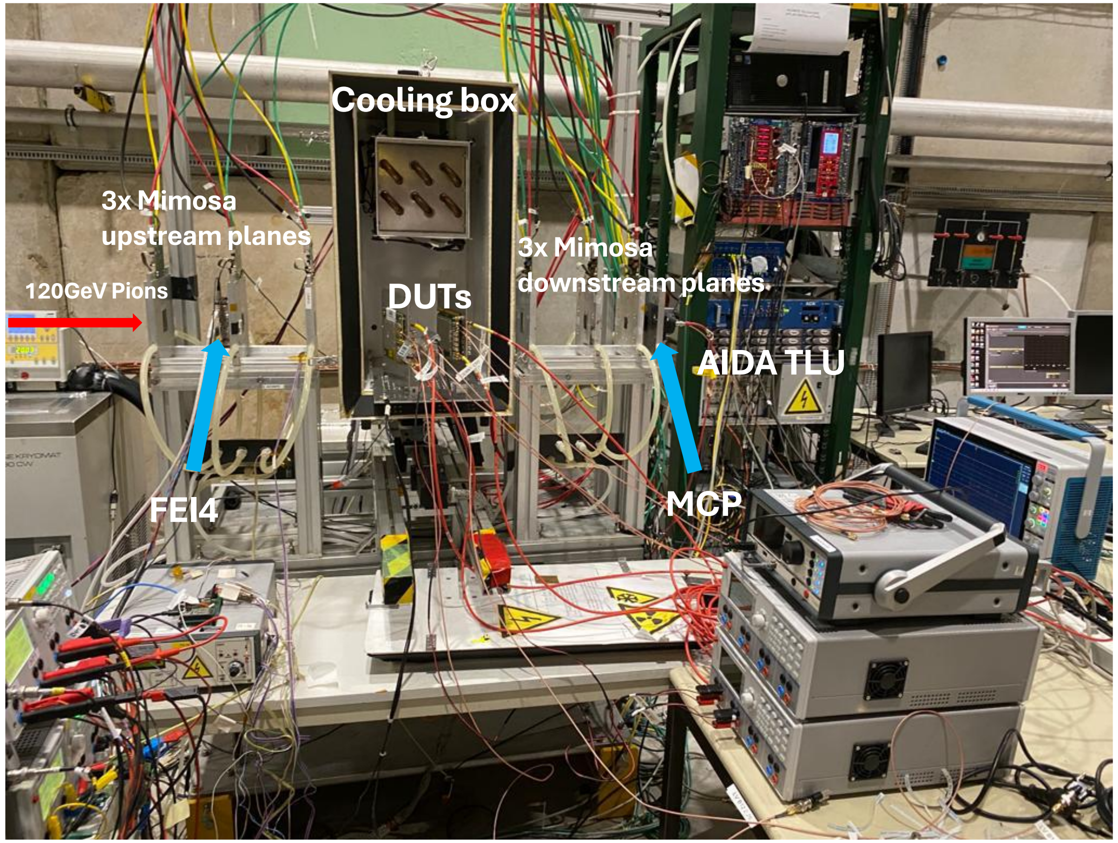
HGTD Test Beam Campaigns



- **CERN SPS** and **DESY**
- **MIMOSA 26** planes: tracking information
- **FEI4**: triggering the region of interest
- **MCP**: timing reference
- Data acquisition framework: **EUDAQ2**
- Trigger logic unit: **AIDA TLU**
- Reconstruction performed with **Corryvreckan**

Sensor testing at test beams:

- **LGAD prototypes (until 2023):** detector R&D, establish/verify requirements, qualify vendors, finalize sensor/wafer design, irradiation tests
- **Sensor preproduction (since 2023):** same design as production, test final wafer/sensor design, establish procedures in preparation for production
- **ALTIROC1/2/3 + sensors**
- **ALTIROC3 + preproduction sensor tested this year at DESY**

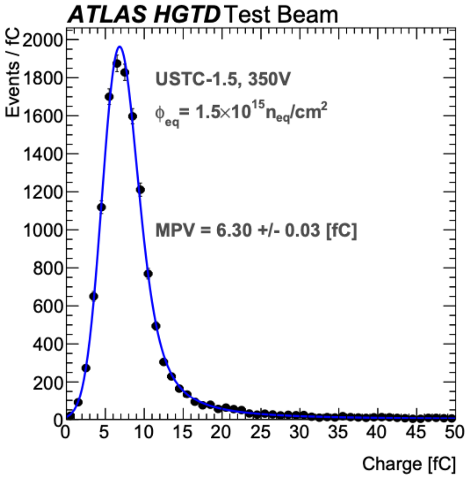


Test beam setup at the H6A beamline of SPS

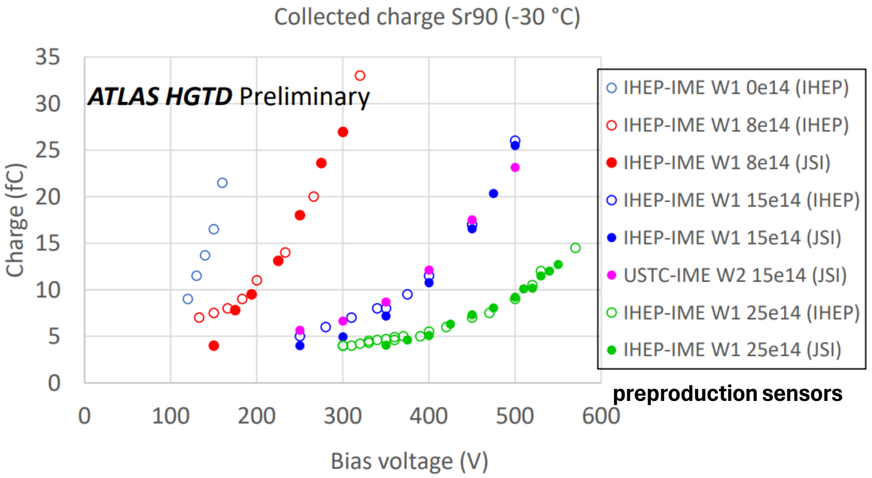
LGAD Sensor Performance at Test Beams

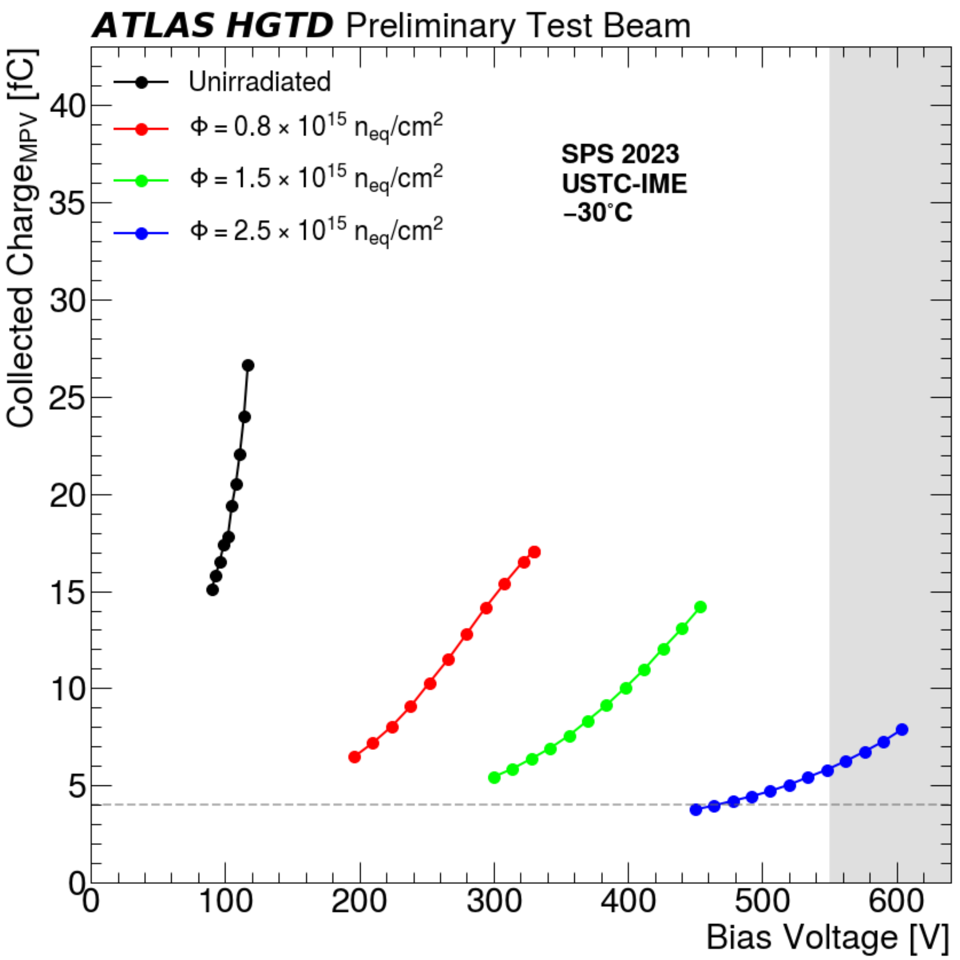
LGAD Performance: Collected Charge

- Charge distribution is a Landau-Gaussian convolution
- Collected charge defined as the most probable value of the fit
- Require at least 4 fC for a sufficient time resolution
- **Preproduction sensors** (irradiated and non-irradiated) **meet the requirements**
- Data taking at -30°C
- Confirmed with Sr90 measurements



S. Ali et al 2023 JINST 18 P05005





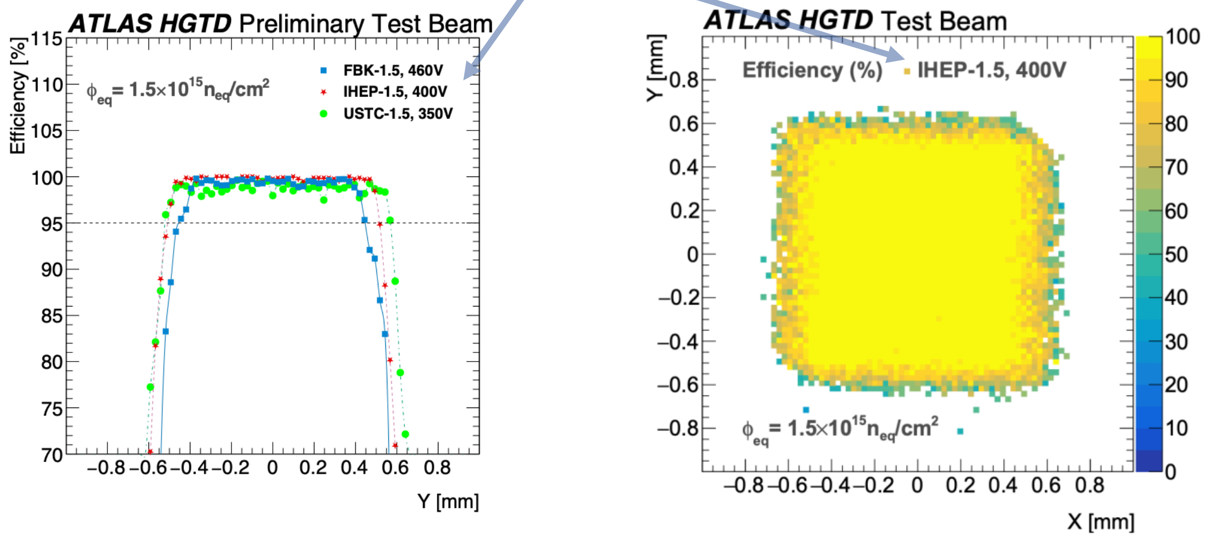
LGAD Performance: Hit Efficiency

- Hit efficiency defined as:

$$\text{Hit efficiency} = \frac{\text{Hits with } q > Q_{cut} \text{ matched to track}}{\text{Total reconstructed tracks}}$$

- Q_{cut} = 2 fC: threshold of the readout ASIC
- Requirement for irradiated sensors (> 95%) met for all fluences
- High efficiency uniformity across the sensor

LGAD prototypes (DESY Test Beam)



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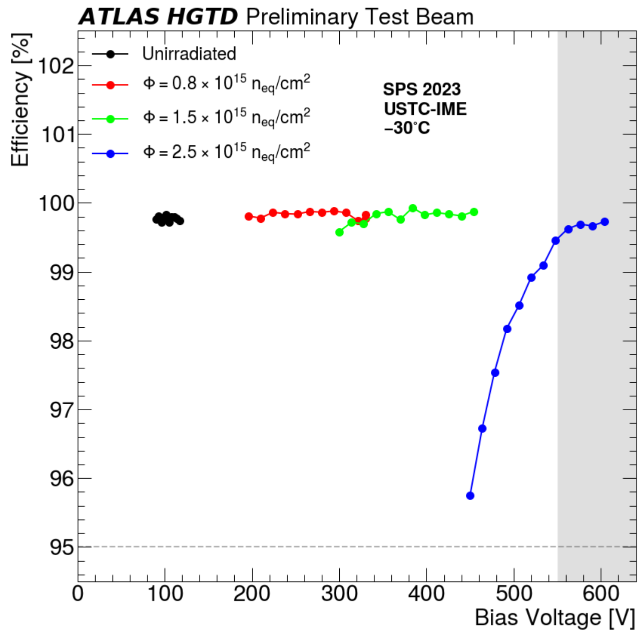


HGTD preproduction sensors at -30°C

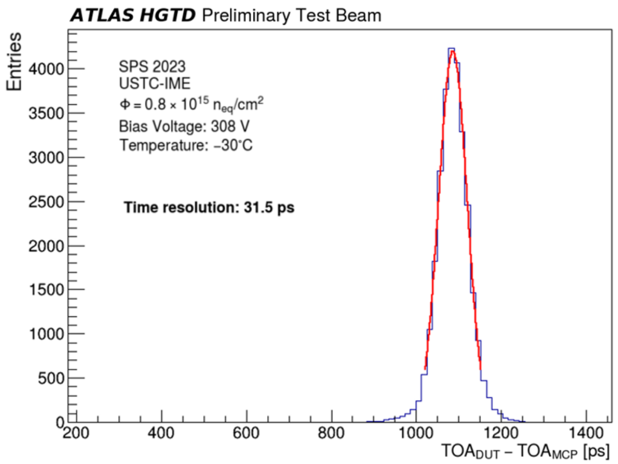
Here: Extra coincidence between DUT and MCP considered to mitigate pile-up

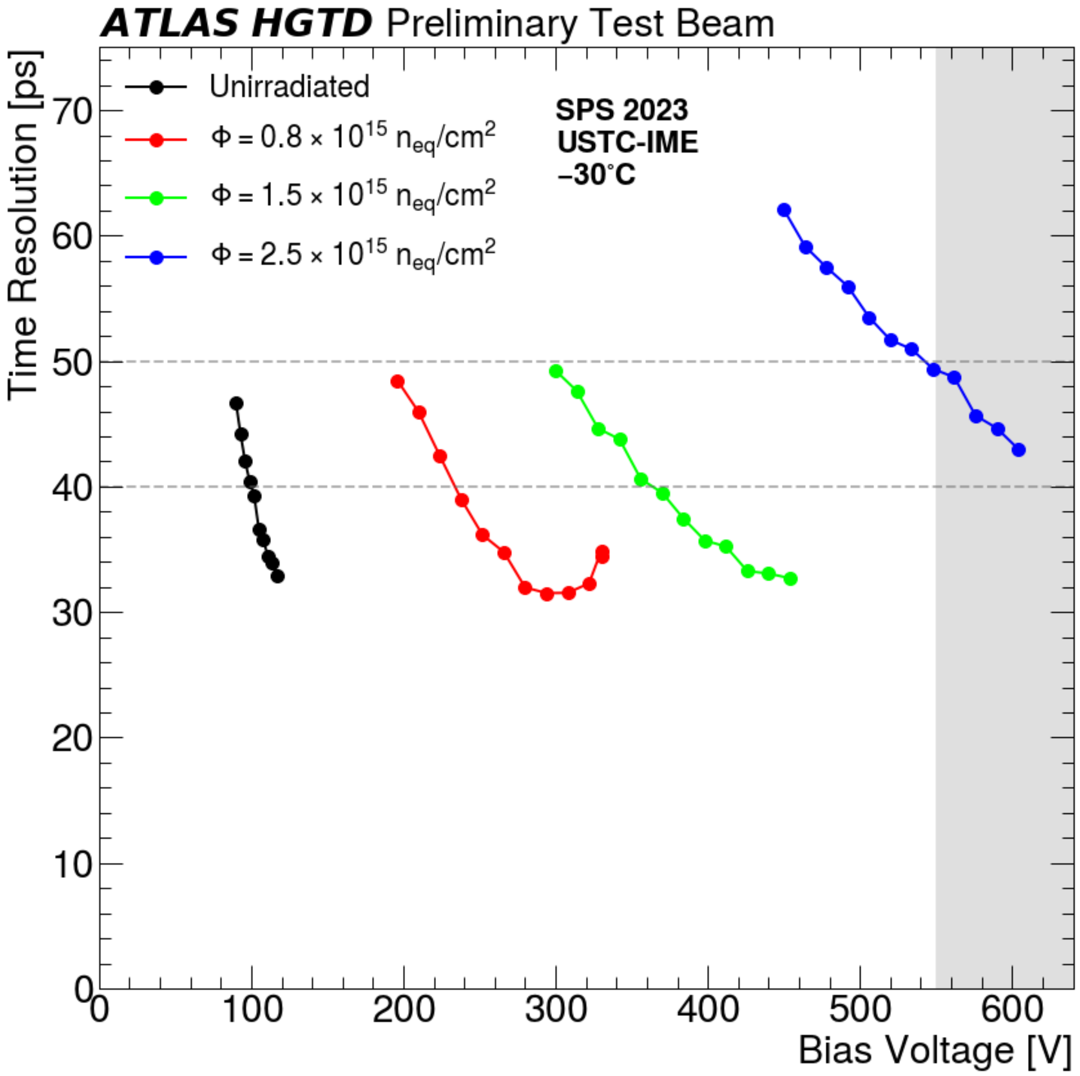
LGAD Performance: Time Resolution

- Time resolution measured with reference detectors (MCP)
- Defined as the standard deviation of the TOA difference between DUT and MCP (convolution of the two resolutions):

$$\sigma_{\text{DUT}} = \sqrt{\sigma^2_{\text{Total}} - \sigma^2_{\text{MCP}}}$$

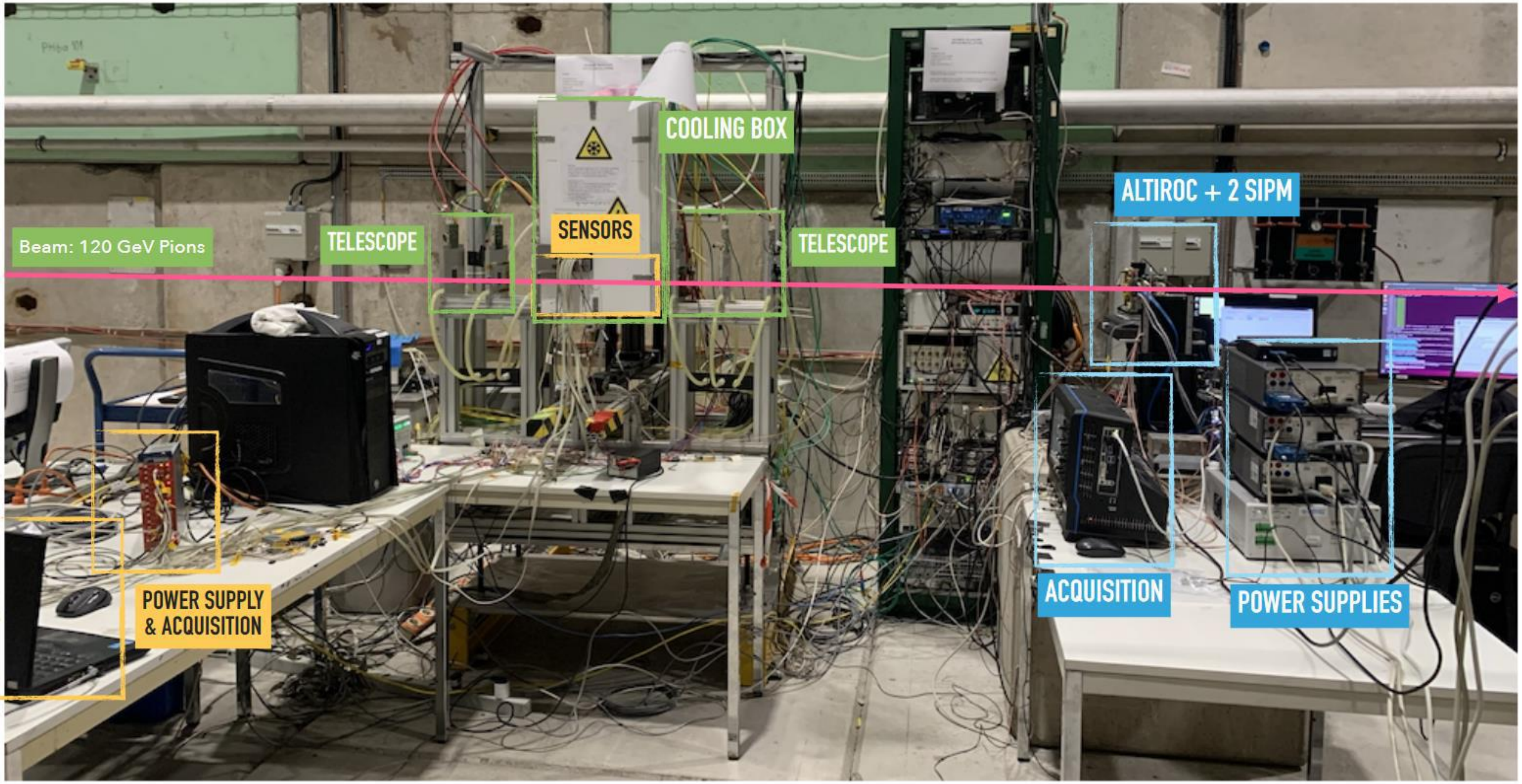
- TOA evaluated using CFD method with f_{CDF} = 50%
- Time resolution of the MCP measured to be 10.6 ps (previous study)
- Time resolution per hit **below 40 ps for unirradiated sensors** and **50 ps for irradiated sensors** (for sensor only, without ASIC) **met**
- Data taking at -30°C





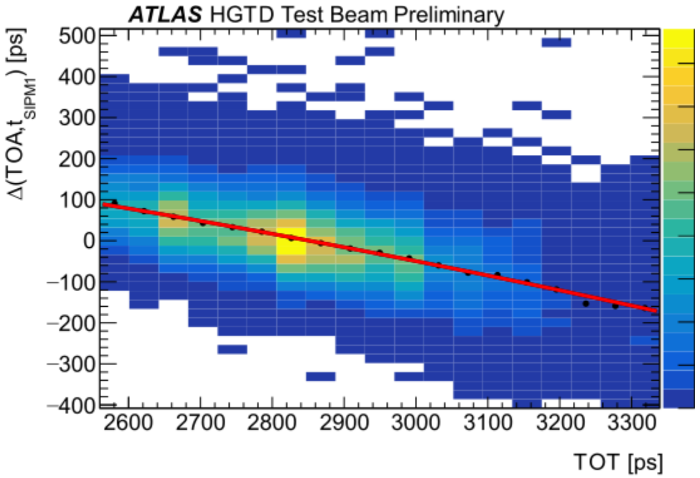
Sensor + ASIC Performance at Test Beams

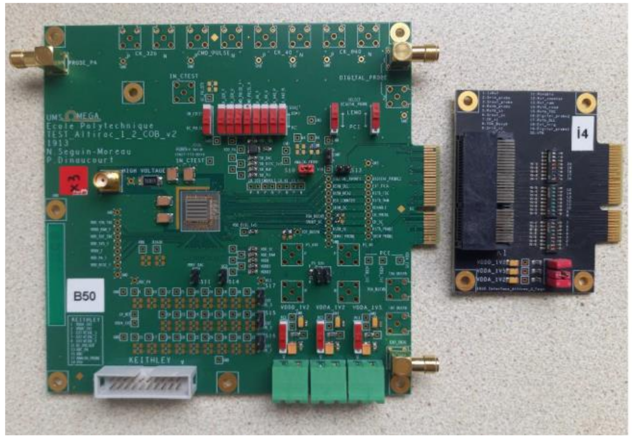
ASIC Test Beam Setup at SPS H6A



ALTIROC1 + Sensor Prototype: Time Resolution

- ALTIROC1: 5×5 small-scale prototype
- ALTIROC1 + Sensor prototype
- Data taking at room temperature
- TOT timewalk correction where TOA vs TOT is flat i.e., TOA > 1600 ps
- Correction: 65.1 ps → 46.3 ps
- Time resolution per hit **below 50 ps for unirradiated sensors** requirement fulfilled



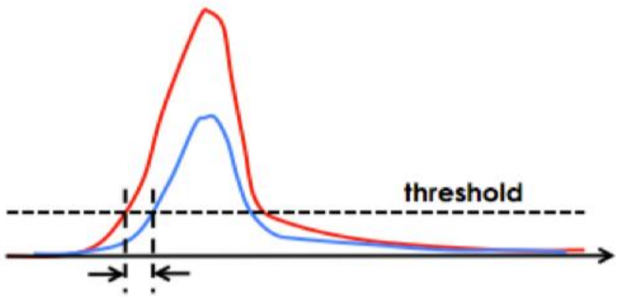


Sensor ASIC

$$\sigma^2_{total} = \sigma^2_{Landau} + \sigma^2_{Timewalk} + \sigma^2_{Jitter} + \sigma^2_{TDC} + \sigma^2_{Clock}$$

- σ^2_{Landau}: non-uniform energy distribution < 25 ps
- $\sigma^2_{Timewalk} = \left(\frac{V_{Th}}{S/t_{rise}} \Big|_{RMS} \right)^2$: < 10 ps can be corrected
- $\sigma^2_{Jitter} = \left(\frac{t_{rise}}{S/N} \right)^2$: largest component (target < 25 ps)
- σ^2_{TDC}: < 5 ps
- σ^2_{Clock}: < 10 ps

Illustration of timewalk correction



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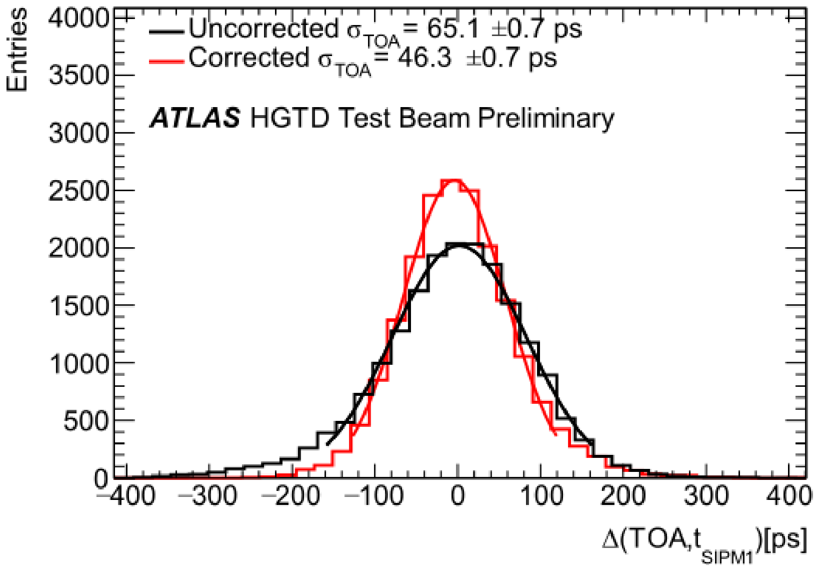
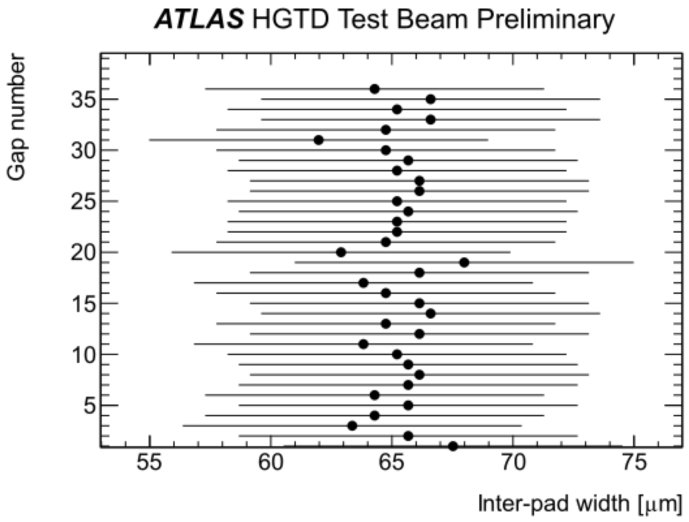
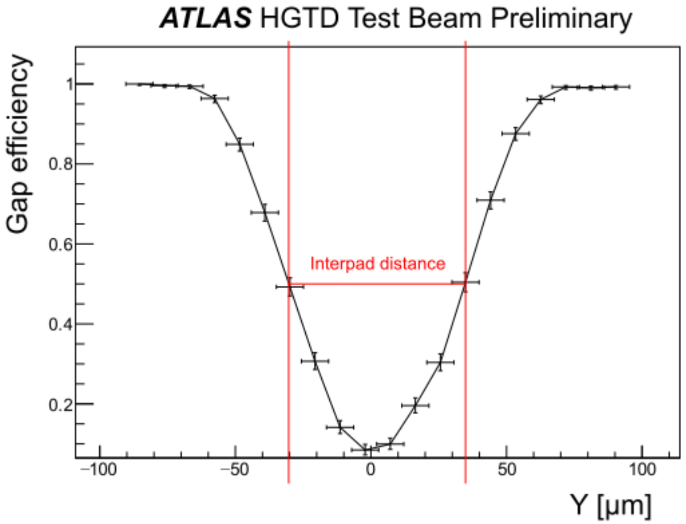
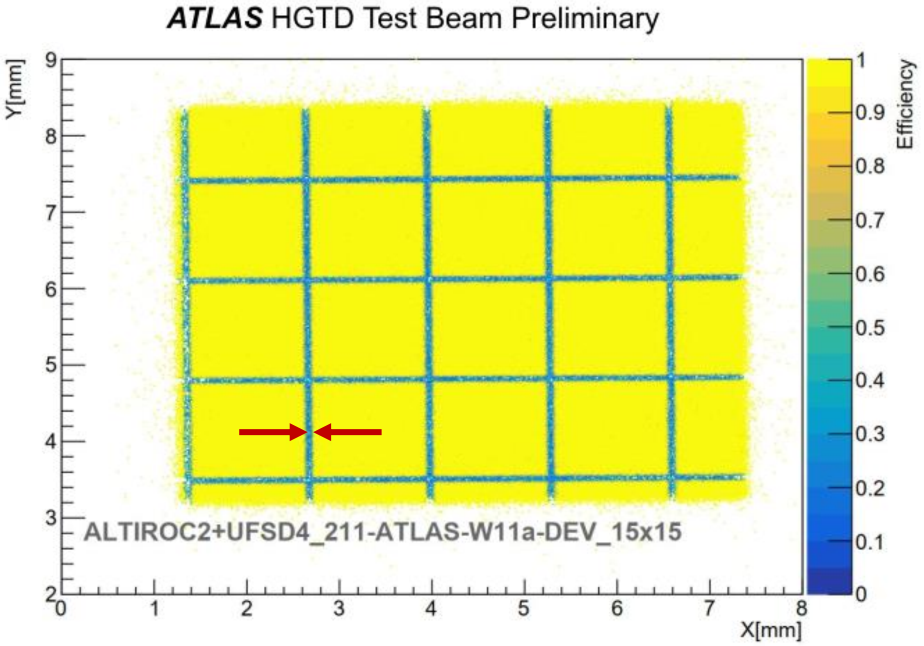


ALTIROC2 + Sensor Prototype: Hit Efficiency and Inter-pad Gap

- ALTIROC2: full scale prototype
- Data taking at room temperature
- Efficiency uniform and close to 100%
- Inter-pad gap: defined as width at 50% efficiency
- Inter-pad width: ≈ 65 μm with good uniformity





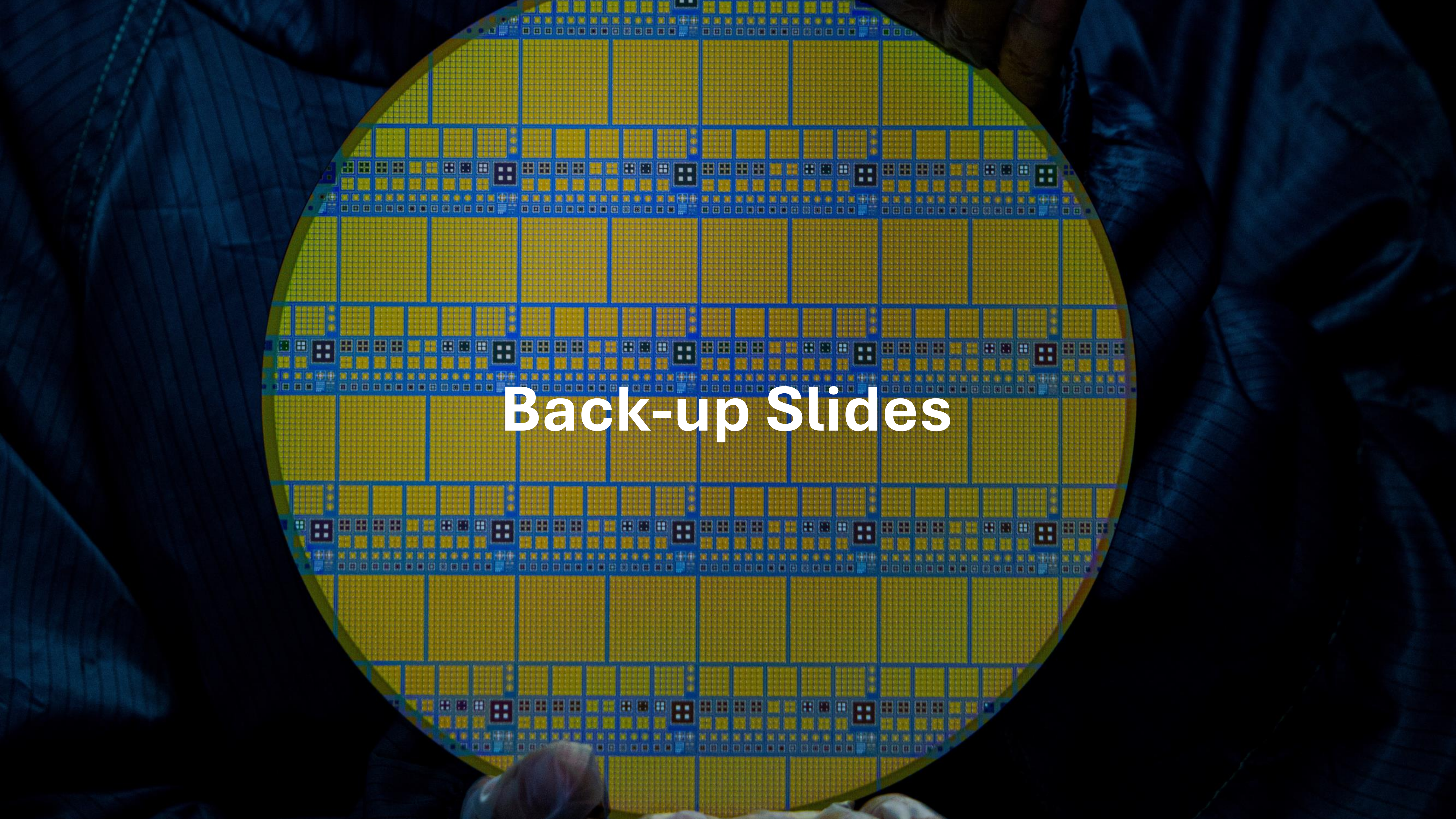


Summary & Outlook

- HL-LHC: pile-up up to 200 interactions per bunch crossing → challenge for the ATLAS detector → HGTD deployed to mitigate pile-up effects
- Low Gain Avalanche Detector (LGAD) technology for HGTD sensors
- Sensors and hybrids extensively tested at HGTD test beams during the previous years
- Preproduction sensors meet requirements in terms of time resolution, collected charge and hit efficiency
- ALTIROC1/2 + Sensor prototypes meet requirements in terms of timing, efficiency and interpad gap
- ALTIROC3 + Preproduction sensor test beam performed at DESY in February - March 2024, analysis ongoing
- Part of the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

Thank you for your attention!

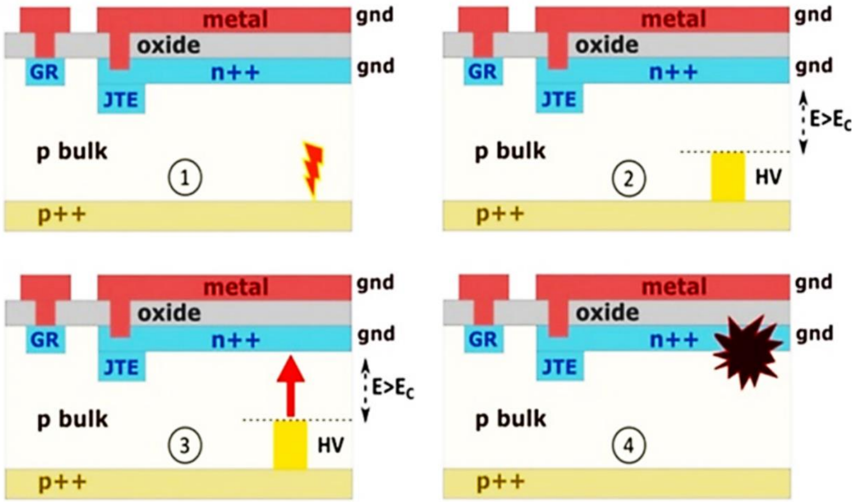
Back-up Slides



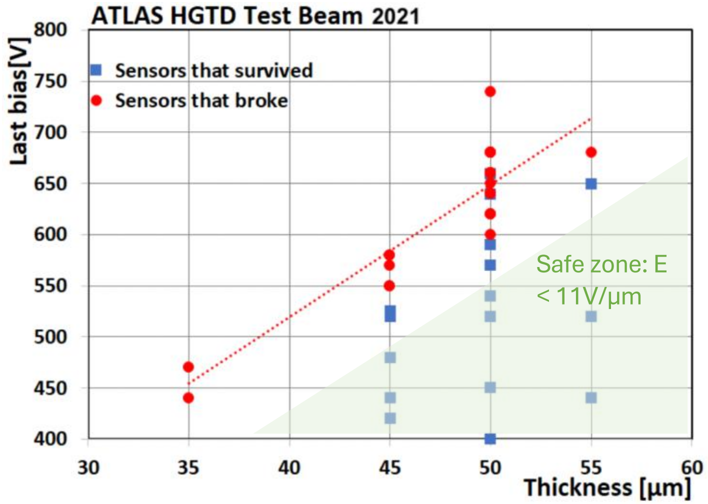
Single Event Burnout (SEB)

- **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 50µm sensor thickness: **550V**



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



Process Quality Check (PQC)

- **Quality Control-Test Structures (QC-TS)** produced along sensors to **monitor the production** and **extract wafer parameters (PQC)**
- Quality of the production relies on sensor measurements by the vendor and **PQC**
- PQC setups deployed at 5 different sites
- Correlate sensor performance with QC-TS measurements based on acceptance criteria
- PQC setup at CERN ready: measurements done automatically with probe card

PQC setup at CERN