LGAD developments for HGTD and for CEPC time of flight detector

The 2023 International Workshop on Circular Electron Positron Collider

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(IHEP, Chinese Academy of Sciences)

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Outline

I. LGAD development for HGTD

II. LGAD development for CEPC time of flight detector

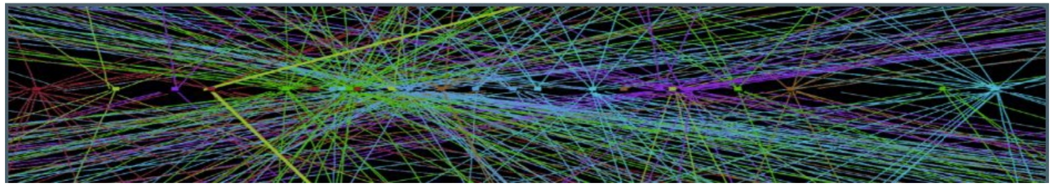
Challenges of HL-LHC

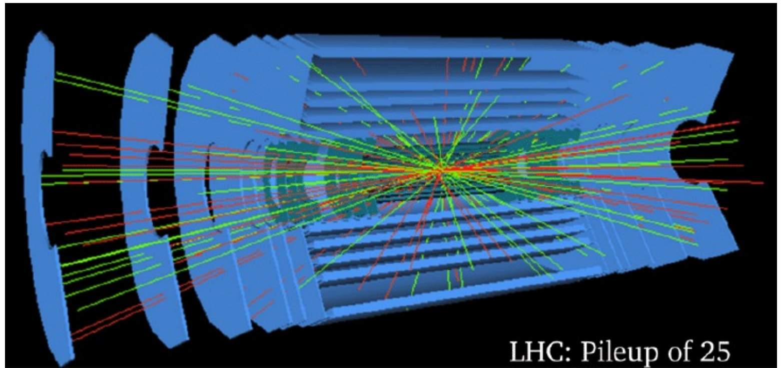
From ~2026, LHC will be upgraded, In ~2029, LHC will run in **"high luminosity"** **, called HL-LHC**

- 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**

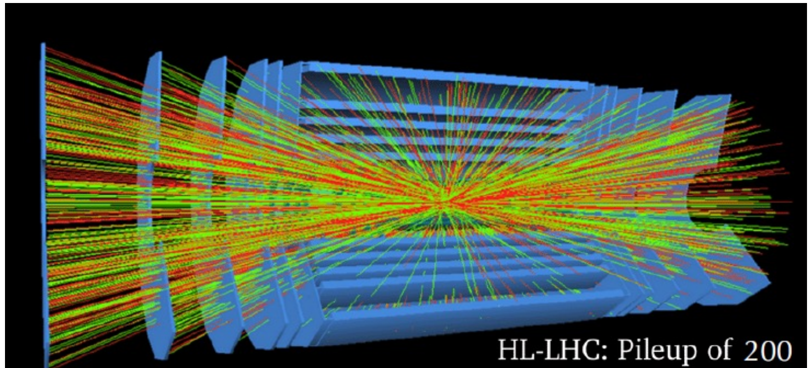
Several LHC experiment sub-systems will operate in the **high rate, hit occupancy and harsh radiation environment**

On average 1.6-2.35 vertices per mm



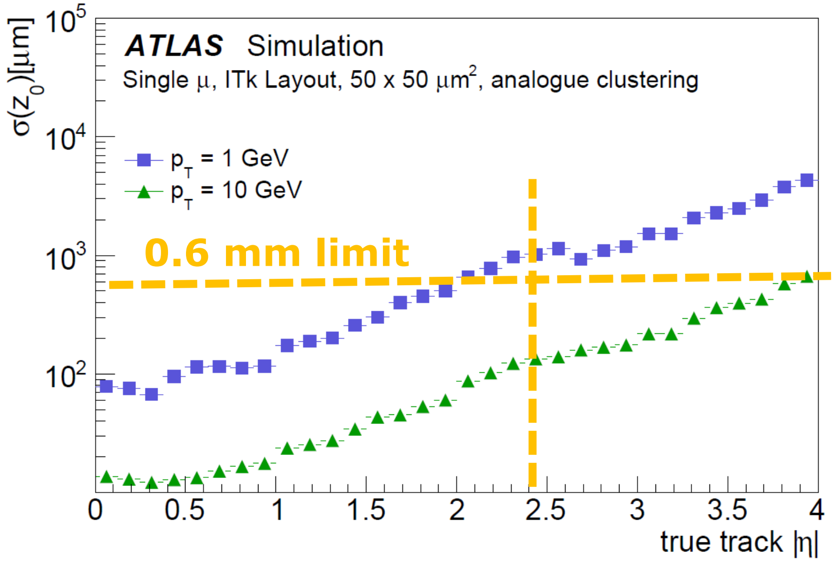


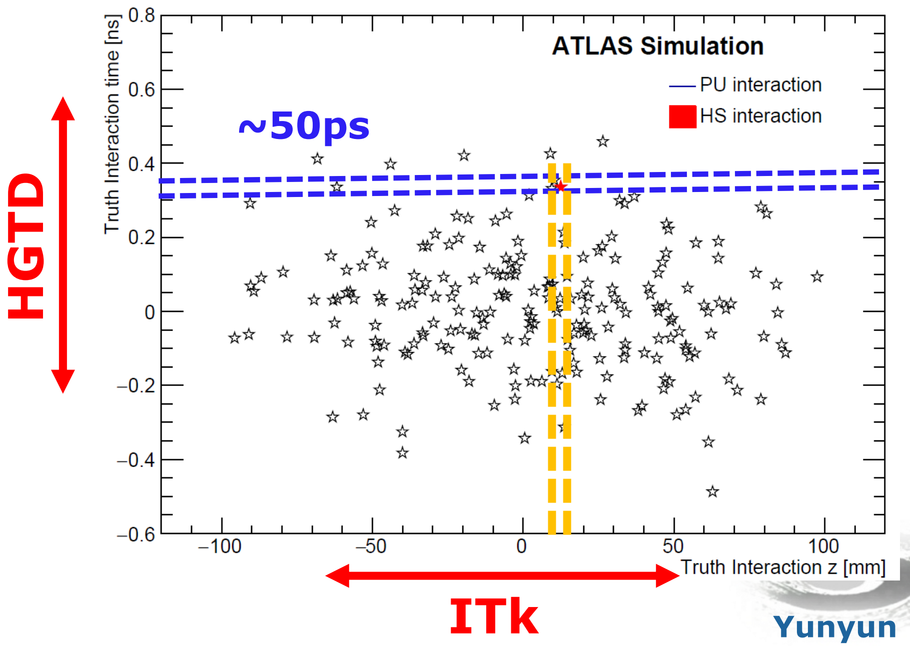
Pileup increases →



Why need the time information?

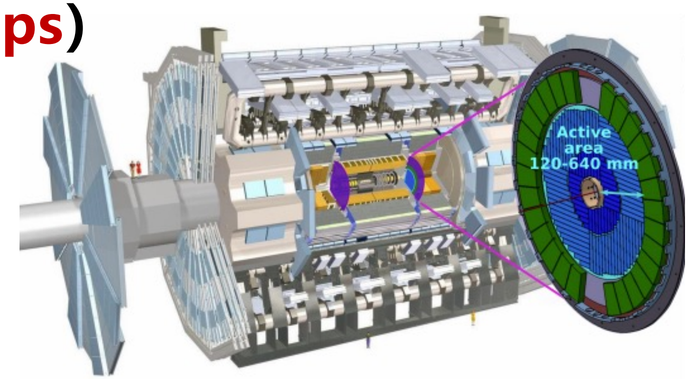
- **At High Luminosity -LHC**
  - Pileup: $<\mu>$ = 200 interactions per bunch crossing ~1.6 vertex/mm on average
- **Problems of the vertex reconstruction in ATLAS**
  - degradation significantly in the forward region compared to the central region
  - Need z_0 resolution < 0.6 mm
  - Liquid Argon based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

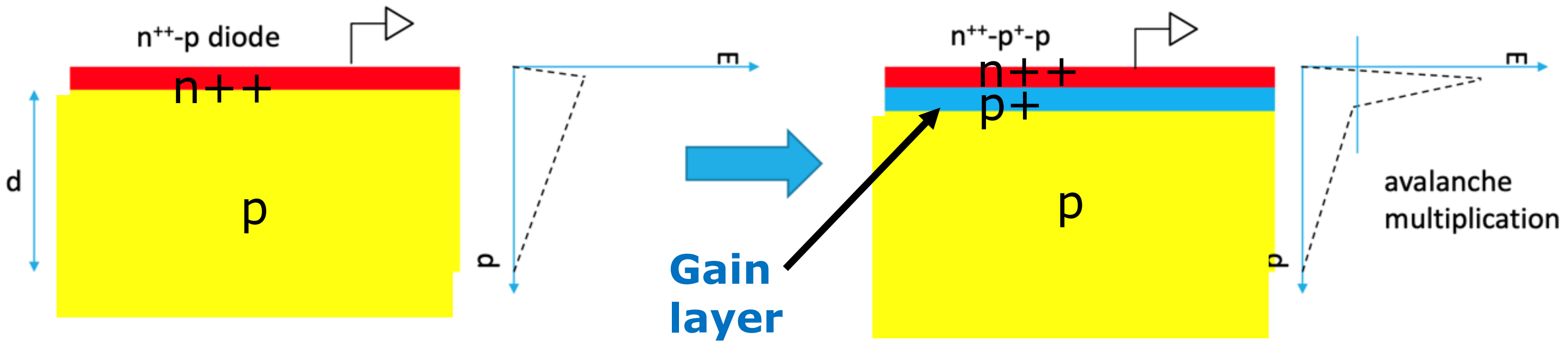
- **A High Granularity Timing Detector (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters to reduce pileup**
- Time resolution for particle 2 orders of magnitude higher (**ns→30 ps**)



- **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: **2.5×10^{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)

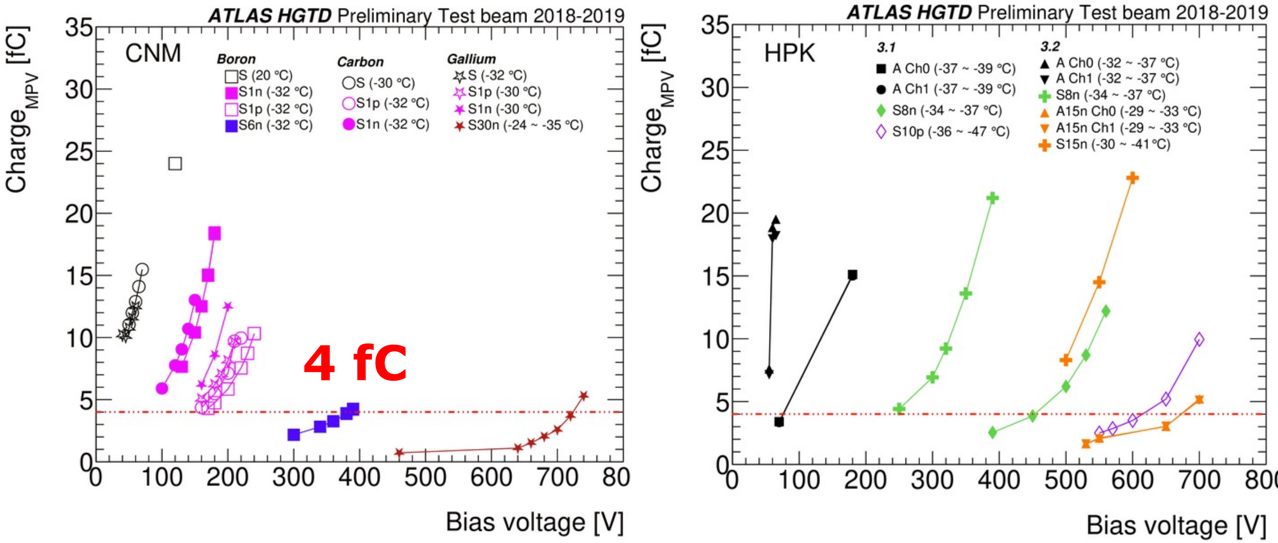
- **Silicon pixel detectors are especially important for the precise determination of tracks and vertices , enabling the selection of interesting events through the identification of b jets (b tagging)**
- **LGAD is a new silicon detector technology developed recent years, that could measure the particle 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



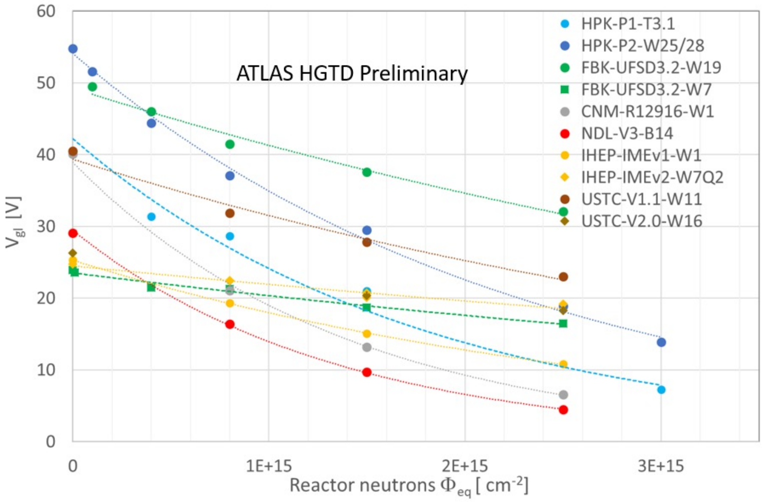
Toward Radiation Hard LGAD

- **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**

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



C.Agapopoulou et al 2022 JINST 17 P09026



Yunyun Fan

Radiation Hard LGAD

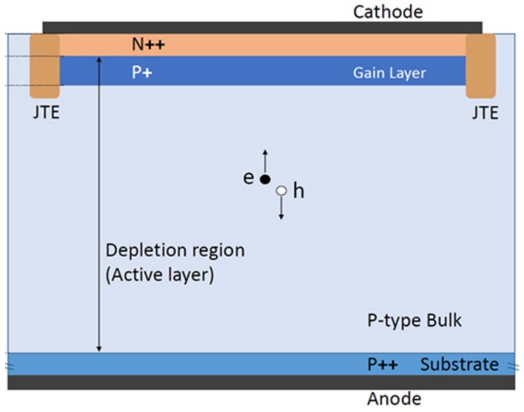
- Aim to **develop radiation hard LGADs** for HGTD

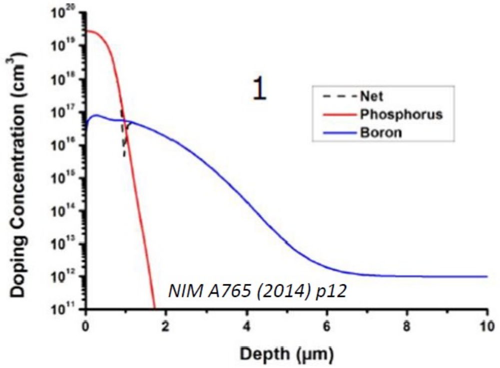
Improve the gain layer design, **acceptor removal coefficient targeting** $1-2\times10^{-16}\ cm^2$

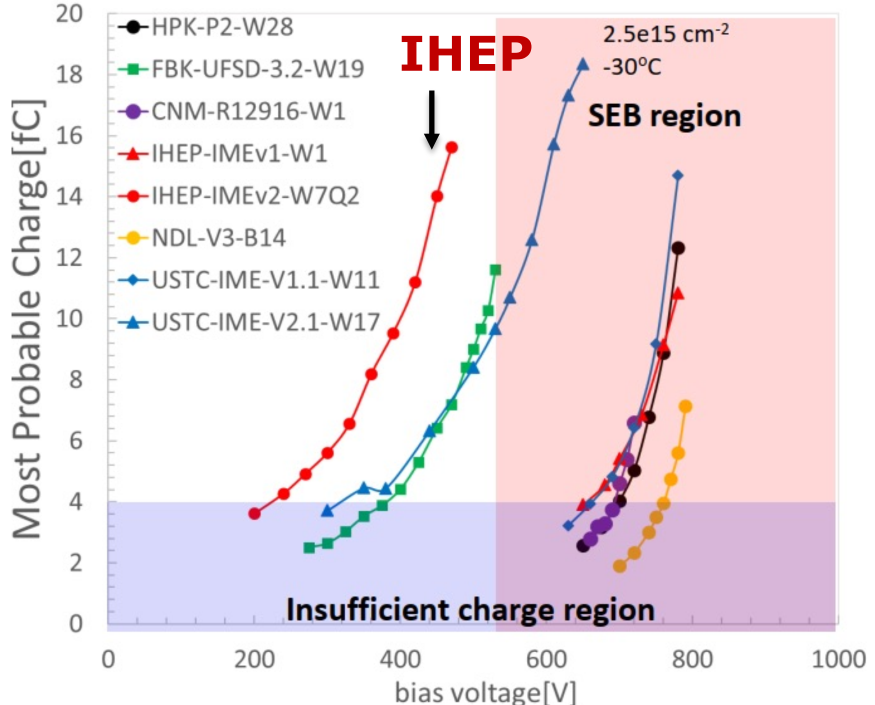
I. Geometry design, such as increase the doping concentration, depth, width, shape

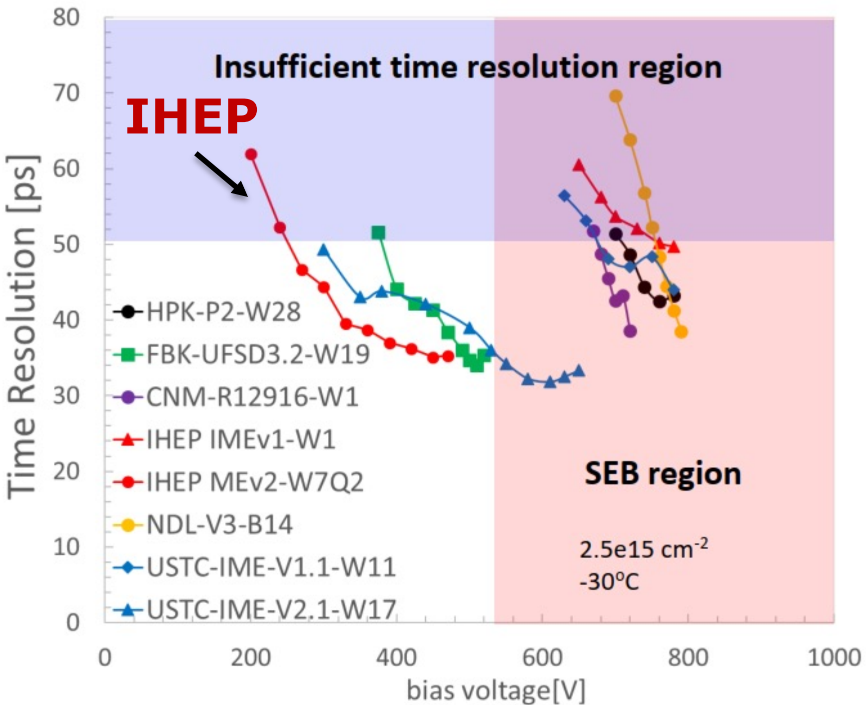
II. Different doping materials, add the Carbon, Ga to gain layer

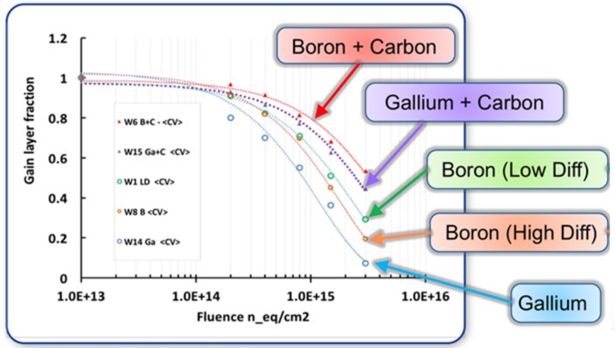
- **Performance of LGAD: B+C > B > Ga**
  - Simultaneously show good enough CC/timing/efficiency after **2.5×10^{15} n$_{eq}$/cm^2**







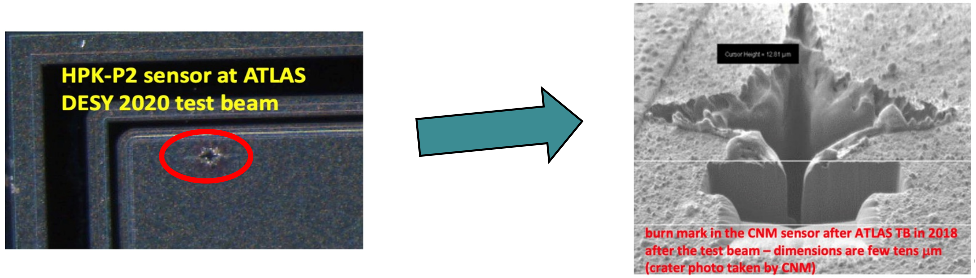




[G.Paternoster, FBK, Trento, Feb.2019]

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)**



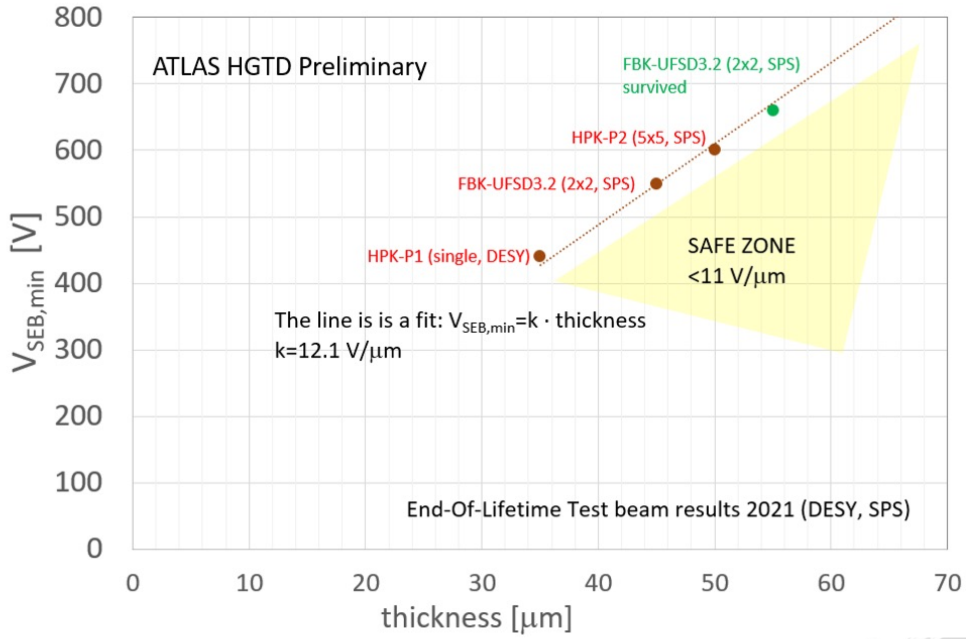
complete irrecoverable failure

- **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)

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 ~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

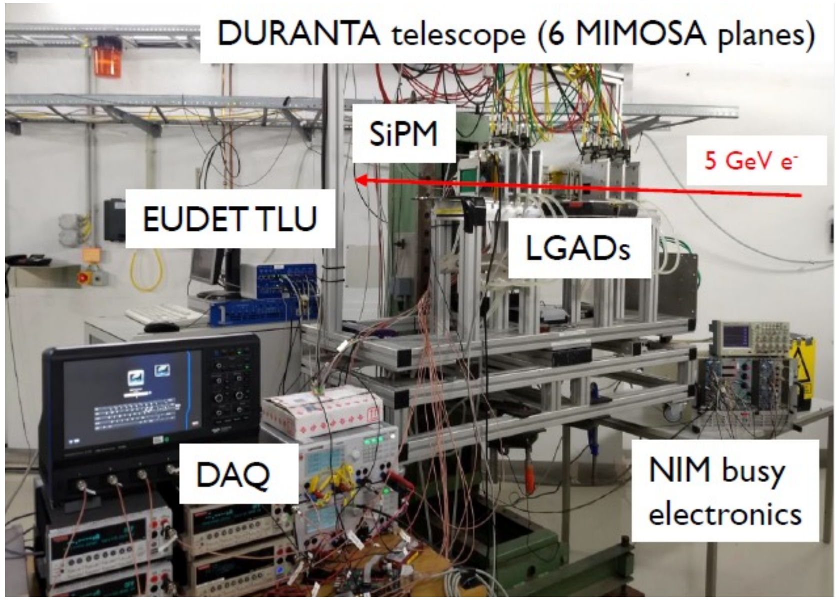
Device name	Vendor	Sensor ID	Implant	Irradiation type	Fluence [n_{eq}/cm^2]	Tested at
CNM-0	CNM	W9LGA35	boron	unirradiated	—	DESY/CERN
FBK-1.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	1.5×10^{15}	DESY/CERN
FBK-2.5	FBK	UFSD3.2 W19	boron + carbon	neutrons	2.5×10^{15}	DESY/CERN
USTC-1.5	USTC-IME	v2.1 W17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

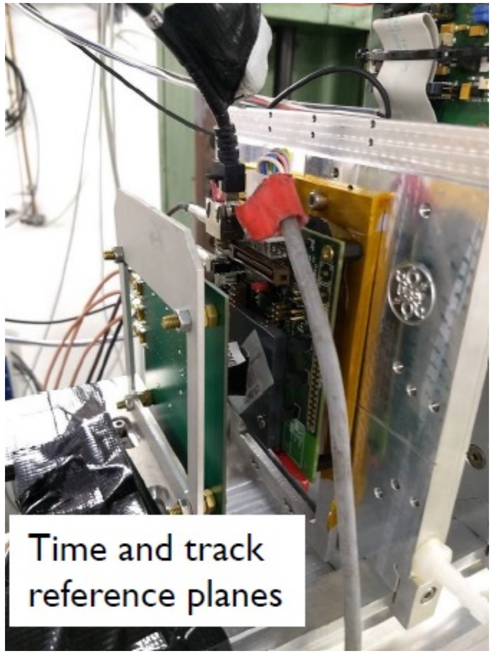
IHEP-IME sensor with shallow carbon

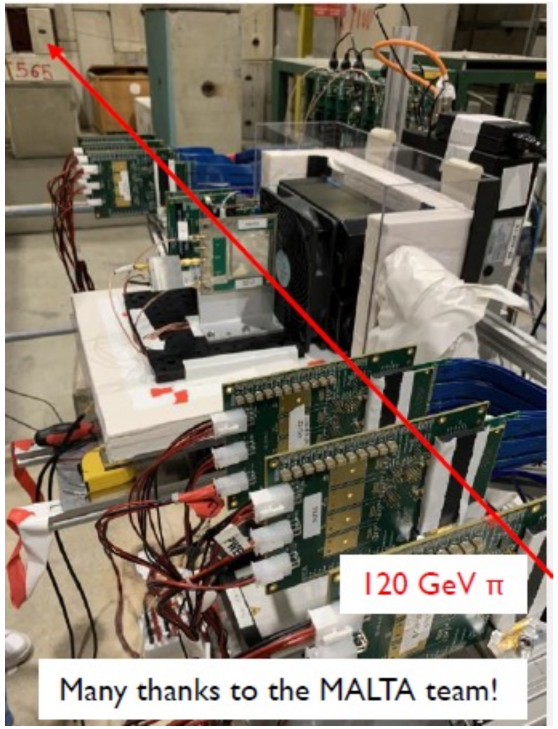
Device name	V_{gl0} [V]	Diffusion	c [cm^2]
FBK-1.5/2.5	50	H	1.73×10^{-16}
USTC-1.5/2.5	27	L	1.23×10^{-16}
IHEP-1.5/2.5	25	CHBL	1.14×10^{-16}

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)



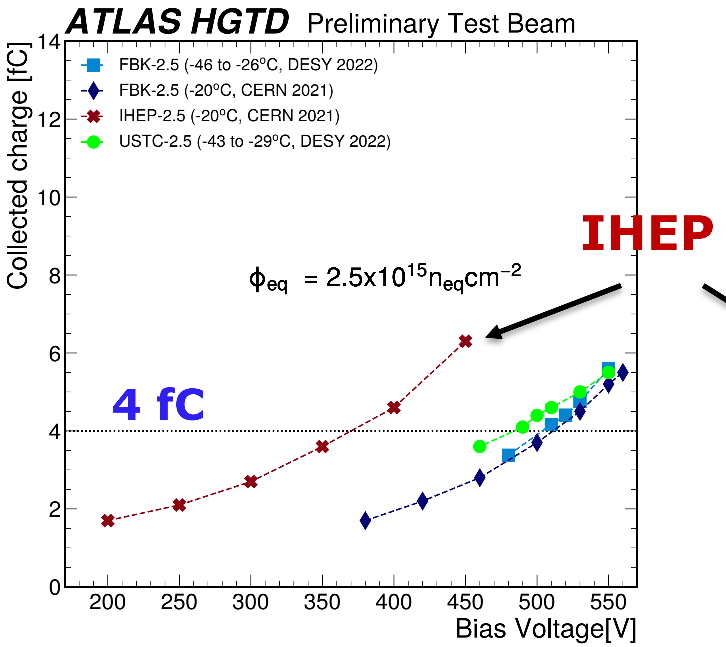


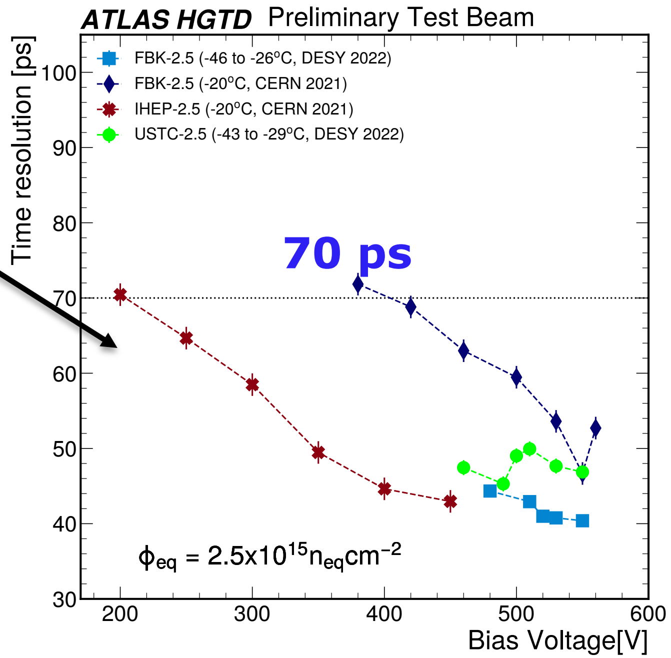


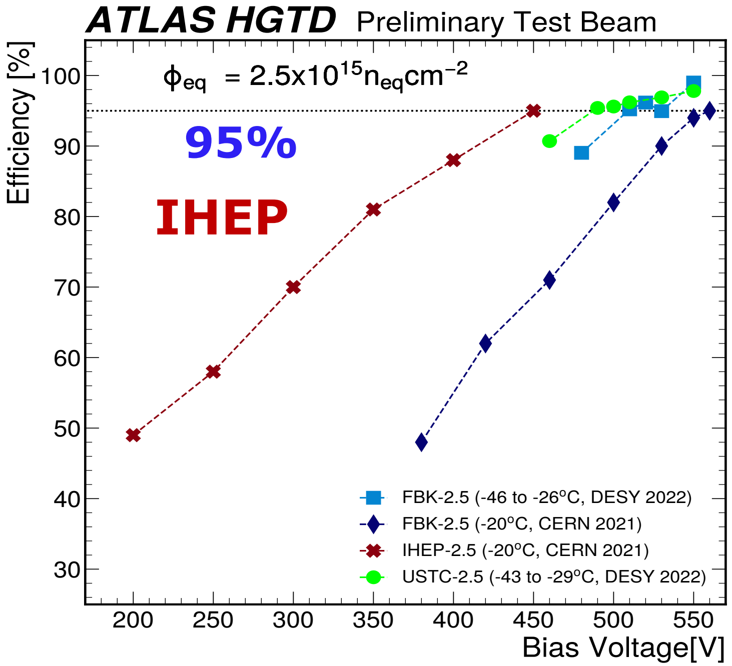
Collected Charge & Time Resolution

- Although irradiated at fluences of to 2.5×10^{15} n_{eq}/cm^2, the LGADs were operated at voltages below 550 V
- **Under these conditions, IHEP-IME LGADs with shallow carbon achieved the objectives of:**
  - Collected charge of more than 4 fC while guaranteeing an optimum time resolution below 70 ps
  - An efficiency larger than 95% uniformly over sensors' surface is obtained 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**

S. Ali et al 2023 JINST 18 P05005

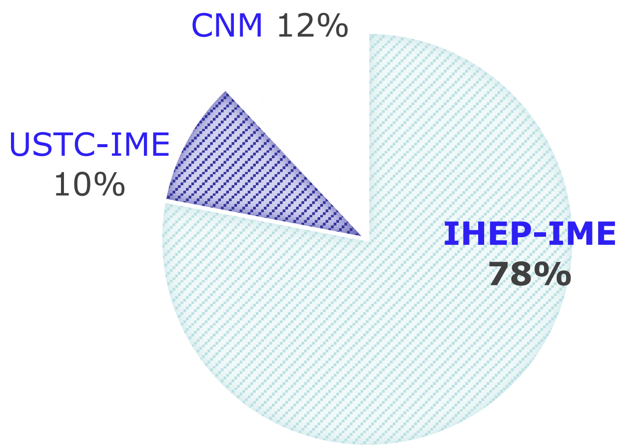






Production of LGAD sensors

- LGAD sensors passed the FDR
- HGTD project of ATLAS needs > 20,000 LGAD sensors (6.4 m^2)
- **2023 IHEP-IME got all the share of the order from CERN tendering**
  - > 10,000 LGAD (54%, **will be produced by IME according to IHEP design**)
  - Compete with HPK, FBK et al.
- **The share of the contribution of the LGAD sensors in HGTD**
  - **IHEP-IME: 78%** (54% from CERN tendering+24% in-kind sensors)
  - UCSC-IME: 10% in-kind sensors
  - CNM: 12% in-kind sensors



Outline

I. LGAD development for HGTD

II. LGAD development for CEPC time of flight detector

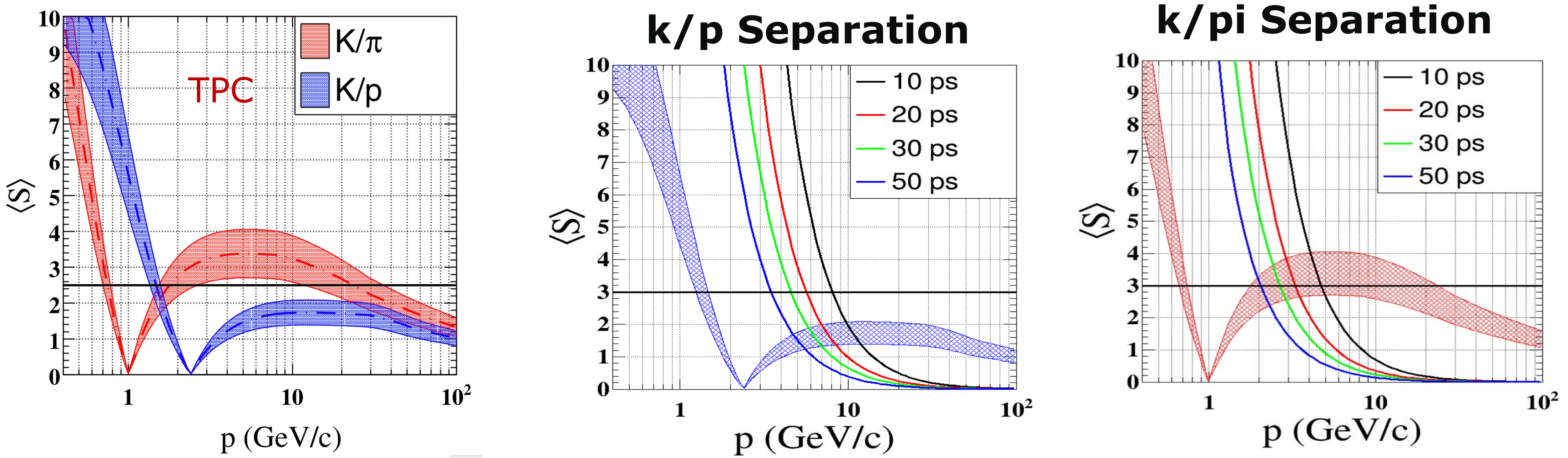
Motivation

- **CEPC will produce 10^{12} Z boson at Z pole: Rich flavor physics program**
- **Particle separation problems** of Gas detector (dE/dx) for CEPC flavor physics:
  - **0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation**
- **CEPC International Advisory Committee: one of the key recommendations**

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

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

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



CEPC timing detector: Concept

- **Two concept designs of the timing detector:**

  I. Only offer the time information, between tracker and calorimeter

  ✓ **Large area LGAD**： high timing resolution (20 ps) serve as timing detector, low gain, high S/N, large pixel size to reduce the readout electronics, put near the SET

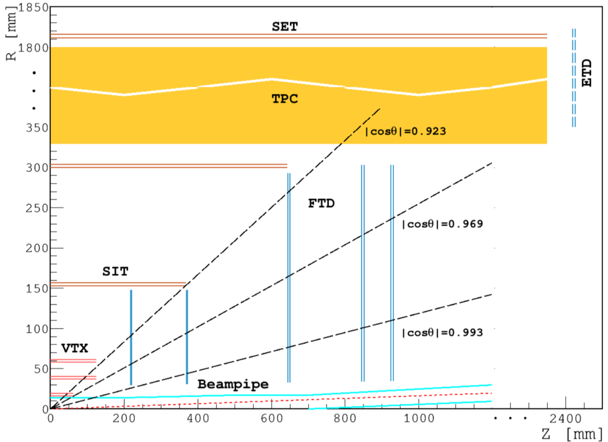
  II. Offer the time and spatial information (4D track) replace the SET

  ✓ **AC-LGAD** ：4 dimension detection (spatial and time resolution) ， 20 pico-second (ps) , 7-10 μm

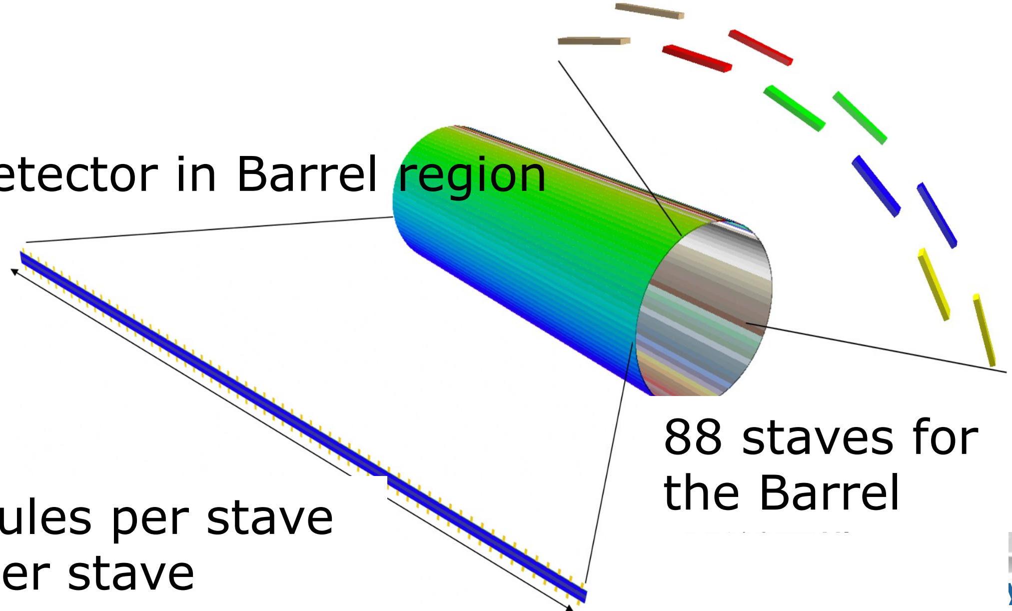
  Close to SET tracker, Radius **~1.8 m**

- **Area of detector (Barrel : 50 m^2 , Endcap 20 m^2)**

  Baseline detector concept in CDR



Timing detector in Barrel region



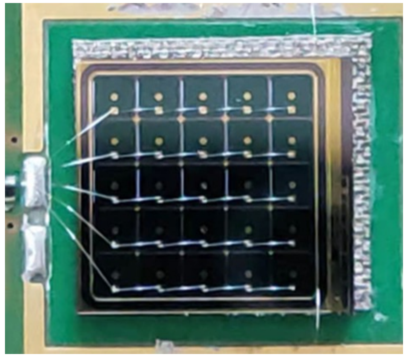
88 staves for the Barrel

60 modules per stave
2.4 m per stave

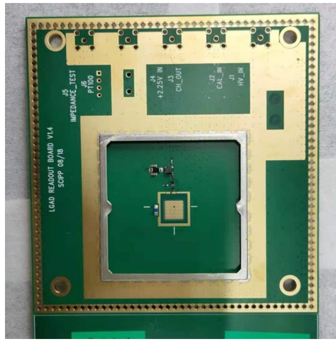
Time Resolution of the Large Aera LGAD

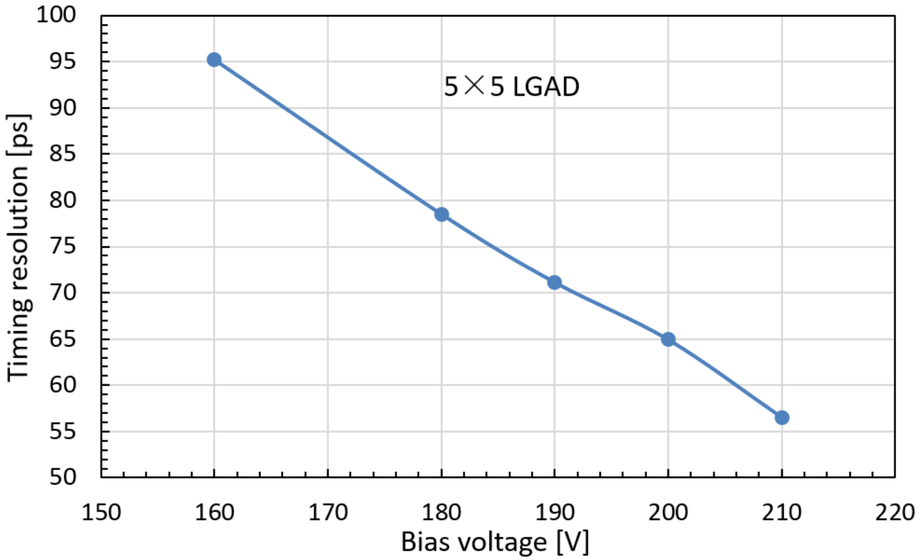
- **Time resolution test of large aera LGAD: 20 ps**
  - Beta source (Sr90)
  - Under test large aera LGAD :
    - **6.5 mm x 6.5 mm** LGAD
    - **5*5 LGAD connected by wire bonding to mimic the large aera LGAD**
  - 1 channels readout board designed by UCSC
- **Best time resolution of large area LGAD is 56 ps**
- Still need optimize the design of IHEP-IME LGAD to improve the time resolution.

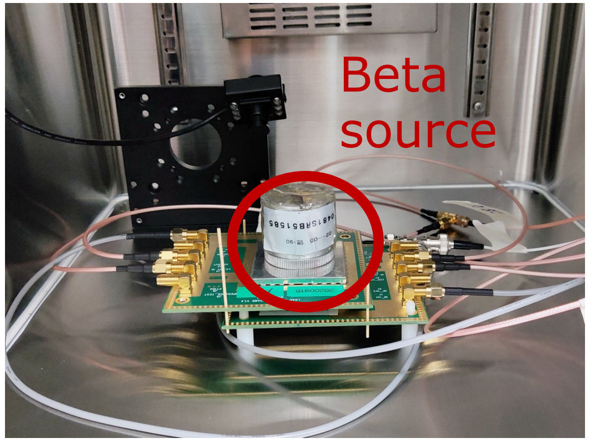
5*5 Large area LGAD sensor Connected by wire bonding



Readout board



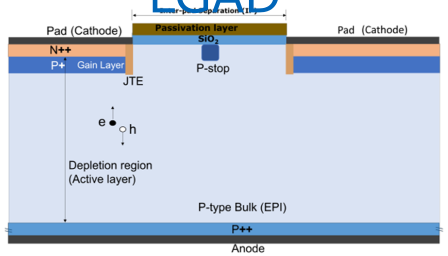




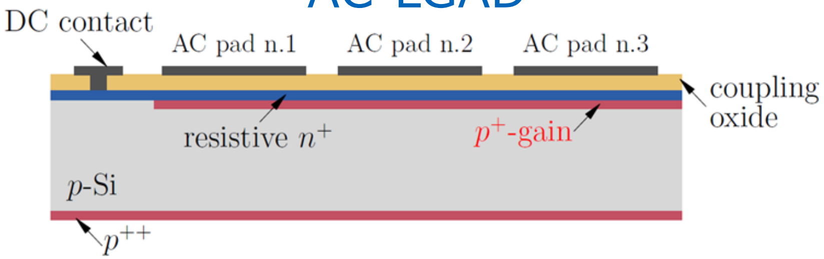
Design and Production of AC-LGAD

- **Aim to 4D track**： **20 ps， 7-10 μm**
- **AC-LGAD:** 4D information, no dead region

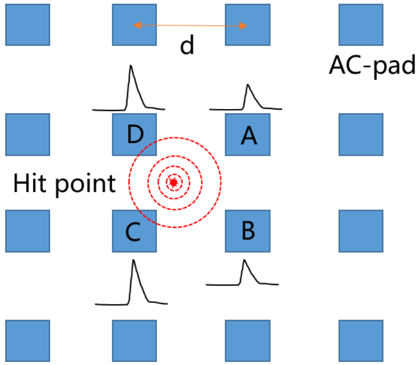
LGAD



AC-LGAD

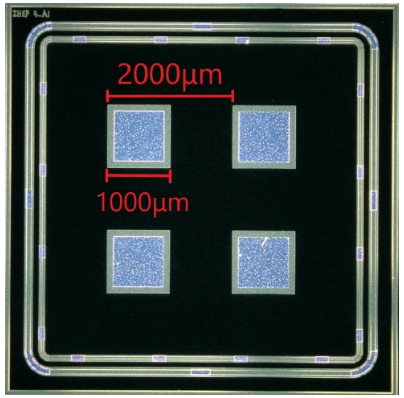


Signal of AC-LGAD

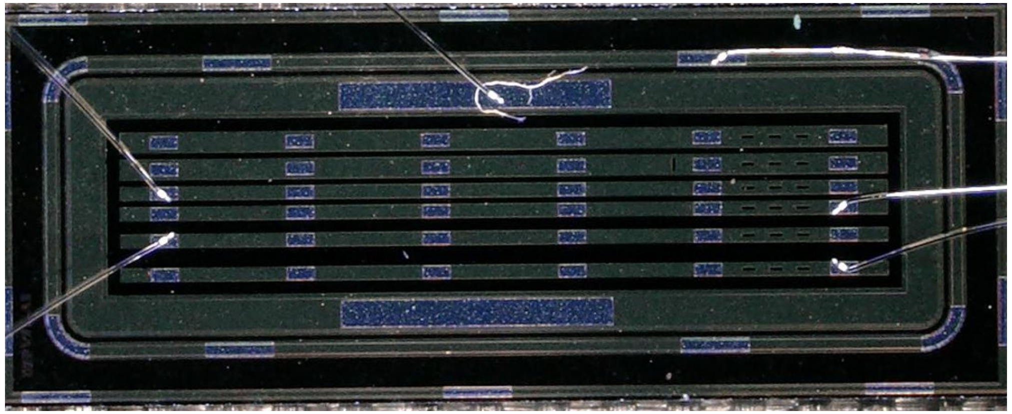


- **Different designs of AC-LGAD in IHEP**
  - ✓ **Pixels AC-LGAD**： reduce the material budget
  - ✓ **Strip AC-LGAD**： no bump bonding，easy to produce

Pixel LGAD

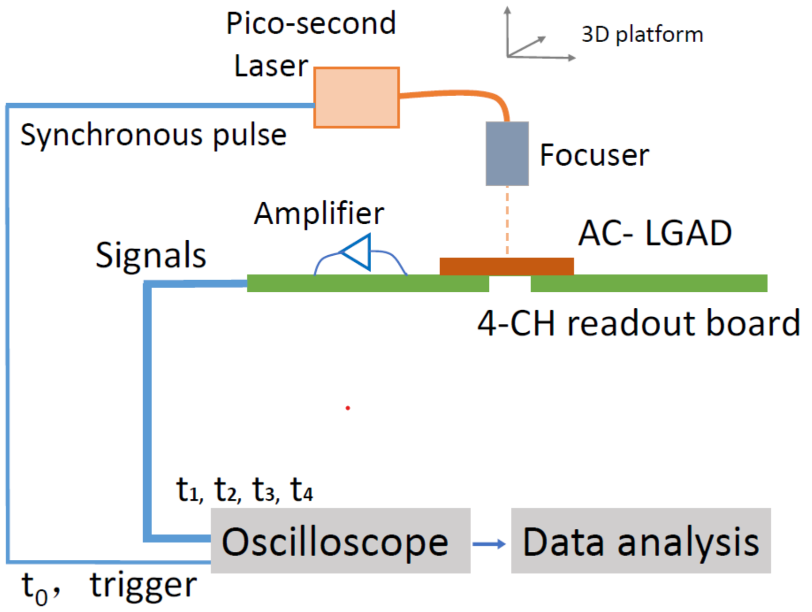


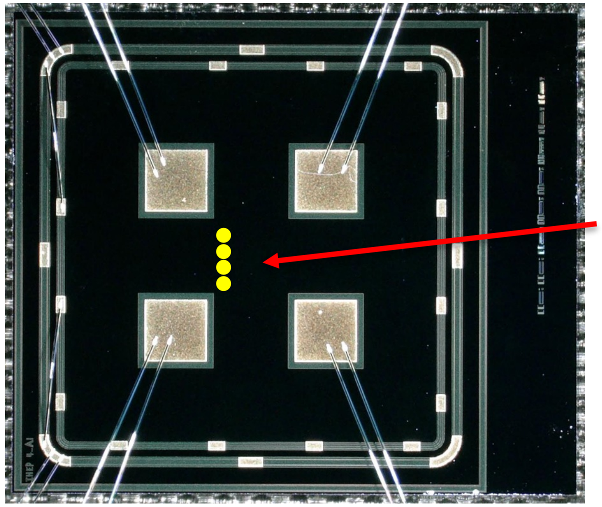
Strip AC-LGAD



Performance Test Setup of AC-LGAD

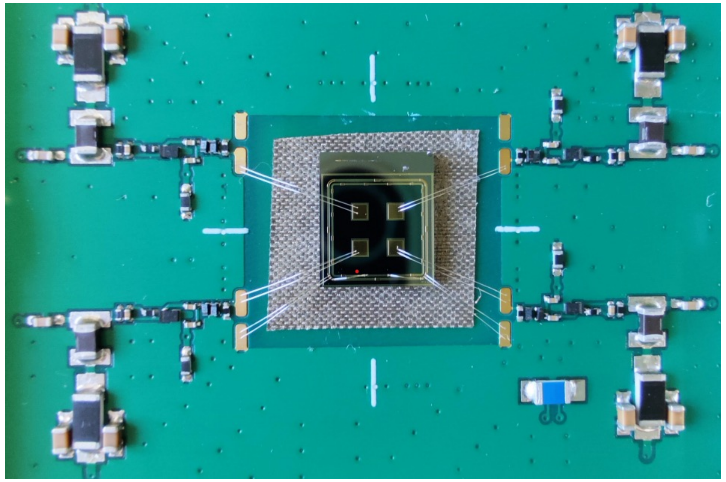
- **Timing and spatial resolution test of AC-LGAD**
- **Transient current technique (TCT)**
- Picosecond Laser: 1065 nm ，spot size10 μm (3σ)
- **4 channels readout board designed by IHEP**
  - 470 Ω Broadband inverting trans-impedance amplifie
  - Reference of 1 channel board designed by UCSC





Laser spot

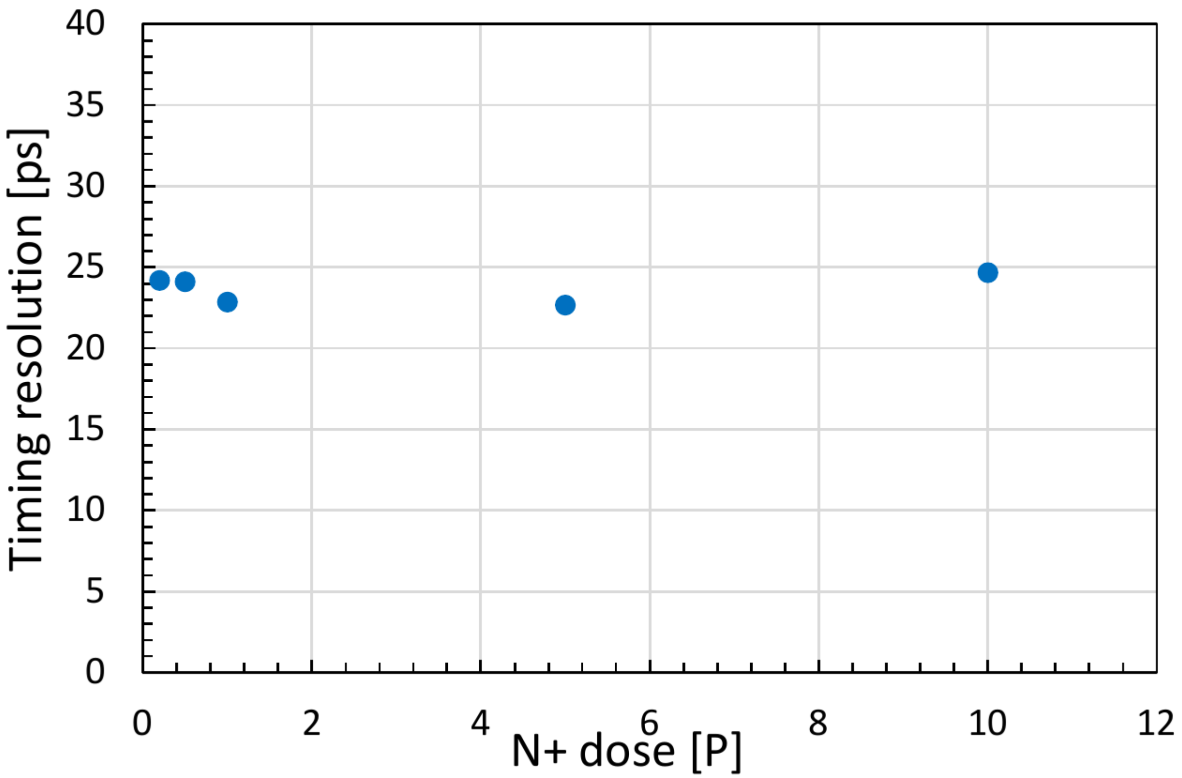
4 channels readout board designed by IHEP



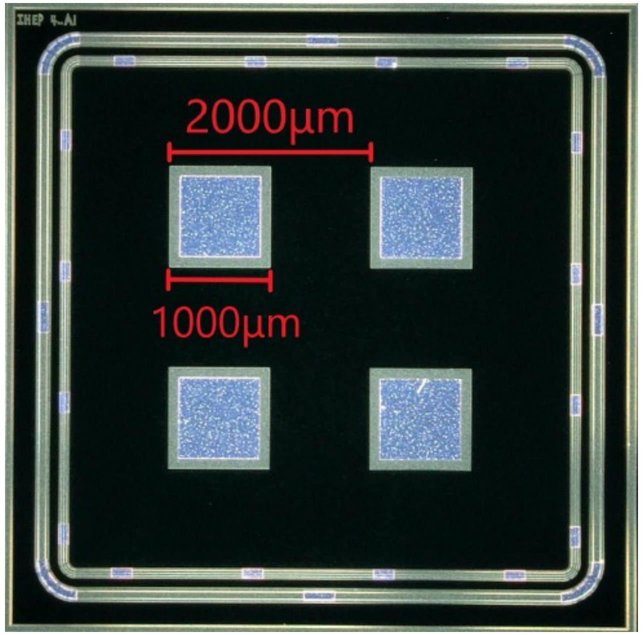
Timing resolution of AC-LGAD

- **Timing resolution of AC-LGAD with different N+ dose**
  - **22~25 ps**
  - N+ very slightly affects the time performance

Timing resolution of AC-LGAD with different N+ dose



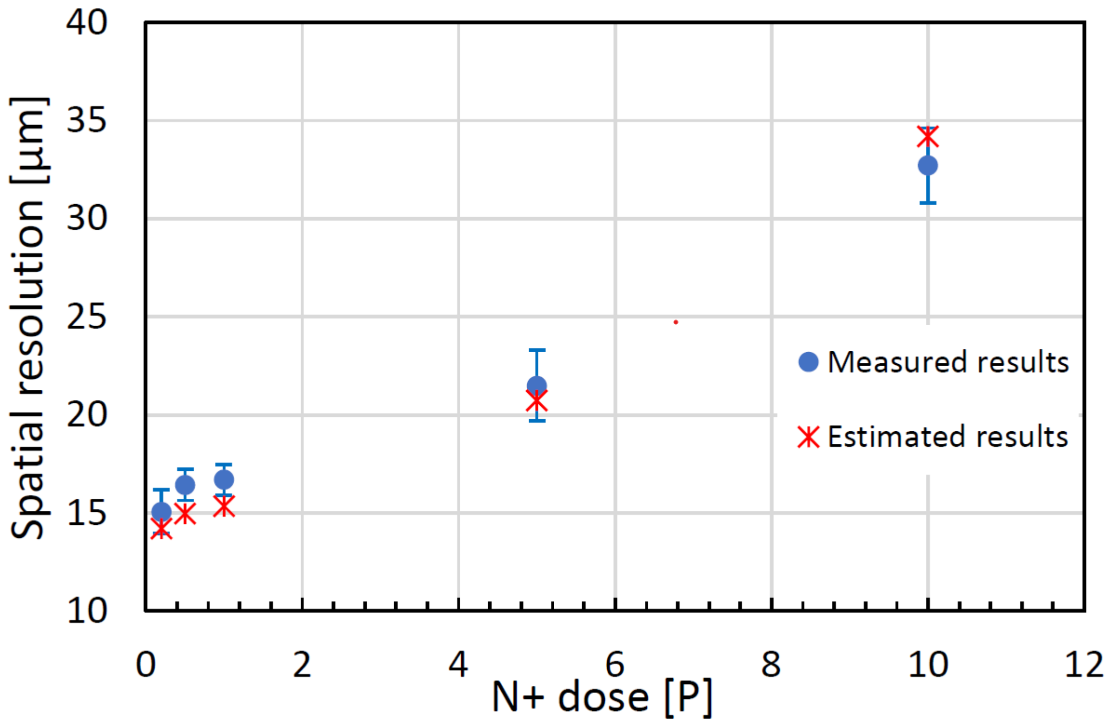
Tested AC-LGAD



Spatial resolution of AC-LGAD

Spatial resolution vs N+ dose

- 10 P → 0.2 P, spatial resolution ⬆ 15 μm (minimum)
- Estimated laser point positions fit the measured well
- **Better than the FBK design** even with 2 times larger pitch



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

Summary

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

A. Pure ToF with only time information :

- ✓ **Aim 20 ps**
- ✓ The time resolution of large area LGAD is **about 56 -100 ps** in Beta test. Need optimization in the future

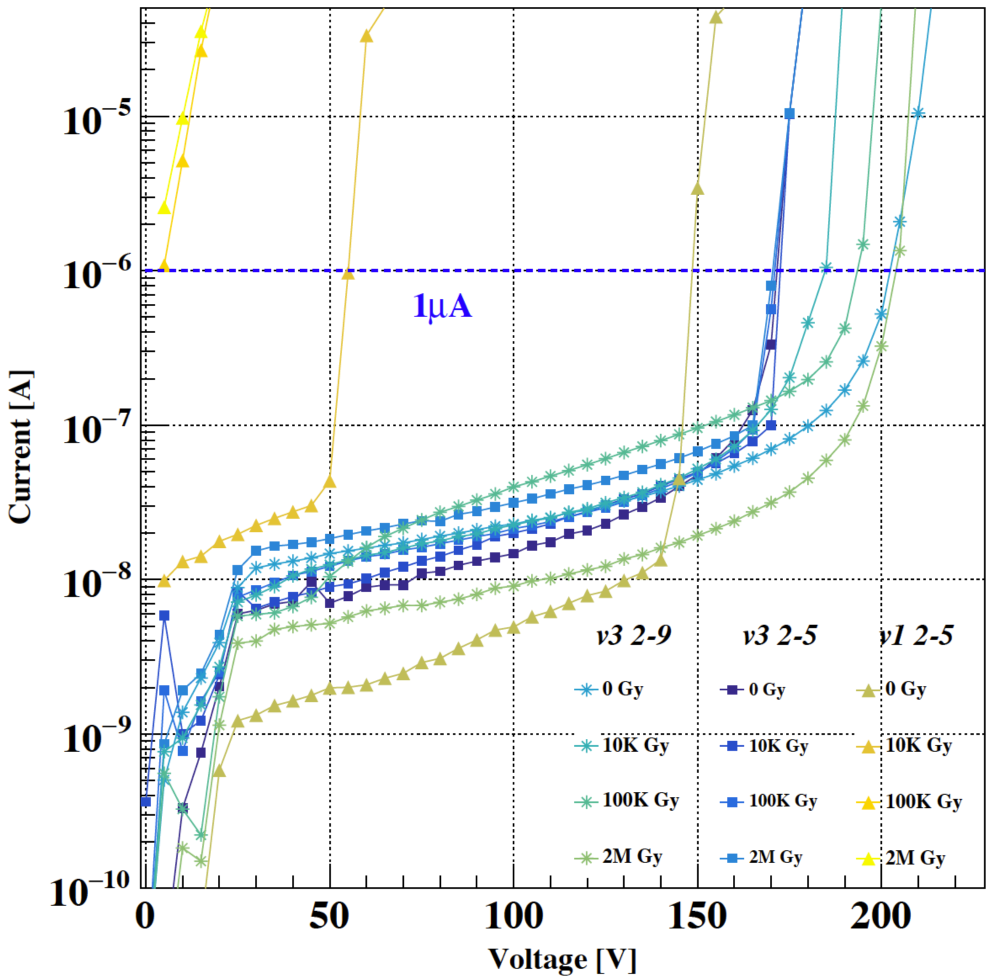
B. **ToF with track information :**

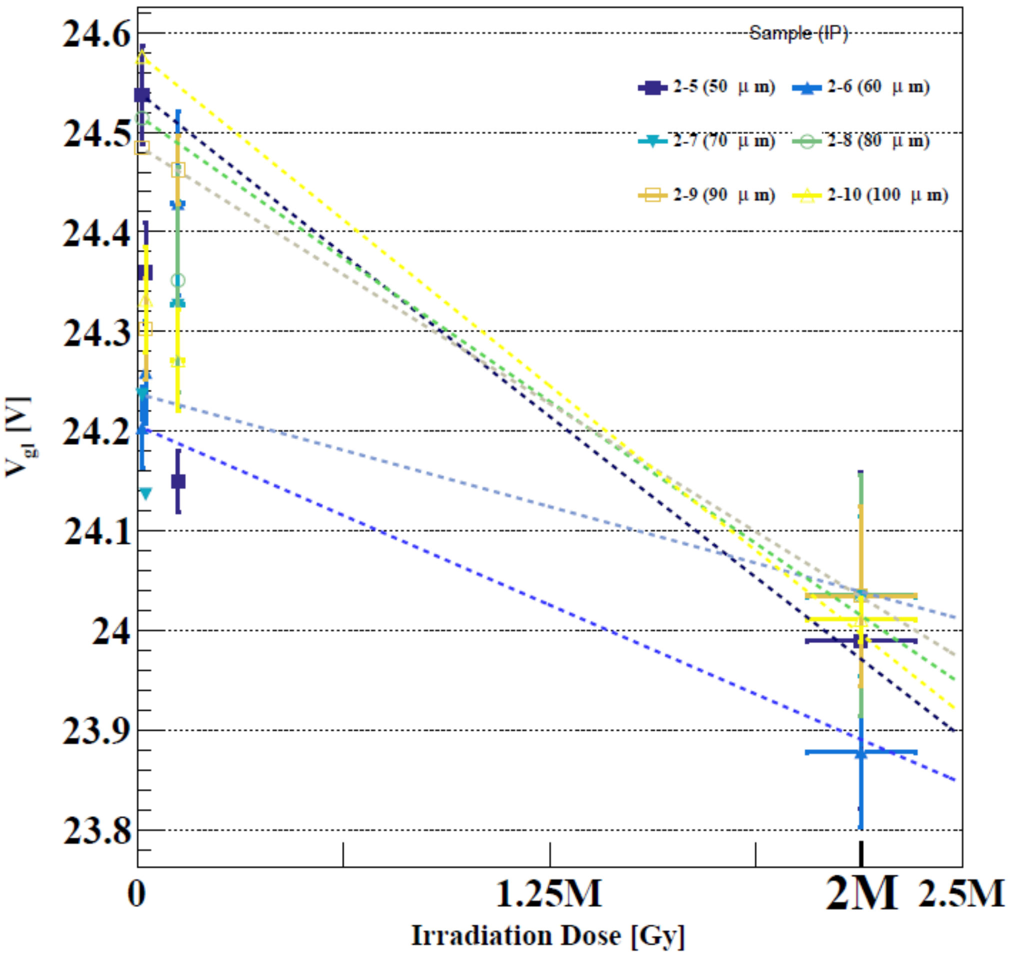
- ✓ **Aim 20 ps , 10 μm**
- ✓ the time resolution and spatial resolution of AC-LGAD could be **22~25ps and 15 μm** according to the laser test

Thanks for your attention！

- **Back up**

- The leakage currents of IHEP-IME LGAD sensors after 2MGy TID dose



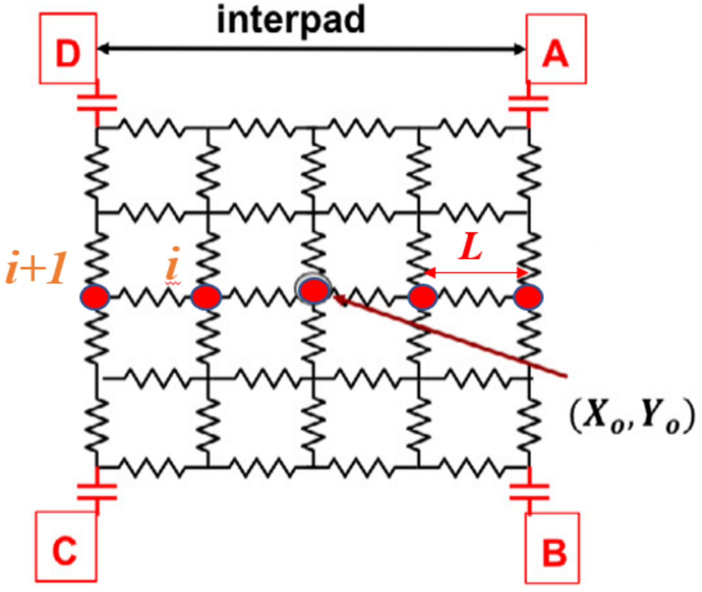


Statusing

	Task Identifiers	Start Dates	Finish Dates	Task Info	Progress	Your Comments
Testing with ASIC	Activity: LGAD Sensors Title: Testing of prototypes bump bonded to ALTIROC2 P2UG ID: R3-SEN-M6-1 ID/UID: 4/4083 Type: Schedule Task	Baseline: 2022-04-25 Working: 2022-06-24 Actual/Expected: 2022-06-24	Baseline: 2022-10-20 Working: 2023-04-28 Actual/Expected: 2023-06-30	Duration: 218d Free Slack: 617d Total Slack: 1014d	Complete(%): 70 COVID Delay(%): 0	
Contract Award	Activity: Tendering Title: Contract Award P2UG ID: SEN-17 ID/UID: 29/3062 Type: Schedule Task	Baseline: 2022-12-30 Working: 2023-03-02 Actual/Expected: 2023-03-02	Baseline: 2023-03-01 Working: 2023-04-14 Actual/Expected: 2023-05-03	Duration: 30d Free Slack: 0d Total Slack: 258d	Complete(%): 100 COVID Delay(%): 0	Notification of the award of the Contract to the Contractor at 3th May. contract modification ongoing, will be finished in June
QA/QC preparation	Activity: Tendering Title: Development of QC system for sensor production P2UG ID: R3-SEN-17-1 ID/UID: 30/4085 Type: Schedule Task	Baseline: 2022-09-26 Working: 2022-11-01 Actual/Expected: 2022-11-01	Baseline: 2023-04-21 Working: 2023-05-30 Actual/Expected: 2023-07-14	Duration: 147d Free Slack: 0d Total Slack: 278d	Complete(%): 60 COVID Delay(%): 0	probe card fabrication ongoing, switch box will be delivered to testing sites
	Activity: Tendering Title: Development of DAQ and DB interface for sensor production P2UG ID: R3-SEN-17-2 ID/UID: 31/4086 Type: Schedule Task	Baseline: 2022-09-26 Working: 2022-11-01 Actual/Expected: 2022-11-01	Baseline: 2023-05-18 Working: 2023-06-26 Actual/Expected: 2023-07-31	Duration: 165d Free Slack: 90d Total Slack: 260d	Complete(%): 50 COVID Delay(%): 0	
preproduction	Activity: Sensors pre-production Title: pre-production (China In-kind) P2UG ID: R3-SEN-18-1 ID/UID: 33/4087 Type: Schedule Task	Baseline: 2022-10-21 Working: 2023-02-06 Actual/Expected: 2023-02-06	Baseline: 2023-04-24 Working: 2023-07-26 Actual/Expected: 2023-07-26	Duration: 119d Free Slack: 0d Total Slack: 170d	Complete(%): 80 COVID Delay(%): 0	Most process finish, sensors without UBM and thinning will be delivered at July for testing.
	Activity: Sensors pre-production Title: pre-production (Spain In-kind) P2UG ID: R3-SEN-18-2 ID/UID: 34/4088 Type: Schedule Task	Baseline: 2023-03-16 Working: 2023-05-19 Actual/Expected: 2023-07-03	Baseline: 2023-08-28 Working: 2023-10-26 Actual/Expected: 2023-11-30	Duration: 114d Free Slack: 0d Total Slack: 251d	Complete(%): 0 COVID Delay(%): 0	radiation testing of last run ongoing
	Activity: Sensors pre-production Title: pre-production (CERN Procurement) P2UG ID: R3-SEN-18-3 ID/UID: 35/4089 Type: Schedule Task	Baseline: 2023-03-02 Working: 2023-04-17 Actual/Expected: 2023-05-04	Baseline: 2023-08-30 Working: 2023-10-17 Actual/Expected: 2023-10-31	Duration: 130d Free Slack: 7d Total Slack: 258d	Complete(%): 10 COVID Delay(%): 0	Detailed Design File and Quality Plan accepted at 9th June. Pre-production fabrication start.

- **7 tasks ongoing**
- **Tendering almost finish. Notification of the award of the Contract to the Contractor at May. Contract modification ongoing, will be finished in June**
- **Pre-production(China in-kind), IHEP-IME and USTC-IME, first batch will finish at July**
- **Pre-production(Spain in-kind), start date is unclear, testing of radiation hardness(JSI, CNM, CERN TB) ongoing**
- **Pre-production(CERN Procurement), start after Notification of the award of the Contract to the Contractor**

The calculation of the timing and spatial resolution



$$X = X_0 + k_x\left(\frac{q_A + q_B - q_C - q_D}{q_A + q_B + q_C + q_D}\right) = X_0 + k_x m$$

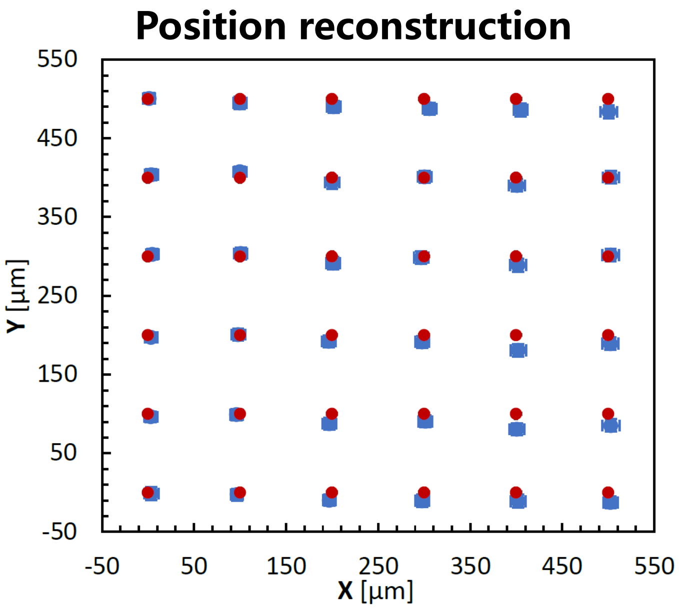
$$Y = Y_0 + k_y\left(\frac{q_A + q_D - q_B - q_C}{q_A + q_B + q_C + q_D}\right) = Y_0 + k_y n$$

$$k_x = L\frac{\sum(m_{i+1} - m_i)}{\sum(m_{i+1} - m_i)^2} \qquad k_y = L\frac{\sum(n_{i+1} - n_i)}{\sum(n_{i+1} - n_i)^2}$$

Discretized Positioning Circuit model (DPC)

- **Assuming resistan**

Position reconstruction with the center mass method



Spatial resolution

$$\sigma^2_{spatial} = \sigma^2_{reconstruction} - \sigma^2_{platform}$$

Timing resolution :

$$\sigma_t = \sigma_{t1+t2+t3+t4}$$