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

Kuo Ma
(University of Science and Technology of China)
On behalf of the ATLAS HGTD Group

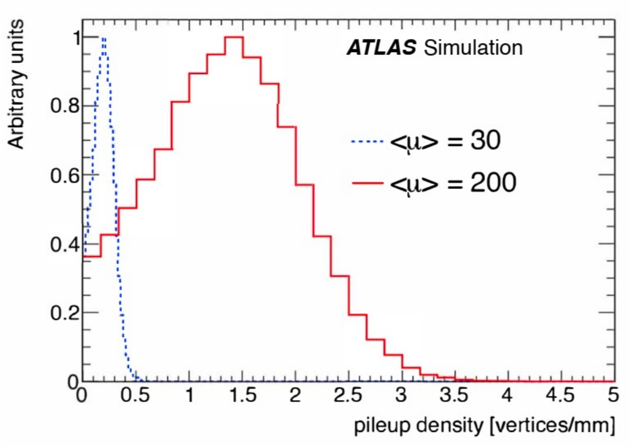
Sep 5th, 2023

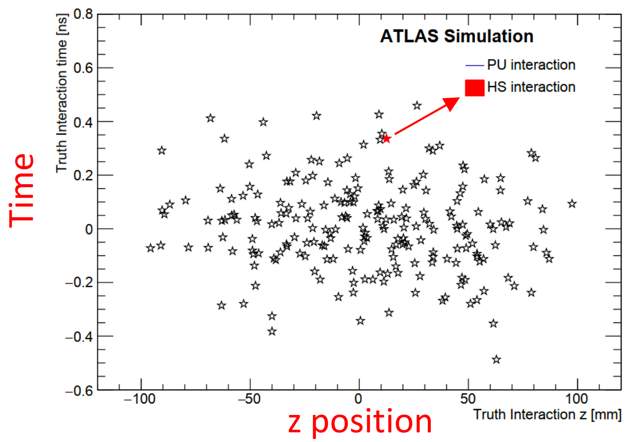
Outline

- ATLAS HGTD upgrade and LGAD technology
- LGAD performance in Laboratory
  - Evolution of radiation hardness
  - Collected charge and time resolution with ^{90}Sr source
- LGAD performance in DESY and CERN test beam
  - LGAD Single Event Burnout
  - Collected charge, time resolution and hit efficiency
- Summary and outlook

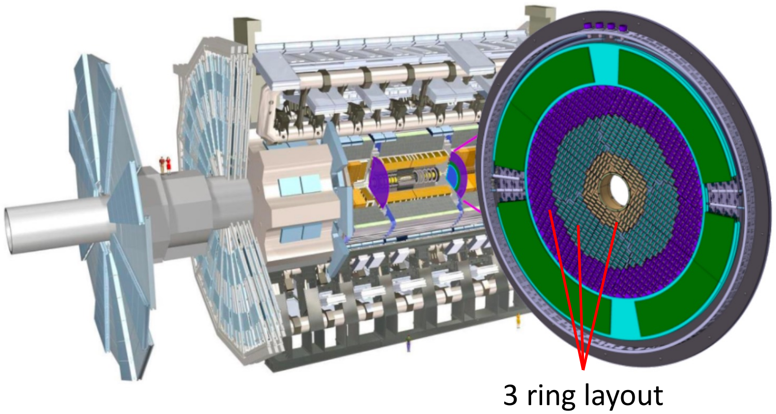
ATLAS High Granularity Timing Detector (HGTD)

- **H**igh-**L**uminosity phase of **LHC** (**HL-LHC**): It's hard to associate track to primary vertex in high pileup environment, especially in the forward region ($2.4 < |\eta| < 4.0$)
- **H**igh-**G**ranularity **T**iming **D**etector (**HGTD**): to measure high-precision time of charged particles in the forward region, complementing the **I**nner **Tr**ac**k**er (ITk)





Introduced in Xuewei's talk

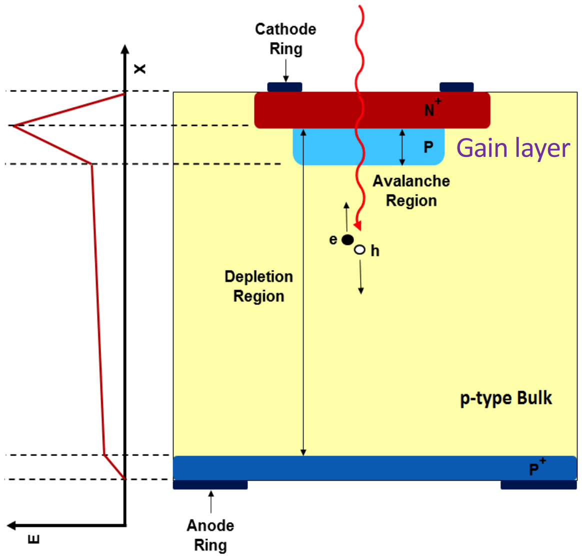


HGTD requirements:

- Withstand intense radiation environment
  - Maximum fluence: 2.5E15 n_{eq}/cm^2
  - Total Ionising Dose (TID): 2 MGy
- Collected charge per hit > 4 fC
- time resolution: 35 ps (start), 70 ps (end) per hit / 30 ps (start), 50 ps (end) per track
- Hit efficiency of 97% (95%) at the start (end)

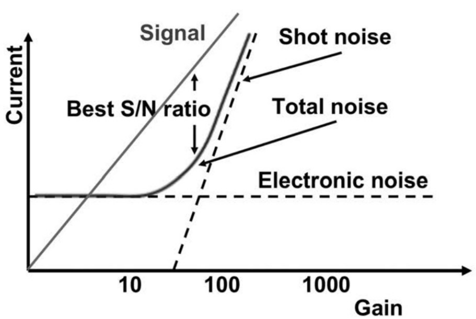
Low Gain Avalache Detector (LGAD)

- N^+-P-P^--P^+ structure, moderate gain (10 ~ 20), ps time resolution (~ 30 ps) and mm position resolution (Granularity: 1.3 × 1.3 mm^2)

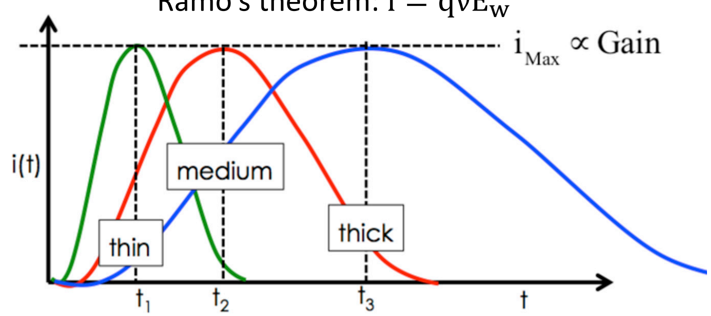


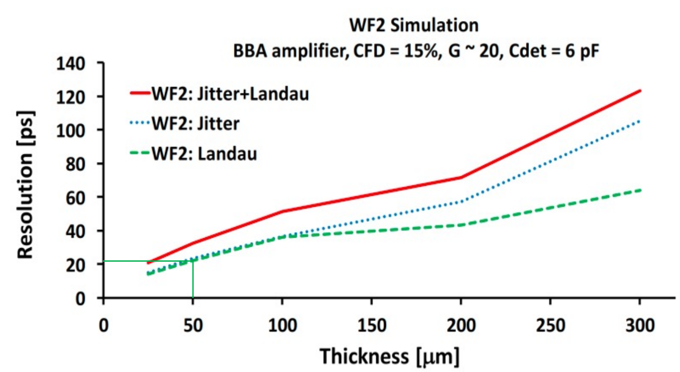
$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Time Walk}}^2 + \sigma_{\text{Landau}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2$$

- $\sigma_{\text{Jitter}} \sim \frac{t_{\text{rise}}}{S/N}$, where t_{rise} is rise time and S/N is signal to noise ratio
- $\sigma_{\text{Time Walk}} \sim \left[\frac{V_{\text{th}}}{S/t_{\text{rise}}}\right]_{\text{RMS}}$, where V_{th} is threshold
- σ_{Landau}: caused by non-uniform energy deposition
- $\sigma_{\text{Distortion}}$: caused by non-saturated velocity ν and non-uniform weighting field E_w
- $\sigma_{\text{Time-to-Digital Convert (TDC)}} \sim 25/\sqrt{12}$ (7.2) ps, can be neglected



Ramo's theorem: $i = q\vec{v}\overrightarrow{E_w}$

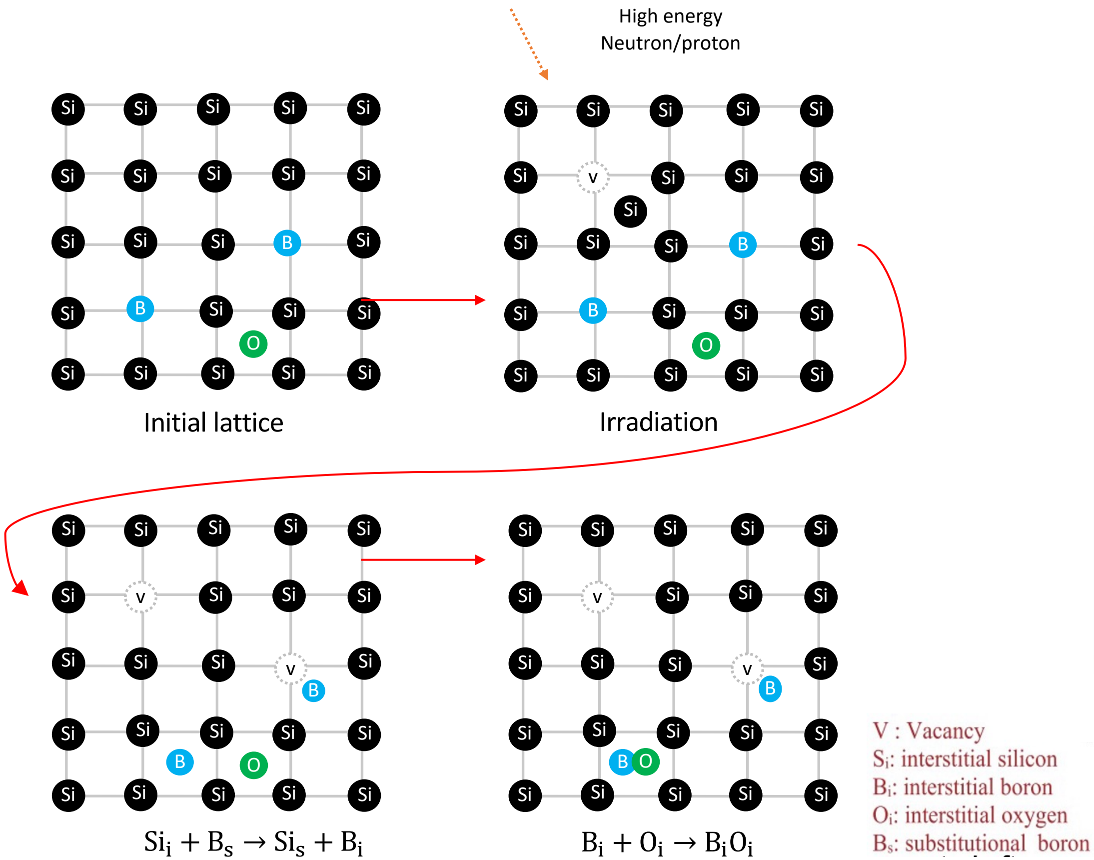




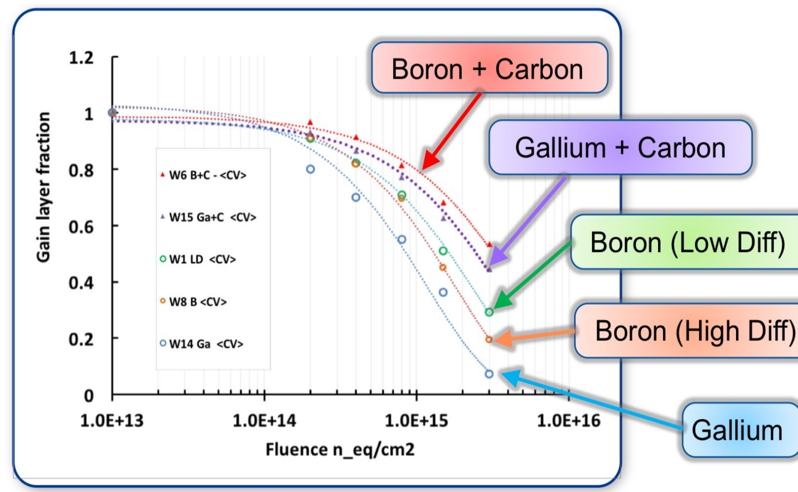
Moderate gain (larger S/N), thin detector (50 µm, faster rise time) and finite segment (Granularity: 1.3 × 1.3 mm^2, uniform weight field) → fast timing

Low Gain Avalache Detector (LGAD) R&D

- The **reduction of effective doping** in the gain layer is caused by the "acceptor removal" process -> LGADs' gain reduces M. Ferrero et al, NIMA, 2019 G. Kramberger et al, 2015 JINST 10 P07006
- Explored use of **different designs**, **doping materials** and **C-enriched substrates** -> Boron + Carbon shows largest gain after irradiation ($C_i + O_i \rightarrow C_iO_i$ competes with $B_i + O_i \rightarrow B_iO_i$)



Acceptor (B_s) removal in the gain layer after irradiation

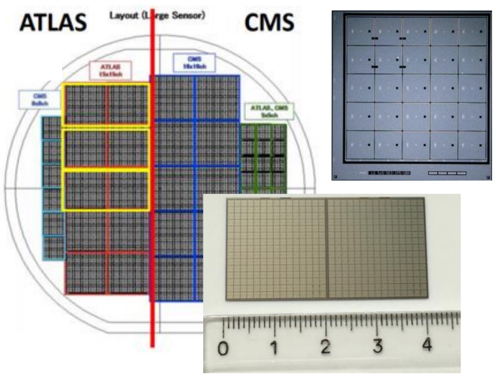


G.Paternoster, TREDI 2019

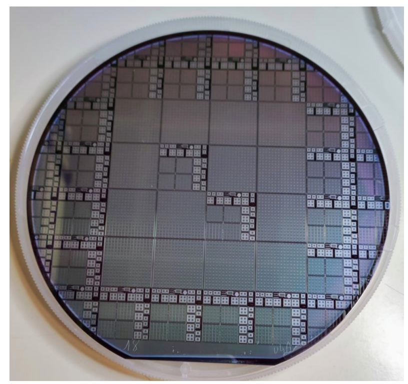
Latest prototypes produced by different venders

- LGADs has been widely studied by many producers in last few years, including:
  - CNM (Spain), FBK (Italy), HPK (Japan), IHEP-IME (China), USTC-IME (China), IHEP-NDL (China) …
- For each vender, the prototypes includes **small-array** sensors (1×1, 2×2…) and **large-array** sensors (5×5 and full-size (15×15) sensor for ATLAS)

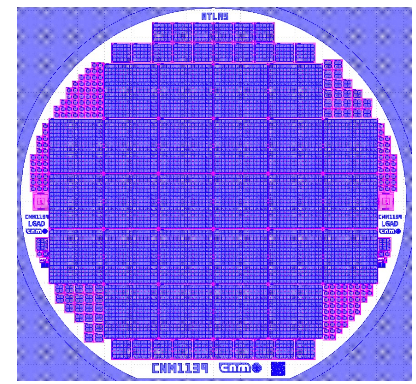
HPK-P2 (2022)



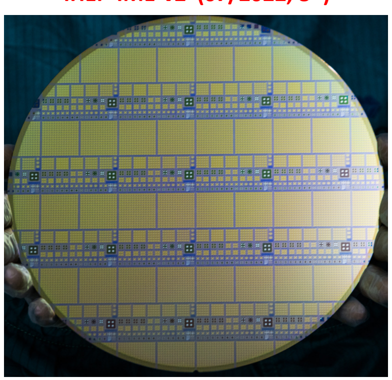
FBK-UFSD 4.0 (2022)



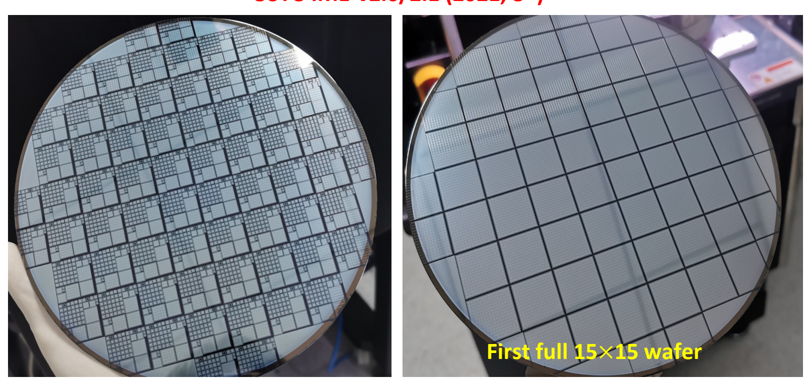
CNM-Run15973 (2022)



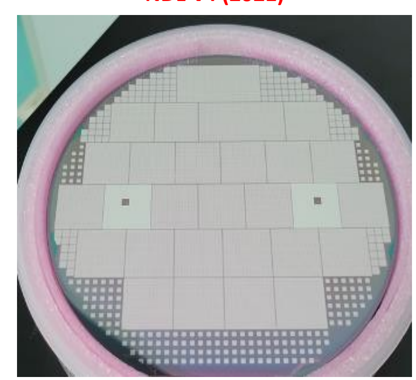
IHEP-IME-v2 (07/2022, 8'')



USTC-IME-v2.0/2.1 (2021, 8'')



NDL-v4 (2021)

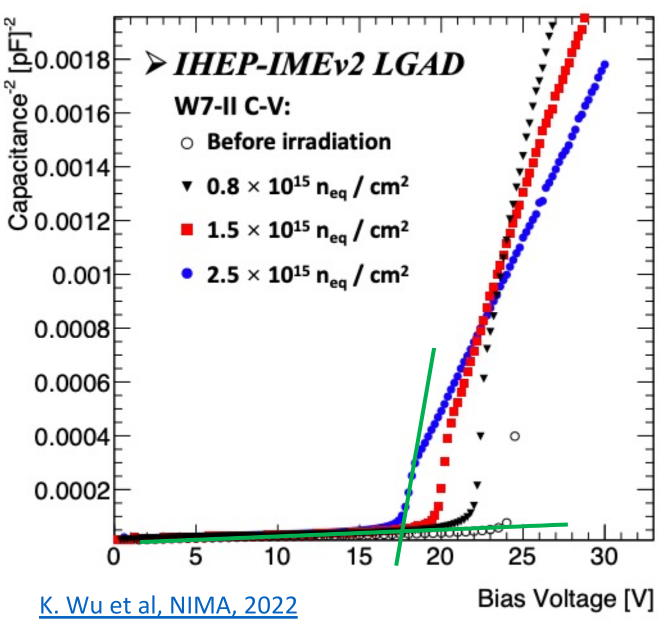


Evolution of radiation hardness

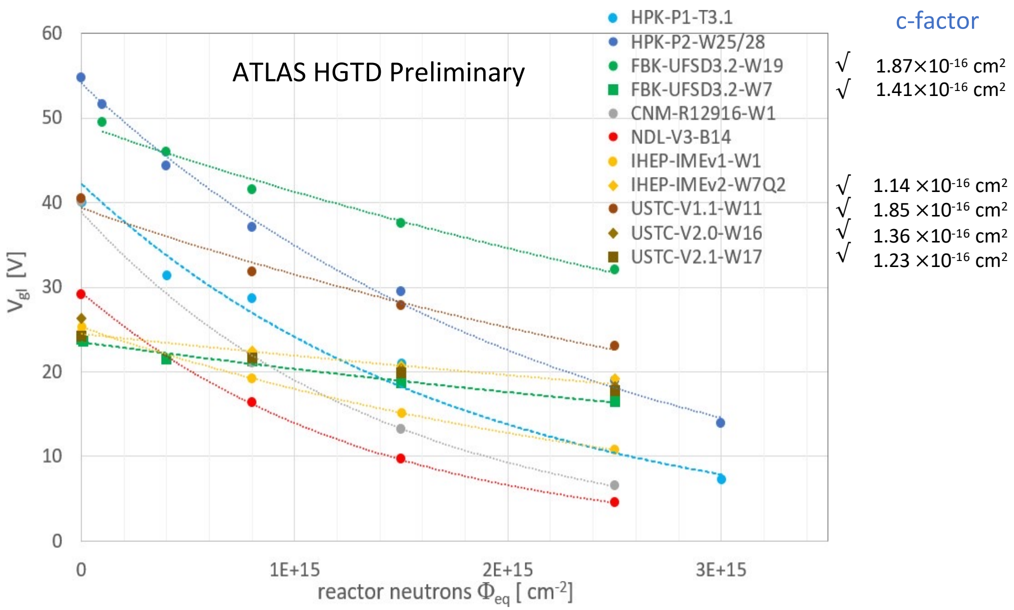
- The key parameter: acceptor removal coefficient (c-factor) (the lower the better)

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

- Optimization directions: adjust carbon enrichment dose and diffusion techniques



K. Wu et al, NIMA, 2022



G. Kramberger, ATLAS HGTD Week, 2022

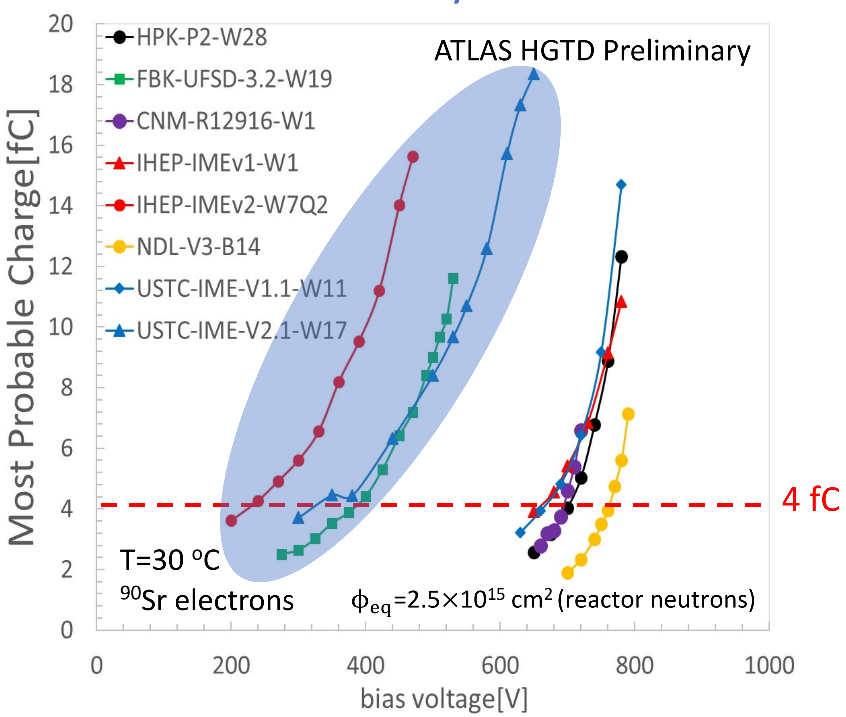
V_{gl} (V_{gl0}), depletion voltage of gain layer (before irradiation), is the voltage value where the two green straight lines intersect

FBK, IHEP-IME, USTC-IME have shown so far to master the process!

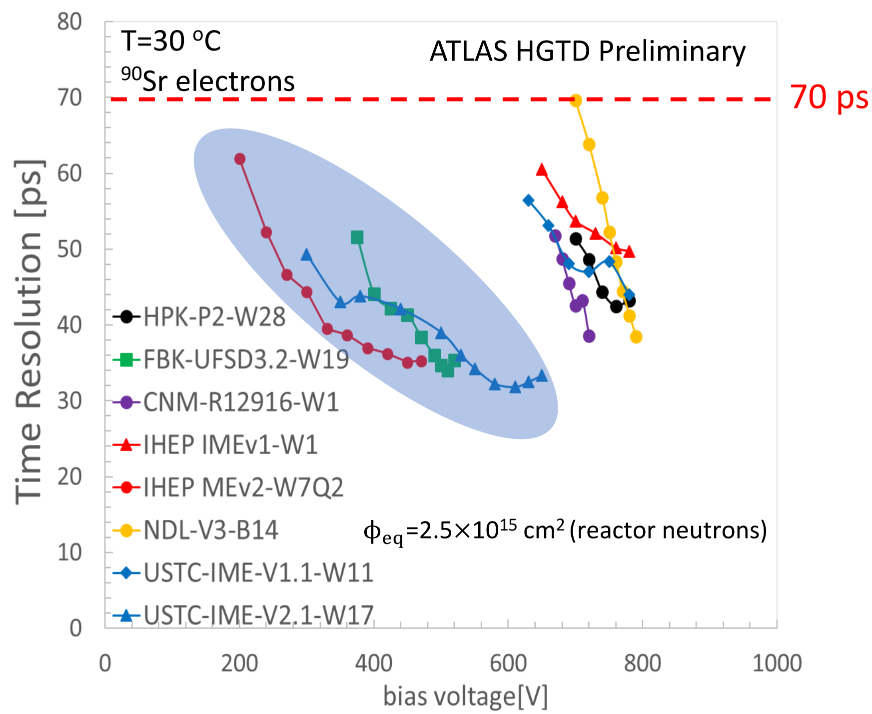
Collected charge and time resolution with ^{90}Sr source

- Sensors were exposed to fluence up to $2.5\times10^{15}\ n_{eq}/cm^2$ at the TRIGA reactor in Ljubljana, Slovenia with fast neutrons
- After irradiation LGADs' performance degrades due to loss of gain -> increase of bias voltage to recover
- Carbon-enriched LGAD (blue region) allows the sensors to be operated at lower voltages

Laboratory results

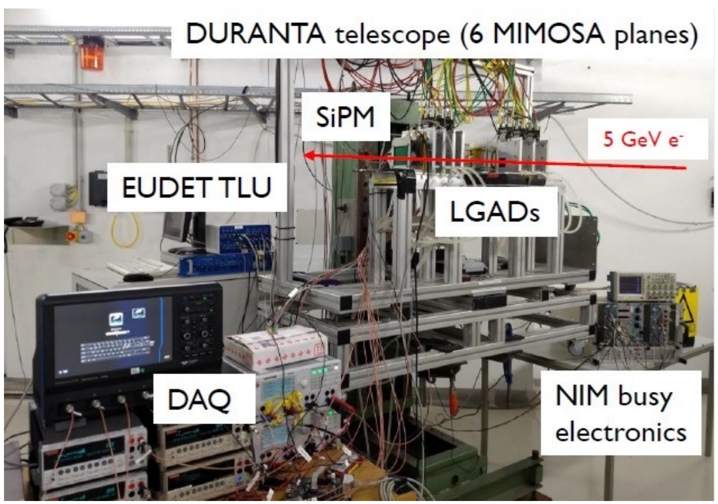


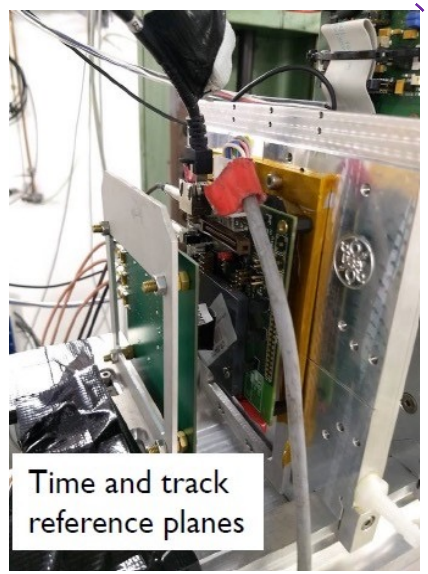
Laboratory results



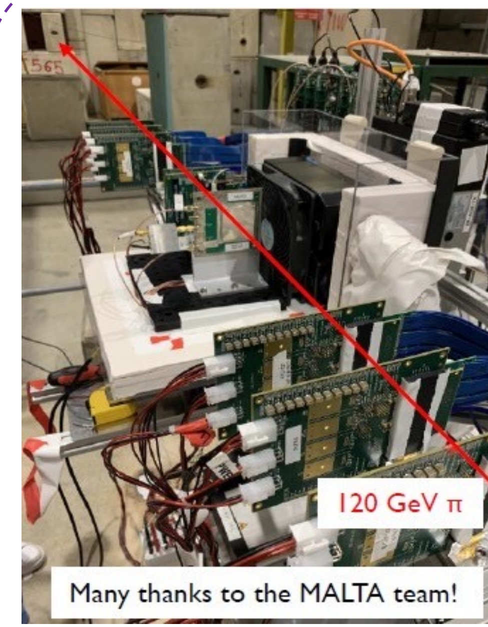
Beam test campaigns

- The collaboration has carried out numerous test beam campaigns and the results are documented in this list of papers: 2018 JINST 13 P06017, 2022 JINST 17 P09026 (2018-2019 data), **2023 JINST 18 P07030 (2021 data), 2023 JINST 18 P05005 (2021 - 2022 data)**
  - Determine safe bias voltages to avoid “Single Event Burnout” (SEB)
  - Qualify carbon-enriched LGADs performance (collected charge, time resolution, and hit efficiency)
  - DESY T22 beamline (5 GeV e^- beam) and CERN North Area SPS H6A beamline (120 GeV pion beam)
  - Use of beam telescope for tracking





Set-up at DESY



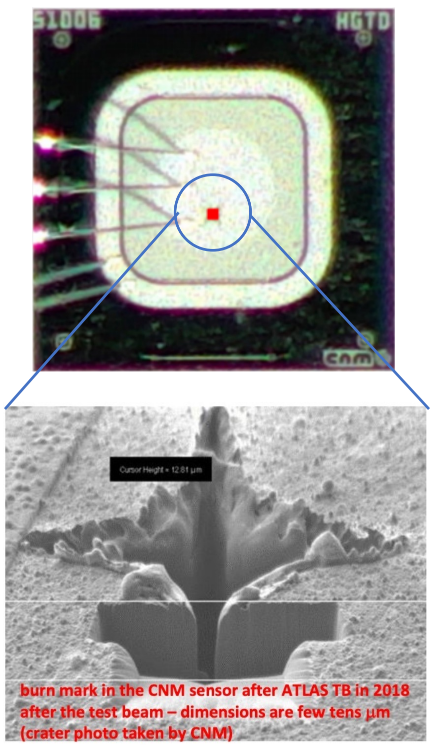
Set-up at CERN

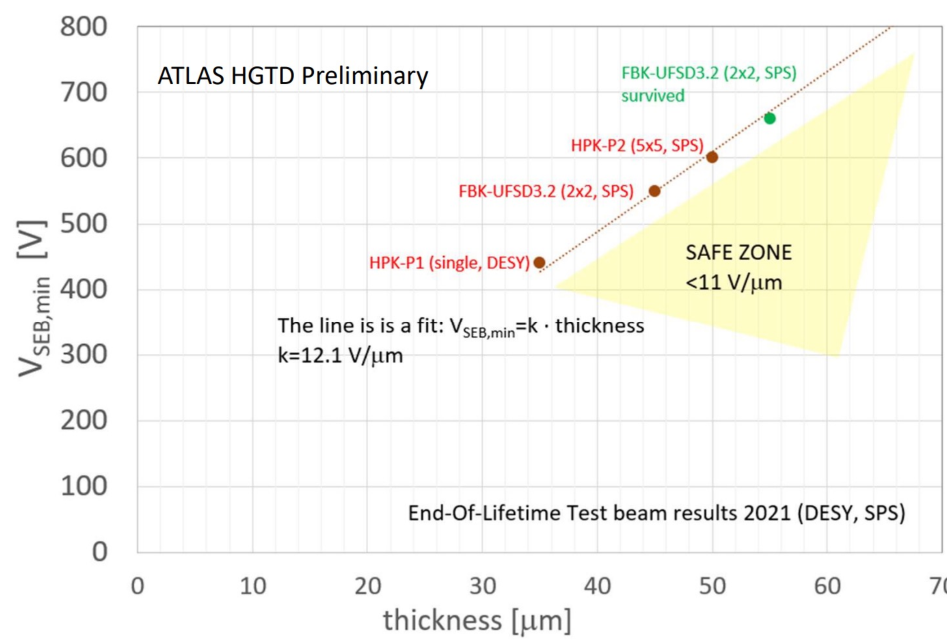
LGAD Single Event Burnout (SEB)

- Single Event Burnout (SEB) has been observed in several test beam campaigns
  - Irreversible breakdown while operating at high voltage (~100 V lower than voltage at laboratory)
  - Observed by CMS/ATLAS/RD50 teams

More details in Xuewei's talk

- A safe zone has been defined
  - Safe zone: electric field < 11 V/μm (50 μm → Max bias voltage is 550 V)





C-enriched LGAD prototypes for HGTD

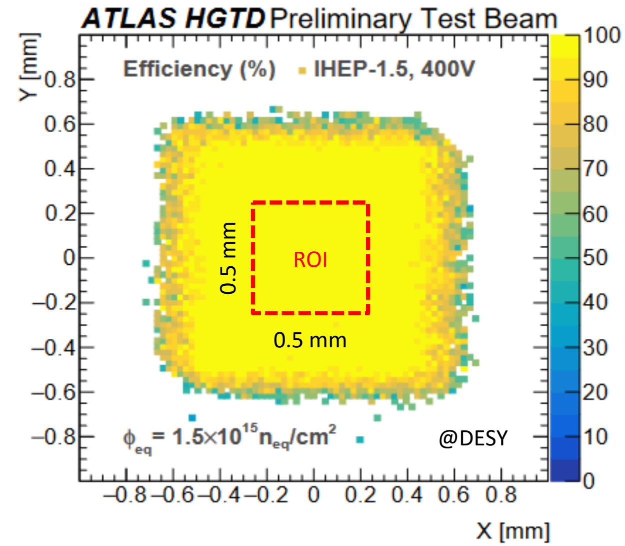
- Tested collected charge, time resolution and hit efficiency of C-enriched prototypes from 3 vendors (FBK, USTC-IME and IHEP-IME)
- LGAD (CNM-0) was used as a time reference at CERN as well as a SiPM device at DESY
- Sensors were exposed to fluences up to 1.5×10^{15} n_{eq}/cm^2 and 2.5×10^{15} n_{eq}/cm^2 at the TRIGA reactor in Ljubljana, Slovenia with fast neutrons
- Bias voltages were kept lower than the SEB voltage

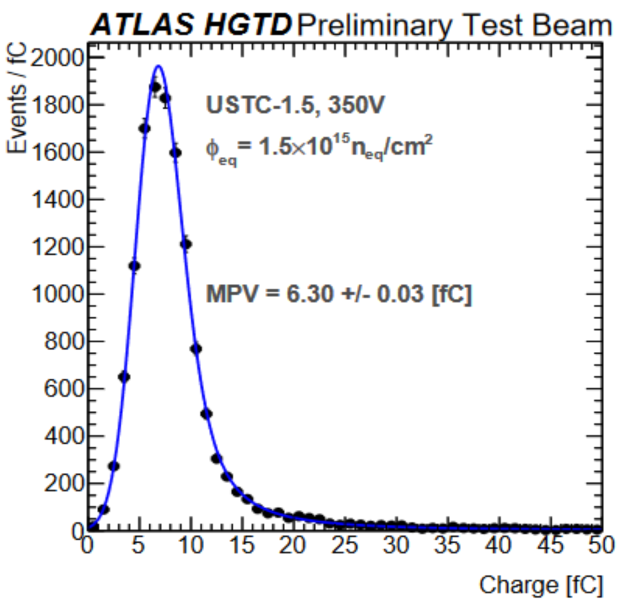
Device name	Vendor	Sensor ID	Implant	Irradiation type	Fluence [n_{eq}/cm^2]	Tested at
CNM-0	CNM	W9LGA35	boron	unirradiated	—	DESY/CERN
FBK-1.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	1.5×10^{15}	DESY/CERN
FBK-2.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	2.5×10^{15}	DESY/CERN
USTC-1.5	USTC-IME	v2.1 W17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

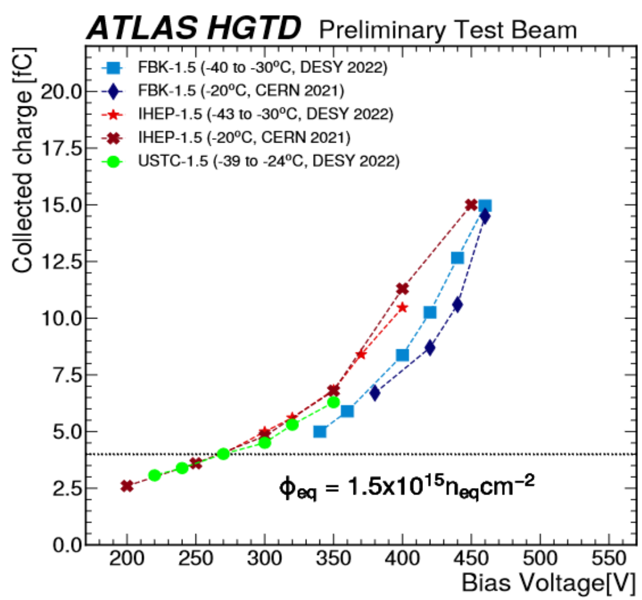
Device name	V_{gl0} [V]	Diffusion	c [cm^2]
FBK-1.5/2.5	50	H	1.73×10^{-16}
USTC-1.5/2.5	27	L	1.23×10^{-16}
IHEP-1.5/2.5	25	CHBL	1.14×10^{-16}

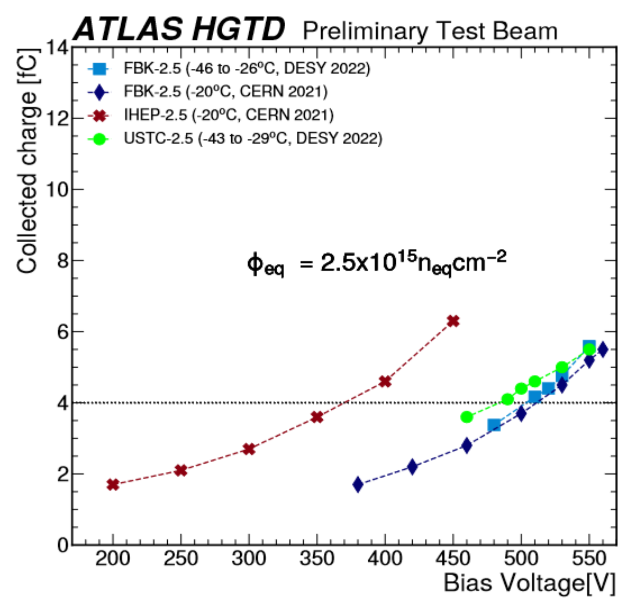
Collected charge

- Distribution of charge in the Region of Interest (ROI) was fitted with a Landau-Gaussian convoluted function
- Collected charge:
  - Defined as the Most Probable Value (MPV) from fit
  - Above the minimum required charge of 4 fC needed for a good timing measurement with the HGTD project





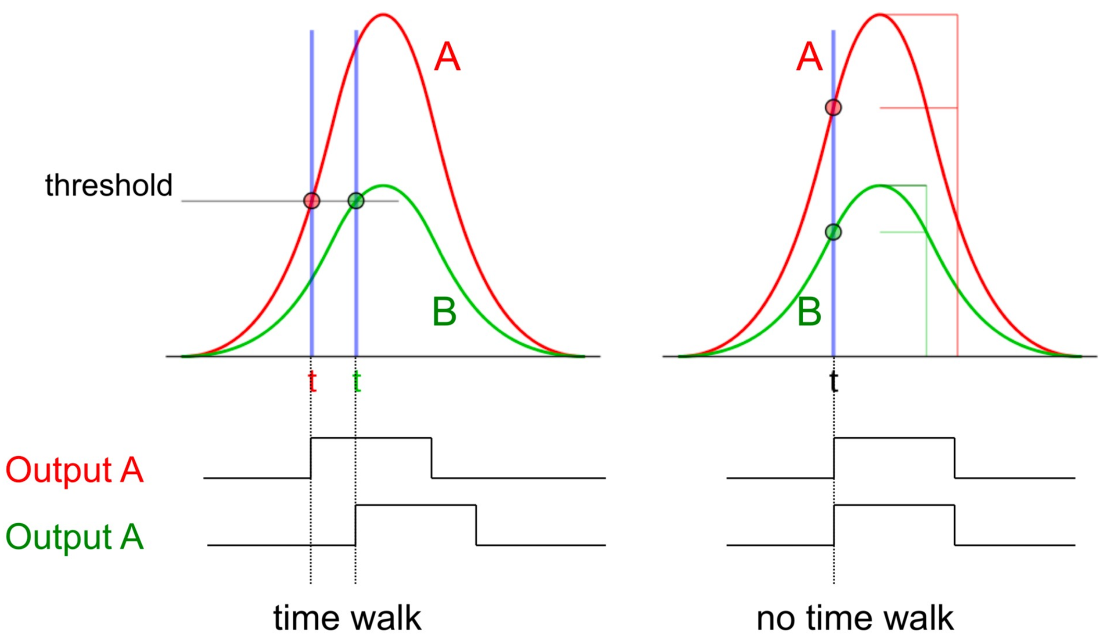




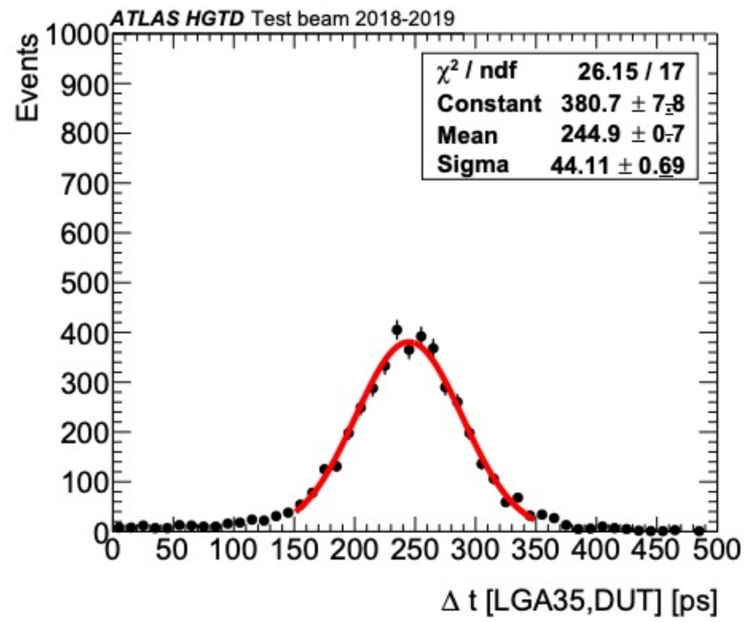
Time resolution method

- **C**onstant **F**raction **D**iscrimination (**CFD**) method was used to calculate **T**ime **o**f **A**rrival (**TOA**) to minimizes the contribution of time walk: 20% for the SiPM and 50% for the irradiated LGADs
- To extract the LGADs' time resolution, the distribution of the difference between the TOA (**ΔTOA**) of the LGADs and that of the time reference device were fitted with a Gaussian function, each of them giving a width σ_{ij}

Constant **T**hreshold **D**iscriminator (**CTD**) | **C**onstant **F**raction **D**iscrimination (**CFD**)

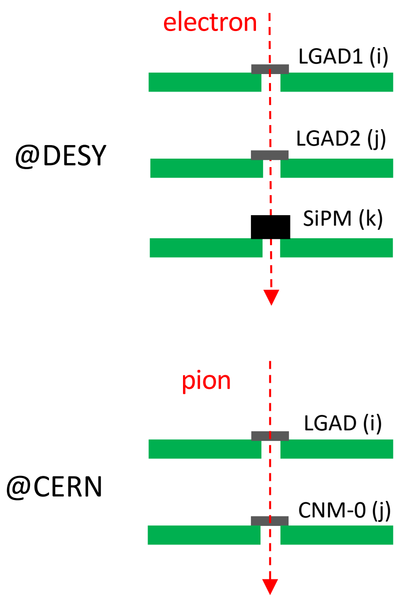


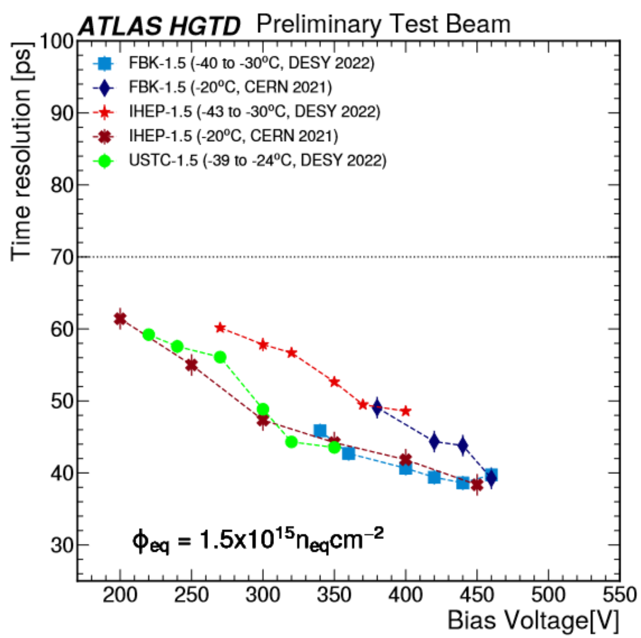
C. Agapopoulou *et al.*, 2022 JINST 17 P09026

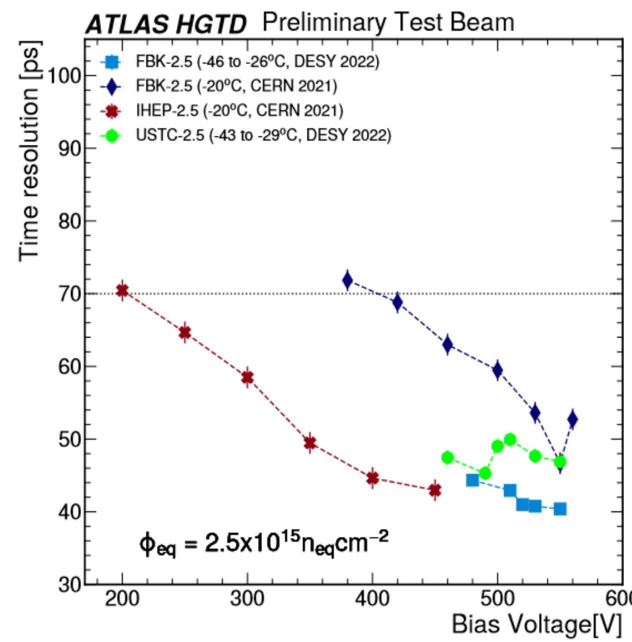


Time resolution

- For set-up at DESY, the ΔTOA of three devices is σ_{ij}, σ_{ik} and σ_{jk}, respectively. So the time resolution of LGADs and reference SiPM are $\sigma_i = \sqrt{(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)/2}$, $\sigma_j = \sqrt{(\sigma_{ij}^2 + \sigma_{jk}^2 - \sigma_{ik}^2)/2}$ and $\sigma_k = \sqrt{(\sigma_{ik}^2 + \sigma_{jk}^2 - \sigma_{ij}^2)/2}$ ($\sigma_{SiPM(k)}$ = 62.6 ps)
- For set-up at CERN, $\sigma_i = \sqrt{\sigma_{ij}^2 - \sigma_j^2}$ (the reference CNM-0 is known, which means σ_j = 55 ps)



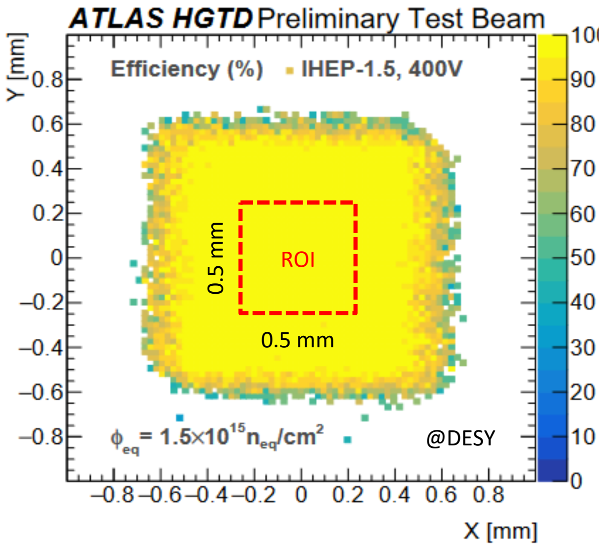


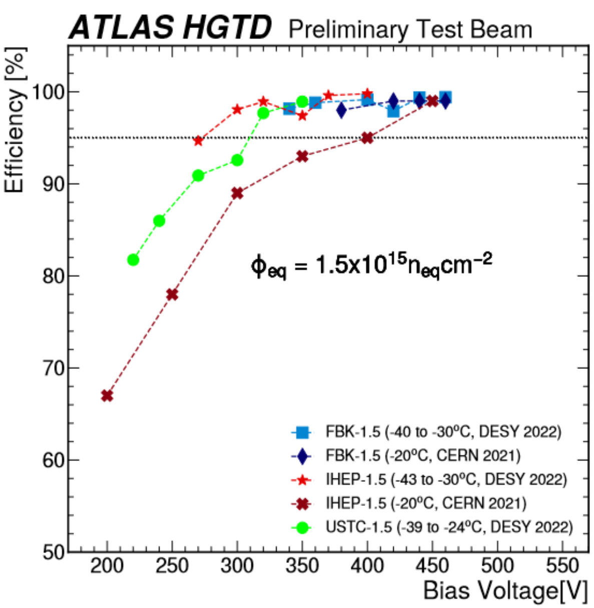


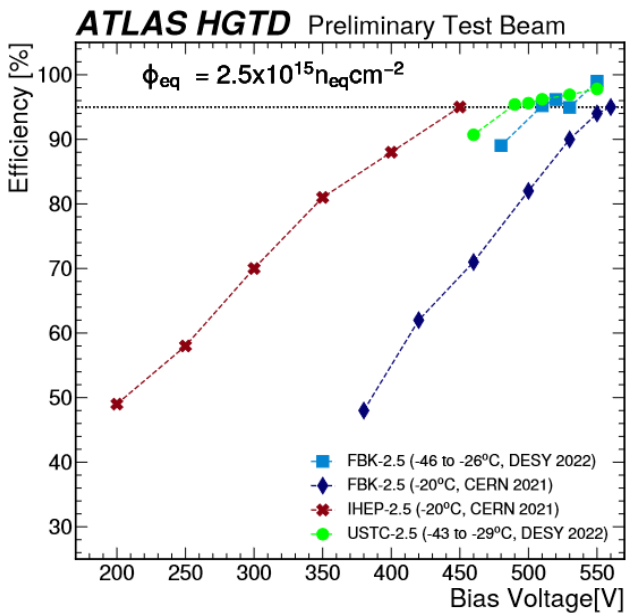
Hit efficiency

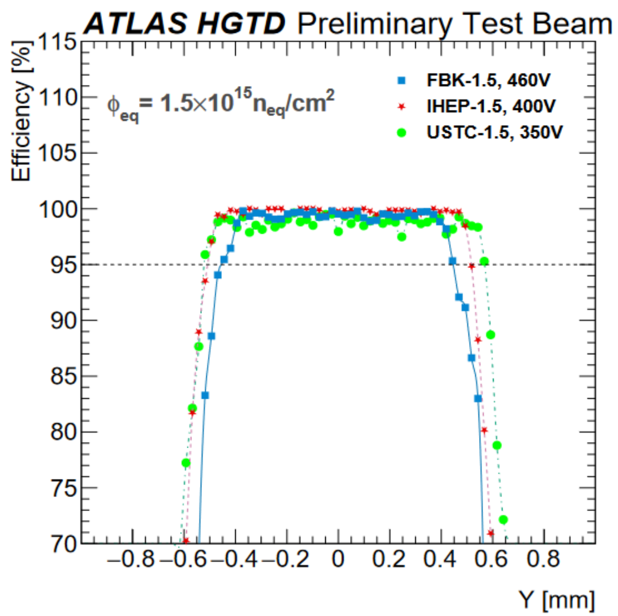
$$\text{Hit Efficiency} = \frac{\text{Rescontructed tracks with } q > Q_{cut}}{\text{Total rescontructed tracks}}$$

- Q_{cut} is set to 2 fC, the minimum achievable threshold of the ALTIROC chip
- Achieved the efficiency of 95% required for HGTD after irradiation









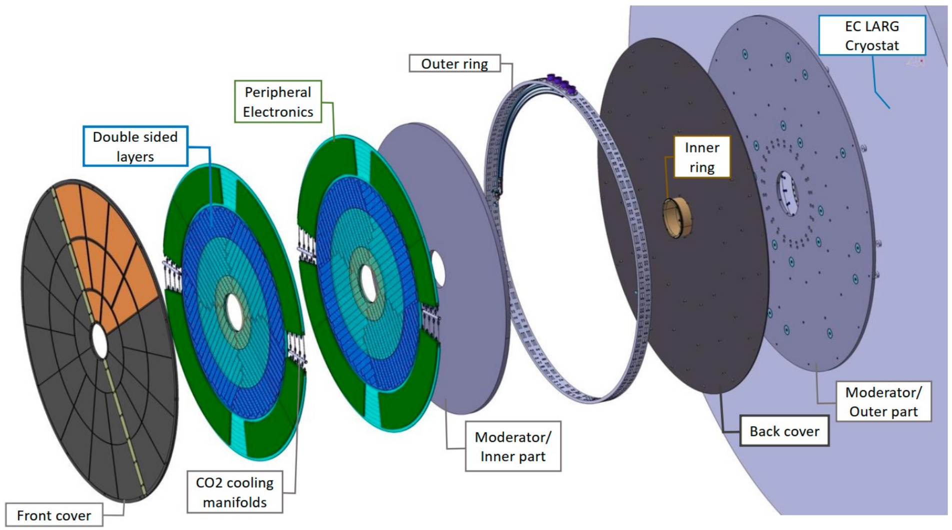
Summary and outlook

- The LGAD, as a **fast timing as well as radiation hard** silicon based detector, has reached a mature state in recent years
- Carbon-enriched LGADs from three vendors (FBK, IHEP-IME and USTC-IME) have been studied both in terms of radiation hardness and performance
  - irradiated at fluences of 1.5 - 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 optimal time resolution better than 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
- Outlook:
  - The IHEP-IME and USTC-IME Pre-production have been started and the laboratory test is ongoing, looking forward to do beam test soon

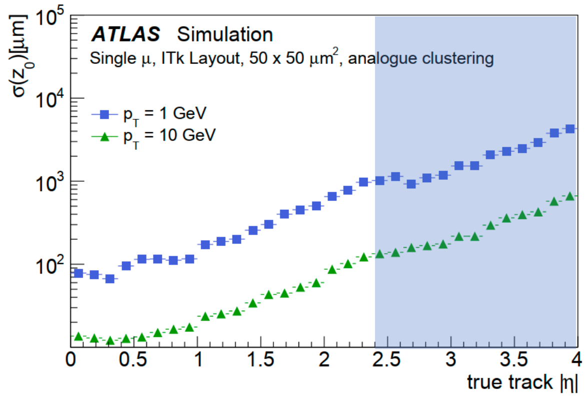
Thanks for your attention!

Back up

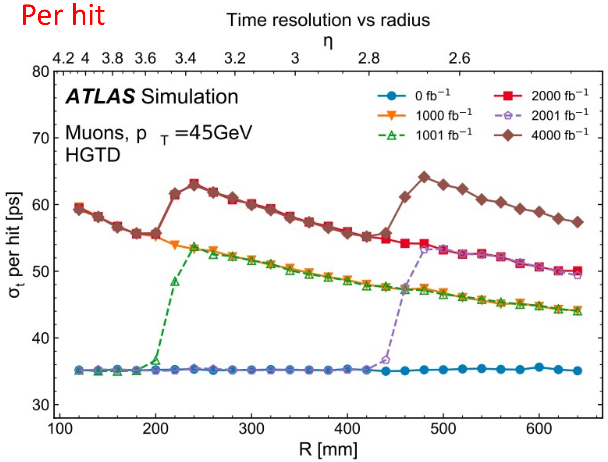
HGTD: Layout and requirements



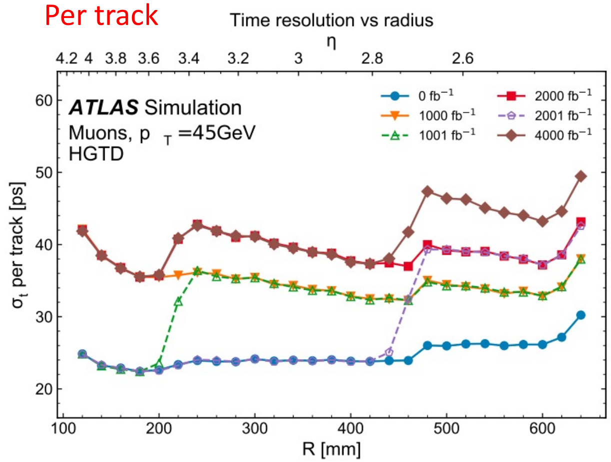
Pseudo-rapidity coverage	$2.4 < \lvert\eta\rvert < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	±3.5 m
Weight per end-cap	350 kg
Radial extension:	
Total	$110\,\text{mm} < r < 1000\,\text{mm}$
Active area	$120\,\text{mm} < r < 640\,\text{mm}$
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.6 M
Active area	6.4 m^2
Module size	30 x 15 pads (4 cm × 2 cm)
Modules	8032
Collected charge per hit	> 4.0 fC
Average number of hits per track	
$2.4 < \lvert\eta\rvert < 2.7$ (640 mm > r > 470 mm)	≈2.0
$2.7 < \lvert\eta\rvert < 3.5$ (470 mm > r > 230 mm)	≈2.4
$3.5 < \lvert\eta\rvert < 4.0$ (230 mm > r > 120 mm)	≈2.6
Average time resolution per hit (start and end of operational lifetime)	
$2.4 < \lvert\eta\rvert < 4.0$	≈ 35 ps (start), ≈ 70 ps (end)
Average time resolution per track (start and end of operational lifetime)	≈ 30 ps (start), ≈ 50 ps (end)



Per hit

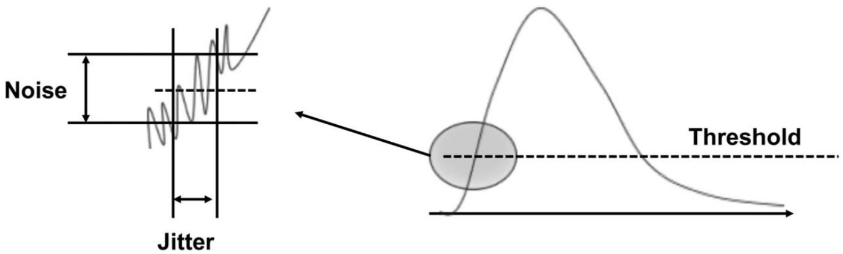


Per track



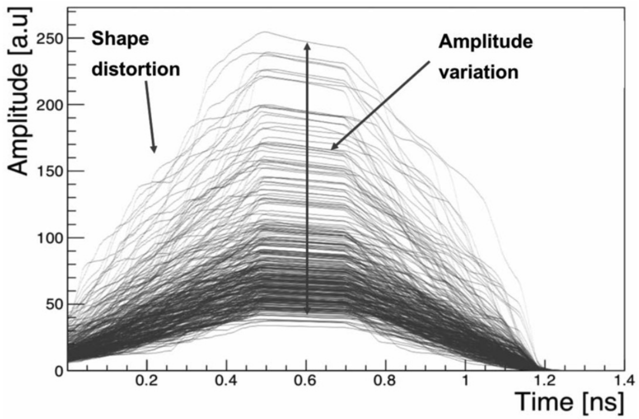
Introduction to the contribution of time resolution

- Jitter



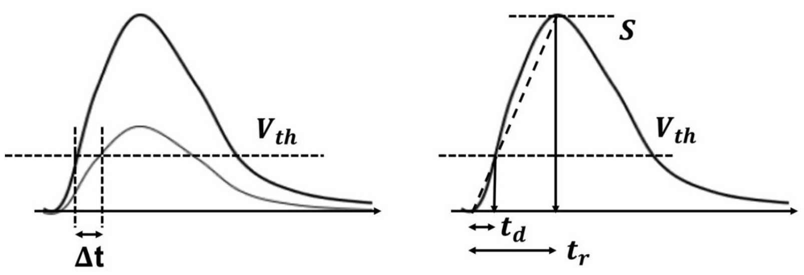
$$\sigma_{Jitter} = \frac{N}{dV/dt} \approx \frac{t_{rise}}{S/n}$$

- Landau noise



WF2 simulation, MIP, 50 μm, Gain ~ 20

- Time walk

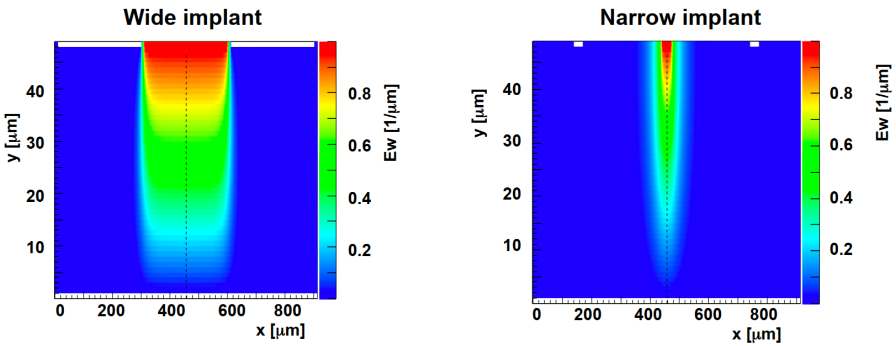


$$\sigma_{TimeWalk} = [t_d]_{RMS} = [\frac{V_{th}}{S/t_{rise}}]_{RMS} \propto [\frac{N}{dV/dt}]_{RMS}$$

- Distortion (distribution of weighting field)

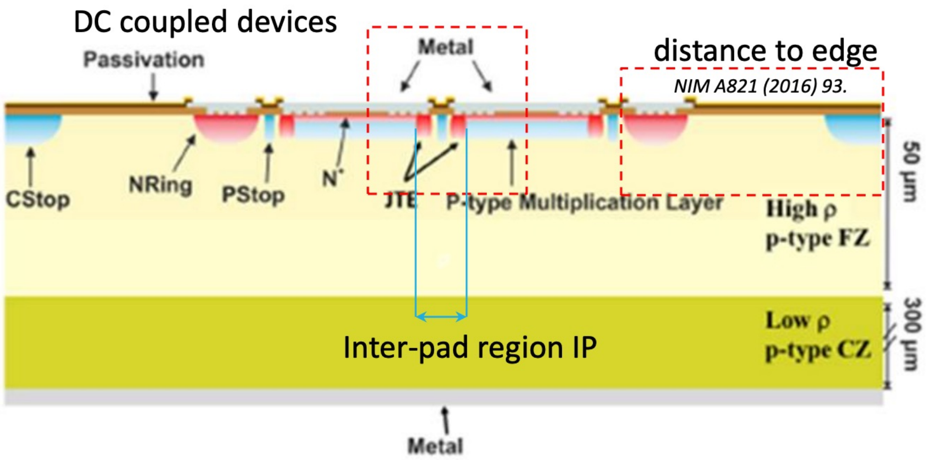
290 μm

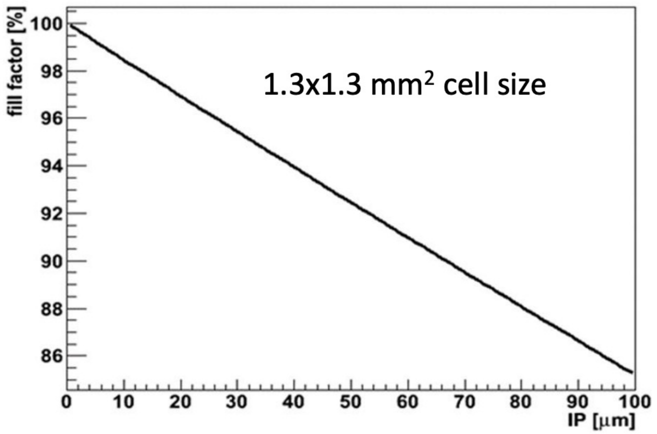
50 μm



Segmented LGADs and Inter-pad region

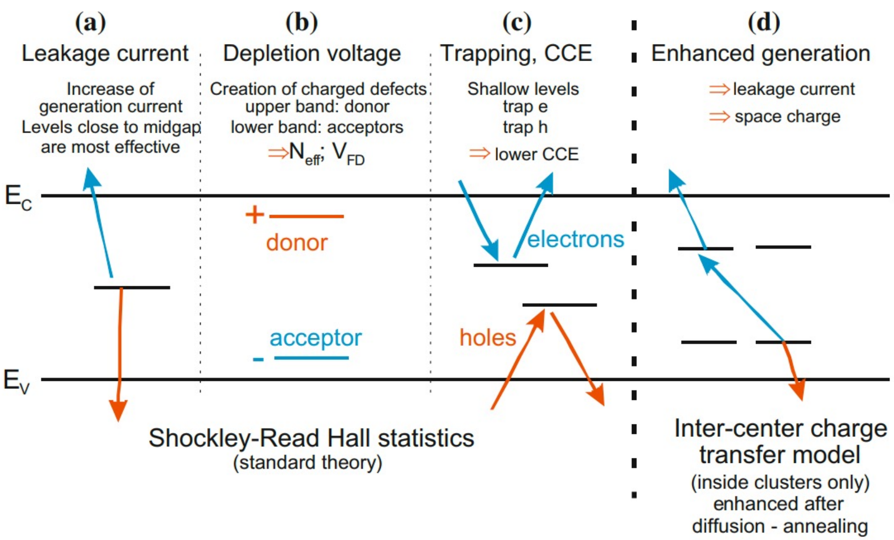
Gregor, Detector Semiar, 2021





- JTE enables efficient isolation of the electrode – allows for segmentation of the LGAD – the key to multi electrode LGADs
- Inter-pad region is the distance between two electrodes. It is effectively the non-active region as it is without the gain and effectively reduces the "fill factor" of the LGAD
- The IP distance can't be too small as in a case of a bad connection – floating pad there is a danger of an early breakdown (~30-90 µm)
- Distance to edge determines the breakdown through the edges and is 300-500 µm

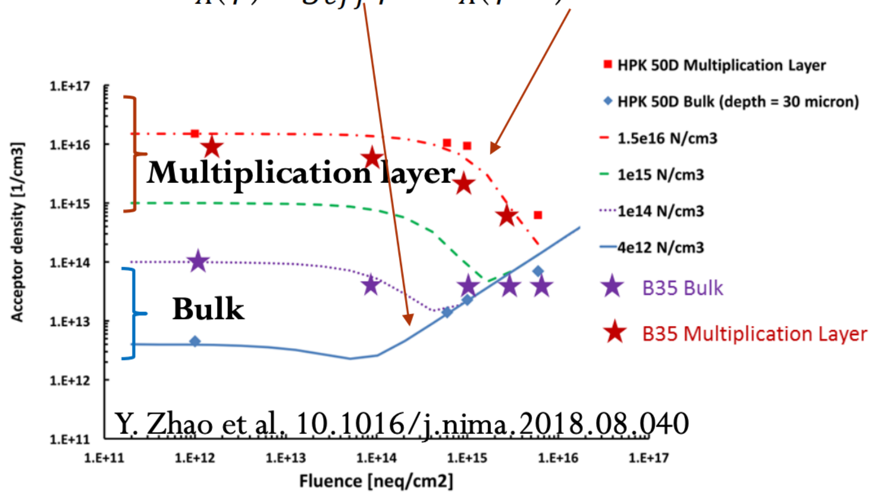
Radiation effect on Silicon



Three main effect:

- Increase of leakage current
- Changes in doping concentration
- Decrease of charge collection

$$N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$$



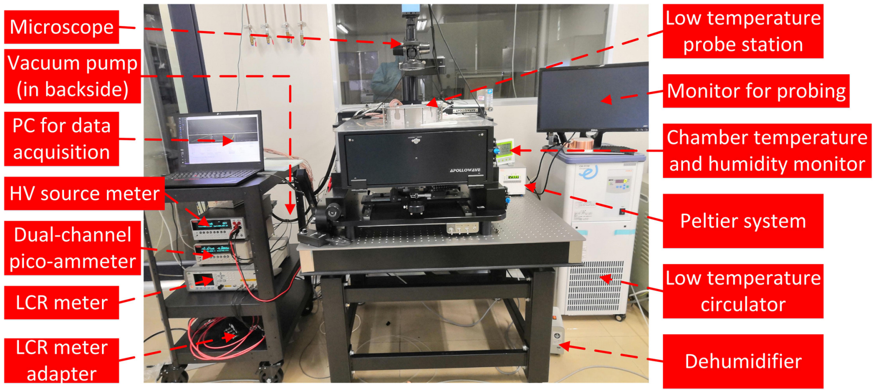
S. M. Mazza et al, PSD12, 2021

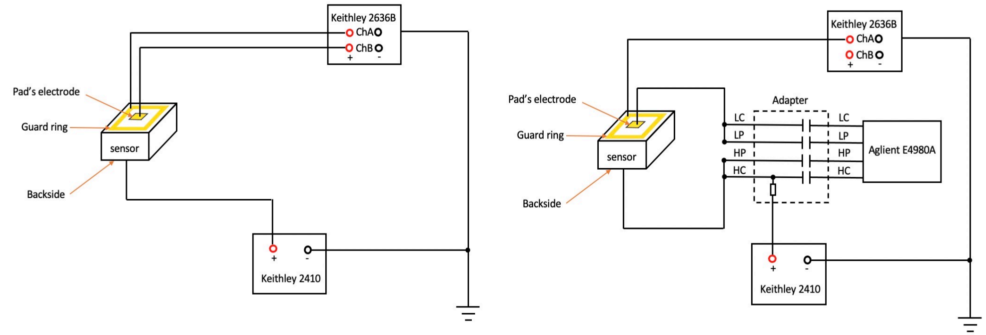
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Acceptor removal mechanism: $N_A(\phi = 0)e^{-c\phi}$
  - Reduction of doping → reduction of gain
  - **C-factor (acceptor removal constant)** depending on detector type (the lower the better)

Experimental techniques for LGADs

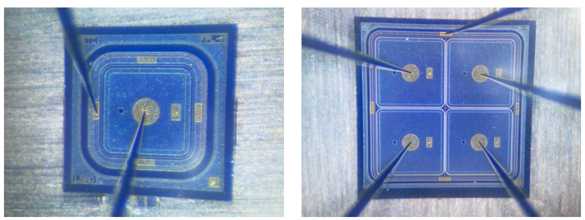
Experimental Techniques	Purposes	Comments
Leakage current-Voltage (IV)	Gain layer depletion voltage ($\mathbf{V_{GL}^{I}}$)	Doping information of gain layer
	Device break down voltage ($\mathbf{V_{BD}}$)	Safe operating voltage range
	Leakage current@V_x or voltage@I_x	Power consumption of circuit
	Inter pad resistance	Isolation between pads
Capacitance-Voltage (CV)	Gain layer depletion voltage ($\mathbf{V_{GL}^{C}}$)	Depletion behavior of gain layer
	Full depletion voltage of the device ($\mathbf{V_{FD}}$)	Depletion behavior of bulk
	Electrode capacitance ($\mathbf{C_{pad}}$)	Depletion behavior of sensor
	Inter pad capacitance	Cross talk between pads
Beta-scope test (^{90}Sr)	Voltage required to collect 15 fC (**V15fC**)	Voltage required to collect 15 fC at -30°C
	Minimum operation voltage ($\mathbf{V_{op,min}}$)	S/N>10, V>4fC, noise < 1.2 noise at low bias, no ghosts, I<500nA/5μA
	Maximum operation voltage ($\mathbf{V_{op,max}}$)	The above conditions can be met
	Time resolution at 4fC (**τ4fC**)	Time resolution at $V_{op,min}$
Transient Current Technology (TCT, laser)	The no-gain distance between two adjacent pads (**Effective IP width**)	No-gain area where collected charge is less than 50%*Max (collected charge)
Test Beam (TB, proton or electron or …)	Hit efficiency	97% (95%) at the start (end)
	Charge collection and timing resolution	35 ps (start), 70 ps (end) per hit

IV & CV setup (USTC for example)



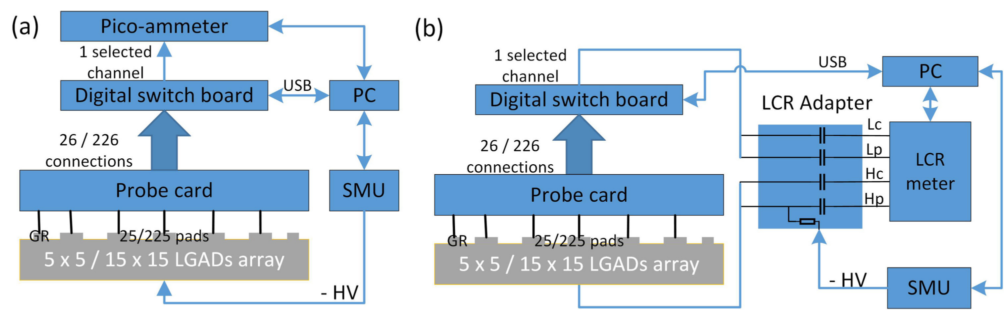


Equivalent circuit diagram of 1×1 LGADs



Tested by probe needles

Tested by probe card



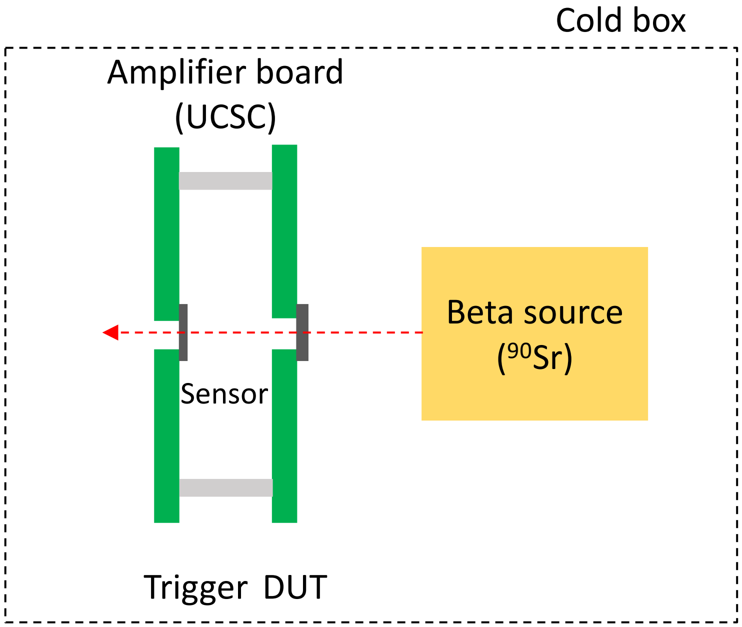
Equivalent circuit diagram of 15×15 LGADs

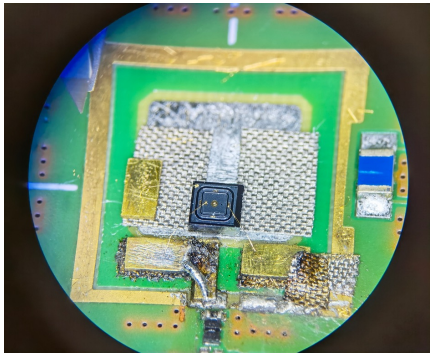
J.J. Ge, NIMA, 2021

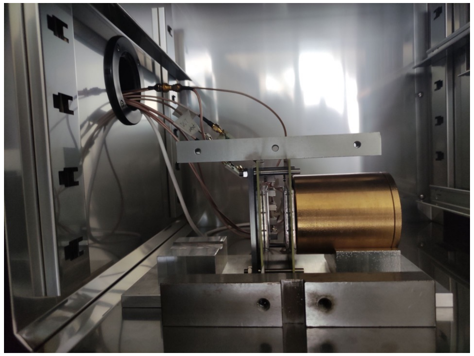
β-scope setup (USTC for example)

C.H. Li, NIMA, 2022

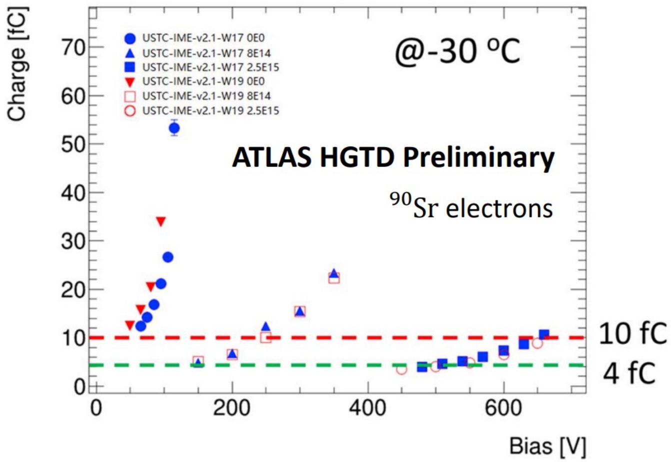
- Tempareture: -30 °C
- Trigger
  - Sensor (HPK Type1.1, un-irradiated) & Pre-amplifier board
  - With the 2nd stage amplifier
  - Bias: -165.00 V
  - σ_t: 33.88 ps
- DUT (Device Under Test)
  - Sensor & Pre-amplifier board
  - With the 2nd stage amplifier
- Oscilloscope
  - Sampling rate: 20 Gs/s
  - Bandwidth: 1 GHz

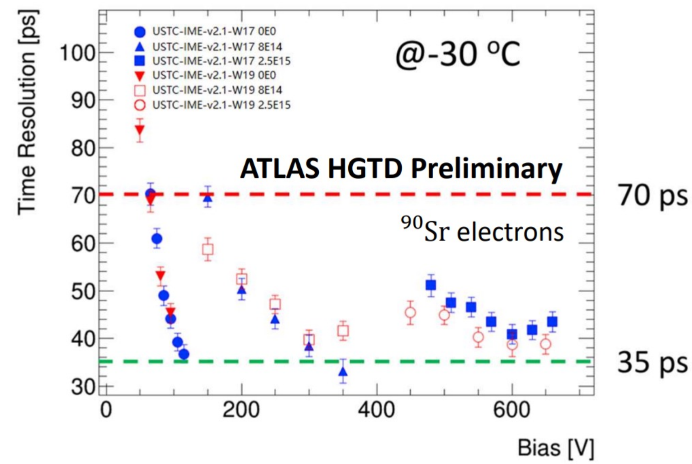




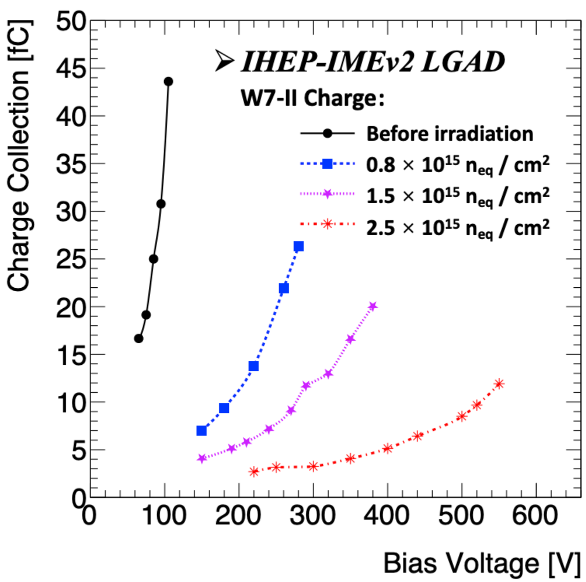


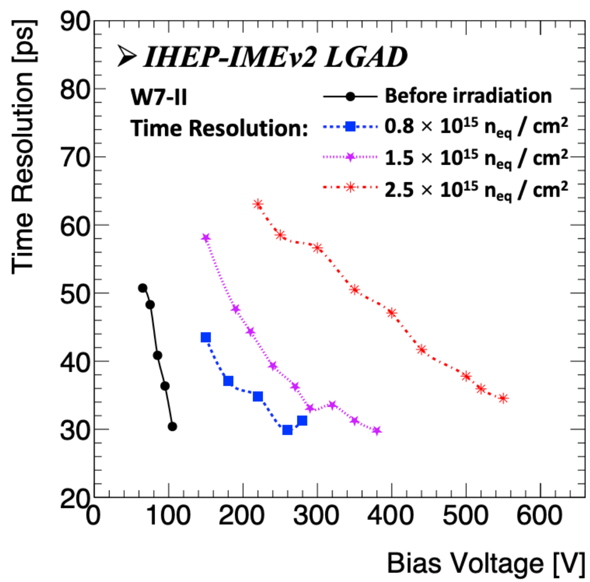
Performance of IME-LGAD prototypes with ^{90}Sr





ATLAS HGTD Public Plots



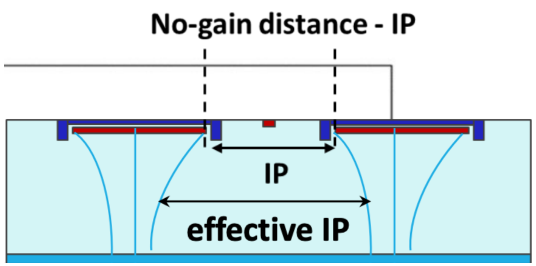


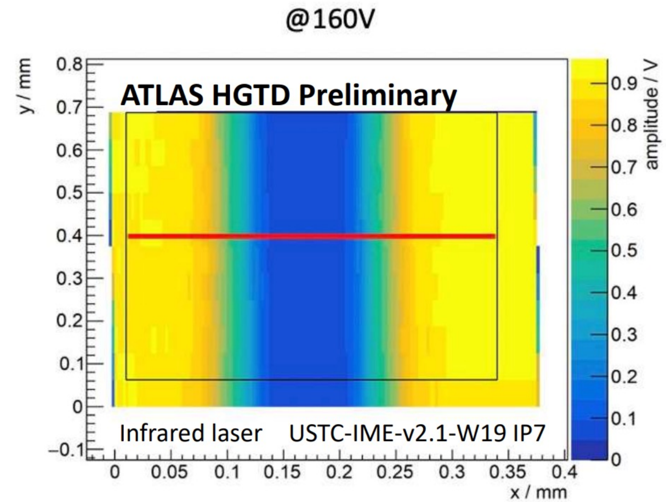
K. Wu et al NIMA, 2022

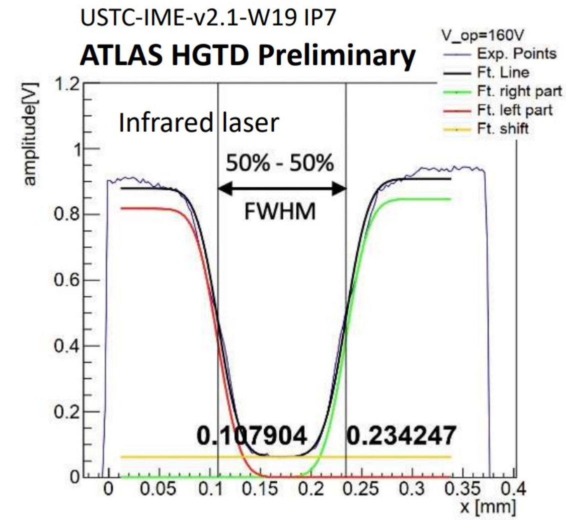
Inter-pad (IP) gap measurements

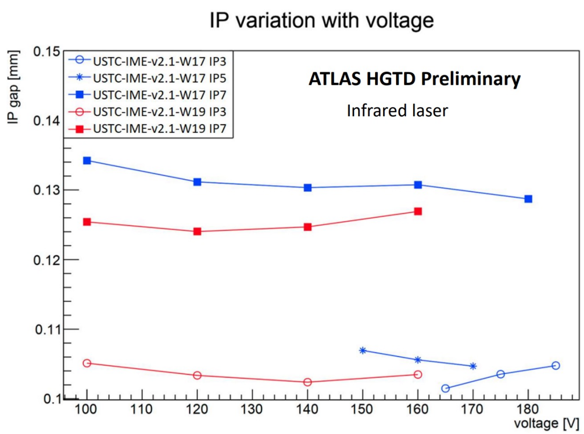
Laser (infra-red, 1064 nm)

ATLAS HGTD Public Plots







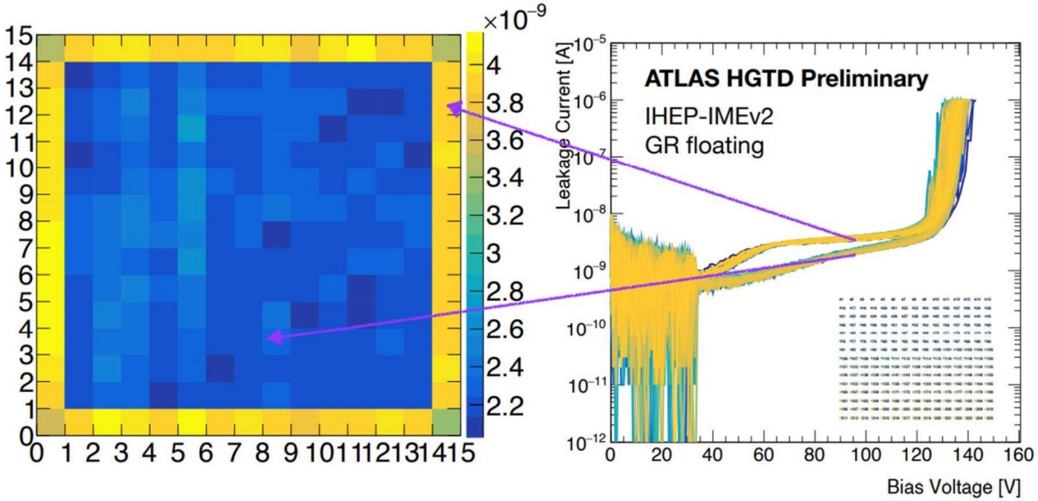


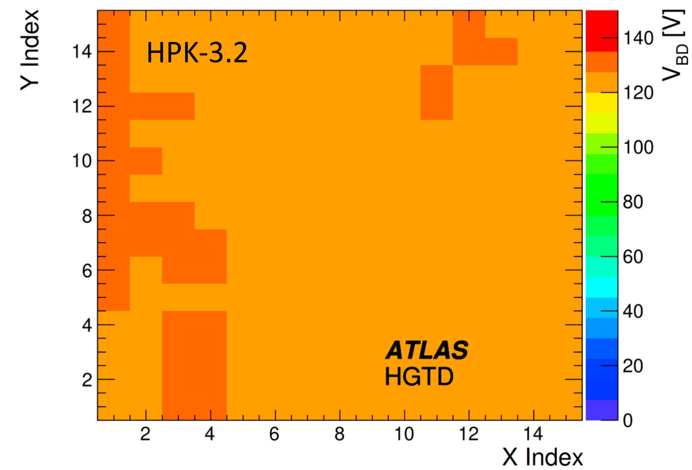
Wafer	$IP_{nominal}$ (Nominal IP)	IP_{eff} (Effective IP)	IP_{eff} - $IP_{nominal}$
W17	30um	100um	70um
	50um	107um	57um
	70um	130um	60um
W19	30um	103um	73um
	70um	124um	54um

- For IP3 and IP5, the effective IP gap is about 100 um. For IP7, the effective IP gap is about 130 um.
- Effective IP gap is large than nominal IP gap from 50-75 um.

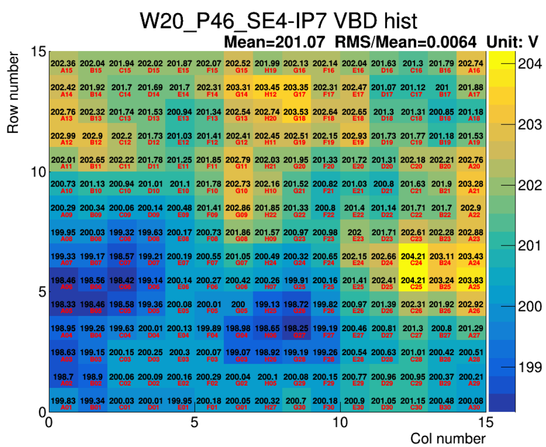
Uniformity of full-size (15×15) LGADs

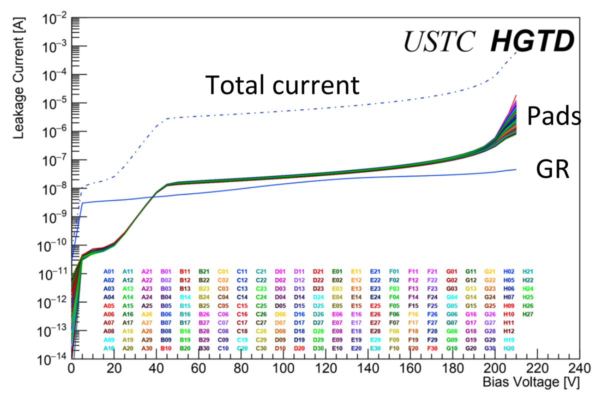
- Tested by single probe needle (neighbors and GR floating)





- Tested by probe card (neighbors and GR are grounded)





- Very homogenous break down voltage ($V_{BD,}$ I_{pad} < 500 nA)
- GR floating affects the outermost pads for IHEP-IME v2 LGADs