# Design and construction of the ATLAS High-Granularity Timing Detector

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on behalf of the ATLAS HGTD Group

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VERTEX 2023

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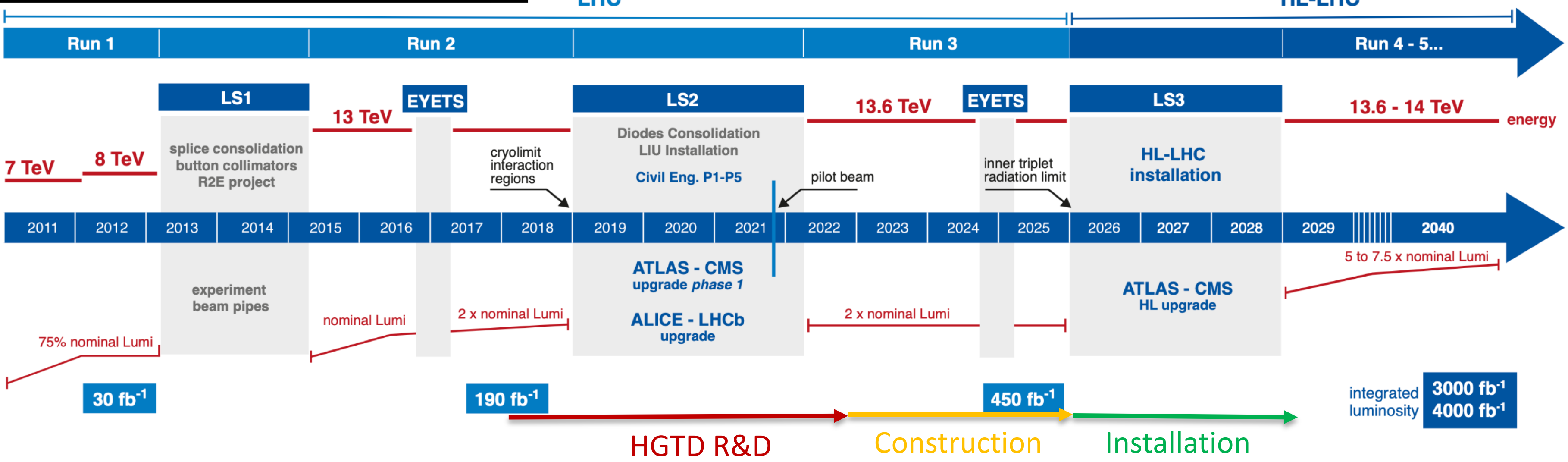
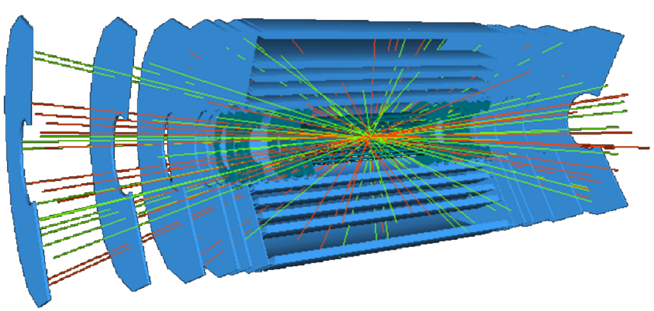
# The LHC upgrade

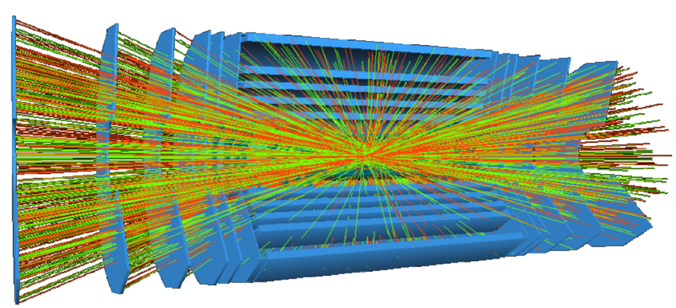
https://hilumilhc.web.cern.ch/content/hl-lhc-project




## ATLAS now …



## … from 2029

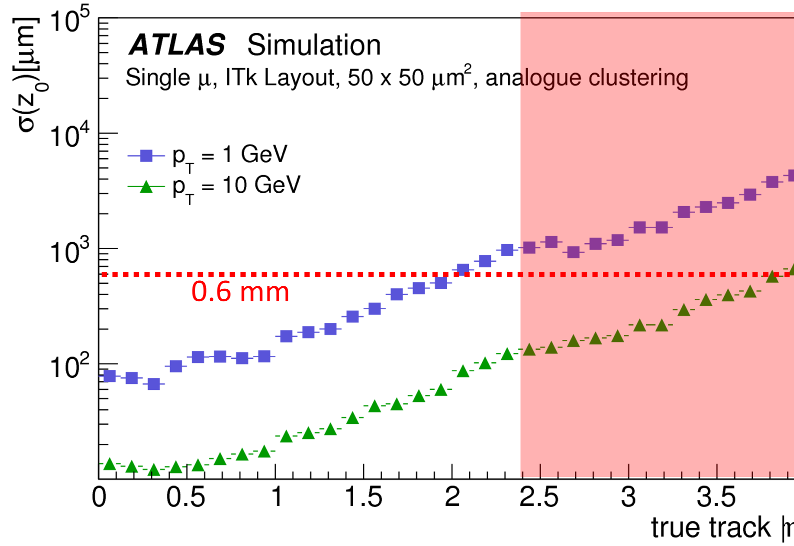


- **LHC**
  - 19 -> 55 Pile-up events

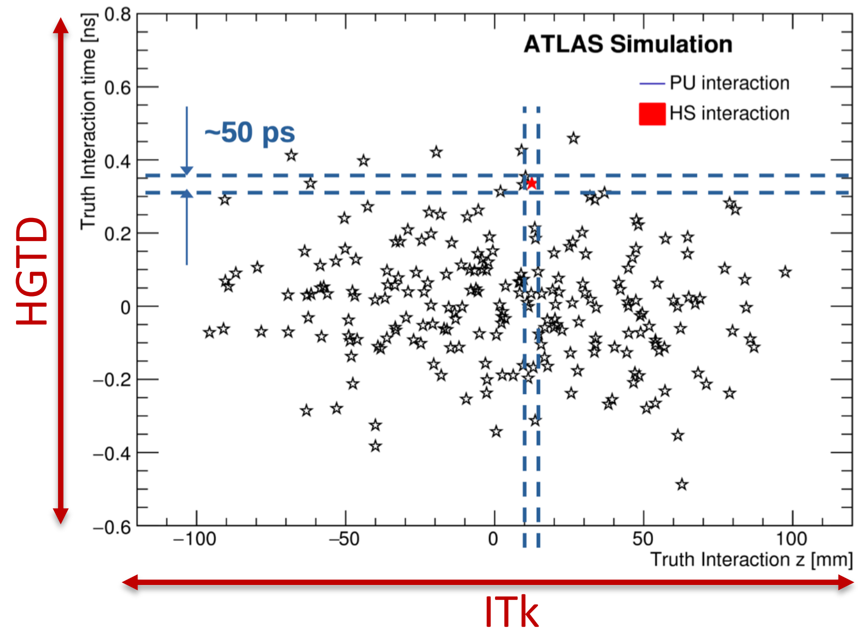
- **High Luminosity LHC (HL-LHC)**
  - 140-200 Pile-up events
  - 1.5 vertex/mm on average

HGTD Public Plots

- **Challenging reconstruction of primary vertices**
  - ATLAS vertex reconstruction and physics objects performance will be significantly degraded in the forward region compared to the central one
    - New Inner Tracker (ITk) has poor z resolution in the forward region
    - Need $z_0$ resolution < 0.6 mm

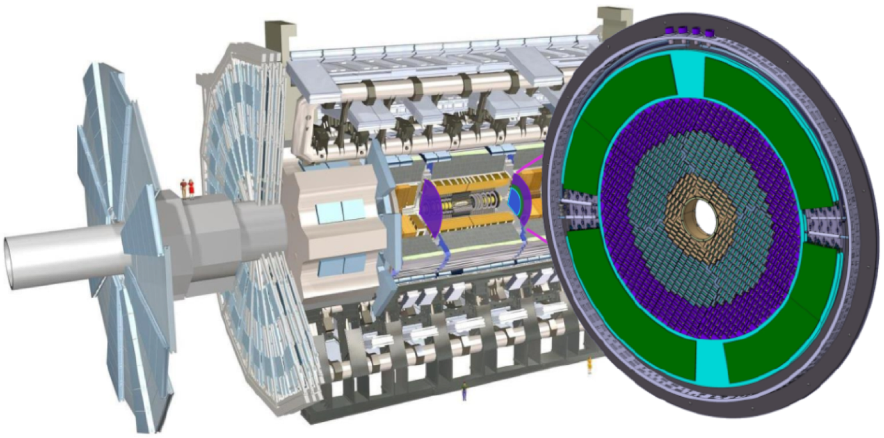



- **Adding timing information improves pile-up rejection and objects reconstruction**
  - Improve performance in the forward region by combining:
    - HGTD high-precision measurement
    - ITk position information
  - In addition, HGTD will provide a direct measurement on the luminosity

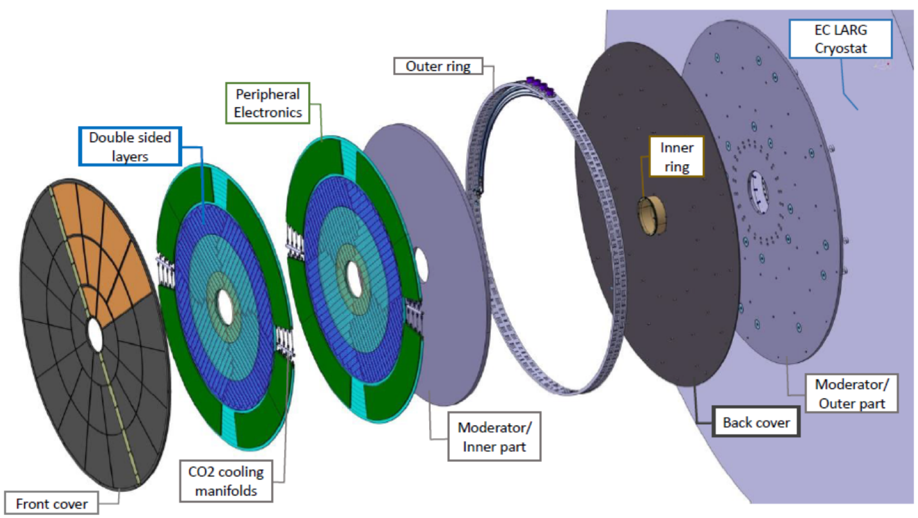


# The HGTD layout

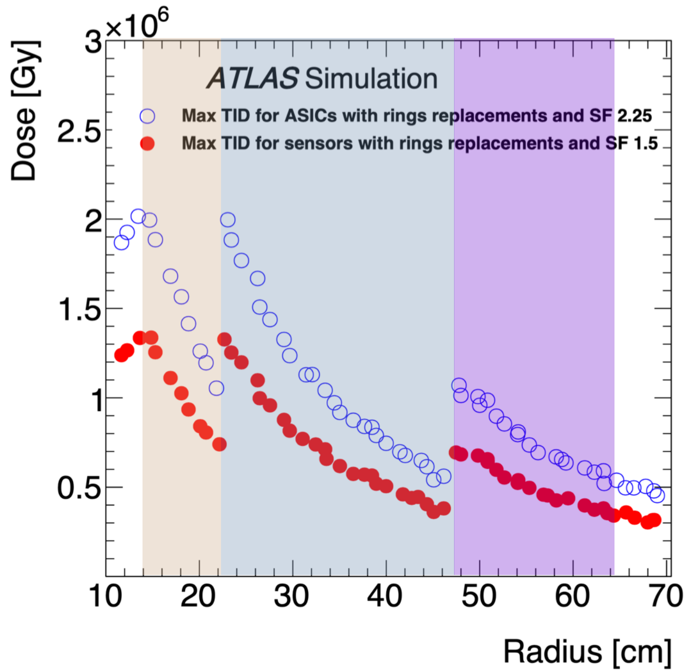
- **The HGTD is designed to provide precise timing information in the large pile-up environment at HL-LHC up to the End of Life (EoL) of the detector**
  - Time resolution target:
    - 30 – 50 ps/track (start – EoL)
  - Luminosity measurement
    - Count number of hits at 40 MHz (bunch-by-bunch)
    - Goal for HL-LHC: 1% luminosity uncertainty

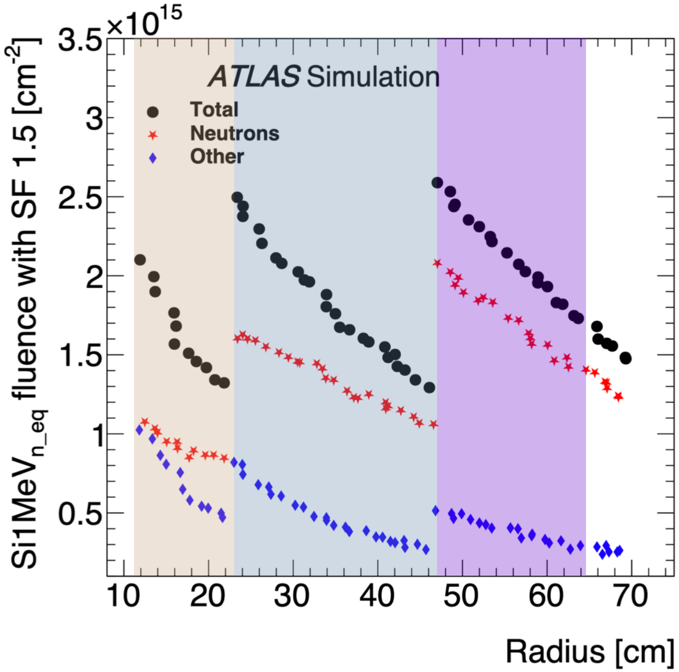


- **Two endcaps located between the barrel and the endcap calorimeters**
  - Two disks per endcap with detectors mounted on both sides
  - Located at ±3.5 m from the interaction point
  - Active area coverage: **$2.4 < |\eta| < 4$**
  - Radius: 120 mm < r < 640 mm



# Radiation environment

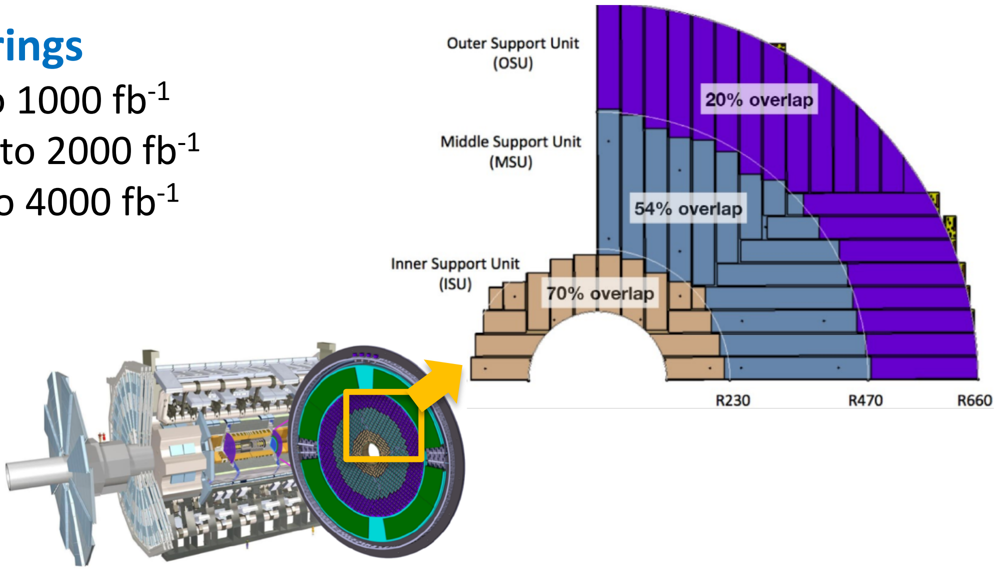



HGTD Public Plots

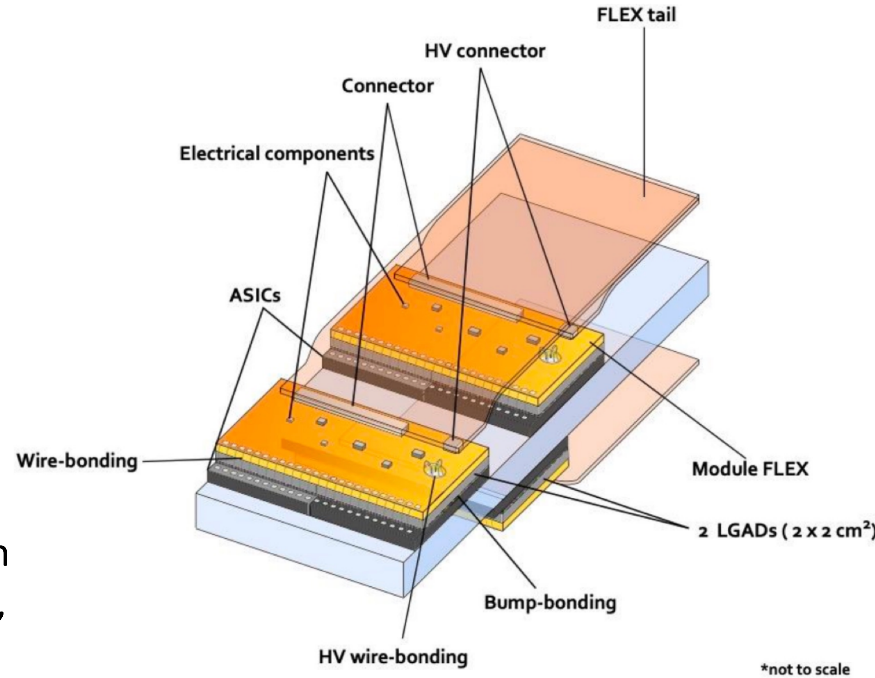
- **Detector segmented into replaceable rings**
  - Inner ring (12 – 23 cm) can stand up to 1000 $fb^{-1}$
  - Middle ring (23 – 47 cm) can stand up to 2000 $fb^{-1}$
  - Outer ring (47 – 64 cm) can stand up to 4000 $fb^{-1}$

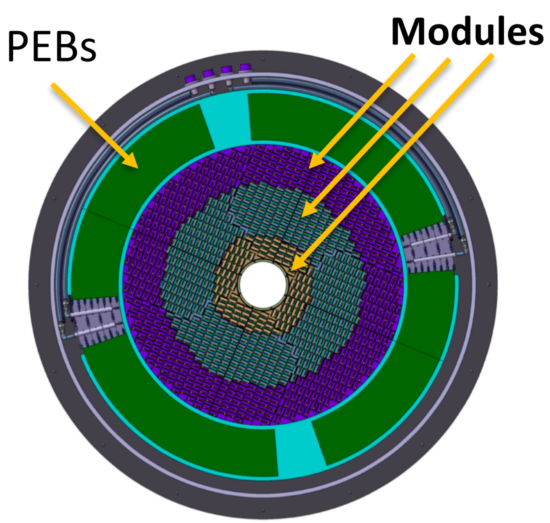
**Maximum fluence:**
**$2.5\times10^{15}$ $n_{eq}/cm^2$** and 2 MGy at the end of HL-LHC

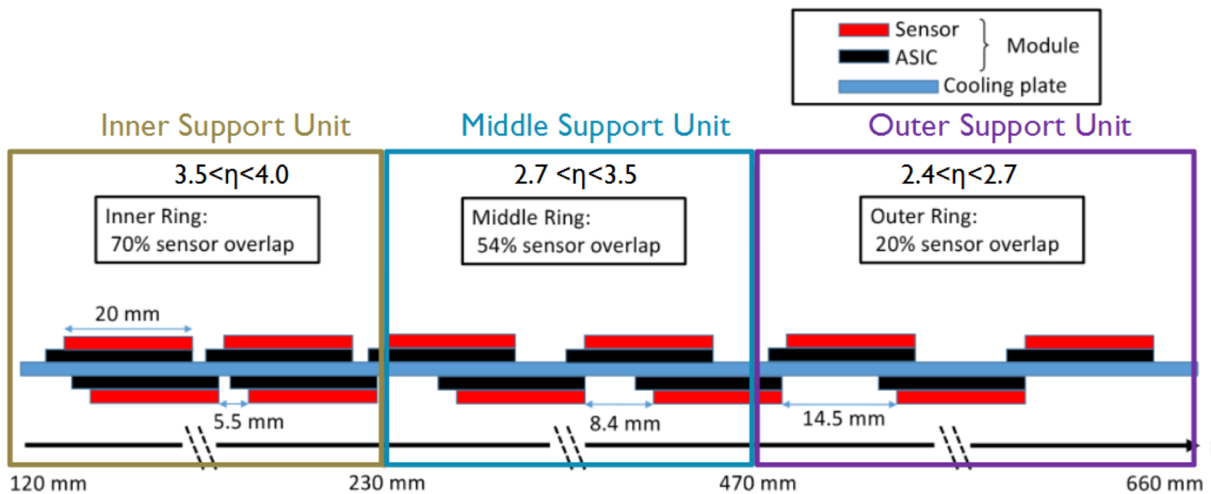


# The HGTD modules

- **Two single-chip hybrids (chip + sensors) connected to the same flex PCB**
  - Total dimension ~2×4 cm$^2$
  - 15×30 channels (15×15 per hybrid)
  - 1.3×1.3 mm$^2$ pixel dimensions
  - 35 – 70 ps/hit (start – EoL)
  - 4 fC collected charge required
- **8032 modules**
  - The module flex is connected via flex tails, arranged in rows, to the Peripheral Electronics Boards (PEB) @ 660 < r < 920 mm
  - Different overlap between modules on inner, middle and outer rings



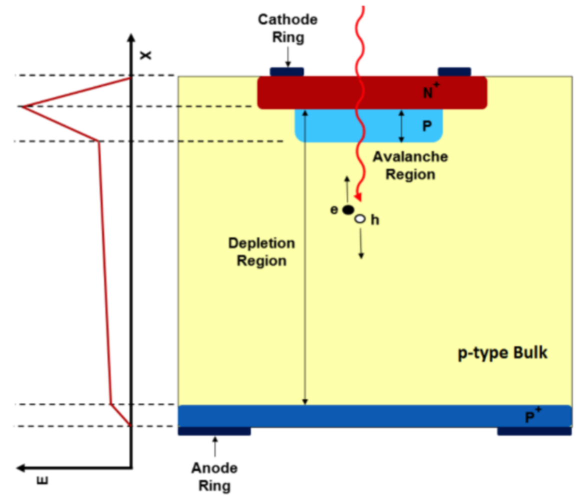



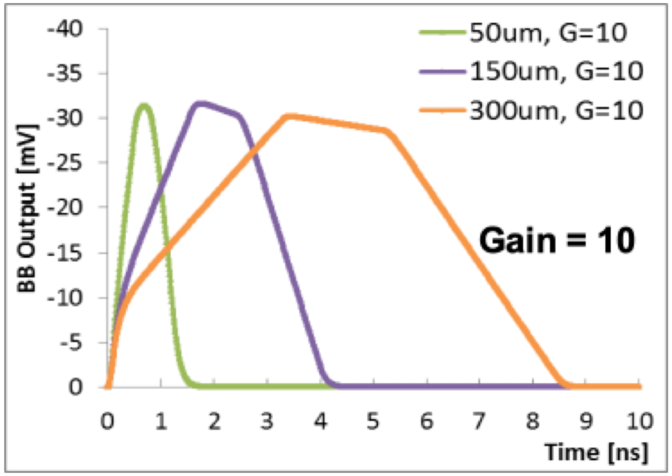
# LGAD sensors

- **HGTD modules need a time resolution of <70 ps per MIP: beyond standard HEP devices**
  - $\sigma^2_{\text{det}} = \sigma^2_{\text{Landau}} + \sigma^2_{\text{elec}}$
  - $\sigma^2_{elec} = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$

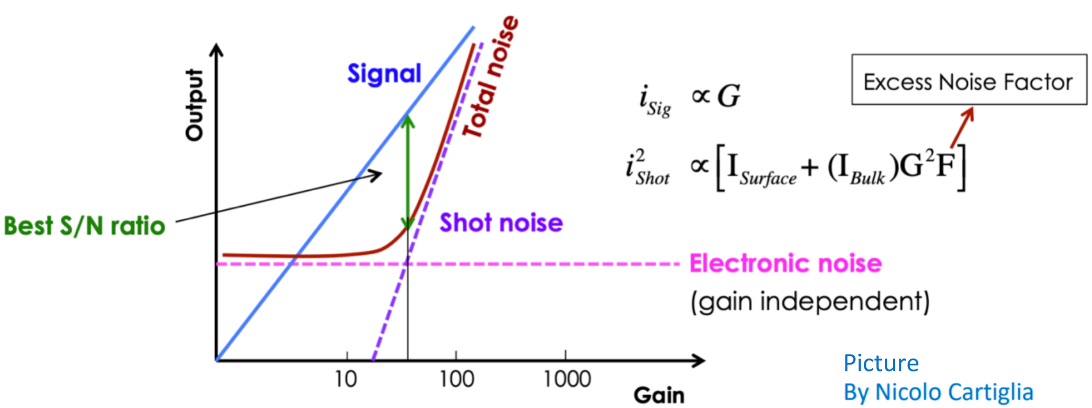
    Jitter    Time Walk




- **Low Gain Avalanche Detectors (LGADs) for HGTD**
  - N-on-p silicon sensors with p-type multiplication layer
    - Fast signal with enhanced S/N
  - Thin active substrates (50 µm)
    - Reduce the Landau contribution to the time resolution
  - Operated in linear mode at low gain (G~10)
    - Improve signal slope controlling noise



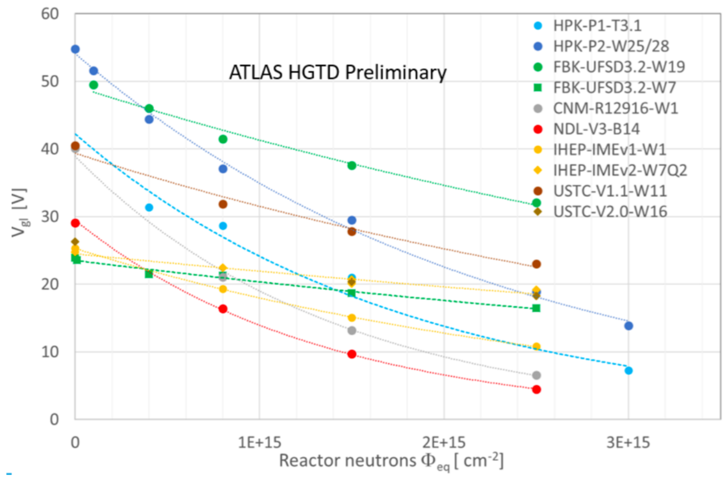

F. Cenna et al, NIM A796 (2015) 149-153

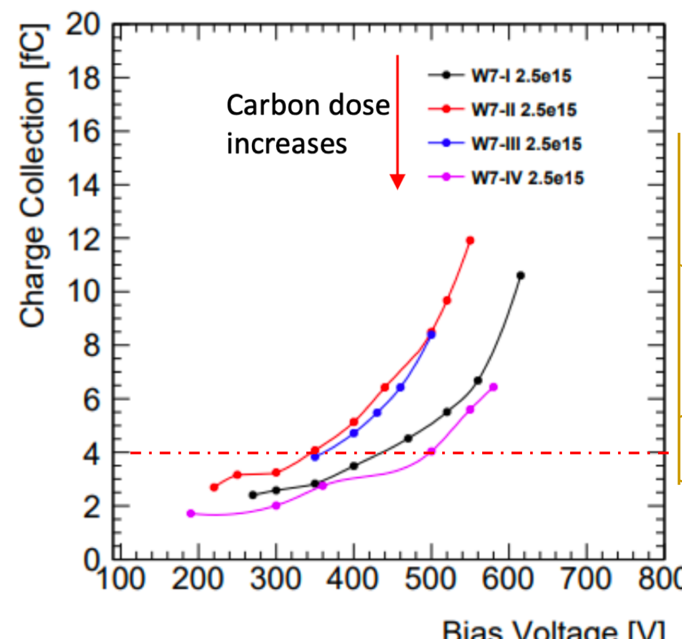



Picture
By Nicolo Cartiglia

# LGAD sensors: radiation hardness

- **Boron doping in gain layer became less active after irradiation (acceptor removal)**
  - LGAD performance degrades due to loss of the gain layer after irradiation
  - Irradiated sensors require higher bias voltage
  - Gain layer depletion voltage: $V_{\mathrm{gl}} = V_{\mathrm{gl0}} \times \exp(-c \times \Phi_{\mathrm{eq}})$
- **Sensors from carbon-enriched wafers have lower acceptor removal coefficient (1-2×10$^{16}$ cm$^2$)**
  - Carbon dose and diffusion parameter also affect the radiation hardness
- **LGAD sensors from many vendors (CNM, HPK, FBK, IME-IHEP, IME-USTC) have been extensively studied during the R&D phase of HGTD**
- **LGAD sensors pre-production for the HGTD project is ongoing**
  - Testing includes Quality Control (QC) and irradiations

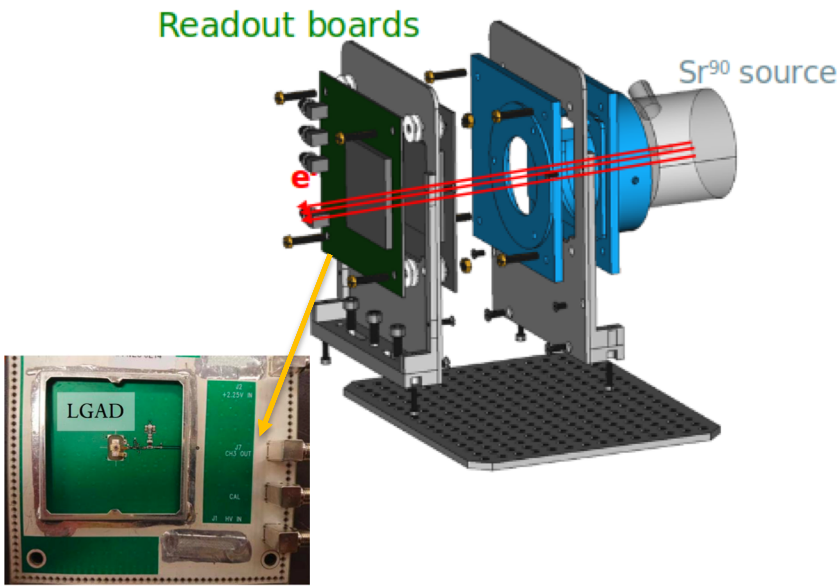


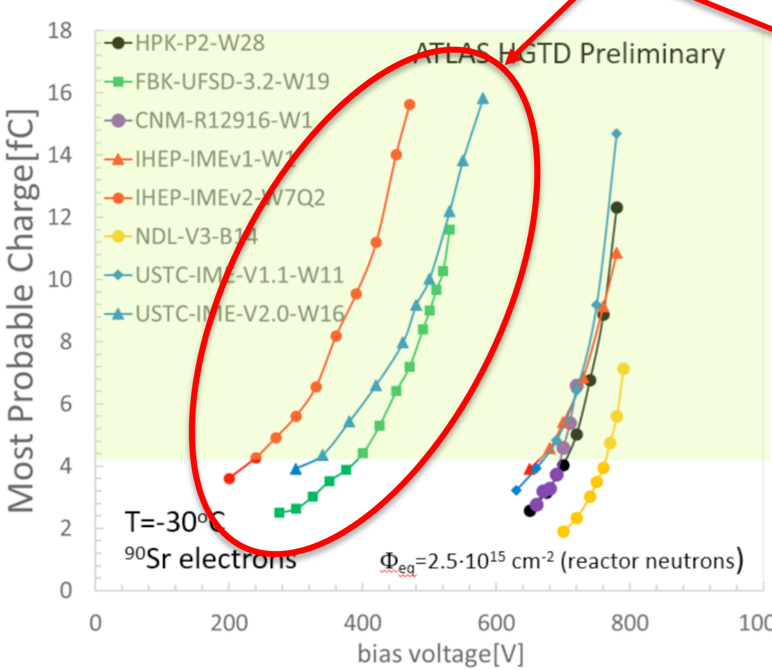



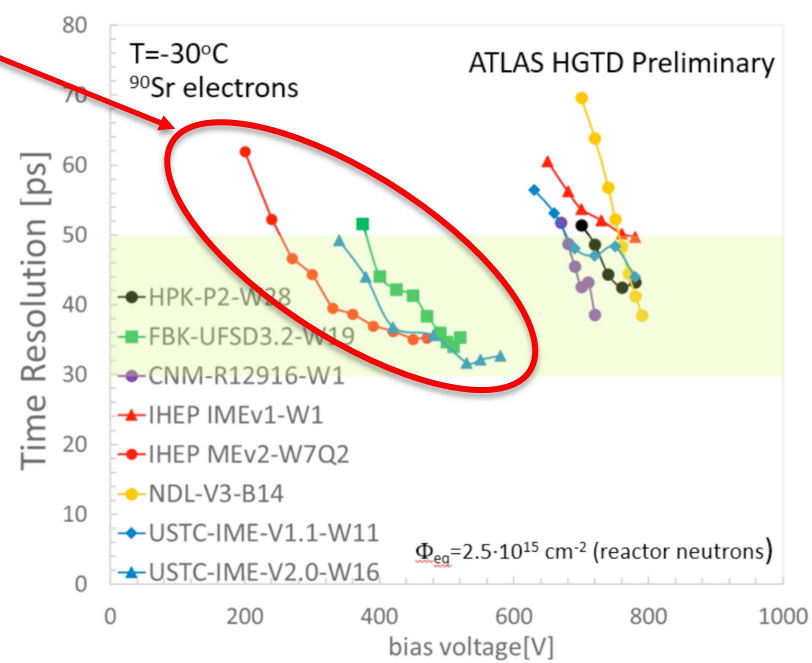

K. Wu et al., NIM A1046 (2022)

# LGAD sensors: laboratory tests

- **IV and CV measurement with probe station**
- **$^{90}$Sr beta telescope**
  - Electrons from $^{90}$Sr source shoot through two sensors
  - Controlled environment in climate chamber (Temperature and Relative Humidity)
  - UCSC boards with commercial amplifier and analog readout by an oscilloscope
- **Carbon-enriched sensors meet the HGTD specifications after irradiation with lower bias voltages (<550 V)**
  - C-enriched sensors: IHEP-IME, FBK, USTC-IME

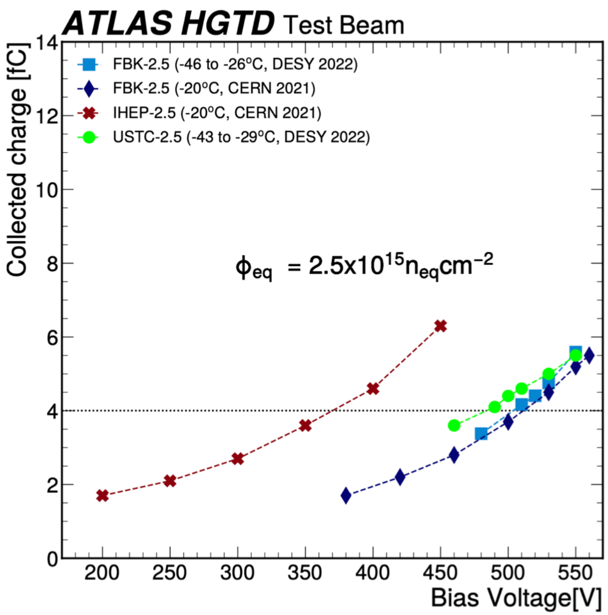


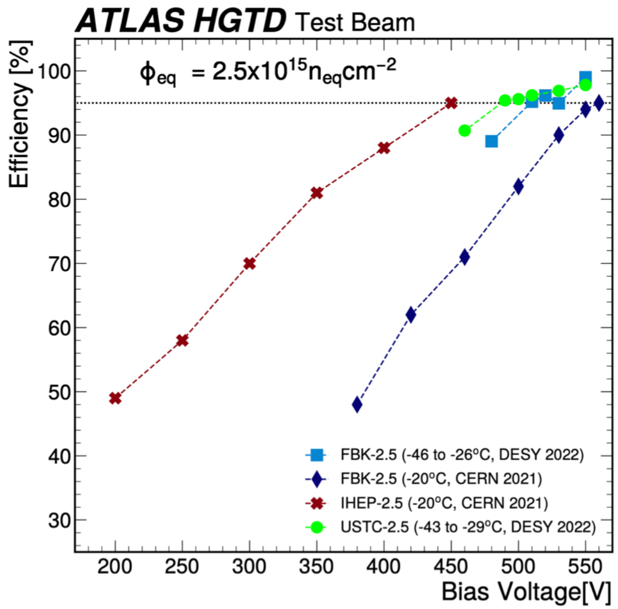



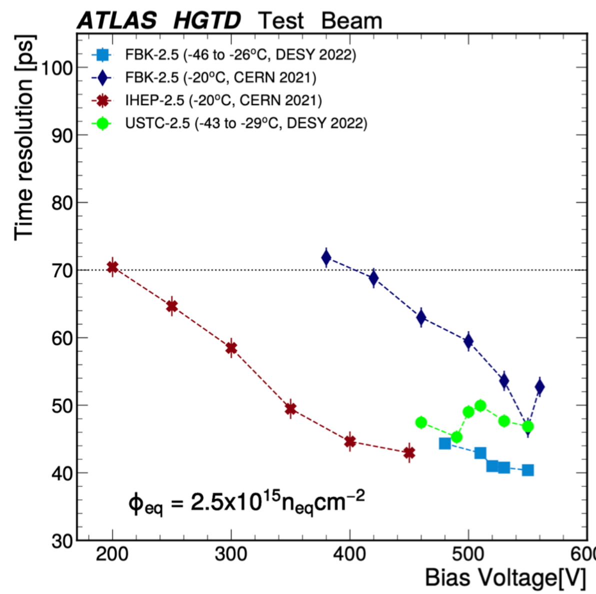



# LGAD sensors: testbeam ($2.5\times10^{15}$)

**Testbeam campaigns at CERN SPS and DESY to study the performance of Carbon-enriched LGAD sensors after irradiation up to $2.5\times10^{15}\ n_{eq}/cm^2$**




## Collected Charge

Q collected defined as the MPV of the landau-gauss convolution

Minimum 4 fC required by ASICs

**Charge collection above 4 fC for all tested sensors**

## Hit Efficiency

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

$Q_{cut}$= 2 fC (min. ASIC threshold)

**Hit Efficiency > 95% for all the C-enriched sensors**

## Time Resolution

Time resolution measured wrt. a reference sensor

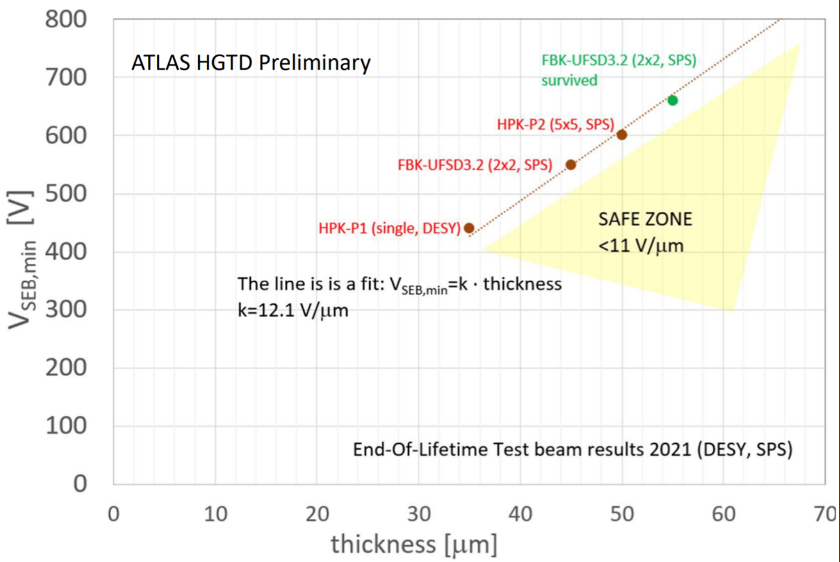
Time resolution of the reference sensor subtracted

**Achieved <70 ps resolution**

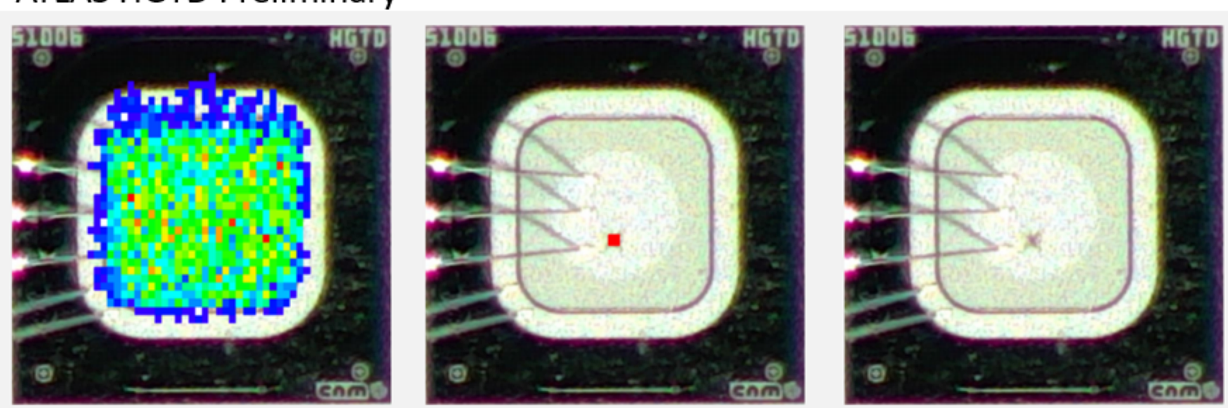
# LGAD single event burnout

- **In testbeam sensors underwent destructive breakdown at lower voltages than in laboratory**

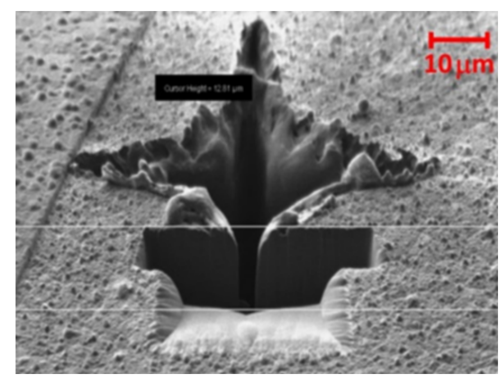
- **Single Event Burnout (SEB) observed on heavily irradiated sensors (~$2.5\times10^{15}$ $n_{eq}/cm^2$) operated with high bias voltage**
  - A single particle depositing enough energy (~tens MeV) leads to destructive breakdown:
    - Electric field collapse in presence of high concentration of free carriers
  - Lifetime tests confirmed that **SEB issue occurs outside the safe operating zone** with E > 11 V/µm (> 550 V for 50 µm thick LGADs)
  - No issue if operated with lower voltage!




ATLAS HGTD Preliminary




Beresford et al, 2023 JINST 18 P07030




Burn mark on a CNM sensor after proton beam irradiation in Fermilab in 2018 (picture produced by CNM)

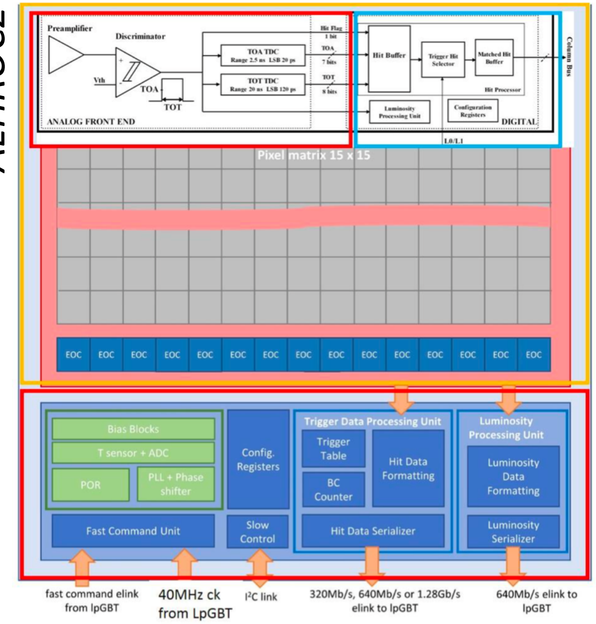
S. Terzo (IFAE, Barcelona) - VERTEX 2023

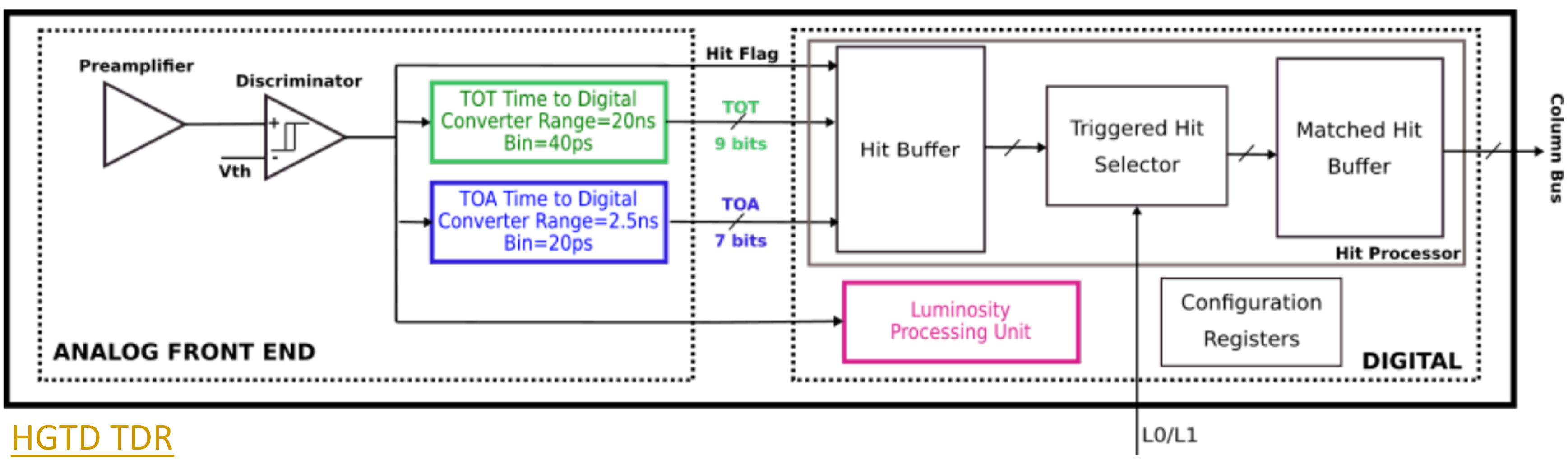
# ALTIROC: the HGTD ASIC

- **ASIC designed in 130 nm CMOS from TSMC**
  - **Requirements to match the performance of LGADs:**
    - Small jitter: 25 ps at 10 fC (< 70 ps at 4 fC)
    - Radiation hard ($2.5\times10^{15}\ n_{eq}/cm^2$, 2 MGy)
    - 2 fC minimum discriminator threshold

- **Prototype status:**
  - **ALTIROC 0 and ALTIROC 1:** Small prototype for analog FE tests (2020 JINST **15** P07007, 2023 JINST 18 P08019)
  - **ALTIROC 2:** First full size prototype (15×15 pixels, 2×2 $cm^2$) with full electronic chain (VPA and TZ amplifier types)
  - **ALTIROC 3:** Prototype up to specs presently under test (only TZ amplifiers implemented)

ALTIROC2

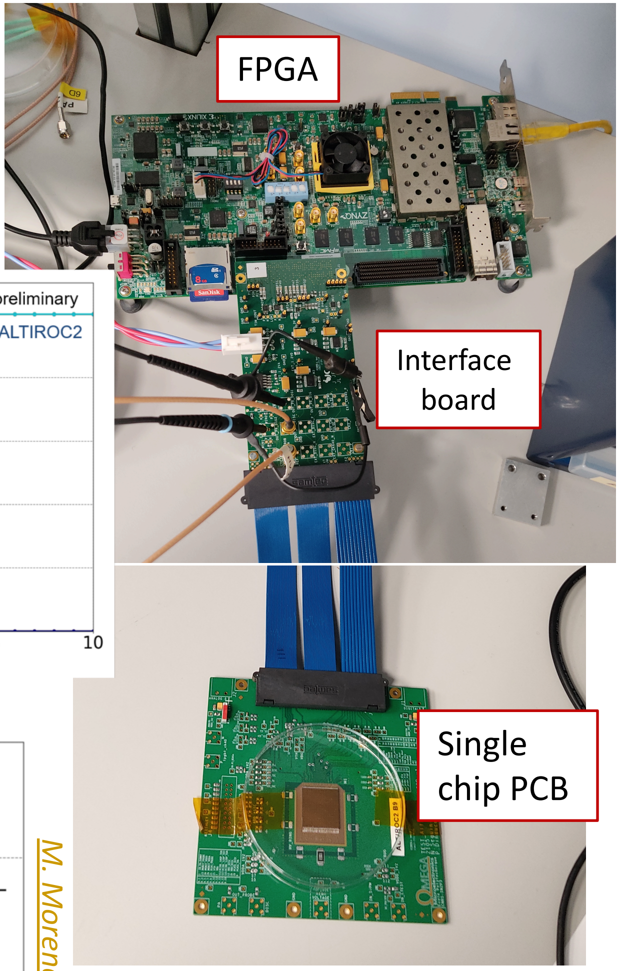


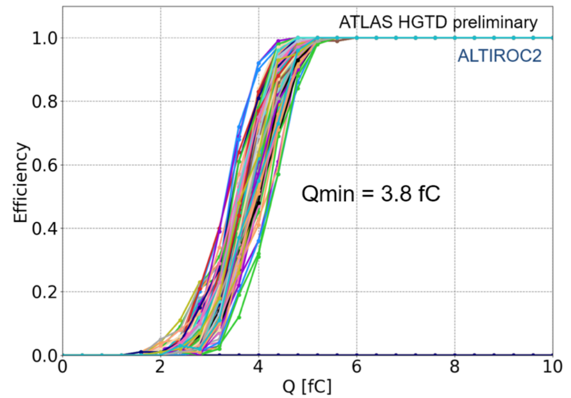



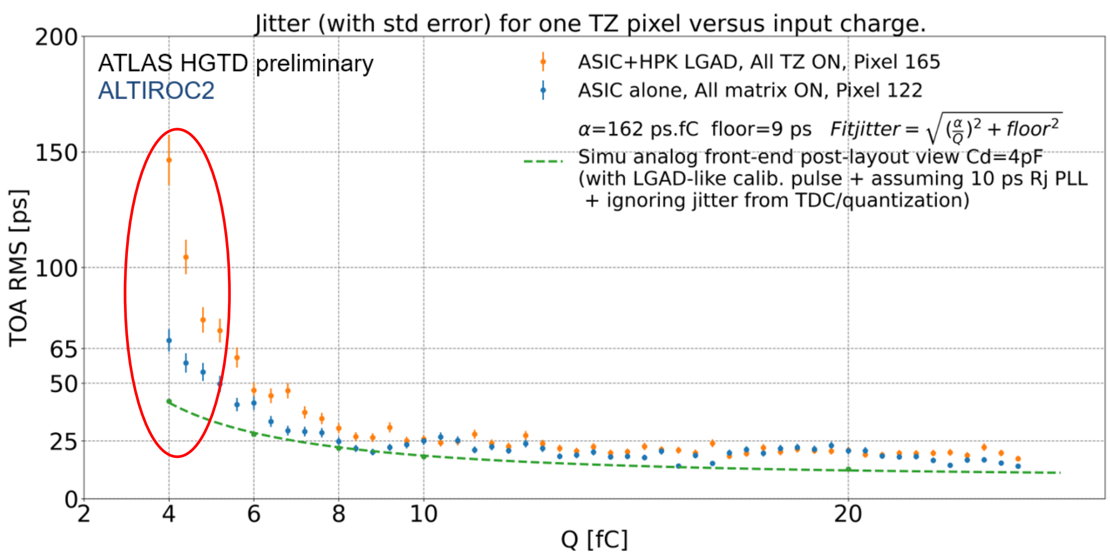

HGTD TDR

# ALTIROC2 performance

- **ALTIROC2 extensively studied with dedicated setups**
  - Tests with ASIC-only and ASIC+LGAD (hybrid) on dedicated PCB and interface boards
  - Tests with hybrids with $^{90}Sr$ and in testbeams
- **Minimum threshold with LGAD <4 fC**
  - Only Transimpedance (TZ) pre-amp analog pixels enabled
- **Jitter ~25 ps @ 10 fC (with sensor)**
  - Discrepancies near threshold charge due to parasitic inductances leading to different sensor-preamp grounds



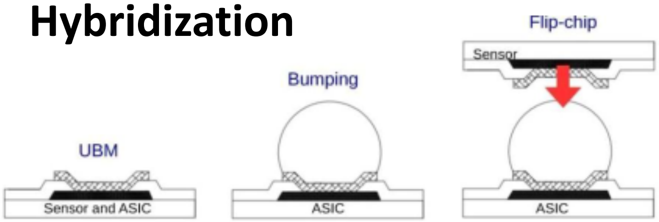



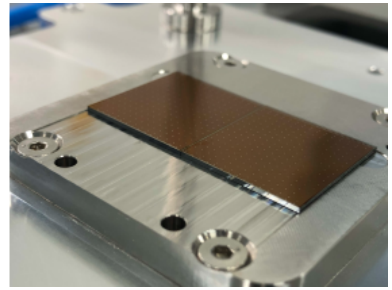

*M. Morenas, TWEEP 2022*

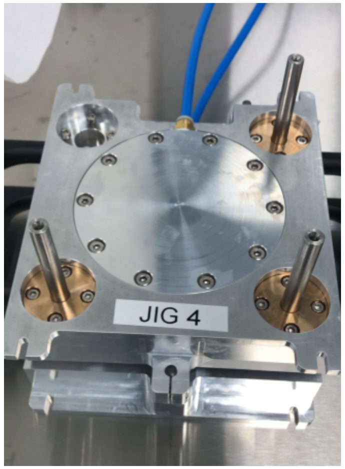
# Module assembly

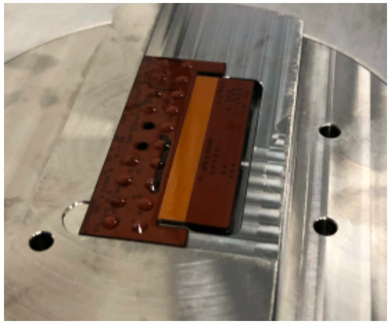
## Hybridization



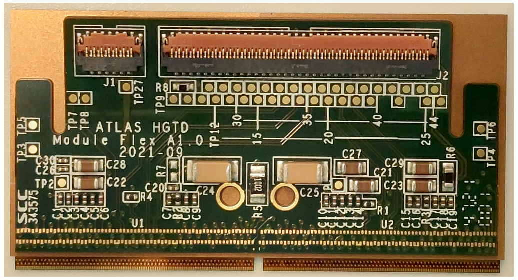

## Flex alignment and gluing





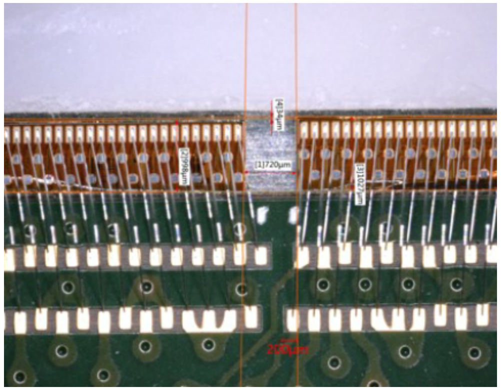



## Metrology

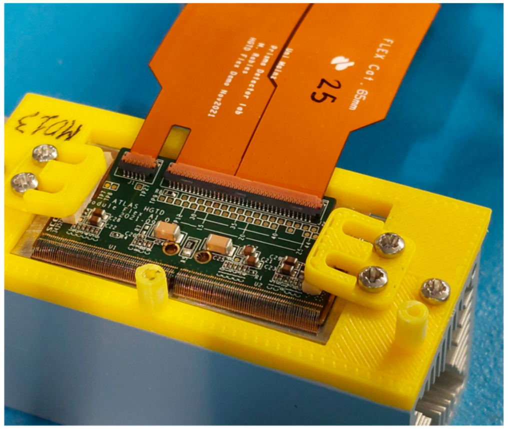


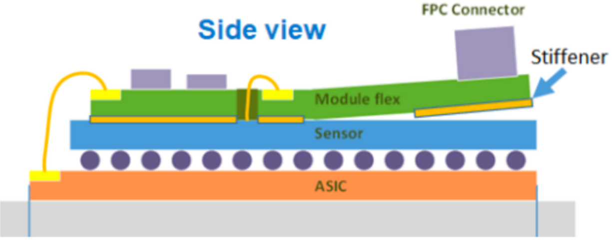

- **6 assembly sites** (IFAE, IJCLab, Mainz, MAScIR, IHEP, USTC)
- **Presently, 2 procedures**
  - **Gantry system**: Robotic pick & place for systematic assembly
  - **Adjustable jigs**: Manual but repeatable

## Wire-bonding and pull tests



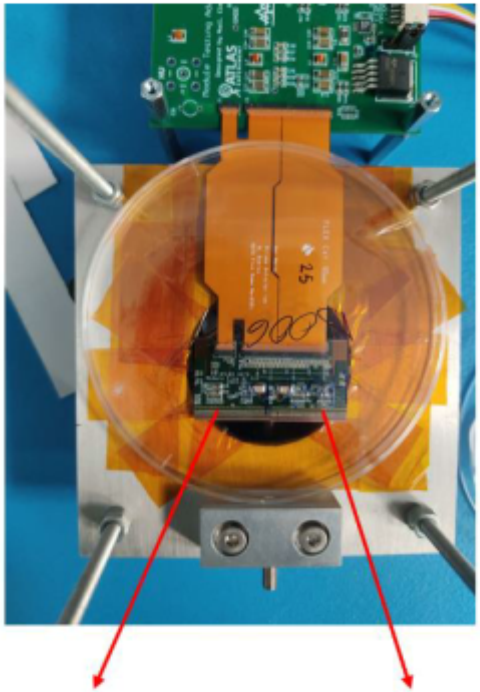
## Final module testing

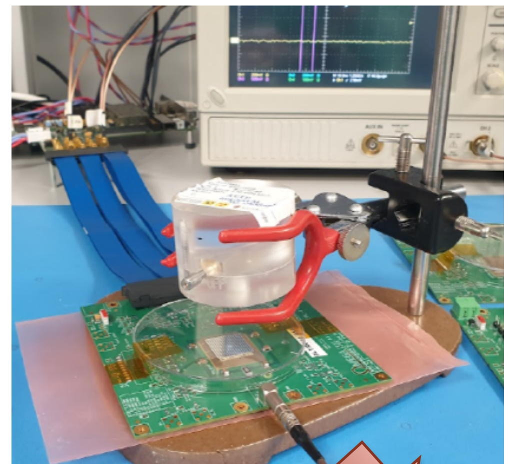




# Bump connectivity

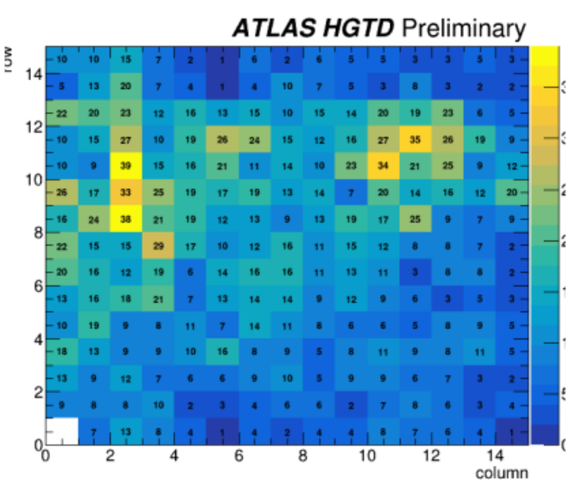
- **Tests on single chip hybrids and full modules**
  - Chip configuration and tuning
  - Lowest threshold (<4 fC) achievable
  - Pixel response to $^{90}$Sr β electrons

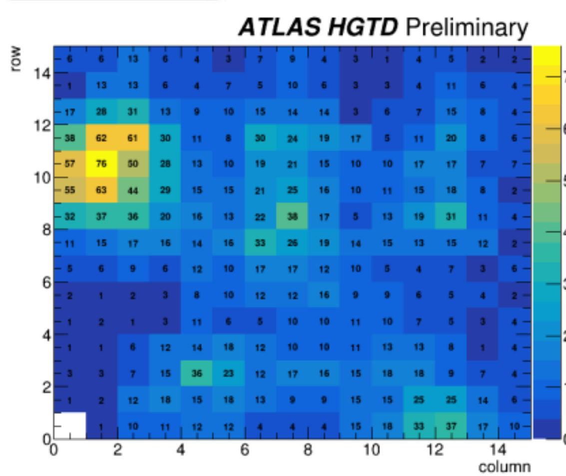


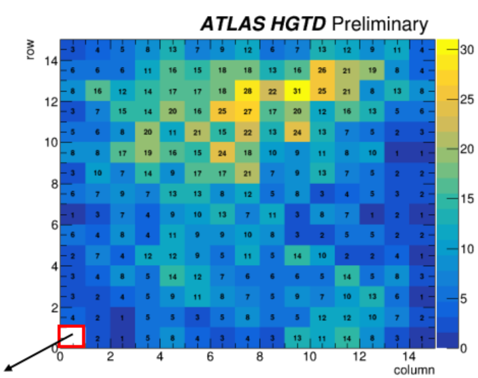


Chip 0

Chip 1



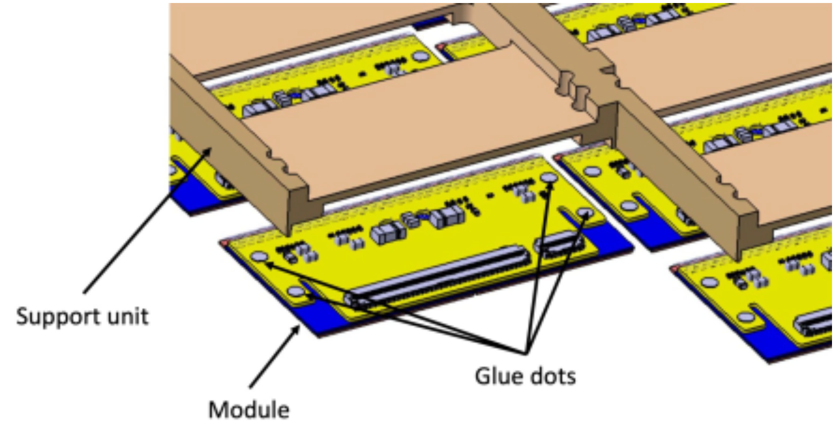

Pixel 0 not bump-bonded for other studies

Occupancy map with Sr-90 source. Sensor biased at = HV 90 V.

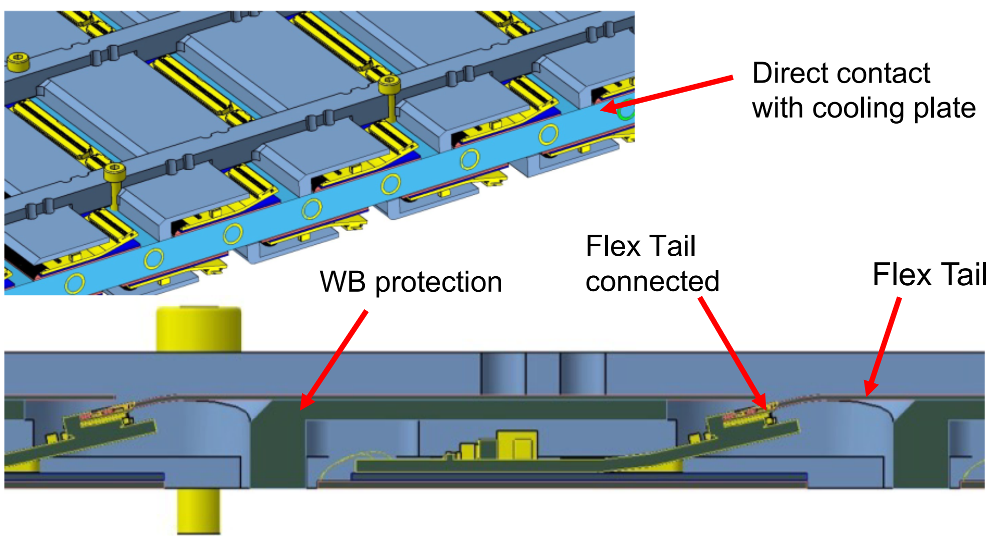
Threshold = 8 fC

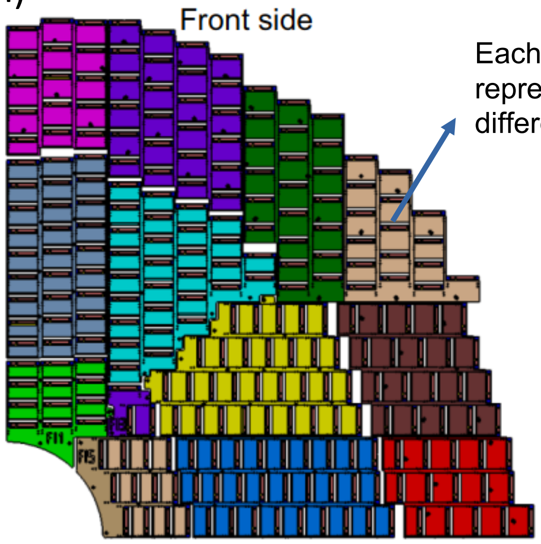
# HGTD Detector Units and flex tails

- **Detector Unit (DU): modules are glued to a support unit**
  - Support units made of PEEK (polyether ether ketone)
  - Gluing tests done using a vacuum plate
  - Glue on top of the flex and support unit lowered onto modules



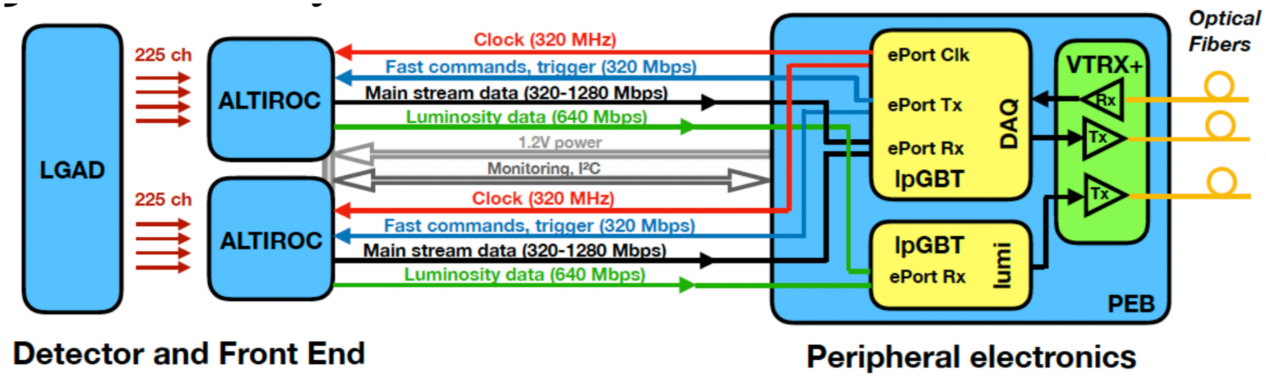

- **Flex tails**
  - Connected to each module and to peripheral electronics board after assembling the full row
  - Manufactured with different sizes
  - Strict constraint for the thickness of the 19 stacks (4.2 mm)



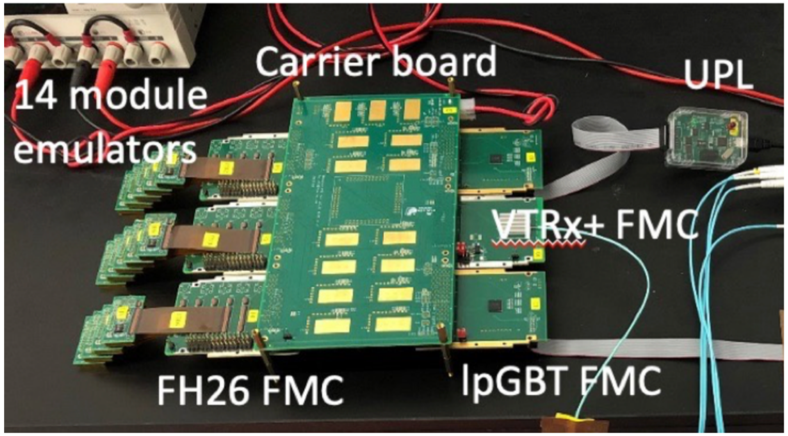



# Peripheral Electronic Boards (PEB)

- **Peripheral Electronic Boards (PEB) are integral components of the detector system:**
  - Play a crucial role in managing data transmission, power distribution, control, and monitoring

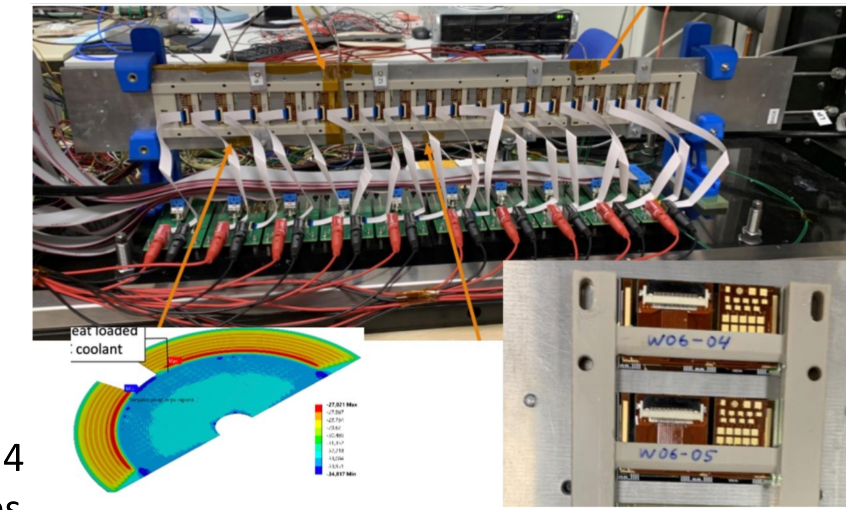



- **Intensive work on characterising all individual components on its prototypes**
  - DC-DC converter Point Of Load regulators (bPOL) 12V: in depth investigated regarding space constraints and power efficiency
  - Intense tests communications via lpGBT with the FELIX readout card
  - MUX64: analogue multiplexer (for monitoring ASIC power and temperature)

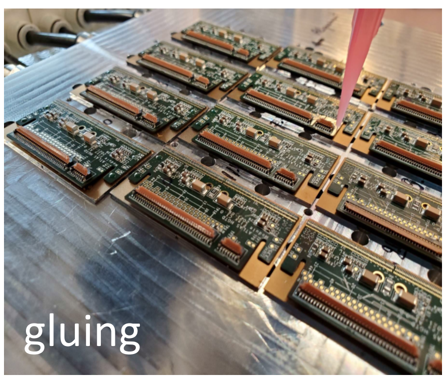


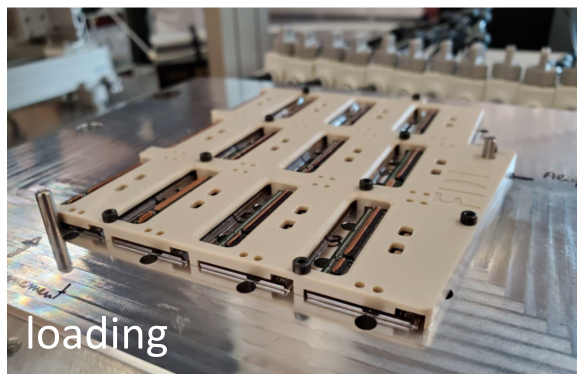
# Demonstrators

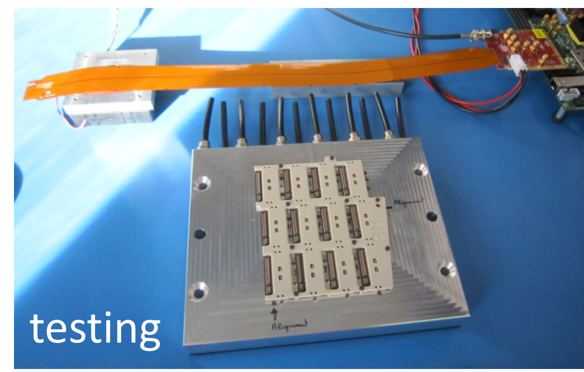
- **Heater demonstrator**
  - Validate the modules dissipating heat on $CO_2$ cooling plate
  - Best thermal material: two graphite layers with thermal grease in between

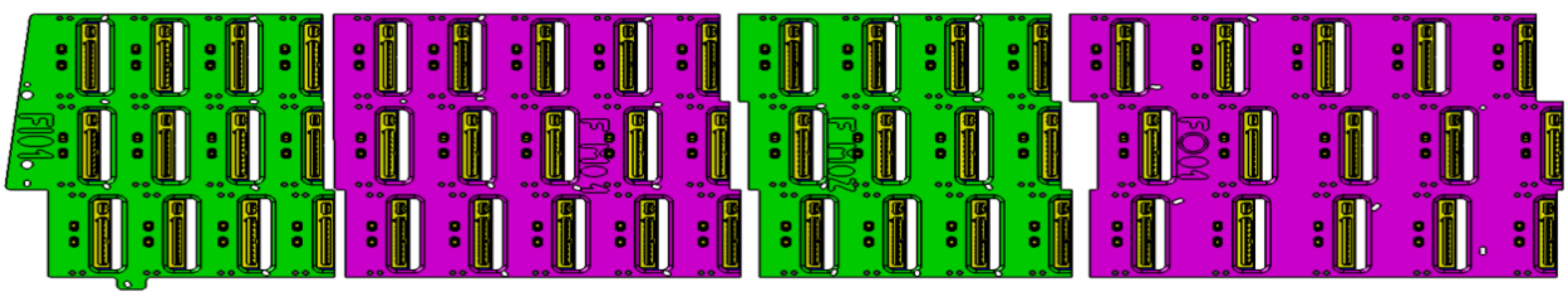



- **Detector Unit (DU) demonstrator**
  - A demonstrator with 54 modules (3 rows and 4 DU) is being built with ALTIROC+LGAD modules



# Summary

- **HGTD will add precision timing information to tracks improving the ATLAS performance in the forward region during HL-LHC**
  - Improve pile-up rejection and object reconstruction
    - Time resolution of 30-50 ps/track
  - Provide luminosity measurements

- **Carbon-enriched LGADs are the chosen sensor technology showing good performance after irradiation to the ultimate HGTD fluence**
  - No SEB observed within the safe operating zone (up to 550 V)
  - Charge collection, hit efficiency and time resolution meet specifications at $2.5\times10^{15}\ n_{eq}/cm^2$
  - Tests on latest pre-production runs is on-going and will proceed over next year

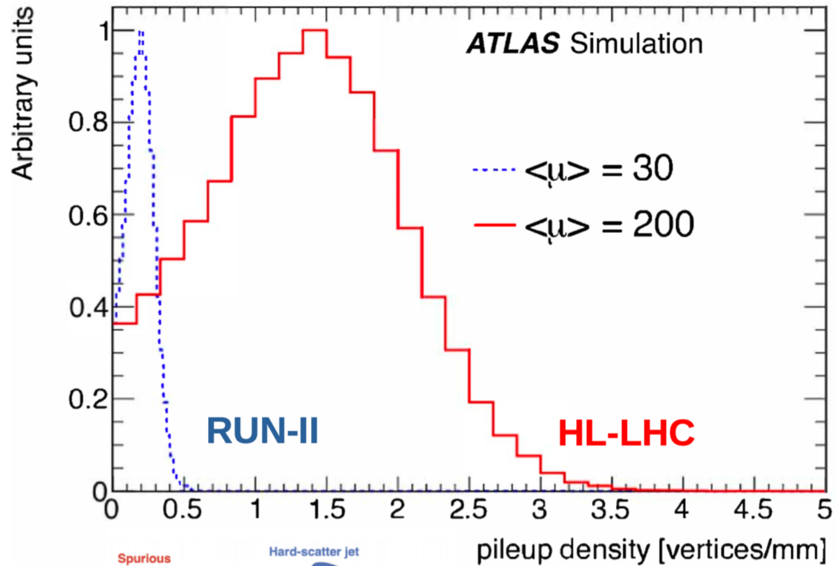
- **The ALTIROC2 full size prototype has been successfully tested and ALTIROC3 has been recently released and its characterisation is on-going**
  - Only TZ pre-amplifiers (have shown good figures for ALTIROC2)
  - Improvements and bug correction towards the final chip
  - ALTIROC3 is the final radiation hard prototype before production

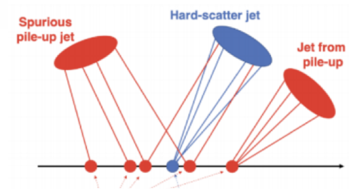
- **Development of methods and tools for hybridization, module assembly and loading is in progress**
  - Assembly sites already produced ~25 prototype modules (with ALTIROC2), mainly for the demonstrator effort
  - First detector units of the demonstrator already built. Testing is in progress

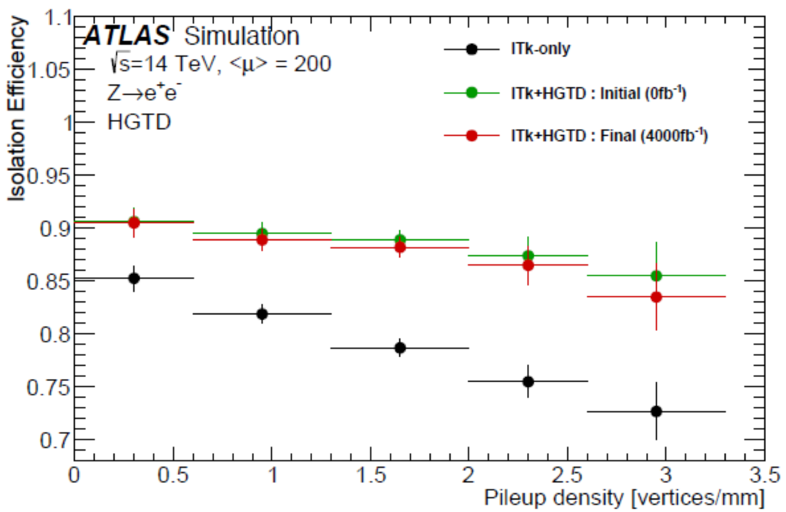
# BACKUP

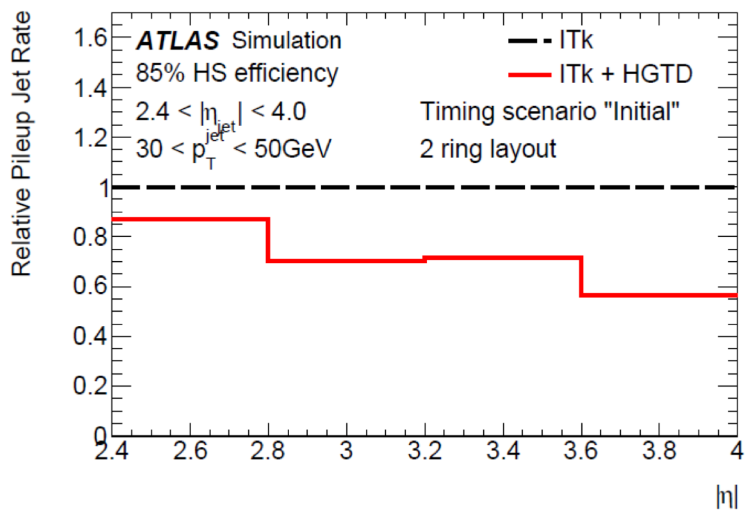
# HL-LHC challenges

- **At HL-LHC: average 1.6 collisions/mm**
  - Pile-up can add jets, create spurious jets, alter the properties of hard scattered jets
- **Examples of improvements with HGTD**
  - **Pile Up (PU) rejection:**
    - PU jets identified by looking at the tracks associated to a jet
    - HGTD can help identifying PU tracks, specially at large η
  - **Electron isolation efficiency**
    - PU tracks can cause electrons to fail isolation requirements
    - HGTD can help maintain high efficiency, specially at high PU



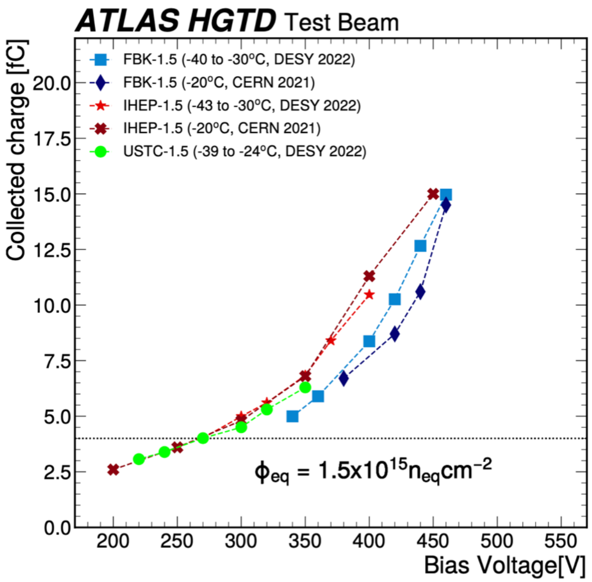



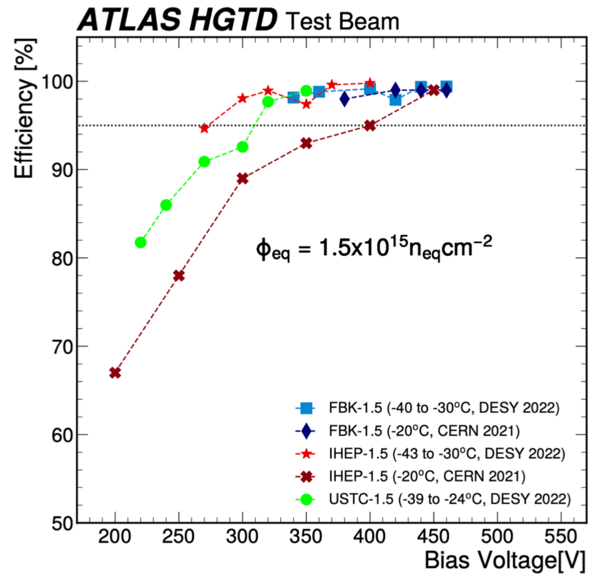



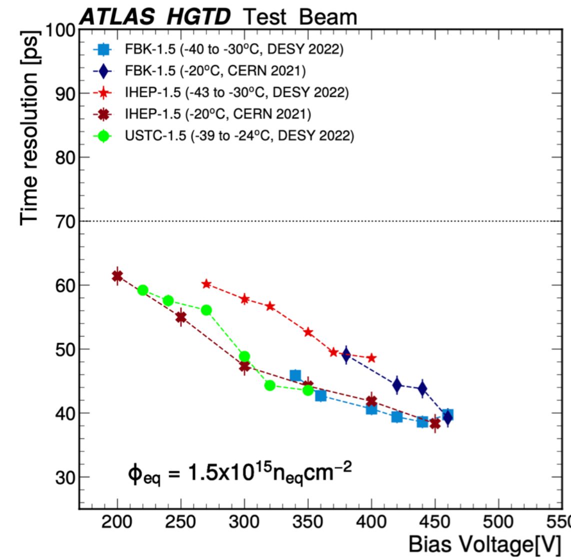



# LGAD sensors: testbeam ($1.5\times10^{15}$)

**Testbeam campaigns at CERN SPS and DESY to study the performance of Carbon-enriched LGAD sensors after irradiation up to $1.5\times10^{15}$ $n_{eq}/cm^2$**




## Collected Charge

Q charge defined as the MPV of the landau-gauss convolution

Minimum 4 fC required by ASICs

**Charge collection above 4 fC for all tested sensors**

## Hit Efficiency

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

$Q_{cut}$= 2 fC (min. ASIC threshold)

**Hit Efficiency > 95% for all the C-enriched sensors**

## Time Resolution

Time resolution measured wrt. a reference sensor

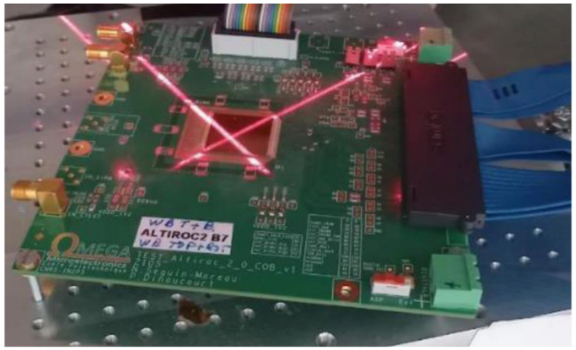
Time resolution of the reference sensor subtracted

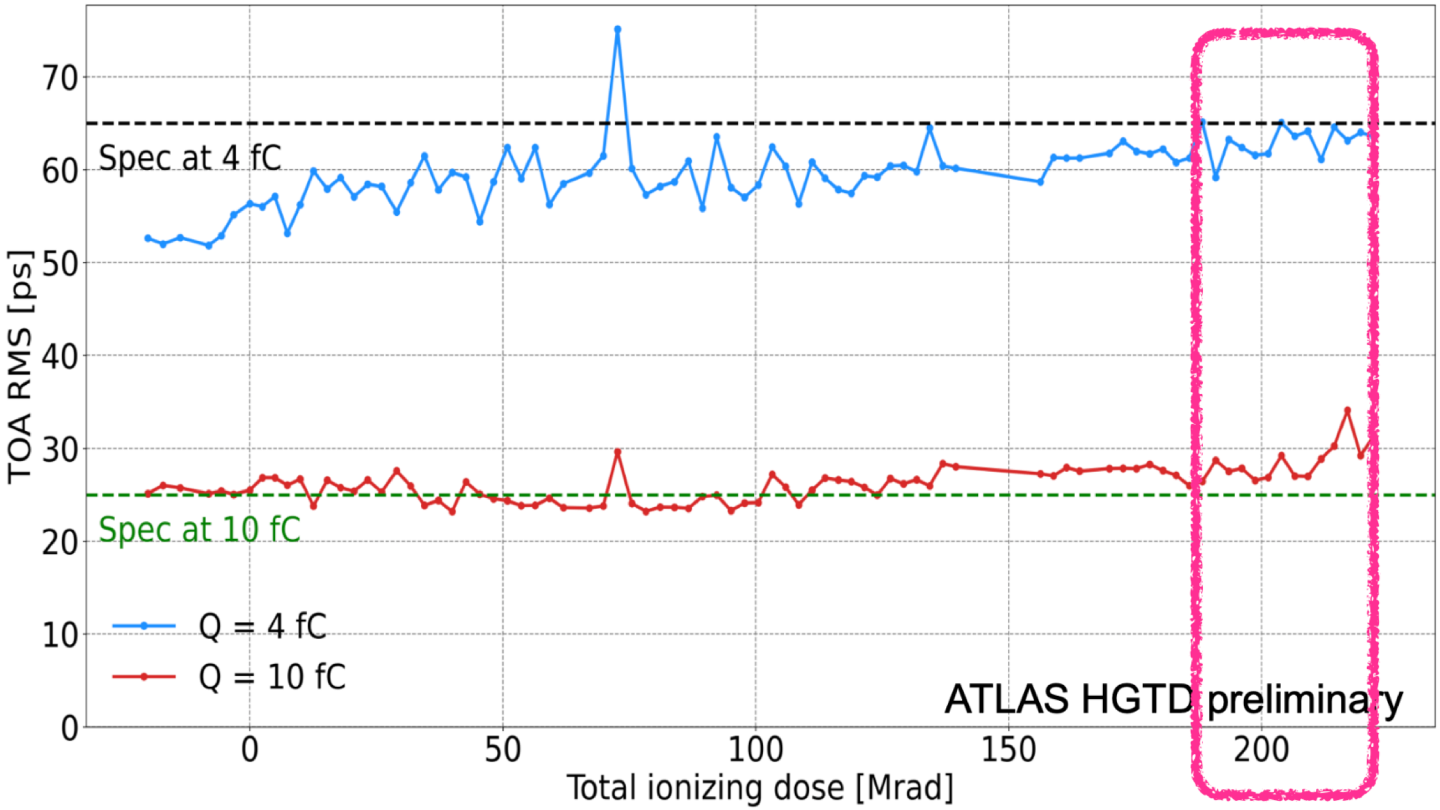
**Achieved <70 ps resolution**

# ALTIROC2: Irradiation studies

- **Radiation influence studied**
  - Up to TID: 220 Mrad
  - Dose rate: 3 Mrad/h
  - Temperature: 22°C

- **Jitter stays stable with the increasing Total ionising does (TID)**



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