Beam-test evaluation of pre-production Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector

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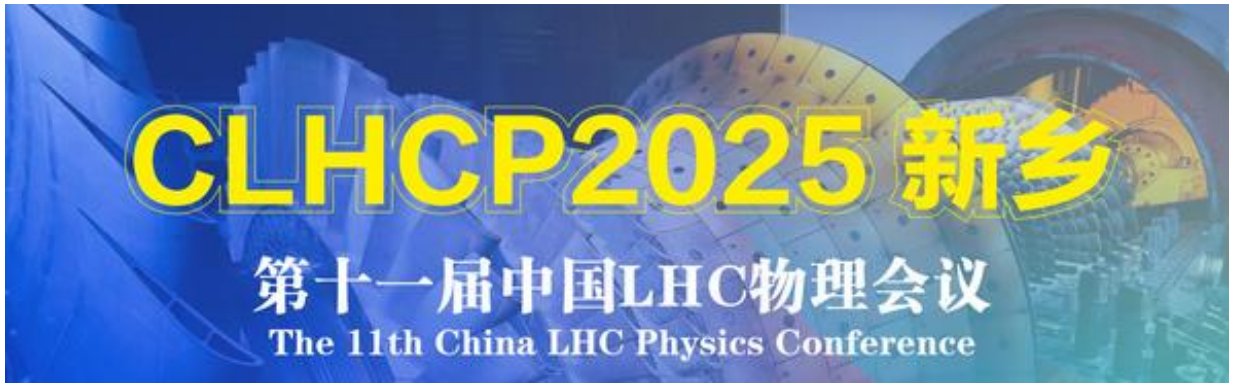


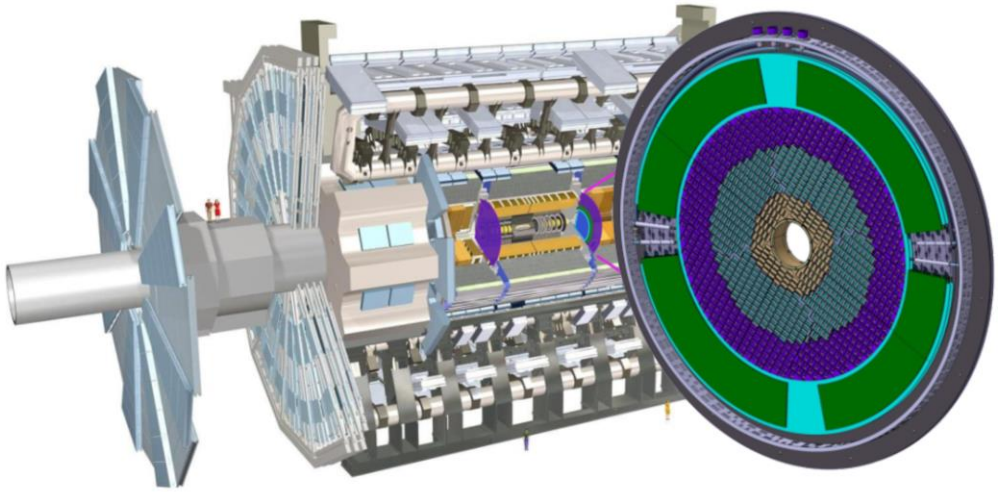
ATLAS EXPERIMENT

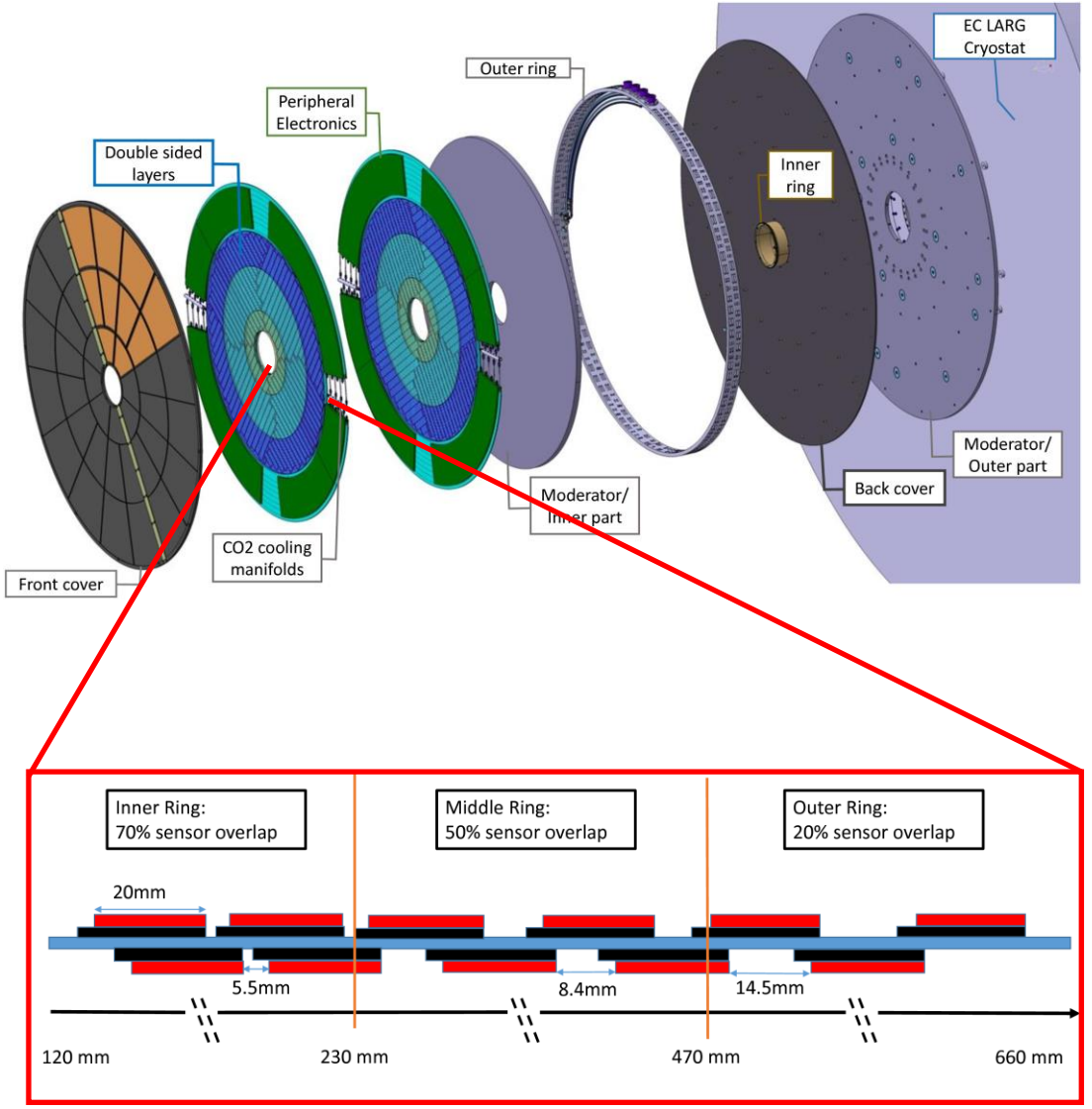
Institute of High Energy Physics
Chinese Academy of Sciences

Outline

- Introduction
- HGTD Sensor
- Test Beam Setup and Data analysis
- LGAD Performance Results
  - Collected Charge
  - Time Resolution
  - Hit Reconstruction Efficiency
- Conclusion and Outlook

High Granularity Timing Detector



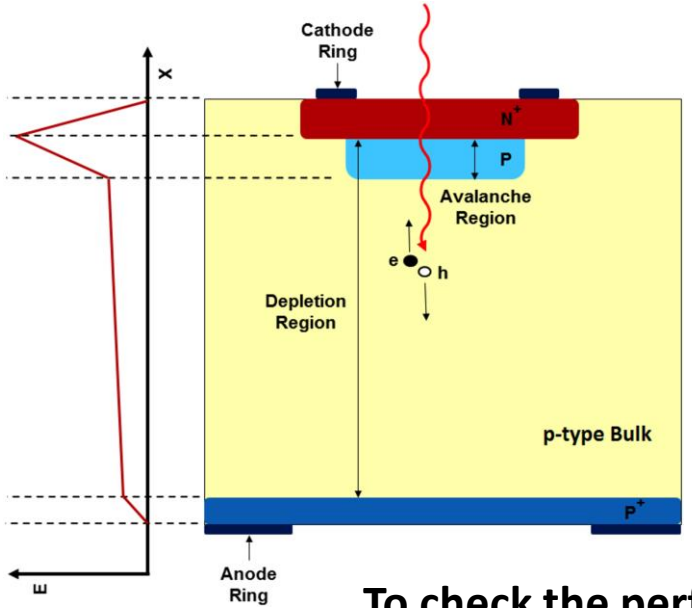


- For **HL-LHC**, HGTD will be install in **ATLAS Phase-II** upgrade to: mitigate pile-up effects in the forward region, and measure per bunch luminosity
- Placed between **Inner Tracker** (ITk) and **Liquid Argon Calorimeter**
- Active area coverage: **$2.4 < |\eta| < 4.0$**
- Consists of **8032 modules** (2 LGAD sensors + 2 r/o ASICs each) **6.4 m^2** of silicon sensors
- Radiation hardness requirements (with replacements of the
- inner and middle rings): Maximum fluence: **2.5×10^{15} n_{eq}/cm^2**

The HGTD LGAD Sensors

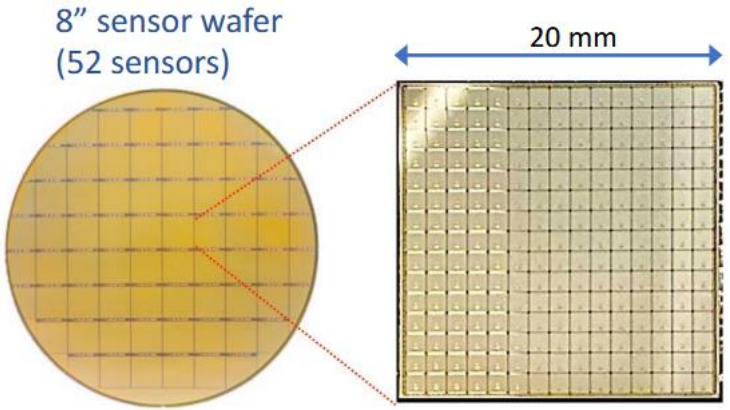
Low Gain Avalanche Detector (LGAD) technology utilized for HGTD

- Each sensor is an array of **15×15 pads**
- Pad size: **1.3 mm×1.3 mm**
- **3.6 M** channels
- Physical / active thickness: **775 µm** / **50 µm**
- Vendors: **IHEP-IME** and **USTC-IME**



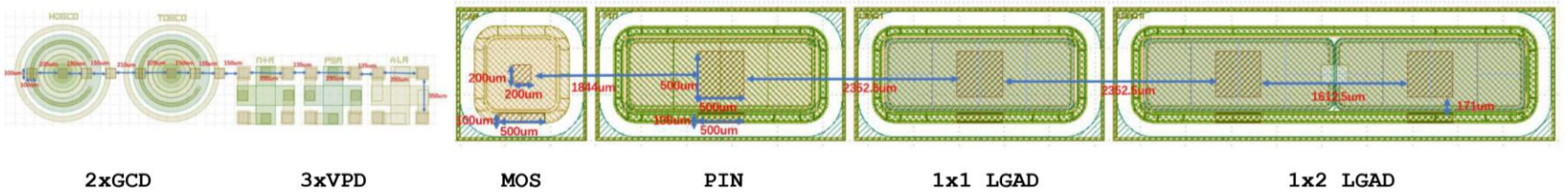
LGAD Technology:

- **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



To check the performance of the sensors:

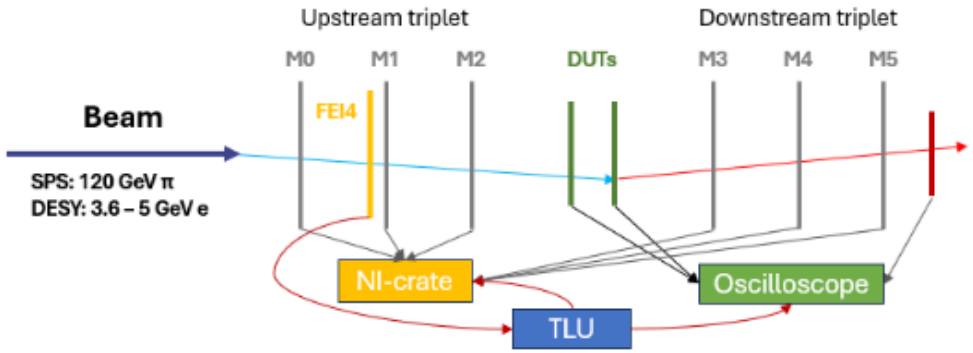
- Single pad LGAD from Control-Test Structures (QC-TS)
- Containing test structures for electrical and functional measurements of technological parameter
- Active area of **2.6 × 0.65 mm²**
- Exposed to fluences up to **2.5 ×10¹⁵ n_{eq}/cm²**

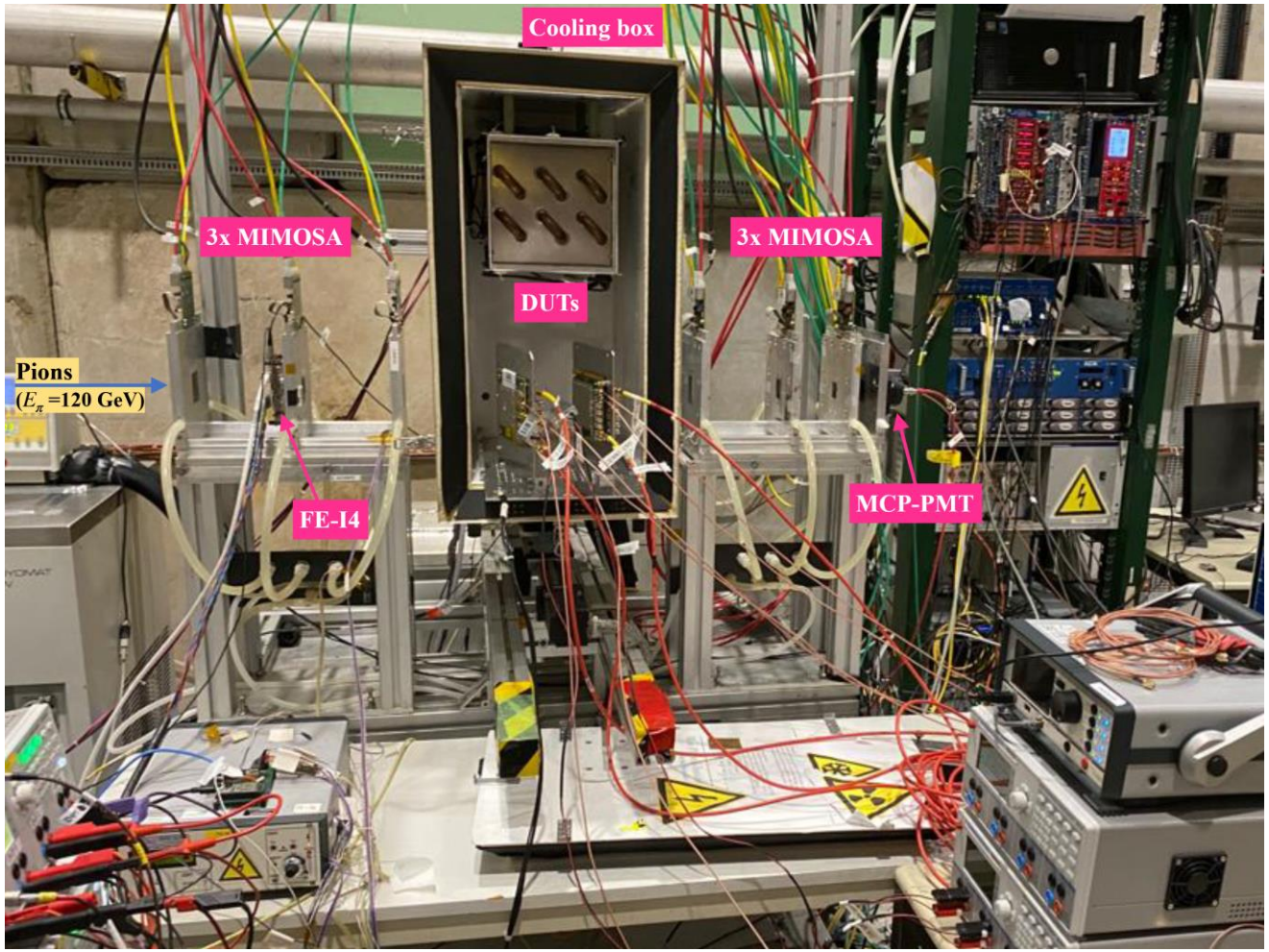


HGTD Test Beam Setup

Beam-test campaigns:
CERN SPS H6A line **120 GeV** pion beam
DESY II test beam facility **5 GeV** electron beam

- **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**





Test beam setup at the H6A beamline of SPS

Track reconstruction and data analysis

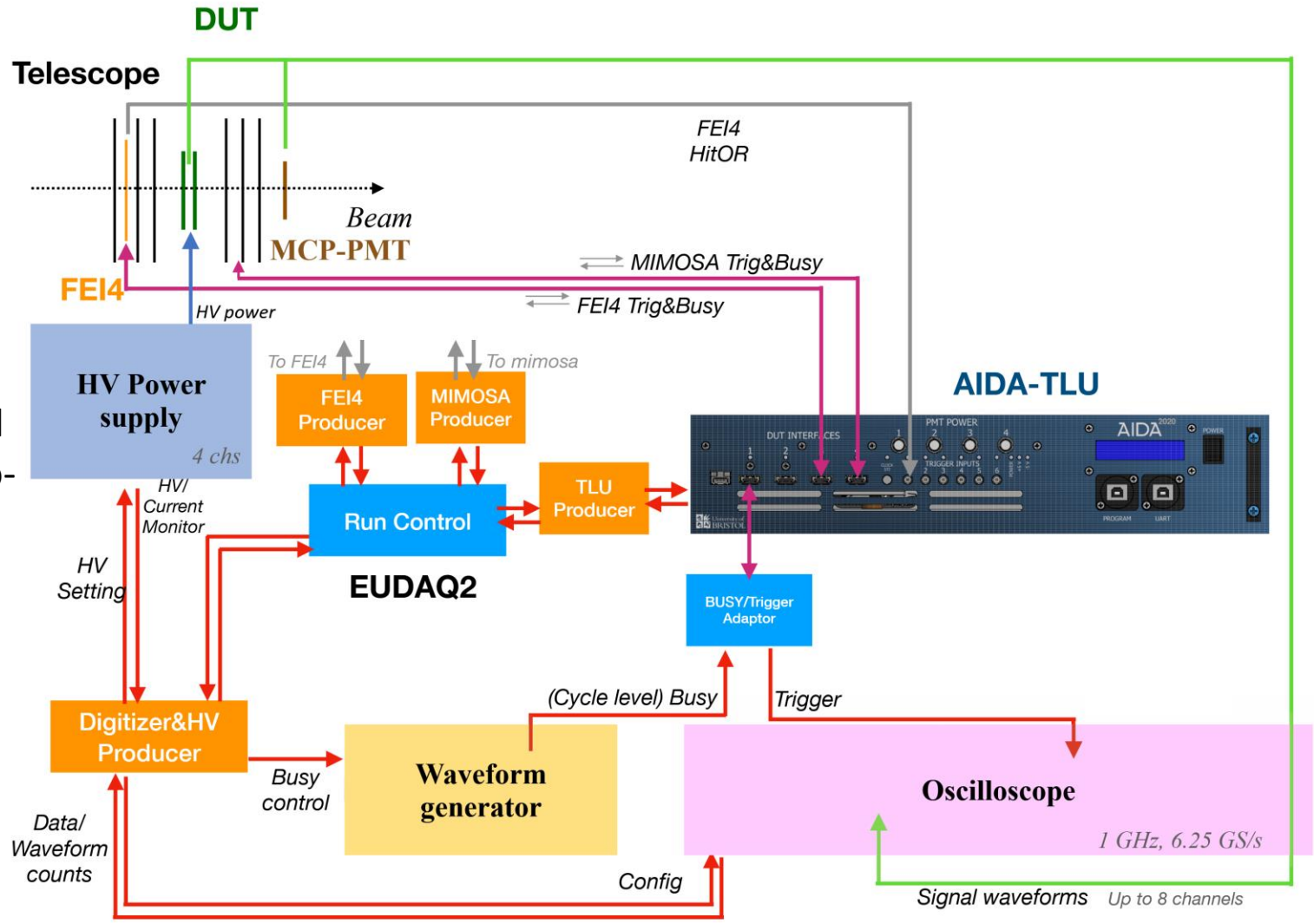
Two independent systems used to collect data:

1- Oscilloscope:

- recorded the waveforms from LGAD and MCP-PMT detectors
- Extracted waveform properties, including signal amplitude, rise time, collected charge, signal-to-noise ratio (SNR), and Time of Arrival (TOA).

2- EUDET-type telescope and FEI4 plane:

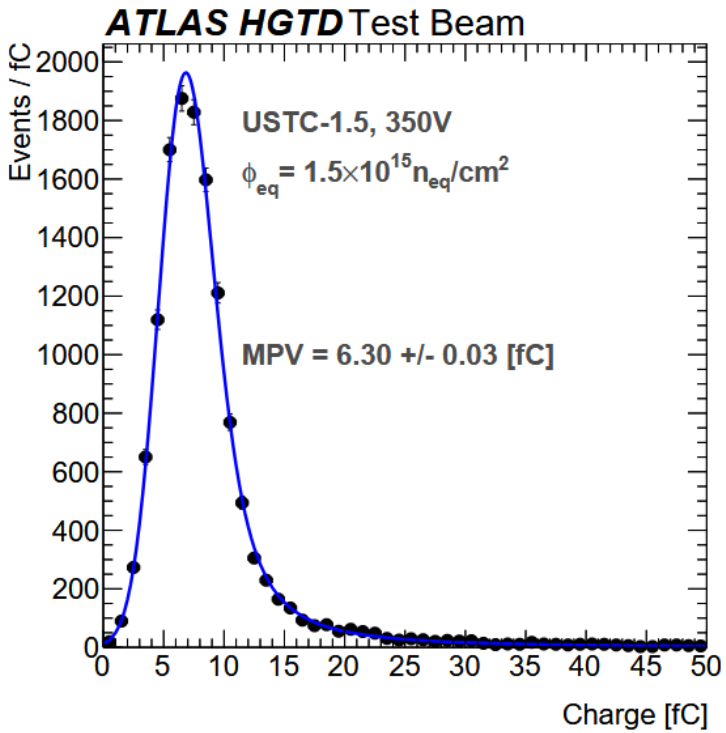
- provided track information
- χ2-based minimization=> alignment of the telescope



Sensor performance results: Collected Charge

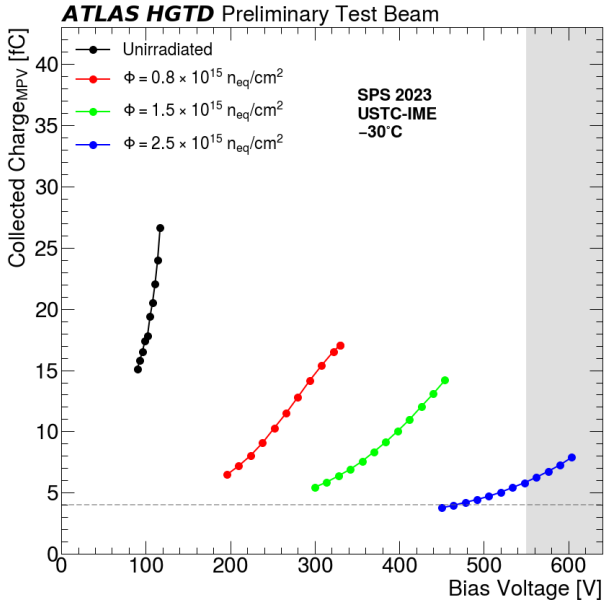
Charge distribution is obtained from events passing the selection: **signal amplitude** and **number of tracks**

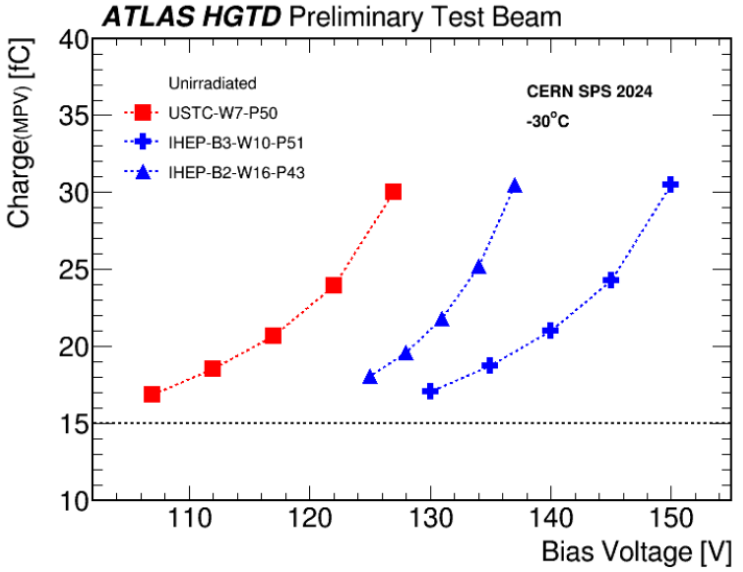
- Fitted with is a **Landau-Gaussian convolution**
- the **most probable value (MPV)** of the fit quantify the collected charge
- Require at least **4 fC (15 fC**) irradiated (Unirradiated) sensors for a sufficient time resolution

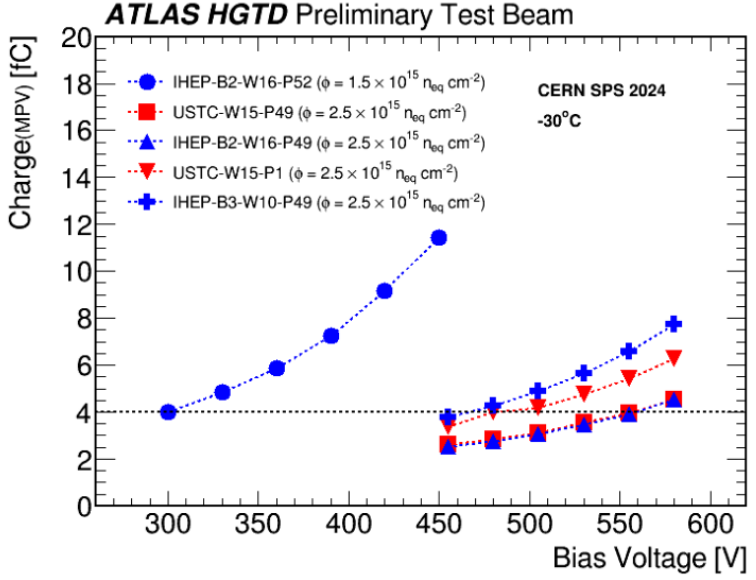


Sensor performance results: Collected Charge

- **MPV** obtained identically for all DUTs across bias voltages
- **Unirradiated sensors** meet the **15 fC requirement** even at low bias
- **Irradiated devices** show **reduced collected charge** due to gain layer damage
- DUTs at **1.5–2.5 × 10^{15} n_{eq}/cm^2** require **higher bias voltages** to reach 15 fC
- At **highest fluence (2.5 × 10^{15} n_{eq}/cm^2)**, all sensors **exceed 4 fC** at **≤ 550 V**





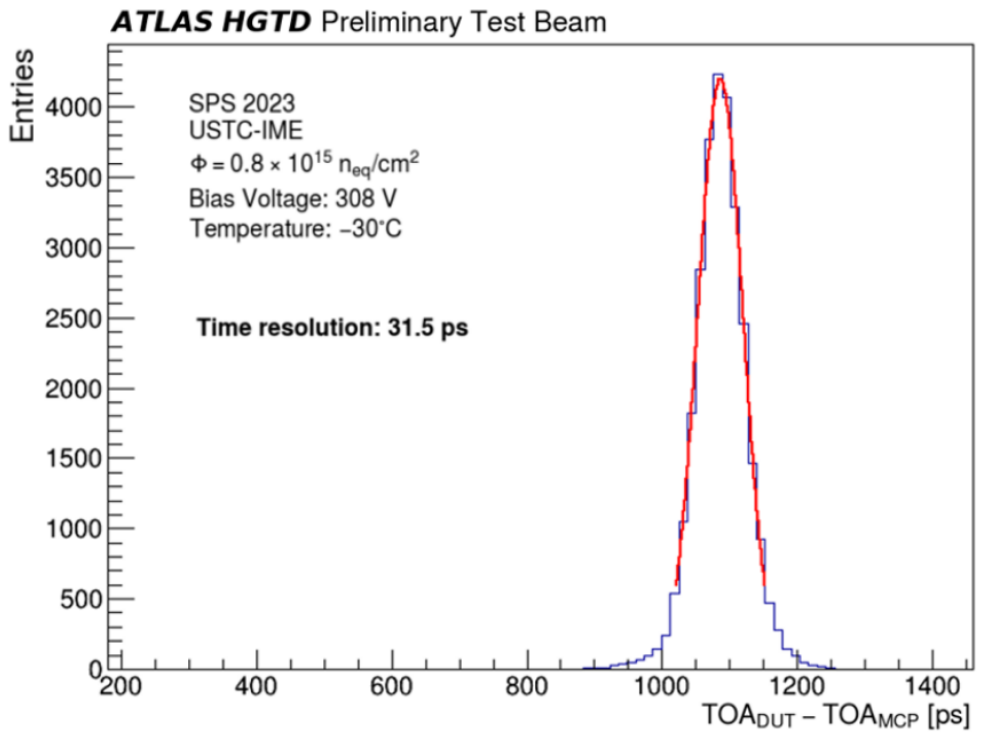


Sensor performance results: Time Resolution

- Time resolution measured with reference detectors (MCP)
- The TOA was extracted using the Constant Fraction Discriminator (CFD) method
  - defined as the point where the signal crosses a fixed fraction
- TOA evaluated using CFD method with fCDF = 50%
- Time resolution the standard deviation of the TOA difference between DUT and MCP (convolution of the two resolutions):

$$\sigma_{DUT} = \sqrt{\sigma^2 + \sigma_{MCP}^2}$$

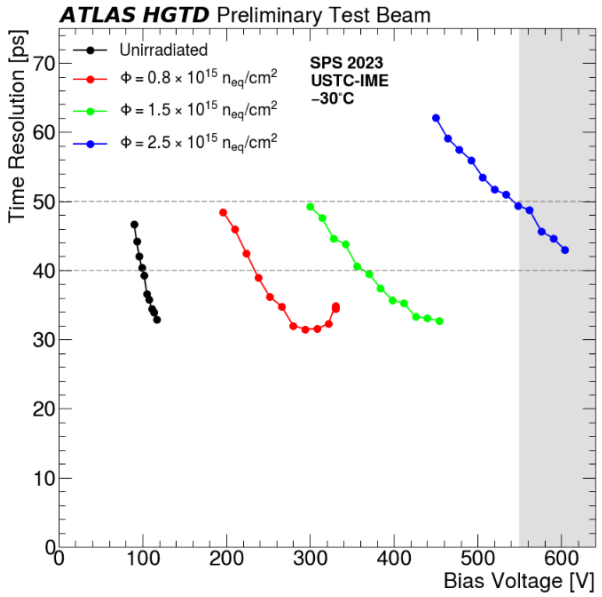
- Time resolution of the MCP measured to be 10.6 ± 0.7 ps

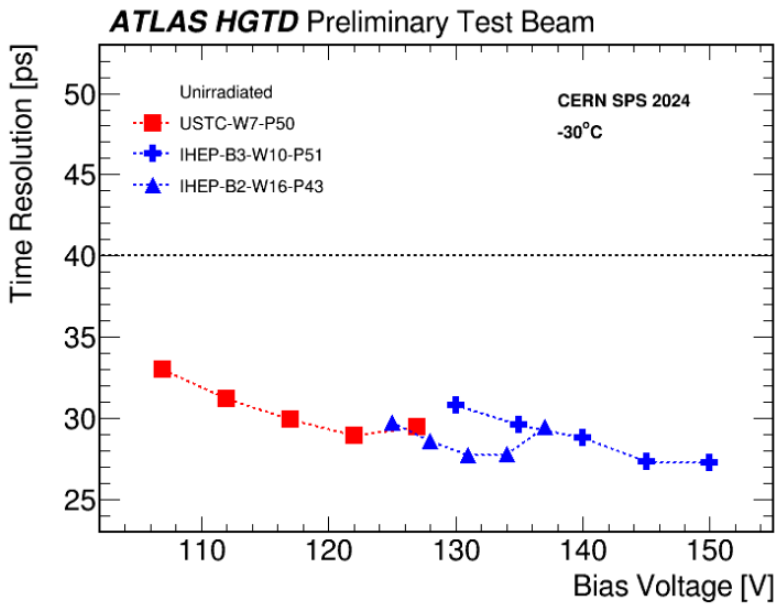


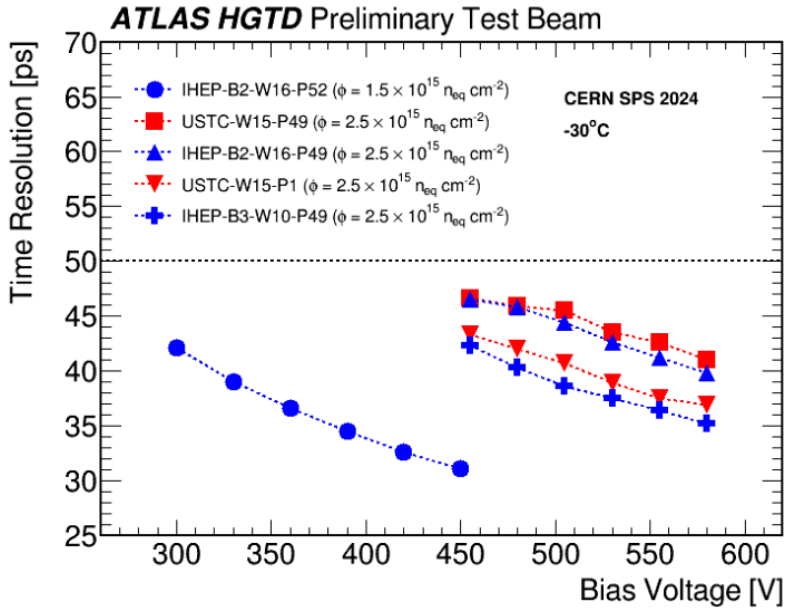
Sensor performance results: Time Resolution

Time Resolution vs. Bias Voltage (USTC & IHEP Sensors)

- **Time resolution** evaluated as a function of **bias voltage** for both sensor types
- **All unirradiated sensors** achieve **< 40 ps** time resolution
- **All irradiated sensors** maintain **< 50 ps** time resolution
- Performance remains **within specifications across tested bias range**







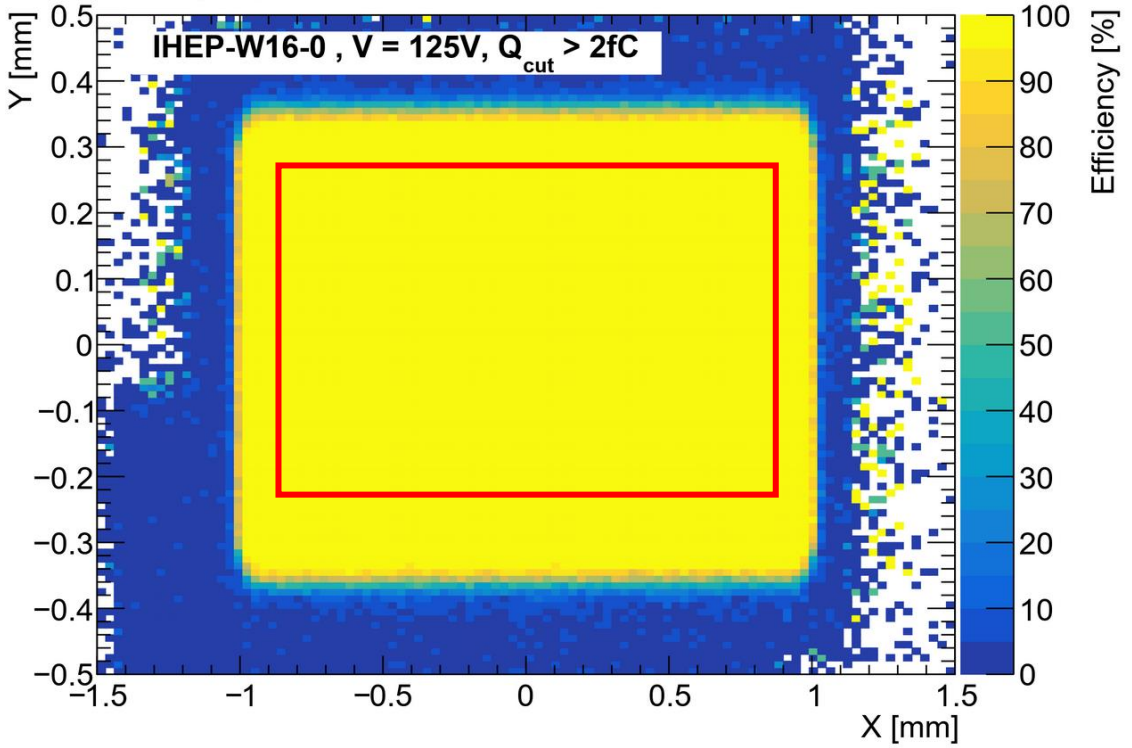
Sensor performance results: Hit efficiency

Hit efficiency defined as:

$$\text{Hit Efficiency} = \frac{\text{Reconstructed tracks with } q > Q_{\text{cut}}}{\text{Total reconstructed tracks}}$$

- Q_{cut} = 2 fC: threshold of the readout ASIC
- The fiducial region is defined as the rectangle centered 60% area of the DUT
- Events with exactly one reconstructed track

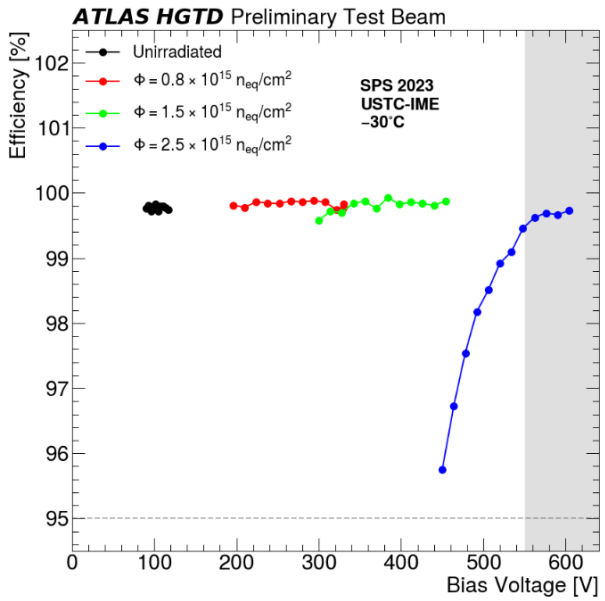
- High efficiency uniformity across the sensor

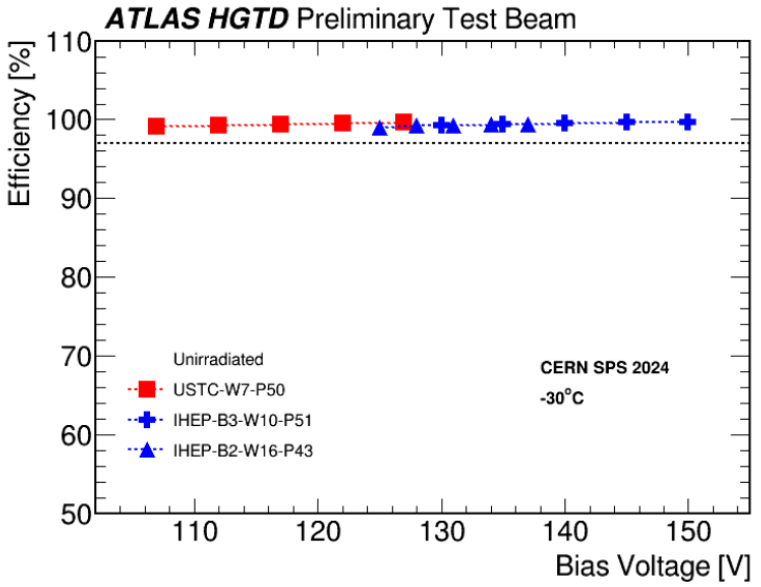


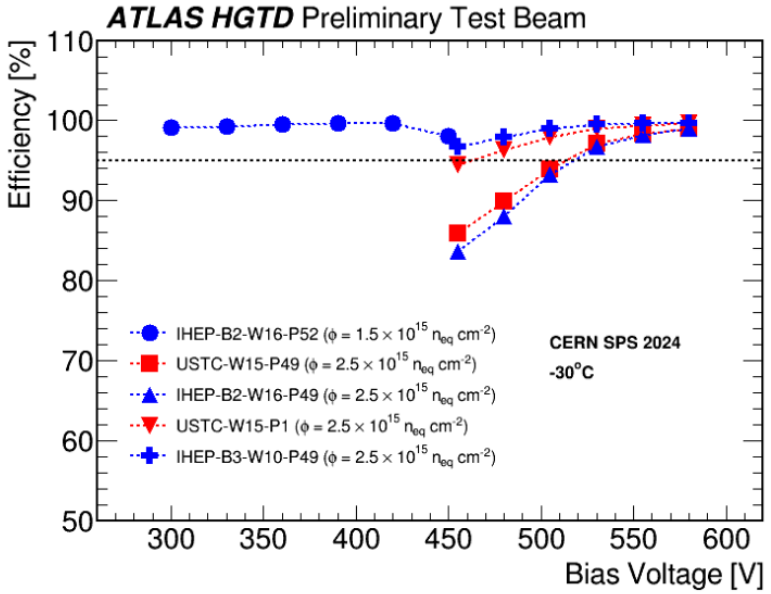
Sensor performance results: Hit efficiency

Hit Reconstruction Efficiency

- **Efficiency requirements:** Unirradiated sensors → **> 97%,** Irradiated sensors → **> 95%**
- **Unirradiated sensors:**
  - Maintain **> 99% efficiency** across all tested bias voltages
- **Most irradiated sensors** (ϕ = 2.5 × 10^{15} n_{eq}/cm^2):
  - All sensor designs achieve the **minimum required 95% efficiency**







Conclusions & Outlook

- **Comprehensive evaluation** of single LGADs (IHEP & USTC) for HGTD pre-production
- **Unirradiated sensors:**
  - Meet **15 fC charge** and **< 40 ps time resolution** requirements at low bias
  - Show **> 99% hit efficiency** and **uniform performance** across the sensor area
- **Irradiated sensors (up to 2.5 × 10^{15} n_{eq}/cm^2):**
  - Maintain **> 4 fC collected charge** and **< 50 ps time resolution**
  - Achieve **≥ 95% efficiency**, demonstrating **strong radiation tolerance**

- **Overall:** Both IHEP and USTC LGADs meet **HGTD performance goals**
- Finalizing for the publication to **JINST** https://cds.cern.ch/record/2941319/
- To evaluate the feasibility of the complete **LGAD-based timing detector** for the **HL-LHC.**
- Full-size sensor tests with final readout ASICs and system-level validation