Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector: laboratory and test beam campaigns

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Outline

- The ATLAS High Granularity Timing Detector (HGTD)
- LGAD sensor for HGTD
- LGAD sensor after Irradiation
- LGAD: laboratory test
- LGAD: test beam results

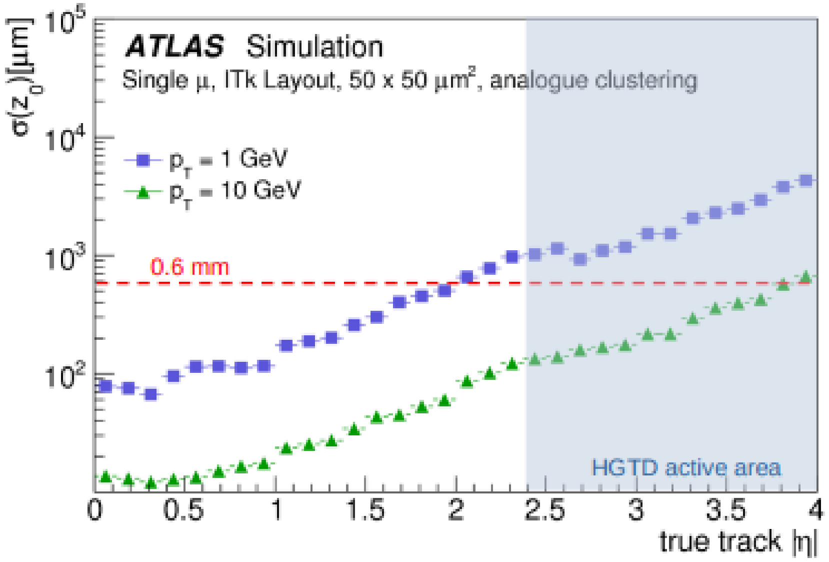
  end-of-lifetime studies, collected charge, time resolution, hit reconstruction efficiency
- Summary

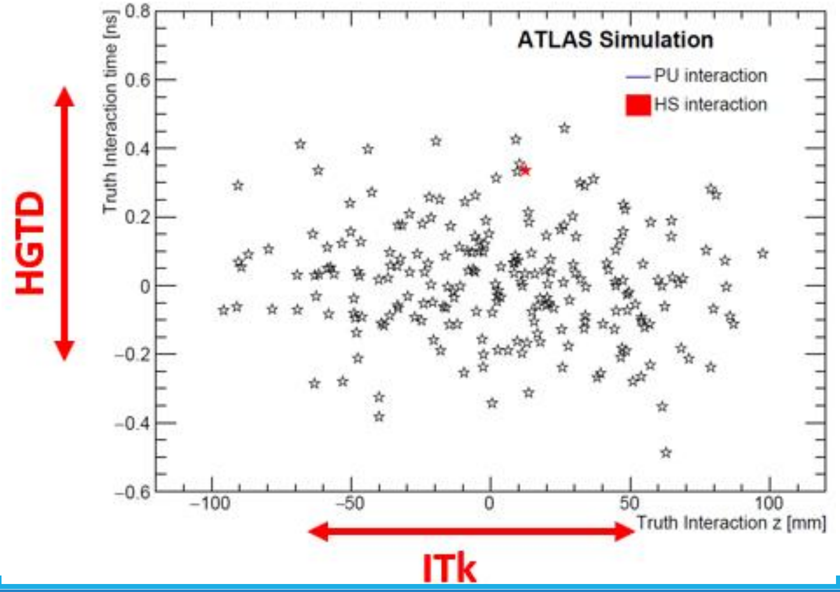
More details about status of HGTD , see Shahzad's talk on 4th Sep.

HGTD detector

- At High Luminosity –LHC:
  - Instantaneous luminosity up to 7.5×10^{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

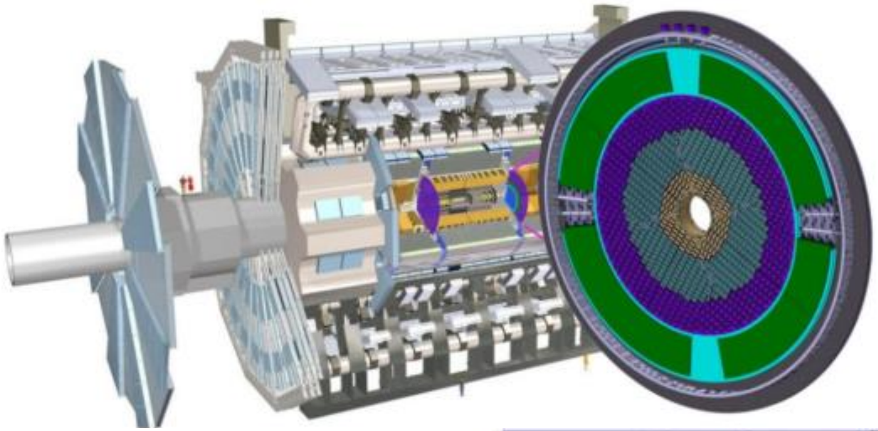
  Degradation is more significant in the forward region compared to the central region
  - Need z_0 resolution < 0.6 mm
  - Liquid Argon based electromagnetic calorimeter has coarser granularity
  - New inner tracker (ITk) has poor z resolution in the forward region
- Timing information can be used to 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

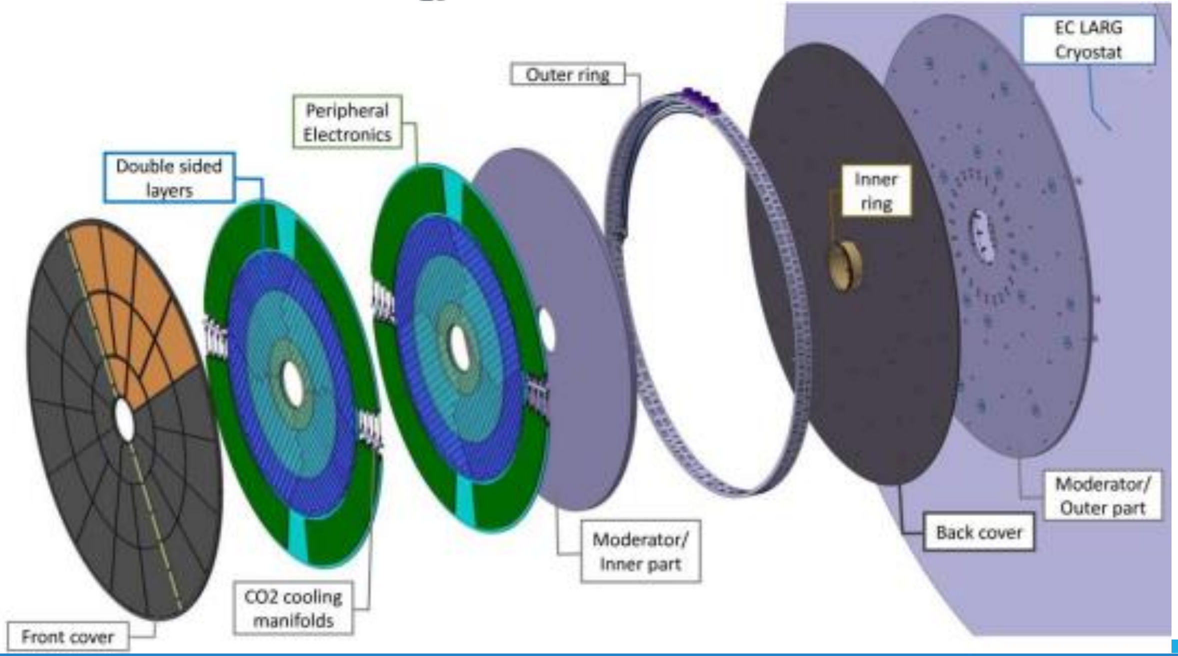
- The High Granularity Timing Detector (HGTD) is designed to provide precise timing information due to increased pile-up in HL-LHC.
  - ~3.6 million 1.3×1.3 mm^2 pixels(channels)
    - 6.4 m^2 active area
  - Time resolution target
    - 30-50 ps /track
    - 35-70 ps/hit up to $4000fb^{-1}$
  - Luminosity 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: $2.4 < |\eta| < 4.0$

Each end-cap

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

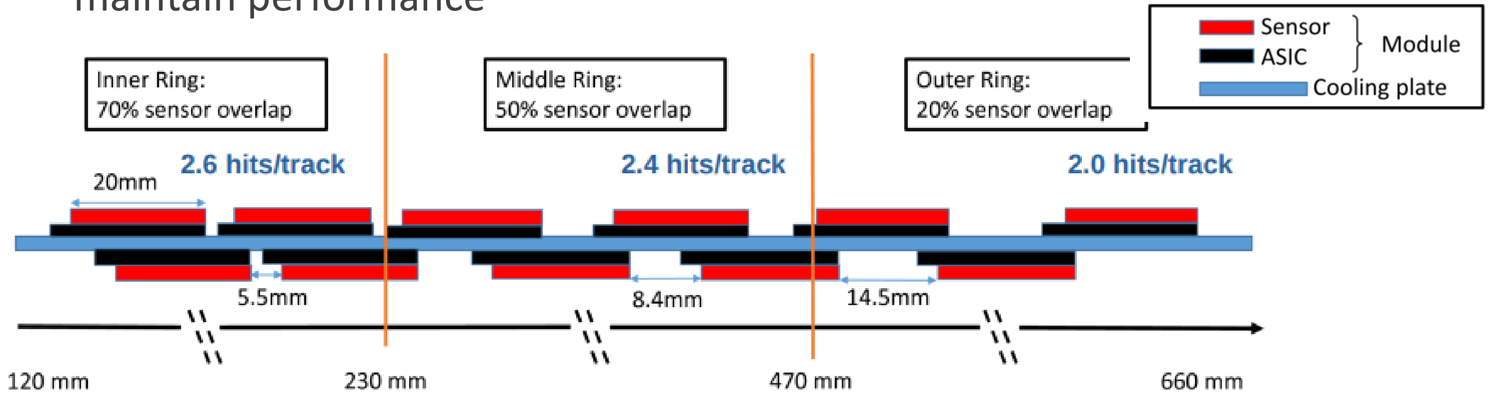


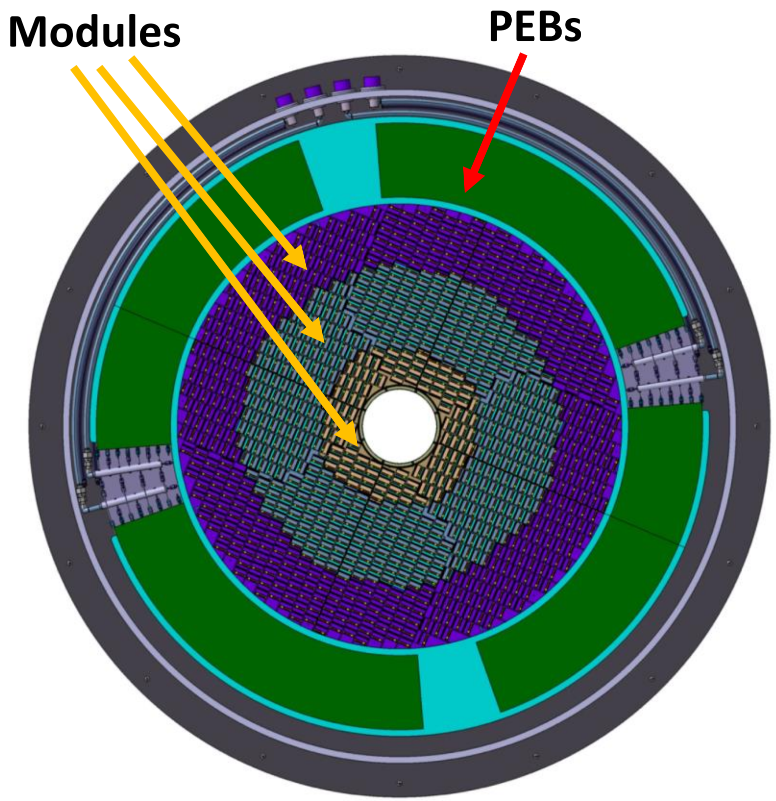
HGTD detector

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

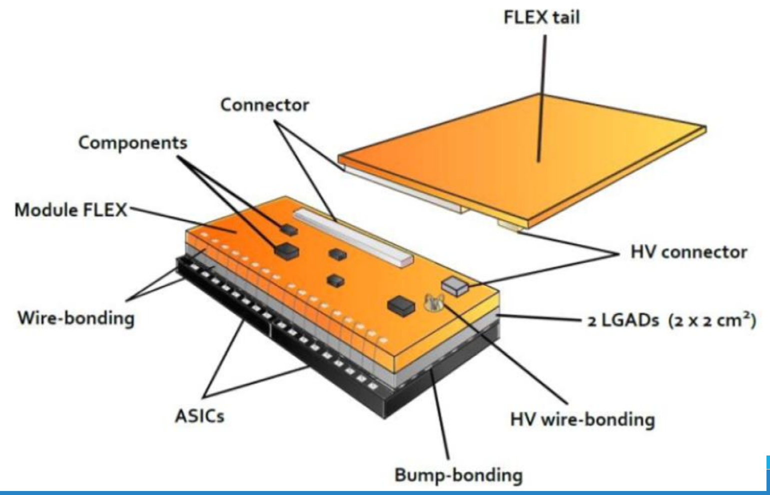




8032 modules, each module:

- consists of two hybrids

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

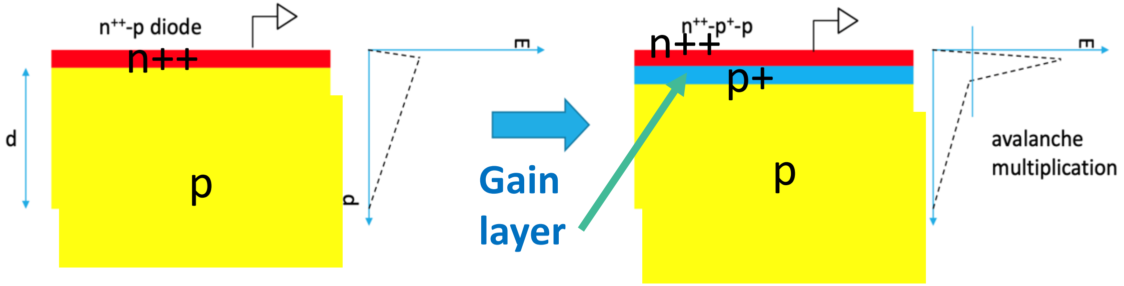


- Two bare modules be connected with one module FLEX
- Module Flex be connected via flex tails, arranged in rows, to the Peripheral Electronics Boards (PEB) @ 660 < r < 920 mm

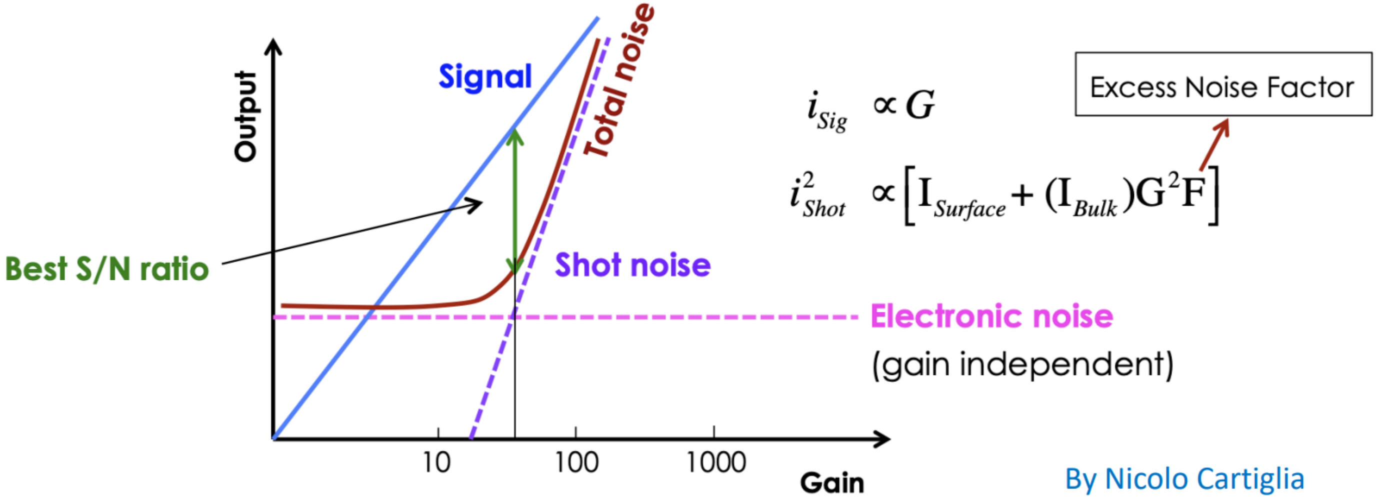
More details about status of HGTD , see Shahzad's talk on 4th Sep.

LGAD sensor

- **Low Gain Avalanche Detectors (LGAD)** is a new silicon detector technology developed recent years, that could measure the particle time at ps precision (20-30ps), mm position resolution before irradiation.
  - Compared with PIN, gain layer between P and N++
  - Work in linear mode, Gain:10~50
  - Thin depleted region to decrease t_{rise} (fast timing)
  - Good Signal/Noise ratio, no self triggering



- Due to its good timing performance, LGAD technology is chosen as detector for HGTD project.



By Nicolo Cartiglia

Noise increases faster than then signal

→ the ratio S/N becomes worse at higher gain

https://doi.org/10.1201/9781003131946

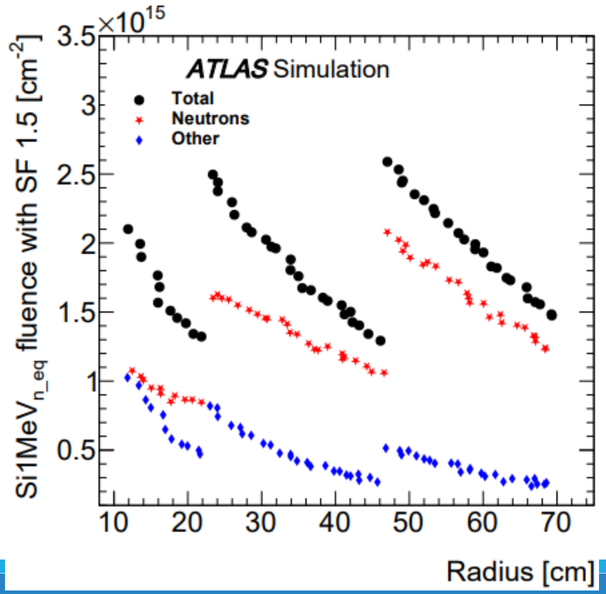
LGAD sensor for HGTD

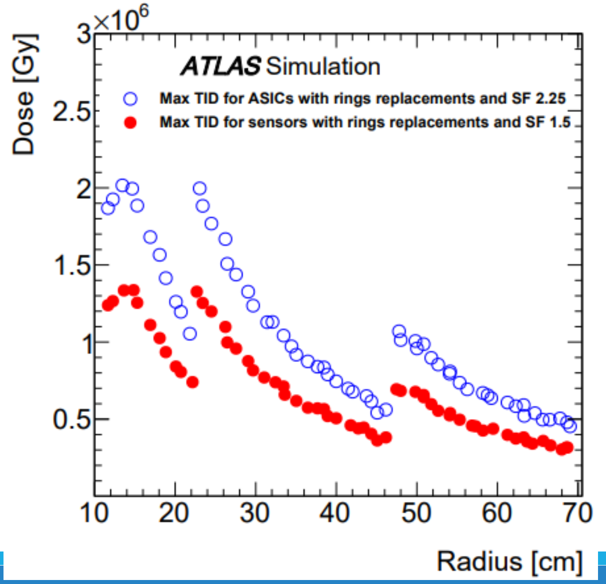
➢ Requirements:

•Size: 15x15 array, 1.3x1.3mm^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

Maximum fluence with replacements

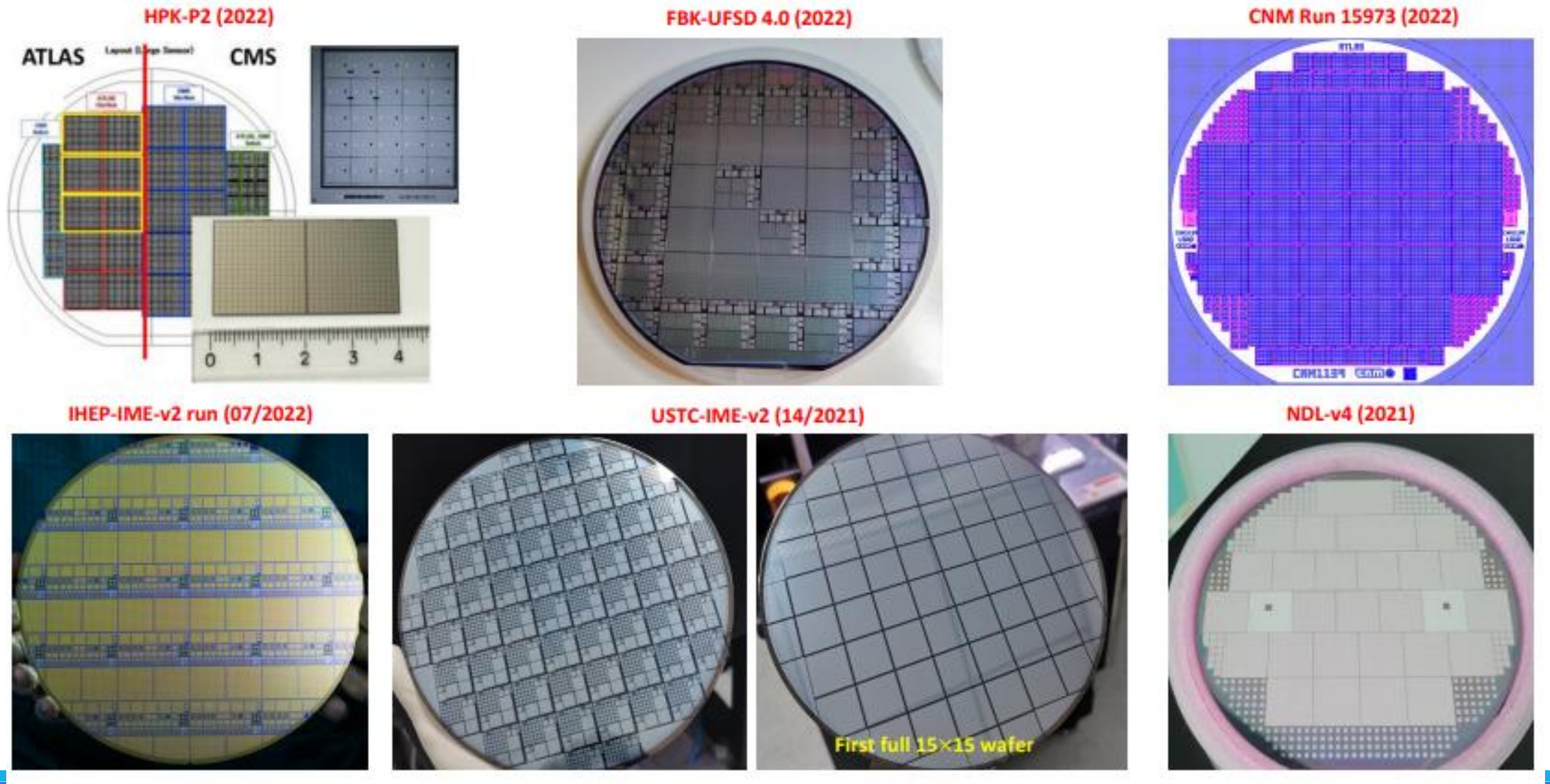
Replacement of inner ring every 1000 fb^{-1} and middle ring at 2000 fb^{-1}





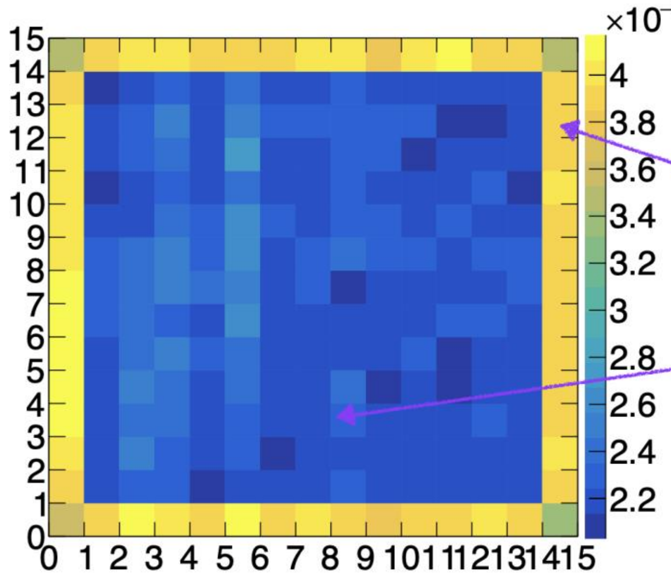
LGAD sensor for HGTD

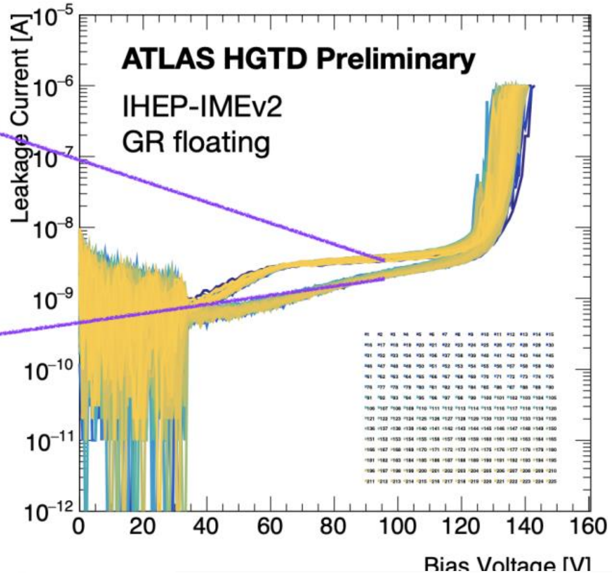
- LGAD sensors from many vendors have been extensively studied during the R&D phase of the HGTD project.
- Active vendors include: HPK (Japan), FBK (Italy), CNM (Spain), IHEP-IME (China), USTC-IME (China), IHEP-NDL (China) …

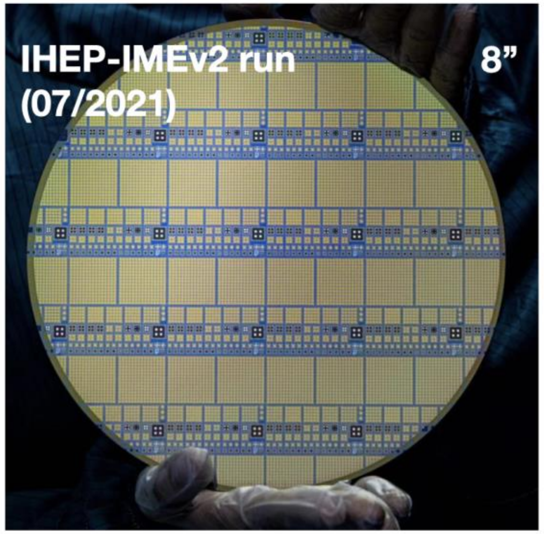


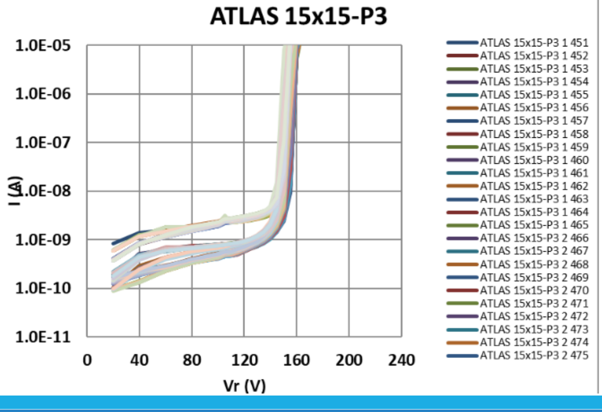
LGAD sensor for HGTD

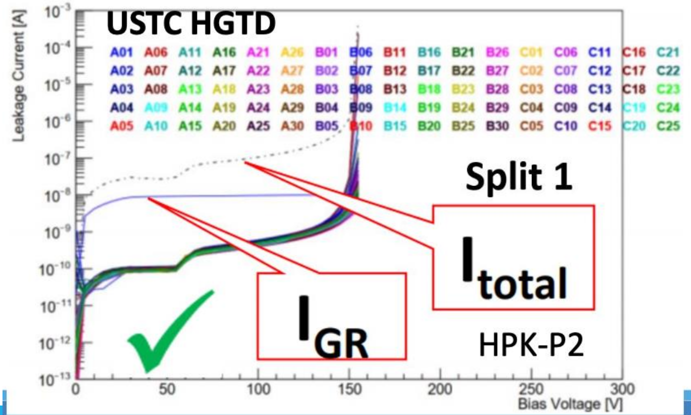
- Good uniformity of full size LGAD prototype (15x15 channels)
  - HPK, FBK, IHEP-IME, USTC-IME, CNM have produced good full-size LGAD prototype.

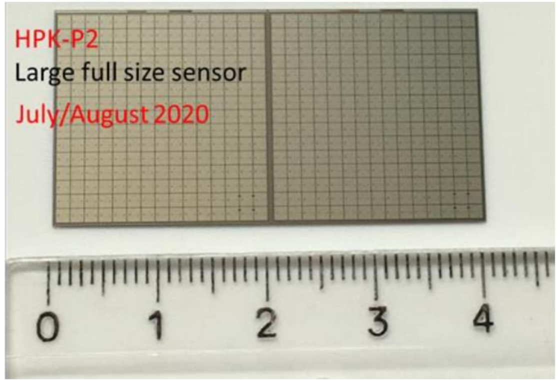








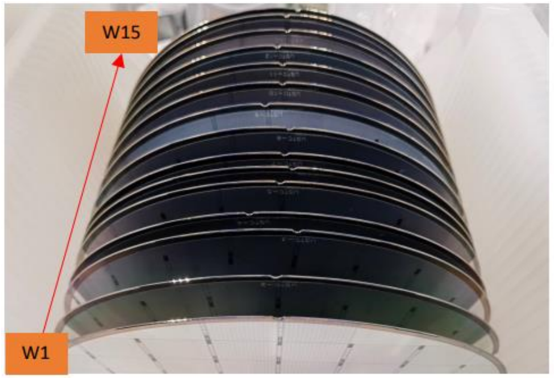


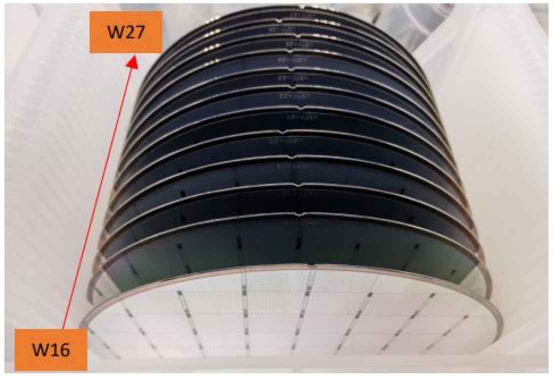


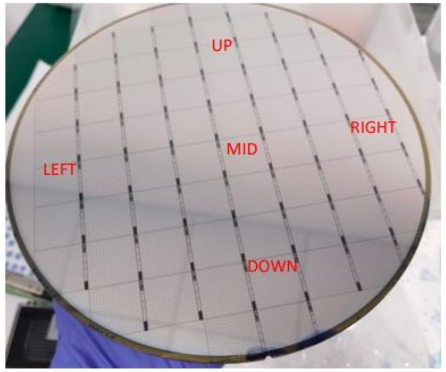
LGAD sensor for HGTD

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

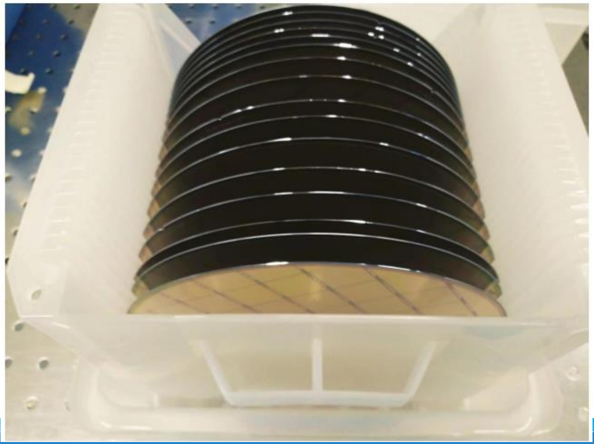
USTC-IME
Pre-production

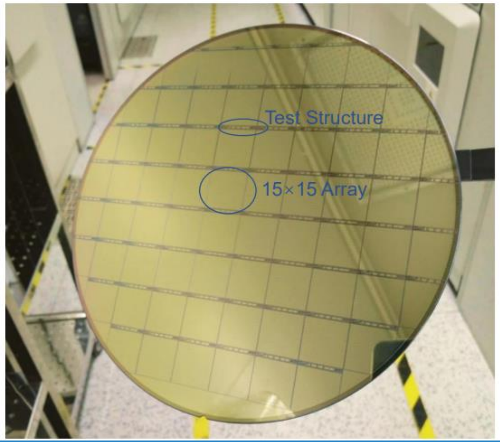






IHEP-IME
Pre-production





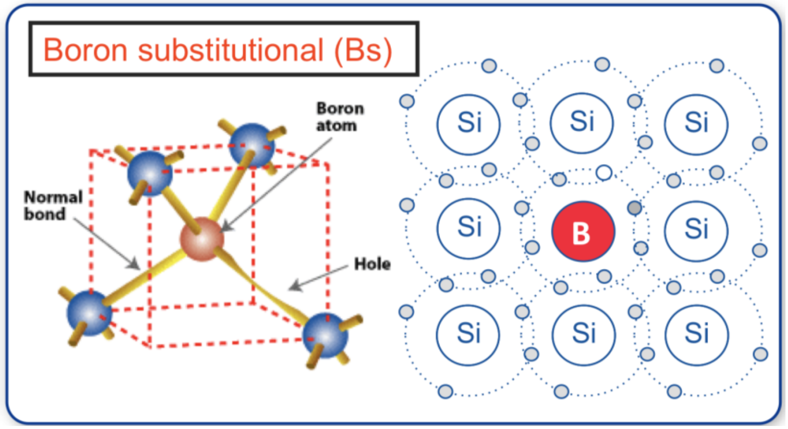
- 15x15 array sensors and test structure
- 52 sensors on one 8inch wafer

LGAD sensor after Irradiation

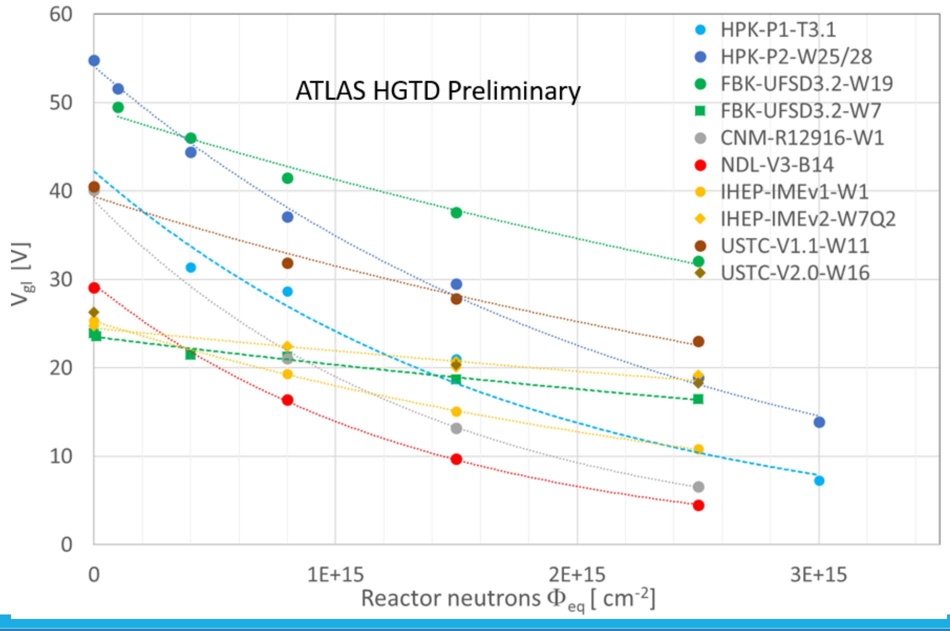
- Main challenge: Radiation Hardness
- Boron doping in gain layer became less active after irradiation （**acceptor remove**）
- Key parameter of the gain degradation is the acceptor removal coefficient: *c factor*

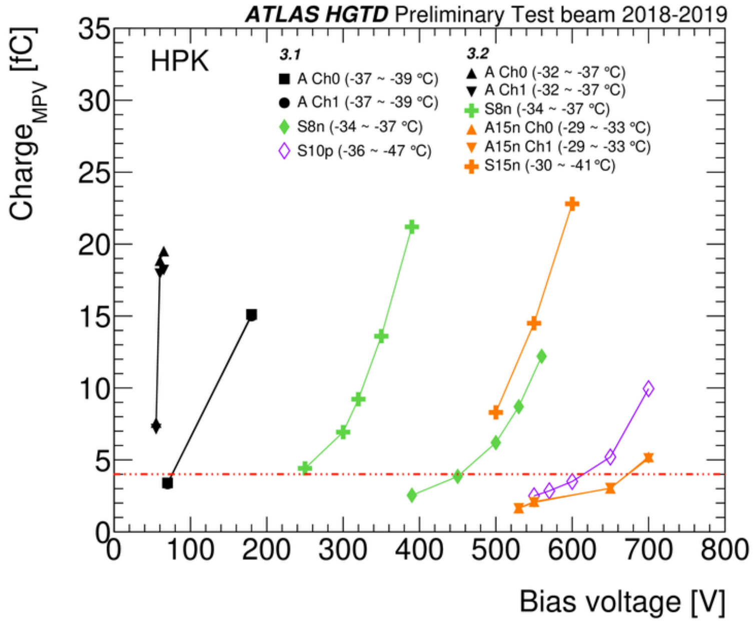
$$V_{gl} = V_{gl0} \times \exp(-\boldsymbol{c} \times \Phi_{eq})$$

- LGAD performance degrades due to loss of the gain layer after irradiation. And irradiated sensors require higher bias voltage to maintain performances.



The c factor is extracted from the behavior of the gain layer active fraction represented as a function of fluence.
The gain layer active fraction is calculated using the gain layer depletion voltage at each fluence, obtained from CV measurements.



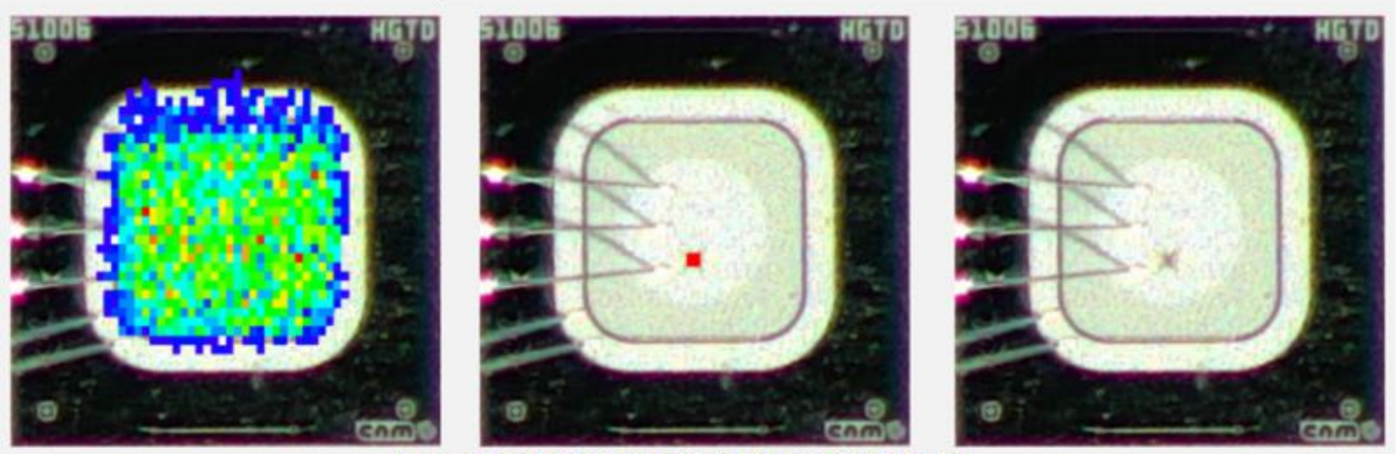


LGAD sensor after Irradiation

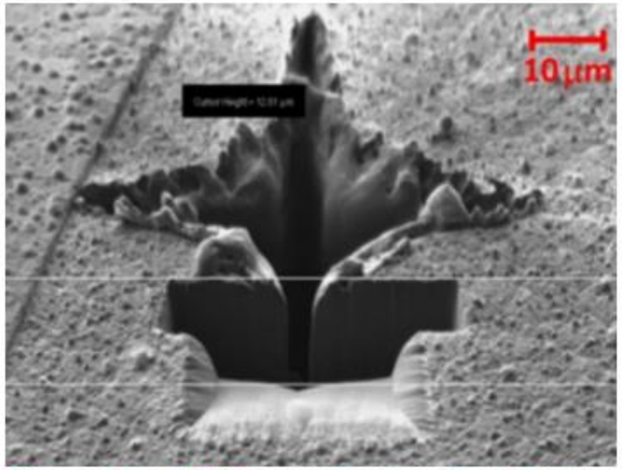
➢Single Event Burnout (SEB):

- During beam test, many of the sensors underwent destructive breakdown at voltages that were ~ 100 V lower than those at which the sensors were successfully operated in laboratory tests.
- RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam.
- A typical star shape burn mark appeared in the location of the particle hitting the sensors.

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)

➢Electric field (V_{bias}/thickness) is the key parameter determining the fatality.

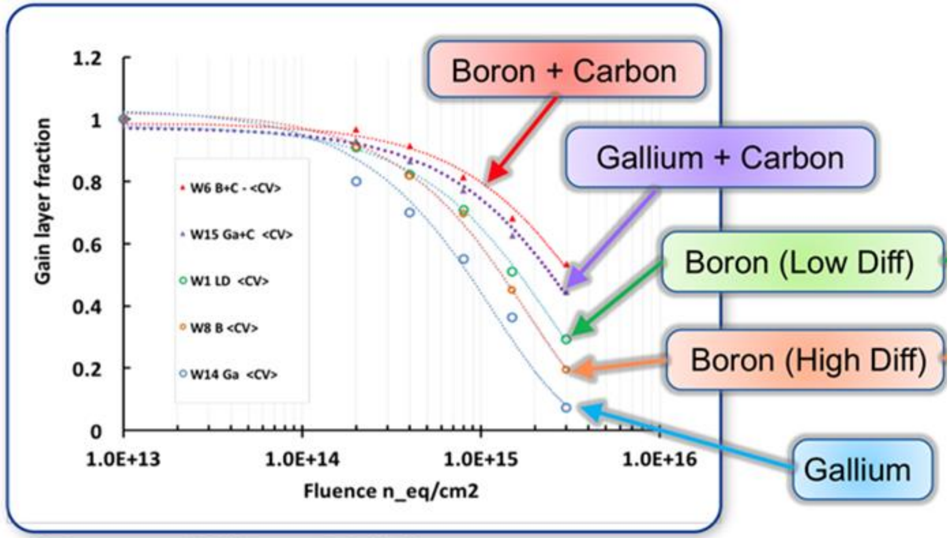
- SEB begin to occur when the average electric field in the sensor becomes larger than 12 V/μm.

LGAD sensor after Irradiation

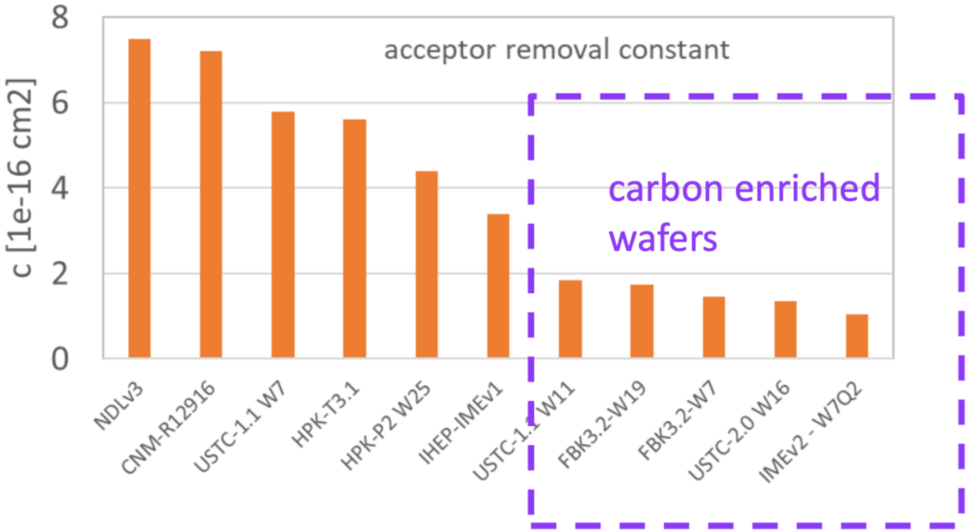
➢ Ways to improve the radiation hardness of LGAD:
- Geometry design, such as changing the doping concentration, depth, width, shape
- Different doping materials: adding the Carbon, Gallium to gain layer

➢ 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.

➢ Multiple runs from several vendors(FBK, IHEP-IME, USTC-IME) using carbon based gain layer were done to optimizate carbon enrichment dose and diffusion techniques.



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



LGAD: laboratory test

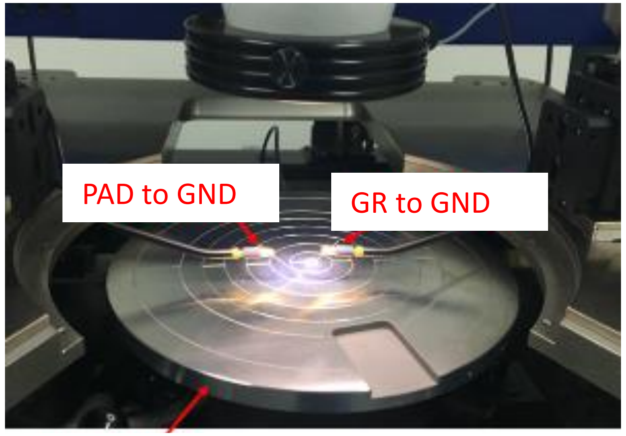
- **Probe station:** I-V, C-V measurement
- **Sr^{90} Beta telescope test** (collected charge, gain, time resolution)

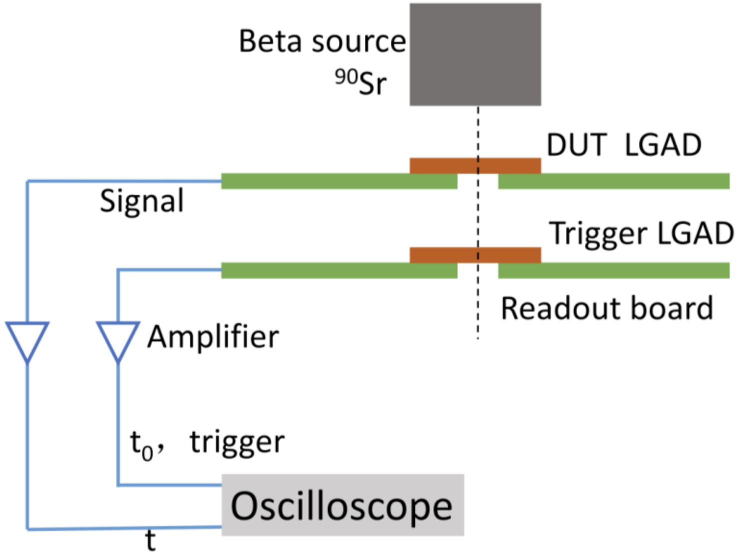
UCSC(University of California, Santa Cruz) boards with commercial amplifier and analog readout by Oscilloscope

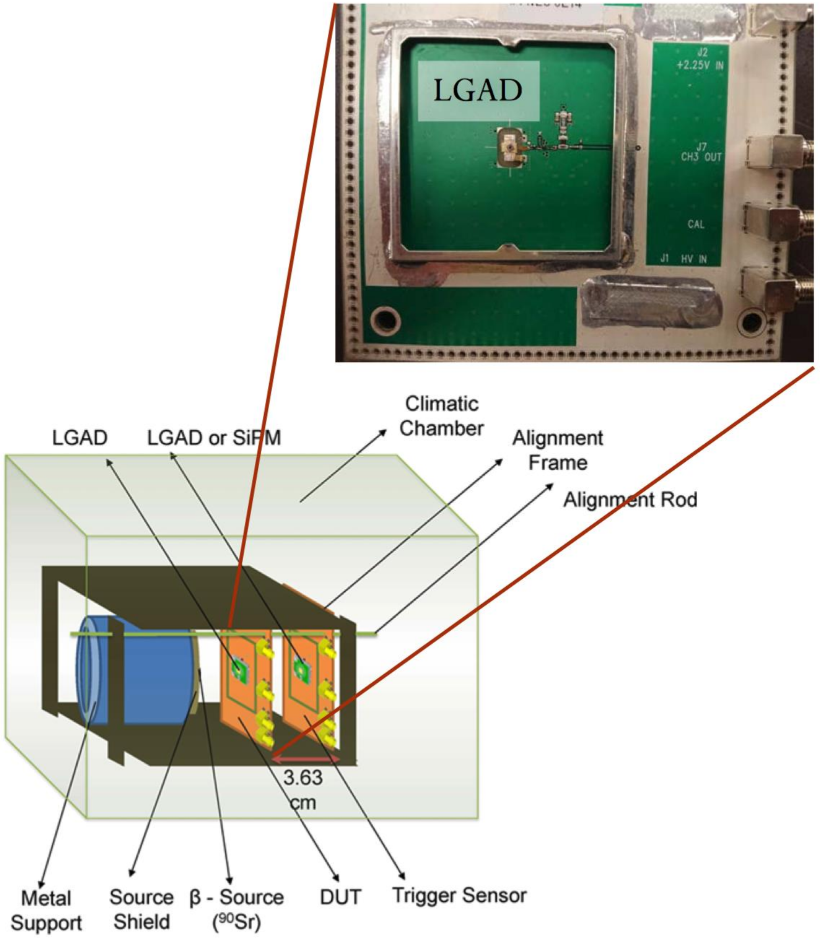
- Less constraints with respect to the ASICs – exploring the limits of the sensors

Timing resolution test: two UCSC boards with two LGADs

- One LGAD is device under test (DUT)
- The other LGAD is used to trigger electrons events from Sr^{90}





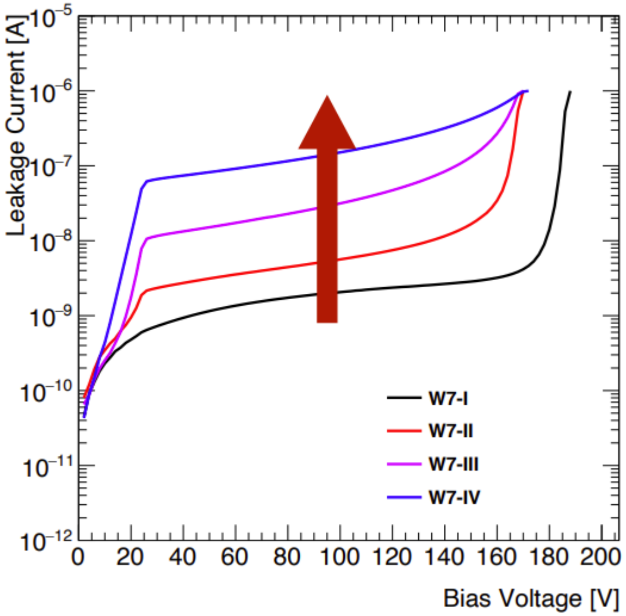


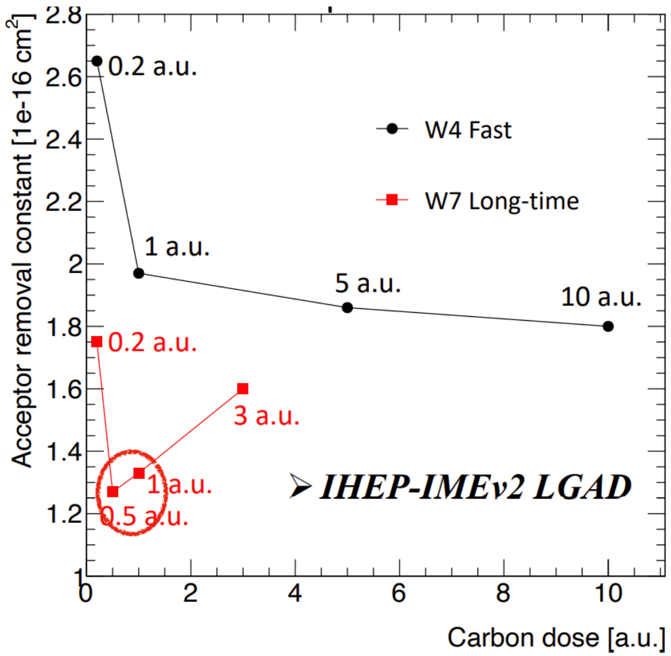
LGAD: laboratory test

- IHEP-IME: sensors with 12 different process parameters(carbon dose and thermal treatment) been fabricated and tested.
- As increasing the carbon dose, the leakage current increase for sensors with carbon implantation and long-time annealing.
- The acceptor removal constant extracted from C-V measurement has a best point, for sensors with 0.5 a.u. carbon dose and long time annealing(W7Q2).

Sensor		Diffuse*	C dose(a.u.)	C factor (x10^16 cm2)
W4	Q1	CLBL	0.2	2.57
	Q2	CLBL	1	1.77
	Q3	CLBL	5	1.60
	Q4	CLBL	10	1.50
W7	Q1	CHBL	0.2	1.62
	Q2	CHBL	0.5	1.14
	Q3	CHBL	1	1.18
	Q4	CHBL	3	1.34
W8	Q1	CHBL	6	1.30 1.32
	Q2	CHBL	8	1.32
	Q3	CHBL	10	1.23
	Q4	CHBL	20	1.29

BEST





https://doi.org/10.1016/j. nima.2022.167697

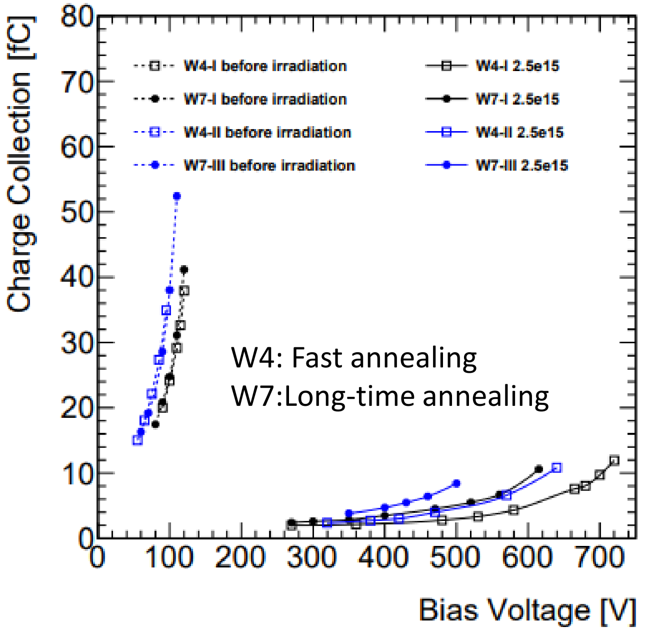
LGAD: laboratory test

IHEP-IME:

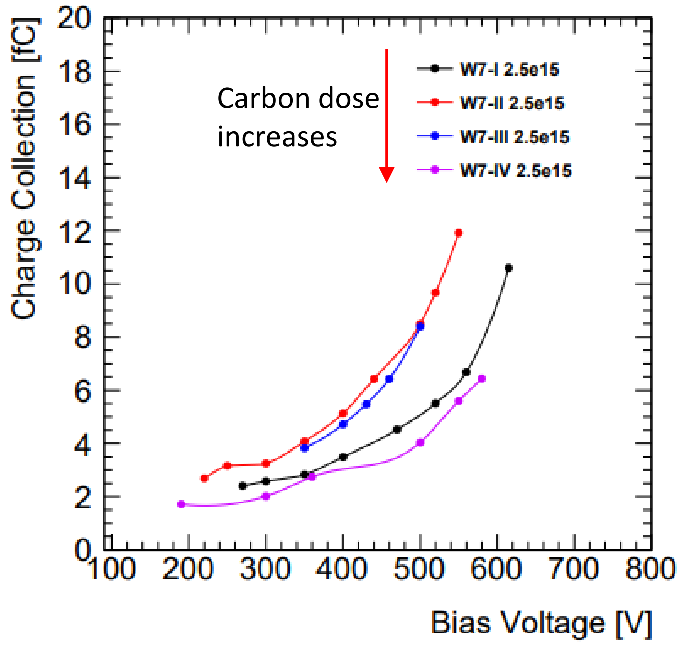
- Beta source testing of irradiated sensors confirmed that sensors with 0.5 a.u. carbon dose and long time annealing (W7-II) can collect 4fC charge at voltage less than 400V.

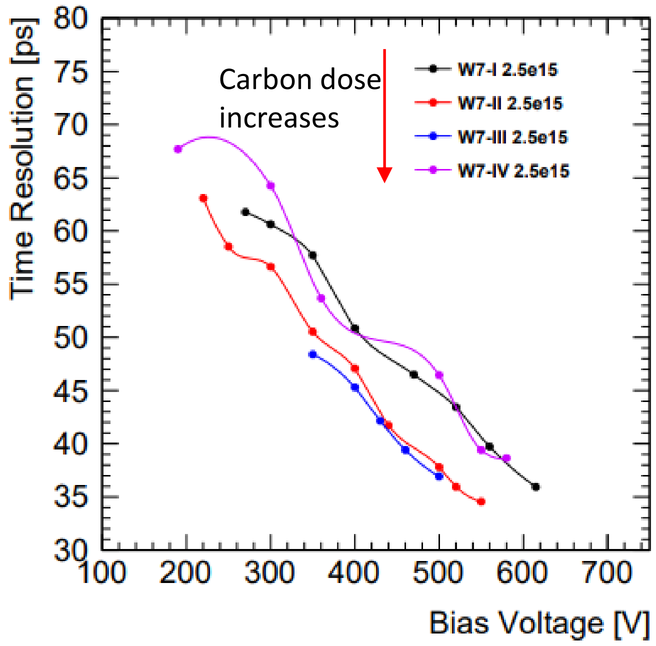
Sensor		Diffuse*	C dose(a.u.)
W4	Q1	CLBL	0.2
	Q2	CLBL	1
	Q3	CLBL	5
	Q4	CLBL	10
W7	Q1	CHBL	0.2
	Q2	CHBL	0.5
	Q3	CHBL	1
	Q4	CHBL	3

Same carbon dose
Different thermal treatment



Same thermal treatment
Different carbon dose





- Carbon dose and thermal treatment are two important process parameters for LGAD sensor irradiation performance improvement.

https://doi.org/10.1016/j. nima.2022.167697

LGAD: laboratory test

FBK-UFSD:

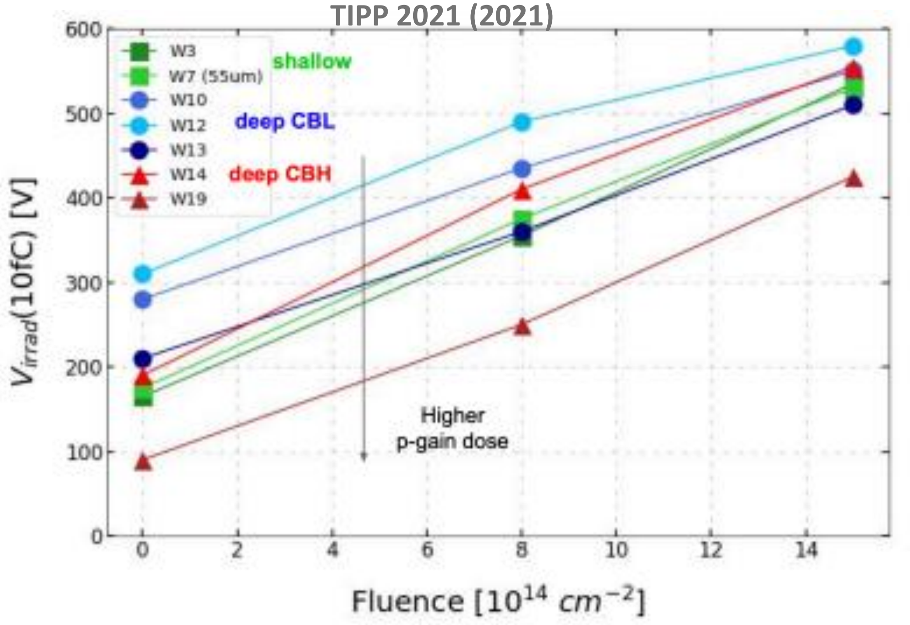
- Sensors with different active thickness and process parameters(carbon dose and thermal treatment) been fabricated and tested.

- Carbon dose and diffusion parameter also affect the radiation performance and the Carbon dose which minimizes radiation damage is between 0.6*A and 1.*A.
- W19 from FBK3.2 with CBH and carbon dose as 0.6*A show best performance.

Wafer #	Thickness	DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	0.98	1.*A	CH-BL
2	45	Standard	0.98	1.*Ab	CH-BL
3	45	Standard	0.98	0.8*A	CH-BL
4	45	Standard	0.98	0.4*A	CH-BL
7	55	Standard	0.98	1.*A	CH-BL
8	45	deep	0.70	1.*A	CBL
9	55	deep	0.70	1.*A	CBL
10	45	deep	0.70	0.6*A	CBL
11	45	deep	0.70		BL
12	45	deep	0.74	1*A	CBL
13	45	deep	0.74	0.6*A	CBL
14	45	deep	0.74	1.*A	CBH
15	55	deep	0.74	1.*A	CBH
16	45	deep	0.74	0.6*A	CBH
17	45	deep	0.74		BH
18	45	deep	0.78	A	CBH
19	45	deep	0.78	0.6*A	CBH

Tornago M., *et al.*
Performances of the latest FBK UFSD production
TIPP 2021 (2021)

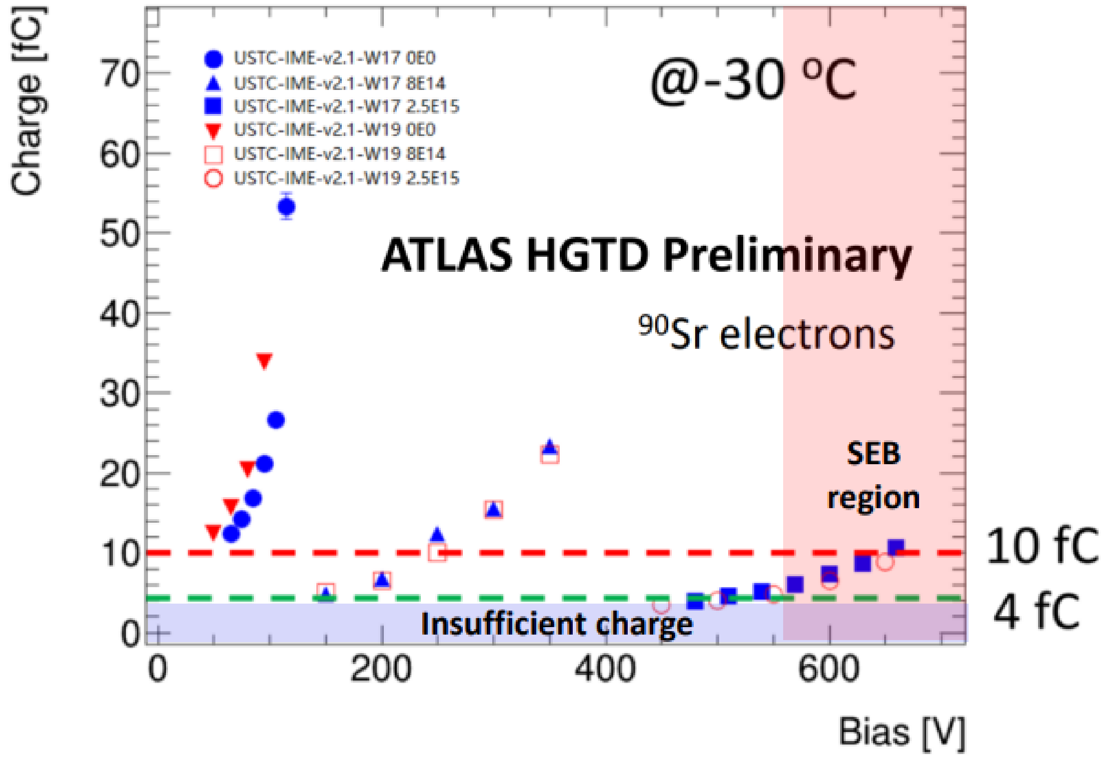
the bias voltage for 10fC charge

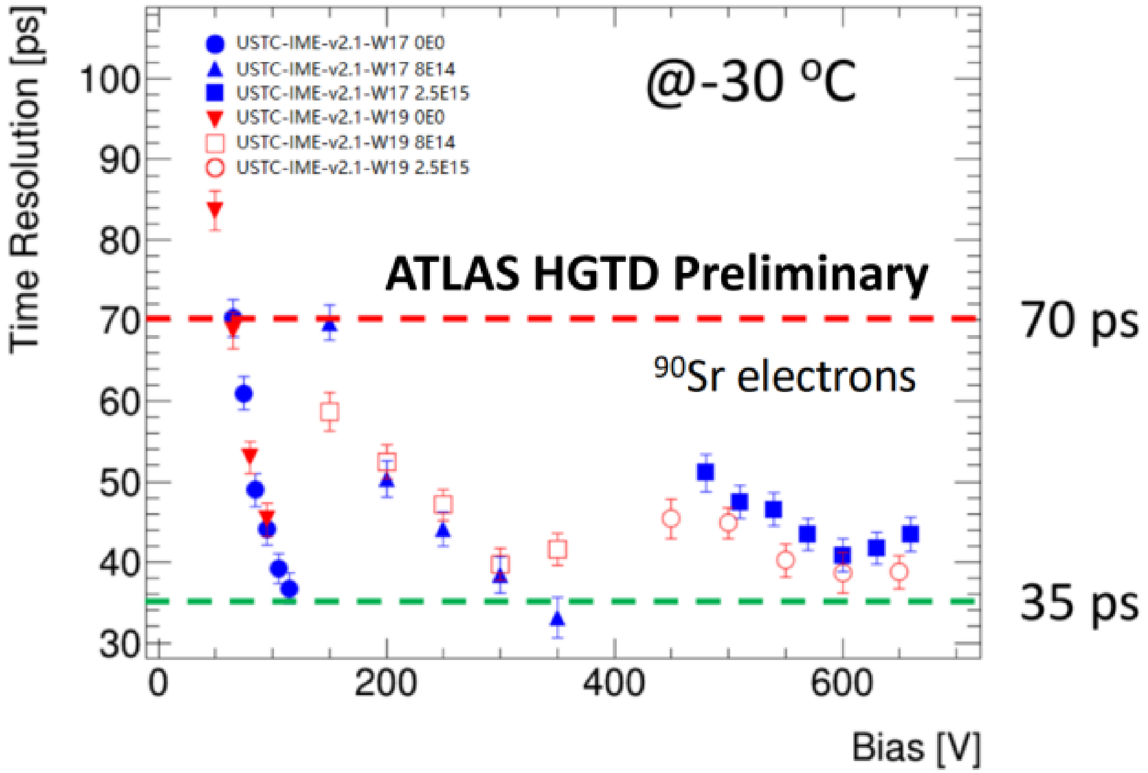


LGAD: laboratory test

USTC-IME:

- Sensors from V2.1 performs good enough over the entire lifetime of the experiment.
- Similar performance of two carbon doses (W17/W19).

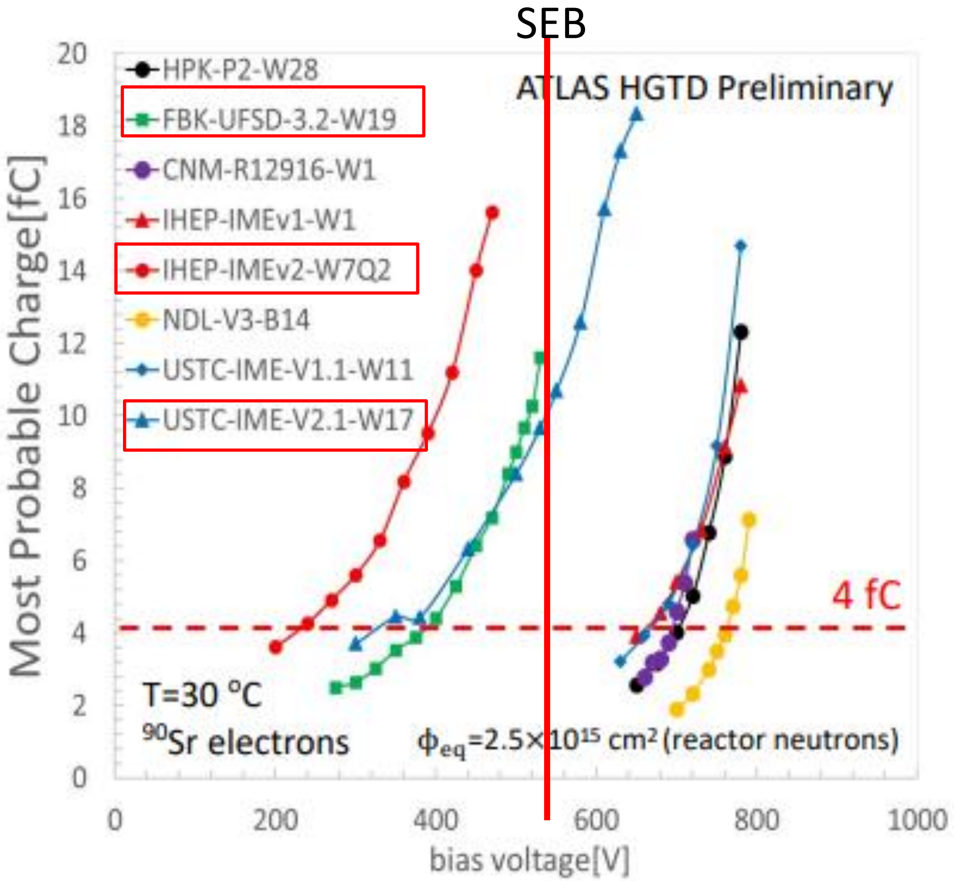


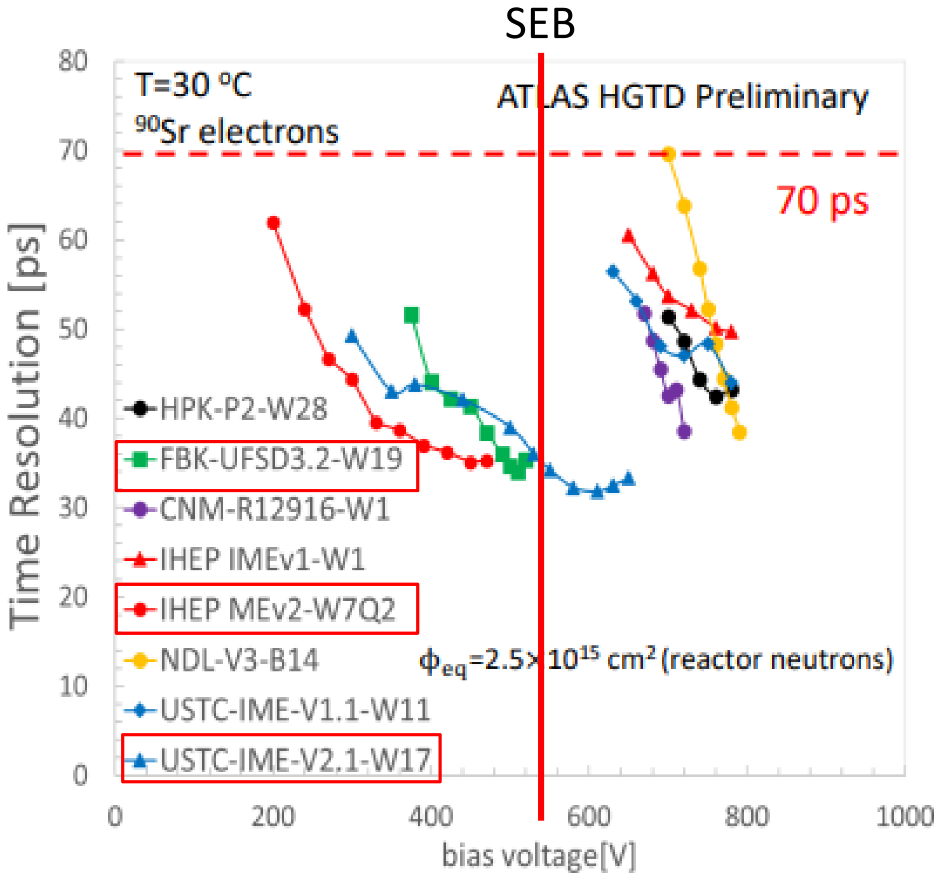


LGAD: laboratory test

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

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





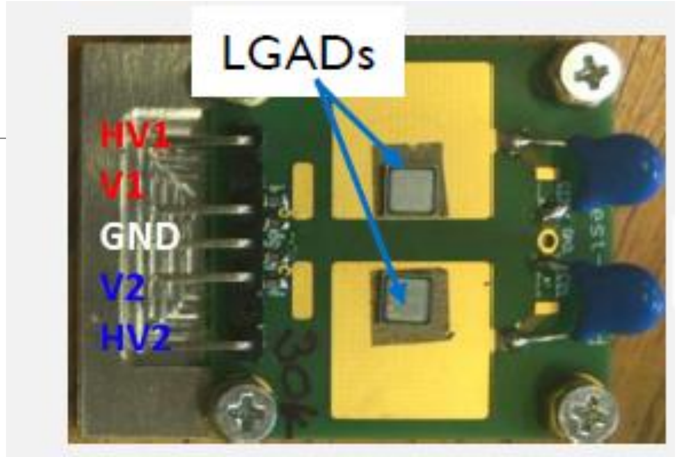
LGAD: beam test

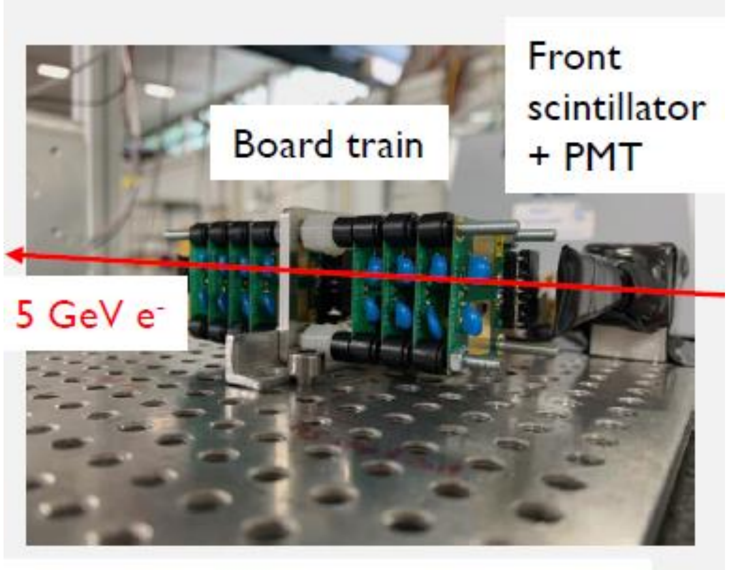
- LGAD end-of-lifetime studies(at -30°C)

  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
  - Irradiated LGADs at different fluences from different vendors
  - Study the limitations of the operational voltage at each fluence

- Procedure:
  - Expose irradiated sensors to beam, keeping track of rate, at 8h per bias point
  - Increase bias until SEBs occur, check if the bias above required voltage for 4fC collected charge
  - 64 sensors been tested





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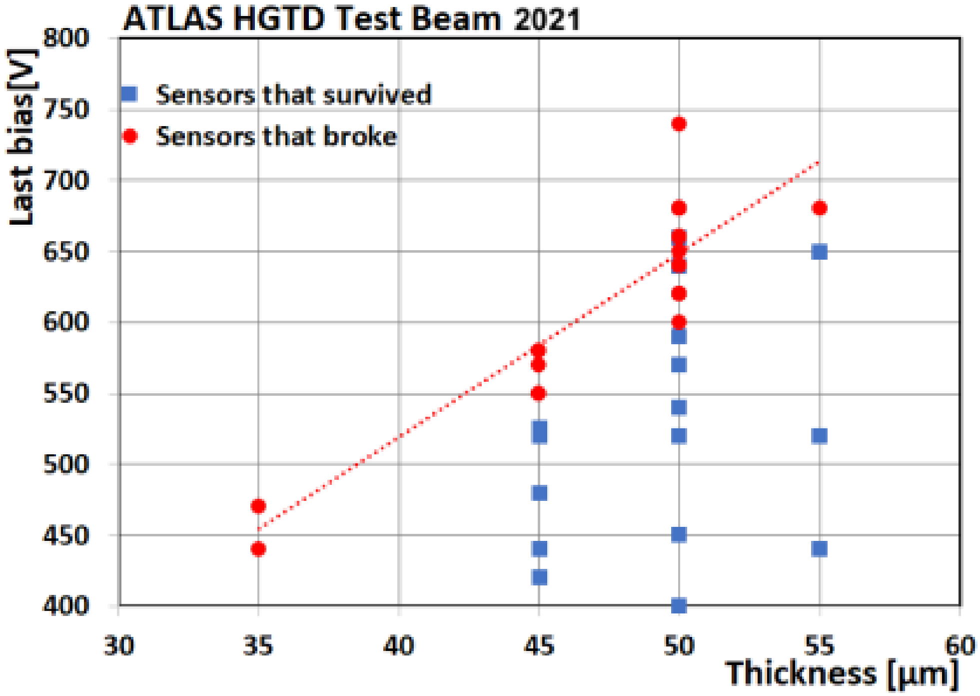
LGAD: beam test

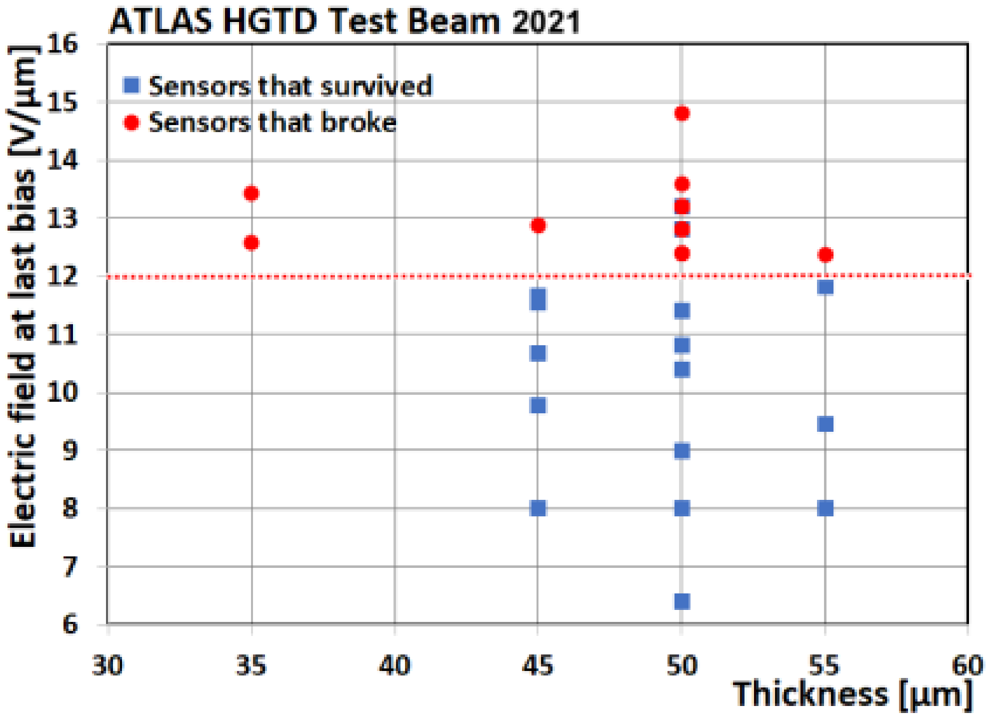
➢Results:

Both beam test campaigns confirmed that SEB issue occurs. Some of the sensors broke at biases lower than those tested in the lab, demonstrating that the particle beam itself causes their mortality.

- 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

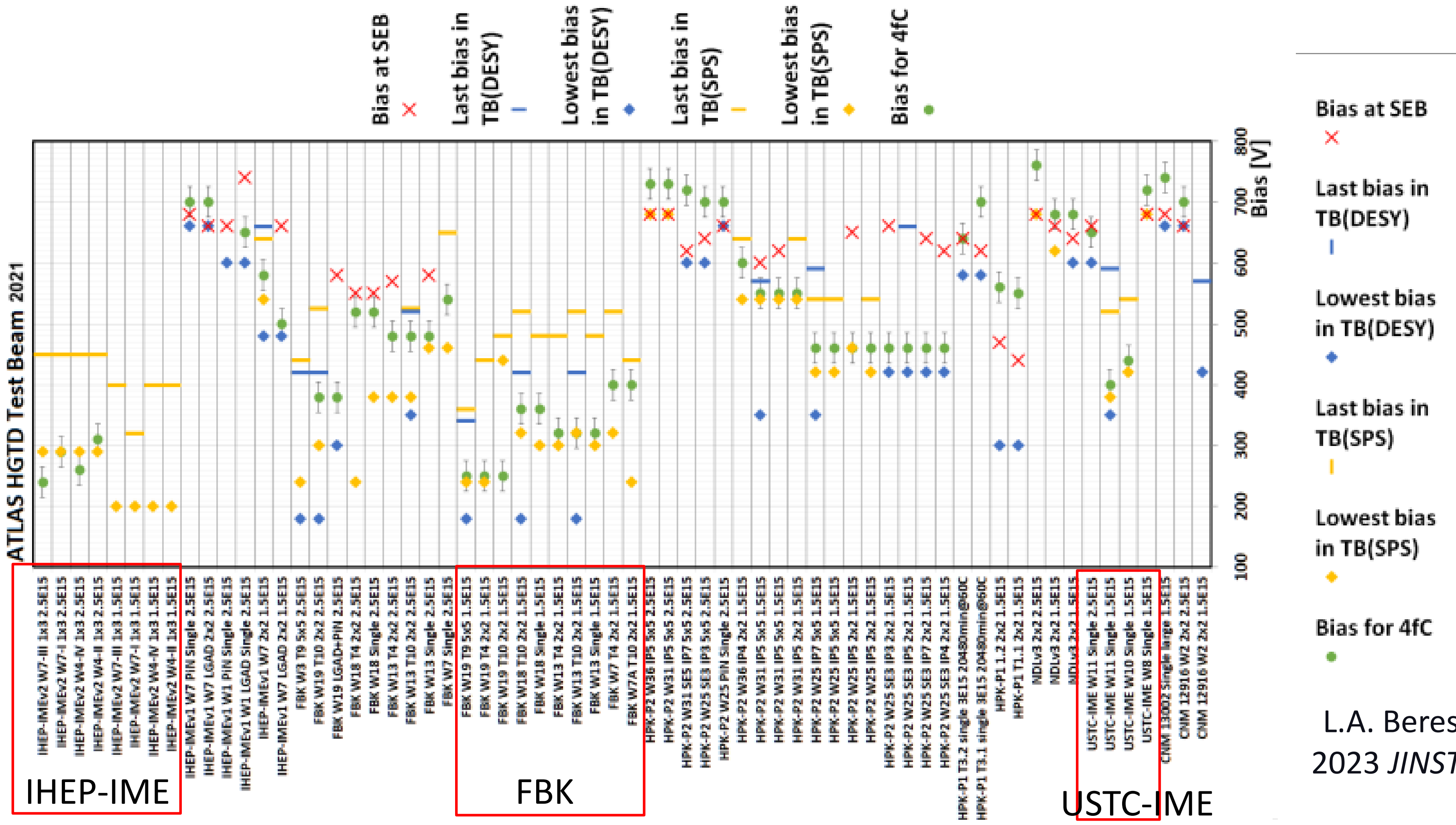
No fatality was observed at $E=V_{bias}/D < 12$ V/µm





LGAD: beam test

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



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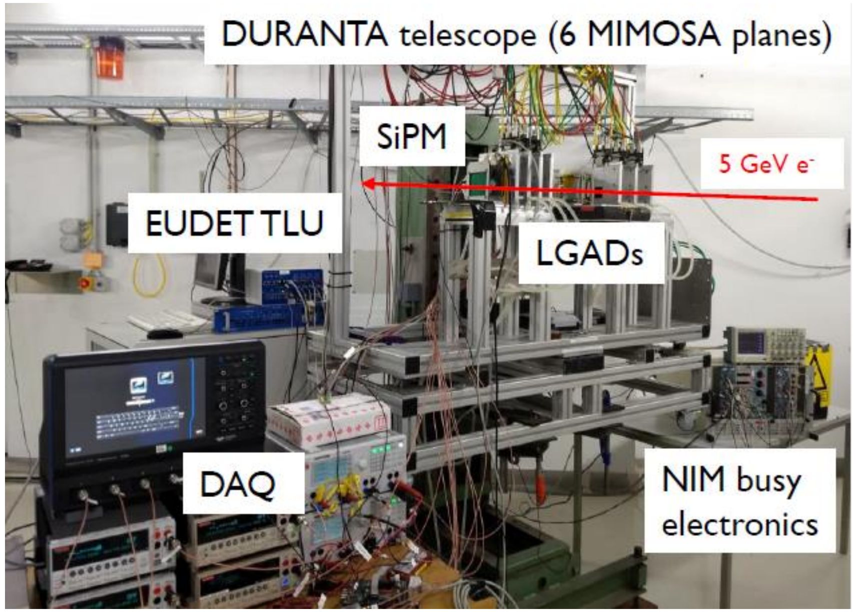
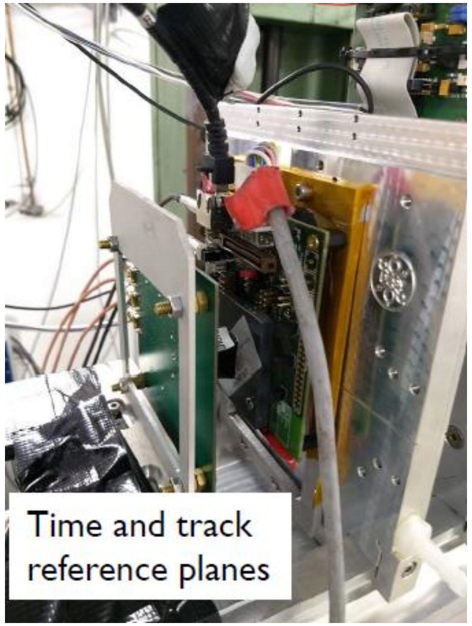
LGAD: beam test

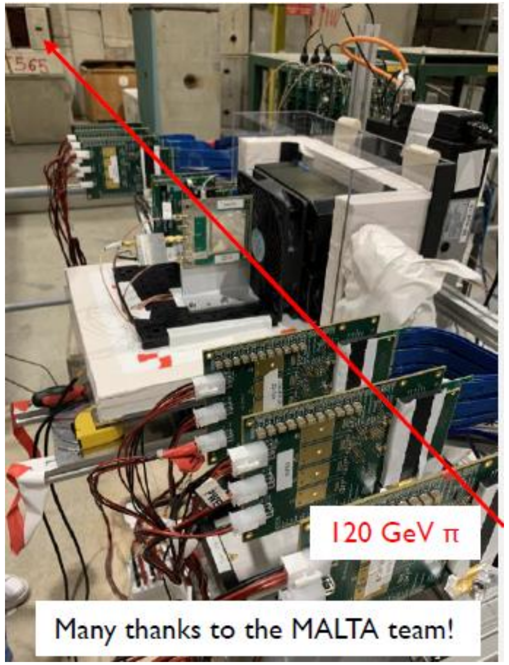
- LGAD performance studies(at -30°C)

  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)







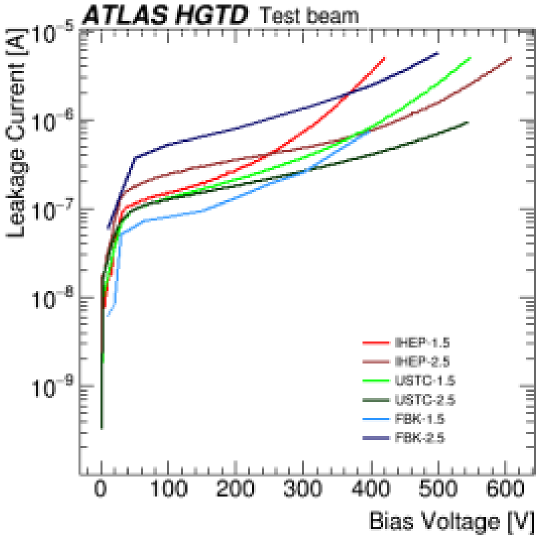
LGAD: beam test

Carbon enriched LGAD sensors from 3 vendors(FBK, USTC-IME and IHEP-IME) with acceptor removal constant as 1~2x10^{-16} cm^2

➢ Procedure:

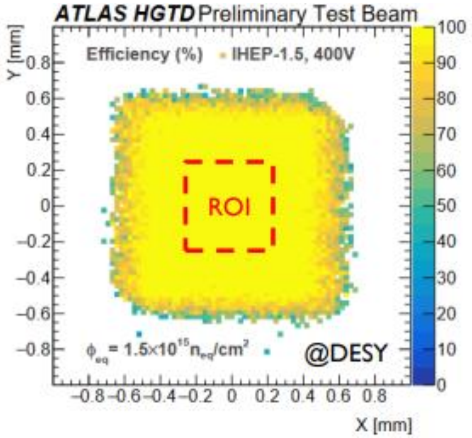
- Sensors irradiated up to 1.5×10^{15} n_{eq}/cm^2 and 2.5×10^{15} n_{eq}/cm^2 at the TRIGA reactor in Ljubljana, Slovenia with fast neutrons
- Expose irradiated sensors to beam, collect the signals from board and then qualify sensor performance (collected charge, timing resolution, efficiency)
- Bias voltages were kept lower than the SEB voltage

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

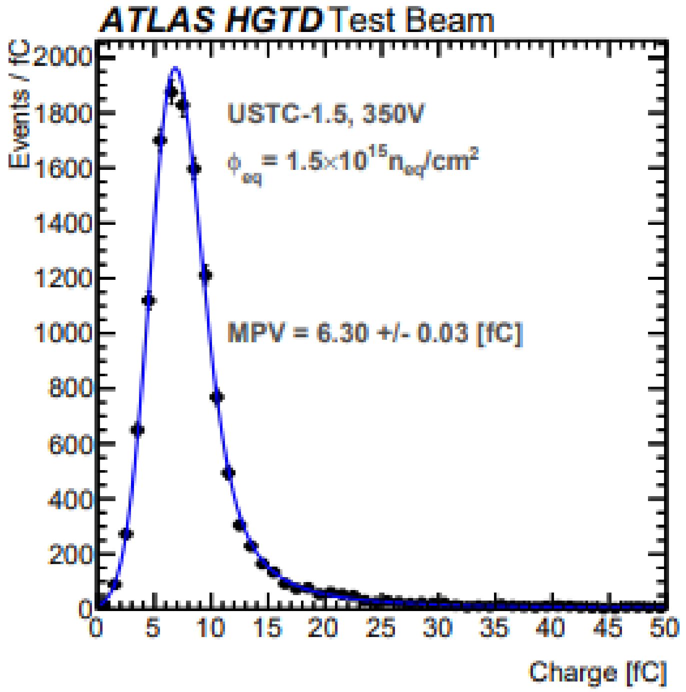


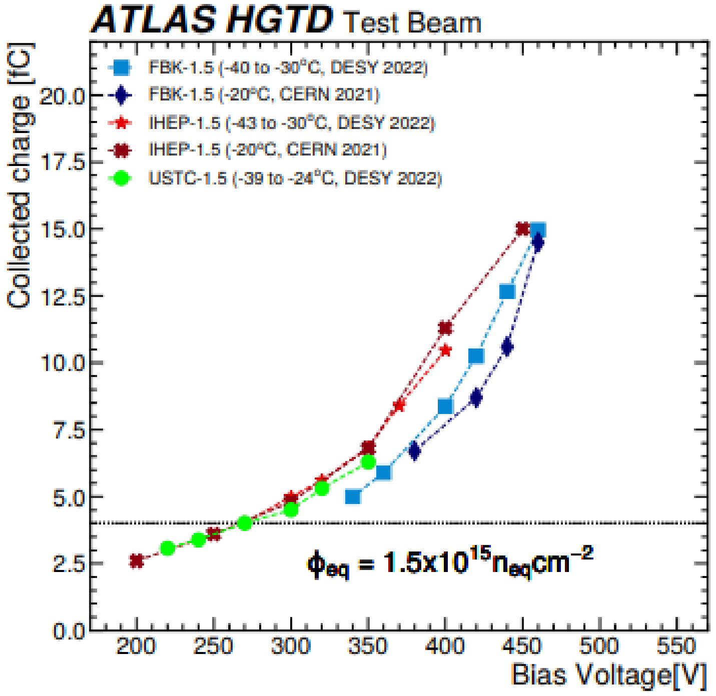
Device name	V_{gl0} [V]	Diffusion	c [cm^2]
FBK-1.5/2.5	50	H	1.73×10^{-16}
USTC-1.5/2.5	27	L	1.23×10^{-16}
IHEP-1.5/2.5	25	CHBL	1.14×10^{-16}

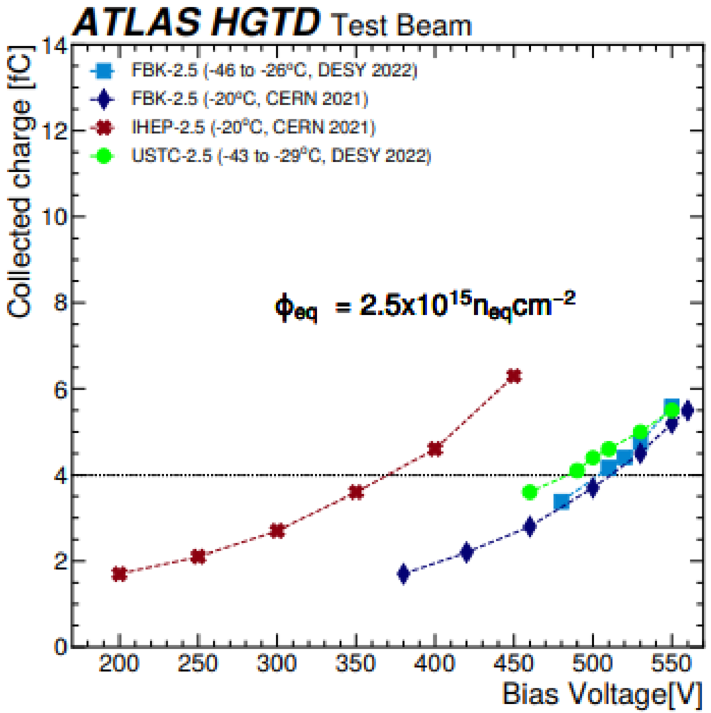
LGAD: beam test



- 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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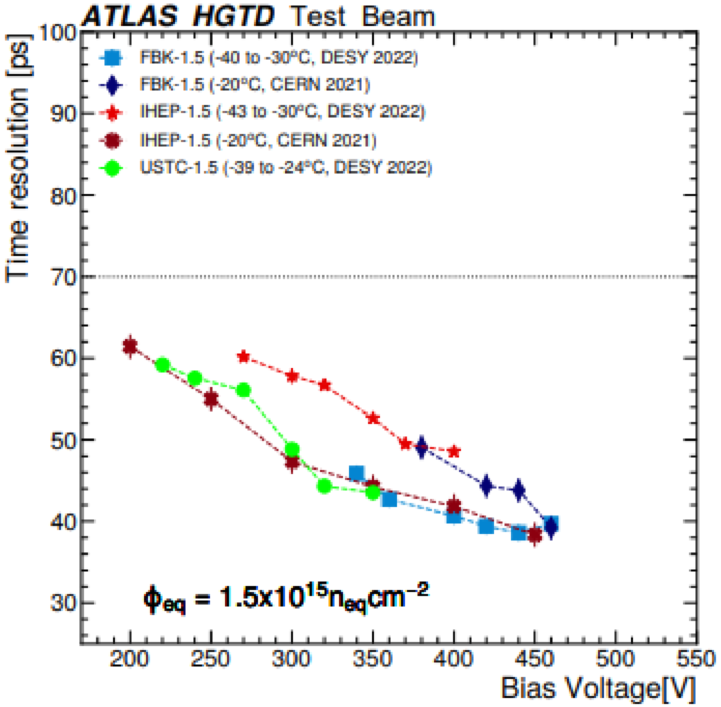
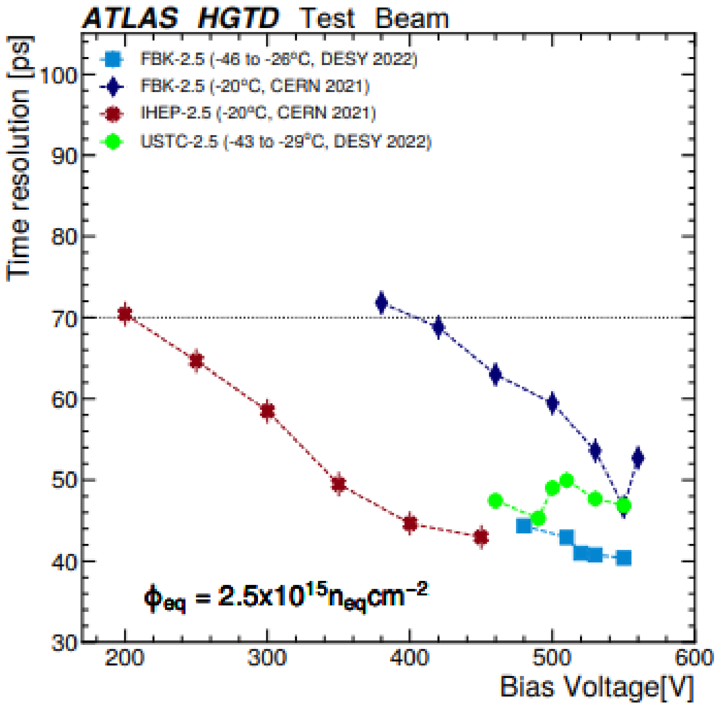
LGAD: beam test

- 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, $\sigma_{\text{CNM}-0}$ =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 2.5×10^{15} n_{eq}/cm^2.

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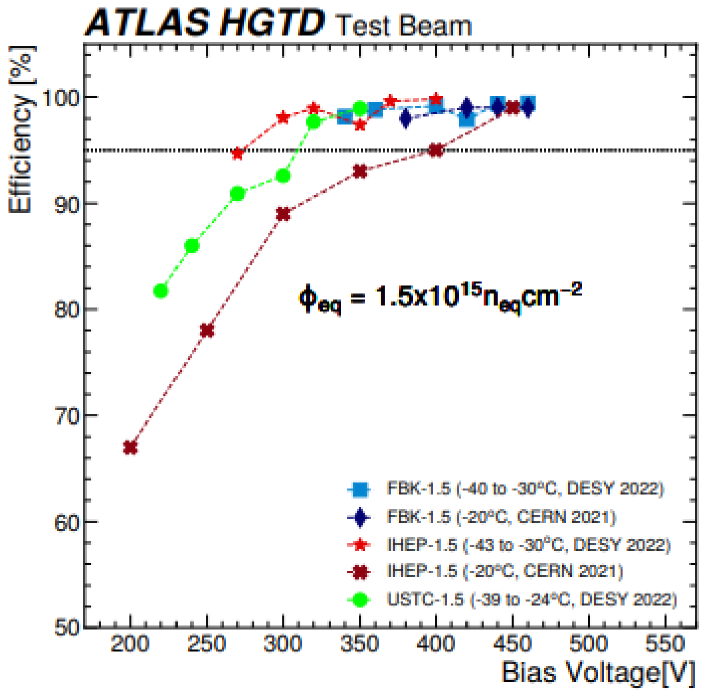
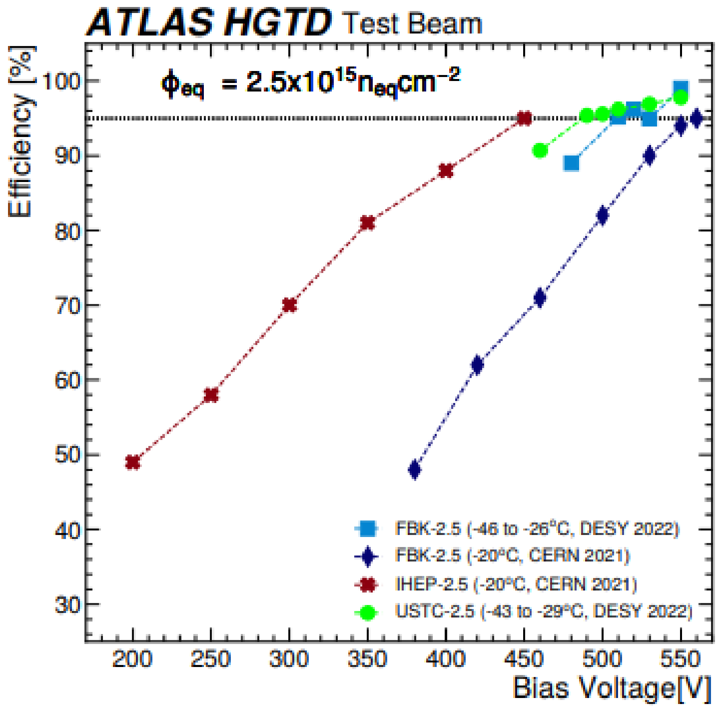
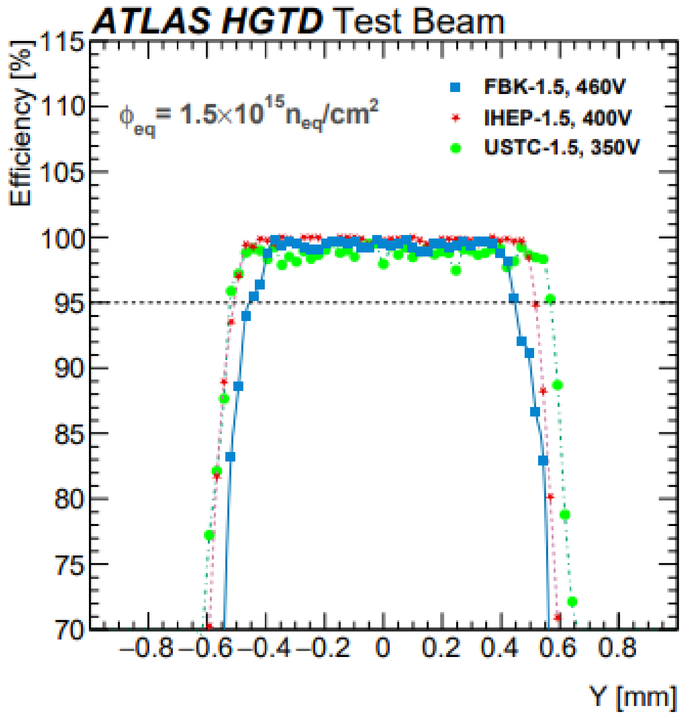
LGAD: beam test

- 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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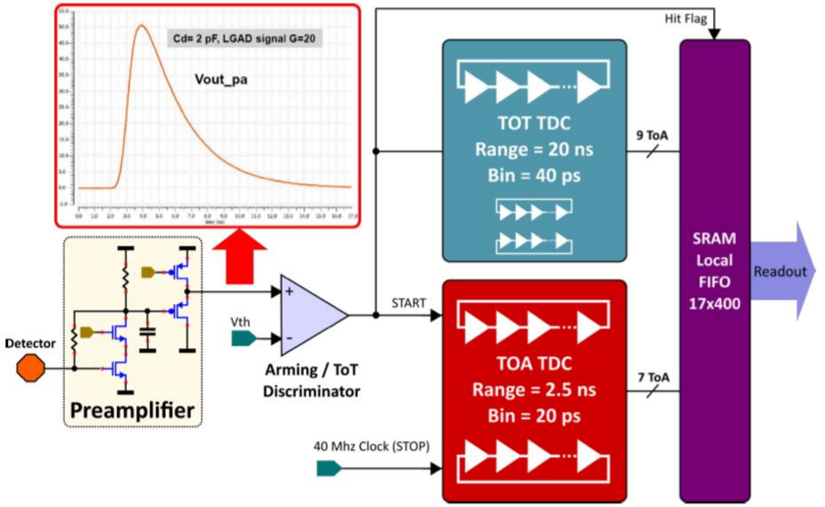
LGAD: beam test

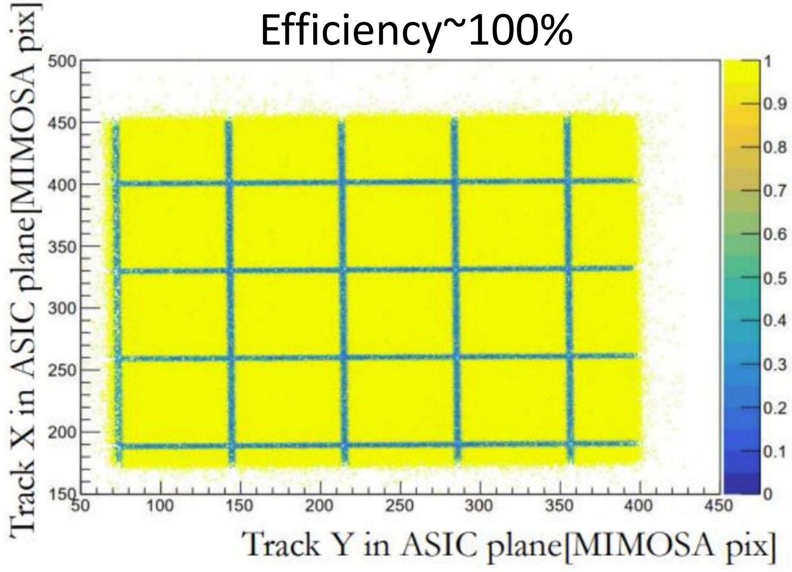
- LGAD readout ship:

  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

- First efficiency measurements in the test beam(CERN SPS, 2023) with ASIC(Altiroc2) and full size detectors FBK4.0.

- LGAD 15x15 array sensors perform as expected.





Summary

- High Granularity Timing Detector (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation to improve performance in the forward region
- LGAD is chosen as sensors for HGTD project as it has good time resolution <30ps.
- Carbon enriched LGAD sensors show good radiation performance.
- Carbon enriched LGAD 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.

Outlook: Testing of sensors from pre-production is ongoing, more results will be shown next.

Beam test of sensors with Altiroc3