Time of flight detector based on Low Gain Avalanche Diodes technology

Zhijun Liang

(Institute of High Energy physics, CAS, China)

ATLAS EXPERIMENT

Outline

I. Low Gain Avalanche Diodes technology (LGAD) for LHC upgrade

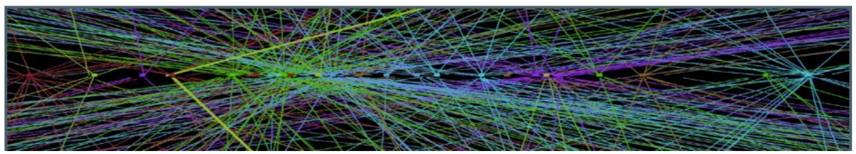
II. LGAD development for CEPC time of flight detector

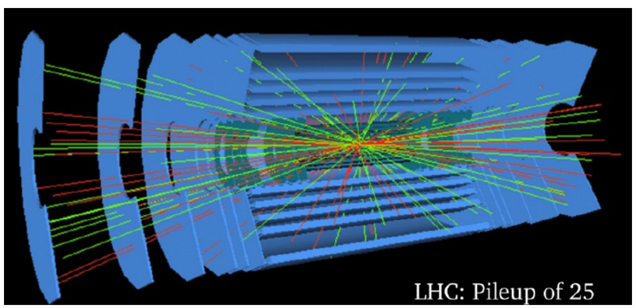
ATLAS EXPERIMENT

Challenges of HL-LHC

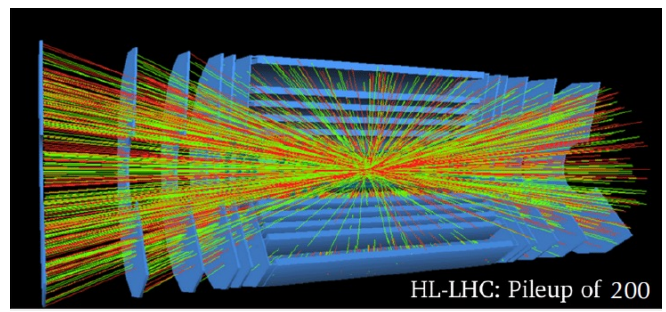
- In ~2029, LHC will run in **"high luminosity"** **, called HL-LHC**
  - The **instantaneous luminosity** will be a factor of ~5 – 7.5 higher than the LHC nominal values
  - 4000 fb^{-1}, collect ~**x10 more data than Run3** in the long term
  - *Pileup* of ~200 vertices per interaction
  - **Track reconstruction:** complexity increases **exponentially or worse with pileup**

On average 1.6-2.35 vertices per mm



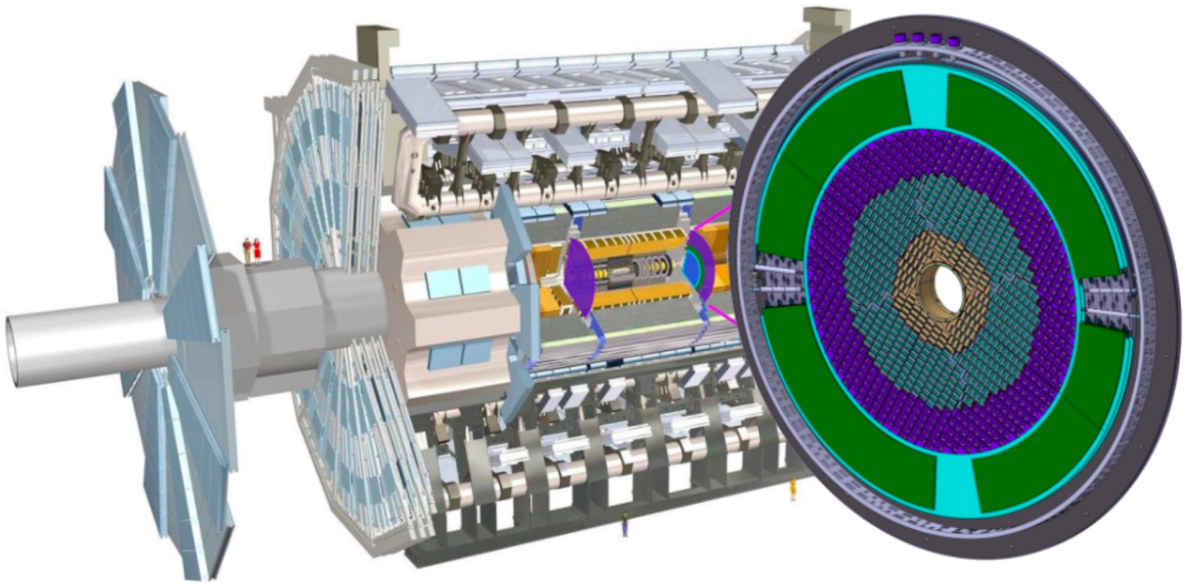


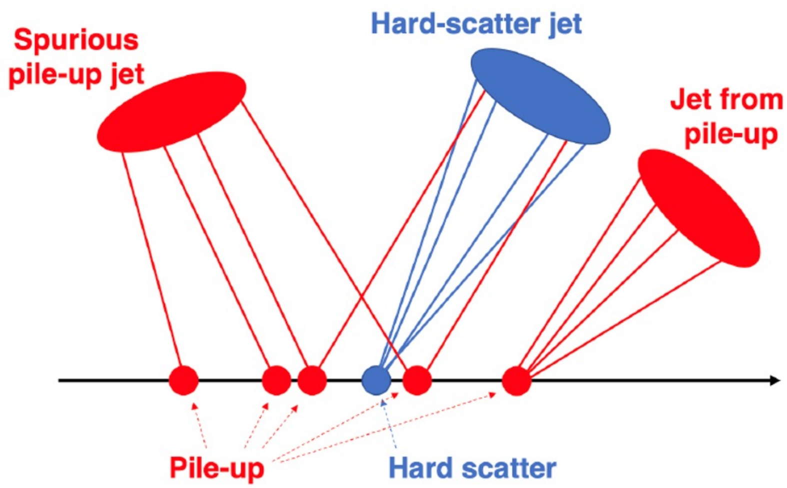
Pileup increases



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**



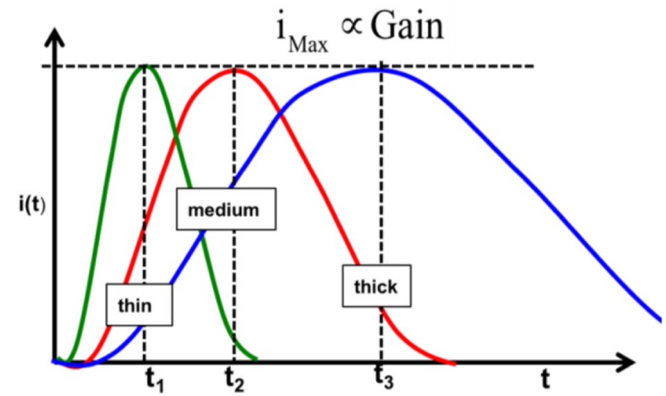


Low Gain Avalanche Detectors (LGAD)

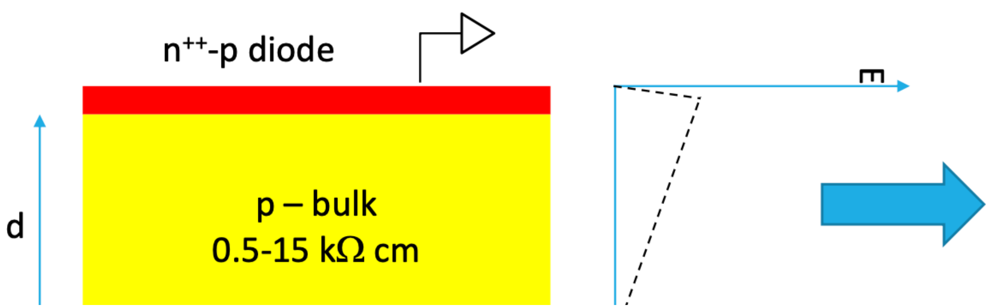
- Compared to APD and SiPM, LGAD has modest gain (10-50)
- High drift velocity, thin active layer (fast timing)
- High S/N, no self-triggering

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

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

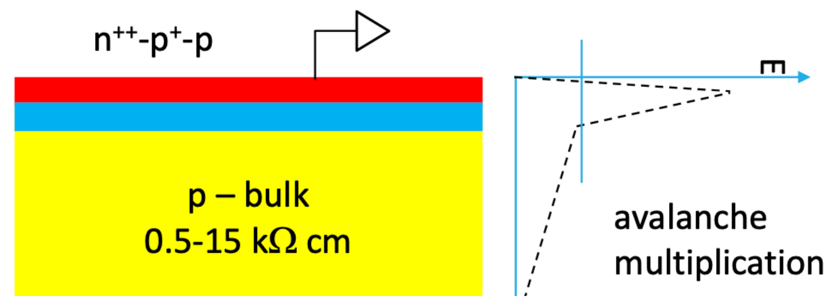


Conventional PiN diode



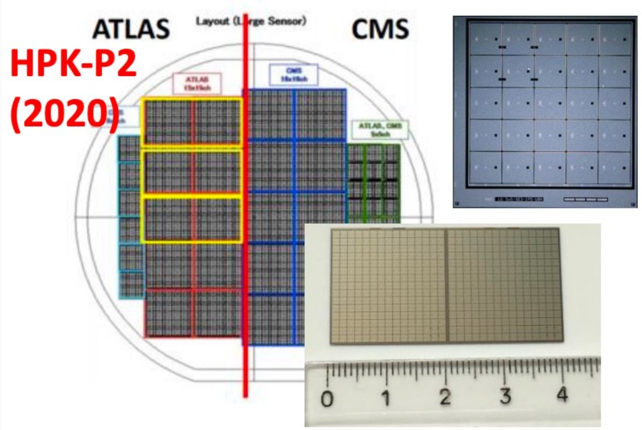
LGAD

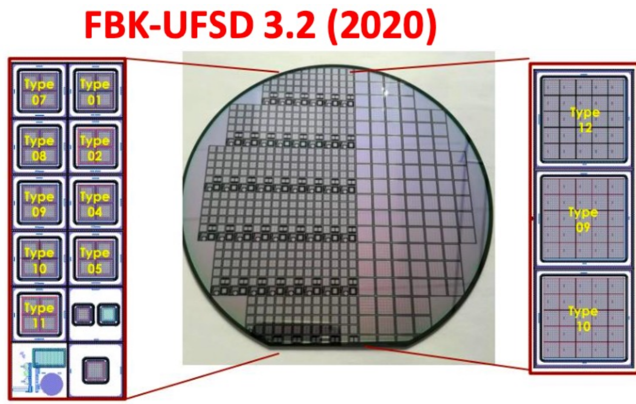
P+ gain layer on top of PIN diode

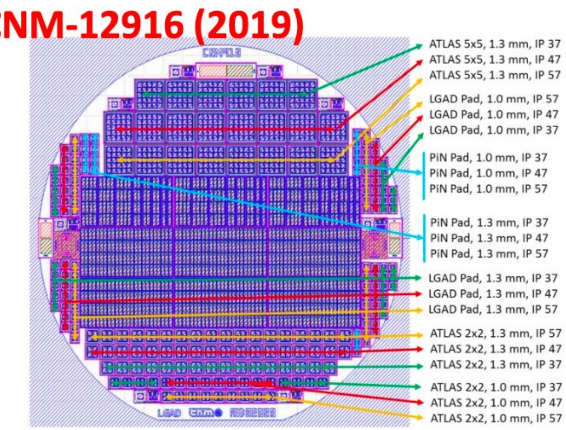


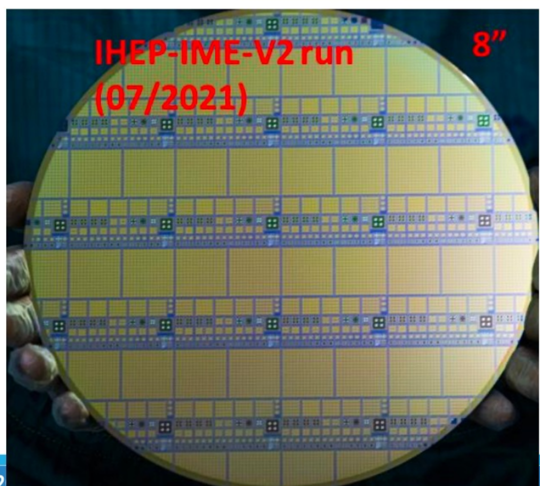
Latest prototypes produced by different vendors

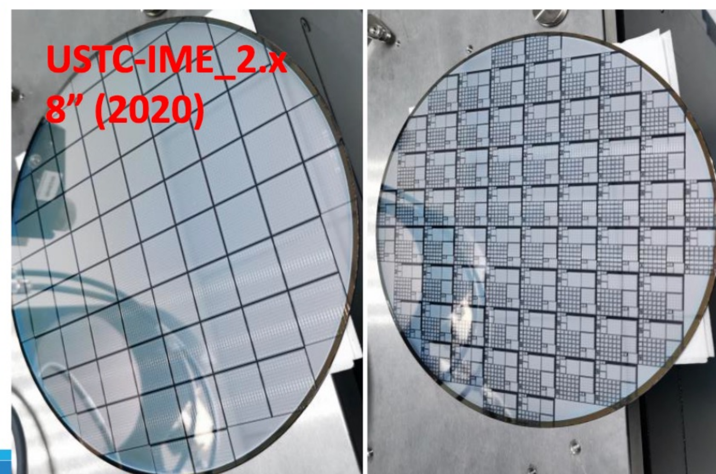
- Lots of prototypes R&D in LGAD in last few years, active vendors includes:
  - IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) …

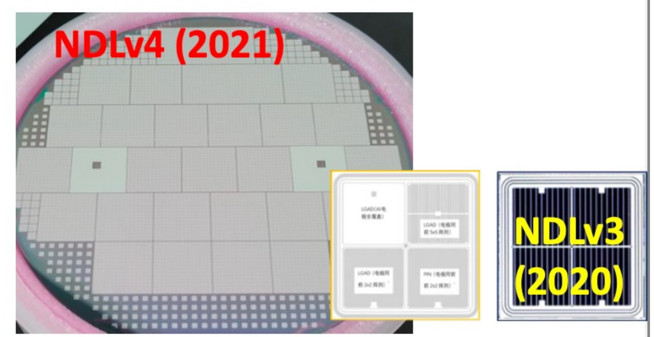










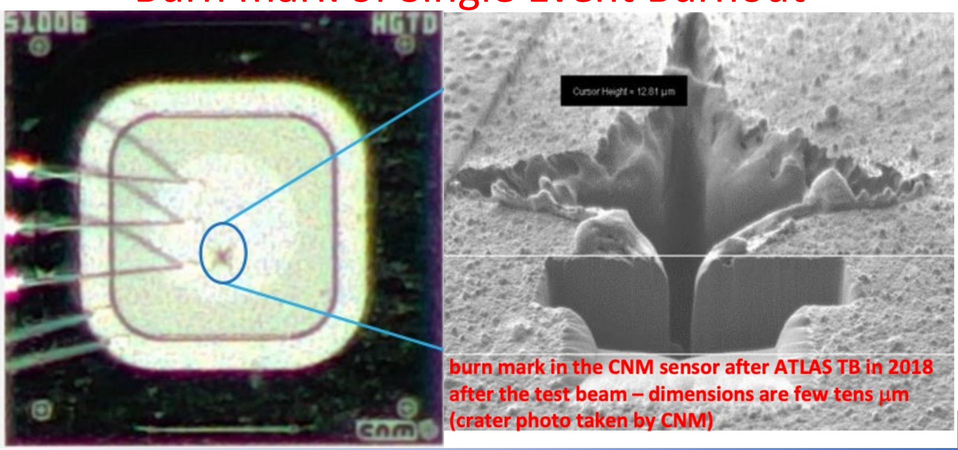


PLANAR TECHNOLOGY – more vendors (e2V, BNL, Micron …)

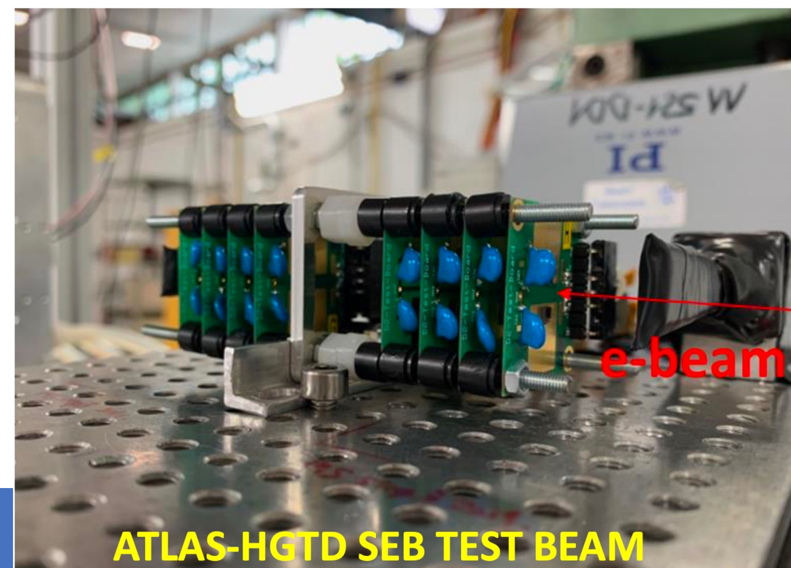
LGAD Single Event Burnout effect (HV stability in the beam)

- RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam
- The key to avoid burnout effect is to operate at low HV
  - Safe region: < 11 V/µm
  - Operate voltage needed to be <550 V (assuming 50 µm thick EPI layer)
- HGTD performed test beam at CERN and DESY
  - 120 GeV at CERN proton beam and 5GeV electron beam at DESY
  - Good performance for Carbon-enriched LGAD
  - Survived at Operation voltage

Burn mark of Single Event Burnout



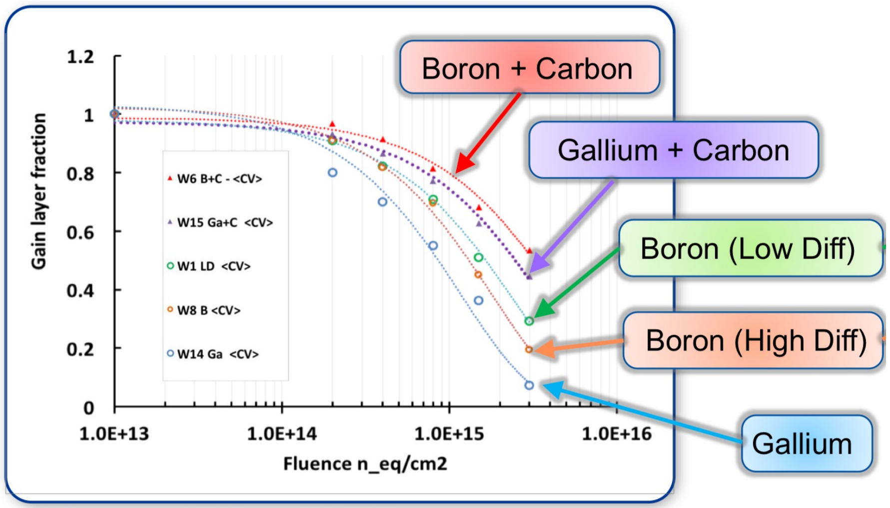
DESY test beam



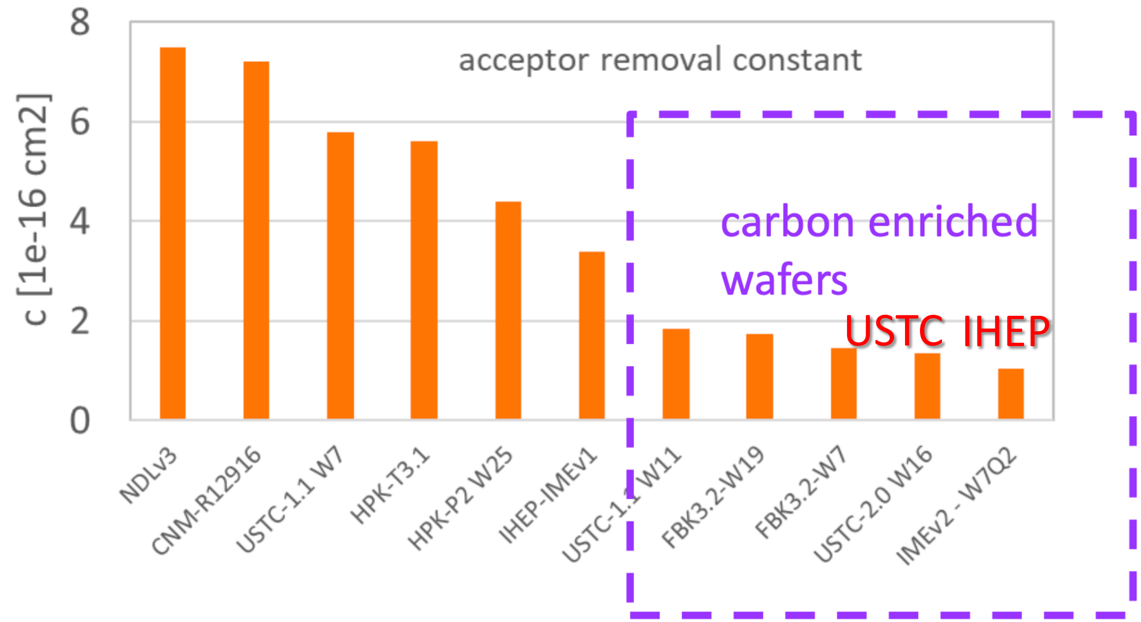
LGAD sensor after Irradiation

- After irradiation, Boron doping in gain layer became less active (Acceptor removal)
- IHEP-IME/FBK/USTC-IME LGAD with carbon
  - Significantly lower acceptor removal ratio
  - Significantly more radiation hard

IHEP and USTC LGAD has the lowest removal rate (most radiation hard)



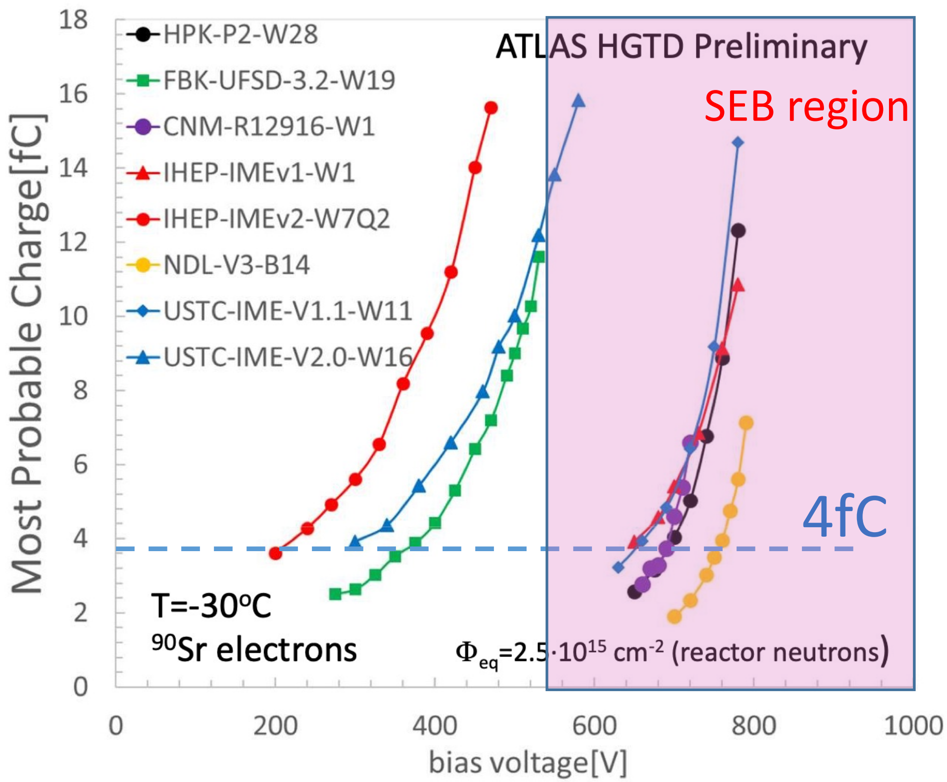
[G.Paternoster, FBK, Trento, Feb.2019]



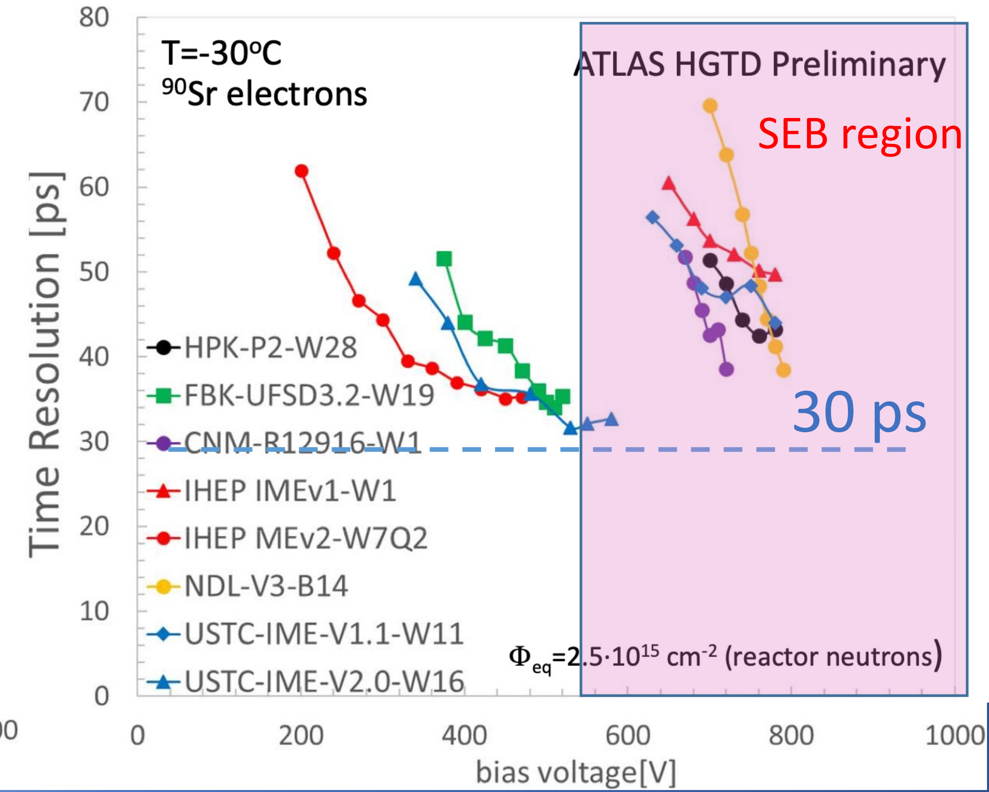
Performance of various LGAD prototypes at 2.5e15 cm^{-2} fluence

- Carbon enriched LGADs fulfil HGTD sensor requirements after irradiation
  - Reach 35ps after 2.5e15 cm^{-2} fluence
- Carbon-enrichment LGAD allows the sensors to be operated at low voltages
  - Single event break down (SEB) may happen if Operation Voltage >550V

Charge collection Vs bias voltage

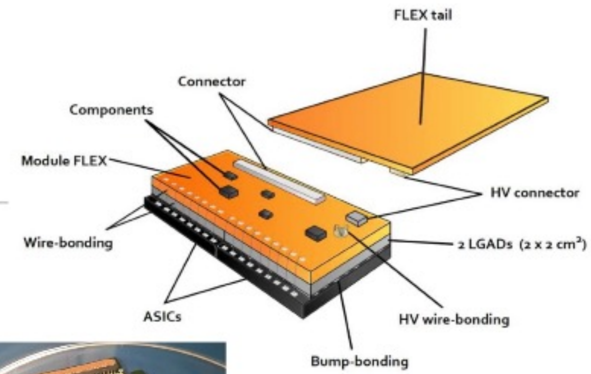


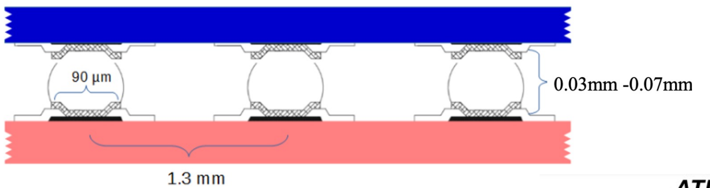
Time resolution of LGADs Vs Bias Voltage



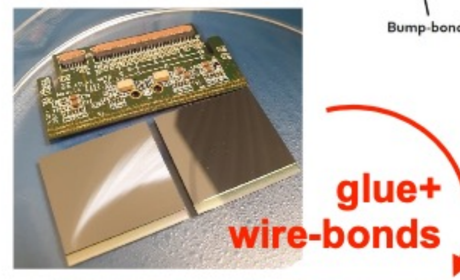
HGTD Module assembly

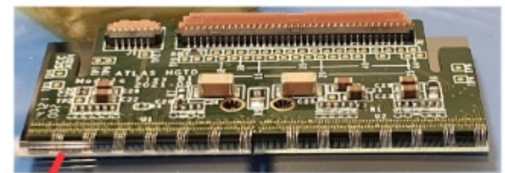
- 225 front-end channels (15 × 15) in each module
  - Fast ASIC and LGAD connected by bump bonding
  - Dead area between pixels is about 50 µm

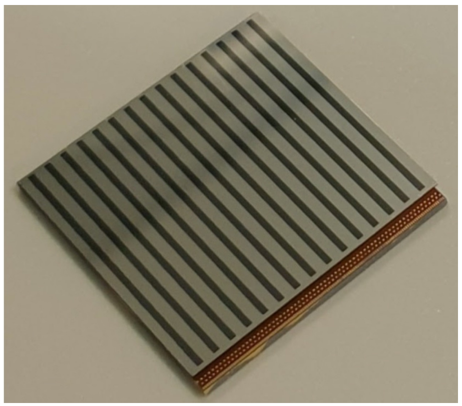


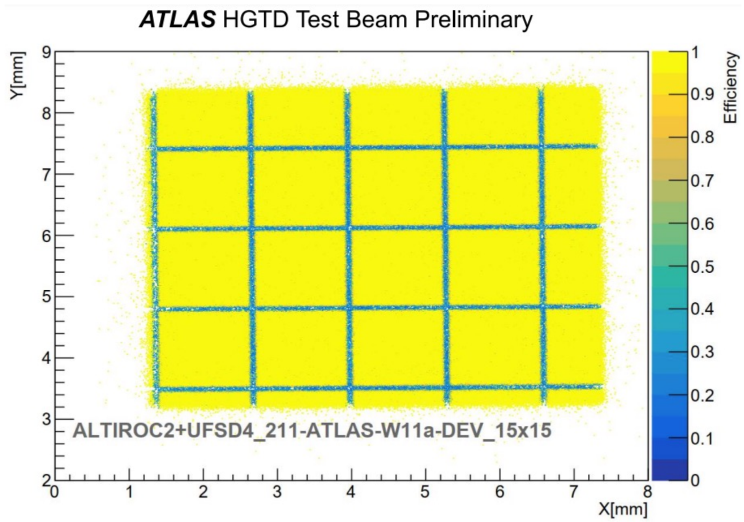


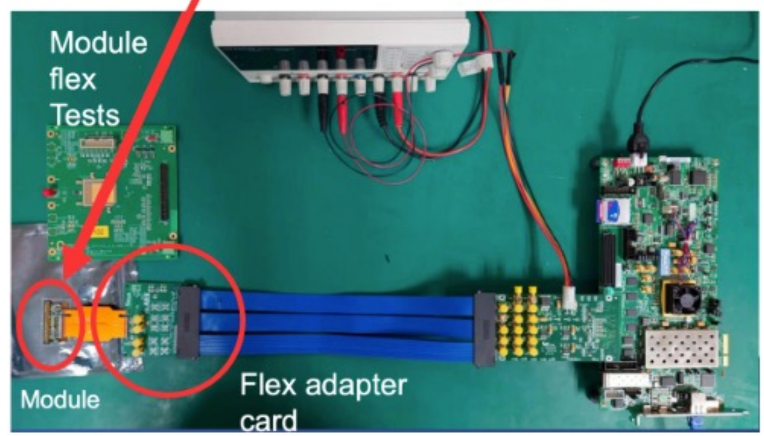
15 × 15 pixels efficiency map
In module beam test





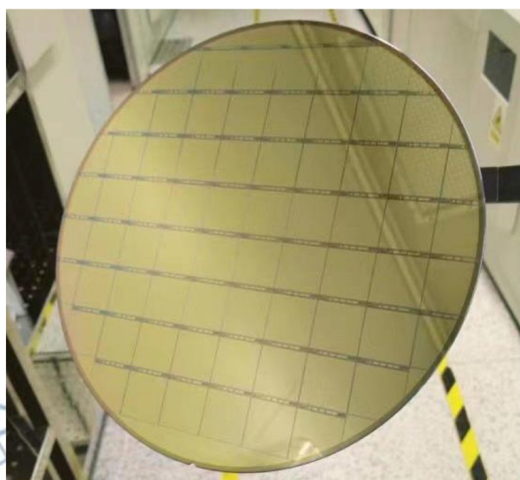


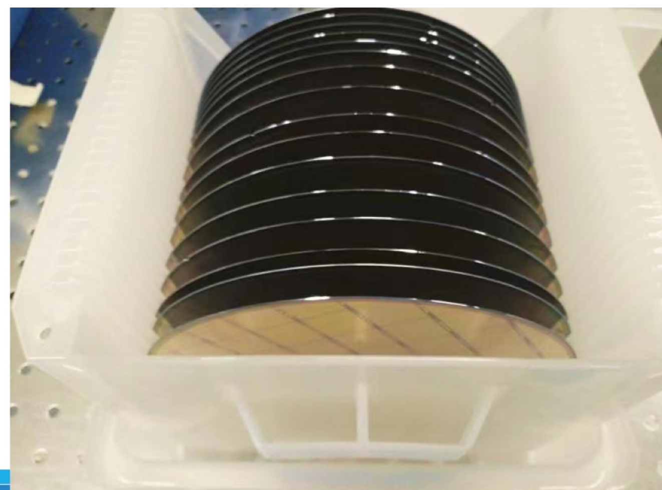




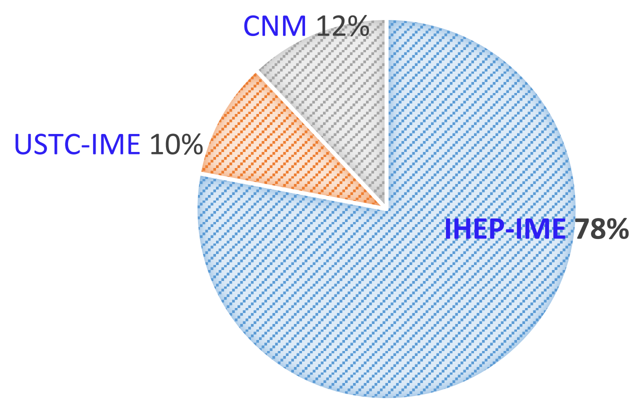
Production of LGAD sensors

- HGTD project of ATLAS needs > 20,000 LGAD sensors (6.4 m^2)
- 2023 LGAD developed by IHEP got all the share of the order from CERN tendering
  - > 10,000 LGAD (54%, **will be produced by IME according to IHEP design)**
  - Compete with HPK, FBK et al. and win the CERN tendering
- The current share of the contribution of the LGAD sensors in ATLAS HGTD
  - **IHEP-IME: 78%** (54% from CERN tendering+24% in-kind contribution)
  - **CNM: 12%** in-kind contribution
  - **USTC-IME: 10%** in-kind contribution
  - **Two Chinese vendor (IHEP/USTC) has more than 88% share**





Share of production between vendors



Outline

I. Low Gain Avalanche Diodes technology (LGAD) for LHC upgrade

II. LGAD development for CEPC time of flight detector

LGAD development for CEPC time of flight detector: Motivation

- CEPC will produce 10^{12} Z boson at Z pole: Rich flavor physics program

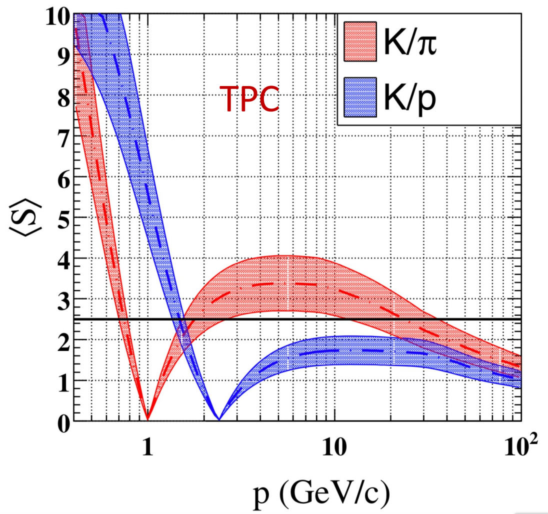
- **Particle separation problems** of Gas detector (dE/dx) for CEPC flavor physics:
  - **0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation**

- **CEPC International Advisory Committee: one of the key recommendations**

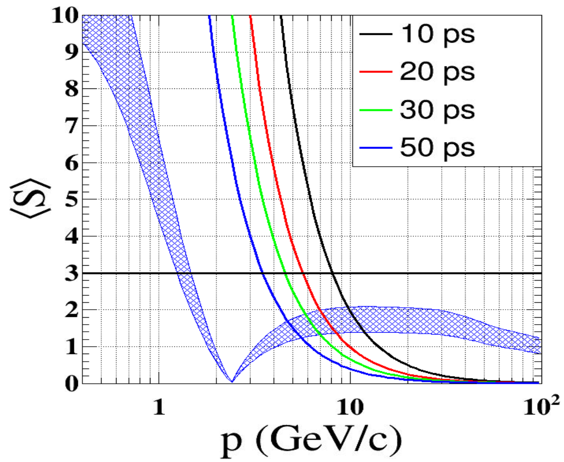
Precision timing detector should be determined as a matter of urgency (4D track)

- **Timing detector is complementary to gas detector:** improves the separation ability

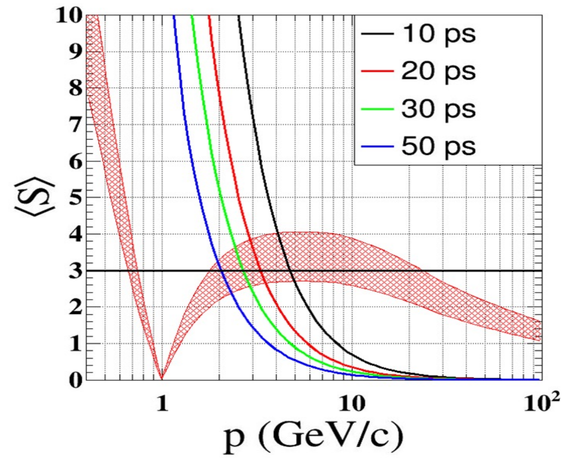
  0 - 4 GeV for K/pi separation, **0 – 8 GeV** for K/p separation



k/p Separation



k/pi Separation



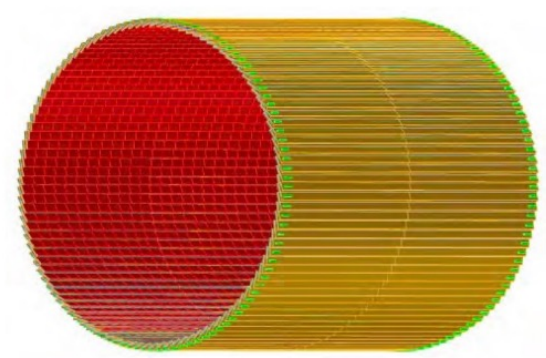
Other LGAD-based TOF detector proposal

- Electron-Ion Collider (EIC)：
  - Outer layer of Tracker and TOF detector
  - Central detector(ETTL, CTTL, FTTL)， Far-Forward detector AC-LGAD
- REDTOP: LGAD tracker
  - 4D tracking reconstruction for multihadron rejection

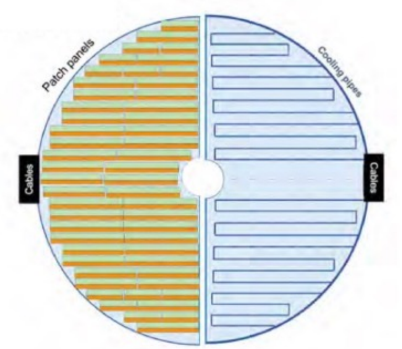
EIC： AC LGAD-based

Outer layer of Tracker and TOF detector

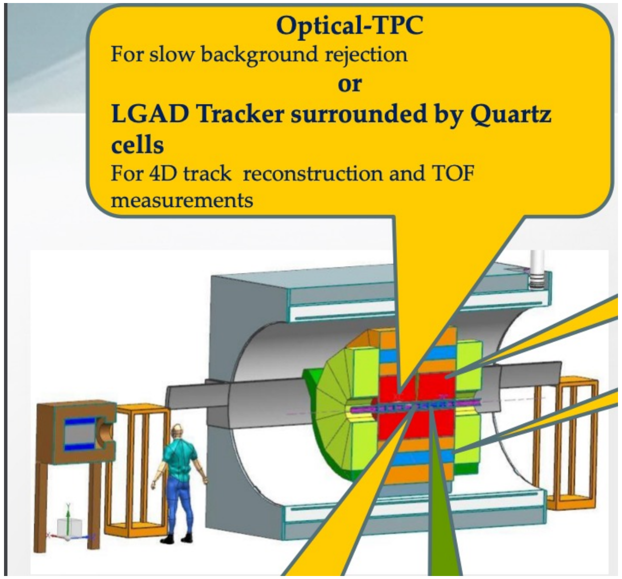
Barrel AC-LGAD detector



Hadron endcap AC-LGAD detector



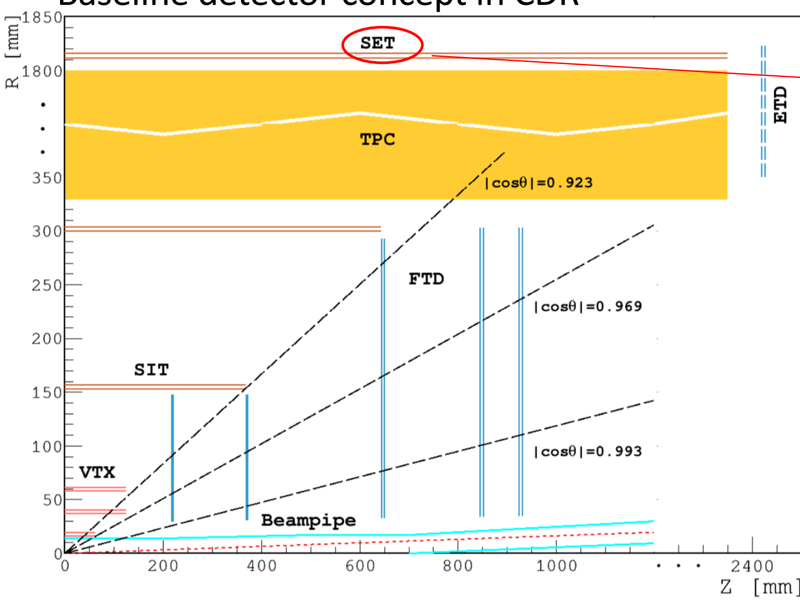
REDTOP: LGAD tracker

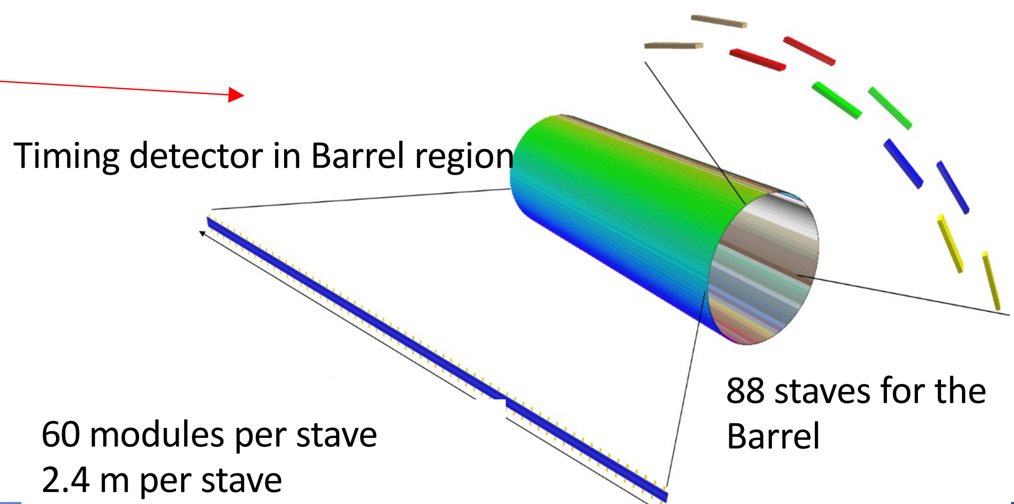


CEPC timing detector: Concept

- CEPC time of flight detector based on LGAD (EIC proposed LGAD-based TOF detector)
  - Area of detector (Barrel : 50 m^2 , Endcap 20 m^2), **~ 10^6 channels**
  - Strip-like sensor (each strip: 4cm × 0.1 cm)
  - Should be part of SET (silicon wrapper layer outside TPC or drift chamber)
    - Serve as Timing detector and part of the tracker
    - Timing resolution: 30-50 ps
    - Spatial resolution: ~ 10 μm

Baseline detector concept in CDR





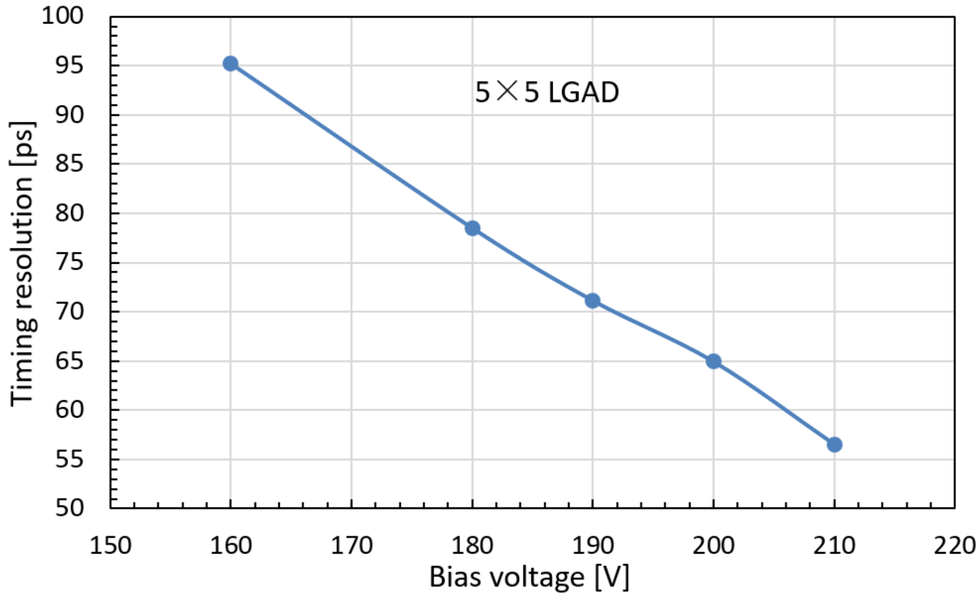
ATLAS HGTD VS CEPC TOF detector

- ATLAS HGTD technology may need to adjust a bit to be used in CEPC
  - Need to develop large-area pad/strip LGAD sensor for CEPC application
  - Reduce the dead area between channels (AC-LGAD development)

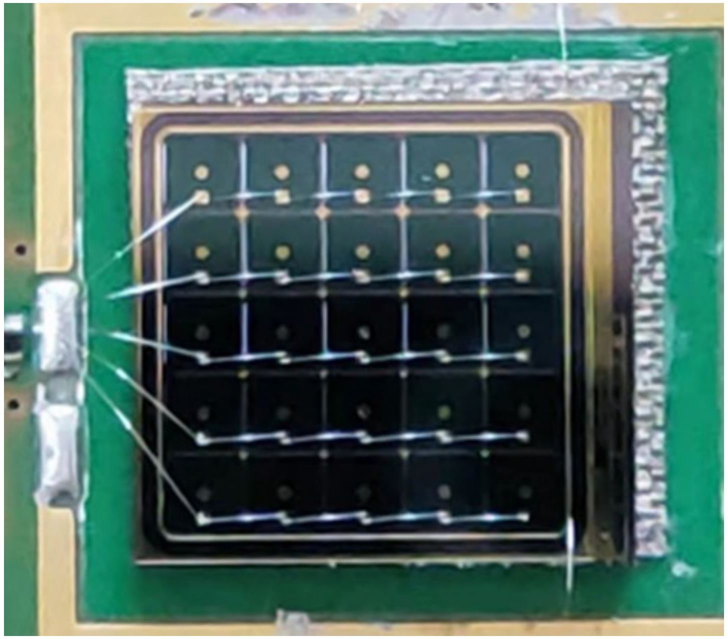
	ATLAS HGTD	CEPC TOF
Area (m^2)	6.4	~ 70
Granularity	mm^2 (1.3 mm ×1.3mm)	~ cm^2 (4cm × 0.05cm)
Channel number	**~ 3.6 × 10^6**	**~ 3.5×10^6**
Module assembly	Bump bonding	Wire bonding at strip
MIP Time resolution	30-50 ps	30-50 ps
Spatial resolution	~ 300 µm	~ 10 µm
Dead area between	~50µm	no dead area

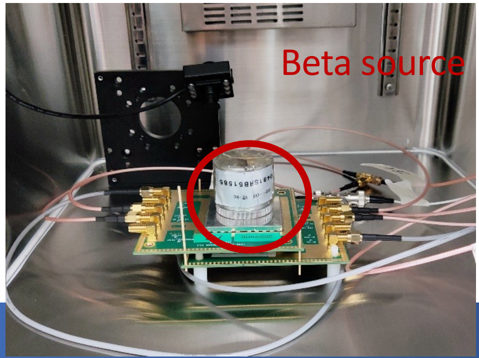
The Large-pad LGAD

- **Time resolution test of large aera LGAD: ~50 ps**
  - Area for one channel : 6.5 mm x 6.5 mm
  - 5 x 5 LGAD connected by wire bonding
    - To mimic the large aera LGAD
  - This result is before any sensor optimization for CEPC



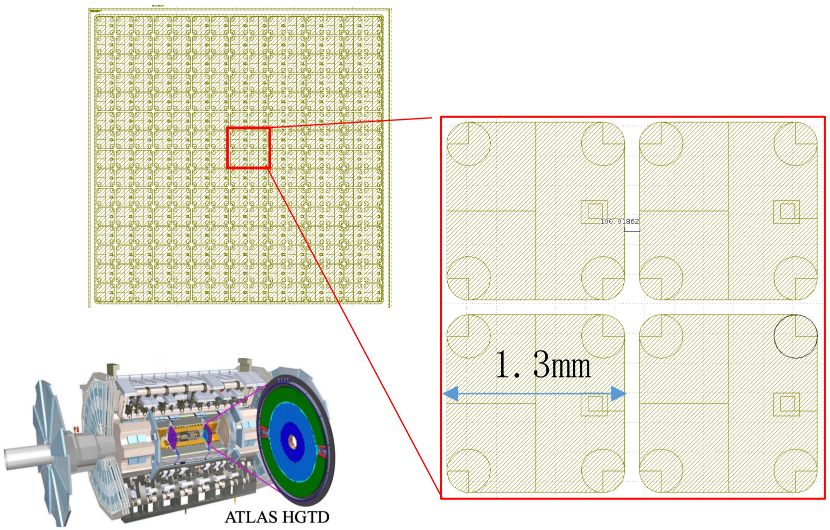
5*5 Large area LGAD sensor
Connected by wire bonding





AC-LGAD introduction

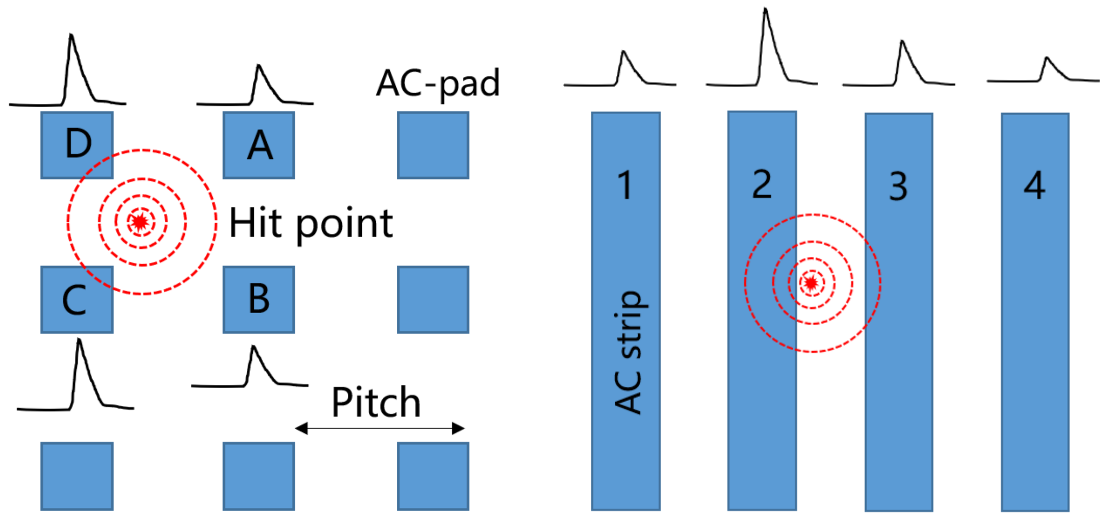
15×15 LGAD for ATLAS HGTD project



- Dead zone : ~0.1mm
- Pixel size: 1.3mm

Smaller Pixel size -> Lower fill factor

AC-LGAD: two layout schemes for AC-pads
(No dead area between channels)



Pixels AC-LGAD:
- Position information: **1 layer (x,y)**
- Bump bonding

Strips AC-LGAD:
- Position information: **2 layers for (x,y)**
- Lower readout electronics density, no bump bonding

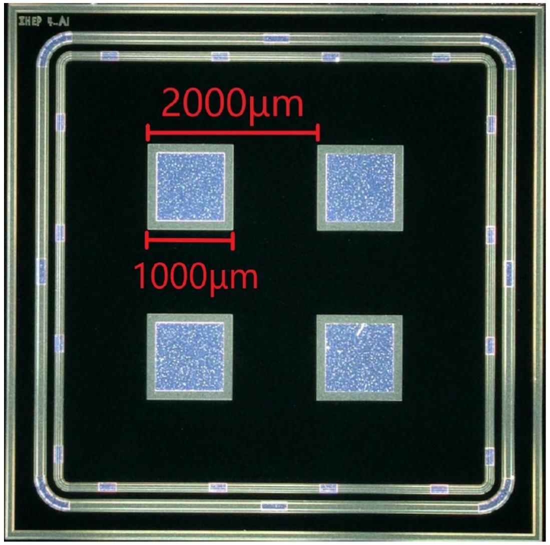
IHEP AC-LGAD R & D

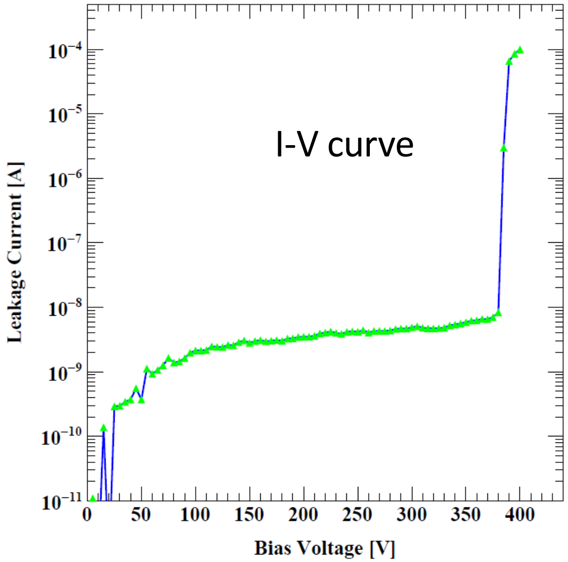
Pixels AC-LGAD：

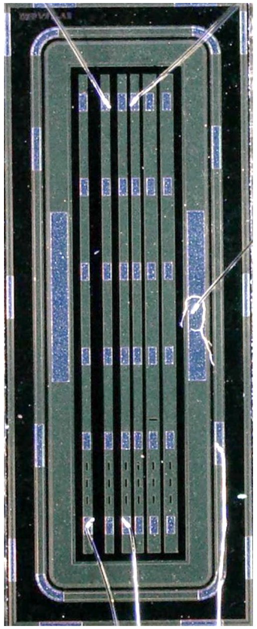
- Position information： 1 layer
- Pitch size 2000um, pad size 1000um
- Different N+ dose ：
    - **10P， 5P， 1P， 0.5P， 0.2P**

Strips AC-LGAD：

- Position information： 2 layer
- Strip length 5.6mm, width 100um
- Different Pitch size：
    - **150um、200um、250um**







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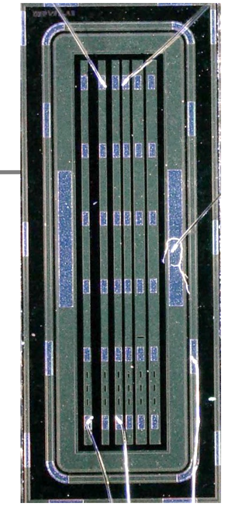
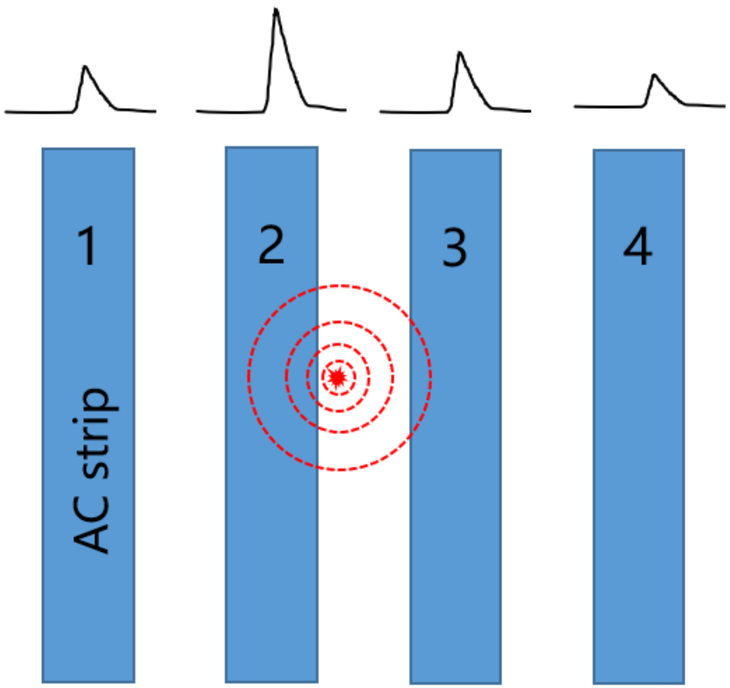
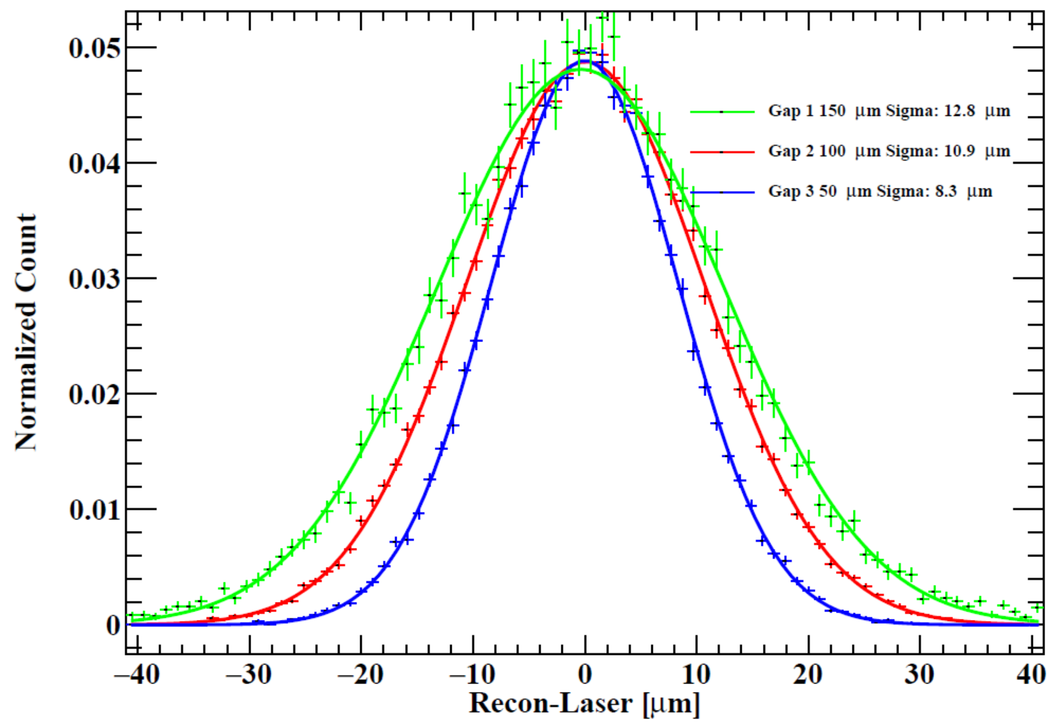
Spatial resolution of AC-LGAD



- Laser test result of strip AC-LGAD sensor
  - It can reach about ~10µm resolution with 150um pitch strip detector
  - While timing resolution of AC-LGAD is still can reach 30-50ps

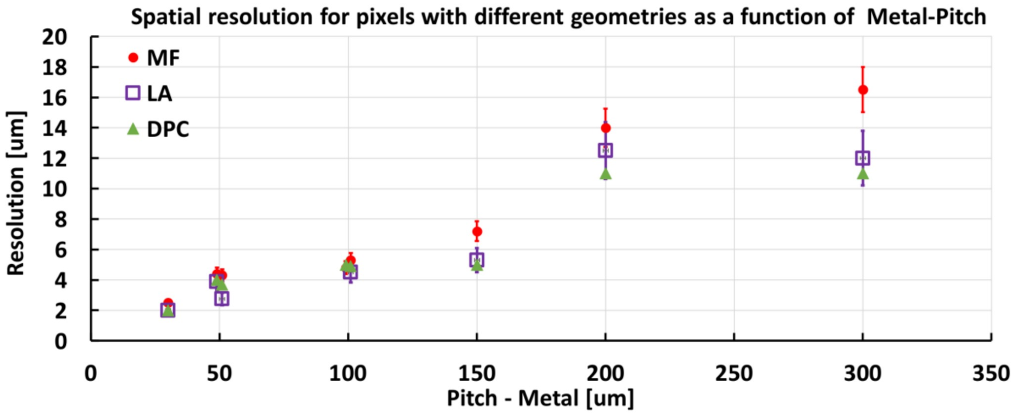




Spatial resolution of AC-LGAD

- Aim for ~10 μm spatial resolution (1D) with 4cm × 0.05cm strip size (500 μm pitch)
  - It is possible to achieve that with AC-LGAD strip detector
  - While keeping 30-50 ps timing resolution

Spatial resolution Vs. pitch size



[1]M. Mandurrino et al., "Demonstration of 200-, 100-, and 50-μm pitch Resistive AC-Coupled Silicon Detectors (RSD) with 100% fill-factor for 4D particle tracking", IEEE Electron Device Lett. 40(11), 1780-1783 (2019), DOI: 10.1109/LED.2019.2943242

[2] A. Apresyan, et al., Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam, Journal of Instrumentation, 15 (2020) P09038, 2020.

Spatial resolution Vs. pitch size
(by IHEP, FBK and BNL)

Sensors	Pitch size [μm]	Spatial resolution [μm]	Time resolution [ps]
IHEP AC-LGAD	2000	15	22 （laser）
FBK AC-LGAD	500	11	32 （laser）
BNL AC-LGAD	100	-	45 （beta source）

Summary

- LGAD developed by IHEP and USTC was chosen to be used in ATLAS upgrade
  - First Chinese silicon sensor used at LHC

- AC-LGAD developed for CEPC
  - TOF and outer layer of tracker
  - cm^2 level granularity
  - No dead area
  - Spatial resolution can reach 10 um level

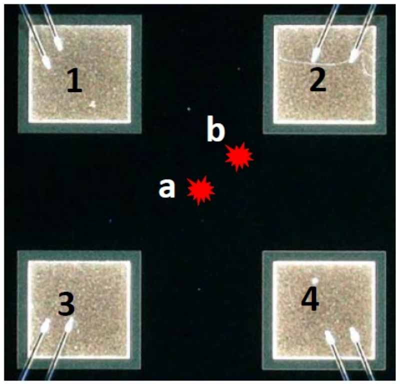
Summary

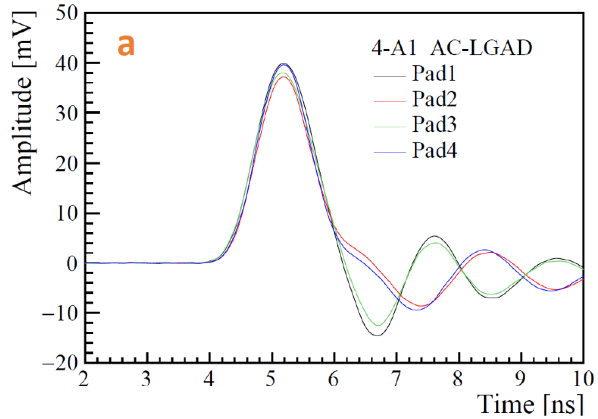
- Although irradiated at fluences of 2.5×10^{15} n_{eq}/cm^2 , the LGADs were operated at voltages below 550 V (safe region of the Single Event Burnout)
- Under these conditions, IHEP-IME LGADs achieved the objectives of:
  - Collected charge of more than 4 fC while guaranteeing an optimum time resolution below 70 ps
  - An efficiency larger than 95% uniformly over sensors' surface is obtained with a charge threshold of 2 fC
- IHEP-IME will contribute 78% LGAD sensors(54% from CERN tendering+24% in-kind sensors) in the HGTD project
- For the CEPC ToF study, two concept designs were mentioned

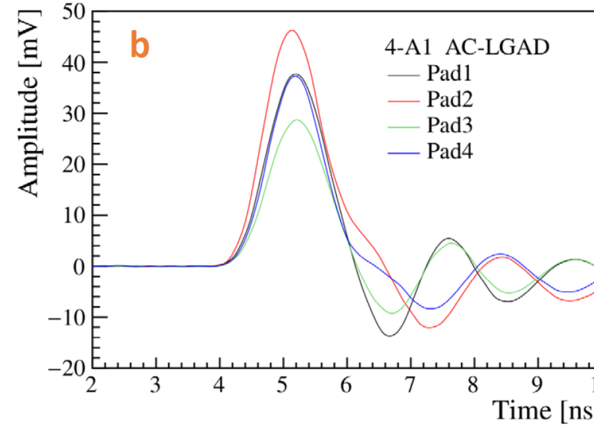
  A. **Pure ToF with only time information：**
    - ✓ **Aim 20 ps**
    - ✓ The time resolution of large area LGAD is **about 56 -100 ps** in Beta test. Need optimization in the future

  B. **ToF with track information：**
    - ✓ **Aim 20 ps， 10 µm**
    - ✓ the time resolution and spatial resolution of AC-LGAD could be **22~25ps and 15 µm** according to the laser test

Laser test result of AC-LGAD

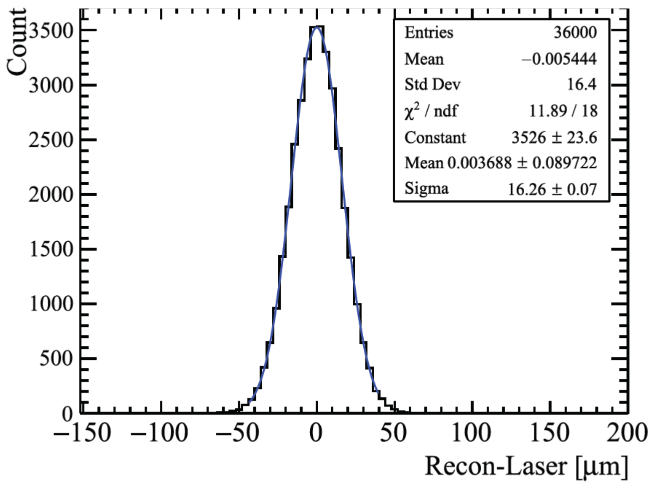


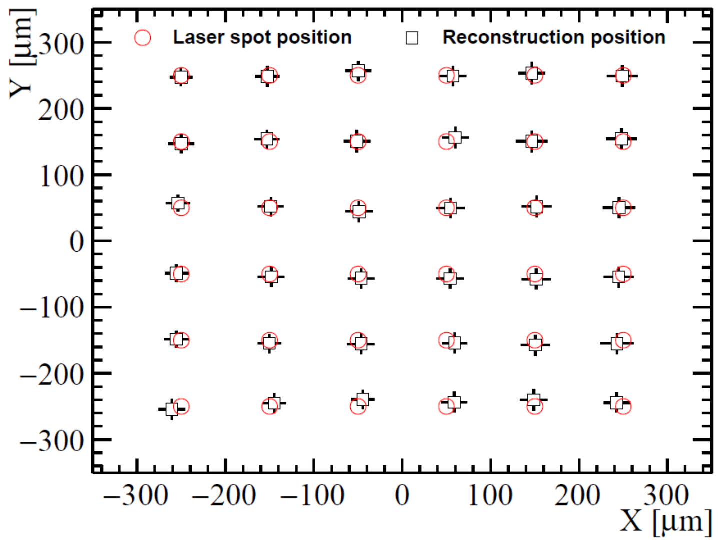




Spatial Resolution

$$\sigma_{spatial} = \sigma_{reconstruction-laser}$$

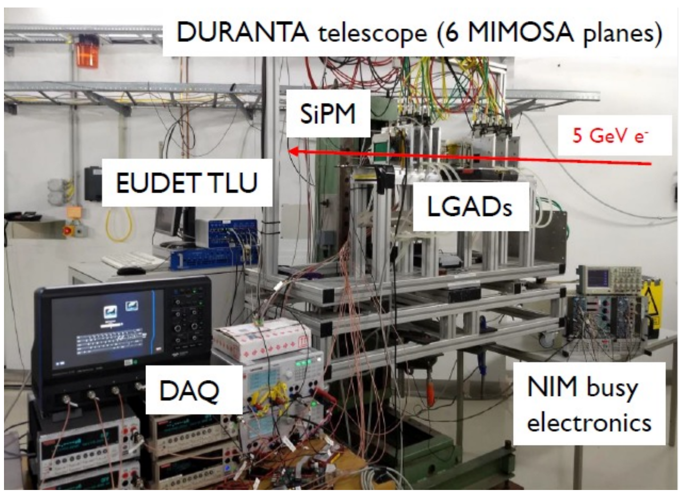


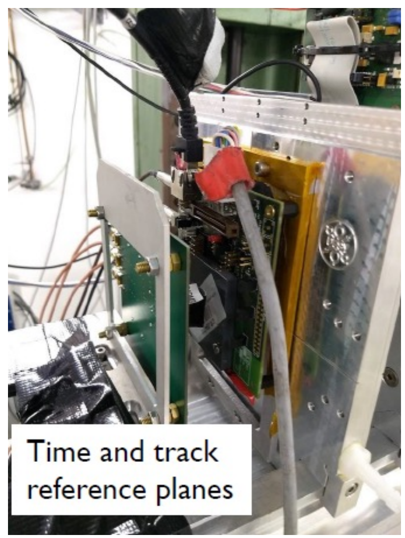


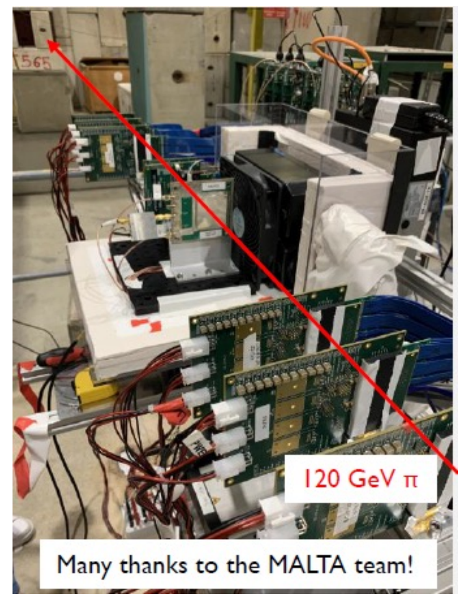
mzli@ihep.ac.cn

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)

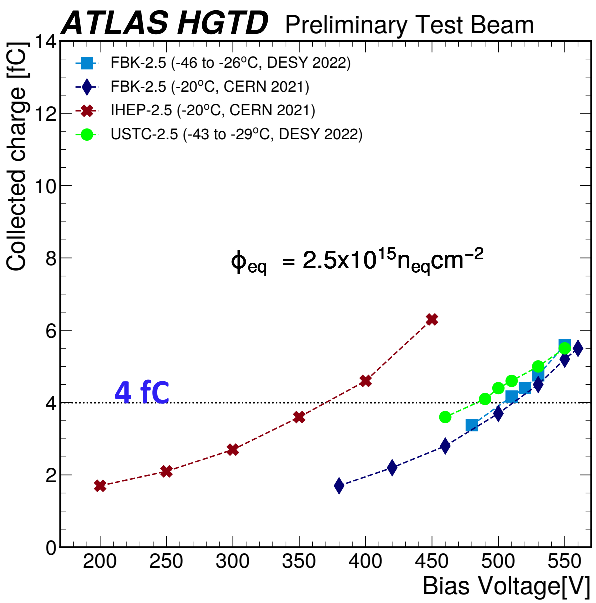


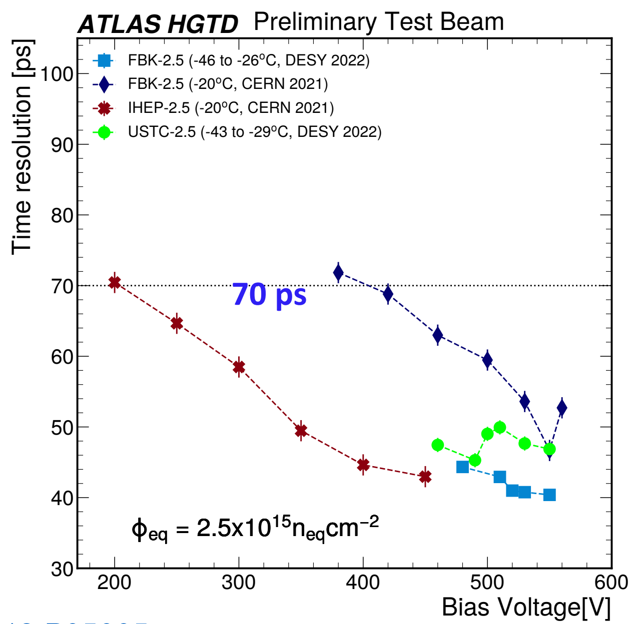


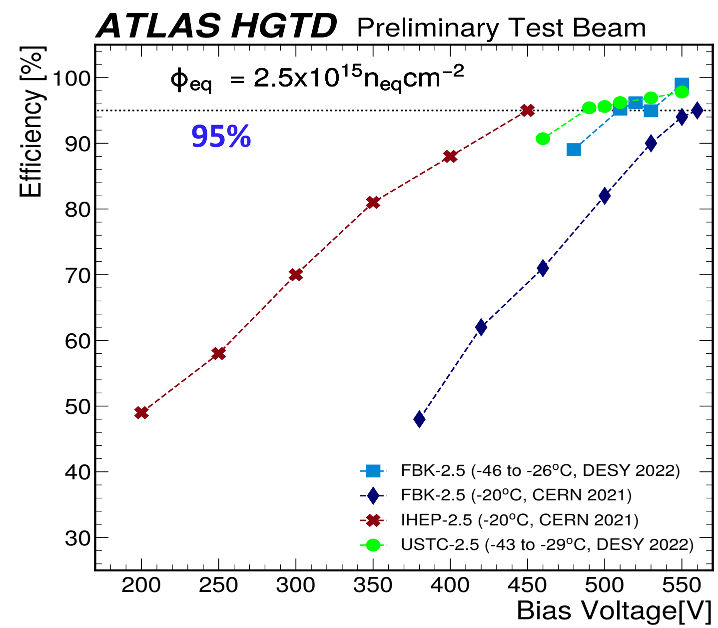


LGAD performance in the test beam

- 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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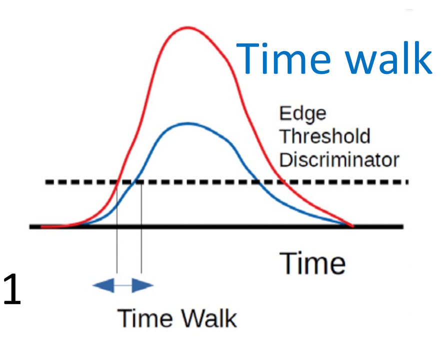
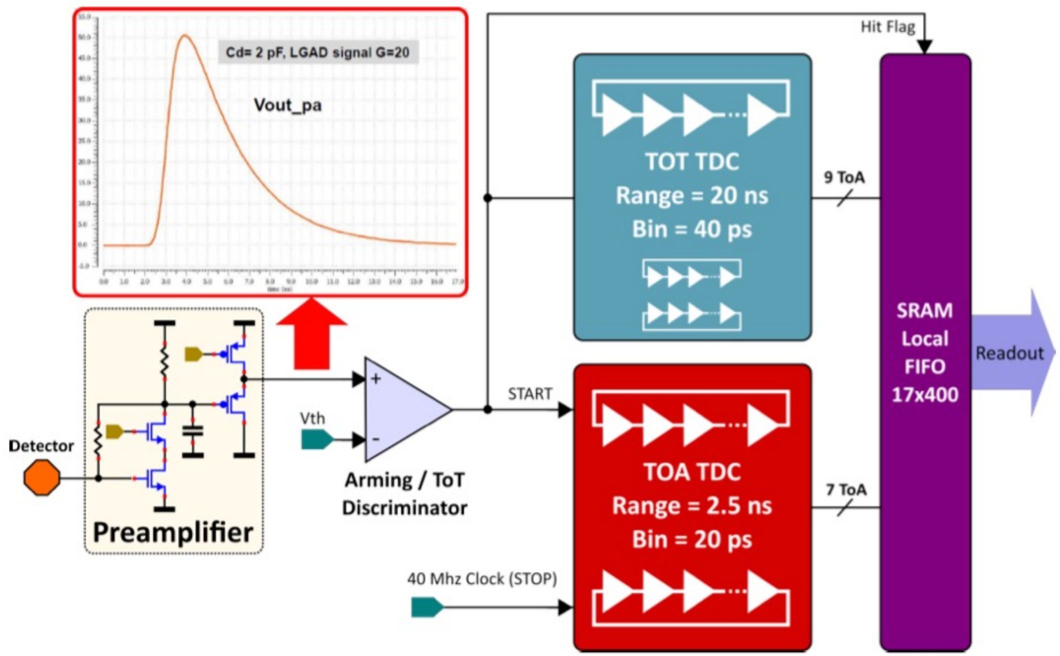
ALTIROC : Fast Timing ASIC

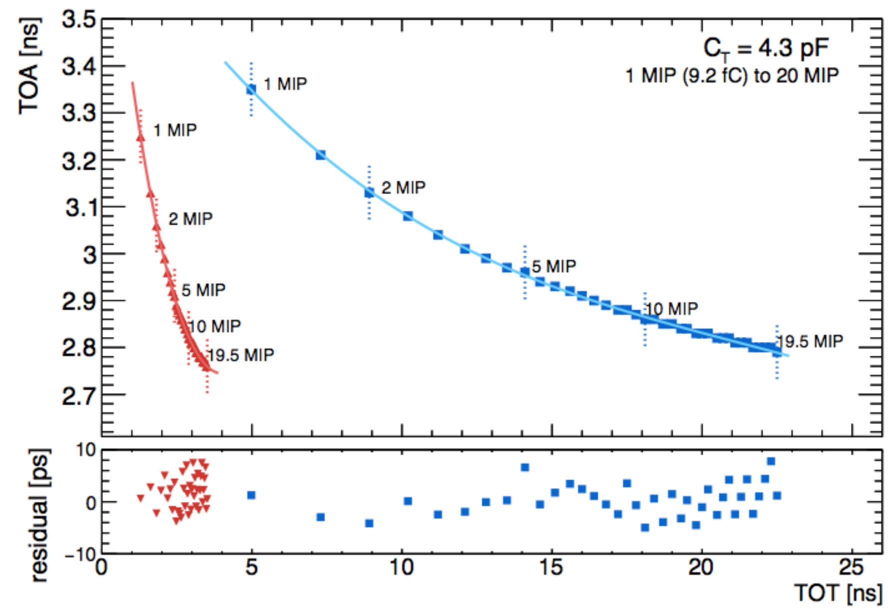
- 225 front-end channels in ALTIROC, each channel has
  - A preamplifier followed by a discriminator:
  - Two TDC (Time to Digital Converter) to provide digital **Hit data**
    - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
    - Time Over Threshold (TOT) : range of 20 ns and a bin of 40 ps (9 bits)
  - One Local memory: to store the 17 bits of the time measurement until L0/L1



ALTIROC timing ASIC in nutshell

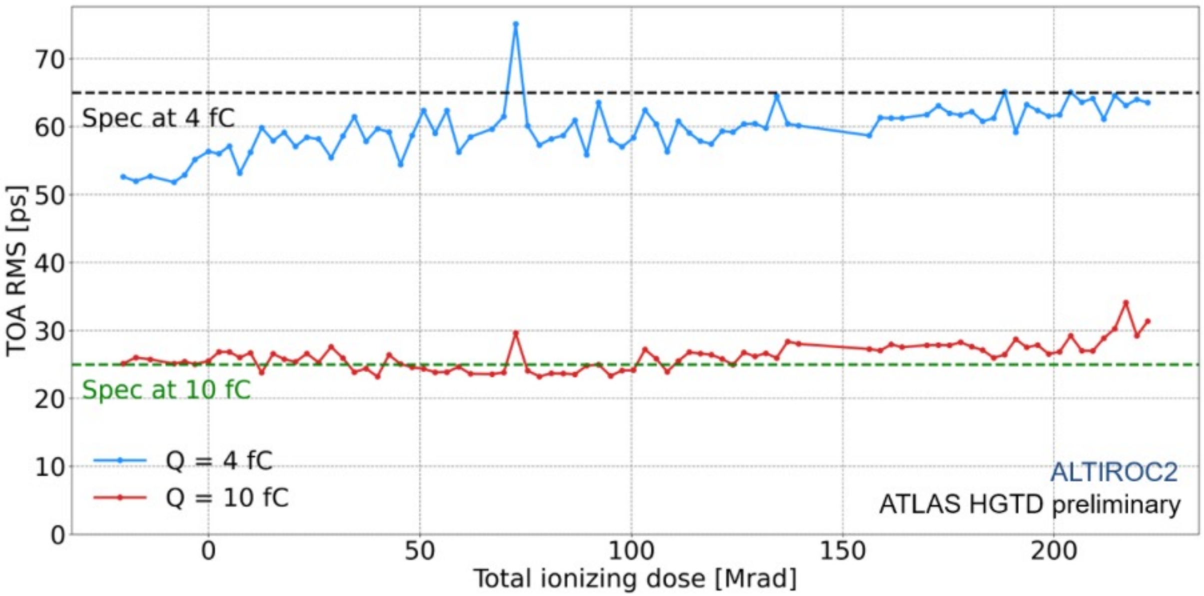


Time walk correction with TOT

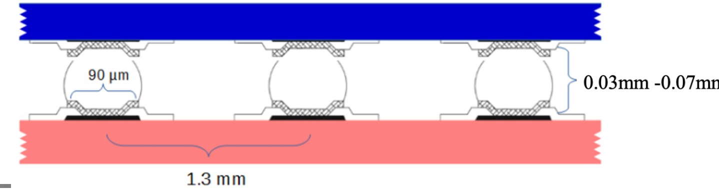


ALTIROC testing

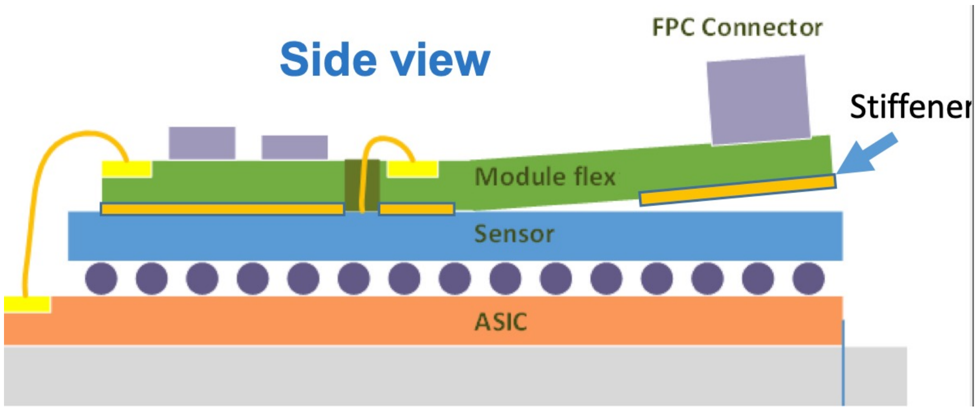
- Very demanding requirement of <70 ps time resolution @ 4 fC
  - LGAD collected charge >10 fC (>4 fC) before (after) irradiation
- Charge injection self-calibration test in ALTIROC
  - ~25 ps jitter @ 10fC
  - Better than 70 ps jitter@ 4 fC
  - Showing stability under radiation up to 220 Mrad total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

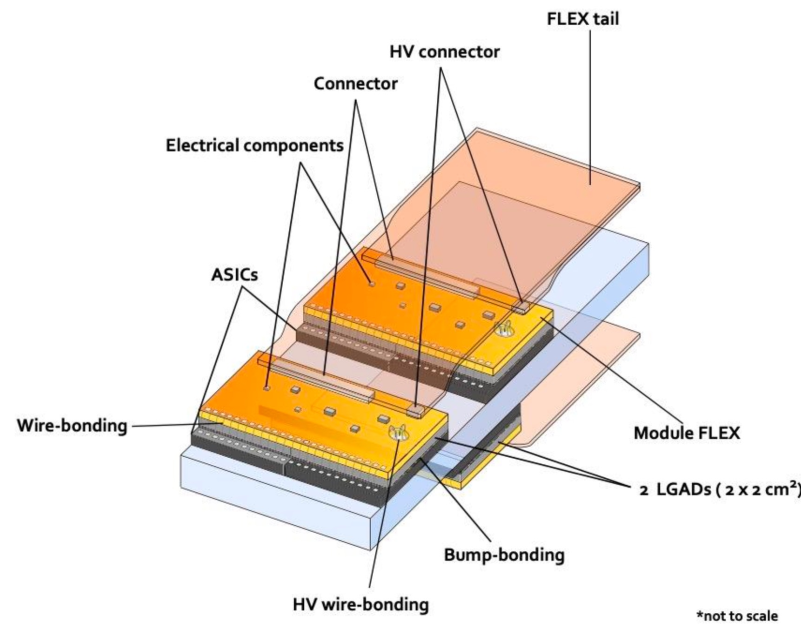


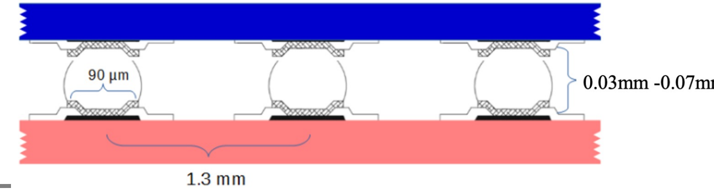
ALTIROC2 full-size hybrid



- HGTD has 8032 total modules, 3.6 M channels, 6.4 m^2
  - **A module consists of one module flex and two hybrids.**
    - There are six 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



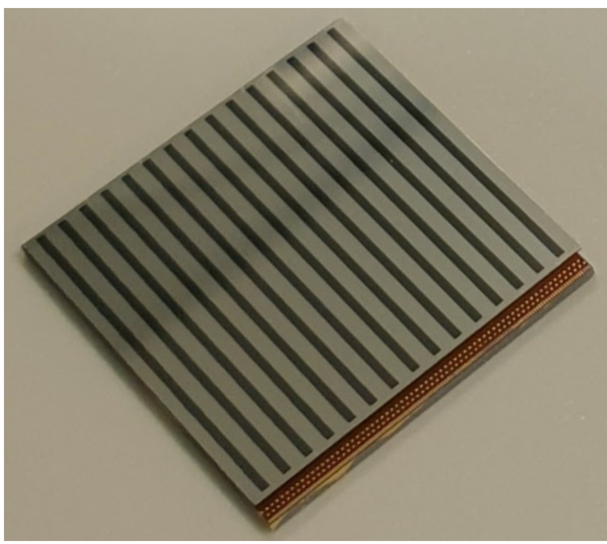




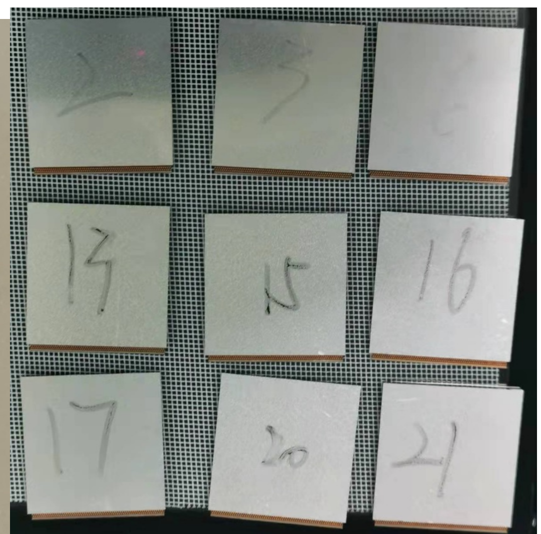
ALTIROC2 full-size hybrid

- Full Size ALTIROC2 full-size bare by different institutes and companies
  - IFAE already fabricated bare module prototype (ALTIROC2 + HPK LGAD, ALTIROC2 + FBK LGAD)
  - IHEP worked with NCAP company, made prototype with ALTIROC2 + IHEP-IME v2 LGAD
  - AEMtec (Germany) company made prototype with ALTIROC2 + FBK LGAD

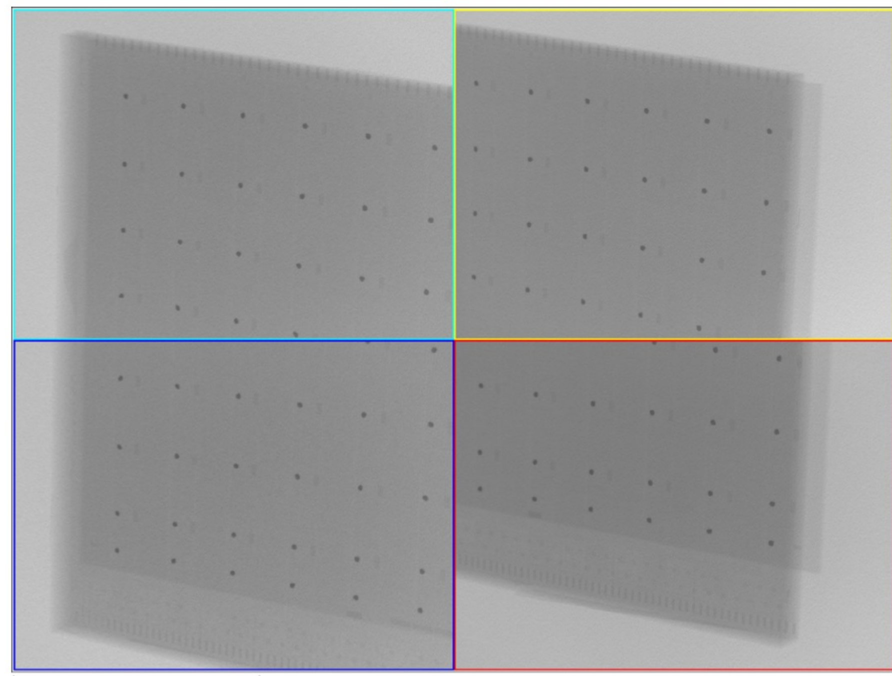
ALTIROC2 + HPK LGAD



ALTIROC2 + IHEP-IME LGAD

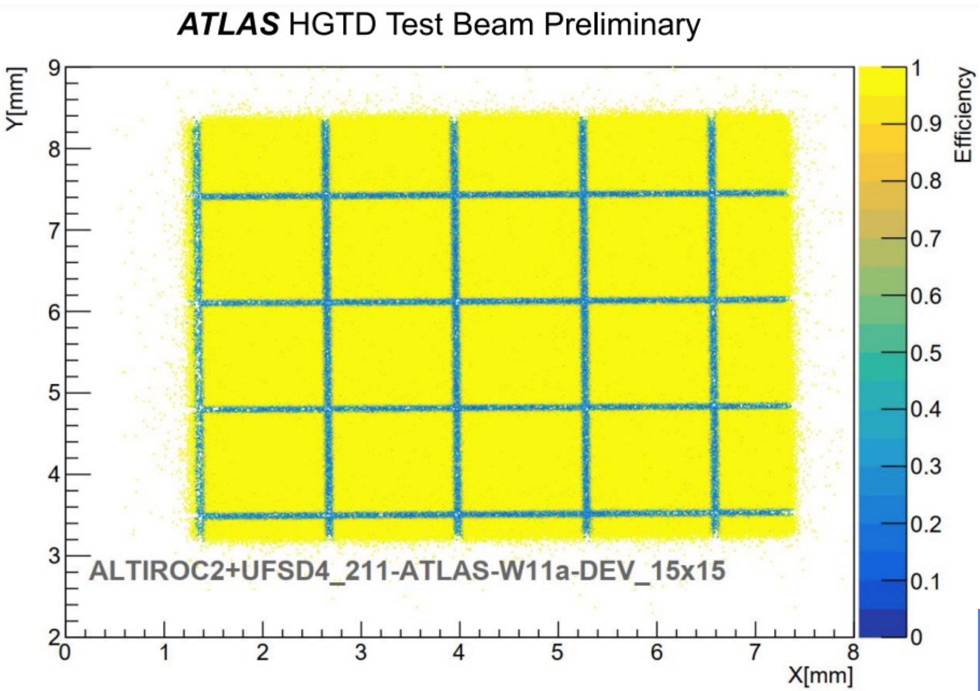


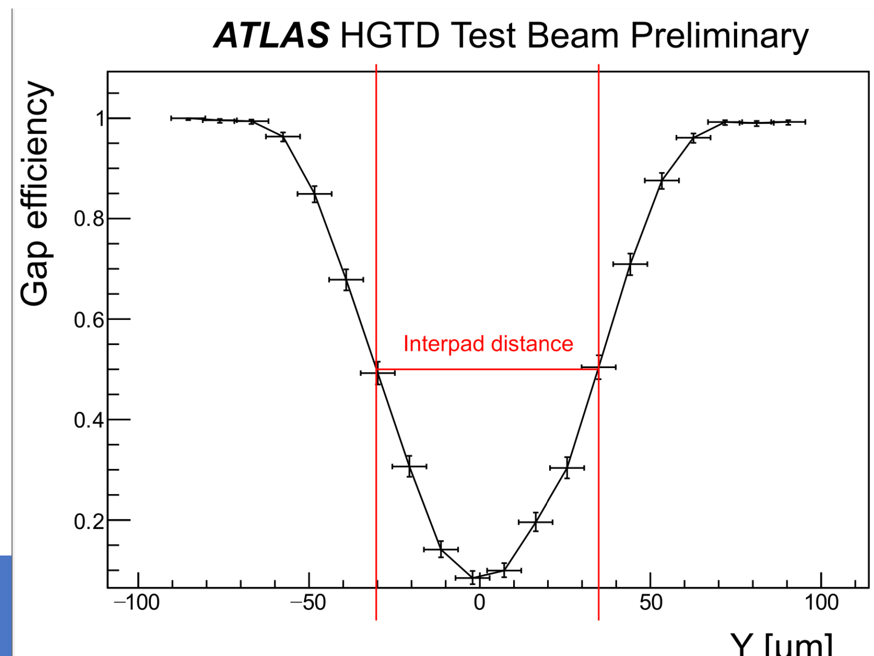
X-ray image of full-size hybrid



Hybrid test beam result

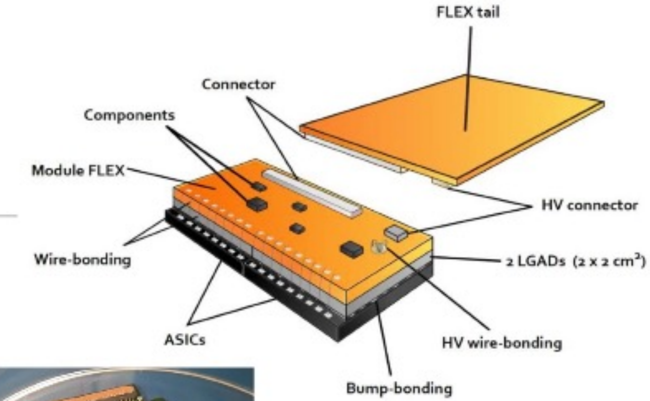
- Hybrid functionality was validated by test beam
  - The EUDET telescope is used for track reconstruction
  - Sensor bias voltage is -180 V, corresponding to a charge of ~20 fC
  - ASIC threshold 4.8 fC
- Close to 100% efficiency in the center of the pixel (pad)
  - The gap between pixels (pads) is about 50μm





Module assembly

- Jigs tools and pick-and-place machine are in development

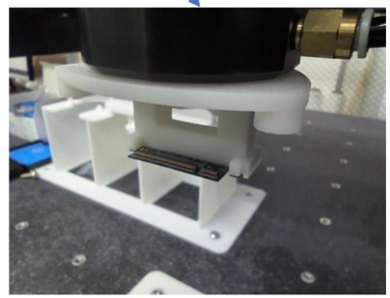


pick-and-place machine

Picking tool

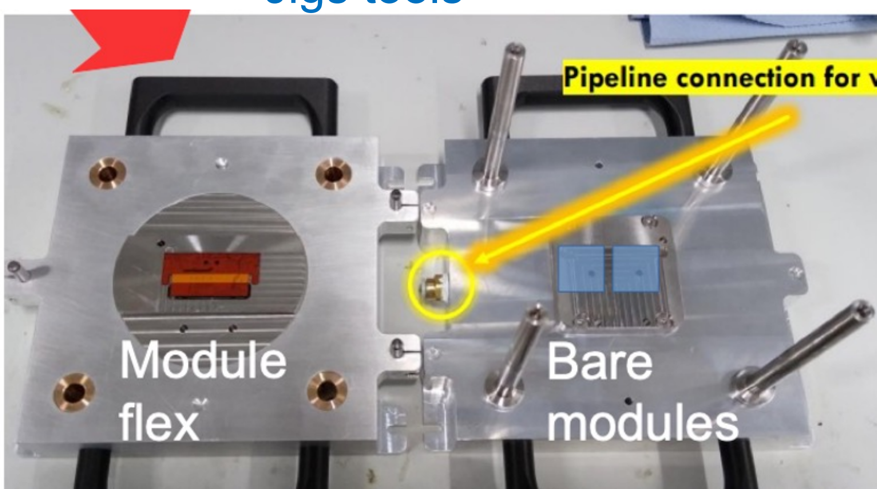
Picking dummy sensor

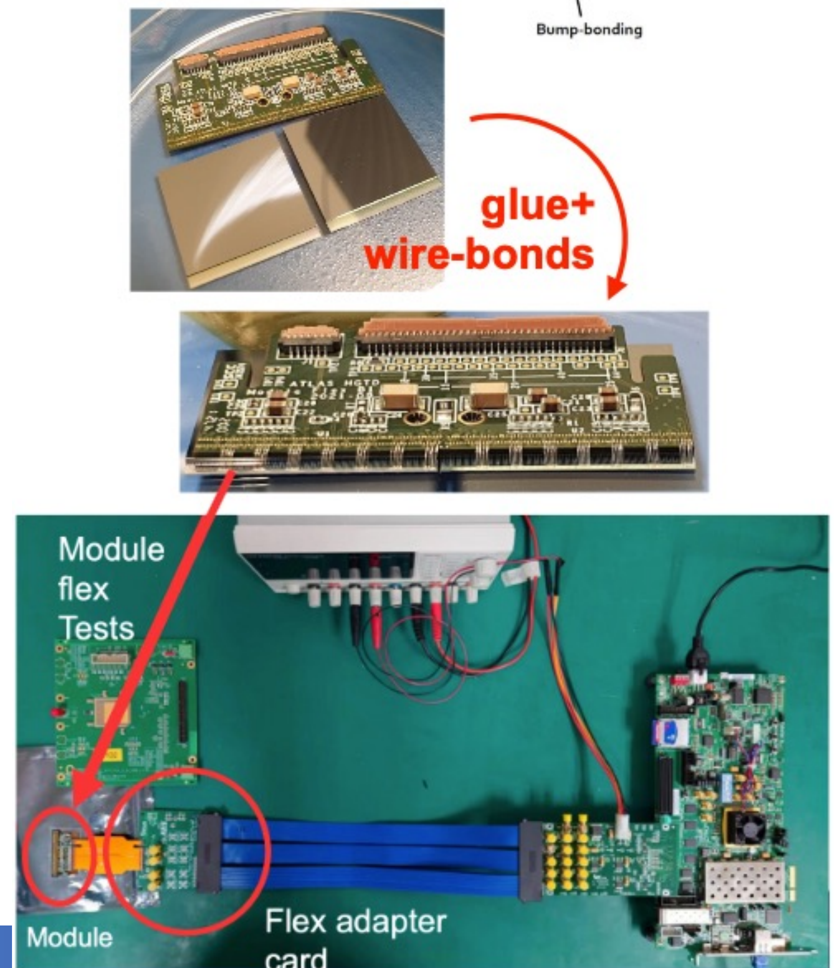
Placing dummy sensor



Picking flex

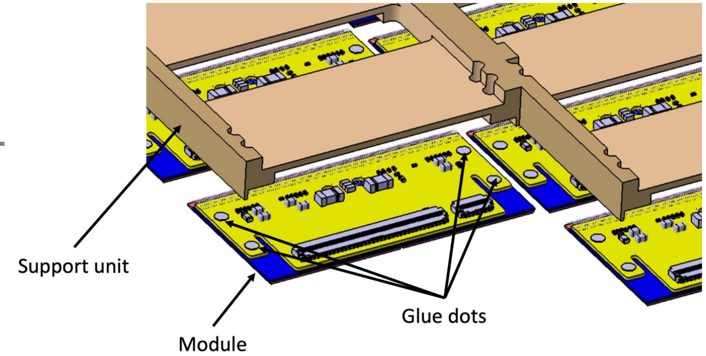
Jigs tools



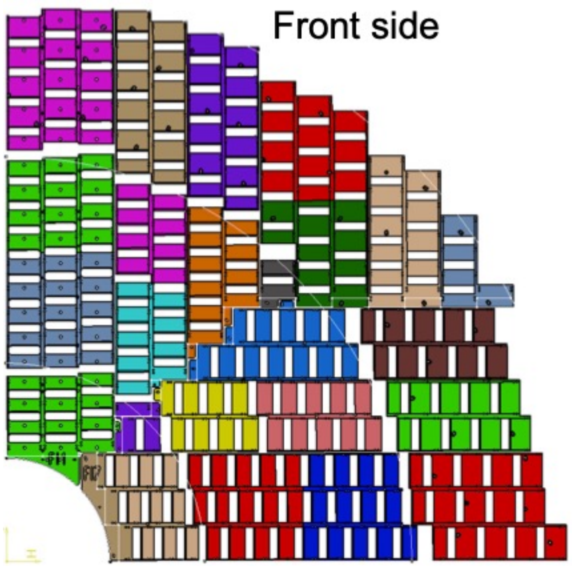


ALTIROC2 full-size hybrid

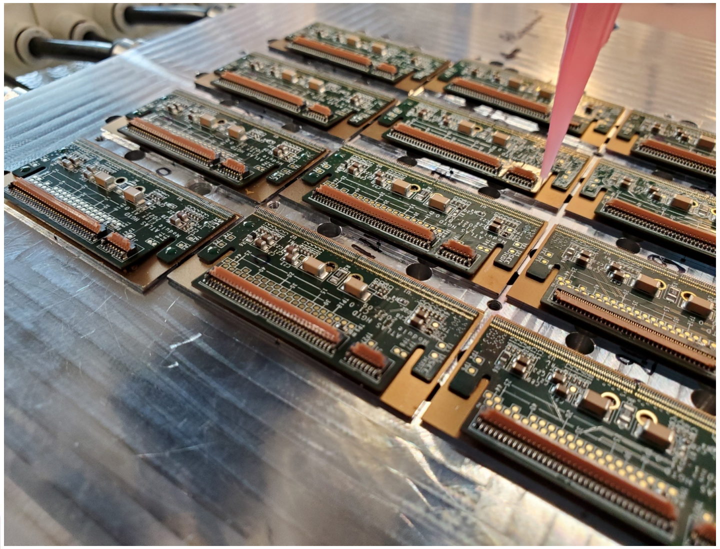
- Modules are installed and glued on support units
  - Challenges :machining of PEEK (flatness <200µm)



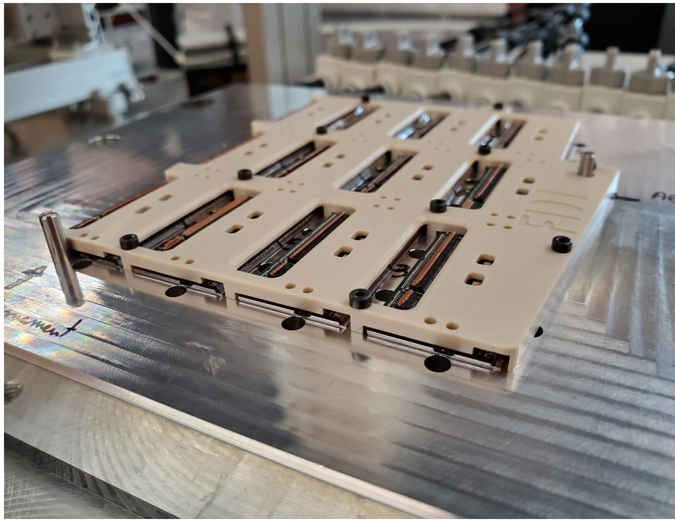
Different color represents different support units.



Gluing modules on support units



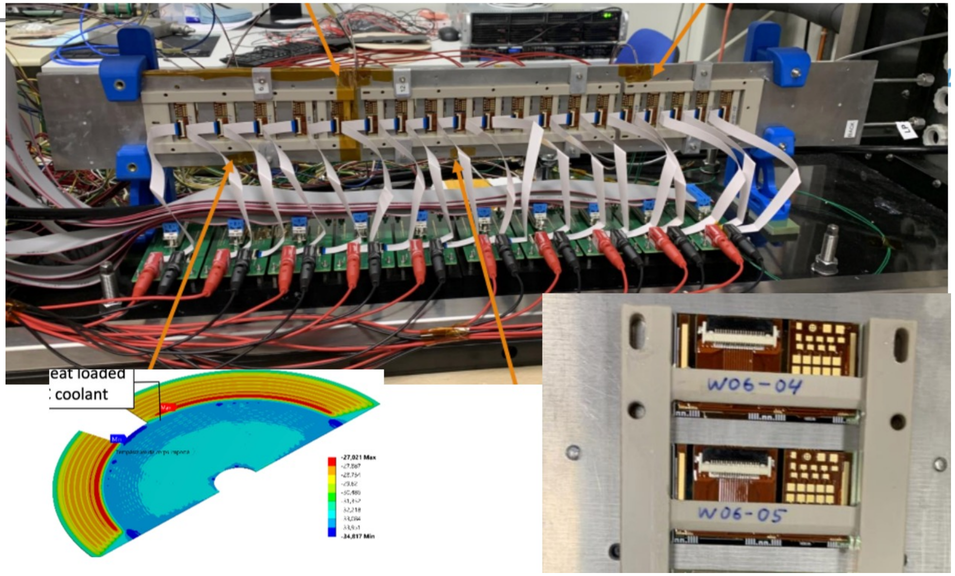
Loading modules on support unit



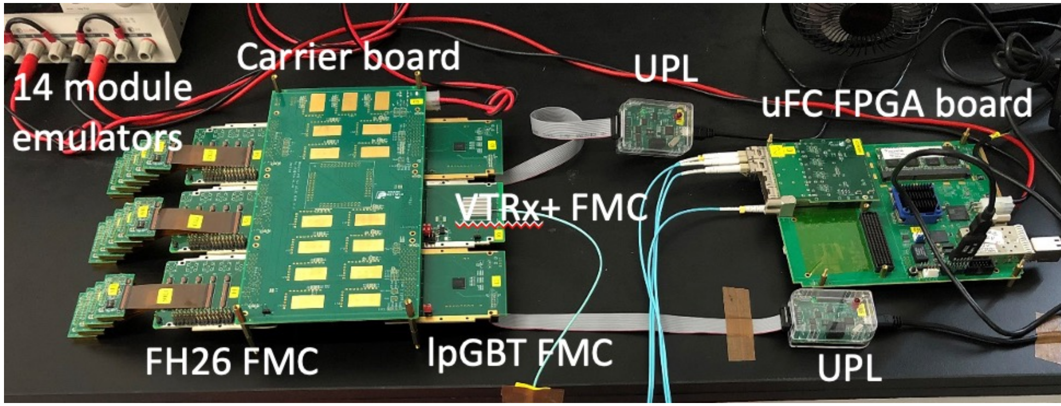
Demonstrator

- Heater demonstrator
  - 19 silicon heaters mounted on a single stave
  - Representing modules dissipating heat
  - on the cooling plate (CO2 cooling)
- DAQ demonstrator
  - Minimum system for full chain readout, from module emulator boards to FELIX board
  - Support up to 14 modules with two lpGBTs and one VTRx+
  - Timing
    - Up to 3 modules @ 1.28Gbps
    - Up to 7 modules @ 640Mbps
    - Up to 14 modules @ 320Mbps
  - Luminosity
    - 7 modules @ 640Mbps

Heater demonstrator



DAQ demonstrator

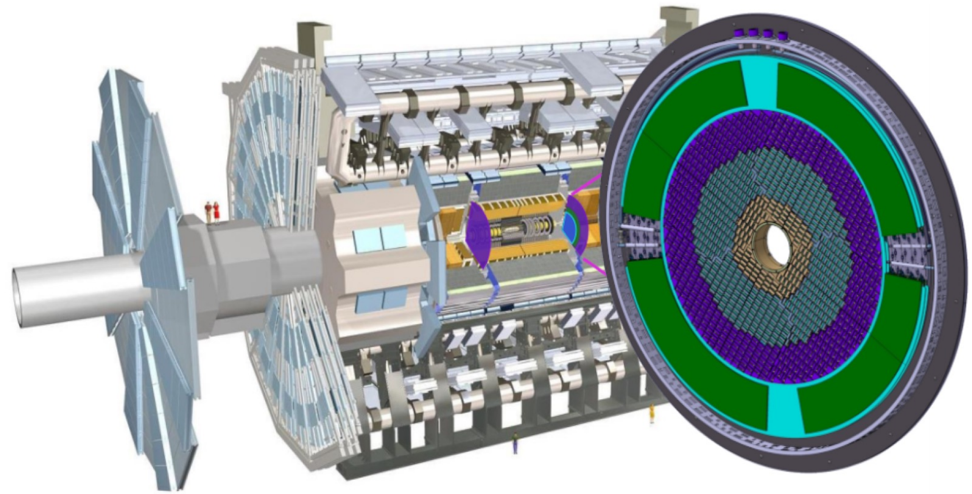


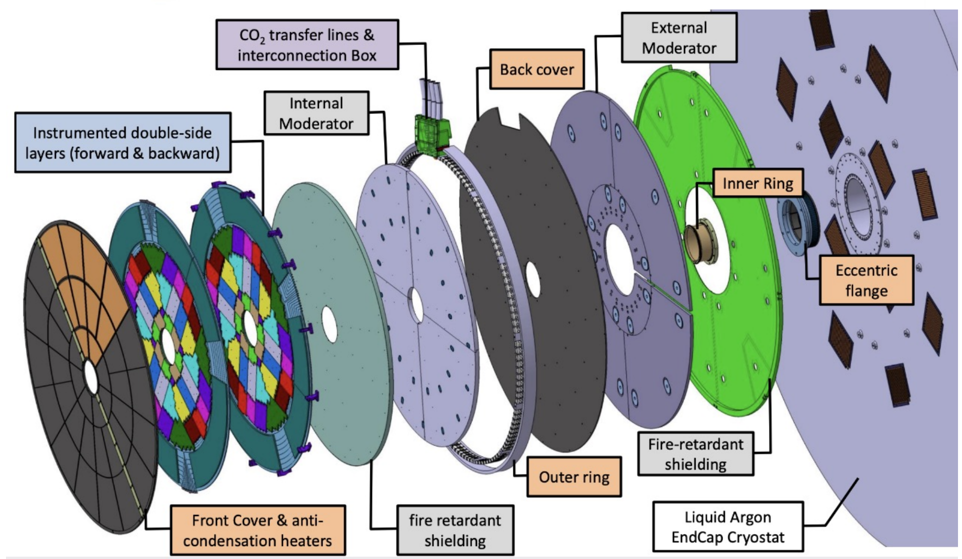
Summary: HGTD detector for ATLAS phase II upgrade

- Good progress in LGAD design fulfilling the radiation hardness requirements
  - Carbon enriched LGADs fulfil HGTD sensor requirements up to **2.5×10^{15} N_{eq} /cm^2**
  - Pre-production has started
- Two round of full-size ASICs have been prototyped, so far all blocks functional
- Concrete implementation of Peripheral electronics components are under test
- Full-size hybrids are in production and showed good results in functional tests
- Demonstrator activities ramping up
- Next milestones:
  - 2023: Peripheral electronics boards and LGAD sensors production started
  - 2024: ASICs, Modules and detector units production started
  - 2026-2027: HGTD detector Integration at CERN, installation

Backup: High Granularity Timing Detector (HGTD)

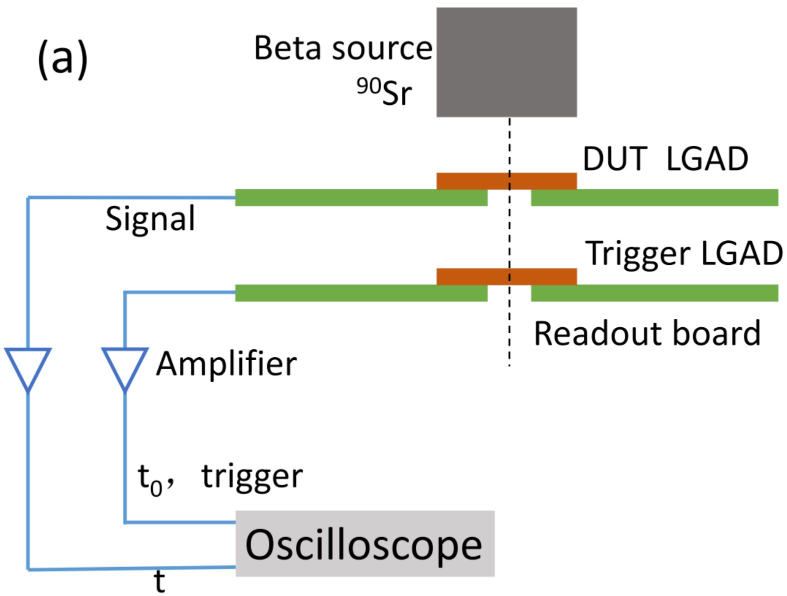
- High precision timing (per-track resolution of **35-50ps** up to 4000 fb-1) to mitigate pileup effects and improve the ATLAS performance in the forward region (**$2.4 \leq |\eta| < 4.0$**)
- Provide online and offline luminosity measurements by transmitting N_{Hits} per ASIC at 40MHz in outer region
  - 2 disks (one per endcap) outside of ITk volume, upstream of the fwd. calorimeters, consisting of **2 double-sided layers** each
  - Very limited space in z-direction ↠ overall thickness of 12.5 cm for each disk
- Silicon sensor technology (LGAD)
- Max expected fluence in “3-ring layout” is **2.5e15 neq/cm²** and sets the radiation hardness requirements for the sensors and electronics

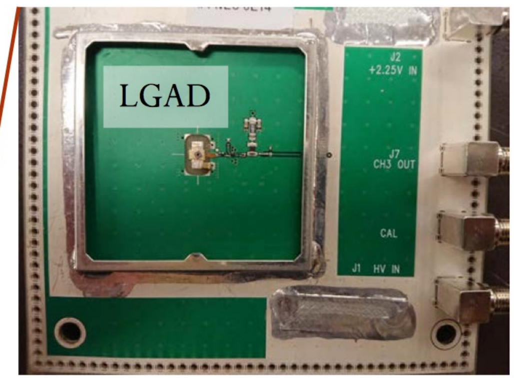


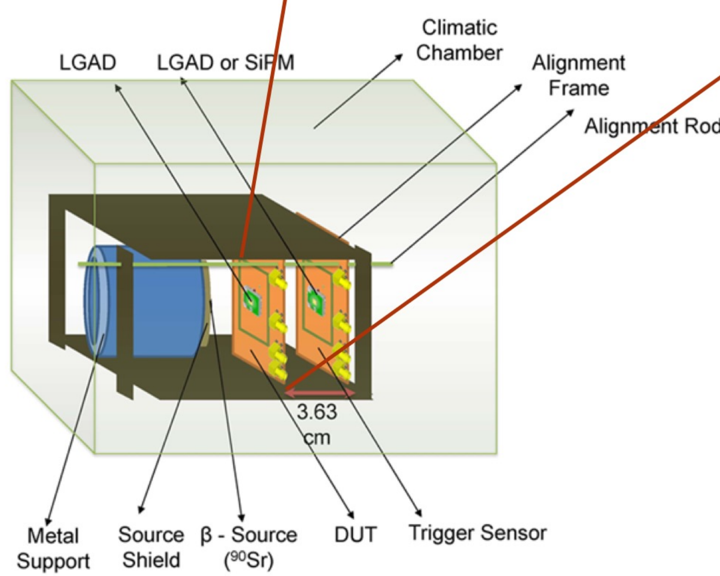


Beta source tests: LGAD timing resolution measurements

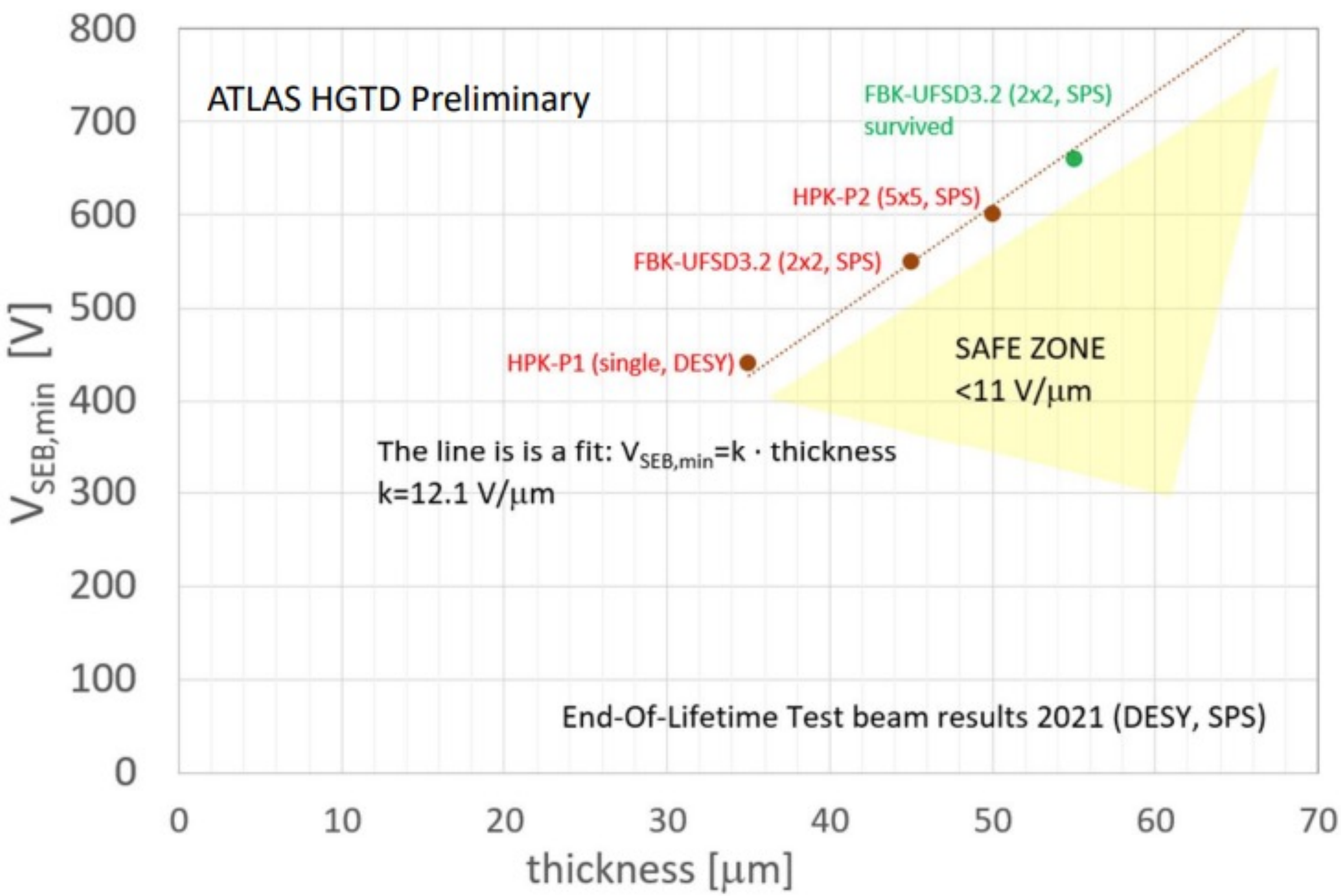
- Sr^{90} Beta telescope test (collected charge, gain, time resolution)
- UCSC boards with commercial amplifier and analog readout by Oscilloscope
  - Less constraints with respect to the ASICs – exploring the limits of the sensors.
- Two UCSC boards with two LGAD
  - One LGAD is device under test (DUT)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





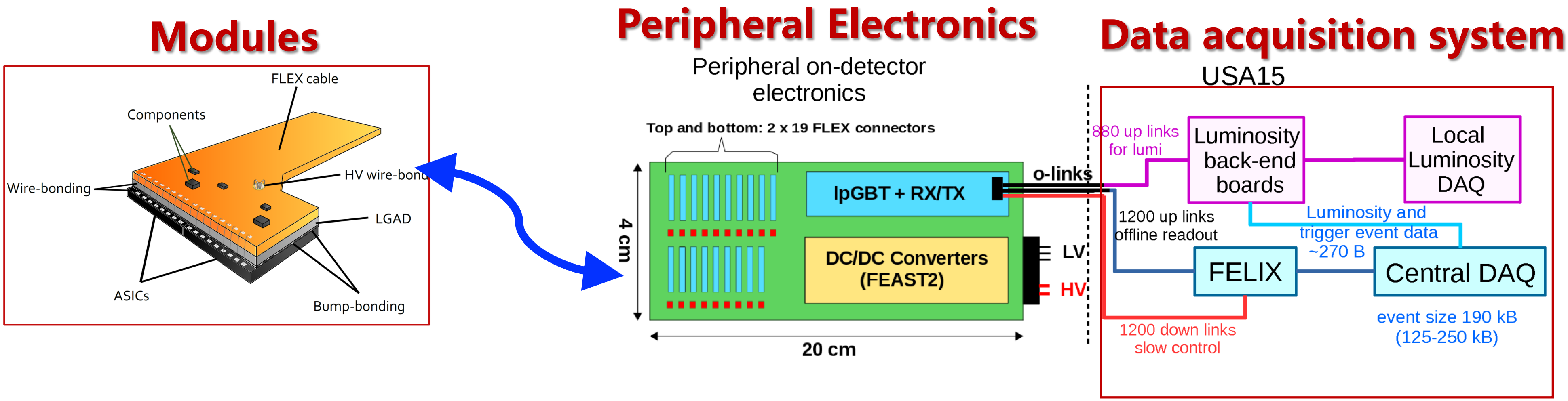


LGAD Single Event Burnout effect (HV stability in the beam)



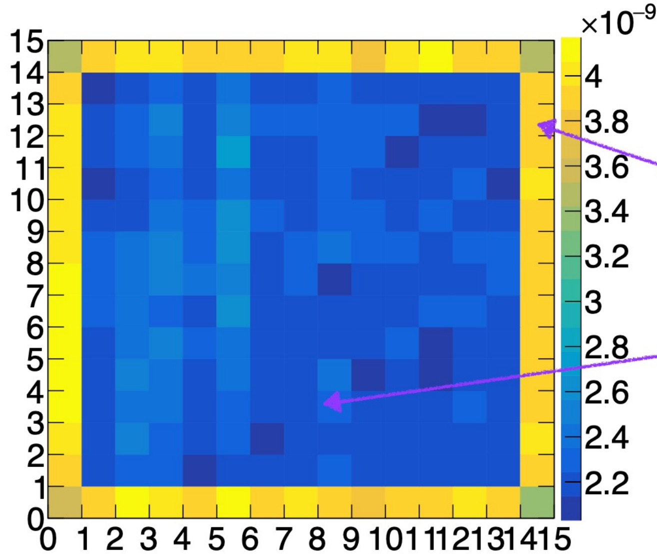
Peripheral board (PEB)

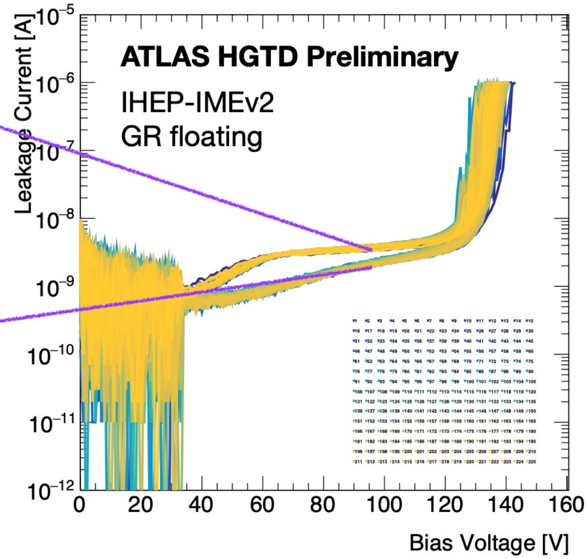
- PEB connects FE to the DAQ system, provides LV&HV to the modules

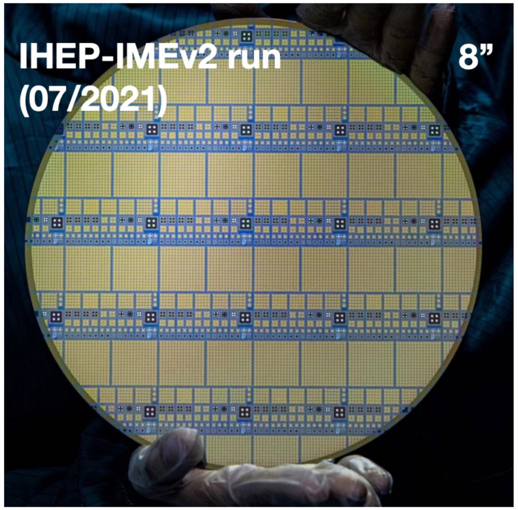


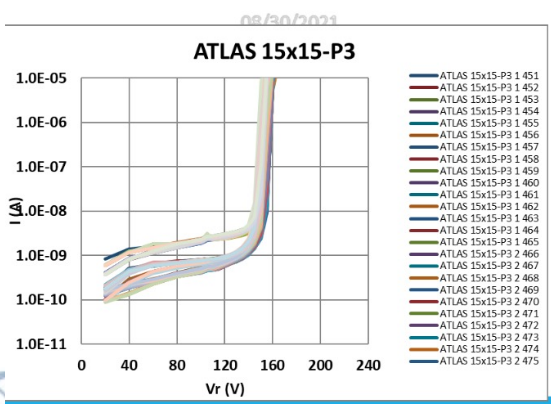
Full size LGAD sensor prototype

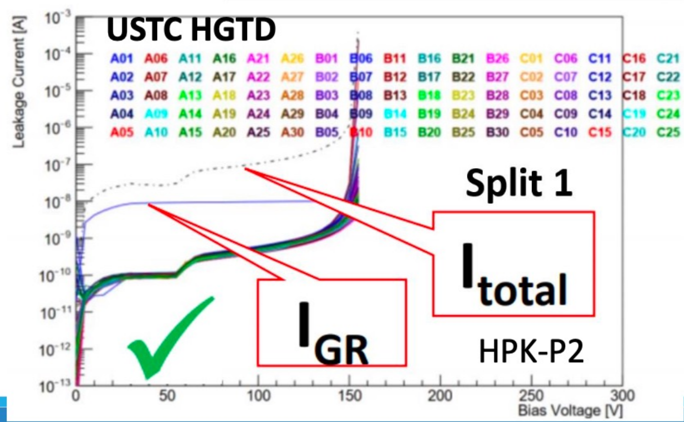
- Good uniformity of full size LGAD prototype (15*15 channels)
  - IHEP-IME, USTC-IME,HPK, FPK, CNM has produced good full-size LGAD prototype.

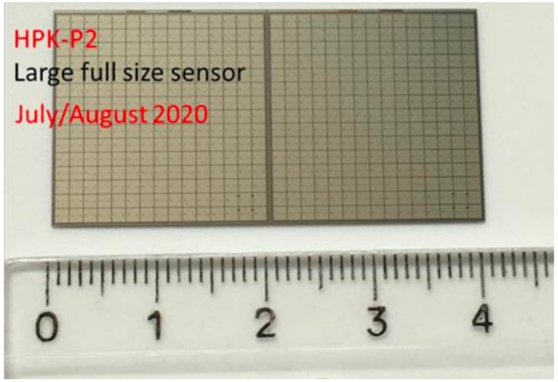










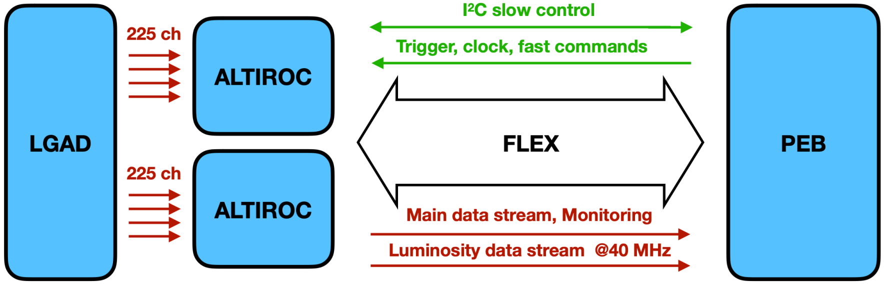


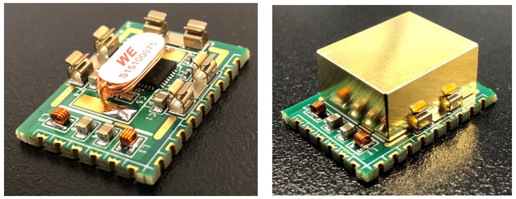
Peripheral electronics board (PEB)

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

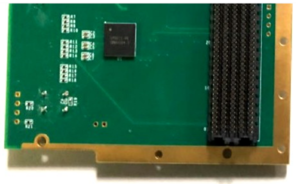
  ↠ need to fulfil space constraints, power efficiency measured
  - Started tests on lpGBT with evaluation board
  - VTRX+: successfully tested 2.56G/10.24G communication, bit error rate ($<10^{-12}$), passed eye diagram test
  - MUX64: analogue multiplexer (for monitoring of ASIC power supply and temperature)

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

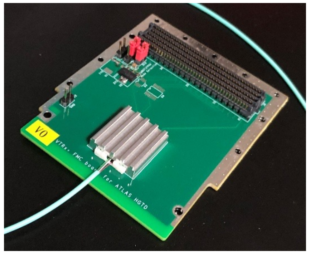




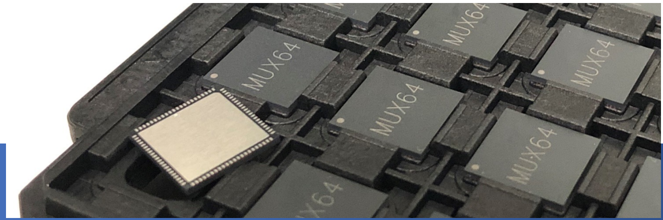
DC/DC converter



lpGBT eval. board



VTRx+ eval. board



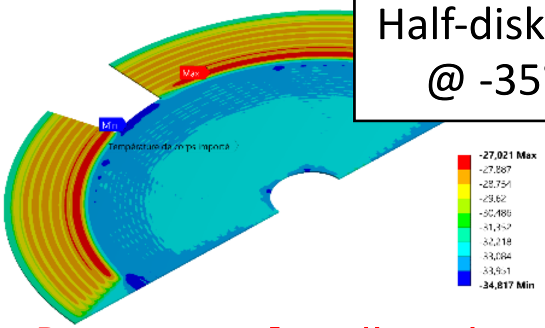
MUX64 in QFN88

HGTD Mechanics and service

- Hermetic vessel and on-detector cooling passed SPR review
- Cooling plate with CO2 loops design and prototyping in good Progress
- Outer ring in progress: Challenging tight junction design with lots of feed-through

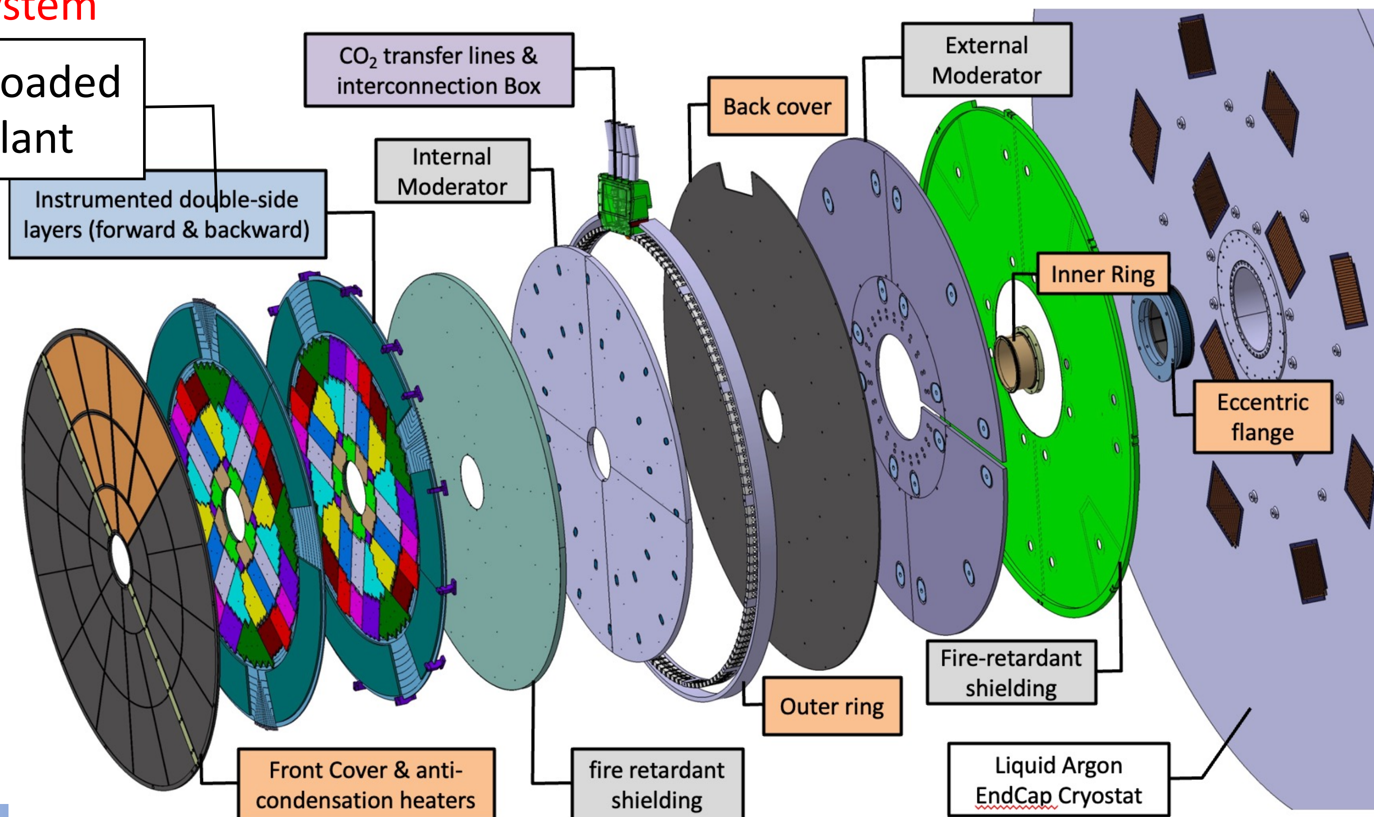
Thermal simulation of cooling system

Half-disk heat loaded @ -35°C coolant



Prototype of cooling plate

Overall view with mechanics main items

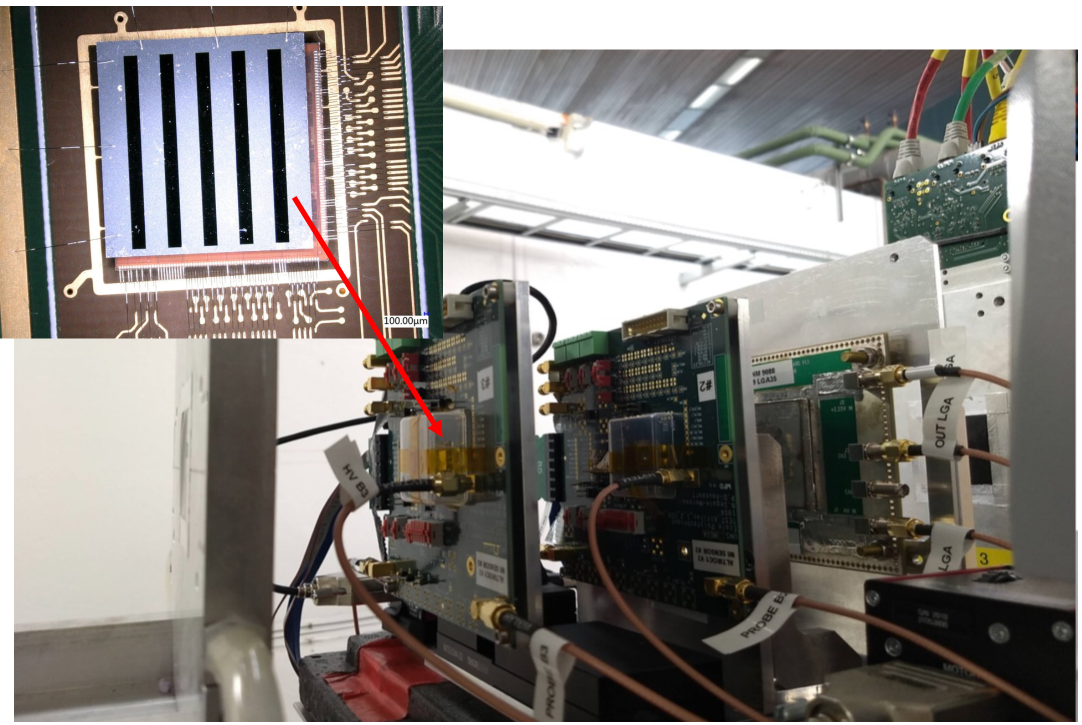


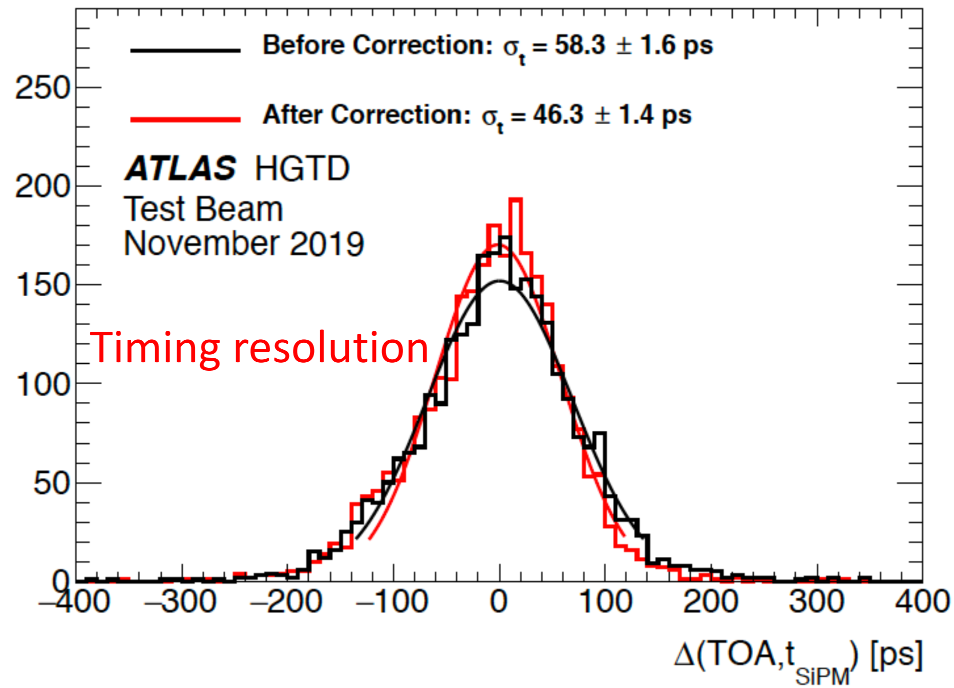
ALTIROC1 mini-modules performance at test beam

- 5*5 channels Mini-modules (ALTIROC1+LGAD) was tested at testbeam
  - 46ps timing resolution after time walk correction

LGAD Landau	25 ps	the reason for part of the high jitter found **26 (known reasons)**
Jitter+system/internal clock+time walk residual	37 ps	
TDC clock	7 ps	Total resolution: 36 ps (likely achievable for 20 fC)/ 70 ps for (4 fC)
Per hit total	46 ps	

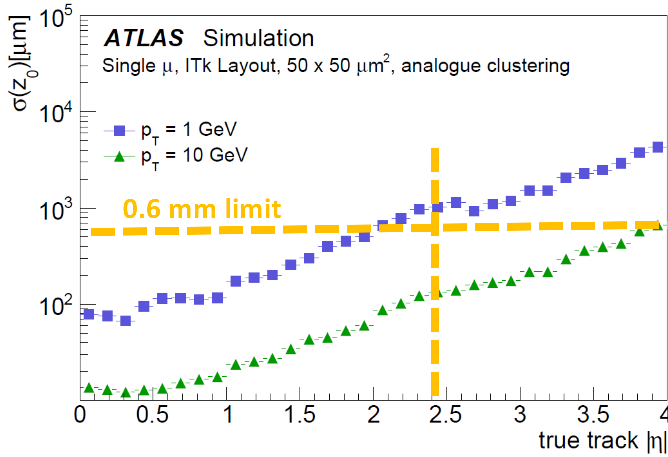
ALTIROC1 mini-modules @ test beam

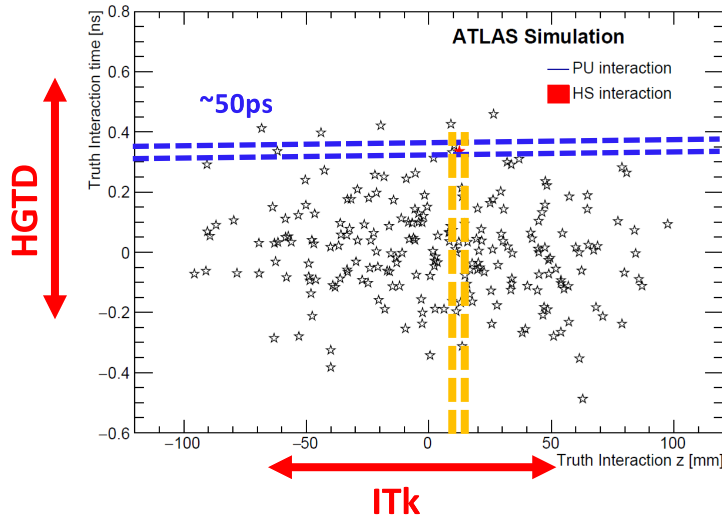




Why need the time information?

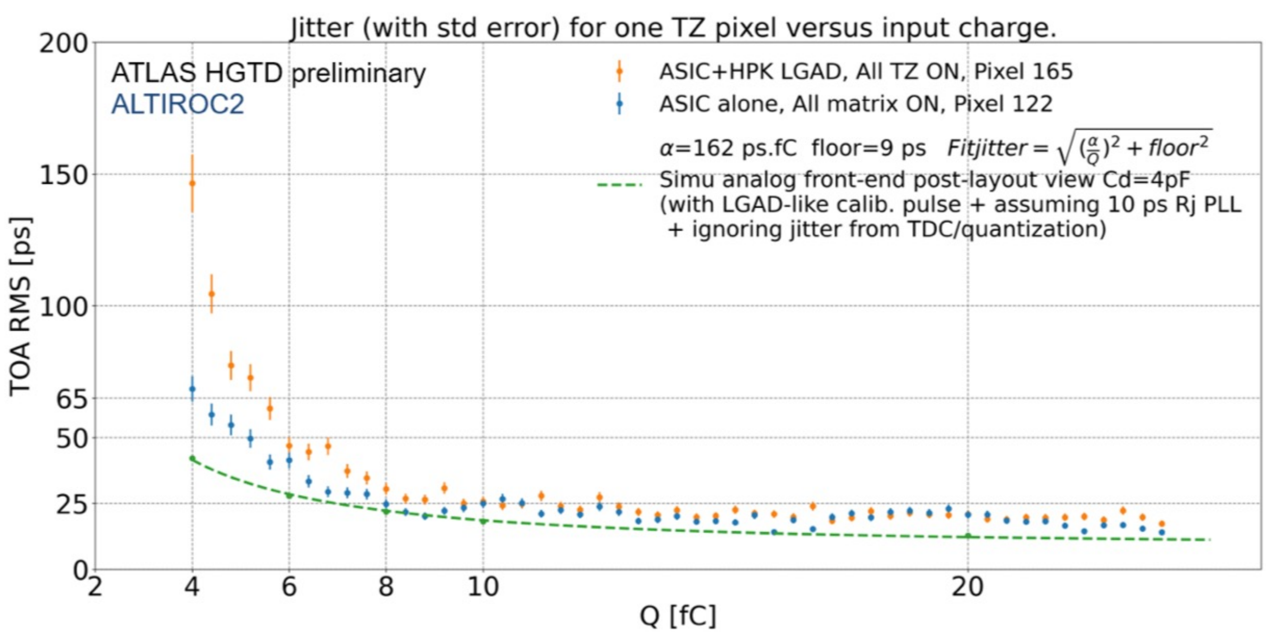
- At High Luminosity -LHC
  - Pileup: <μ>= 200 interactions per bunch crossing ~1.6 vertex/mm on average
- Problems of the vertex reconstruction in ATLAS
  - degradation significantly in the forward region compared to the central region
  - Need z_0 resolution < 0.6 mm
  - Liquid Argon based electromagnetic 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

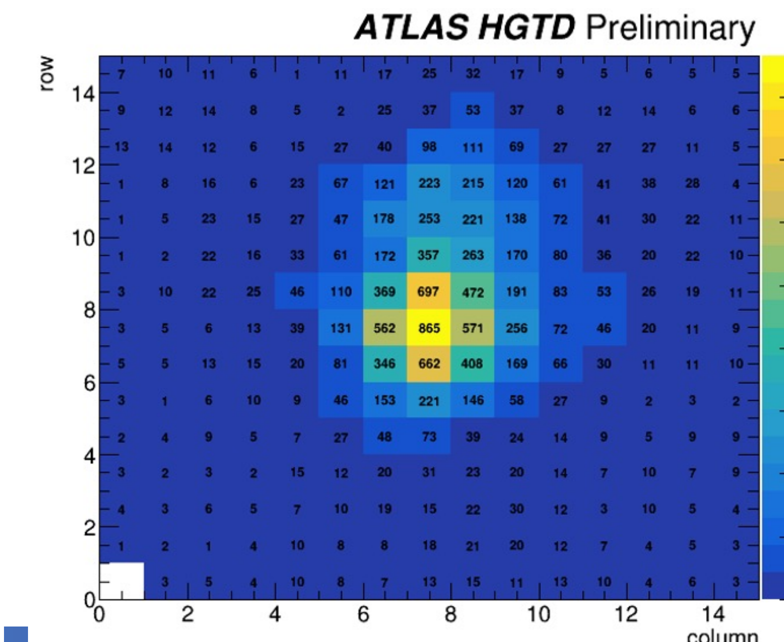




Hybrid tests

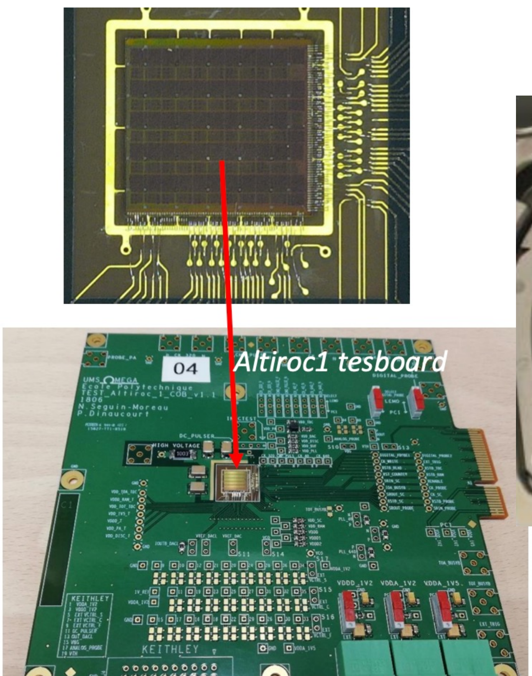
- Tests on-going of ALTIROC2 using dedicated PCB and interface board
  - ASIC-only and ASIC+LGAD tests after hybridization
  - Sr90 and testbeams performed with bare modules
  - Jitter as function of charge with ALTIROC2 ASIC alone and ASIC+LGAD with at least all TZ preamplifier channels enabled
  - Performance at low charge understood due to parasitic inductances separating sensor/ preamplifier grounds



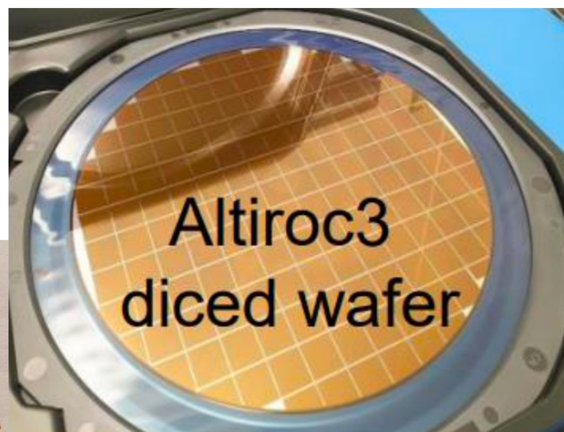


ALTIROC R & D

- ALTIROC0 – preamplifier + discriminator waveform sampling on the oscilloscope
- ALTROC1– 5x5 array with complete analogue front end (discriminator + TDC)
- ALTIROC2– 15x15 array with almost complete functionalities
  - First Full-size ASIC prototype ~2x2 cm^2 with 225 readout channels
- ALTIROC3- 15x15 array with complete functionalities
  - Digital-on top design, fix on TDC (TOT/TOA), radiation hard design



ALTIROC3 wafer



ALTIROC2 test bench setup