The High-Granularity Timing Detector for ATLAS at HL-LHC

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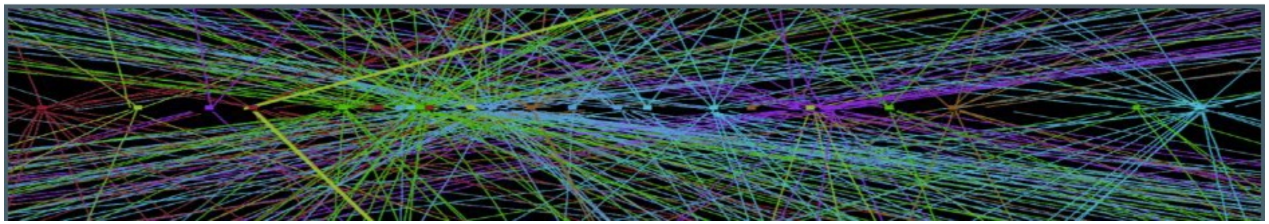
on behalf of the ATLAS HGTD group

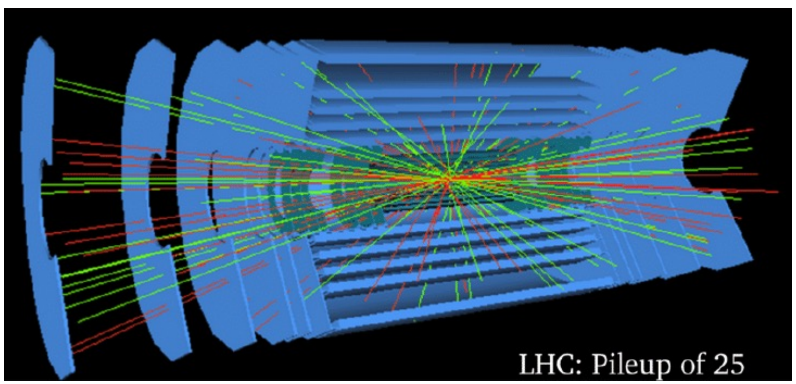
Pixel 2024, Nov 18-22, 2023

Challenges of HL-LHC

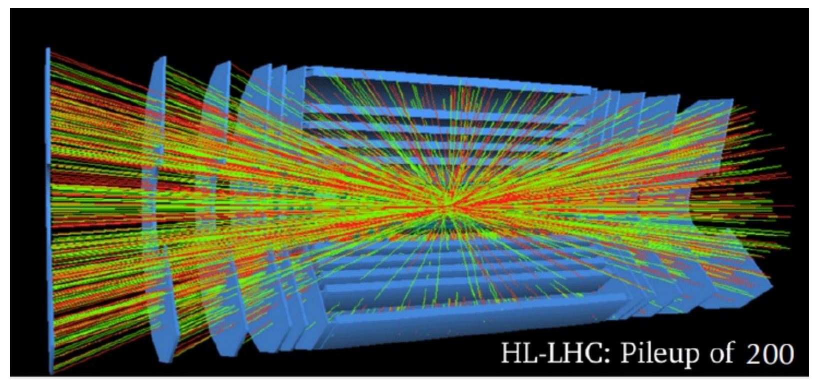
- In ~2030, LHC will run in **"high luminosity"** **, called HL-LHC**
  - The **instantaneous luminosity** will be a factor of ~5 – 7.5 higher than the LHC nominal values
  - 4000 fb^{-1}, collect ~**x10 more data than Run3** in the long term
  - *Pileup* of ~200 vertices per interaction
  - **Track reconstruction:** complexity increases **exponentially or worse with pileup**

On average 1.6-2.35 vertices per mm



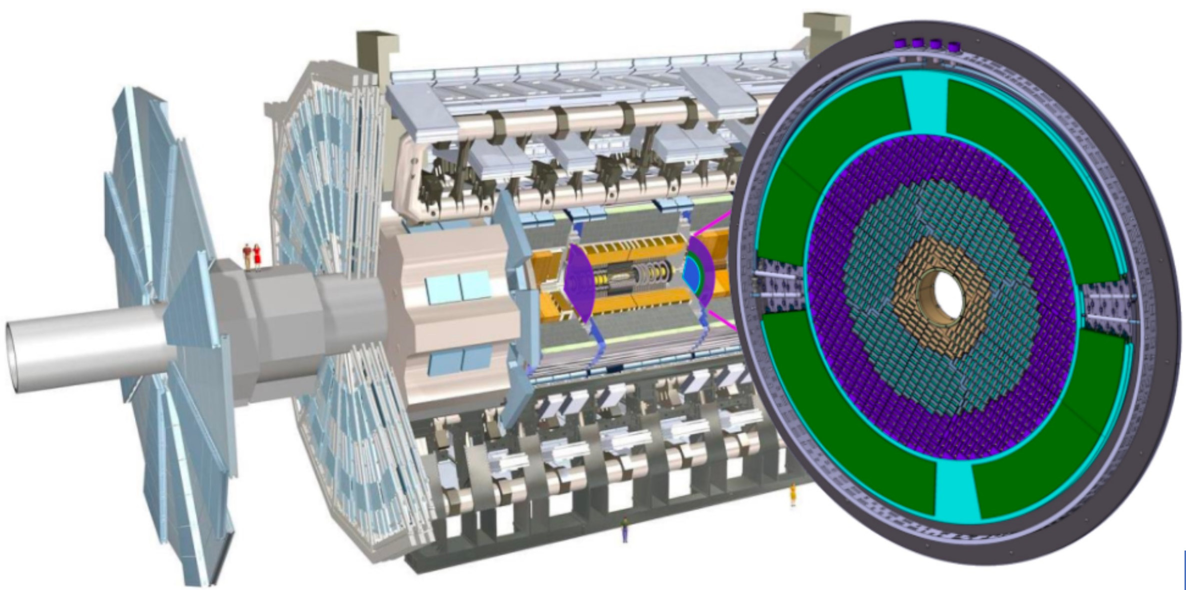


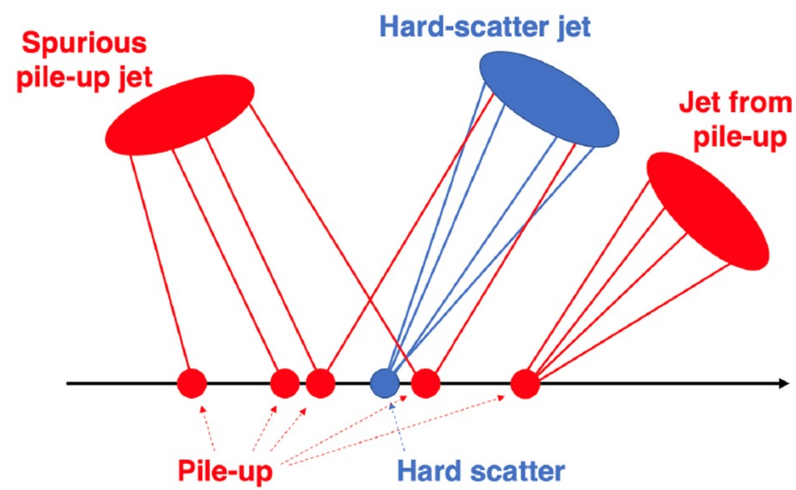
Pileup increases



High Granularity Timing Detector (HGTD)

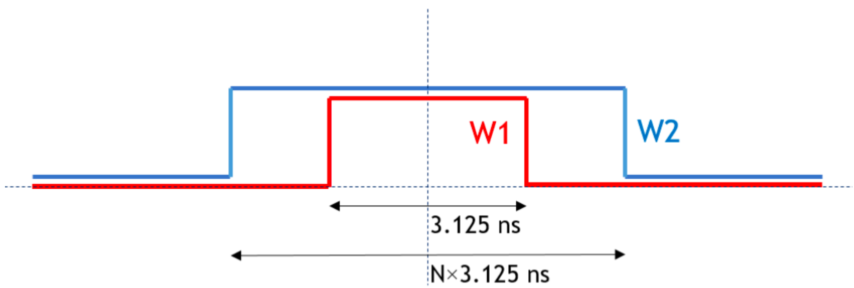
- **HGTD aim to reduce pileup contribution at HL-LHC**
  - **Timing resolution is required to be better than 30 ps (start) - 50 ps (end) ps per track**
- **6.4 m^2 area silicon detector and ~ 3.6 × 10^6 channels**
- **High Granularity: Pixel pad size: 1.3 mm × 1.3 mm**
- **Radiation hardness : 2.5×10^{15} N_{eq}/cm^2 and 2 MGy**

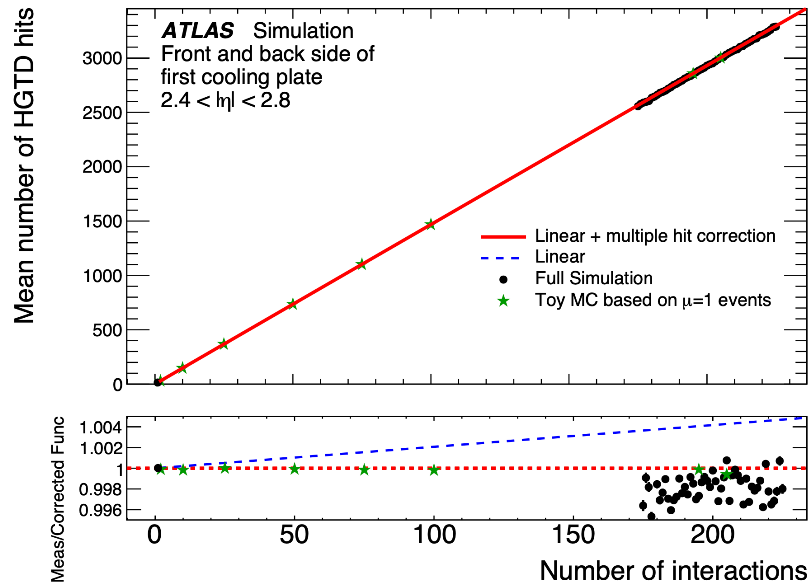




HGTD as luminometer

- **Number of hits per bunch crossing read out by each ASIC**
  - **In the region of 2.4 < |η| < 2.8 (8512 channels!)**
- **Additionally hit count in larger time window recorded**
  - **Used to determine backgrounds (e.g. afterglow)**
- **Lumi data sent constantly for each bunch crossing**
  - **This is independent of trigger**



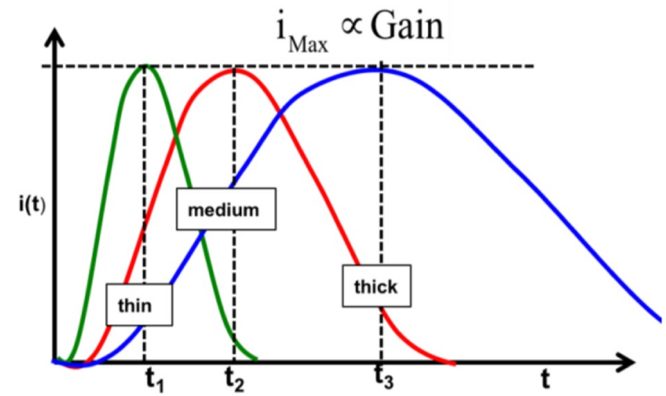


Low Gain Avalanche Detectors (LGAD)

- Compared to APD and SiPM, LGAD has modest gain (10-50)
- High drift velocity, thin active layer (fast timing)
- High S/N, no self-triggering

$$\sigma^2_{jitter} = \left(\frac{t_{rise}}{S/N}\right)^2$$

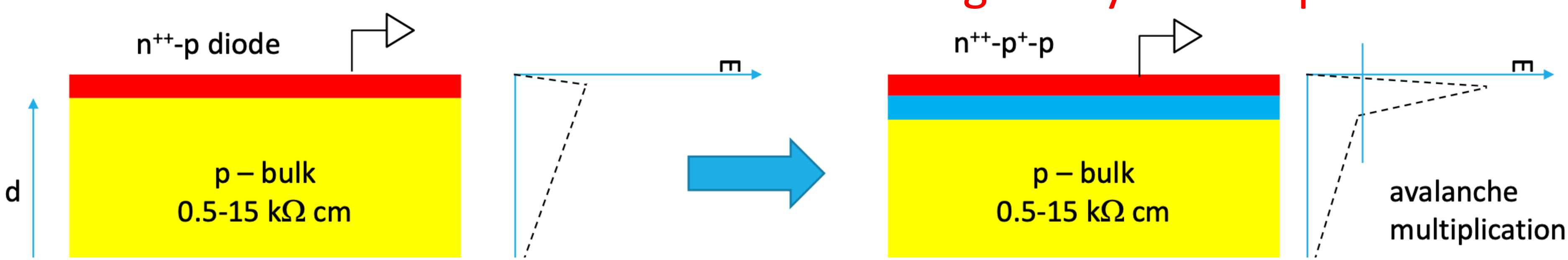
  - Modest gain to increase S/N
  - Need thin detector to decrease t_{rise}



LGAD

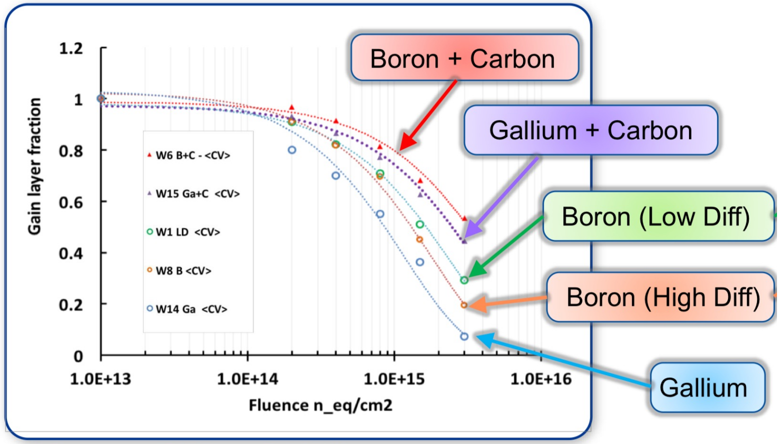
P+ gain layer on top of PIN diode

Conventional PiN diode

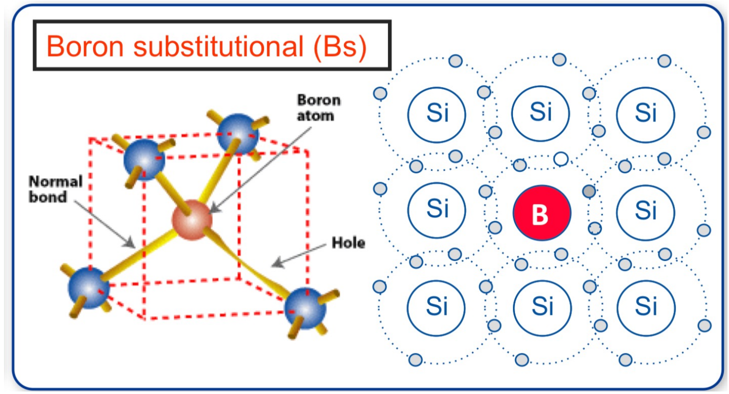


Challenge : LGAD sensor radiation hardness

- 2020, RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam
  - The key to avoid SEB is reduce the acceptor removal, reduce the operation voltage

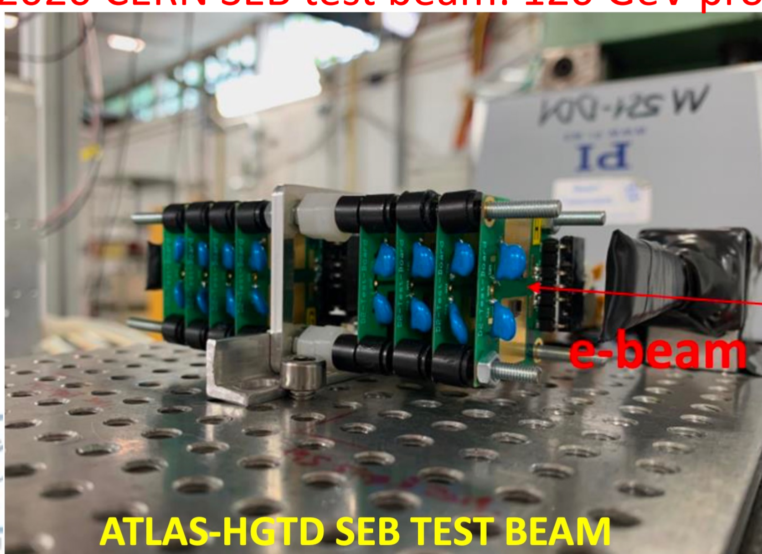


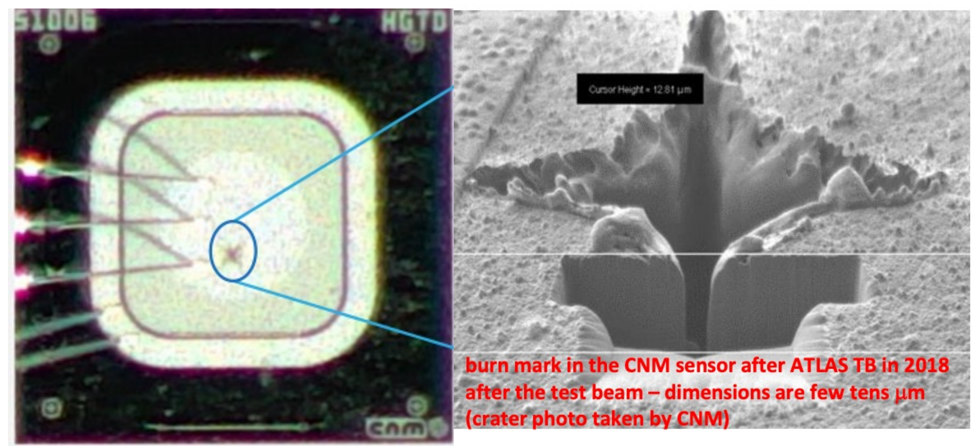
[G.Paternoster, FBK, Trento, Feb.2019]



Single Event Burnout (SEB) effect

2020 CERN SEB test beam: 120 GeV proton

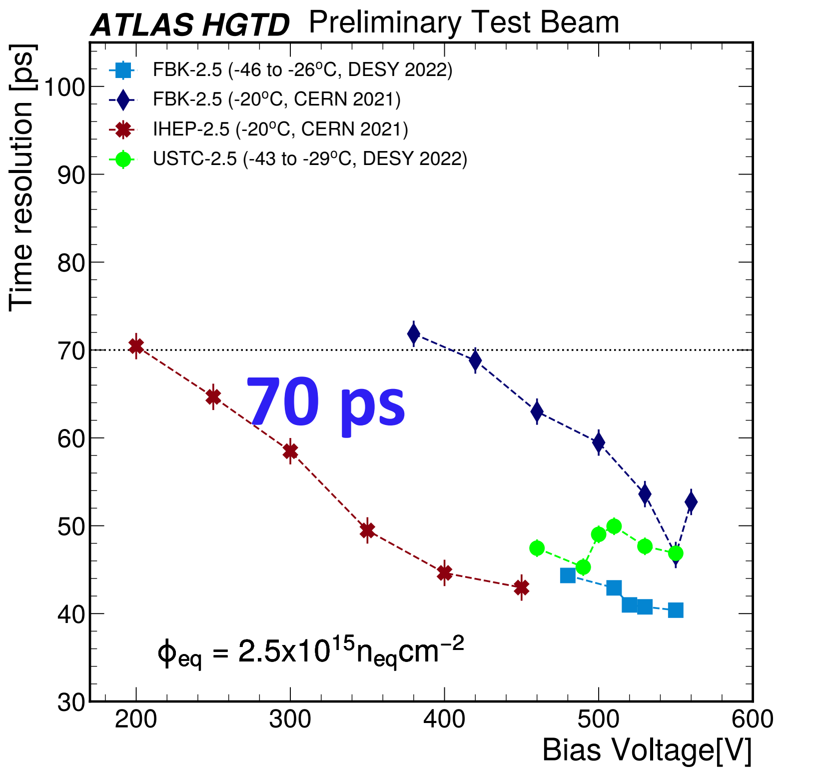


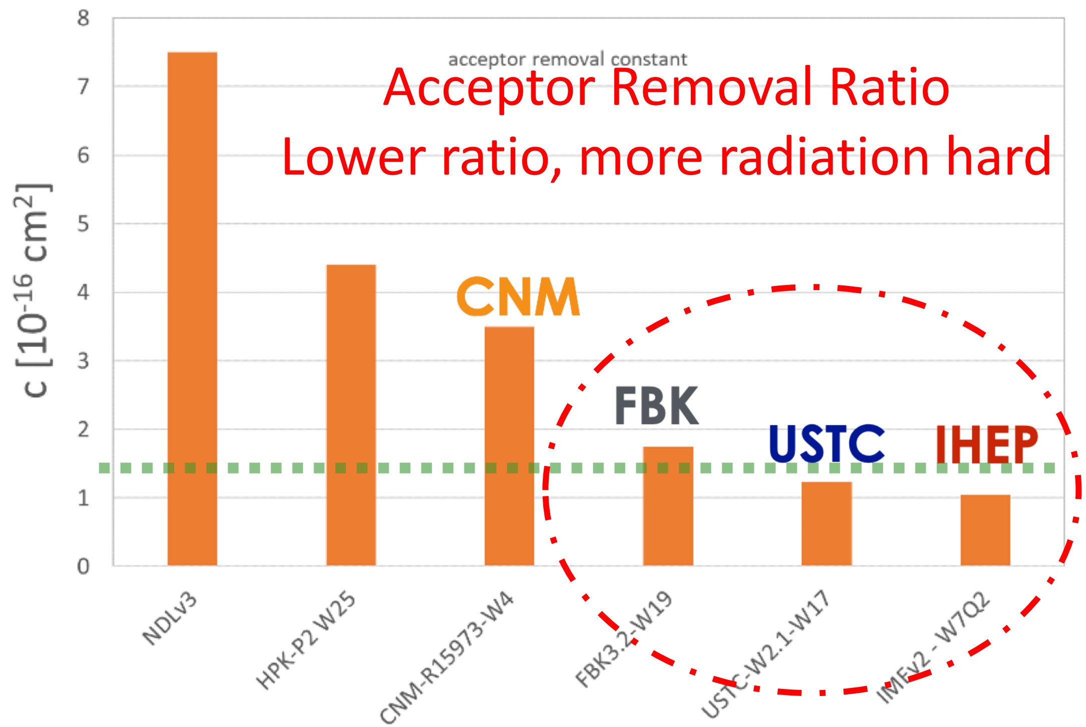


LGAD sensor after Irradiation

- Carbon-enriched LGAD (FBK/USTC/IHEP) is more radiation hard
  - Carbon "stabilized" boron doping
  - After 2.5×10^{15} n_{eq}/cm^2, carbon-enrished sensor can operate below 550 V

→ Avoid single event breakdown (Electric field lower than 11V/μm)



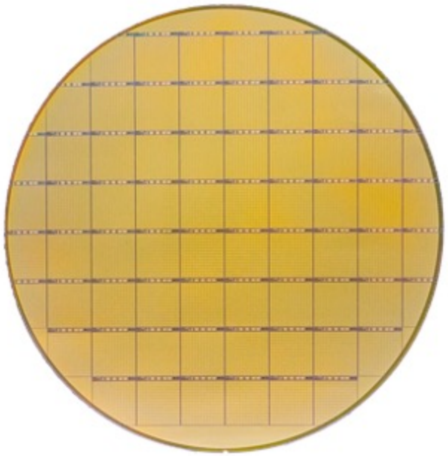


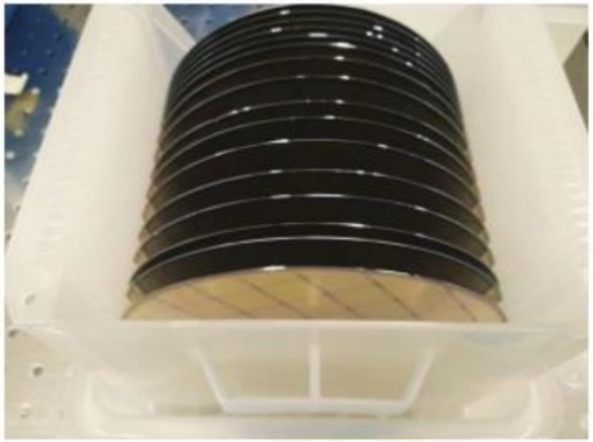
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HGTDPublicPlots

LGAD sensors pre-production

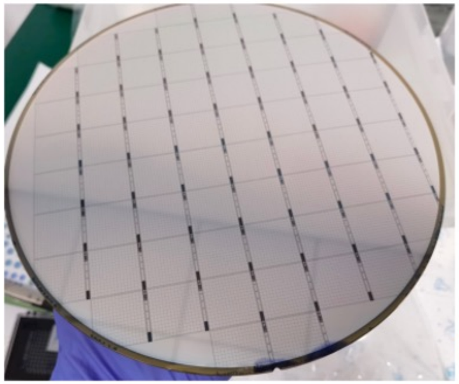
- Pre-production in 2024
  - Fabricated 1100 full-size sensors during pre-production → 5% of production
- Production Readiness Review passed on July 2024, ready for mass production
- The production share:
  - IHEP-IME: 90%, USTC-IME: 10%

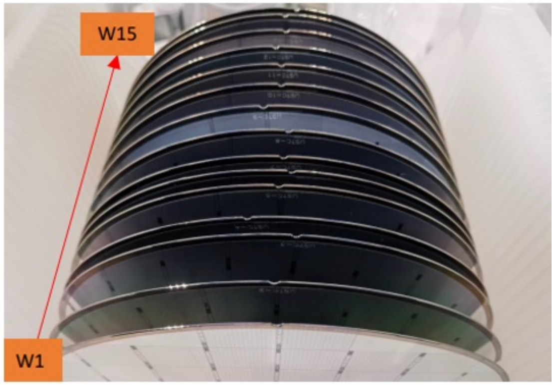
IHEP-IME Pre-production





USTC-IME Pre-production

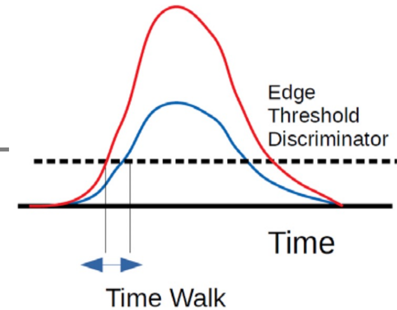


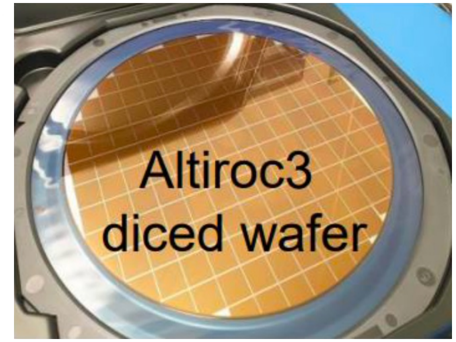


ALTIROC : Fast Timing ASIC

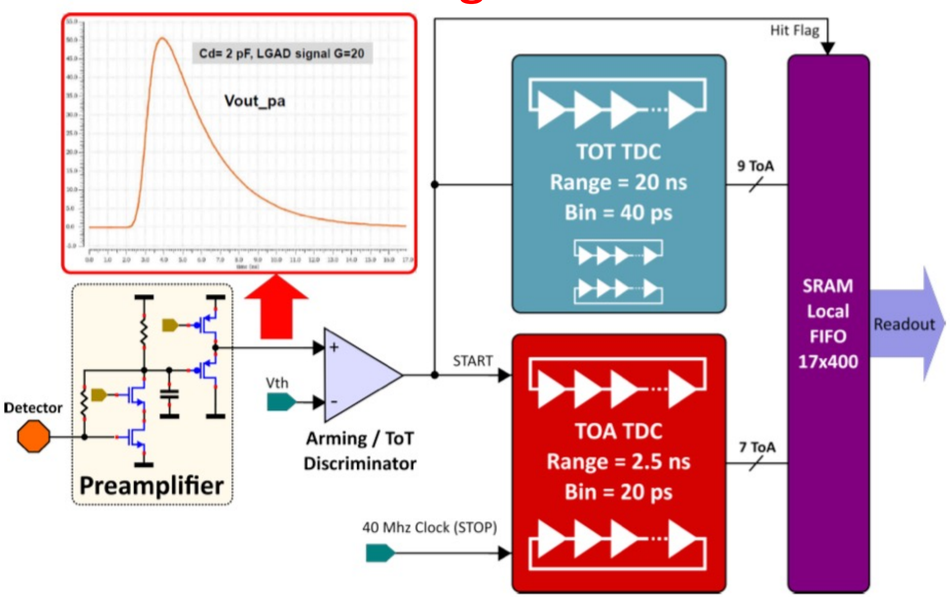
- 3 rounds of full-size ASIC development:
  - ALTIROC2, ALTIROC3, ALTIROC-A (aim to use for production)
- 225 front-end channels in ALTIROC, each channel has
  - A preamplifier followed by a discriminator:
  - Two TDC (Time to Digital Converter) to provide digital **Hit data**
    - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
    - Time Over Threshold (TOT) : range of 20 ns and a bin of 40 ps (9 bits)

Time walk

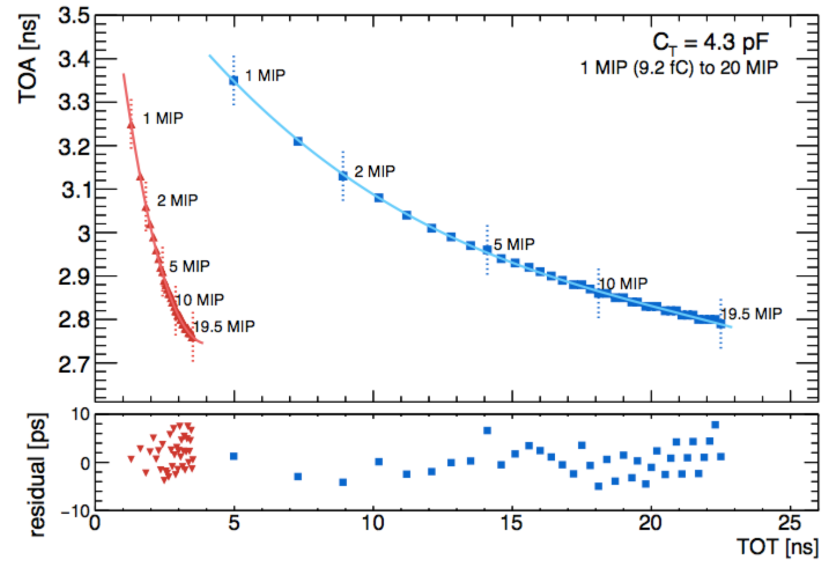




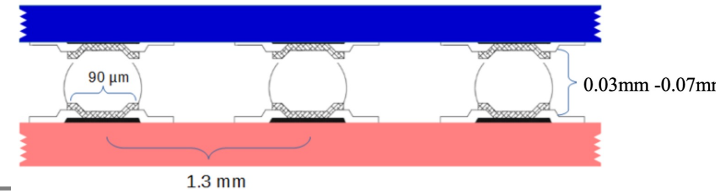
ALTIROC timing ASIC in nutshell



Time walk correction with TOT

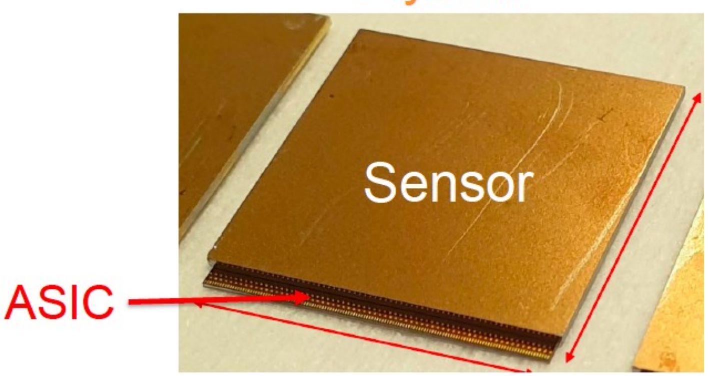


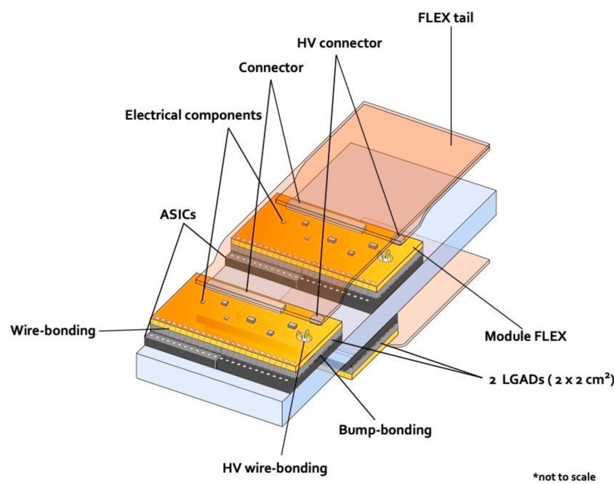
Modules and Hybrids



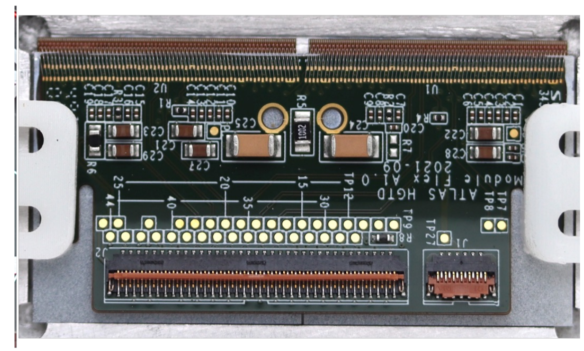
- HGTD has 8032 total modules, 3.6 M channels, 6.4 m^2
  - **A module consists of one module flex and two hybrids.**
    - 6 module production sites in HGTD project
  - **Hybrid: One LGAD sensor bump bonded to one readout ASIC (ALTIROC chip)**
    - **Low-Gain Avalanche sensors (LGAD) (15 × 15 pads of 1.3 x 1.3 mm^2)**
  - **One Flexible -PCB (module flex)** glued on top of two hybrids
  - Flexible tail connected module to outer radius electronics

Hybrid

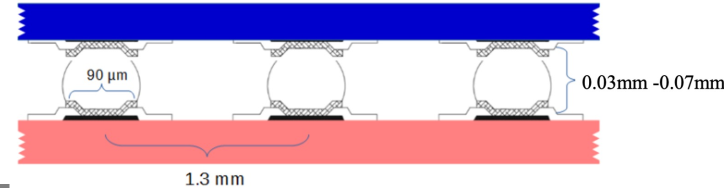




Module

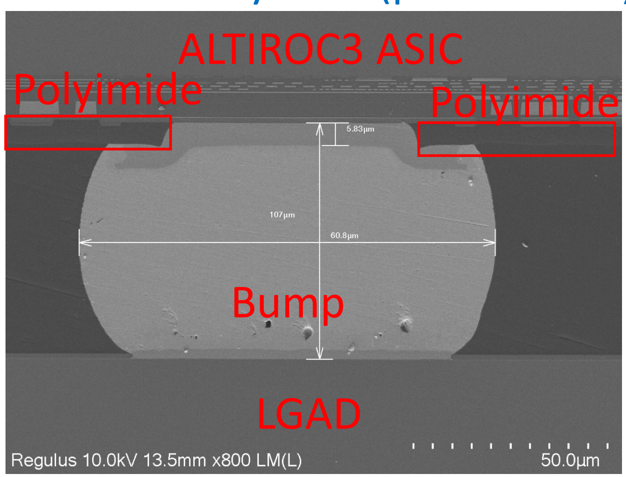


Hybrid

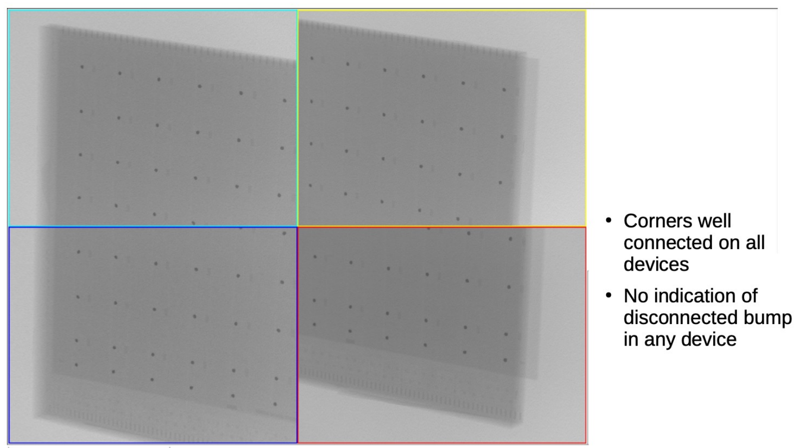


- Full-size hybrids for ALTIROC2/ ALTIROC3/ ALTIROCA have been built
  - More than 100 hybrids for ALTIROC3, ~10 hybrids for ALTIROC-A
- To improve robustness of modules during thermal cycle.
  - Switch to using thick sensor as baseline (775um), instead of thin sensor (300um)
  - Polyimide layer for ALTIROC3/ALTIROC-A wafer by NCAP China → Softer, correct opening
  - More mechanical Guard ring bumps designed for ALTIROC-A and pre-production LGAD.
- Hybrid by new baseline has much better thermal stability

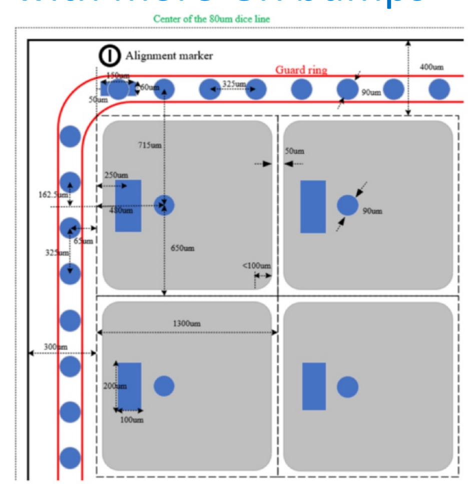
ALTIROC3 hybrids (profile view)



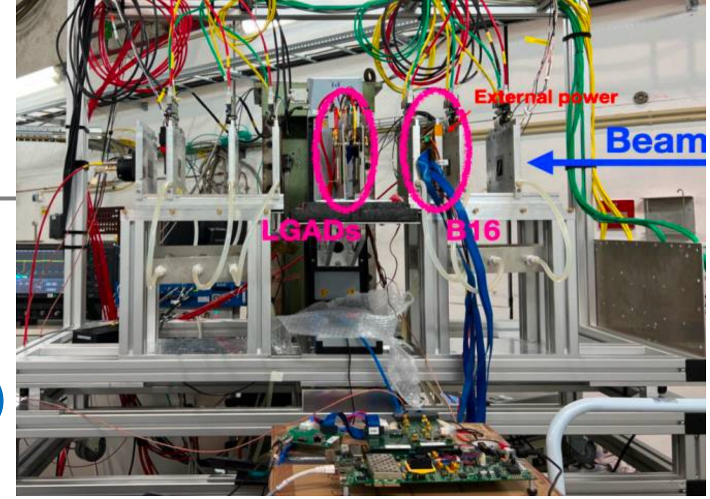
X-ray image of full-size hybrid



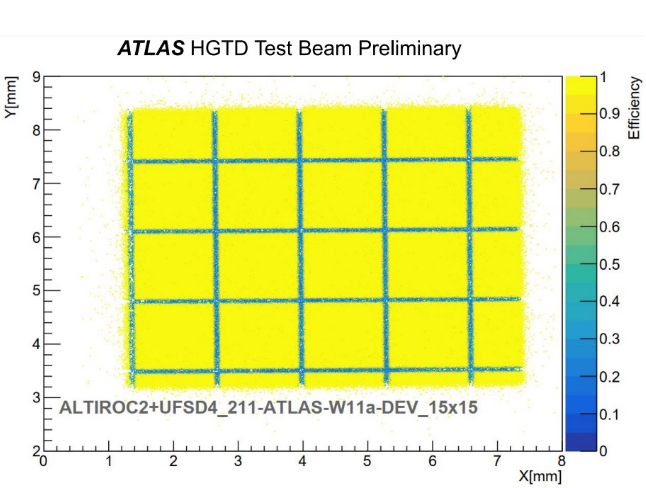
ALTIROC-A hybrids design with more GR bumps

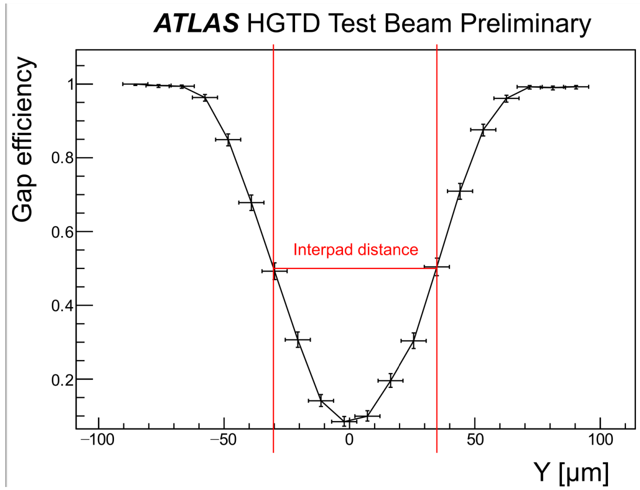


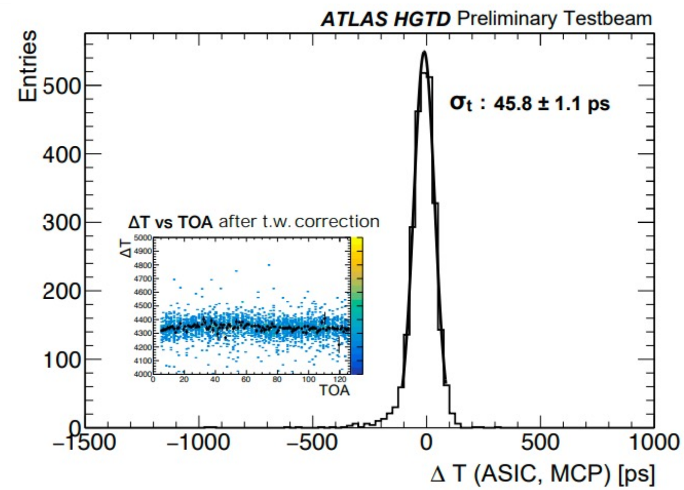
Hybrid test beam result



- Hybrid functionality was validated by test beam
  - The EUDET telescope is used for track reconstruction
- Close to 100% efficiency in the center of the pixel (pad)
  - The gap between pixels (pads) is about 50μm
- Time resolution of ALTIROC3 hybrids is better than 50ps
- ALTIROCA hybrids and Irradiated ALTIROC3 and are also validated recently







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Module assembly

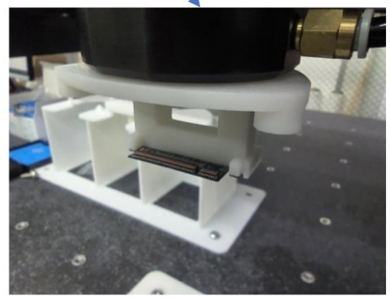
- Jigs tools and pick-and-place machine developed
- Both approaches met the specification

pick-and-place machine

Picking tool

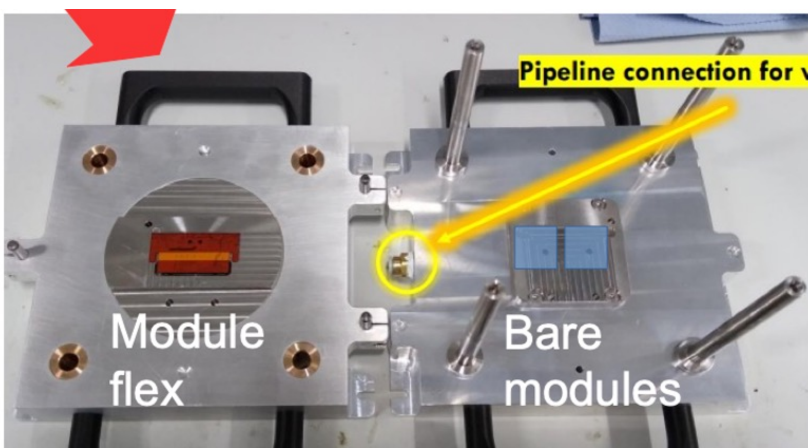
Picking dummy sensor

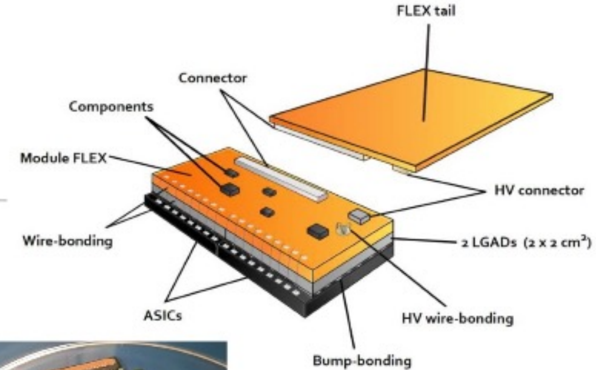
Placing dummy sensor

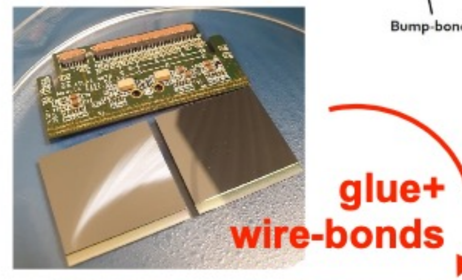


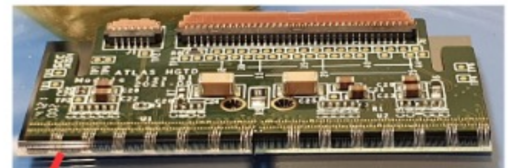
Picking flex

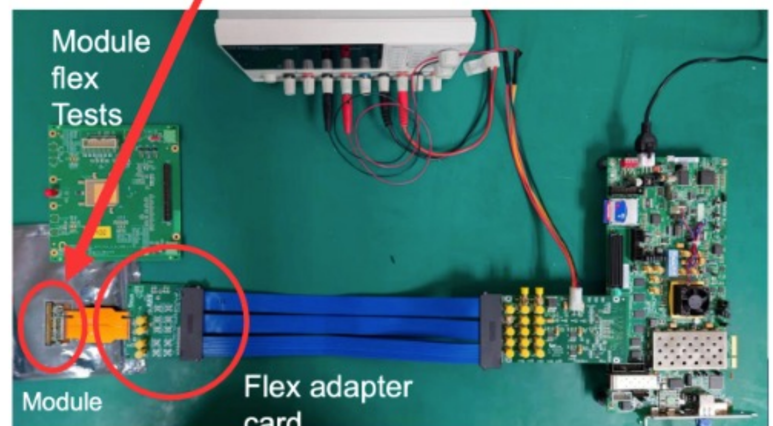
Jigs tools





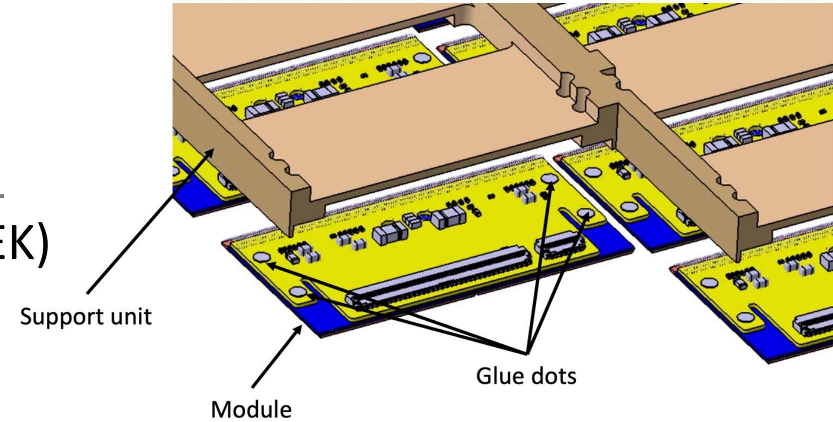




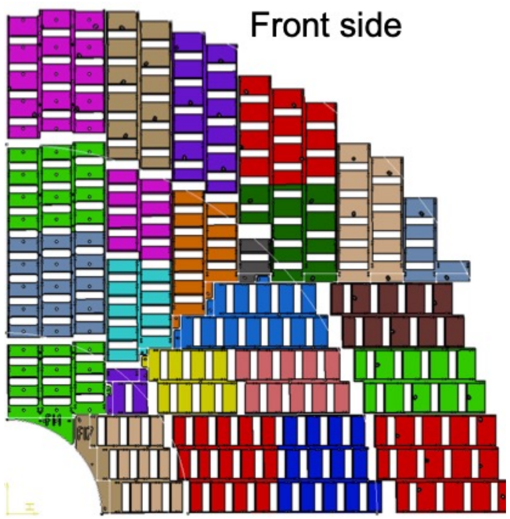


Detector units

- Modules are installed and glued on support units (PEEK)
- Two sites have produced detector units prototypes
  - Loading procedures validated

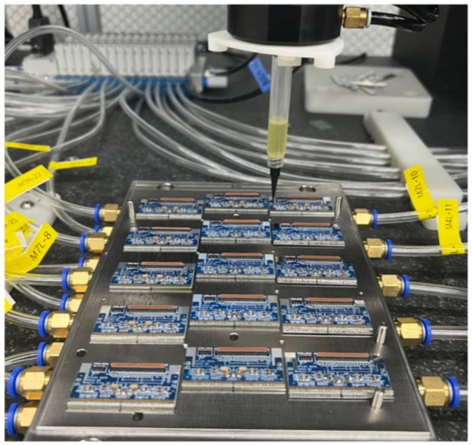


Different color represents different support units.

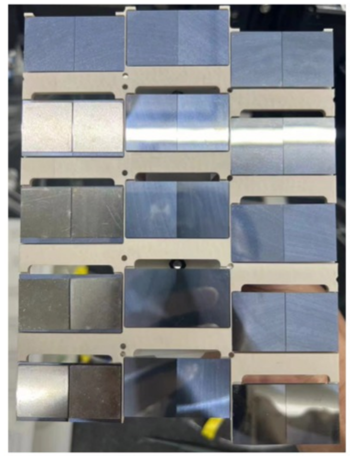


Gluing modules on support units

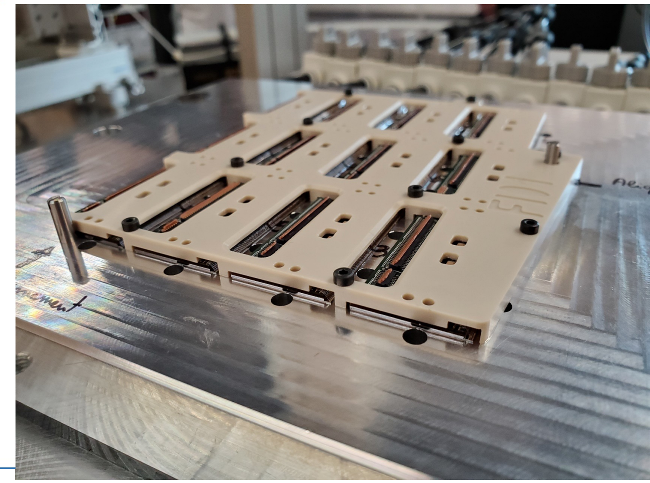
Dispensing with GluingTool



Backside view after removal



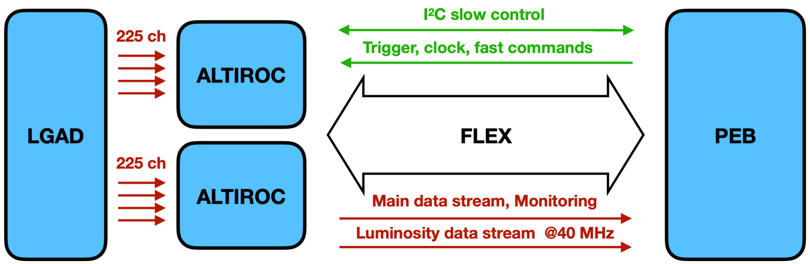
Loading modules on support units



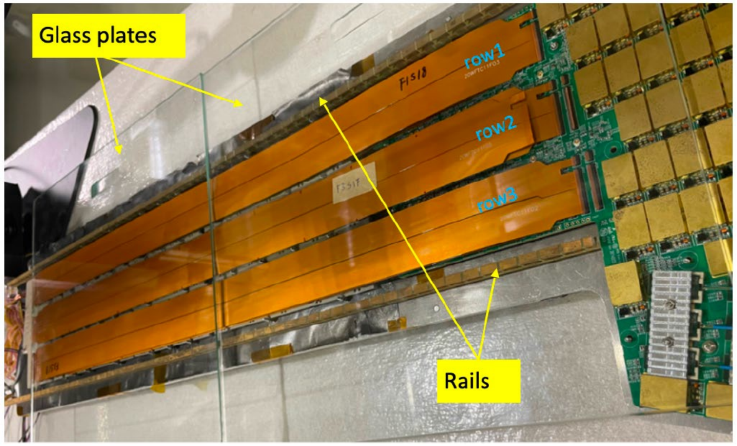
More details in Sergei's talk on Friday

Peripheral Electronics Boards, flex tail

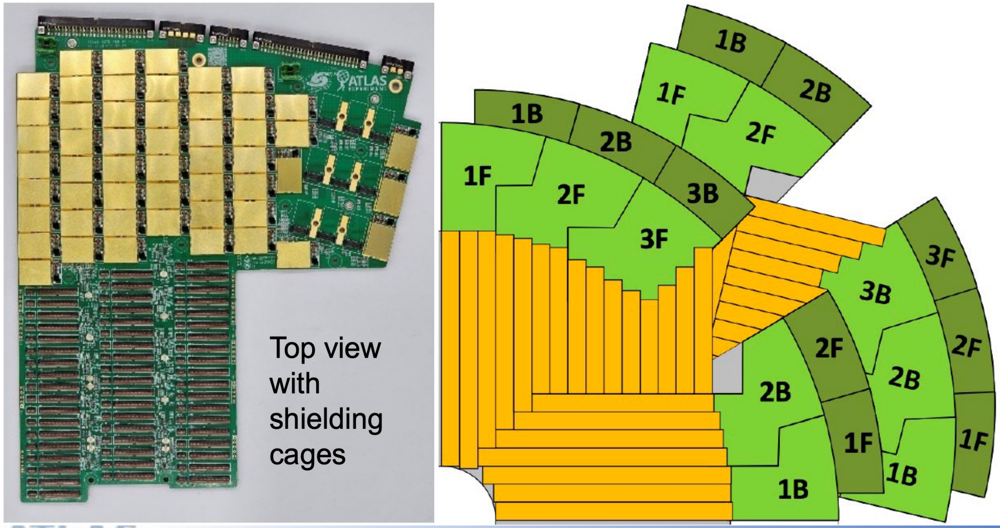
- 1st Peripheral Electronics Boards (PEB) prototyped, tested in demonstrator
  - 6 different type PEB, the most complex one PEB1F prototyped
- 3 vendors made prototypes for Flex tails
  - Length calculation has been updated and validated in demonstrator.



Flex tail prototype (length up to 75cm)



Peripheral Electronics Boards prototype

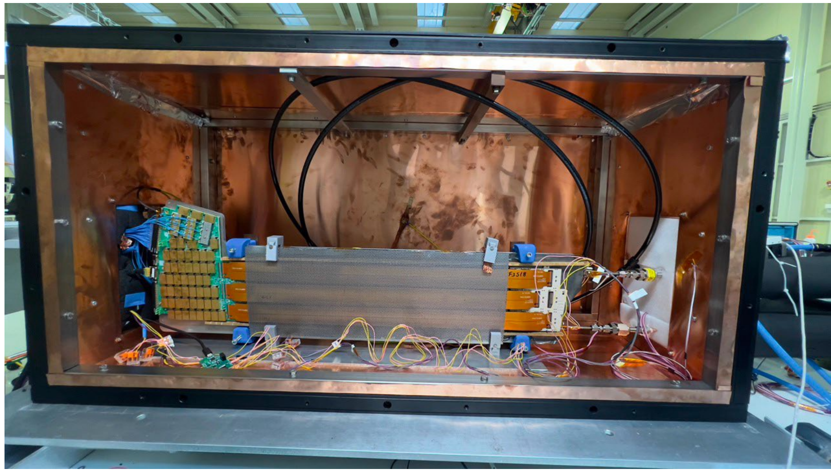


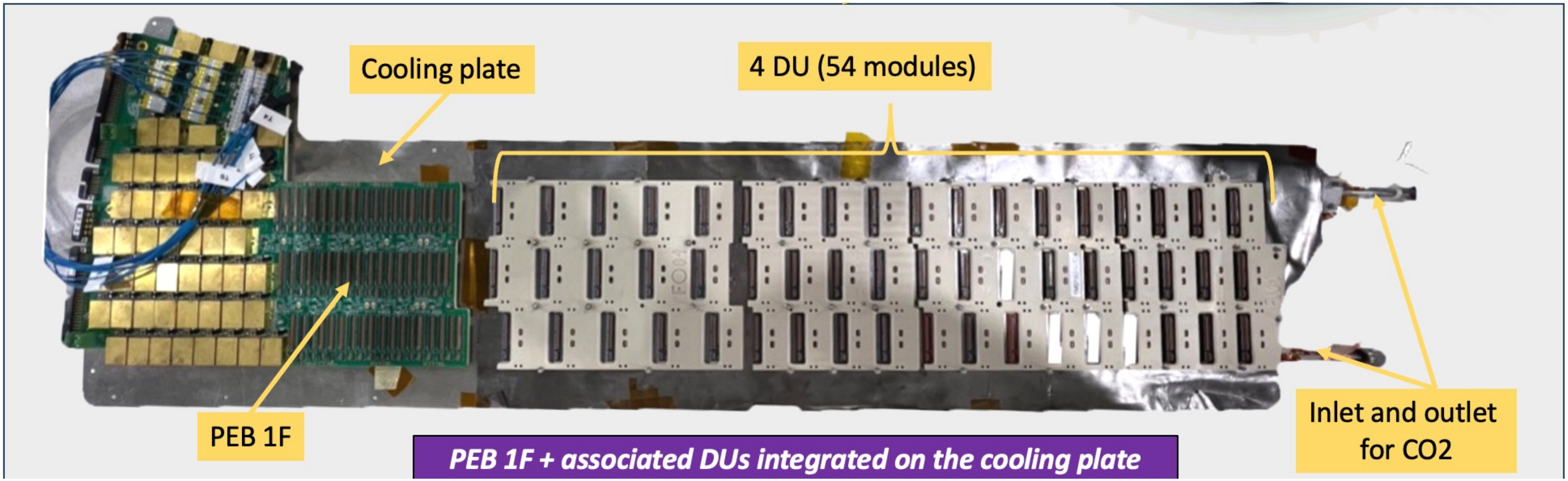
Components on PEB1F

Peripheral board	Modules	lpGBT	bPOL12v	MUX	VTRx+
1F	55	9+3	52	9	9

Demonstrator

- Demonstrator represent one slice of detector
  - Consist of 4 detector units (54 modules)
  - Readout with multi-modules by PEB1F with Felix DAQ
  - Can operated at -30C with CO2 cooling





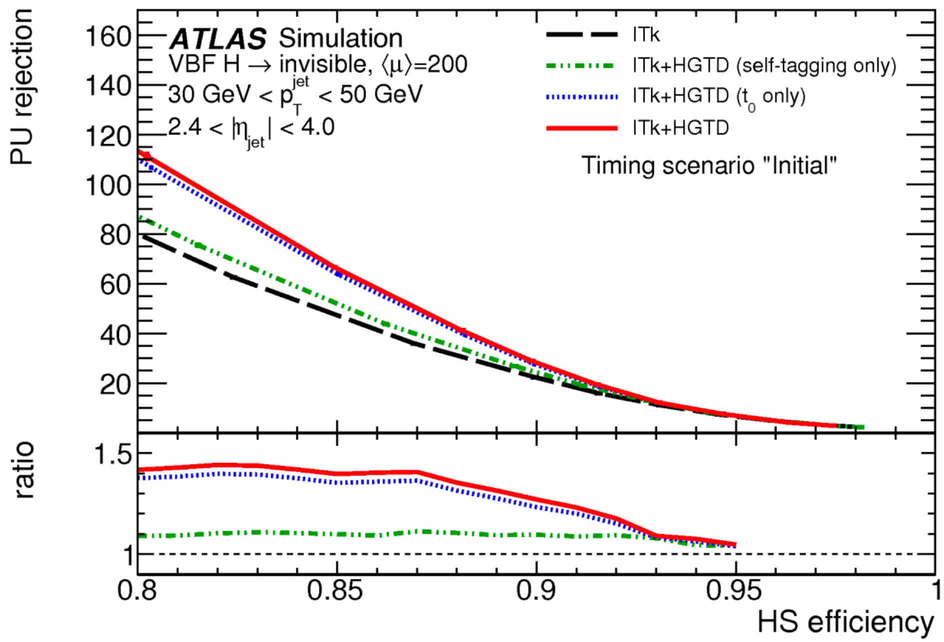
Summary: HGTD detector for ATLAS phase II upgrade

- Developed LGAD fulfilling the radiation hardness requirements
  - Carbon enriched LGADs fulfil HGTD sensor requirements up to **2.5×10^{15} N_{eq} /cm^2**
  - Pre-production done, ready for final production
- Three round of full-size ASICs have been prototyped
  - Performance of the ASIC and hybrids has been validated in test beam
- Full-size hybrids ,modules and detector units are prototyped
- Demonstrator activities ramping up, verifying components in the system
  - including Peripheral Electronics Boards, flex tail, modules and detector units …

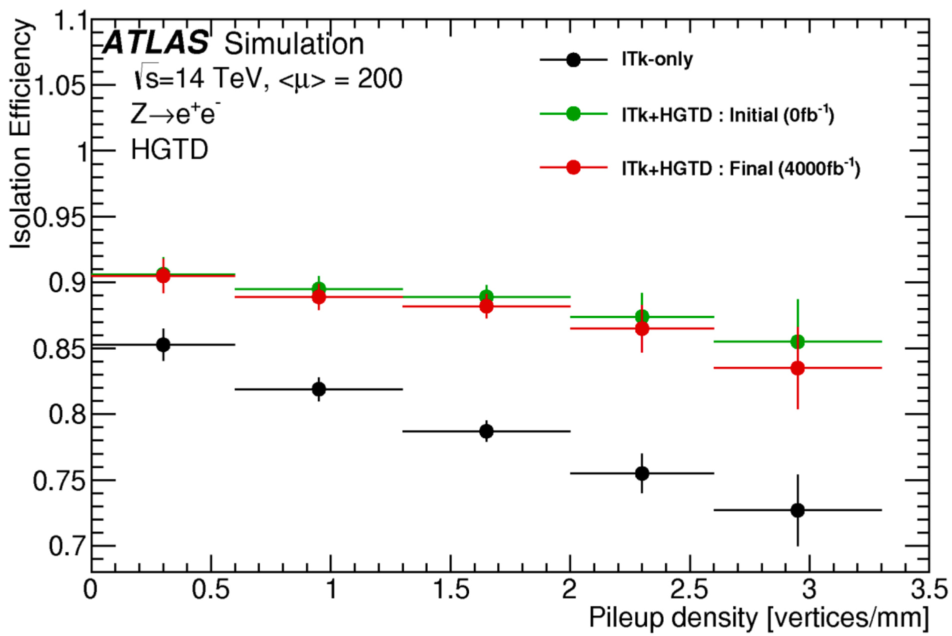
Backup

Physics performance

Suppression of pile-up jets

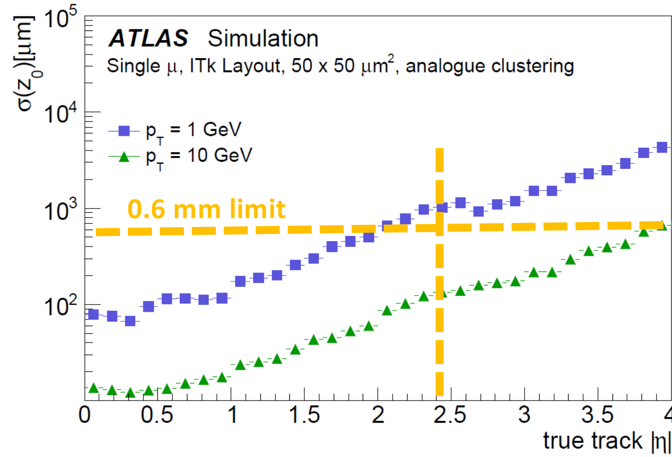


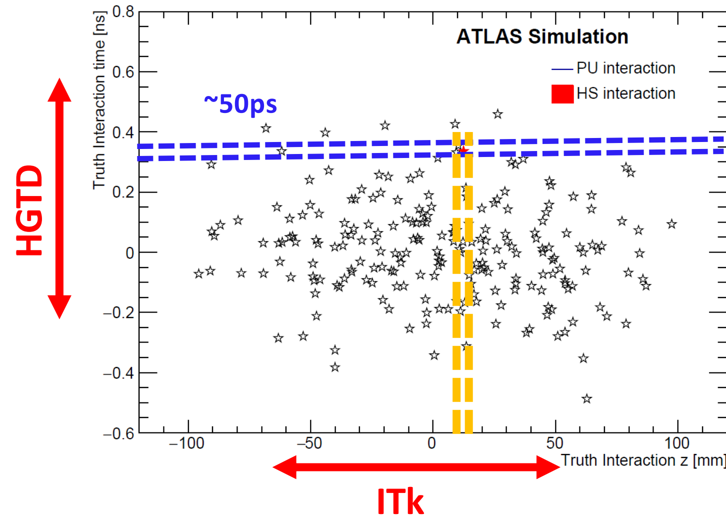
Efficiency of track isolation requirement for forward e-



Why need the time information?

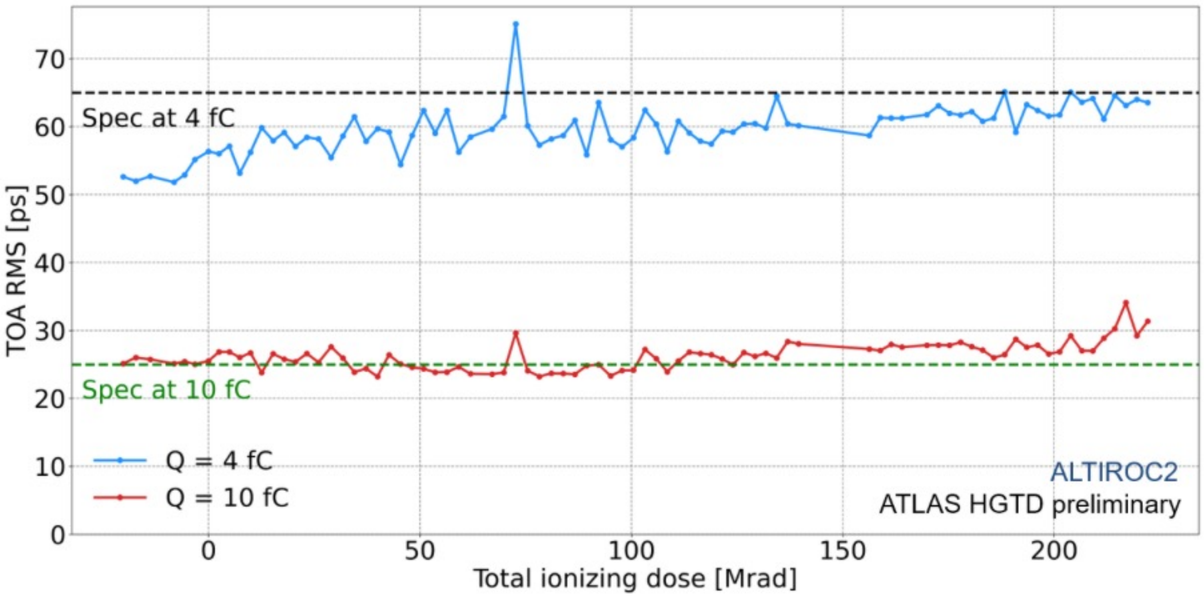
- At High Luminosity -LHC
  - Pileup: <μ>= 200 interactions per bunch crossing ~1.6 vertex/mm on average
- Problems of the vertex reconstruction in ATLAS
  - degradation significantly in the forward region compared to the central region
  - Need z_0 resolution < 0.6 mm
  - Liquid Argon based electromagnetic calorimeter has coarser granularity
  - New inner tracker (ITk) has poor z resolution in the forward region
- Using timing information easier to reconstruct vertices
- Timing information is necessary for the HL-LHC





ALTIROC testing

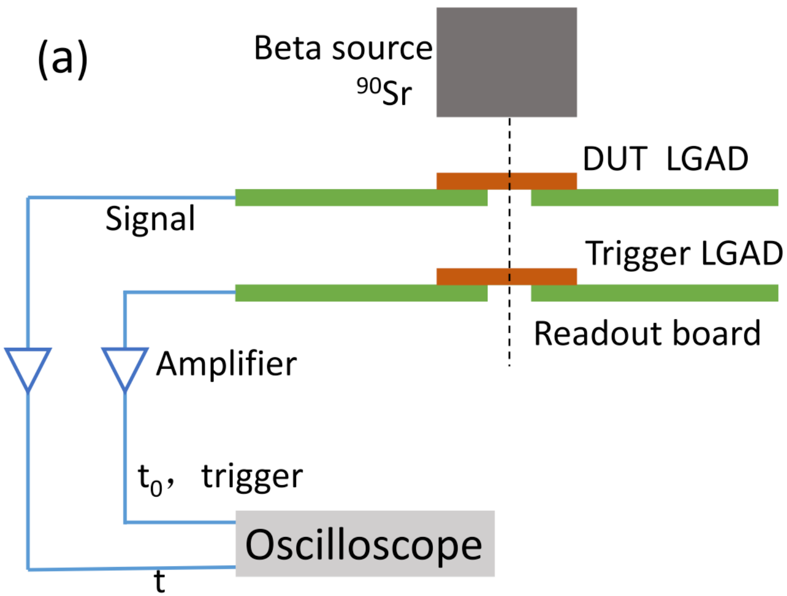
- Very demanding requirement of <70 ps time resolution @ 4 fC
  - LGAD collected charge >10 fC (>4 fC) before (after) irradiation
- Charge injection self-calibration test in ALTIROC
  - ~25 ps jitter @ 10fC
  - Better than 70 ps jitter@ 4 fC
  - Showing stability under radiation up to 220 Mrad total ionization dose

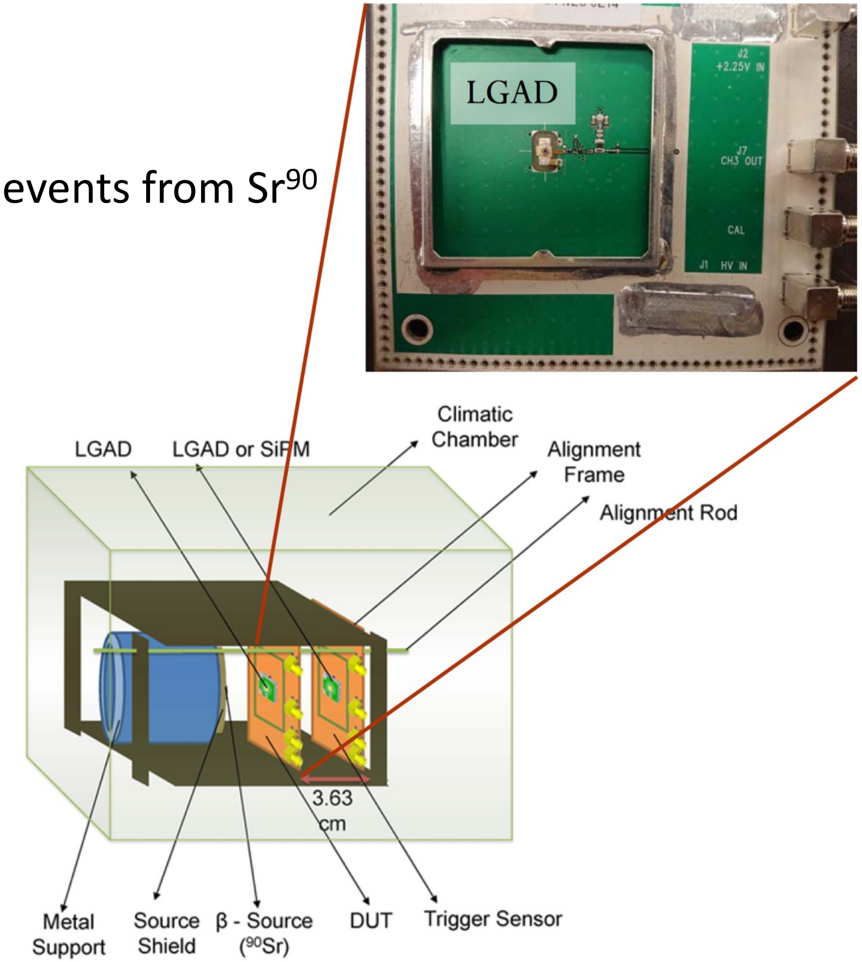


Beta source tests: LGAD timing resolution measurements

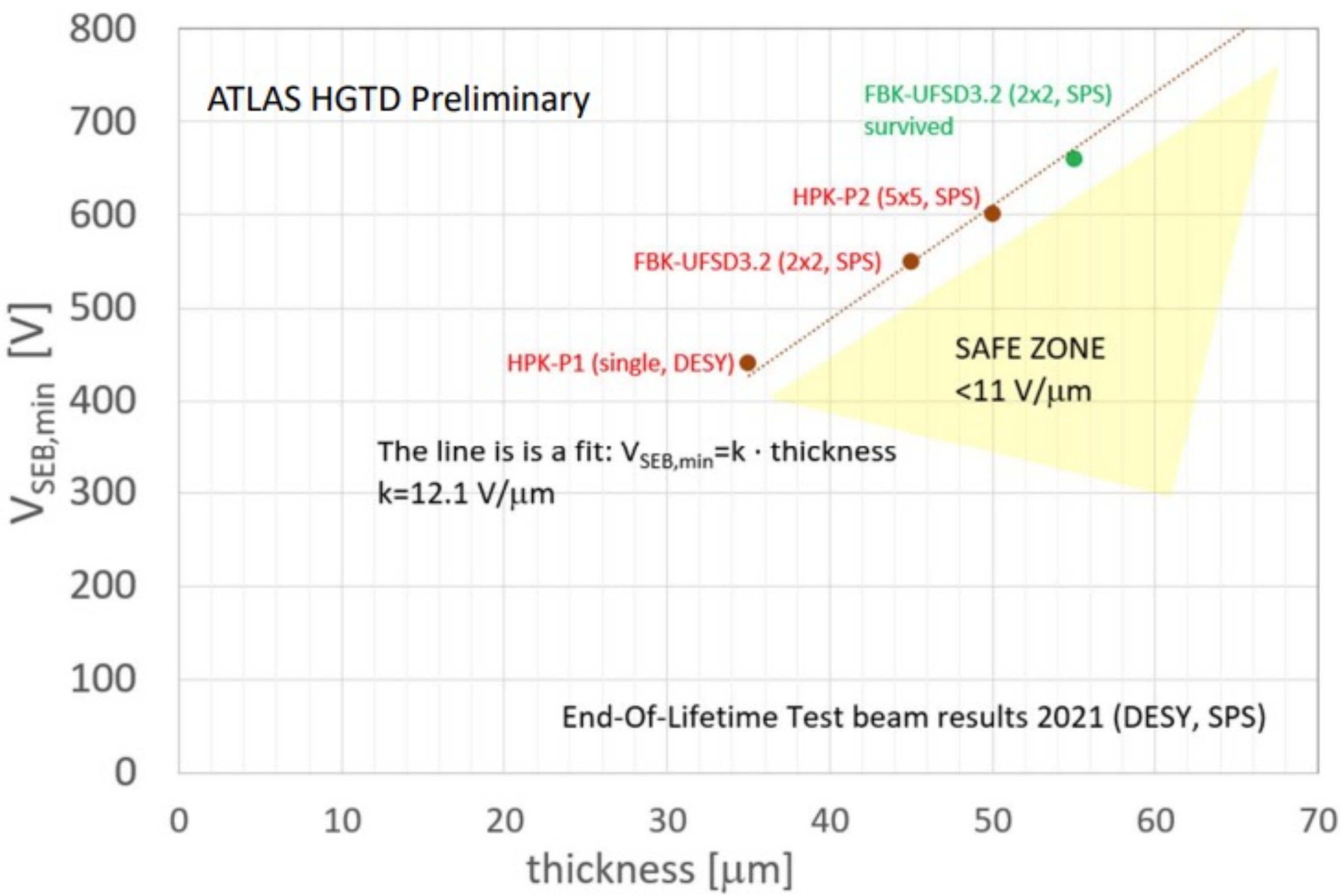
- Sr^{90} Beta telescope test (collected charge, gain, time resolution)
- UCSC boards with commercial amplifier and analog readout by Oscilloscope
  - Less constraints with respect to the ASICs – exploring the limits of the sensors.
- Two UCSC boards with two LGAD
  - One LGAD is device under test (DUT)
  - Another LGAD is used to trigger electrons events from Sr^{90}

(a)



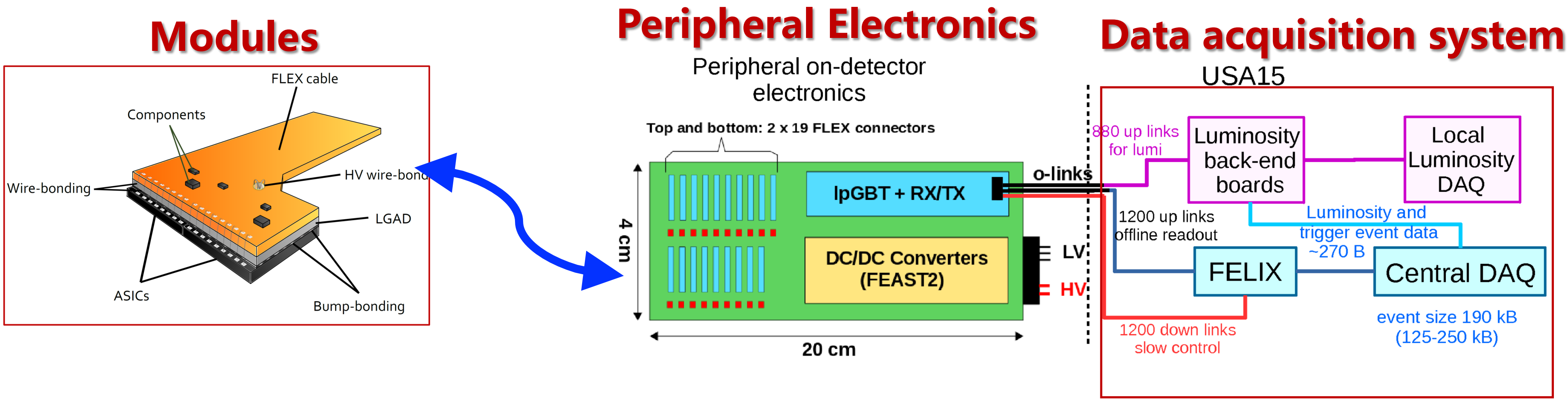


LGAD Single Event Burnout effect (HV stability in the beam)



Peripheral board (PEB)

➢PEB connects FE to the DAQ system, provides LV&HV to the modules

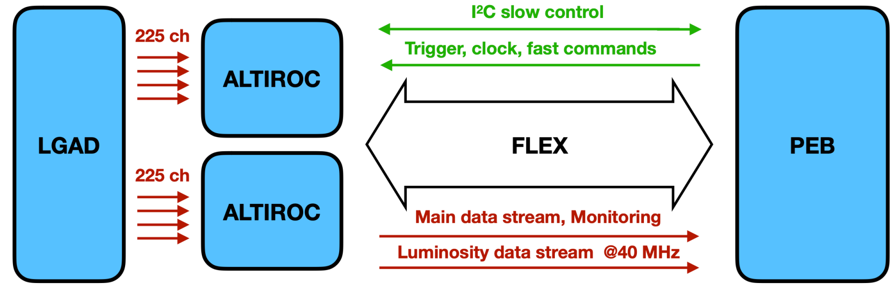


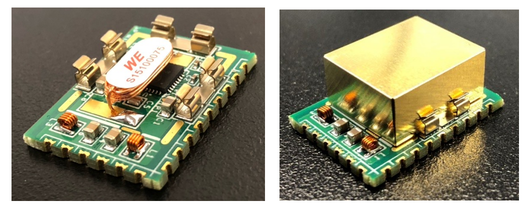
Peripheral electronics board (PEB)

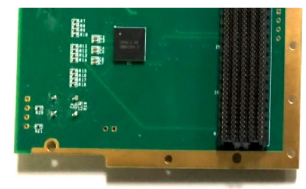
- Work on the characterization of all individual components, prototypes under production:
  - Detailed testing of the DC/DC converter (bPOL12V), different options under consideration

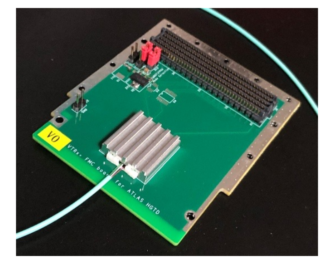
  ↠ need to fulfil space constraints, power efficiency measured
  - Started tests on lpGBT with evaluation board
  - VTRX+: successfully tested 2.56G/10.24G communication, bit error rate (<10^{-12}), passed eye diagram test
  - MUX64: analogue multiplexer (for monitoring of ASIC power supply and temperature)

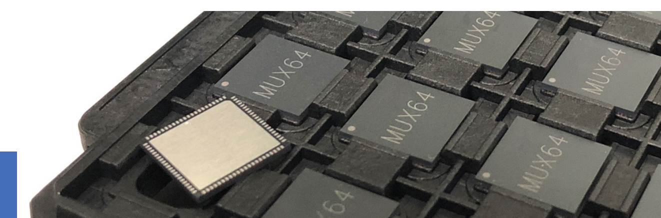
  ↠ basic functionality confirmed, On-resistance larger than expected (further investigations necessary)




DC/DC converter


lpGBT eval. board


VTRx+ eval. board

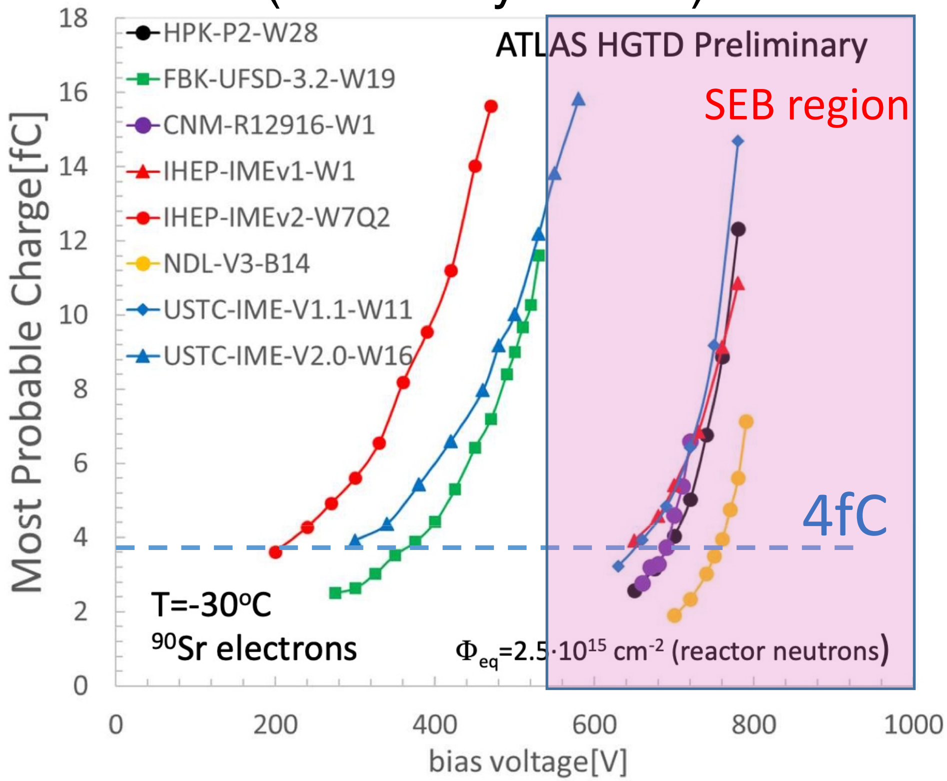


MUX64 in QFN88

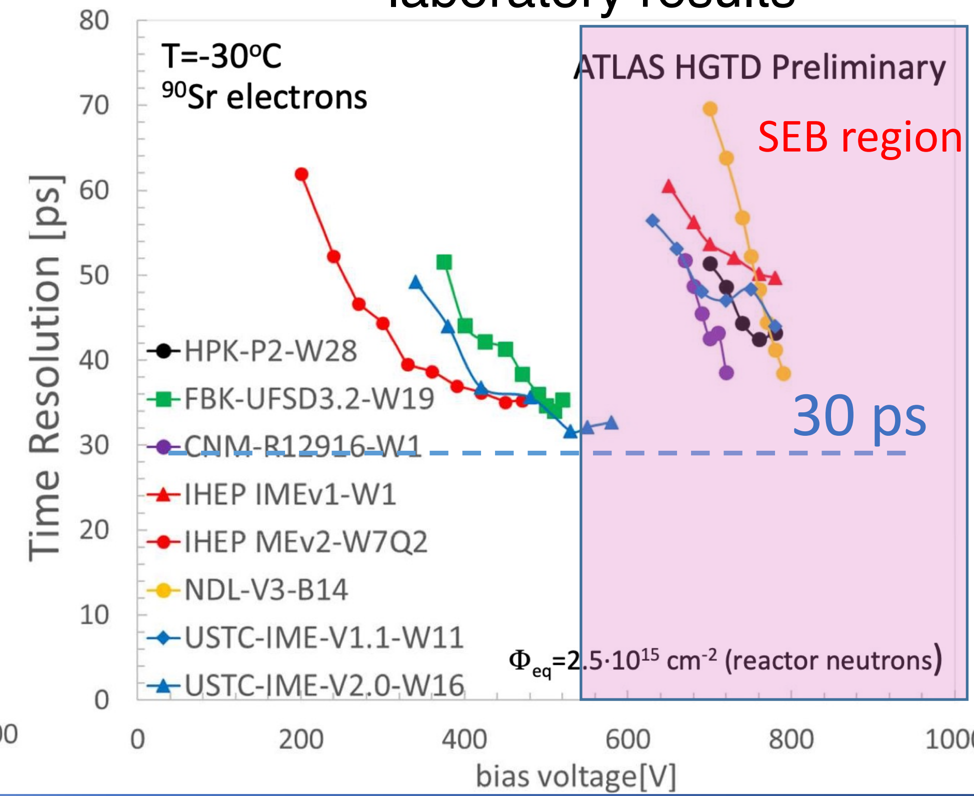
Performance of various LGAD prototypes at 2.5e15 cm^{-2} fluence

- Carbon enriched LGADs fulfil HGTD sensor requirements after irradiation
- Carbon-enrichment LGAD allows the sensors to be operated at low voltages
  - Single event break down (SEB) may happen if Operation Voltage >550V

Time resolution of LGADs Vs Bias Voltage (laboratory results)

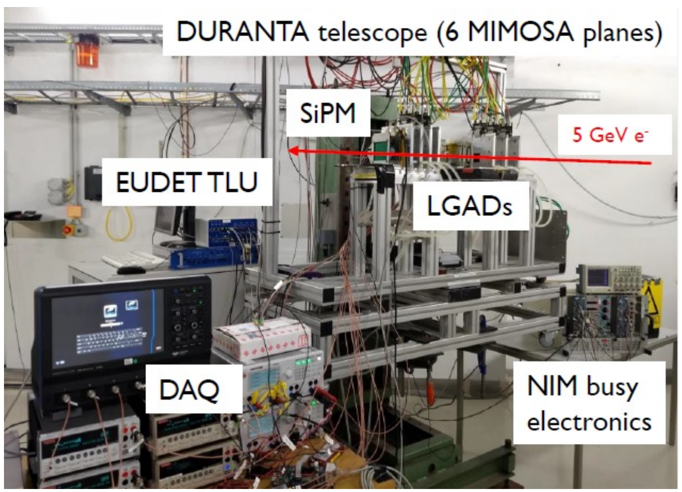


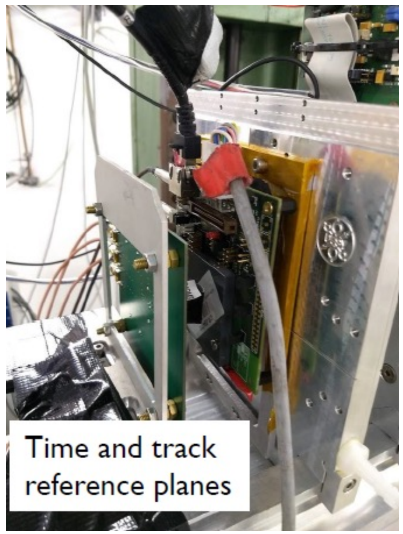
Charge collection Vs bias voltage laboratory results

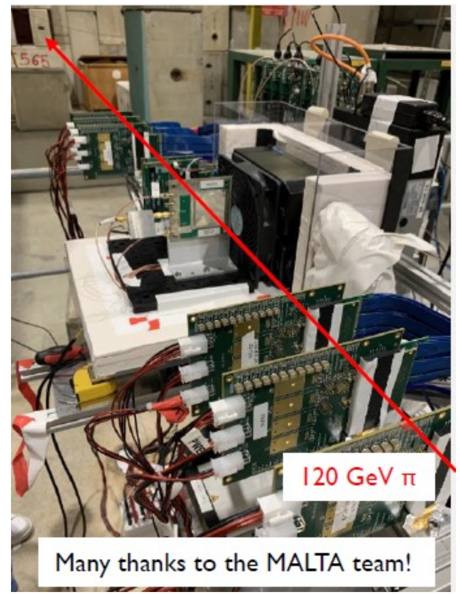


LGAD sensor Performance at test beam

- Test beam @DESY and @SPS in 2021 (setup)
  - CERN North Area SPS H6A beamline (120 GeV pion beam)
  - DESY T22 beamline (5 GeV e-beam)
  - Tracking Use of beam telescopes for tracking (EUDET-type 10 µm/MALTA 5µm)
  - Time reference：LGAD (CNM 0) used as a time reference in some tests (CERN SPS) as well as a SiPM device (DESY)

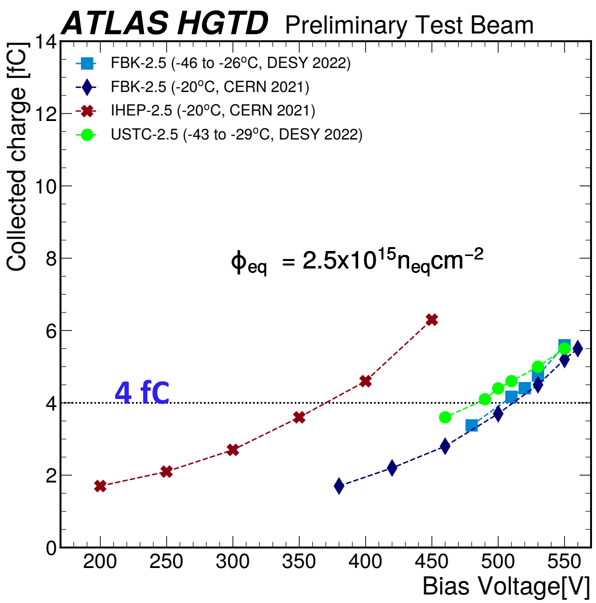


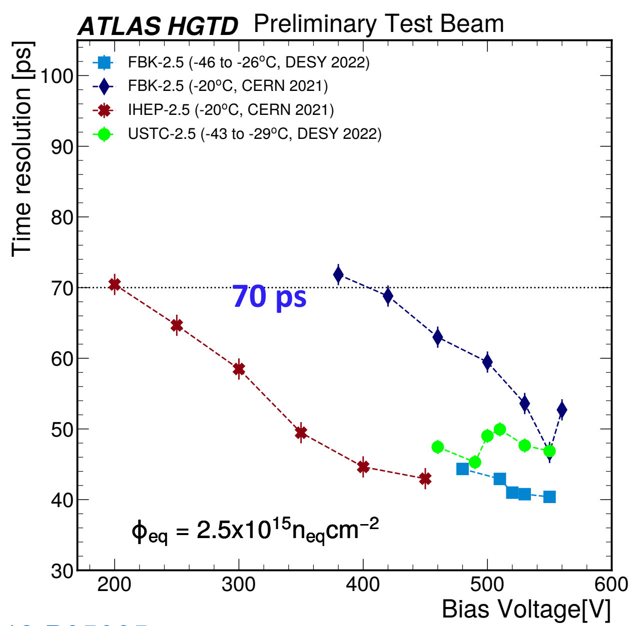


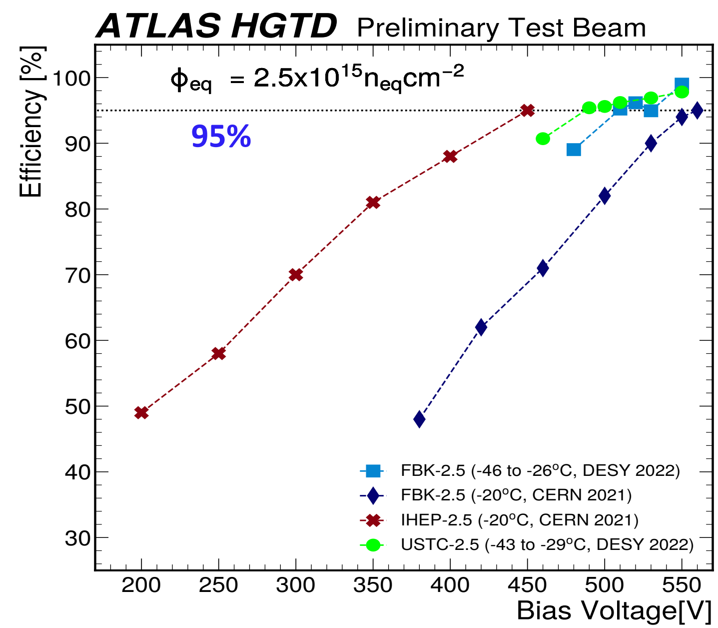


LGAD performance in the test beam

- After fluences of 2.5×10^{15} n_{eq}/cm^2, the LGADs were operated at voltages below 550 V
- Under these conditions, LGADs with shallow carbon achieved the objectives of:
  - Collected charge of more than 4 fC
  - while guaranteeing an optimum time resolution below 70 ps
  - An efficiency larger than 95% uniformly over sensors' surface is obtained
  - These results confirm the feasibility of an LGAD-based timing detector for HL-LHC







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