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

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Outline

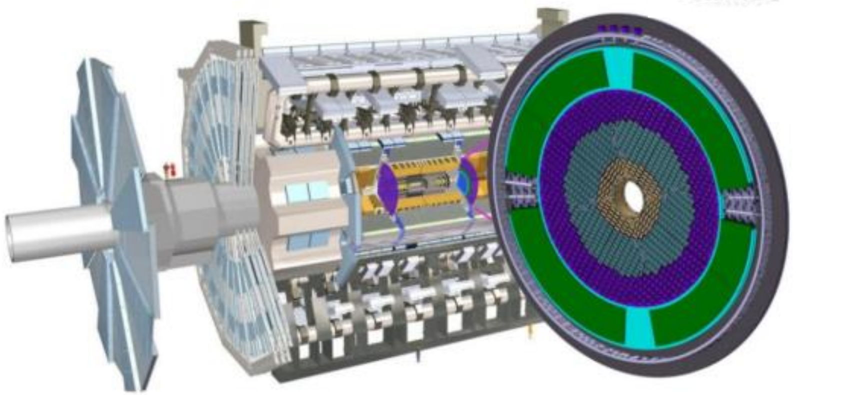
- LGAD sensor for HGTD
    - HGTD project
    - LGAD introduction
    - laboratory test
    - test beam results
- LGAD sensor for CEPC
- Summary

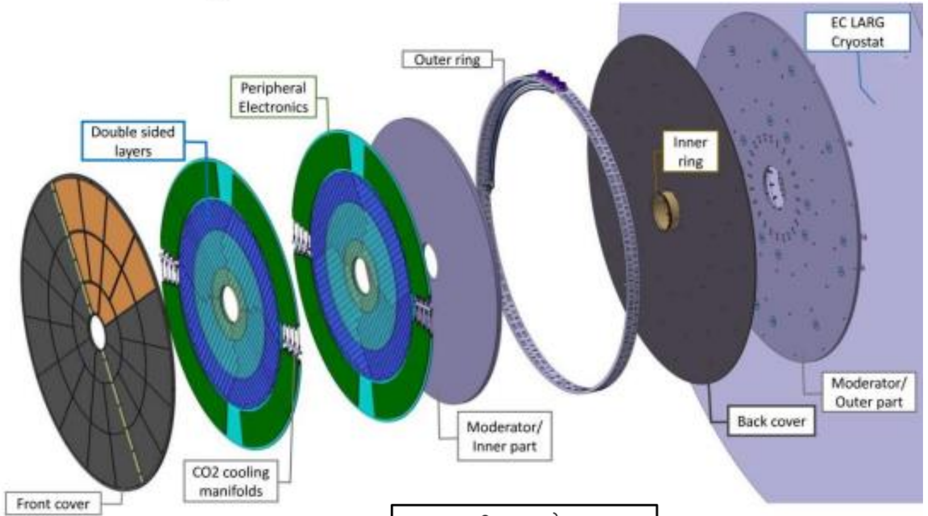
HGTD detector

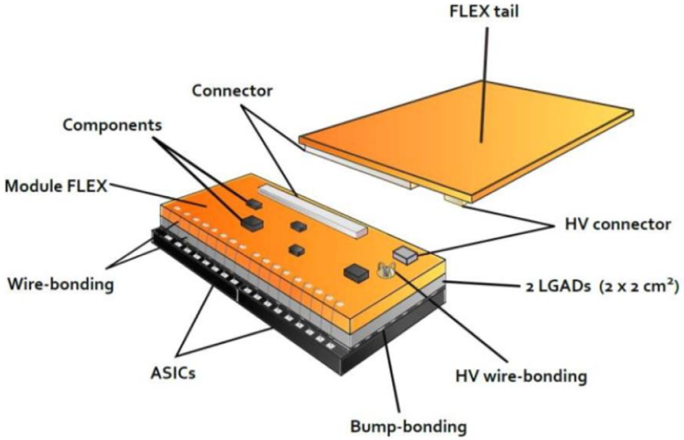
- The High Granularity Timing Detector (HGTD) is designed to provide precise timing information due to increased pile-up in HL-LHC.
  - ~3.6 million 1.3×1.3 mm^2 pixels(channels)
    - 6.4 m^2 active area
  - Time resolution target
    - 35-70 ps/hit up to 4000fb^{-1}
  - Luminosity measurement
    - Goal for HL-LHC: 1% luminosity uncertainty

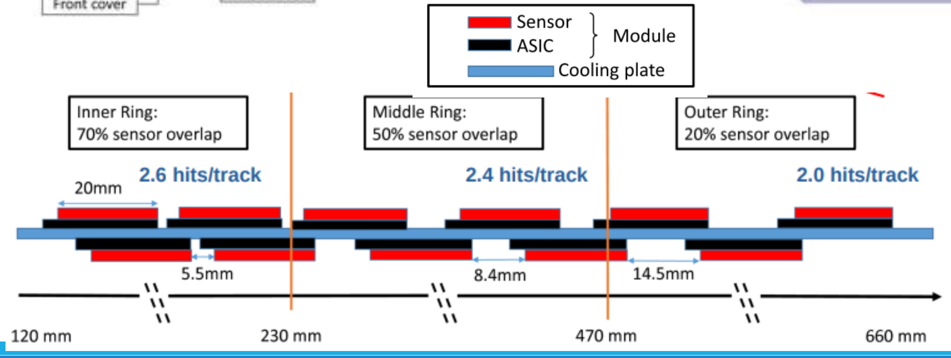
- **8032 modules, each module:**
  - consists of two hybrids (2 sensors+ 2 ASICs)
  - 2x4cm^2, 15x30 channels

- **~21000 LGAD sensors**
  - 15x15 array
  - Pixel size: 1.3mmx1.3mm





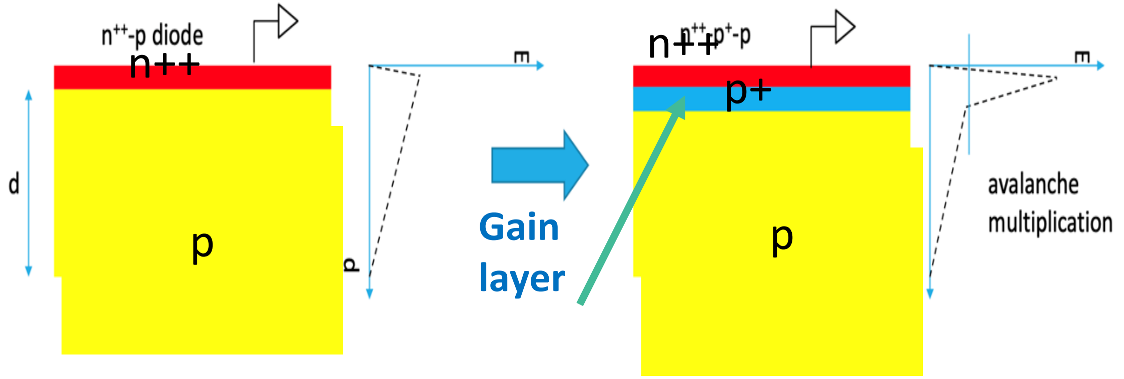




LGAD sensor

➢ **Low Gain Avalanche Detectors (LGAD)： good timing resolution(<35ps)**

- Work in linear mode, Gain:10~50
- Thin depleted region(~50um) to decrease t_{rise} (fast timing)
- Good Signal/Noise ratio, no self triggering



➢ LGAD technology is chosen as detector for HGTD project.

Requirement:

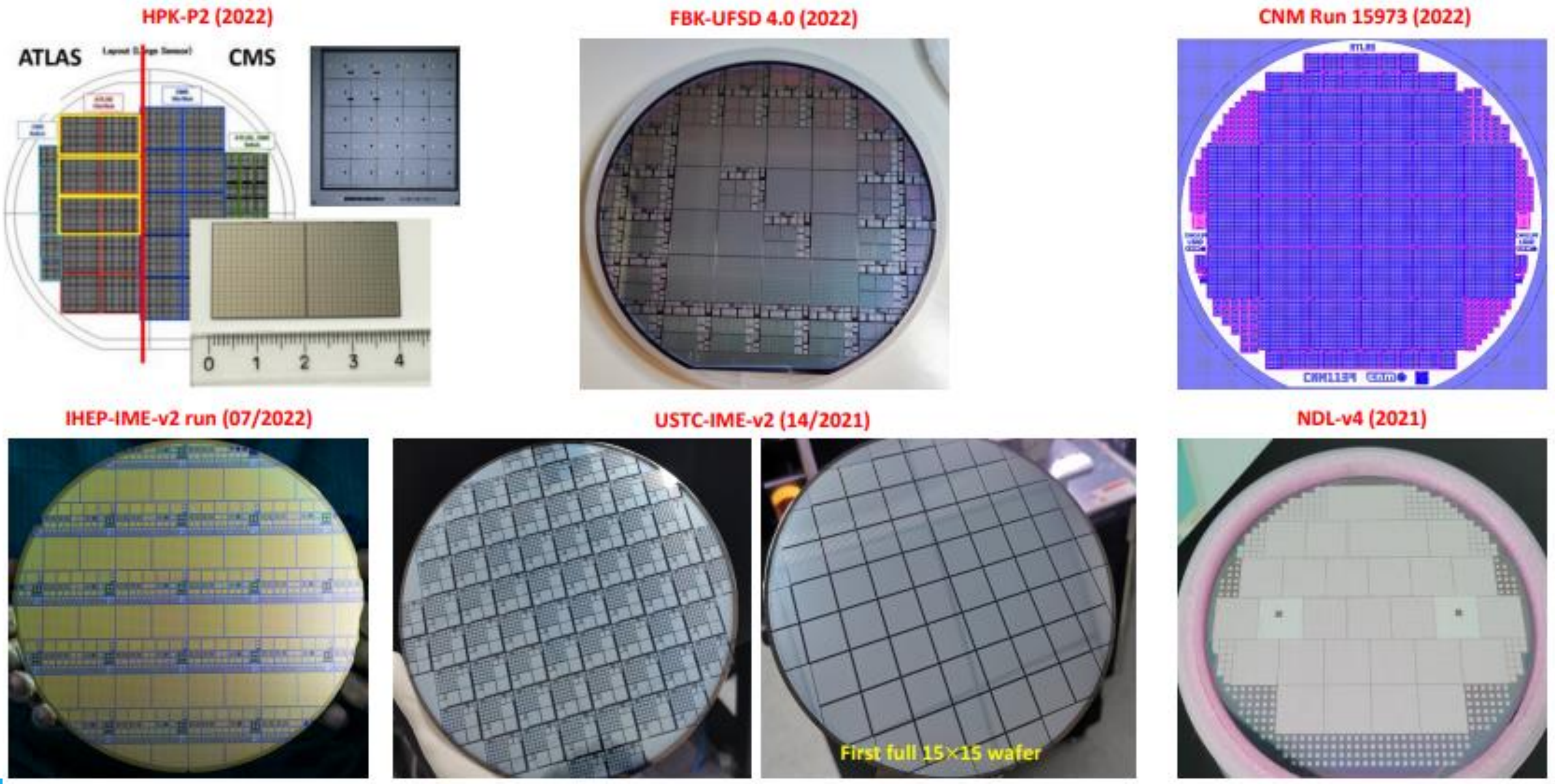
- Size: 15x15 array, $1.3 \times 1.3 mm^2$ pixel size
- Active thickness: 50um(Thin: faster rise time, lower impact from radiation)
- LGAD sensor can withstand the lifetime of the HL-LHC running: irradiation requirement

  Maximum n_{eq} fluences: 2.5×10^{15} n_{eq}/cm^2

  Total Ionizing Dose (TID): 2 MGy at the end of HL-LHC (4000 fb^{-1})
- Time resolution: 35ps (start), 70ps (end) per hit, while 30ps (start), 50ps (end) per track
- Collected charge per hit >4fC (minimum charge needed by the ASIC to hold good time resolution)
- Hit efficiencies of 97% (95%) at the start (end) of their lifetime

LGAD sensor for HGTD

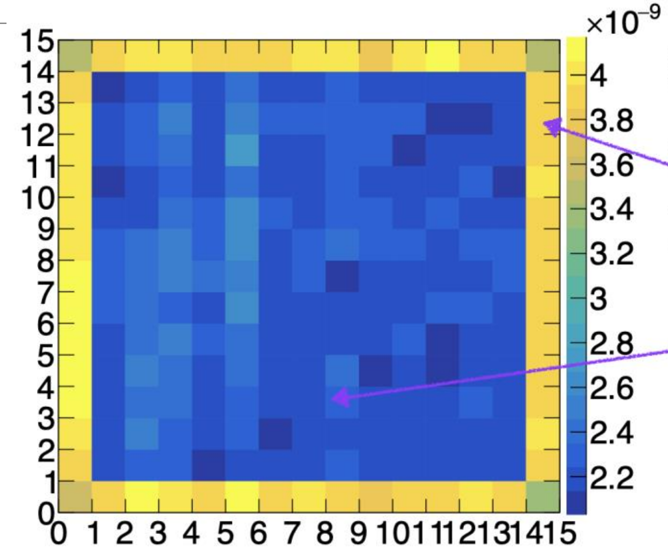
- LGAD sensors from many vendors have been extensively studied during the R&D phase of the HGTD project.
- Active vendors include: HPK (Japan), FBK (Italy), CNM (Spain), IHEP-IME (China), USTC-IME (China), IHEP-NDL (China) …

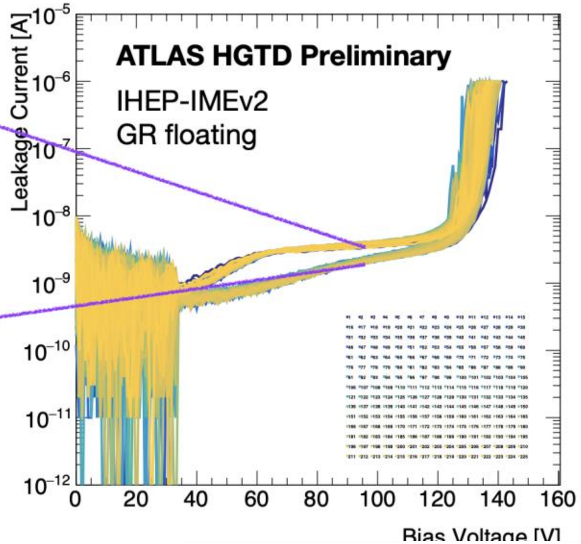


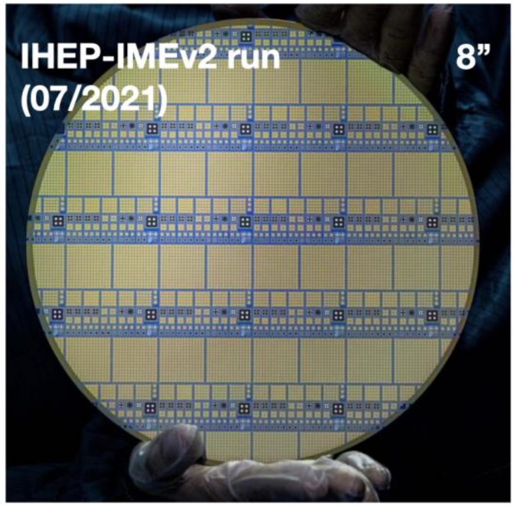
LGAD sensor for HGTD

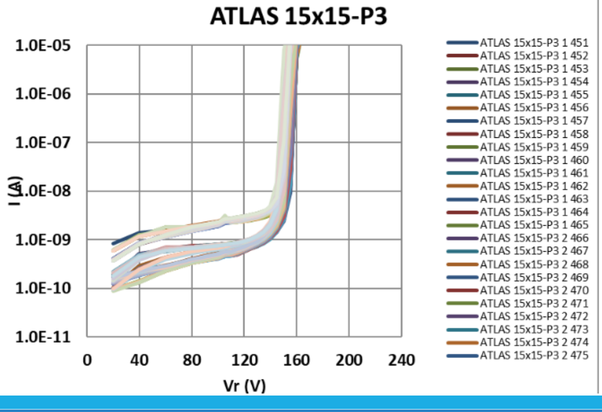
➢ **Good uniformity of full size LGAD prototype** (15x15 channels)

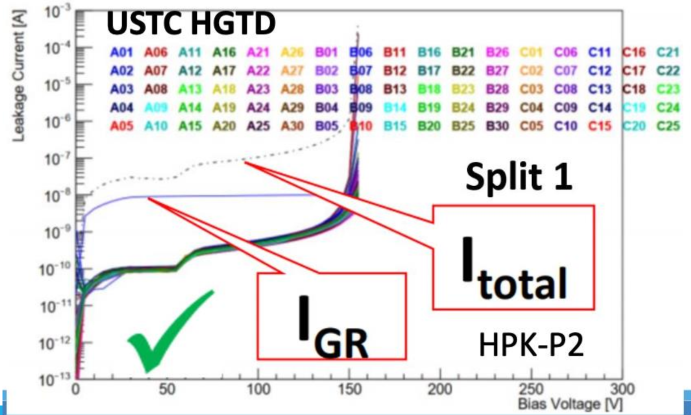
- HPK, FBK, IHEP-IME, USTC-IME, CNM have produced good full-size LGAD prototype.

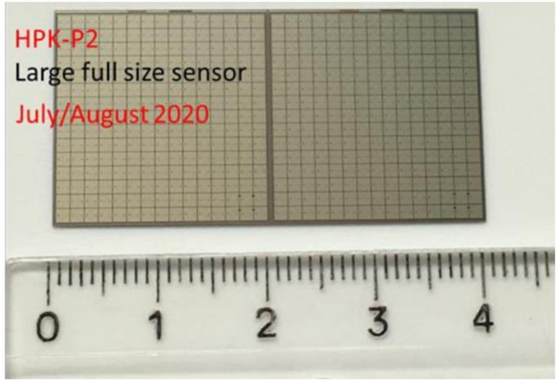












LGAD sensor after Irradiation

➢Main challenge: Radiation Hardness

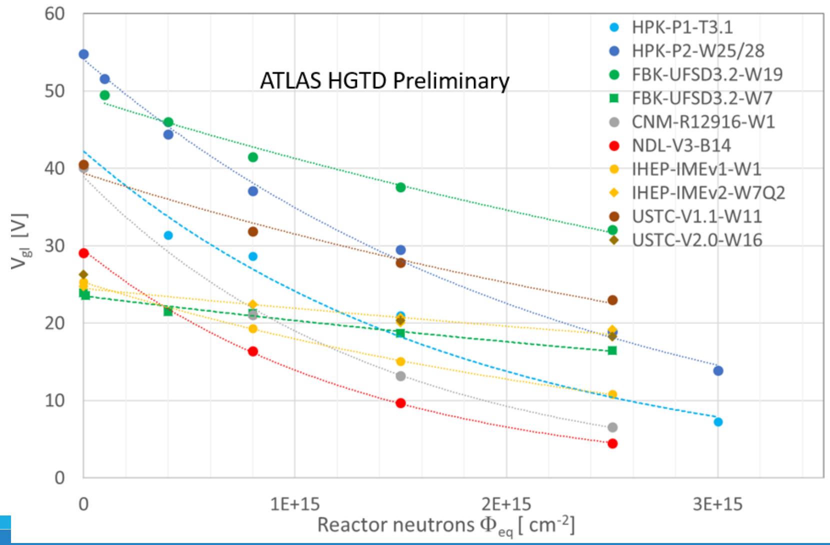
➢Boron doping in gain layer became less active after irradiation（**acceptor remove**）

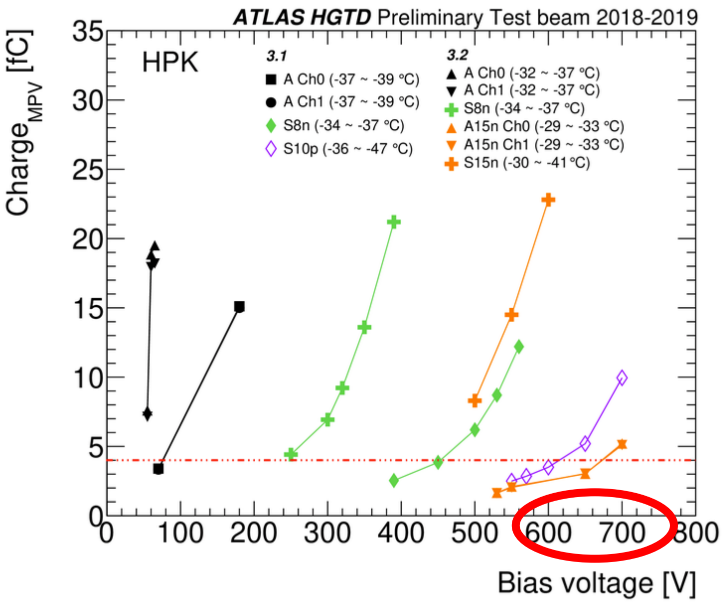
➢Key parameter of the gain degradation is the acceptor removal coefficient: *c factor*

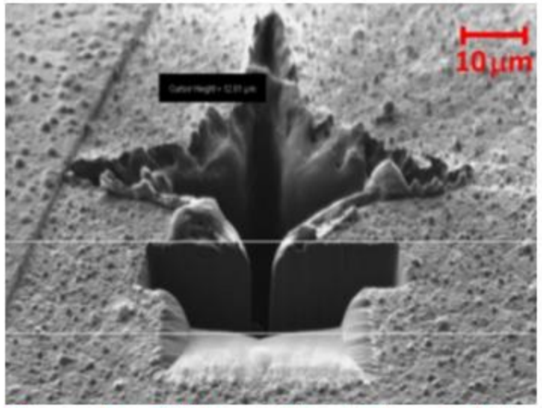
$$V_{gl} = V_{gl0} \times \exp(-\boldsymbol{c} \times \Phi_{eq})$$

➢Irradiated sensors require higher bias voltage to maintain performances.

➢Single Event Burnout (SEB) Occur- when irradiated sensors 2.5 x 10^{15} n_{eq}/cm^2) operated with high bias voltage







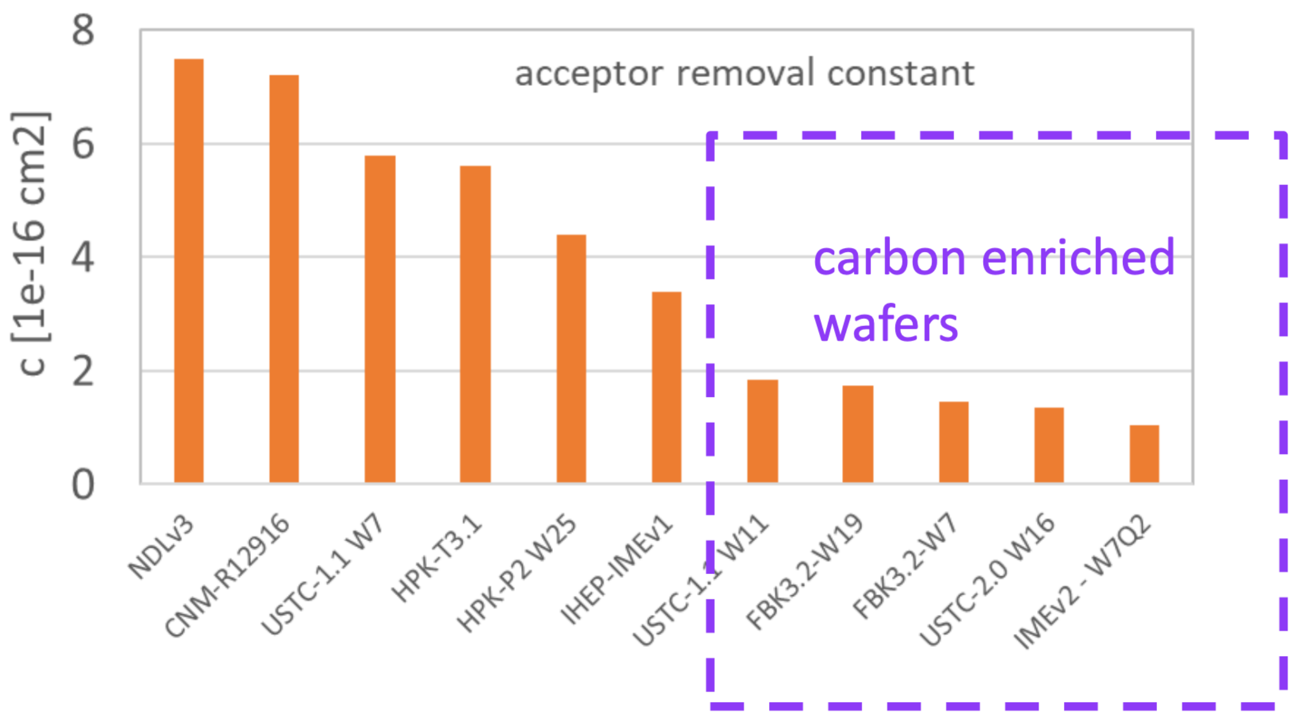
Burn mark on a CNM sensor after proton beam irradiation in Fermilab in 2018 (picture produced by CNM)

- RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam.

LGAD sensor after Irradiation

- To improve the radiation hardness of LGAD:
  - Design of gain layer： changing the doping concentration, depth, width, shape；
    adding the Carbon, Gallium to gain layer

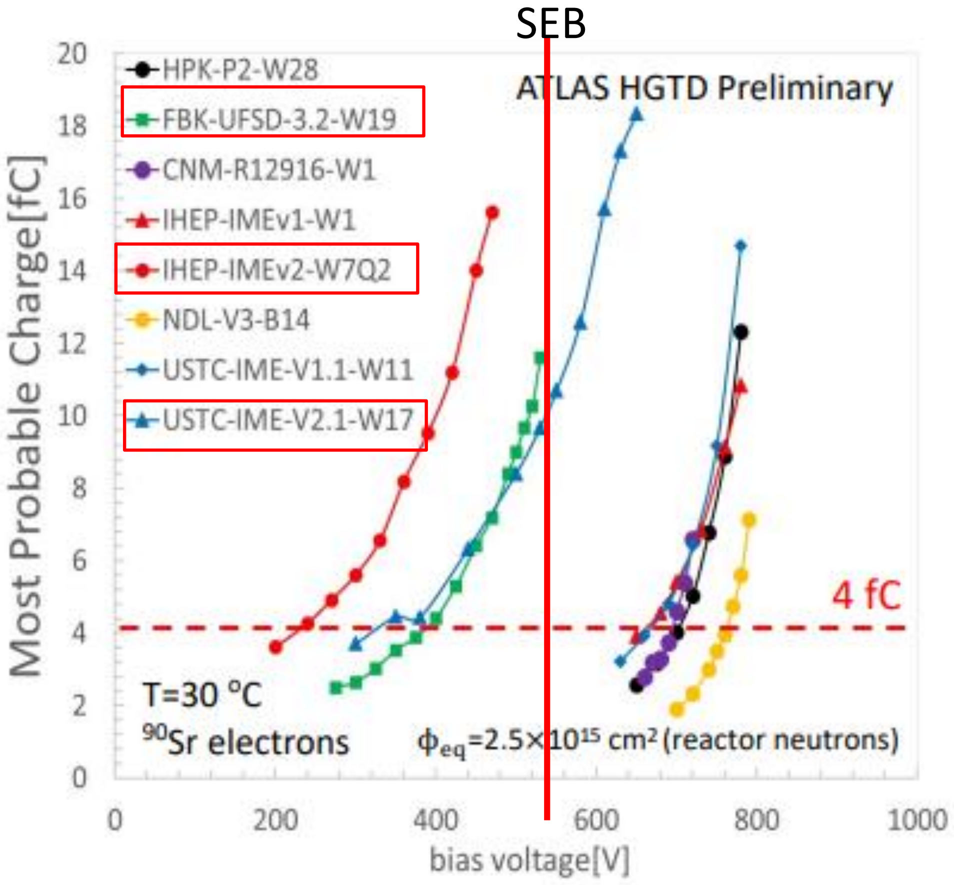
- Sensors from carbon enriched wafers show very low acceptor removal coefficient(1-2$\times 10^{-16}$ cm^2), which would reduce the required voltage for enough charge collection and avoid the SEB.

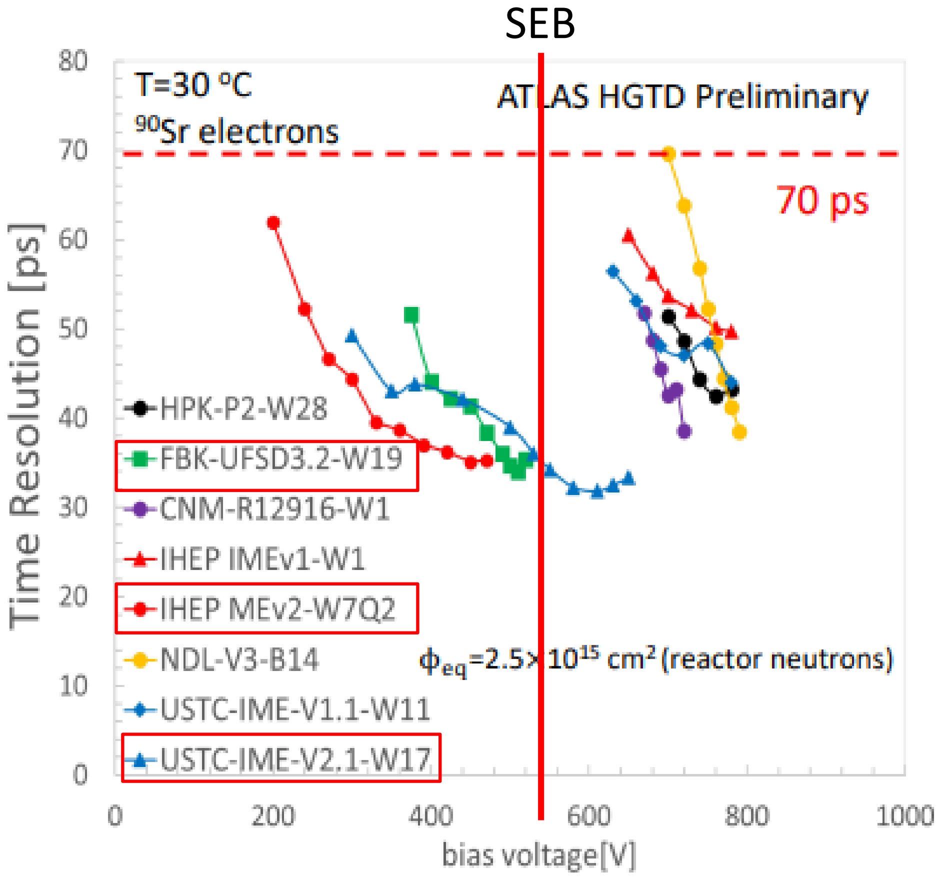


LGAD: laboratory test

- Sensors from vendors(FBK,IHEP-IME,USTC-IME) with carbon enrichment show good enough **CC/timing after 2.5×10^{15} n_{eq}/cm^2** at voltage less than SEB requirement.

- These sensors performs good enough over the entire lifetime of the experiment.





LGAD: beam test

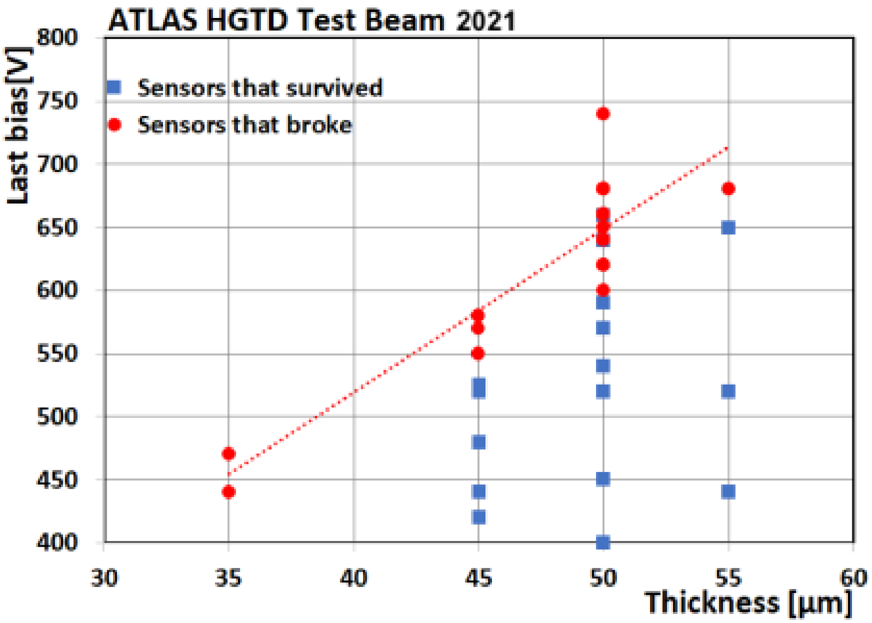
➢LGAD end-of-lifetime studies(at -30℃)

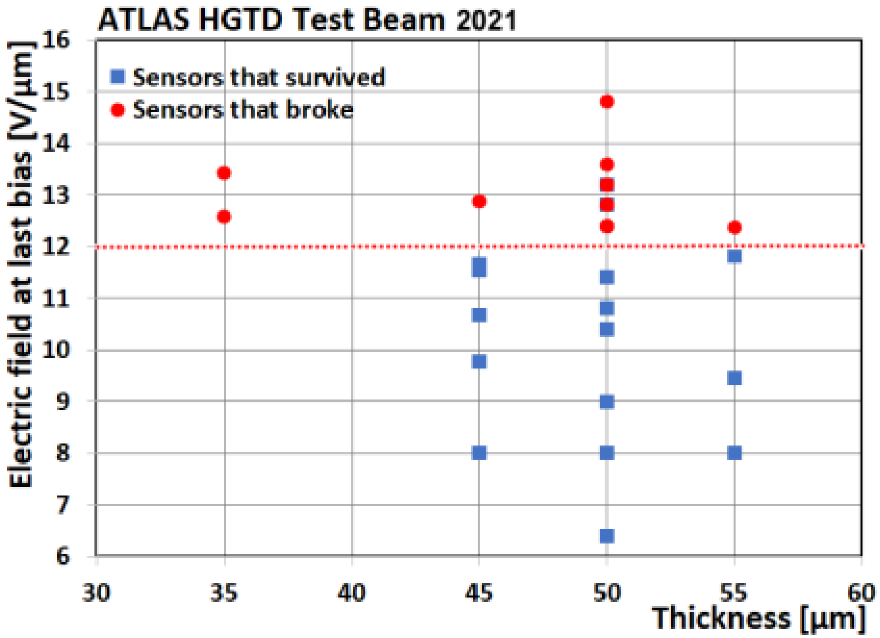
Beam test were done on irradiated LGADs to check candidate sensors are safe from SEB at biases meeting HGTD specifications.

➢Test beam @DESY(3 GeV electrons) and @CERN SPS(120 GeV pions) in 2021

- Using EUDET-type telescope + thermal box + TLU

- Sensors with a larger active material thickness were able to withstand a higher bias
- start to break once they reach 12 V/μm regardless of the LGAD design





No fatality was observed at $E=V_{bias}/D < 12$ V/μm

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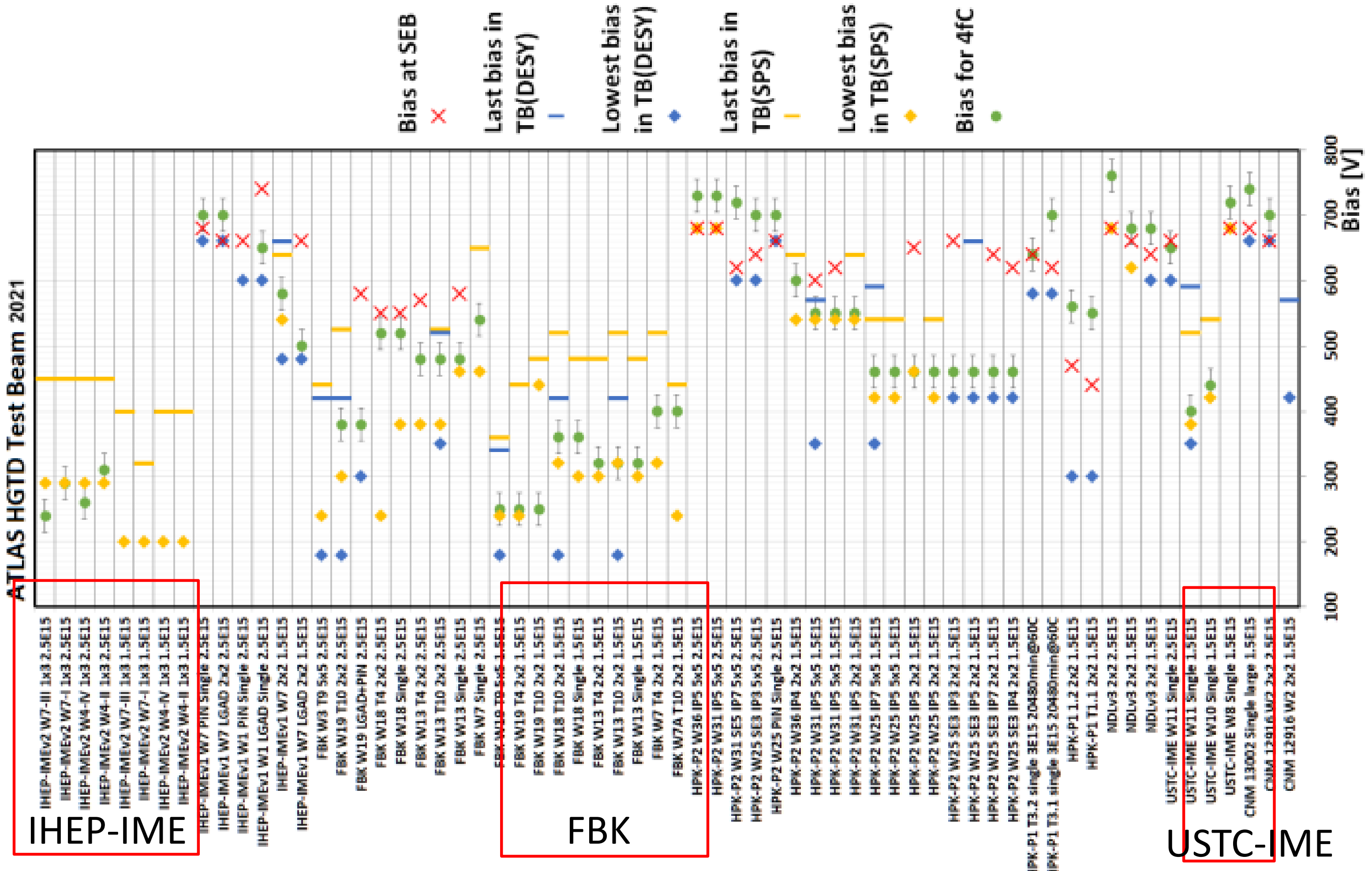
LGAD: beam test

➤ **All carbon based gain layer sensor are safely below SEB threshold at the required performance.**



Bias at SEB
Last bias in TB(DESY)
Lowest bias in TB(DESY)
Last bias in TB(SPS)
Lowest bias in TB(SPS)
Bias for 4fC

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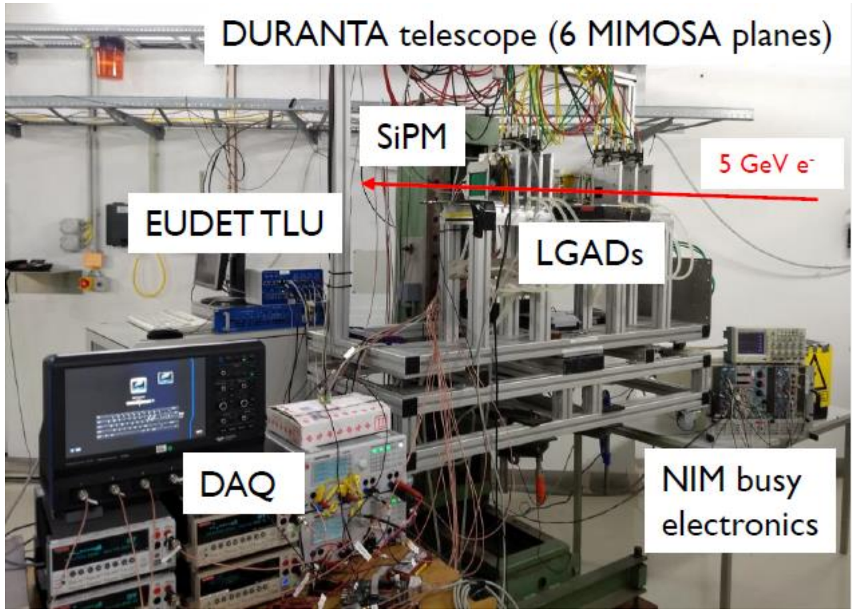
LGAD: beam test

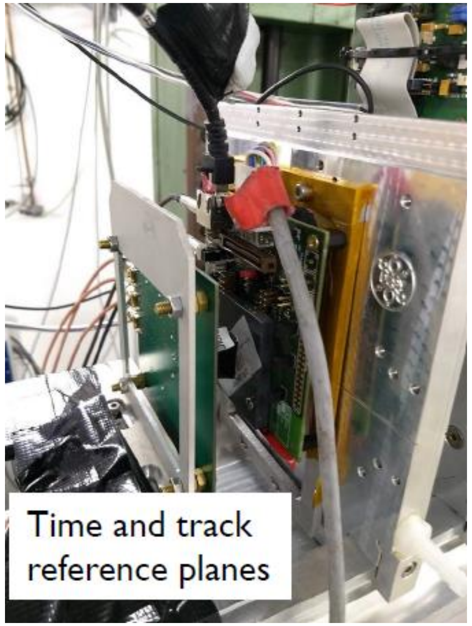
- **LGAD performance studies(at -30℃)**

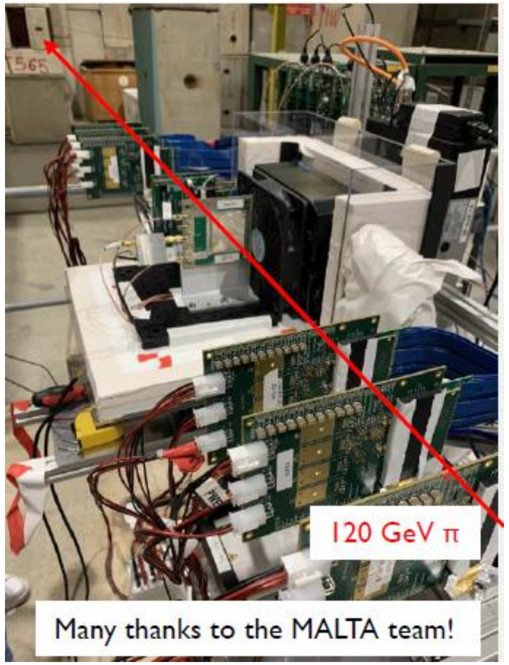
  Qualify sensor performance for most promising LGAD(Carbon enriched)

- Test beam @DESY and @CERN SPS in 2022
  - CERN North Area SPS H6A beamline (120 GeV pion beam)
  - DESY T22 beamline (5 GeV e-beam)
  - Beam telescopes for tracking (EUDET-type/MALTA)
  - C-enriched prototypes from 3 vendors(FBK, IHEP-IME and USTC-IME)

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

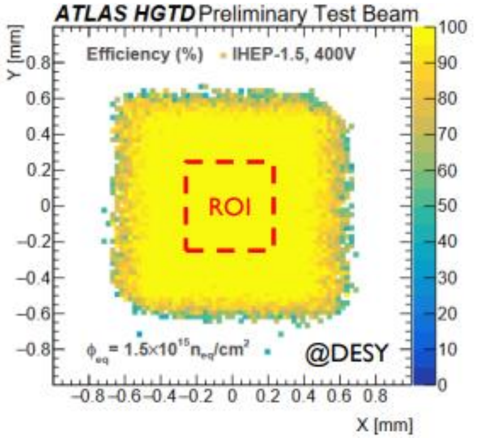


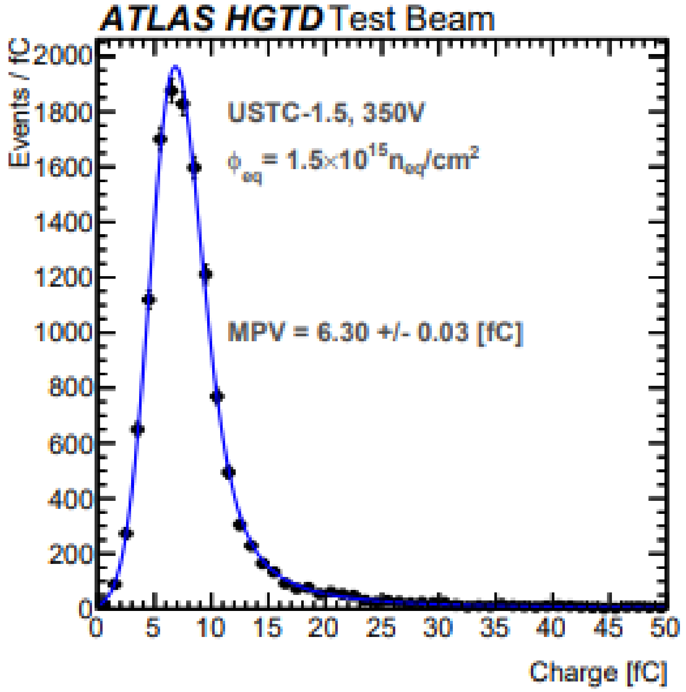


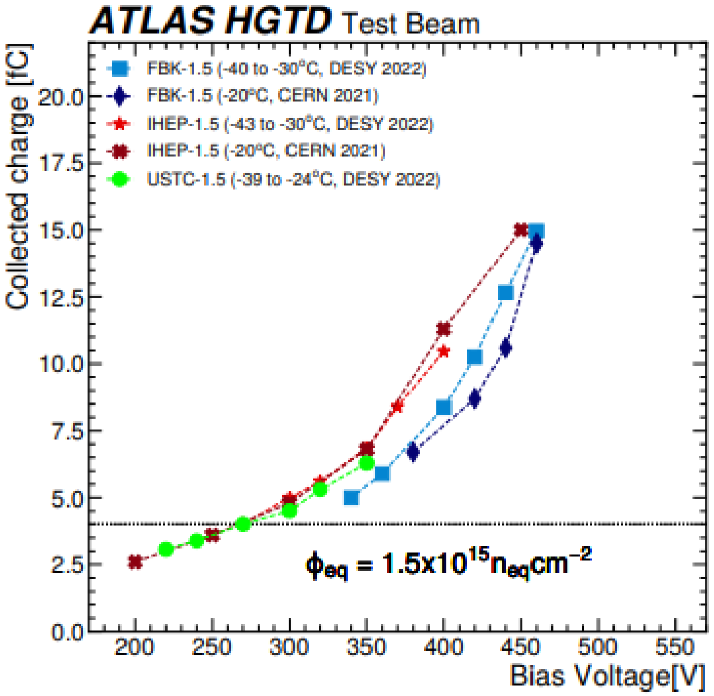


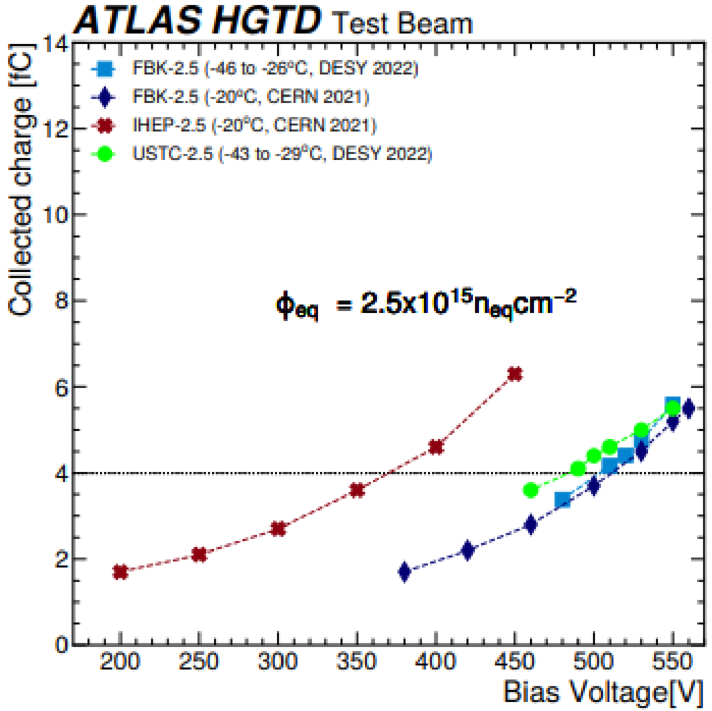
LGAD: beam test

- ➢Distribution of charge in the ROI be fitted with a Landau-Gaussian convoluted function
- ➢Collected charge is defined as the most probable value (MPV) from fit
- ➢LGAD sensors can collect 4fC charge (minimum charge needed by the ASIC to hold good time resolution) at voltage lower than 550V(SEB safe zone).









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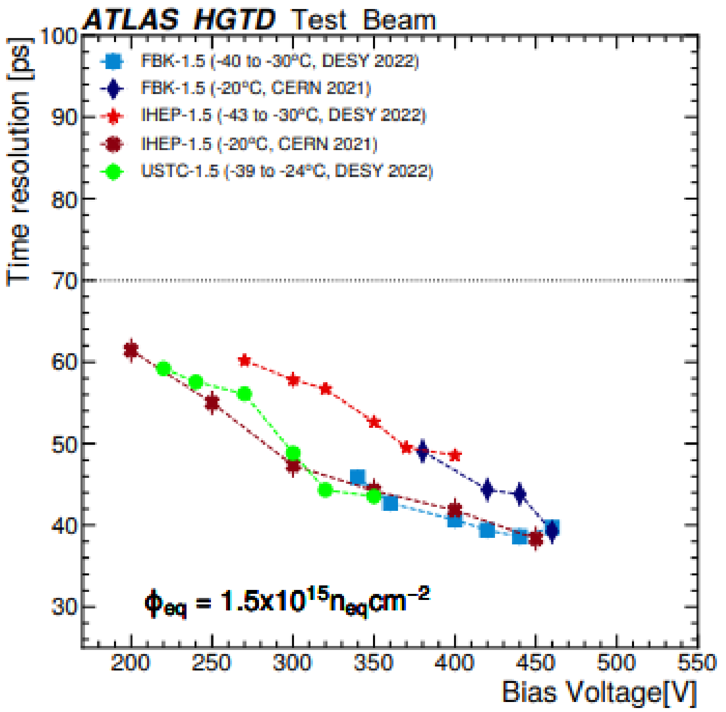
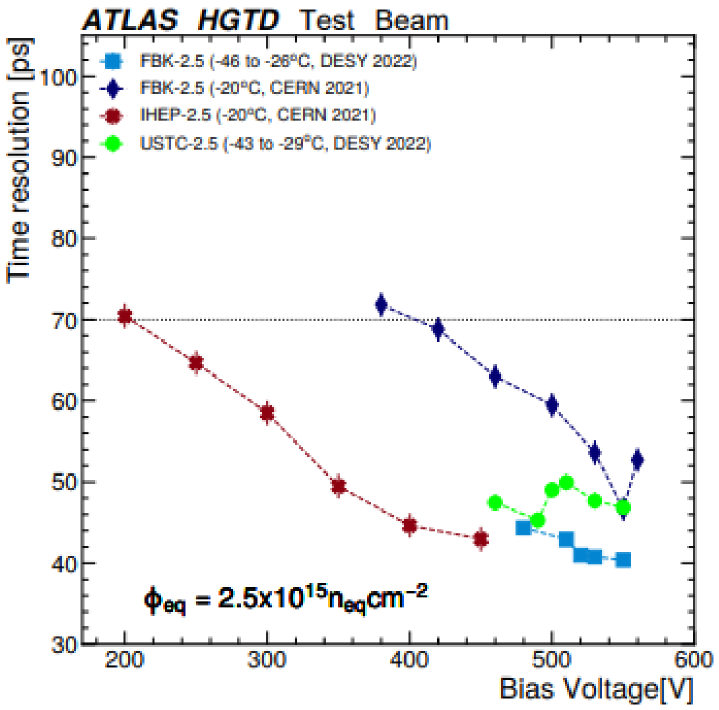
LGAD: beam test

- To extract the DUTs' time resolutions, the distributions of the difference between the TOA of the DUTs 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 tested (σ_{SiPM}=62.6 ps, $\sigma_{\mathrm{CNM}-0}$ =54.8 ps), then the time resolution of the testing one can be calculated using the above formula.





Carbon enriched sensors have <70 ps timing resolution after 2.5x10^{15} n$_{eq}$/cm^2.

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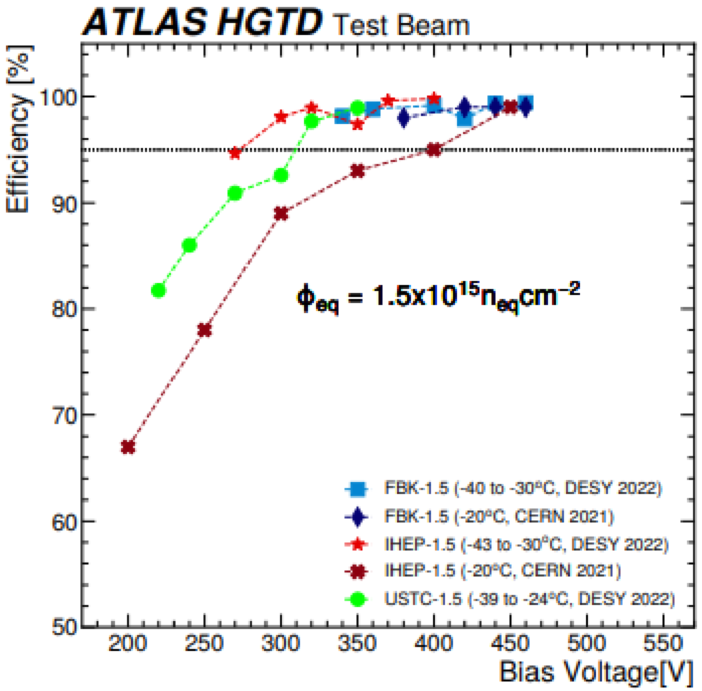
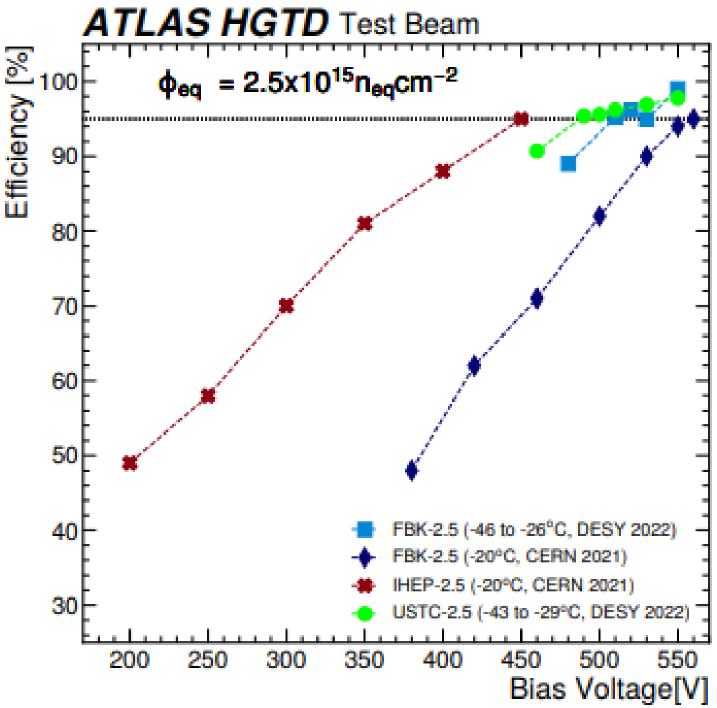
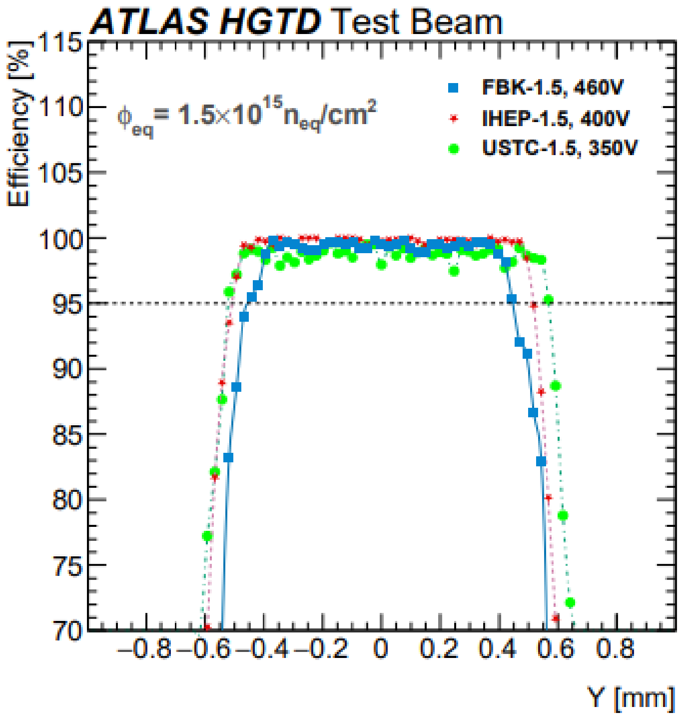
LGAD: beam test

- ➢Hit Efficiency is set according to the formula: $$\text{Hit Efficiency} = \frac{\text{Reconstructed tracks with } q > Q_{cut}}{\text{Total reconstructed tracks}}$$
- ➢Q_{cut} is set to 2 fC, the minimum achievable threshold of the future ALTIROC chip
- ➢ **LGAD sensors can achieved the efficiency of 95%, which is required for good operation of the future HGTD after irradiation**







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LGAD: beam test

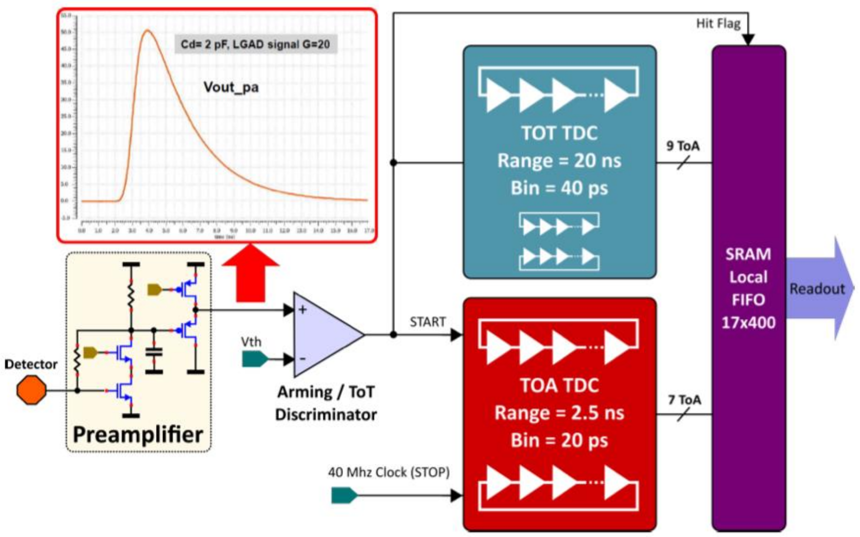
- LGAD readout ship: (ALTIROC3 under testing)

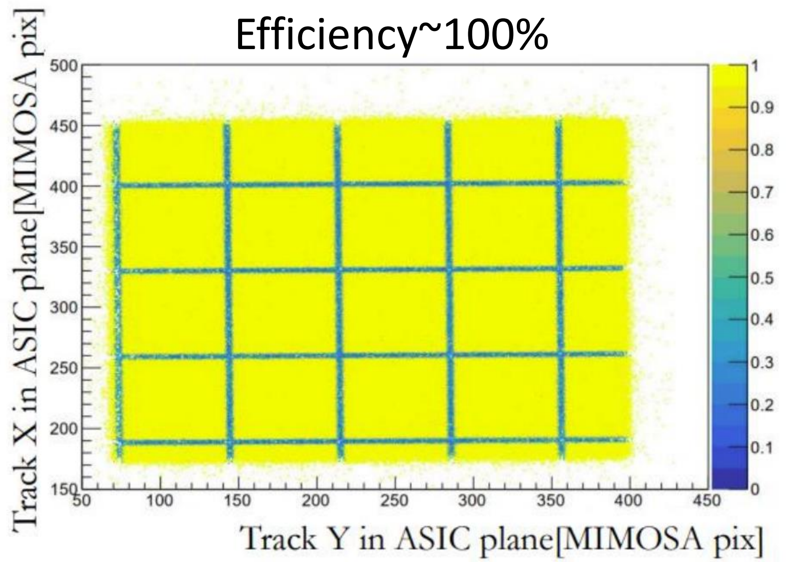
225 front-end channels in ALTIROC, each channel has

- A preamplifier followed by a discriminator
- Two TDC (Time to Digital Converter) to provide digital Hit data
- One Local memory: to store the 17 bits of the time measurement until L0/L1 trigger

- **Efficiency measurements** in the test beam(CERN SPS, 2023) with ASIC(ALTIROC2) and full size detector FBK4.0.

- Timing resolution of LGAD 15x15 array sensors with ASIC be tested in TB(DESY, 10.2023), results be shown next.





LGAD sensor for HGTD

- LGAD sensors pre-production for HGTD project is ongoing.(In-kind and CERN procurement)
- Several batches of LGAD sensors be fabricated. (USTC-IME, IHEP-IME)

Pre-production：

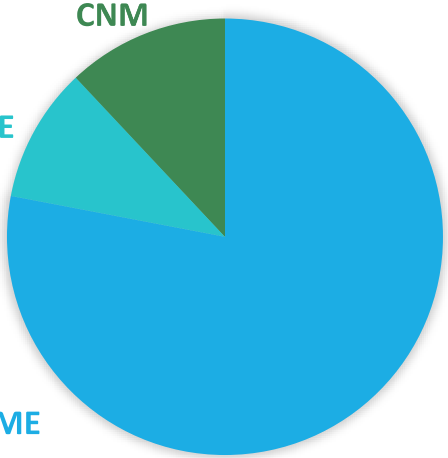
IHEP-IME：

24%(in-kind)

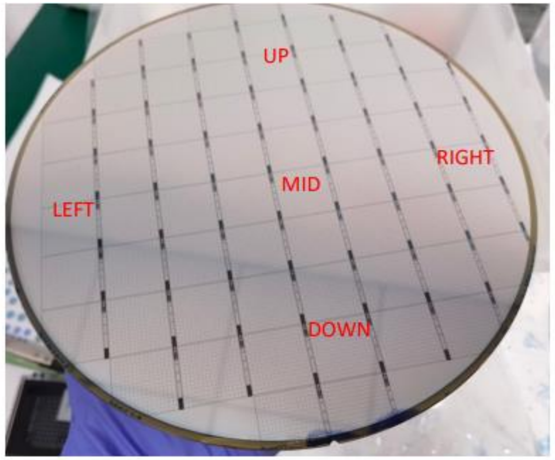
54%(CERN procurement)

USTC-IME: 10%(in-kind)

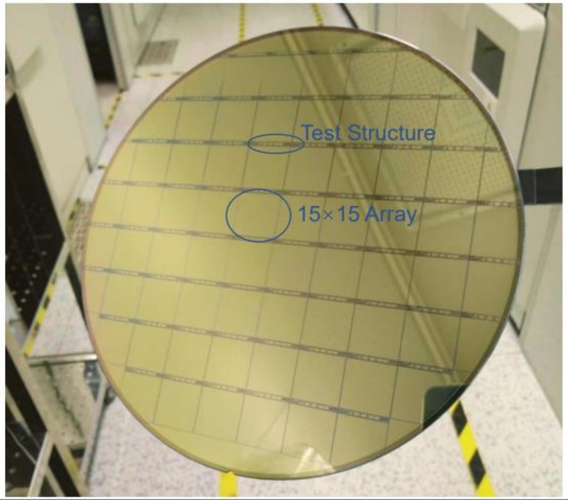
CNM: 12%(in-kind)



USTC-IME
Pre-production
27wafers be fabricated



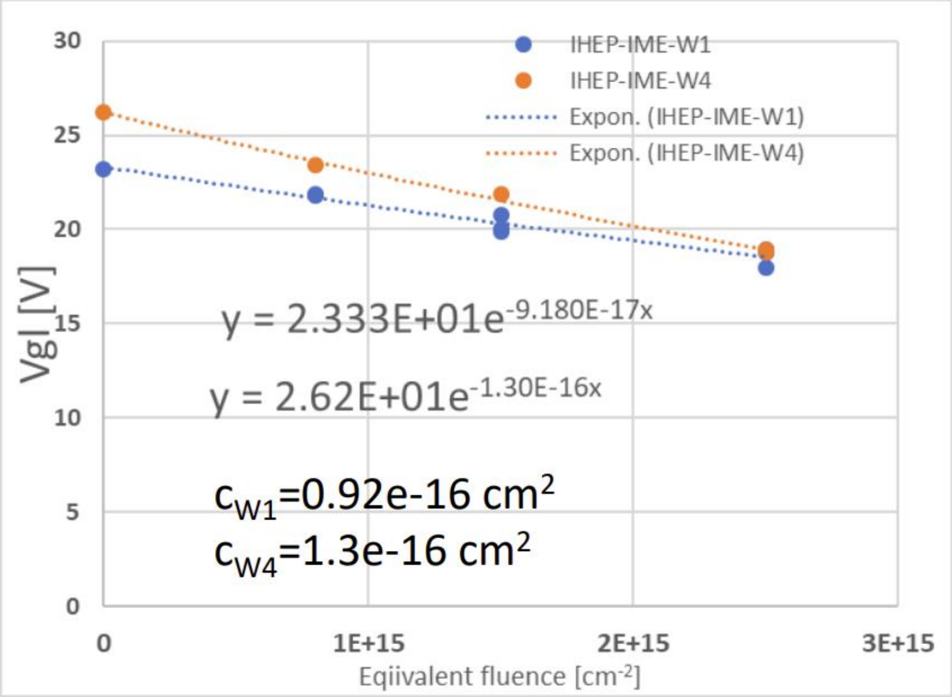
IHEP-IME
Pre-production
>80 wafers be fabricated

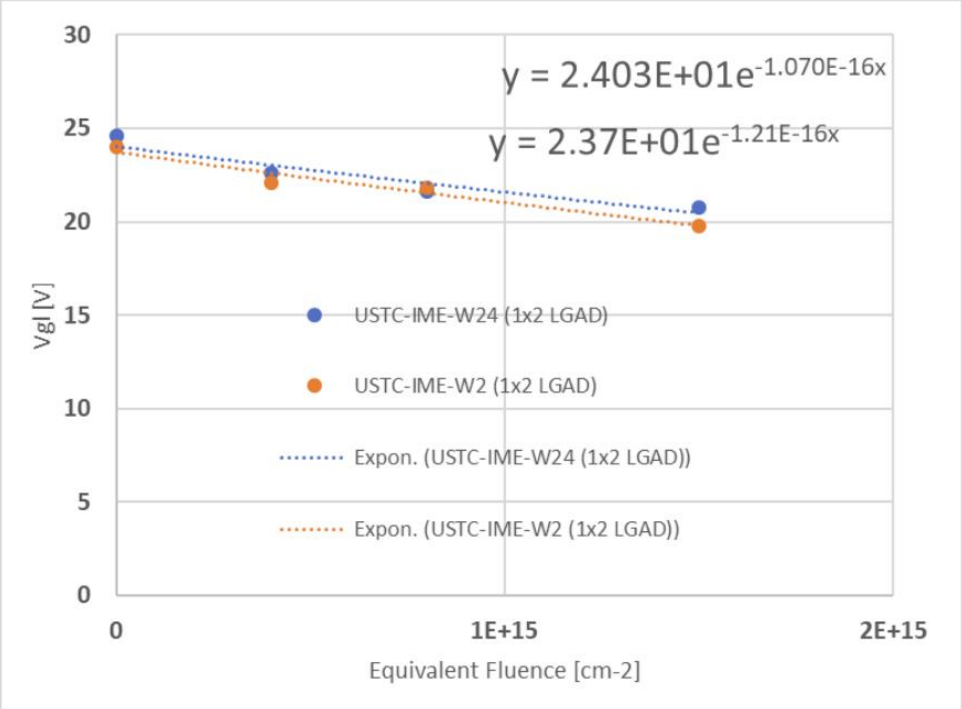


- 15x15 array sensors and test structure
- 52 sensors on one 8inch wafer

LGAD sensor for HGTD

- Preliminary results of sensors from pre-production show comparable irradiation performance with R&D run.





- QC-system(probe card, switch matrix, DAQ system) for sensors quality assurance is prepared. Testing including QC in institutes and irradiation testing is ongoing.

- Production will start at April next year.

LGAD sensor for CEPC

Use timing information of particle for better physics program

Motivation

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

- **Particle separation** of Gas detector (dE/dx) for CEPC flavor physics:

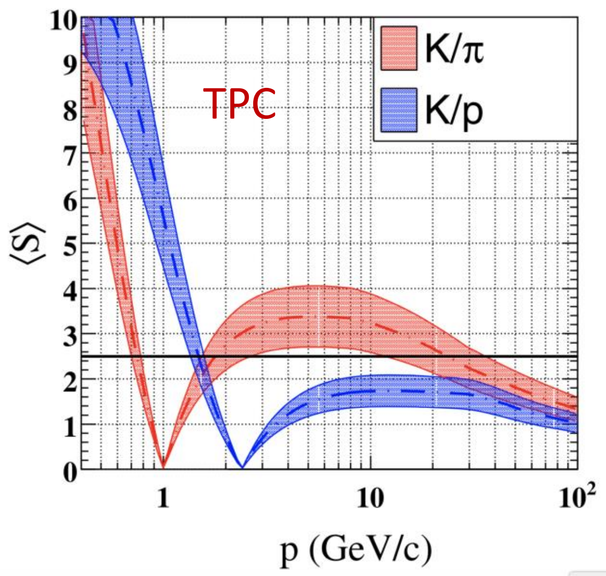
  0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation

- **Combined gas detector with Timing detector: Particle separation ability improved**

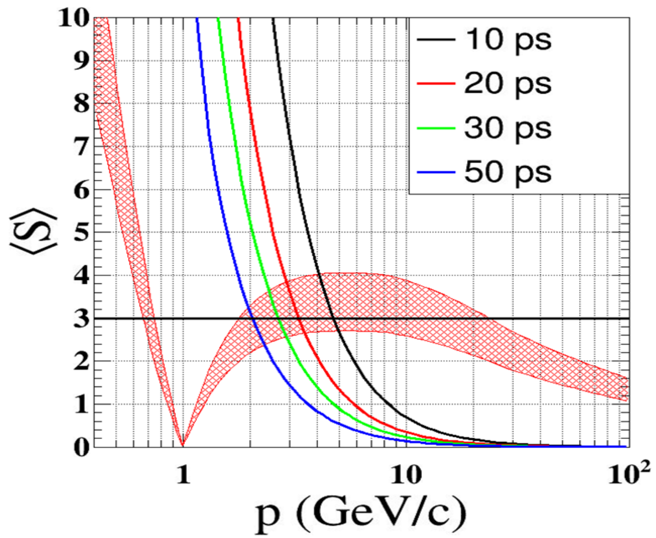
  0 - 4 GeV for K/π separation, **0 – 8 GeV** for K/p separation

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

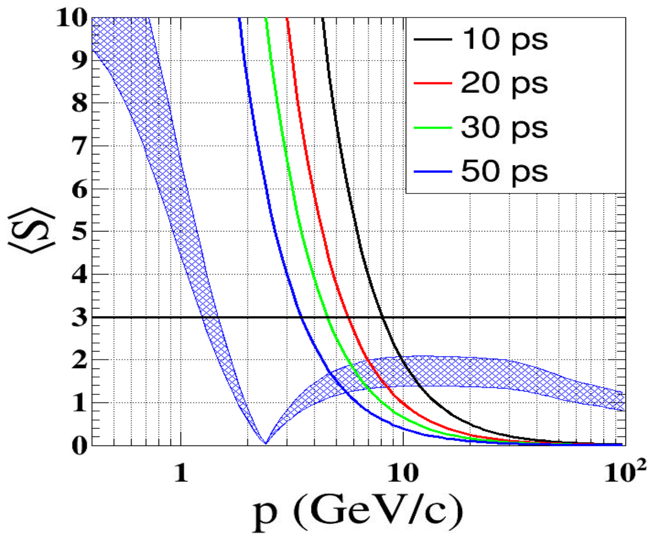
  Precision timing detector should be determined as a matter of urgency (4D track)



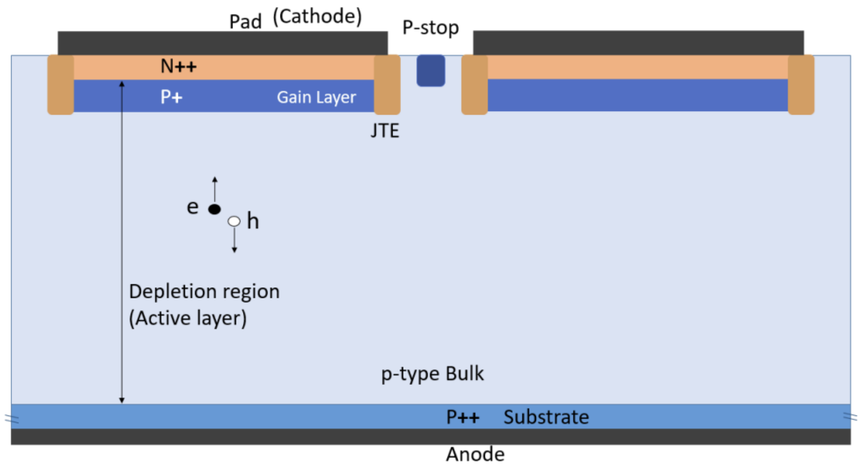
k/π Separation

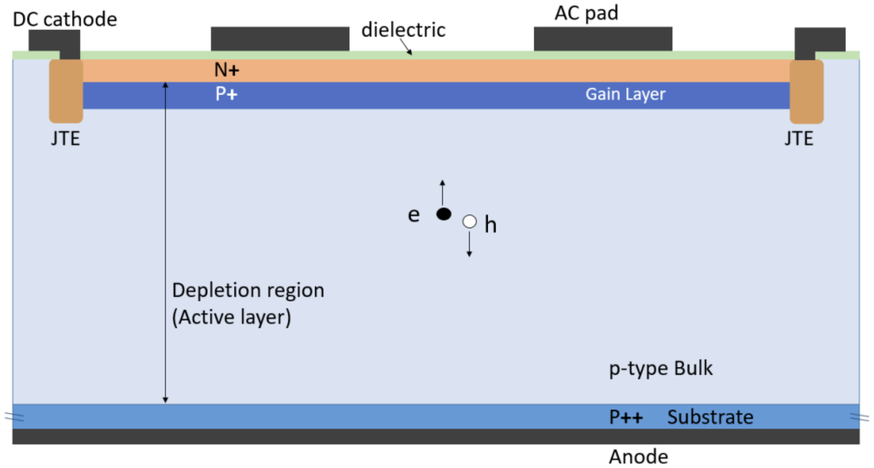


k/p Separation



AC-LGAD





HGTD standard LGAD

Pixel size: 1.3mmx1.3mm

Dead zone: 100um

Time resolution: <30ps

AC coupled metal pads with a thin dielectric (SiO_2, Si_3N_4)

No dead zone (100% fill factor)

Position resolution: 5~10 um

Time resolution ~ 30ps

Application:

Electron-Ion Collider (EIC)：

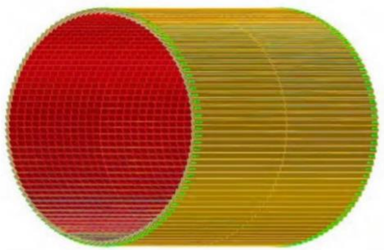
Central detector(ETTL, CTTL, FTTL)， Far-Forward detector

REDTOP: LGAD tracker, 4D tracking reconstruction for multihadron rejection

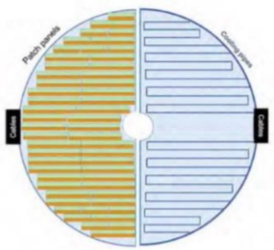
EIC： AC LGAD-based

Outer layer of Tracker and TOF detector

Barrel AC-LGAD detector



Hadron endcap AC-LGAD detector



CEPC TOF detector

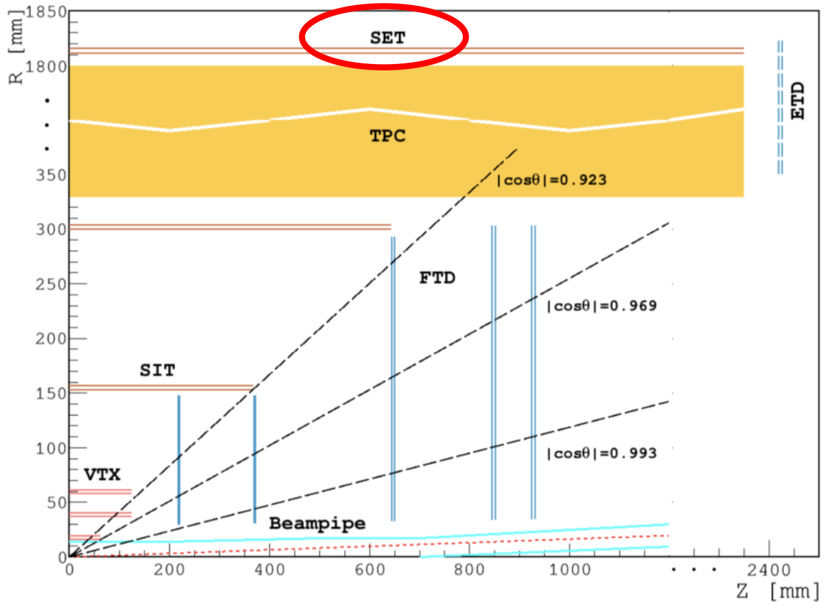
CEPC time of flight detector based on LGAD：

- Be part of SET (silicon wrapper layer outside TPC or drift chamber)

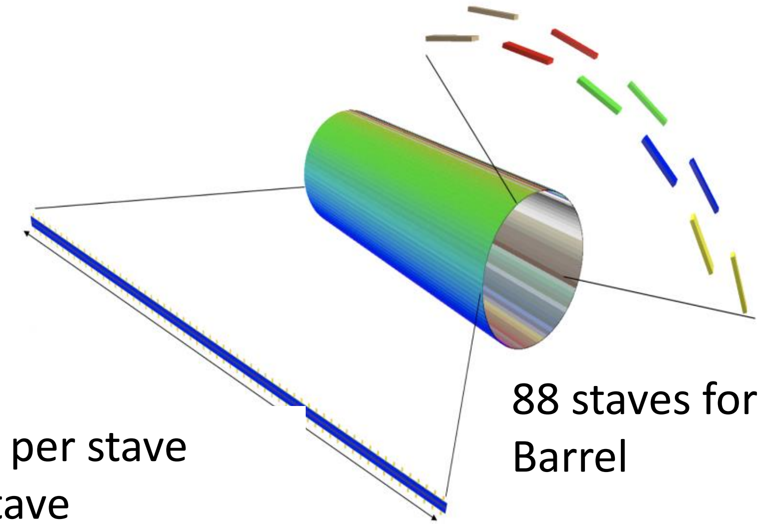
Timing resolution: 30-50 ps, Spatial resolution: ~ 10 μm

- Area of detector (Barrel : 50 m^2 , Endcap 20 m^2)
- Strip-like sensor (each strip: 4cm × 0.1 cm): to reduce the readout channel

Baseline detector concept in CDR



Timing detector in Barrel region



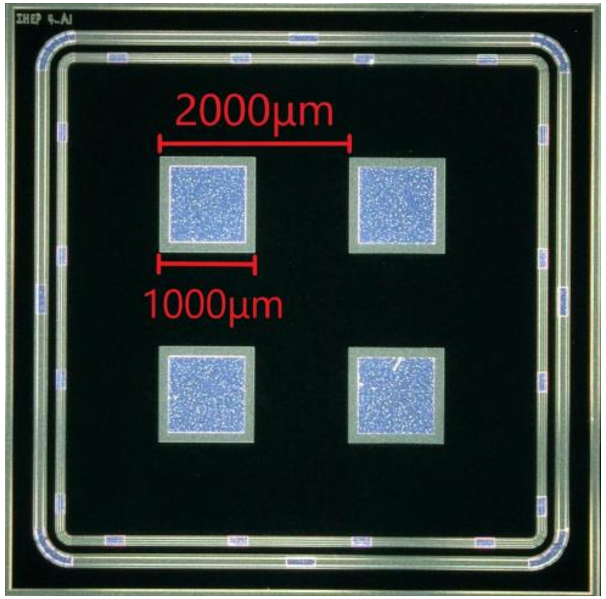
60 modules per stave
2.4 m per stave

88 staves for the Barrel

Design and Production of AC-LGAD

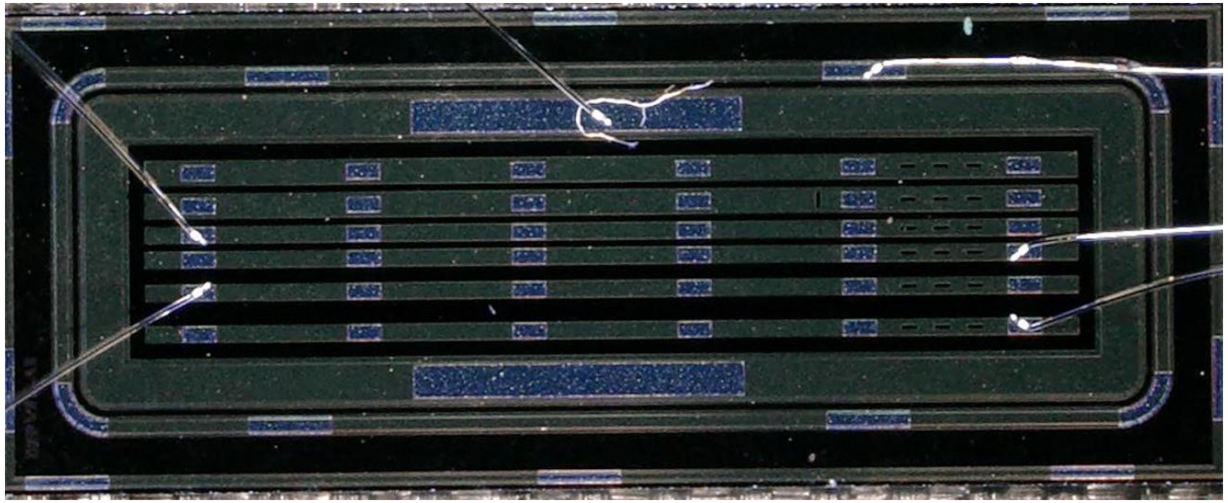
IHEP AC-LGAD design

Pixel AC-LGAD



Different process parameters:
n+ dose(phosphorus): 10P to 0.2P

Strip AC-LGAD



- Strip length 5.6mm
- pitch-pad:
  250-100um
  200-100um
  150-100um

Spatial resolution of AC-LGAD

Pixel AC-LGAD：(pitch-pad: 2mm-1mm)

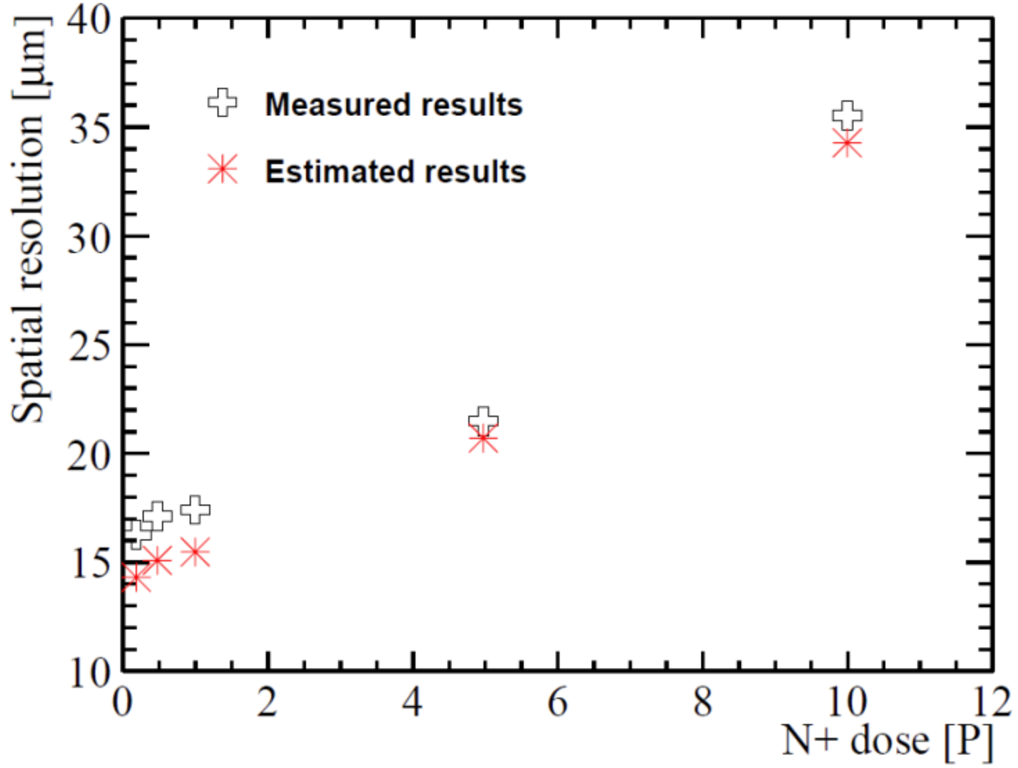
- 10 P → 0.2 P, spatial resolution reduce to 15um

Strip AC-LGAD:

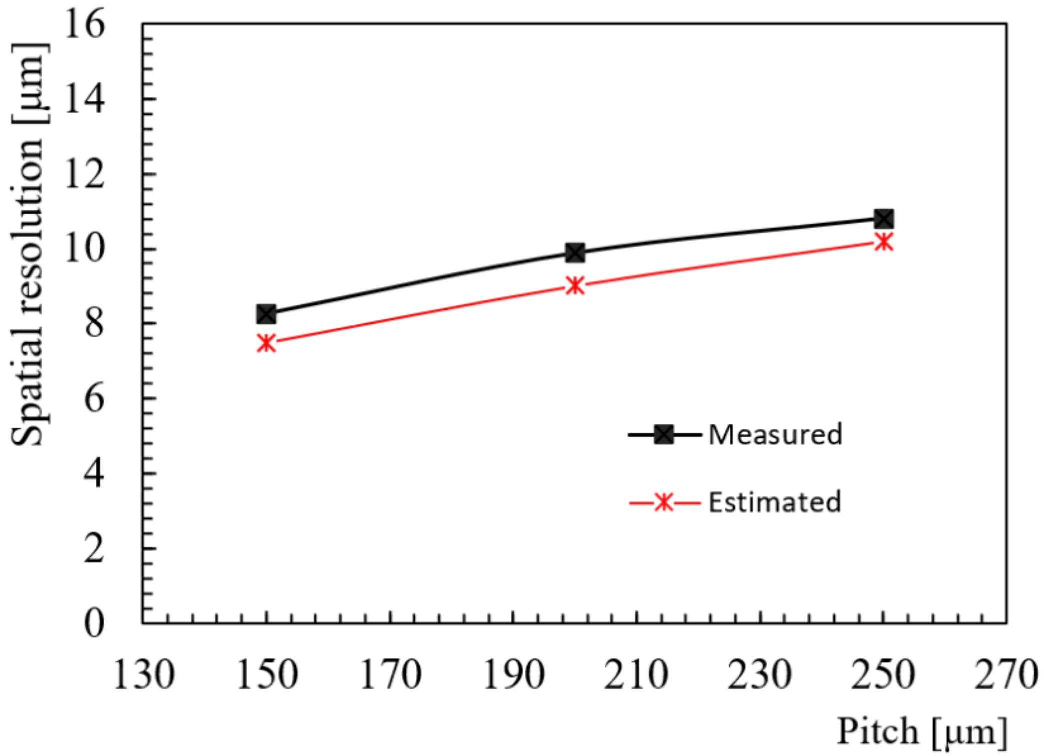
(pitch-pad: 250-100um, 200-100um, 150-100um)

Pitch size 250um →150um, spatial resolution 11→ 8 μm

Spatial resolution vs n+ dose



Spatial resolution vs pitch size



Summary

LGAD for ATLAS HGTD project:

- LGAD is chosen as sensors for HGTD project as it has good time resolution <30ps to improve pile-up.
- Carbon enriched LGAD sensors show good radiation performance. The sensors(FBK, IHEP-IME, USTC-IME) fill the HGTD requirement, including charge collection, time resolution and hit efficiency.

  Irradiated sensors work at lower than 550V

  Collected charge> 4fC

  Time resolution better than 70 ps

  An efficiency larger than 95%
- Laboratory test and Beam test all confirm the feasibility of an LGAD-based timing detector for HL-LHC.

LGAD for CEPC project:

- CEPC time of flight detector based on LGAD for Particle separation ability improvement
- AC-LGAD can provide spatial and timing information, be used for CEPC TOF detector.

Backup

HGTD detector

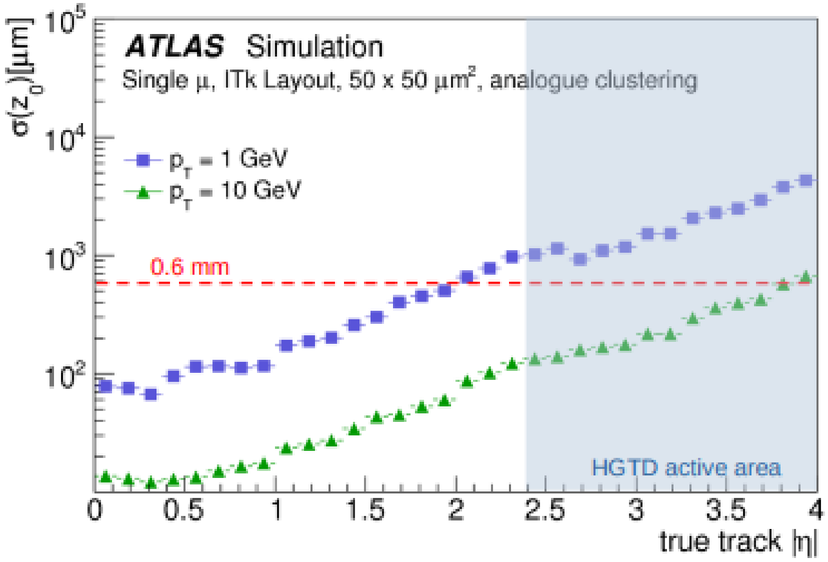
- At High Luminosity –LHC:
  - Instantaneous luminosity up to $7.5 \times 10^{34}\ cm^{-2}s^{-1}$
  - Pileup: $<\mu>$= 200 interactions per bunch crossing ~1.6 vertex/mm on average

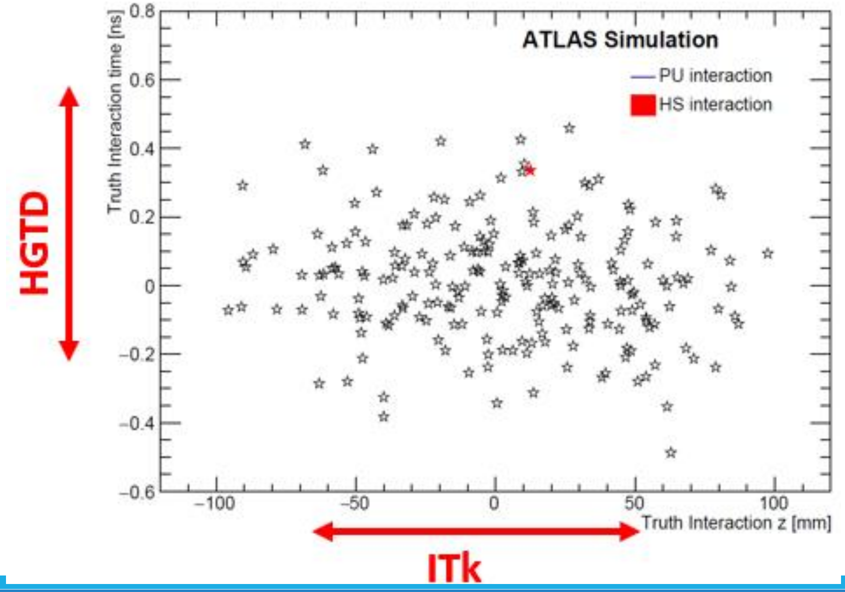
- Problems of the vertex reconstruction in ATLAS

  Degradation is more significant 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

- Timing information can be used to improve pile-up rejection and objects reconstruction

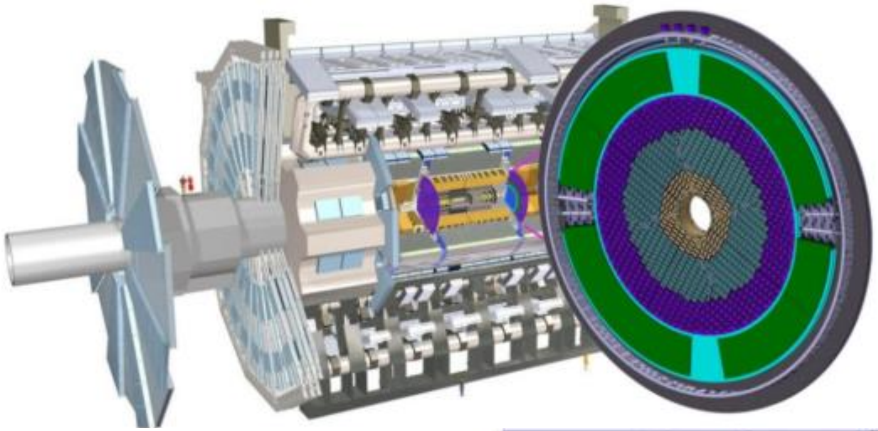
- A High Granularity Timing Detector (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation
  - Combining HGTD high-precision time measurement and ITk position information (vertices longitudinal impact parameter)
  - Will improve performance in the forward region
  - In addition, will provide a direct measurement on the luminosity





HGTD detector

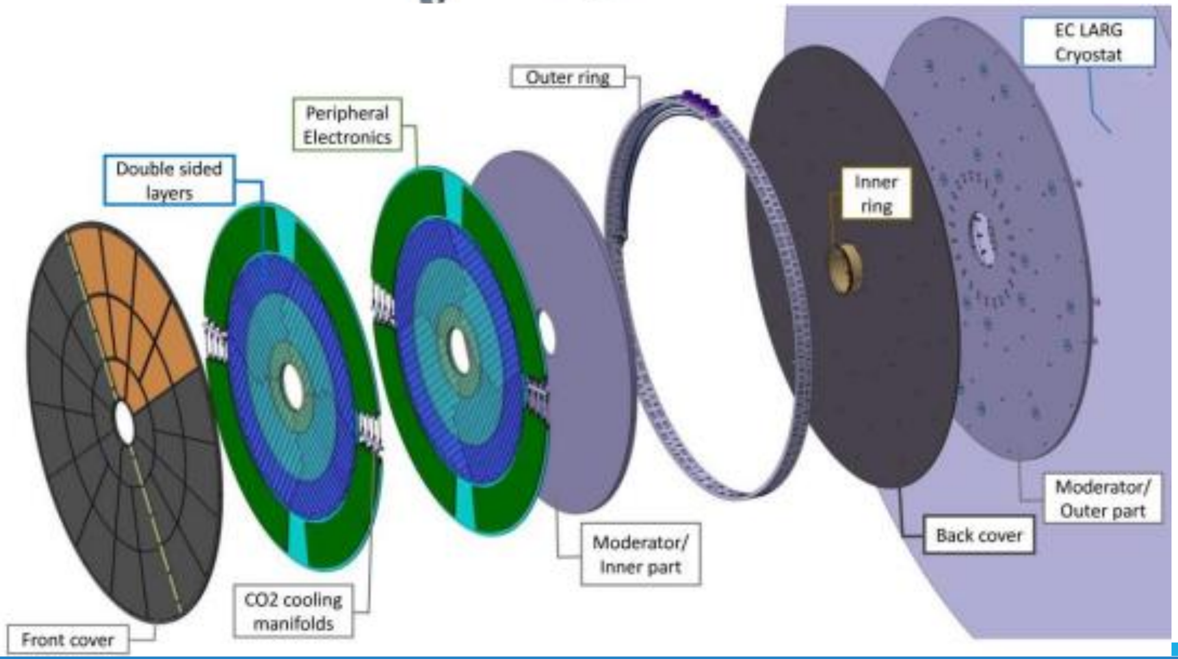
- The High Granularity Timing Detector (HGTD) is designed to provide precise timing information due to increased pile-up in HL-LHC.
  - ~3.6 million 1.3×1.3 mm^2 pixels(channels)
    - 6.4 m^2 active area
  - Time resolution target
    - 30-50 ps /track
    - 35-70 ps/hit up to $4000fb^{-1}$
  - Luminosity measurement
    - Count number of hits at 40 MHz (bunch by bunch)
    - Goal for HL-LHC: 1% luminosity uncertainty



- **Two end-caps**
  - z ≈ ±3.5 m from the nominal interaction point
  - Total radius: 11cm < r < 100 cm
  - Active detector region: 2.4 < |η| < 4.0

Each end-cap

- Two instrumented disks, rotated by 15° for better coverage

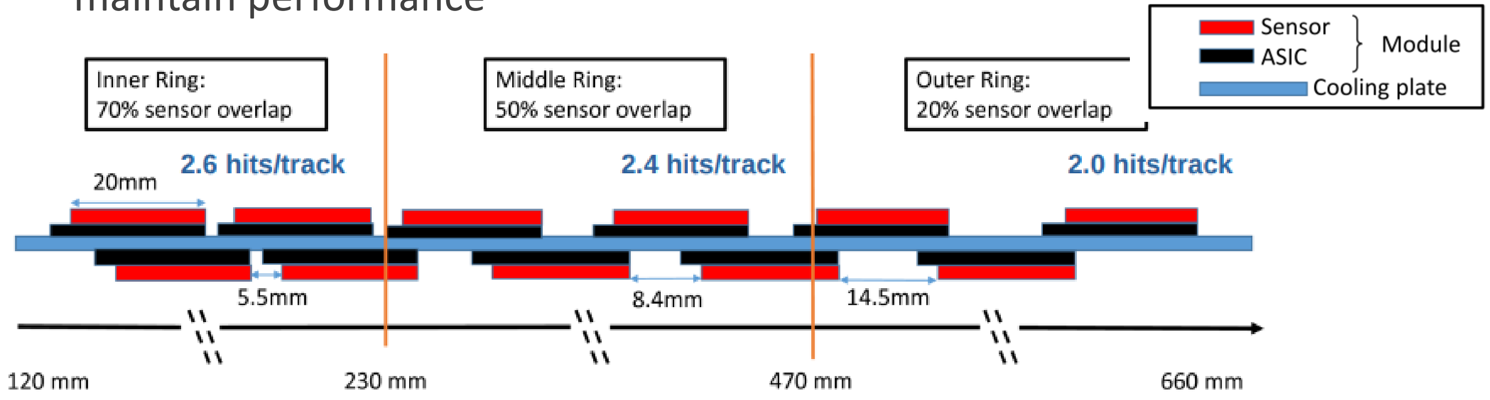


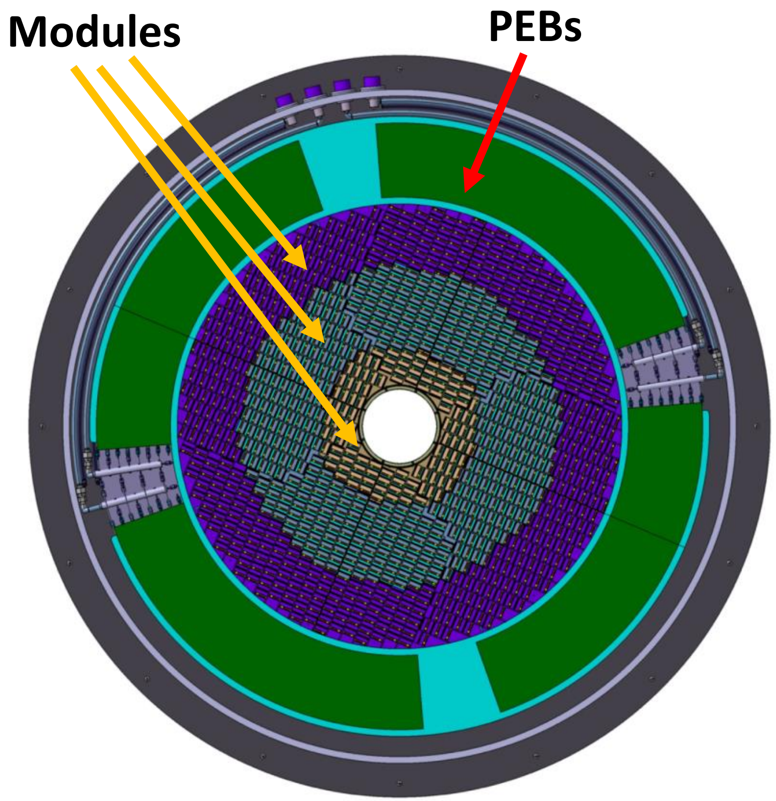
HGTD detector

2 disks, each Disk:

- Double-sided layers mounted on a cooling plate
- 3 rings layout regarding to the fluence received

  Overlap between modules on inner, middle and outer ring
- Replacement of inner ring every 1000 fb^{-1} and middle ring at 2000 fb^{-1} to maintain performance

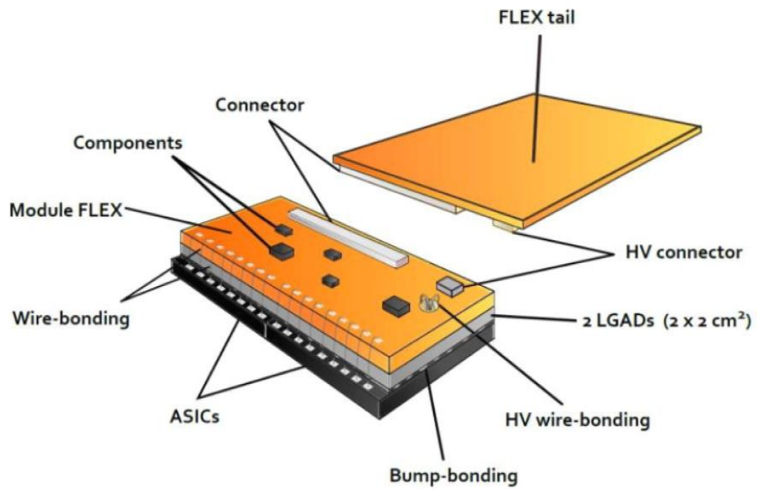




8032 modules, each module:

- consists of two hybrids

  (2 sensors+ 2 ASICs)
- 2x4cm^2, 15x30 channels



- Two bare modules be connected with one module FLEX
- Module Flex be connected via flex tails, arranged in rows, to the Peripheral Electronics Boards (PEB) @ 660 < r < 920 mm

More details about status of HGTD , see Shahzad's talk on 4th Sep.