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

FAST 2023
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Yunyun Fan on behalf of ATLAS HGTD group

31st, May,2023

Outline

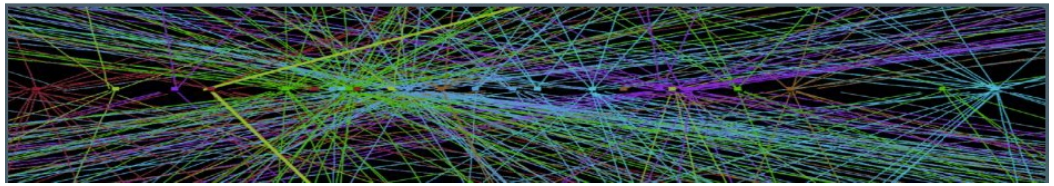
Challenges of HL-LHC

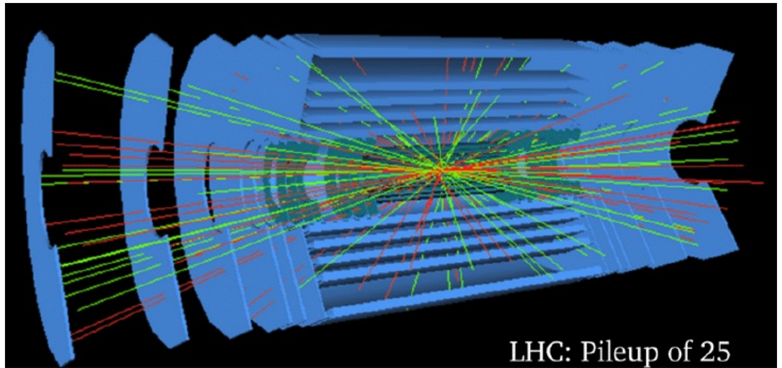
From ~2026, LHC will be upgraded, In ~2029, LHC will run in **"high luminosity"** **, called HL-LHC**

- increase the number of collisions per unit time
- The **instantaneous luminosity** will be approximately 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**

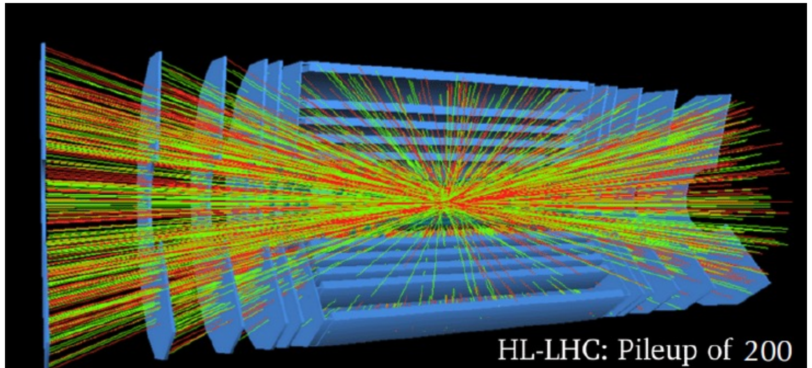
Several LHC experiment sub-systems will operate in the **high rate, hit occupancy and harsh radiation environment**

On average 1.6-2.35 vertices per mm



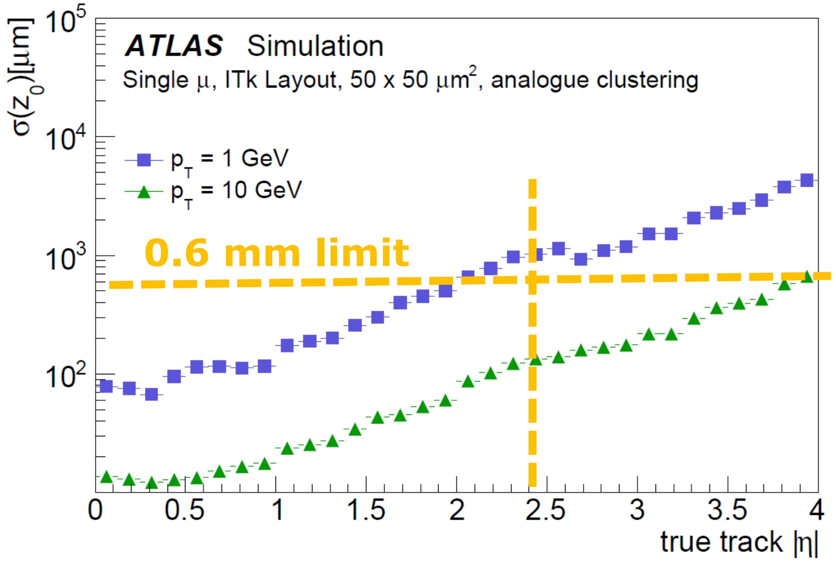


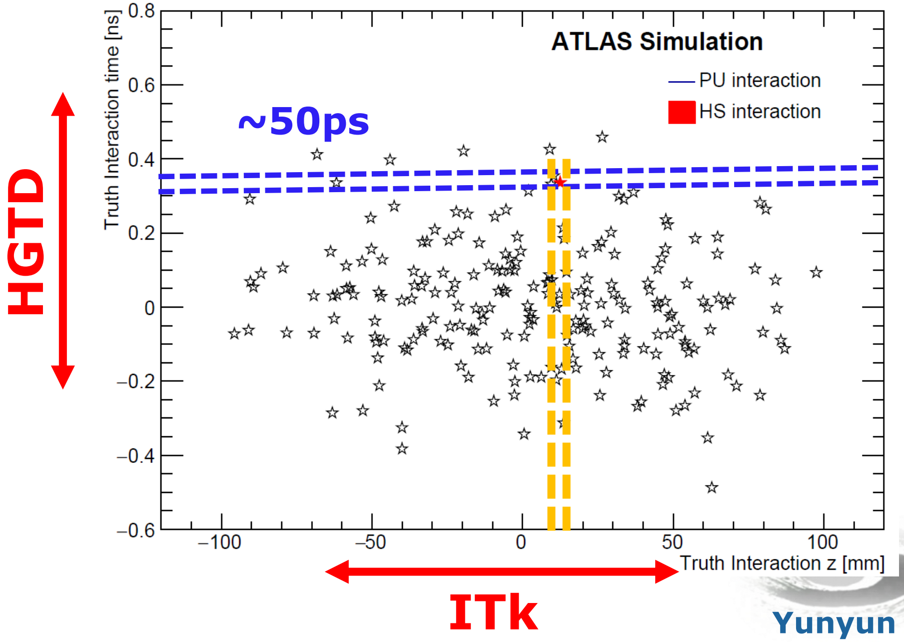
Pileup increases



Why need the time information?

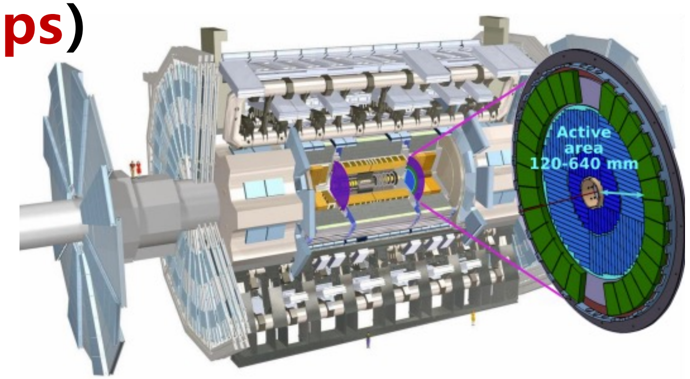
- **At High Luminosity -LHC**
  - Pileup: $<\mu>= 200$ interactions per bunch crossing ~1.6 vertex/mm on average
- **Problems of the vertex reconstruction in ATLAS**
  - degradation significantly in the forward region compared to the central region
  - Need z_0 resolution < 0.6 mm
  - Liquid Argon based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





High Granularity Timing Detector (HGTD)

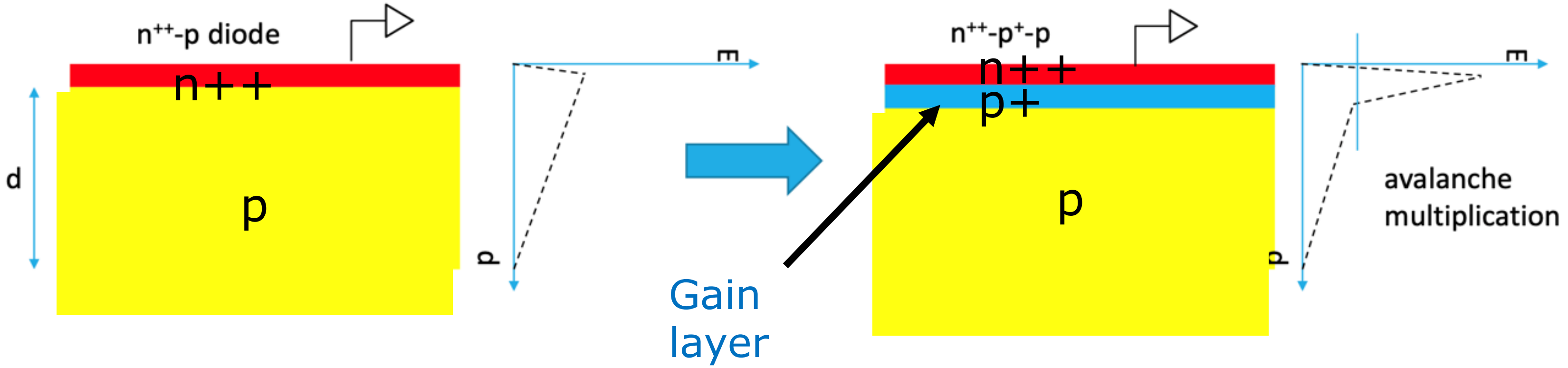
- **A High Granularity Timing Detector (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters to reduce pileup**
- Time resolution for particle 2 orders of magnitude higher (**ns→30 ps**)
- **Reduce the pileup in HL-LHC**
  - Detector area: 6.4 m^2, time resolution: 30 ps
  - mm granularity, 3.6 million readout channels



- **Detector can withstand the lifetime of the HL-LHC running (3 ring layout)**
  - Maximum n_{eq} fluences: $\mathbf{2.5\times10^{15}\ n_{eq}/cm^2}$
  - Total Ionising Dose (TID): **2 MGy** at the end of HL-LHC (4000 fb^{-1})
  - Average time resolution: **35 ps (start), 70 ps (end) per hit** / **30 ps (start), 50 ps (end) per track**
  - Collected charge per hit **>4 fC**
  - Hit efficiencies of **97% (95%)** at the start (end)of their lifetime

Low Gain Avalanche Detectors (LGAD)

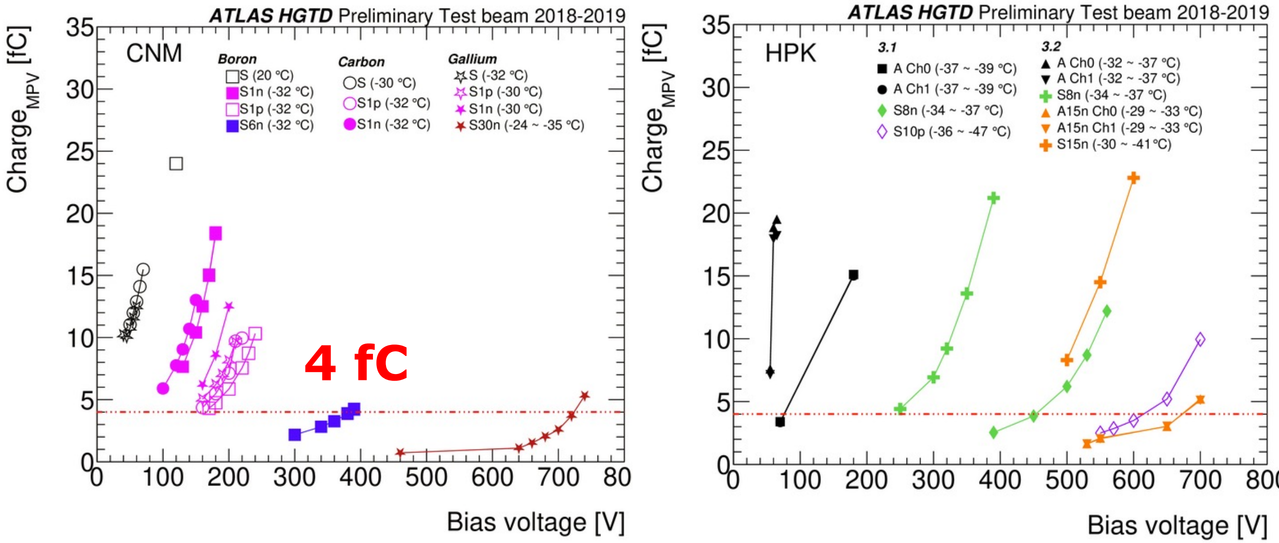
- Silicon pixel detectors are especially important for the precise determination of tracks and vertices , enabling the selection of interesting events through the identification of b jets (b tagging)
- LGAD is a new silicon detector technology developed recently, that could measure the particle time at ps precision (20 – 30 ps) mm position resolution before irradiation
- Compared with APD and SiPM, LGAD has moderate gain (10-50)
  - High S/N (high efficiency) , no self triggering
  - Thin depleted region decrease t_{rise} (fast timing) , increase the electric field and electron drift velocity



Toward Radiation Hard LGAD

- **Could (LGADs) operate at harsh HL-LHC radiation environment of high fluences beyond 10^{15} n_{eq}/cm^2 ?**
- LGAD sensors have been extensively studied during the R&D phase of the HGTD project
  - Performance degrades due to loss of the gain layer
  - Increase the bias voltage to maintain performances, leads to single event burnout （SEB）
  - Key parameter of the gain degradation is the **acceptor removal coefficient**

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



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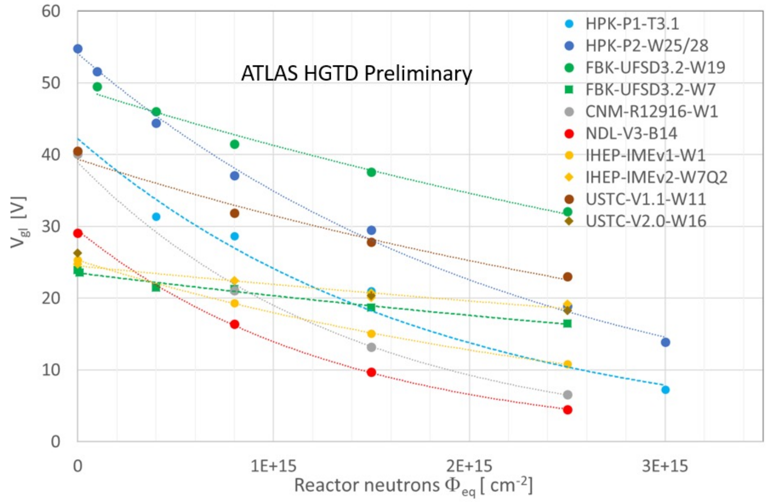


Toward Radiation Hard LGAD

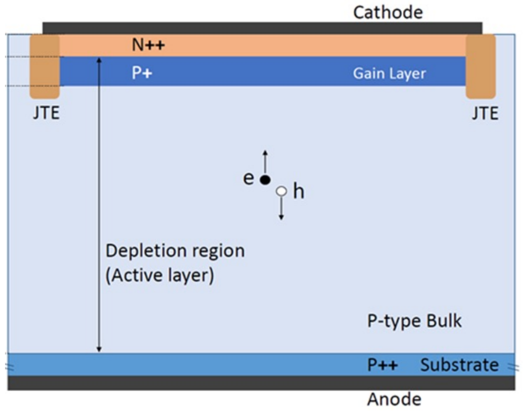
- Aim to **develop radiation hard LGADs** for HGTD

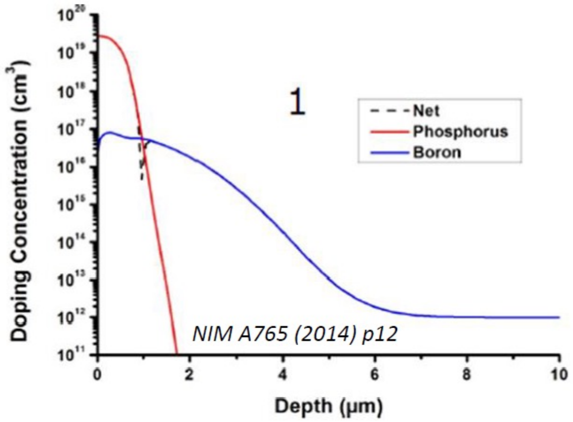
  Improve the gain layer design, **acceptor removal coefficient targeting $1 - 2\times10^{-16}\ cm^2$**

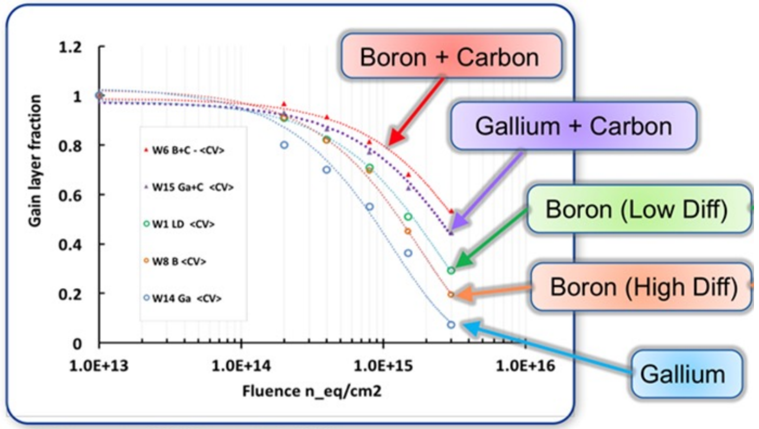
  I. Geometry design, such as increase the doping concentration, depth, width, shape

  II. Different doping materials, add the Carbon, Ga to gain layer

- **Performance of LGAD: B+C > B > Ga**
  - B+C sensors have larger charge collection than B and Ga at the same bias voltage
  - Tested sensors with (B, B+C GL) from several vendors (this talk)
  - Simultaneously show good enough CC/timing/efficiency in the test beam after **$2.5\times10^{15}\ n_{eq}/cm^2$**

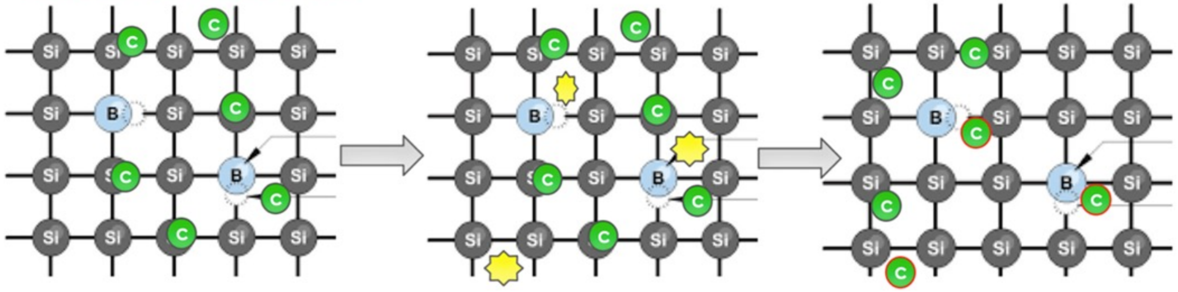






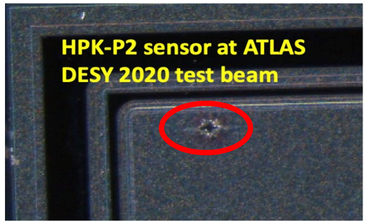
[G.Paternoster, FBK, Trento, Feb.2019]

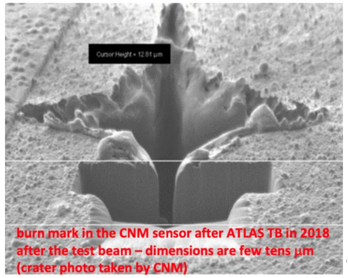
Carbon enriched wafer: interstitial defects filed with C instead of with B



LGAD Measurements with Particle Beams

- **Motivation : check the performance in real beam conditions and compare with the results from lab measurement from Sr90**
- **Goal :**
  – Qualify sensor performance (timing resolution, efficiency, collected charge) from different manufacturers
  – How to avoid **"single event burnout" (SEB)**



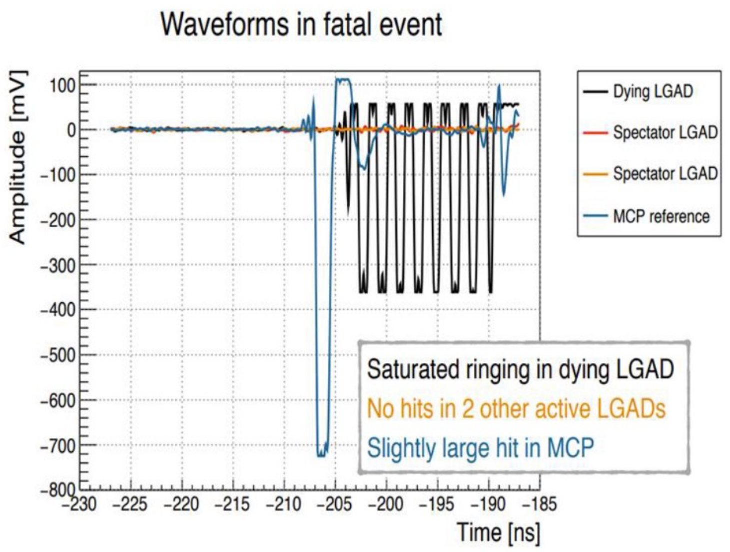


complete irrecoverable failure

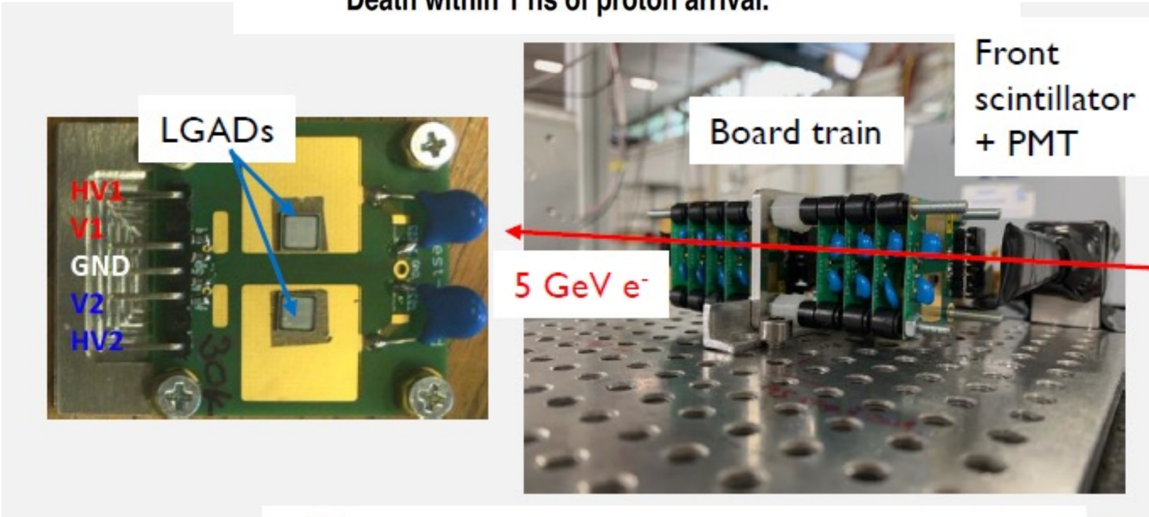
- **3 testbeam campaigns** in 2021 and early 2022:
  - SEB studies at DESY and CERN SPS
  - Performance studies (timing resolution, efficiency, collected charge)
    - Time reference : SiPM+quartz bar, CNM unirradiated LGAD
    - Track reconstruction : EUDET-type telescope (DESY) , MALTA telescope (CERN)

LGAD End-of-Lifetime

- **Single event burnout （SEB）: observed in testbeam**
  - Triggered by single particle
  - Destructive breakdown of irradiated LGAD at high voltages
  - Seen by CMS/ATLAS/RD50 teams
- **Goal：**
  - Gain **more information on SEB** mechanism
  - Determine safe bias voltages to avoid SEB
  - Check candidate sensors are safe from SEB at biases meeting HGTD specifications
- **Experimental setup (DESY and SPS):**
  - Cold measurements at -30 °C CERN / -20 °C ~-45 °C DESY
  - Irradiated LGADs after different fluences from different vendors
  - Study the limitations of the operational voltage at each fluence
  - Different geometries (change in rate): single pad, 2×2, 5×5



Death within 1 ns of proton arrival.



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

Mechanism Study of Single Event Burnout

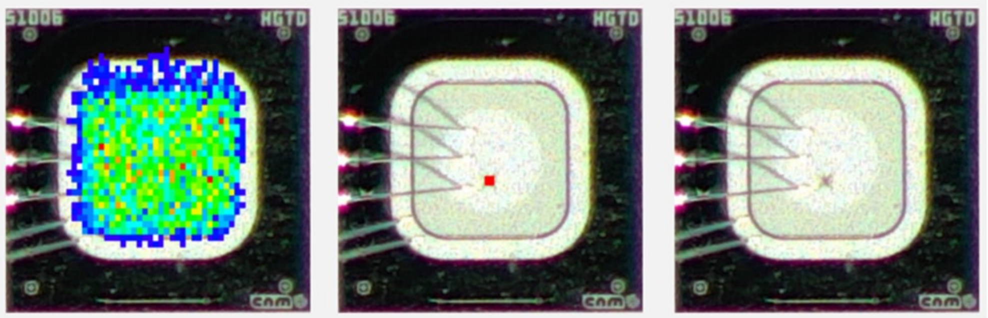
Sensor list for both ETL and HGTD test beam carefully prepared in order to determine the **answers to the following questions:**

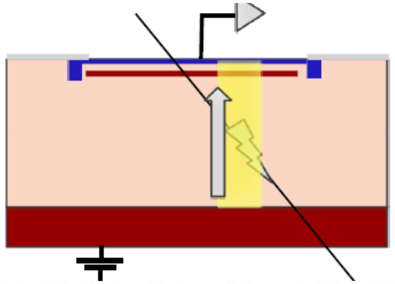
1. different fluences LGAD does irradiation matter? **NO**
2. irradiated PINs does intrinsic gain matter? **NO**
3. 0.1 MGy g irradiated PINs does bulk damage matter? **NO**
4. 35,45,50 m m thick LGADs effect of thickness? **YES**
5. different producers does process matter? **NO**

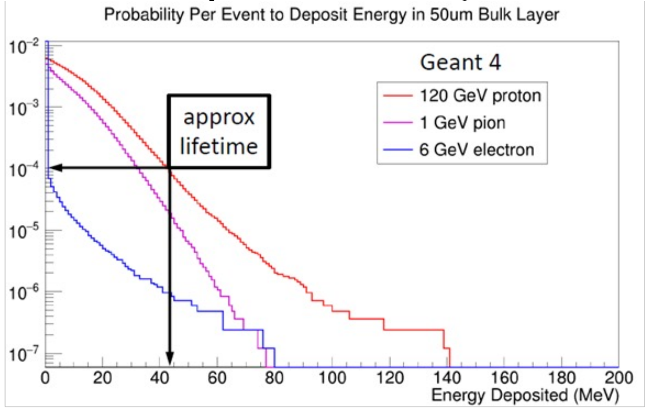
Effect of rare large energy deposits:

- **Electric field (V/thickness)** is key parameter determining the fatality. E field collapse in present of high concentration of free carriers.
- Agree with simulation results from Geant4
- At high bias voltage, the energy deposits of 40-50 MeV could produce 150 μJ heat which could melt the silicon with 50 μm thickness and radius of 10 μm

ATLAS HGTD Preliminary







Probability Per Event to Deposit energy in 50um Bulk layer

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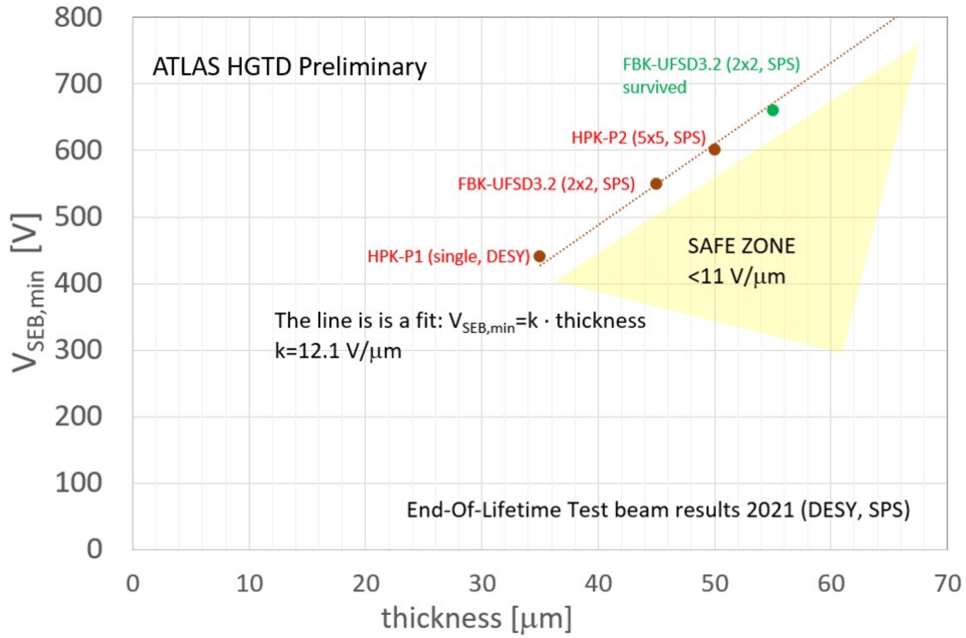
Safe Operational Voltage

- According to DESY and SPS , **"safe zone" at <11V/µm exist**
  - 74 sensors tested, 55 survived to voltages expected to meet HGTD specs
  - SEB only appears above a certain bias voltage while the 4 fC is obtained at the same time, even after irradiation
  - Carbon helps to reduce the gain layer degradation, thus reduce the operation bias voltage of highly irradiated sensor
- **The SEB probability**
  - **DESY in June 2021 (6 GeV electrons)** about 10^{-6} to $\sim 10^{-5}$ depending on irradiation, for ~12 V/µm
  - **SPS in November 2021** (120 GeV pions) below 10^{-5}



Could the sensor performances still meet the HGTD specs in this safe zone?

LGAD Prototypes for HGTD

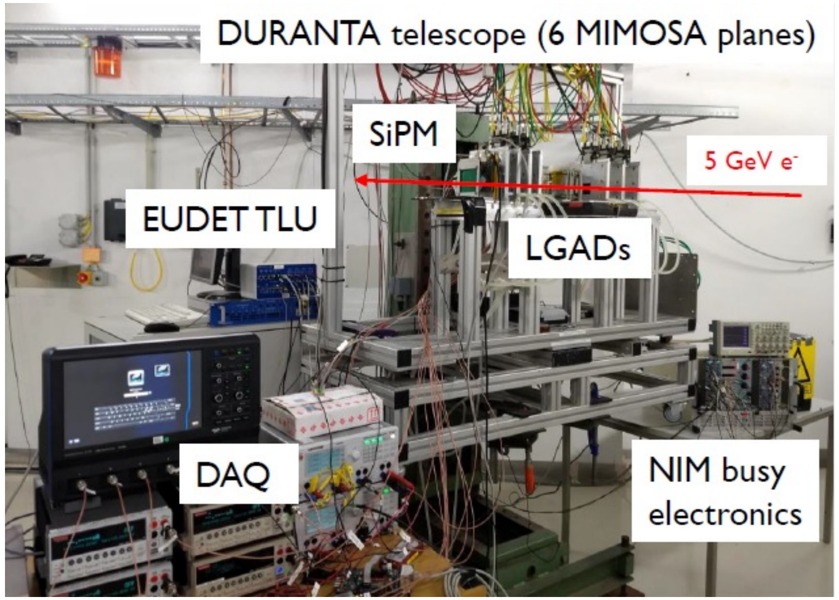
- **Tested most promising LGAD** : C-enriched prototypes from 3 vendors(FBK, USTC-IME and IHEP-IME)
- Sensors irradiated up to 1.5×10^{15} n_{eq}/cm^2 and 2.5×10^{15} n_{eq}/cm^2 at the TRIGA reactor in Ljubljana, Slovenia with fast neutrons
- Qualify sensor performance (timing resolution, efficiency, collected charge)
- Bias voltages were kept lower than the SEB voltage

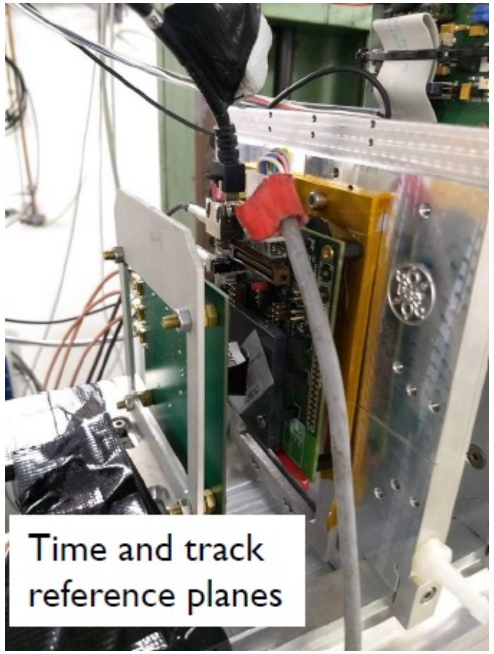
Device name	Vendor	Sensor ID	Implant	Irradiation type	Fluence $[n_{eq}/cm^2]$	Tested at
CNM-0	CNM	W9LGA35	boron	unirradiated	—	DESY/CERN
FBK-1.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	1.5×10^{15}	DESY/CERN
FBK-2.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	2.5×10^{15}	DESY/CERN
USTC-1.5	USTC-IME	v2.1 W17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

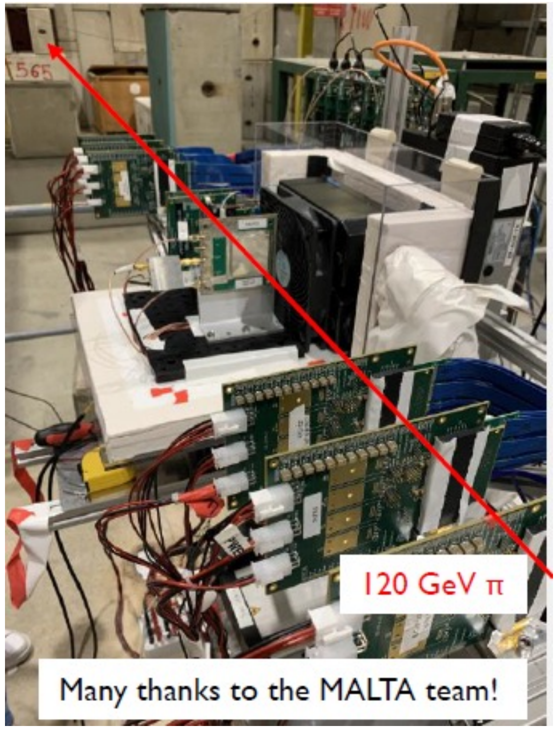
Device name	V_{gl0} [V]	Diffusion	c [cm^2]
FBK-1.5/2.5	50	H	1.73×10^{-16}
USTC-1.5/2.5	27	L	1.23×10^{-16}
IHEP-1.5/2.5	25	CHBL	1.14×10^{-16}

Performance Study

- **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 um/MALTA 5um)
  - Time reference : LGAD (CNM 0) used as a time reference in some tests (CERN SPS) as well as a SiPM device (DESY)



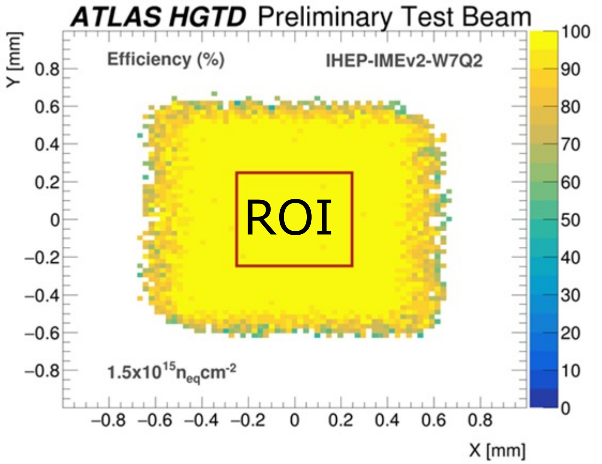


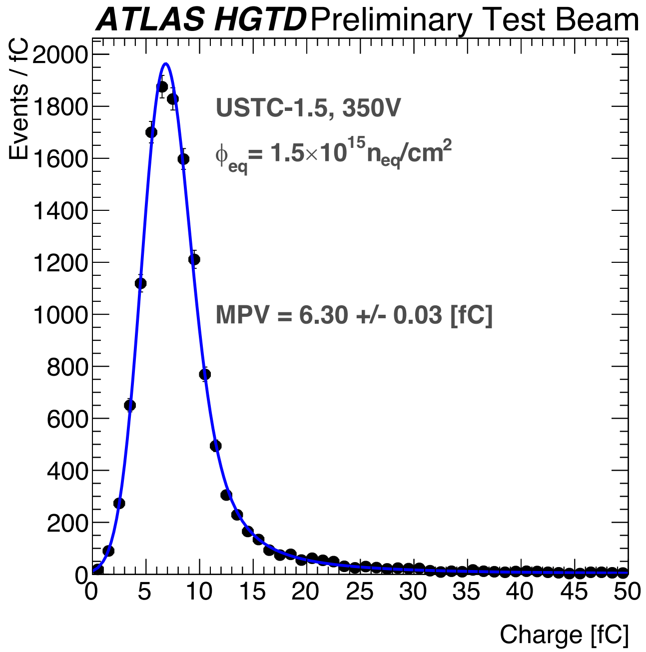


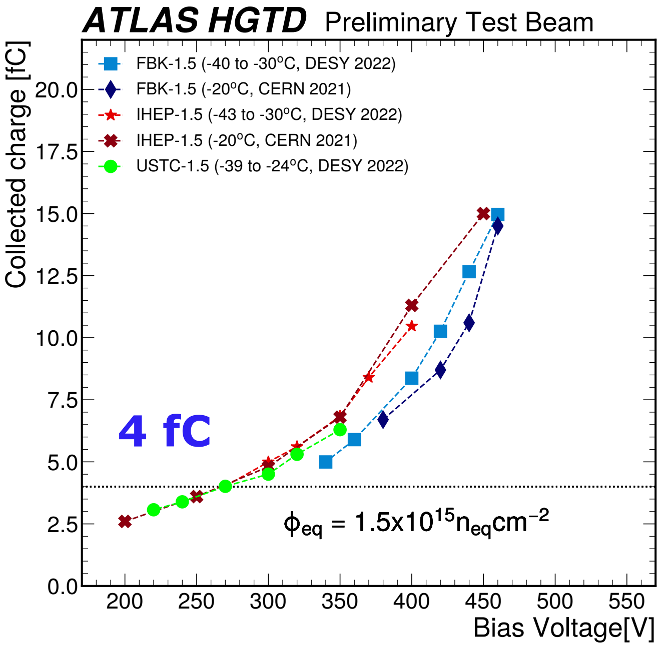
Collected Charge

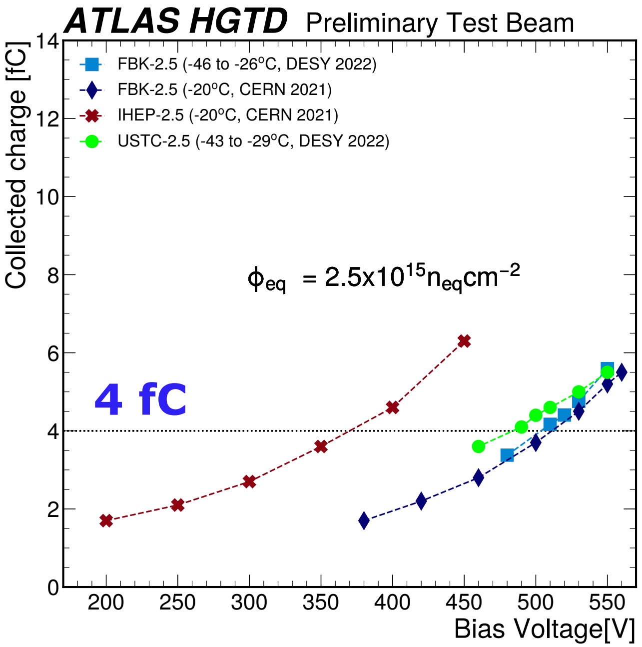
Collected charge:

- Distribution of charge in the Region of Interested (ROI) fitted with a **Landau-Gaussian convoluted function** to get the global collected charge
  - Defined as the most probable value (MPV)
  - Above the minimum required charge of 4 fC needed for a good timing measurement with the future HGTD







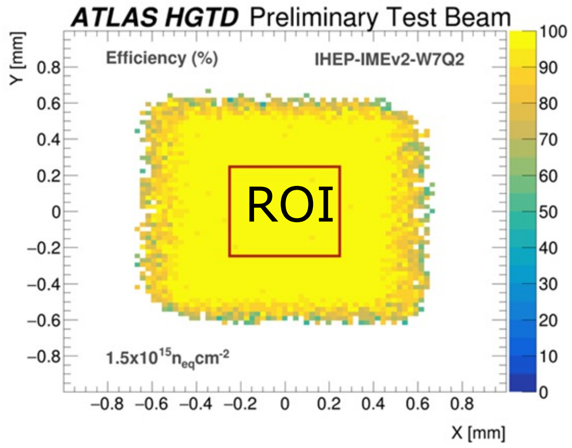


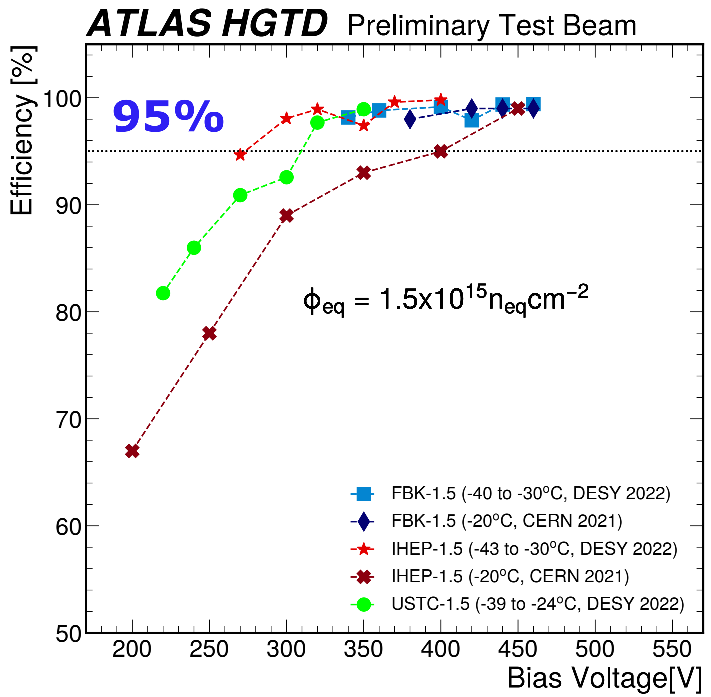
S. Ali et al 2023 JINST 18 P05005

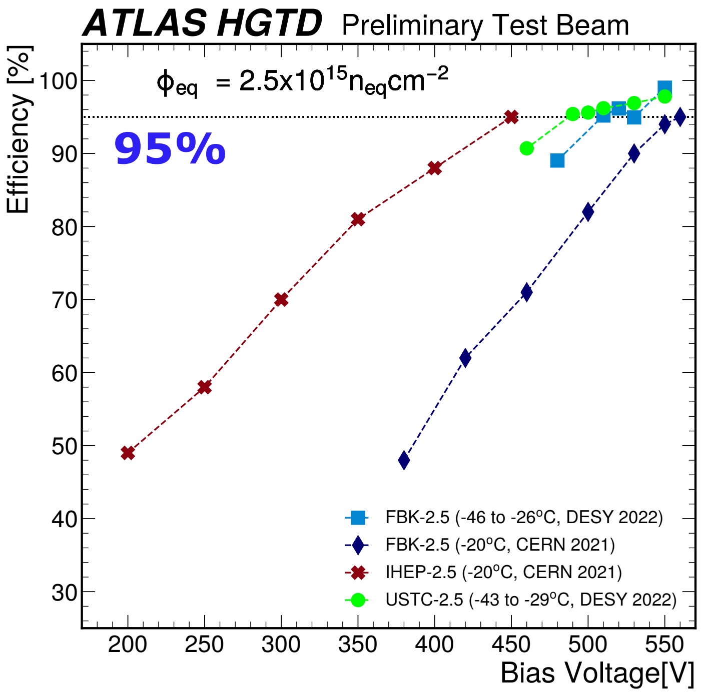
Hit Efficiency

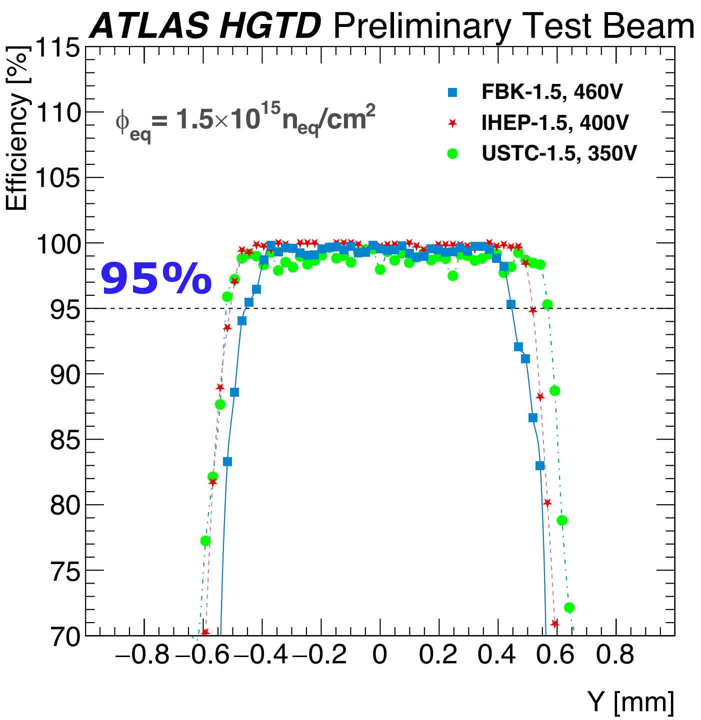
$$Hit\ Efficiency = \frac{Reconstructed\ tracks\ with\ q\ >\ Q_{cut}}{Total\ reconstructed\ tracks}$$

- q is the collected charge, Q_{cut} is 2 fC which is the minimum achievable threshold of the future ALTIROC chip
- Achieved the efficiency of 95% required for good operation of the future HGTD after irradiation









Time Resolution

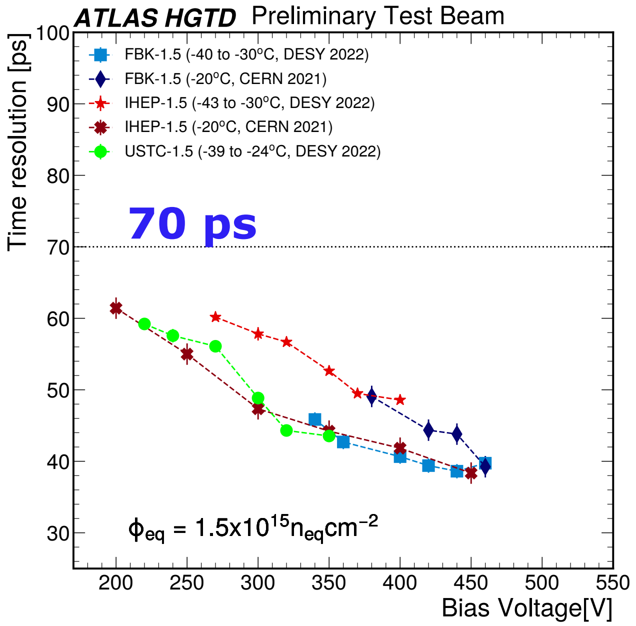
- To extract the LGADs' time resolutions, the distributions of the difference between the TOA of the LGADs and that of the time reference device were fitted with a Gaussian function, each of them giving a width σij

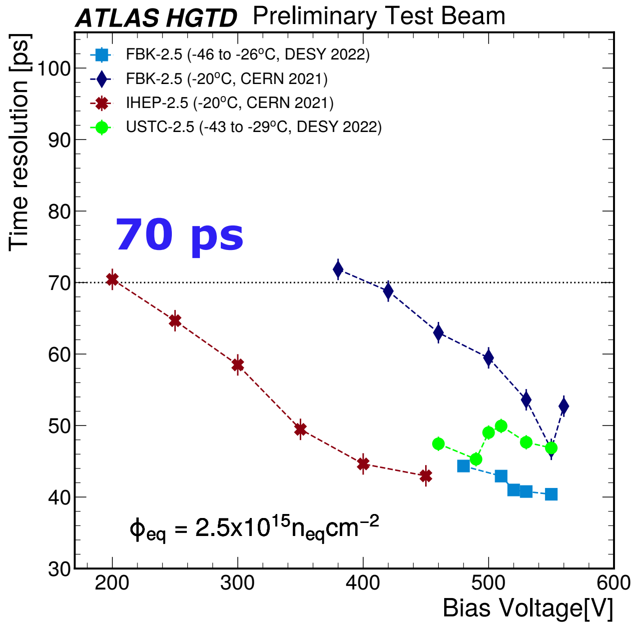
$$\begin{cases} t_1 - t_2 \\ t_1 - t_{\text{SiPM}} \\ t_2 - t_{\text{SiPM}} \end{cases} \qquad \sigma_{ij} = \sigma_i \oplus \sigma_j$$

- 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 subtracted (σ_{SiPM}=62.6 ps, σ_{CNM-0}=54.8 ps)
- Constant Fraction Discrimination: 20% before irradiation and 50% after irradiation





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Yunyun Fan

Summary and outlook

- The High Granularity Timing Detector requires high-performance and radiation-resistant sensors
- Choose promising technologies based on results from several beam test campaigns
  - LGADs irradiated to simulate their end-of-life state and studied with charged-particle beams at DESY and CERN in 2021 and 2022
  - Carbon-enriched LGADs from three vendors (FBK, IHEP-IME and USTC-IME) have been studied both in terms of radiation resistance and performance
- Although irradiated at fluences of to 1.5×10^{15} n_{eq}/cm^2 and 2.5×10^{15} n_{eq}/cm^2, the LGADs were operated at voltages below 550 V
- **Under these conditions, 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
- **These results confirm the feasibility of an LGAD-based timing detector for HL-LHC**
- **Ongoing studies on the performance of ALTIROC2+full sensor**
- **We aim to irradiate full size modules**

Thanks for your attention！

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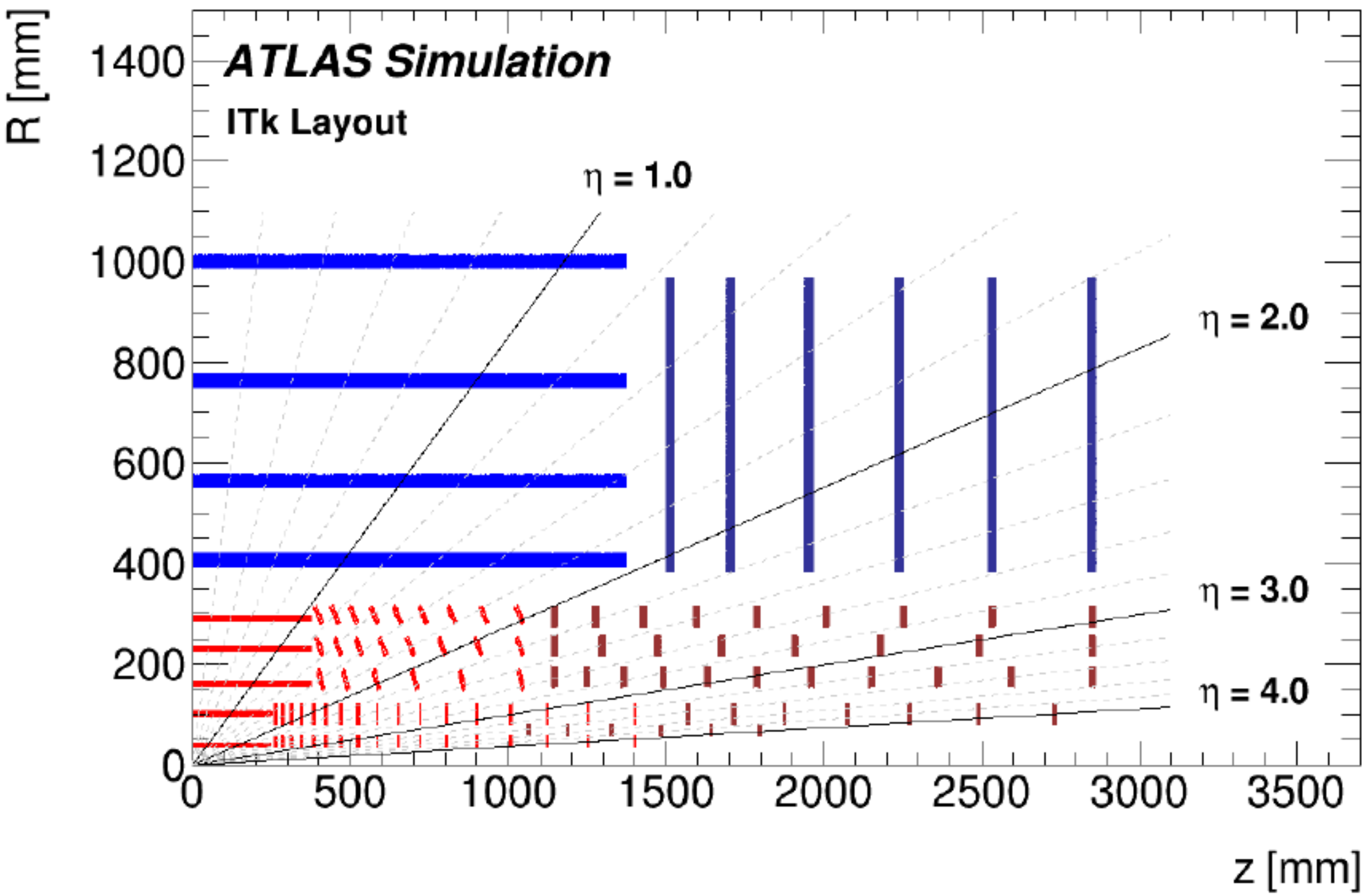
- **Back up**


ATLAS Simulation
ITk Layout
η = 1.0
η = 2.0
η = 3.0
η = 4.0
R [mm]
z [mm]
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
3500

Sensor performance: MALTA telescope at SPS

(more info: JINST 15 P02005 2020 or this talk)

- **MALTA monolithic CMOS sensor prototype produced in 180nm TowerJazz technology**
- Matrix of 512 x 512 pixels of 36.4 x 36.4 μm^2 size
  - Tracking resolution of ~5 μm (6 layers)
  - Efficiency of almost 100 %
  - Also take high intensity beams *(unlike MIMOSA)*

At SPS: permanent parasitic setup in H6A
- 6 Malta Planes
- Cold box with climate chamber
- Special supports made for LGAD sensors

Special MALTA runs performed July-Nov 2021

Toward radiation hard LGAD

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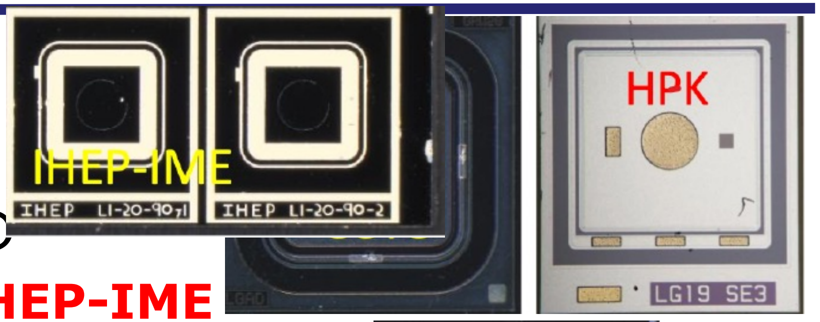
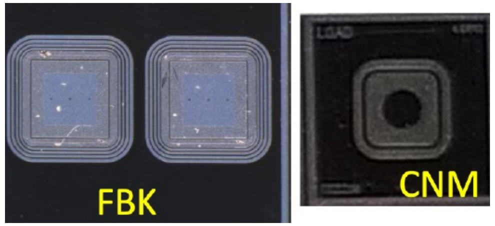
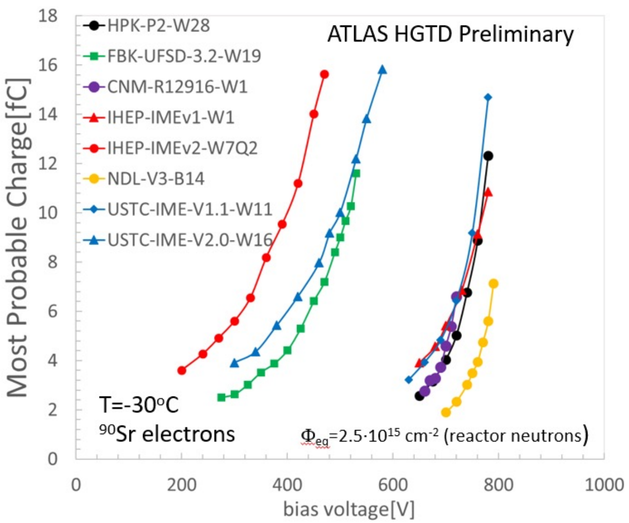
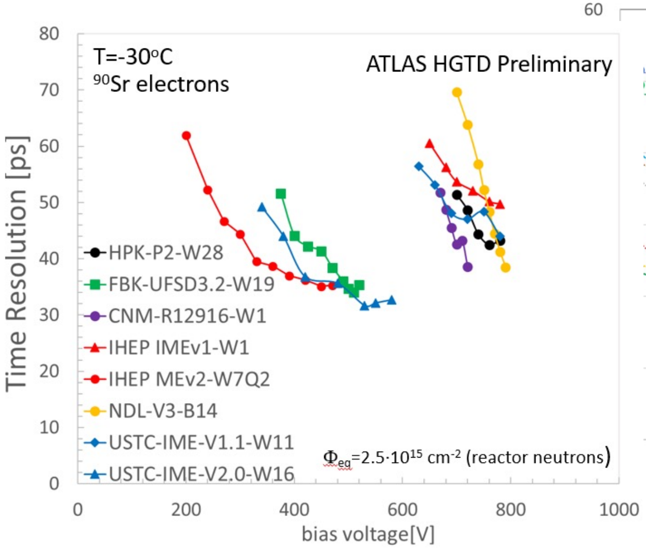
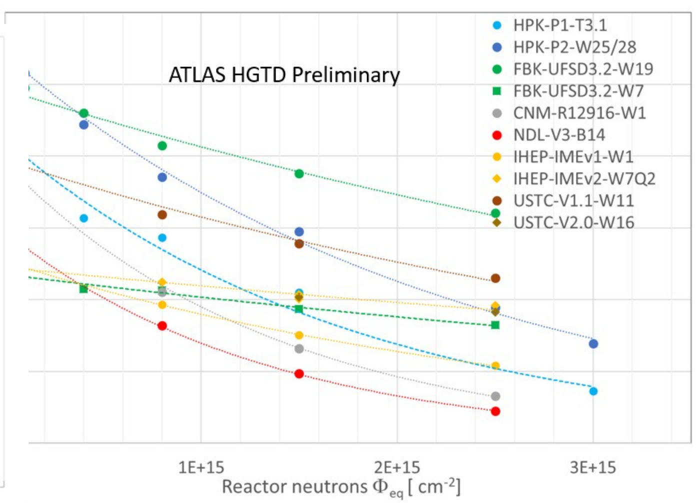


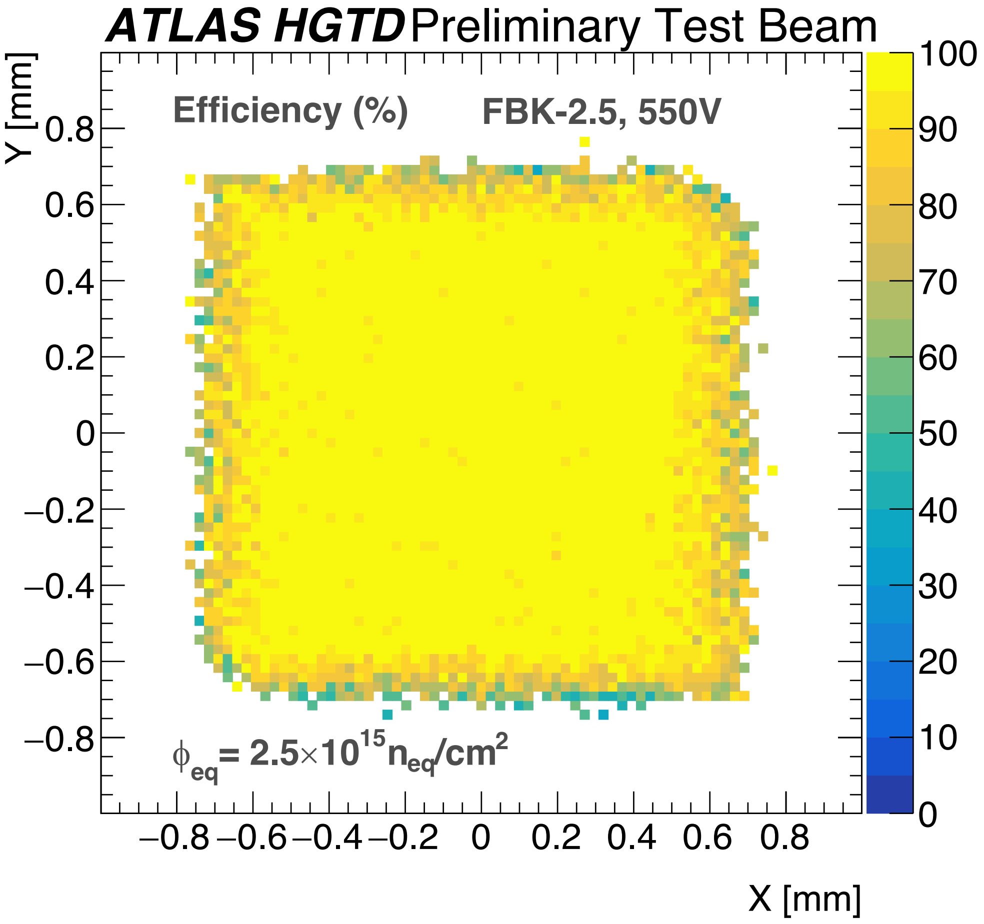
IHEP-IME









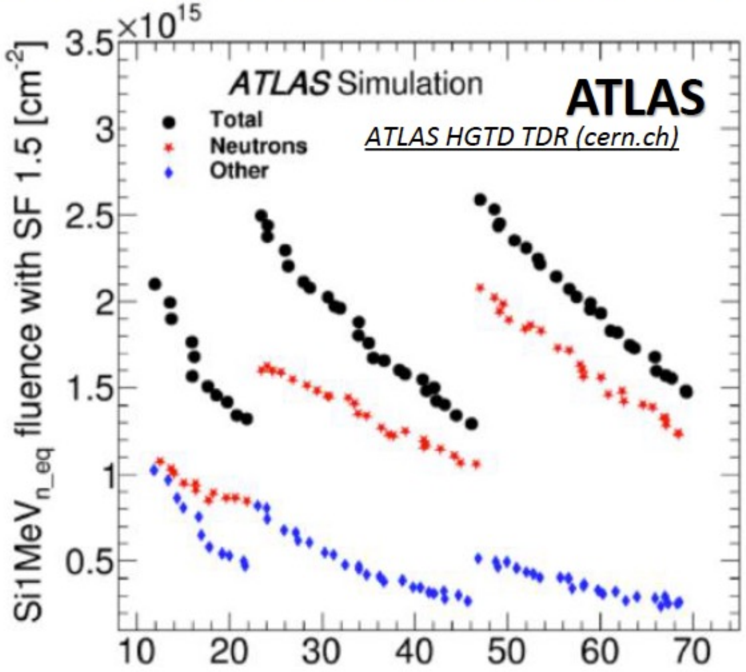


ATLAS HGTD Preliminary Test Beam
Efficiency (%)
FBK-2.5, 550V
ϕ_{eq} = 2.5×10^{15} n_{eq}/cm^2
Y [mm]
X [mm]
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
100
90
80
70
60
50
40
30
20
10
0

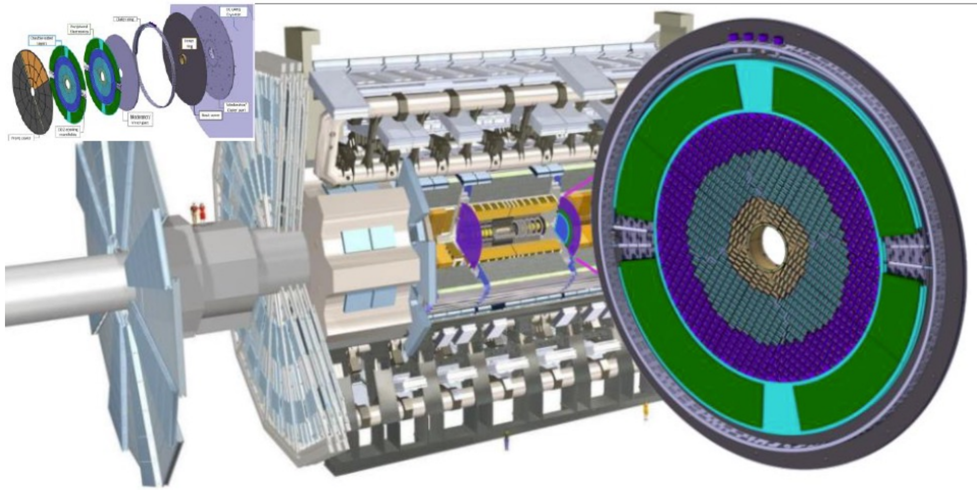
ATLAS will do replacements:

- Inner ring (IR) R< 230 mm - every 1000 fb^{-1}
- Middle ring (MR) R>230 mm && R<470 mm – every 2000 fb^{-1}
- Outer ring (OR) R>470 mm (42% of HGTD) – never

SIZEABLE CONTRIBUTION OF CHARGED HADRONS TO TOTAL FLUENCE



ATLAS – High Granularity Timing Detector



ATLAS-HGTD TDR

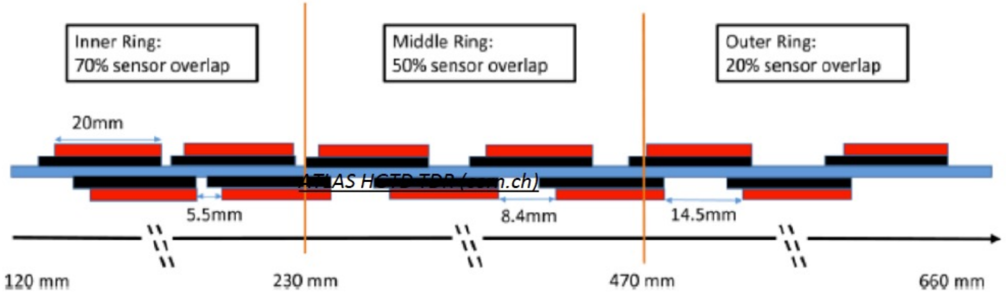
Layout :

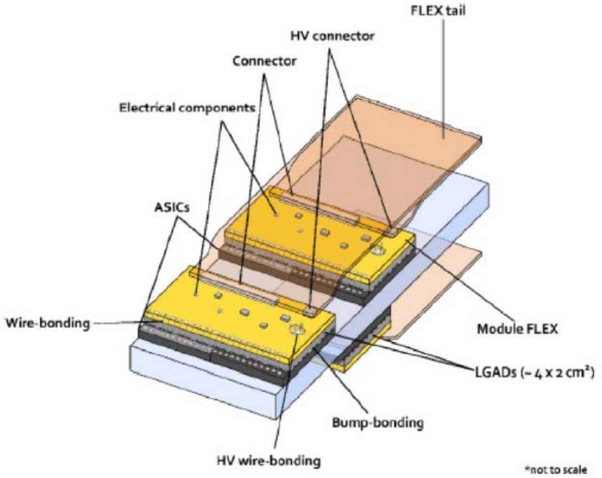
- Two double-instrumented disks per end-cap

~2.0 – 2.4 - 2.6 points/track

2.4 < |η| < 4, 120 mm < r < 640 mm , z=350 cm

- 3.6 M channels operating at -30°C (6.4 m^2 of Si)





Module is very similar to the pixel modules (less concern about the material)

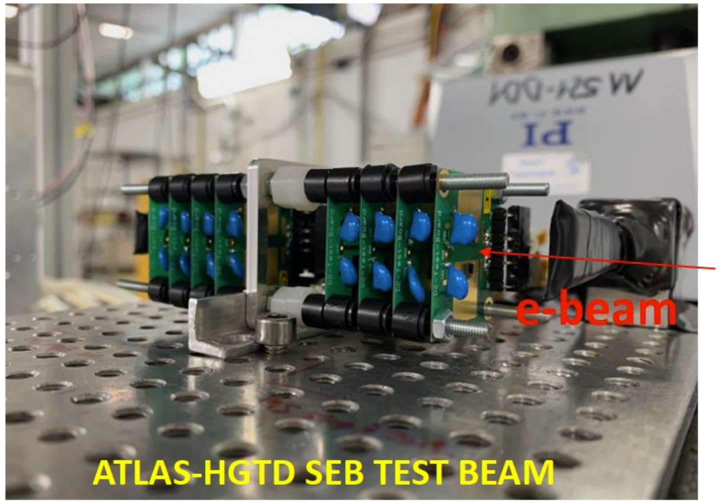
A single beam particle is responsible for the fatality

Sensor list for both ETL and HGTD test beam carefully prepared in order to determine the answers to the following questions:

- different fluences LGAD – **does irradiation matter?** - NO
- irradiated PINs – **does intrinsic gain matter?** - NO
- 0.1 MGy γ irradiated PINs – **does bulk damage matter?** - NO
- 35,45,50 μm thick LGADs – **effect of thickness?** - YES
- different producers – **does process matter?** - NO

Average electric field in the device is the critical driver:

- safe region - < 11 V/μm
- danger region - ~11-12 V/μm
- SEB region - >12 V/μm



Finding in the recent test beam campaigns:
(https://indico.cern.ch/event/1029124/contributions/4411270/)

- around 10-30 k 120 GeV p are required for SEB at voltages at >12 V/μm
- around 1M 3-6 GeV electrons are required for SEB at voltages at >12 V/μm (tested 3 thicknesses)

It is crucial for both experiments to show longevity of the sensors in the beam conditions.

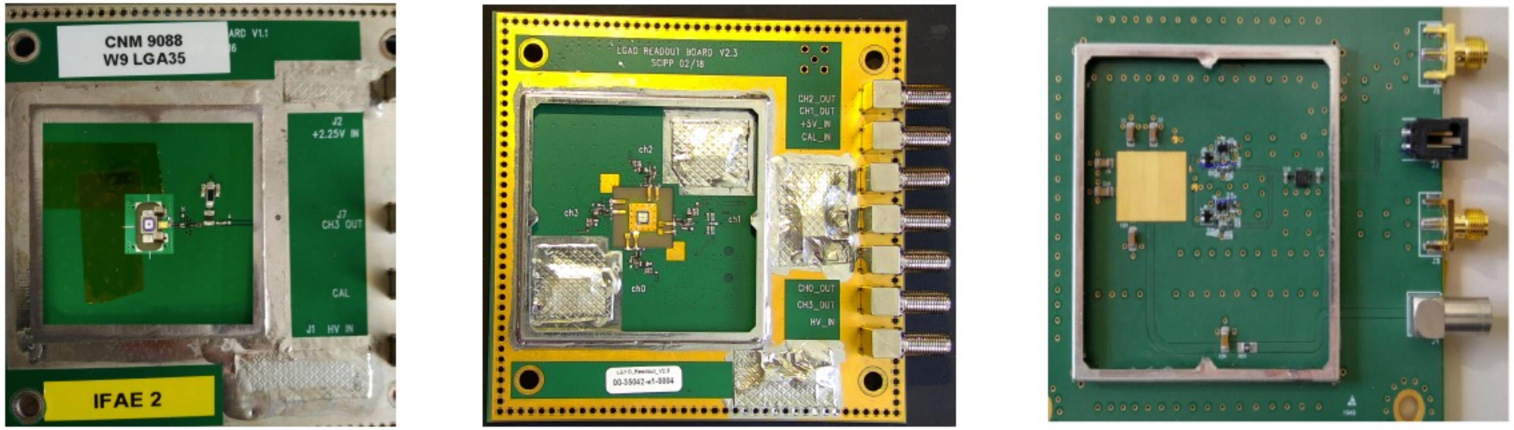


Figure 5. LGAD read-out boards: UCSC single-channel version (left), UCSC four-channel version (centre) and KU two-channel version (right).

LGAD sensors were assembled on 10 cm × 10 cm read-out and amplification boards using double-sided conductive tape. These boards were developed at the University of California Santa Cruz (UCSC) [22] in two versions: single-channel for single-pad LGADs and four-channel for 2 × 2 LGAD arrays. The LGAD front-side metal pad layer was coupled to the input of an on-board transimpedance first-stage amplifier via multiple wire bonds to reduce the inductance, while the guard ring was grounded. The single-channel version (figure 5 (left)) only includes this first amplification stage based on a single-transistor common emitter design that acts as an inverting transimpedance amplifier. For further amplification, it uses an external second-stage amplifier with hermetic E/B cover design from Mini-Circuits with a gain of about 10 and a 2 GHz bandwidth. The four-channel version (figure 5 (centre)) includes, in addition to the first amplification stage, two more amplifiers with a voltage divider between them resulting in a total gain of about 200 at a 1.6 GHz

- **Charge multiplication happens : 300kV/cm = 30 V/ µm**