Performance studies of Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector

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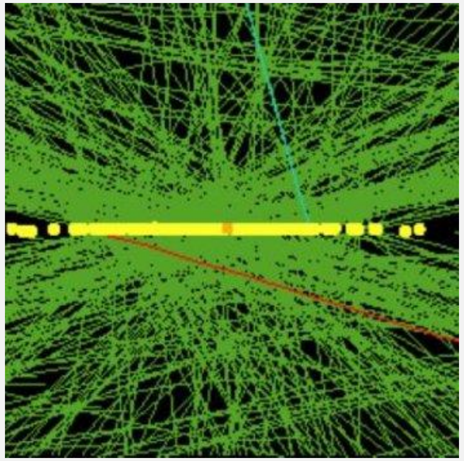
Outline

- Motivation
- The ATLAS High Granularity Timing Detector (HGTD)
- Sensor activities in HGTD
- LGAD End-of-Lifetime
- LGAD performance with charged-particle beams
  - Collected charge, time resolution, hit efficiency
- Summary and outlook

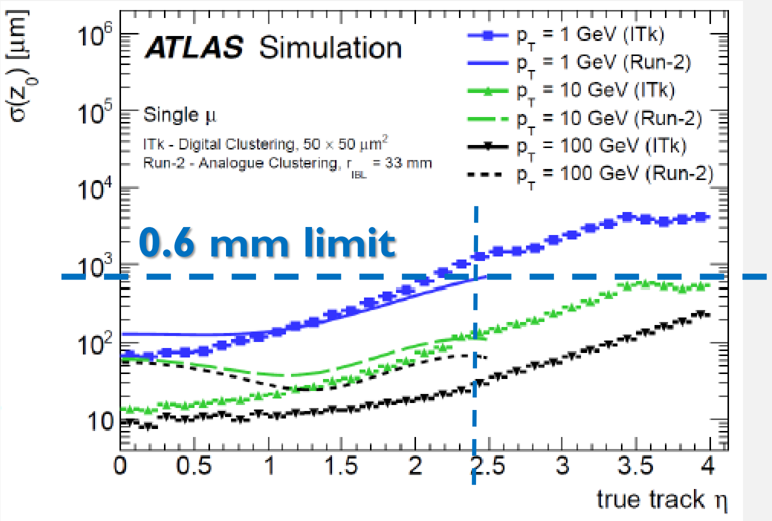
Motivation for LGAD-based detectors

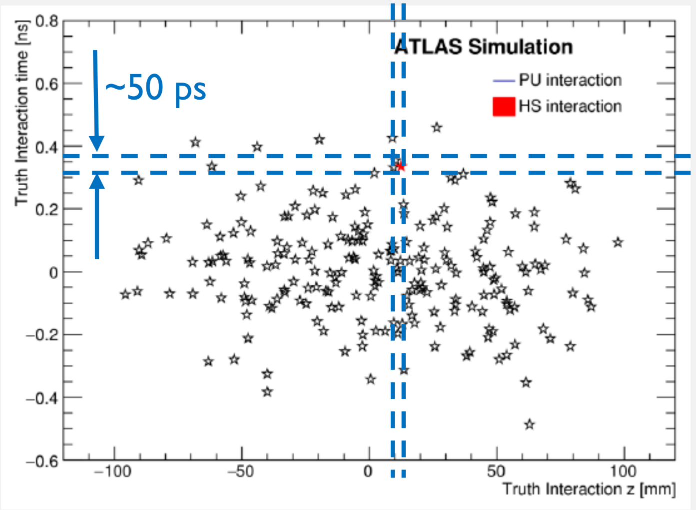
- Silicon pixel detectors are especially important for the precise determination of tracks and vertices, enabling the selection of interesting events through the identification of b-jets (b-tagging)
- Particle accelerators are improved to further probe the energy frontier delivering higher energies and increasing the number of collisions per unit time
- At High-Luminosity phase of the LHC (HL-LHC):
  - The instantaneous luminosity will be approximately a factor of ~5 higher than the LHC nominal values
  - Several LHC experiment sub-systems will require an upgrade in order to cope with the high rate, hit occupancy and radiation environment
- New solutions have to be found for the silicon sensors and the associated front-end electronics
- Interest to study **L**ow **G**ain **A**valanche **D**etectors (LGADs) and their performance at high fluences beyond 10^{15} n_{eq}/cm^2
  - Excellent time resolution of about 30 ps before irradiation
  - Performance remains challenging due to degradation of the gain layer
  - Investigate new doping materials (B, Ga), substrates and new geometries
  - Deliver thin sensors providing good time resolution, fine segmentation, radiation hardness



Why timing is so important?

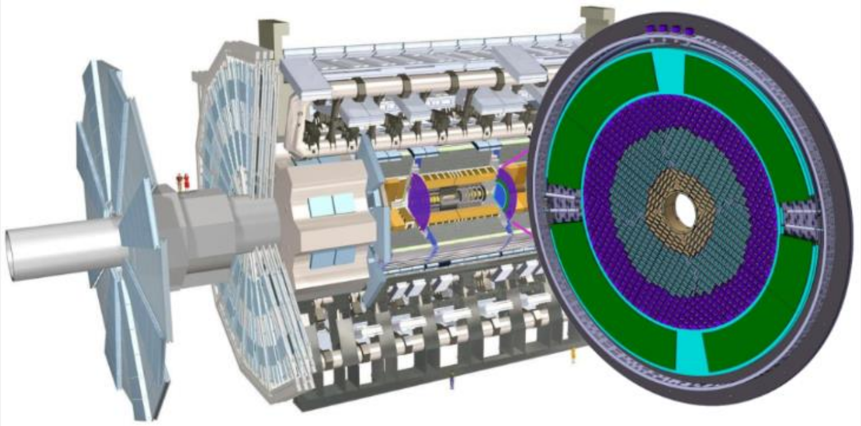
- At the HL-LHC
  - Instantaneous luminosities up to L ≃ 7.5×10^{34} cm^{-2} s^{-1} (×5 current L_{inst})
    - Pile-up: $<\mu>$ = 200 interactions per bunch crossing → ~1.5 vertex/mm on average
  - Vertex reconstruction and physics objects performance of ATLAS will be significantly degraded in the forward region compared to the central region
    - Need z_0 resolution <0.6 mm
    - Liquid Argon based electromagnetic calorimeter has coarser granularity
    - New inner tracker (ITk) has poor z resolution in the forward region
  - Push to higher luminosity → timing becomes more and more important
    - Using timing information easier to reconstruct vertices
- A **High Granularity Timing Detector** (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation
  - Improve performance in the forward region by combining
    - HGTD high-precision time measurement
    - ITk position information (vertices longitudinal impact parameter)



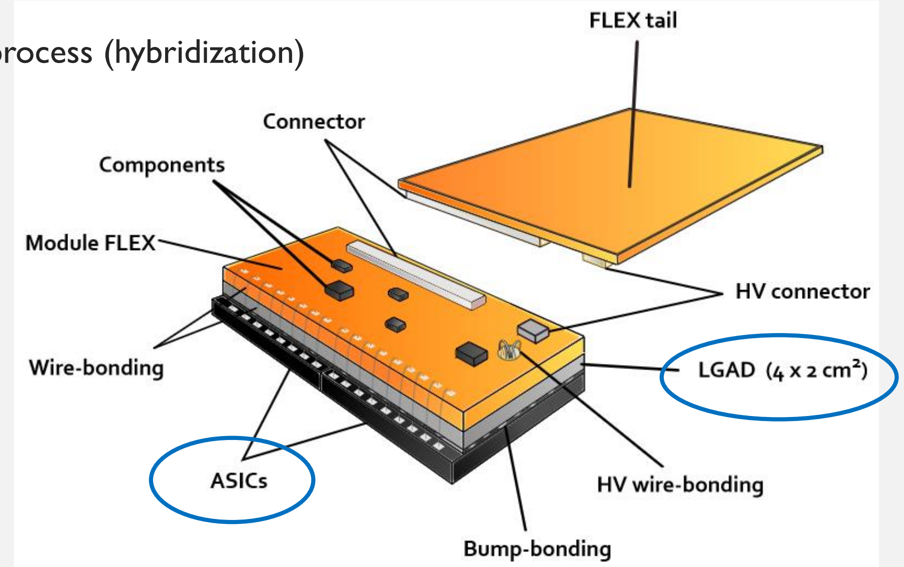


HGTD detector

- Detector quite constrained by the space available and the harsh radiation environment
- HGTD designed for operation with $<\mu>$ = 200 and 4000 fb^{-1}
  - Recover electron ID, track & jet reconstruction and b-tagging
- Two instrumented double-sided layers mounted in two cooling/support disks per end-cap
- LGAD technology chosen
  - It provides an internal gain (good time resolution) while providing a good S/N ratio (good efficiency)
  - Sensors will be operated at -30 °C to mitigate impact of irradiation
  - Connected to dedicated front-end electronics ASICs (ALTIROC) through flip-chip bump bonding process (hybridization)



- Requirements:
  - Detector can withstand the lifetime of the HL-LHC running (3 ring layout)
    - Maximum n_{eq} fluences: 2.5×10^{15} n_{eq}/cm^2
    - Total Ionising Dose (TID): 2 MGy at the end of HL-LHC (4000 fb^{-1})
  - Average time resolution: 35 ps (start), 70 ps (end) per hit / 30 ps (start), 50 ps (end) per track
  - Collected charge per hit >4 fC
  - Hit efficiencies of 97% (95%) at the start (end) of their lifetime

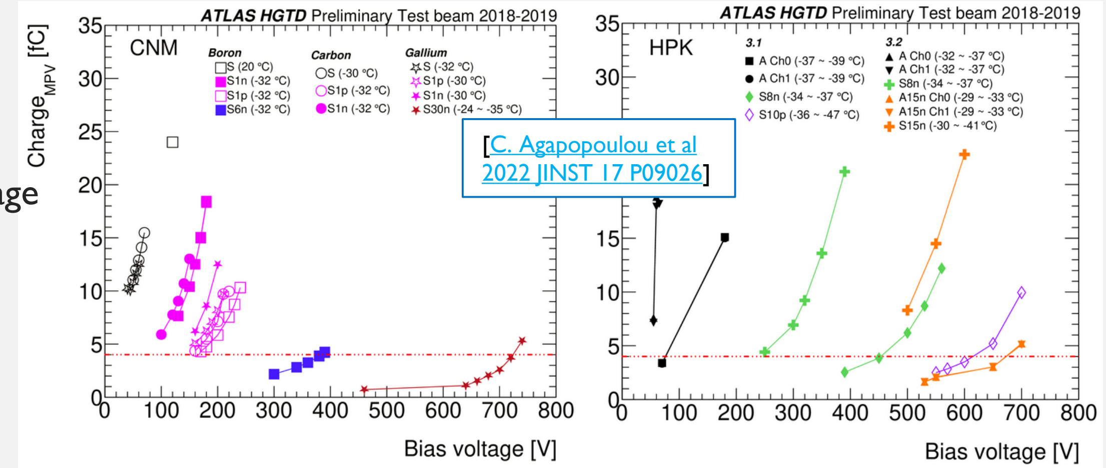


Sensor activities in HGTD

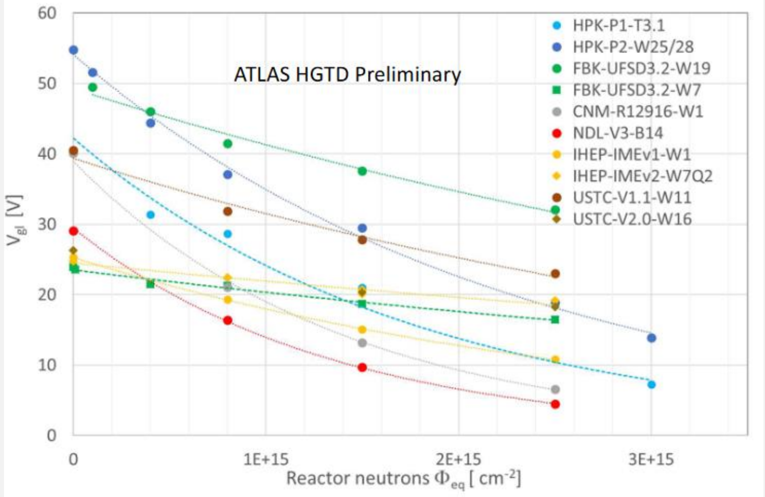
- LGAD sensors have been extensively studied during the R&D phase of the HGTD project
- Investigations towards radiation hard LGADs for HGTD
  - Explored use of different designs, doping materials and C-enriched substrates
  - B+C sensors have larger charge collection than B and Ga at the same bias voltage
    - C helps to diminish the effect of gain reduction with irradiation
  - Studies of performances and radiation hardness
    - Acceptor removal coefficient targeting 1-2×10^{-16} cm^2

$$V_{gl} = V_{gl0} \times \exp(-c \times \phi_{eq})$$

    - Optimization carbon enrichment dose and diffusion techniques
- Tested sensors with (B, B+C GL) from several vendors (this talk)
  - Simultaneously show good enough CC/timing/efficiency in the test beam after 2.5×10^{15} n_{eq}/cm^2
- Ongoing studies on the performance of ALTIROC2+full sensor
  - We aim to irradiate full size modules



[C. Agapopoulou et al 2022 JINST 17 P09026]

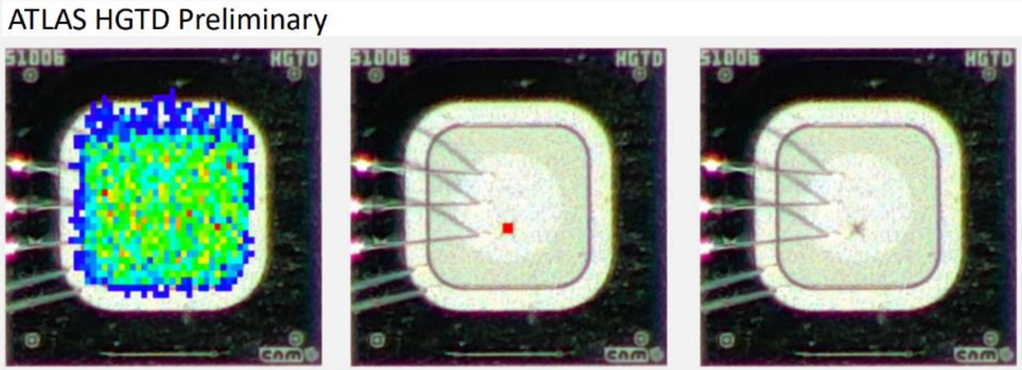


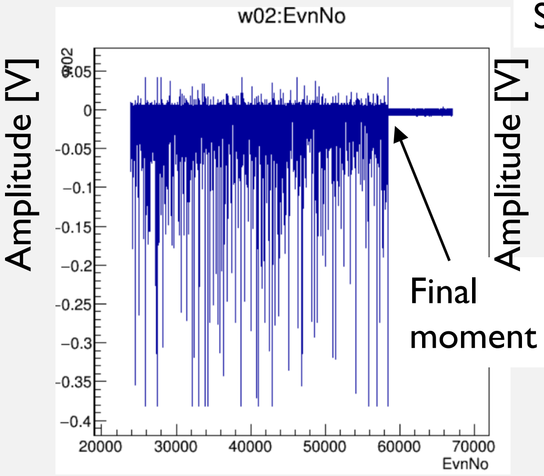
LGAD performance studies
[paper under review]

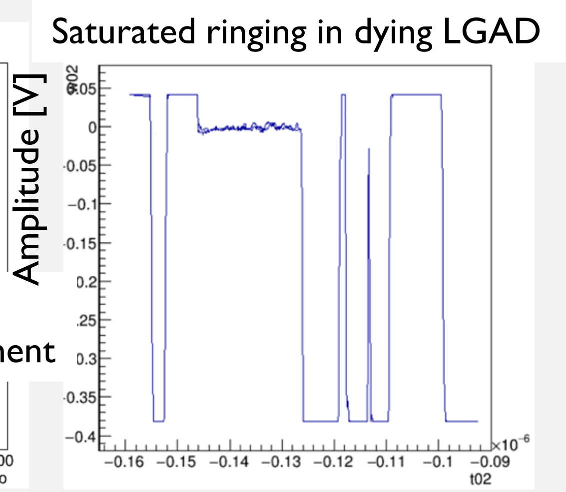
LGAD End-of-Lifetime

LGAD end-of-lifetime studies [paper under review]

- Major concern for operation stability of LGADs after irradiation
  - After irradiation LGAD timing performance degrades due to loss of gain → increase of bias voltage to recover
    - Some devices showed irreversible breakdown while operating in these conditions (~100V lower than operated at lab)
    - Observed in most vendors at different test beam facilities
  - Determine the safe operating voltage that these sensors can withstand
    - Common effort ATLAS/CMS/RD50 Collaborations to find mitigating measures
    - Exposed large number of sensors to charged-particle beams
    - Single Event Burnout (SEB): usually triggered by single particle. Large energy deposits: electric field collapse in present of high concentration of free carriers. Electric field (V_{bias}/thickness) is the key parameter determining the fatality
    - Destructive events begin to occur when the average electric field in the sensor becomes larger than 12V/µm
  - Most promising solution is Carbon enrichment, which would reduce the required voltage and therefore extend the lifetime

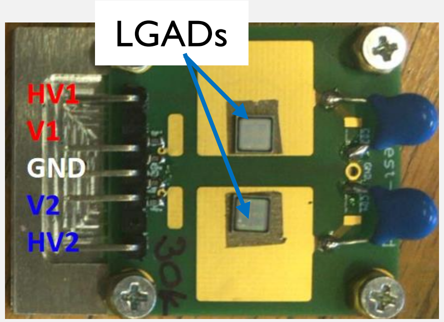


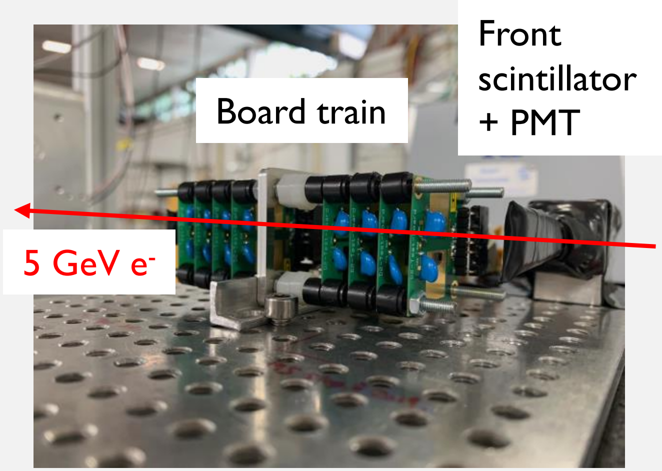


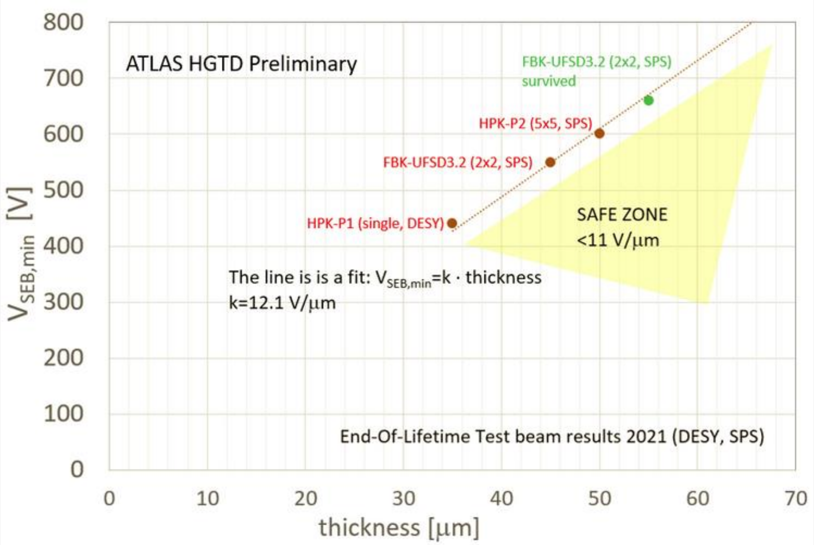


LGAD End-of-Lifetime tests

- Test beam @DESY and @SPS in 2021
  - Using EUDET-type telescope + thermal box + TLU
  - LGAD end-of-lifetime studies (cold measurements at -30 °C)
    - Irradiated LGADs at different fluences from different vendors
    - Study the limitations of the operational voltage at each fluence
    - Use different geometries (change in rate): single pad, 2×2, 5×5
  - Goals:
    - Gain more information on single event burnout (SEB) mechanism
    - Determine safe bias voltages to avoid SEB
    - Check candidate sensors are safe from SEB at biases meeting HGTD specifications
  - Procedure:
    - Expose irradiated sensors to beam, keeping track of rate, at 8h per bias point
    - Increase bias until SEBs occur, check if above required voltage for 4fC collected charge
- Both beam test campaigns confirmed SEB issue occurs → safe zone <11 V/µm
  - 74 sensors tested, 55 survived to voltages expected to meet HGTD specs
  - SEB probability ~10^{-6} to ~10^{-5} depending on irradiation, for ~13V/µm

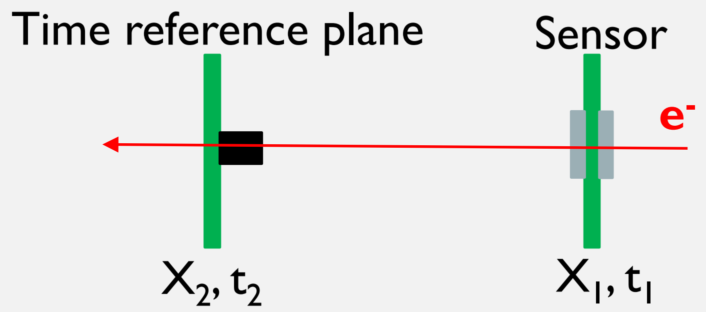


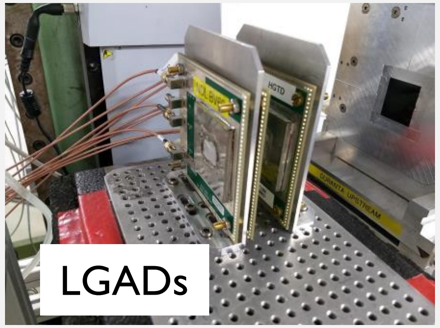


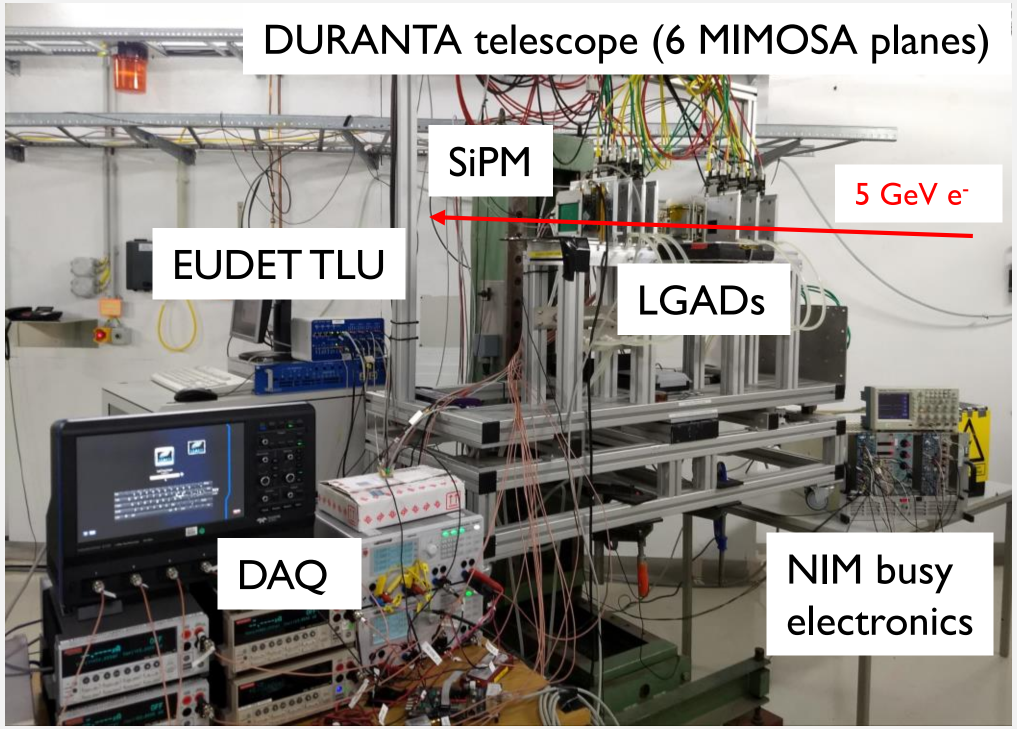


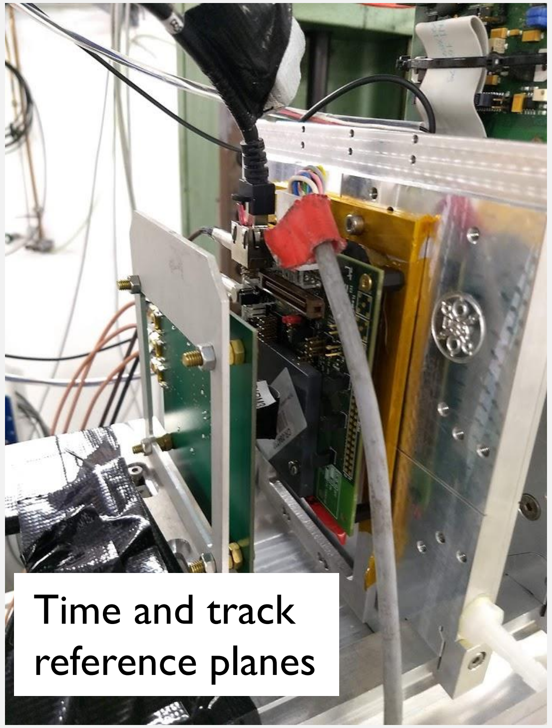
Beam test campaigns

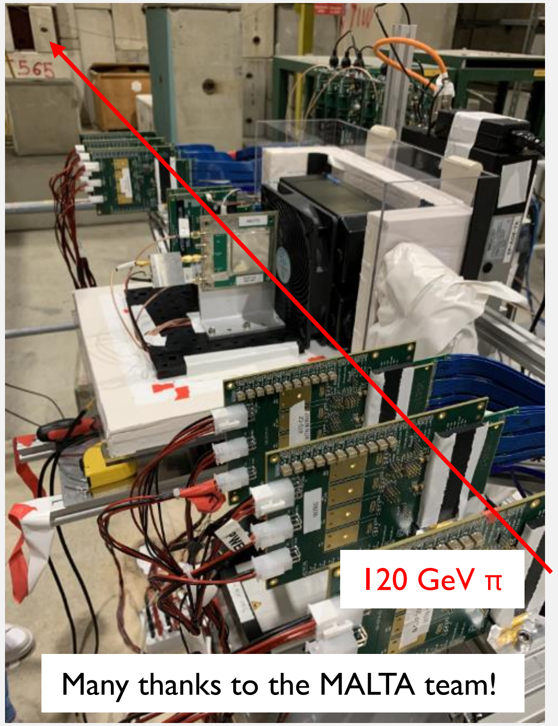
- Different facilities in 2021 and 2022:
  - CERN North Area SPS H6A beamline (120 GeV pion beam)
  - DESY T22 beamline (5 GeV e^- beam)
  - Use of beam telescopes for tracking (EUDET-type/MALTA)











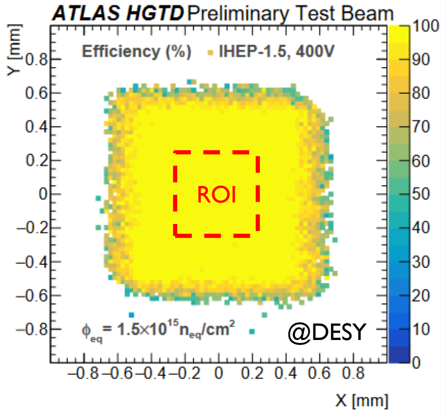
LGAD prototypes for HGTD

- Tested C-enriched prototypes from 3 vendors (FBK, USTC-IME and IHEP-IME)
- LGAD (CNM-0) used as a time reference in some tests (CERN-SPS) as well as a SiPM device (DESY)
- Sensors were exposed to fluences up to 2.5×10^{15} n_{eq}/cm^2 at the TRIGA reactor in Ljubljana, Slovenia with fast neutrons
- Bias voltages were kept lower than the SEB voltage

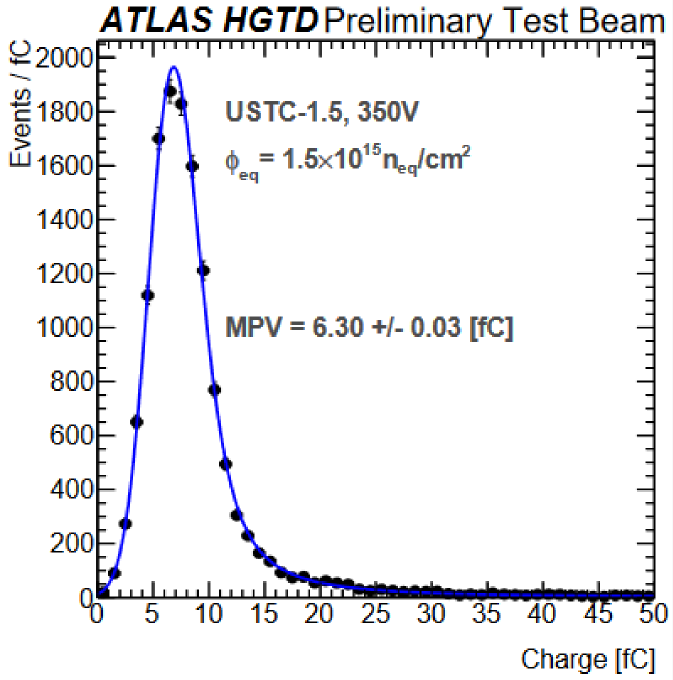
Device name	Vendor	Sensor ID	Implant	Irradiation type	Fluence [n_{eq}/cm^2]	Tested at
CNM-0	CNM	W9LGA35	boron	unirradiated	–	DESY/CERN
FBK-1.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	1.5×10^{15}	DESY/CERN
FBK-2.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	2.5×10^{15}	DESY/CERN
USTC-1.5	USTC-IME	v2.1 W17	boron + carbon	neutrons	1.5×10^{15}	DESY
USTC-2.5	USTC-IME	v2.1 W17	boron + carbon	neutrons	2.5×10^{15}	DESY
IHEP-1.5	IHEP-IME	v2 W7 Q2	boron + carbon	neutrons	1.5×10^{15}	DESY/CERN
IHEP-2.5	IHEP-IME	v2 W7 Q2	boron + carbon	neutrons	2.5×10^{15}	CERN

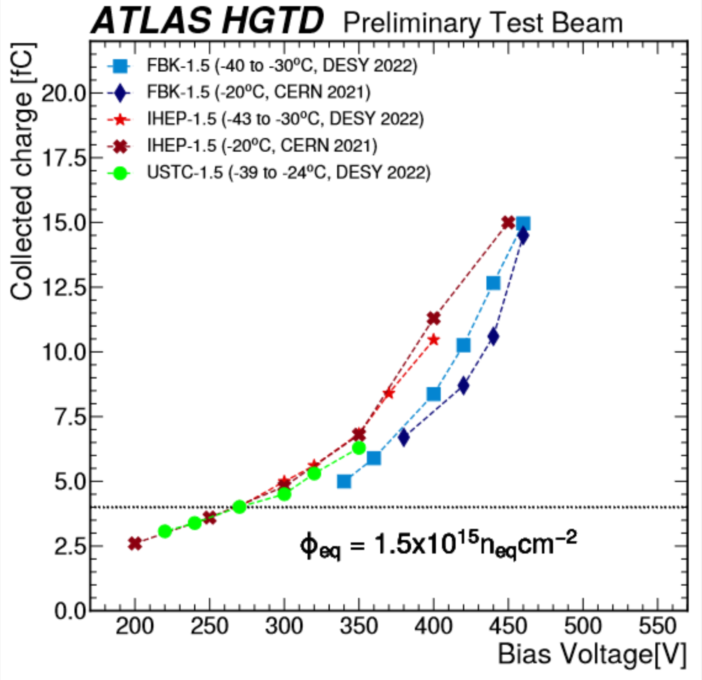
Device name	V_{gl0} [V]	Difussion	c [cm^2]
FBK-1.5/2.5	50	H	1.73×10^{-16}
USTC-1.5/2.5	27	L	1.23×10^{-16}
IHEP-1.5/2.5	25	CHBL	1.14×10^{-16}

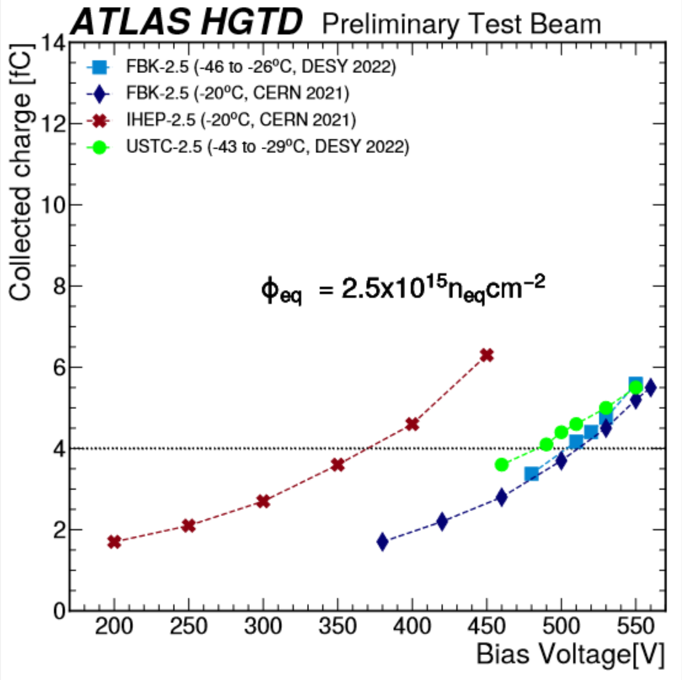
Collected charge



- Distribution of charge in the ROI fitted with a Landau-Gaussian convoluted function
- Collected charge:
  - Defined as the most probable value (MPV) from fit
  - Above the minimum required charge of 4 fC needed for a good timing measurement with the HGTD

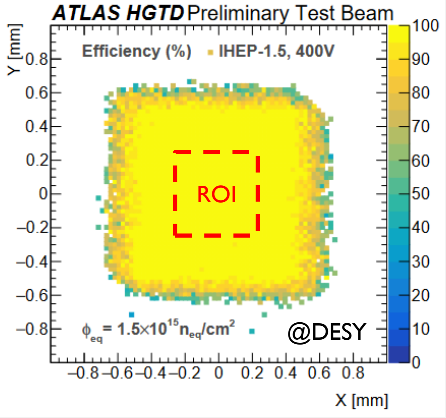




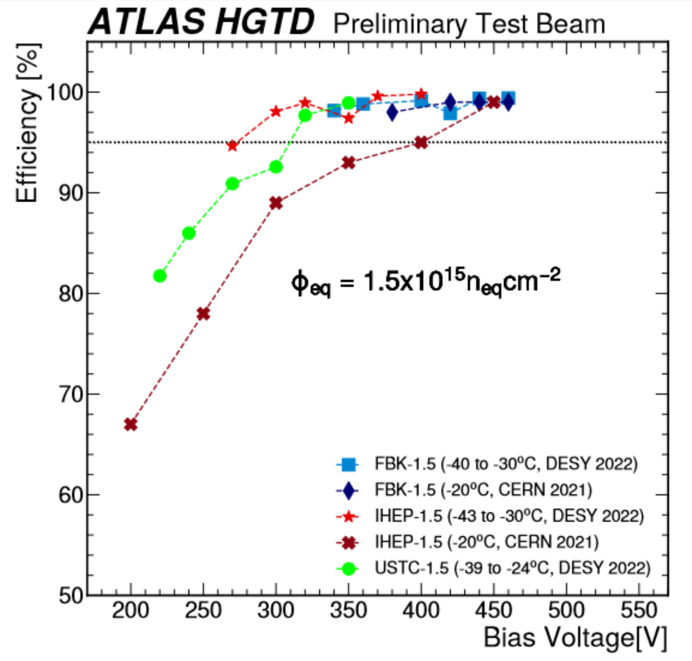


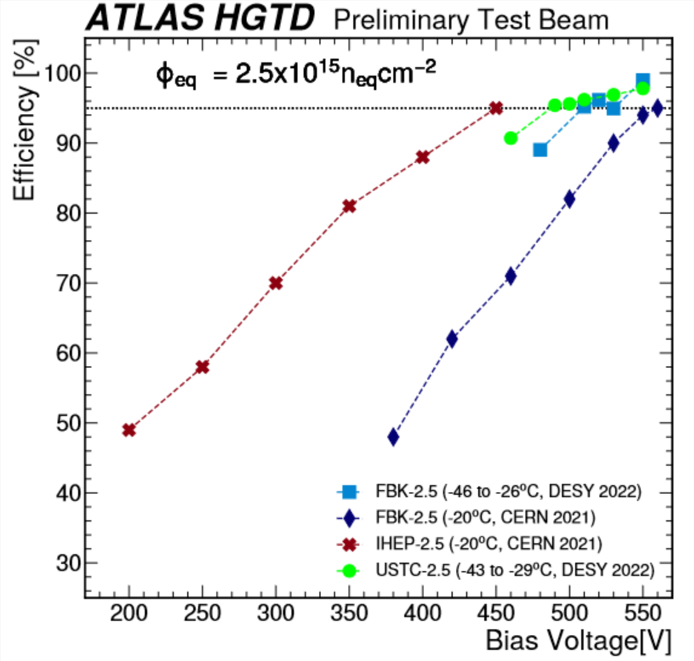
Hit efficiency

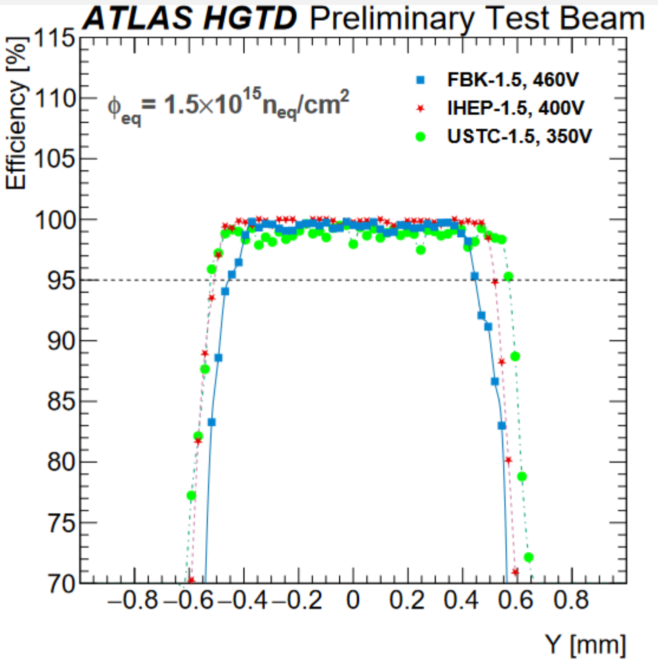
$$\text{Hit Efficiency} = \frac{\text{Reconstructed tracks with } q > Q_{cut}}{\text{Total reconstructed tracks}}$$



- Q_{cut} is set to 2 fC, the minimum achievable threshold of the future ALTIROC chip
- Achieved the efficiency of 95% required for good operation of the future HGTD after irradiation

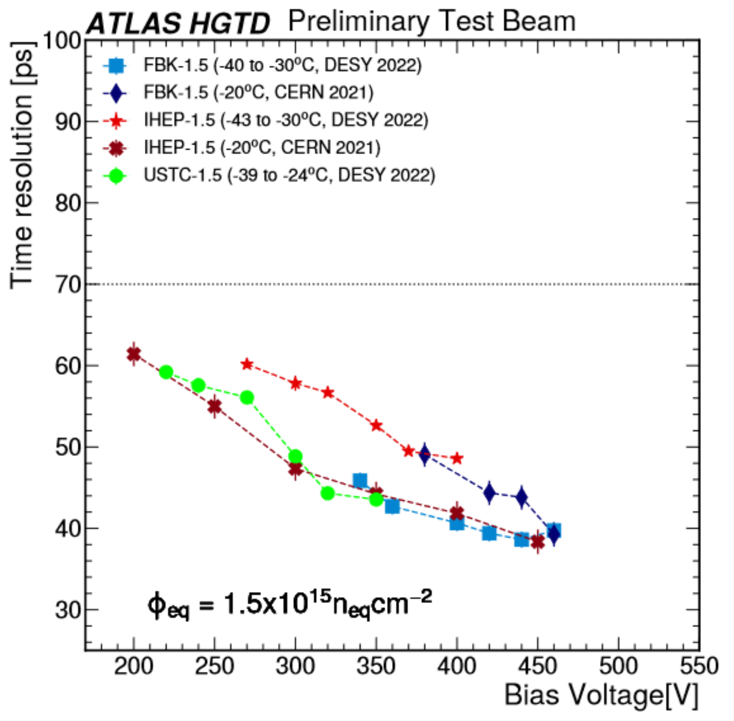


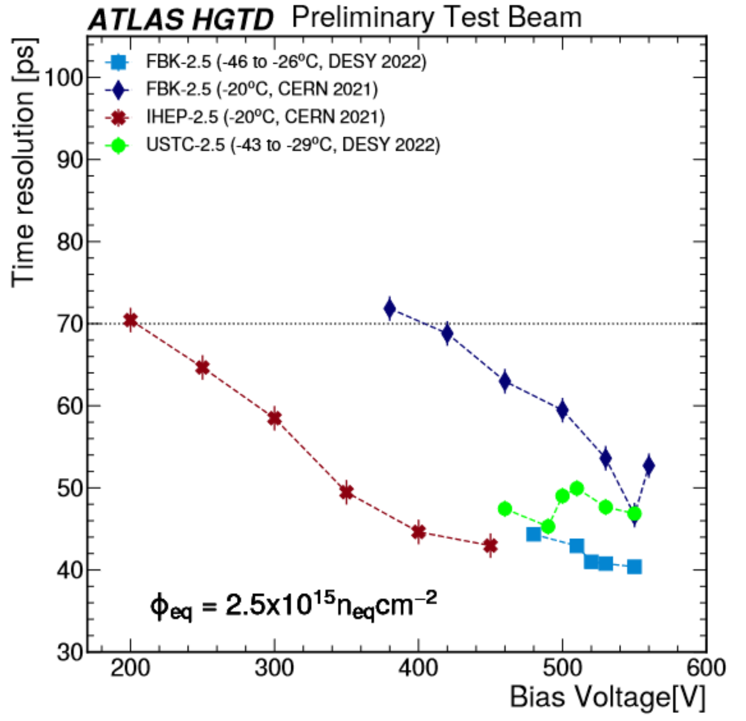




Time resolution

- To extract the LGADs' time resolutions, the distributions of the difference between the TOA of the LGADs and that of the time reference device were fitted with a Gaussian function, each of them giving a width σ_{ij}
- Having 3 devices, the resolution of each one is calculated as $\sigma_i = \sqrt{\frac{\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2}{2}}$
- Time resolution of time reference devices are already subtracted (σ_{SiPM}=62.6 ps, σ_{CNM-0}=54.8 ps)





Summary and outlook

- The High Granularity Timing Detector requires high-performance and radiation-resistant sensors
  - Choose promising technologies based on results from several beam test campaigns
    - LGADs irradiated to simulate their end-of-life state and studied with charged-particle beams at DESY and CERN in 2021 and 2022
- Carbon-enriched LGADs from three vendors (FBK, IHEP-IME and USTC-IME) have been studied both in terms of radiation resistance and performance
  - Although irradiated at fluences of 1.5 - 2.5 × 10^{15} n_{eq}/cm^2, the LGADs were operated at voltages below 550 V
  - Under these conditions, LGADs achieved the objectives of:
    - A collected charge of more than 4 fC while guaranteeing an optimum time resolution below 70 ps
    - An efficiency larger than 95% uniformly over the sensor's surface is obtained with a charge threshold of 2 fC
  - 2 papers submitted for publication are under review
- These results confirm the feasibility of an LGAD-based timing detector for HL-LHC
- Future plans: Looking forward the new C-enriched production from CNM to be tested soon this year

THANK YOU FOR YOUR ATTENTION

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