LGAD development and its application for X-ray detection

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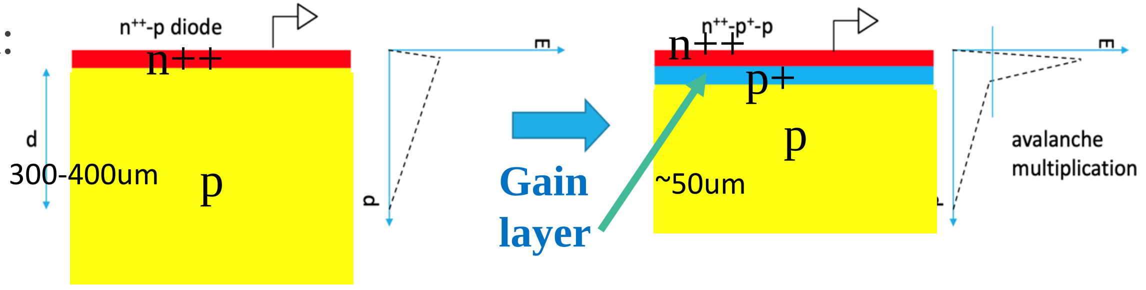
- LGAD introduction
- LGAD development at IHEP
- LGAD application for X-ray detection
- Summary

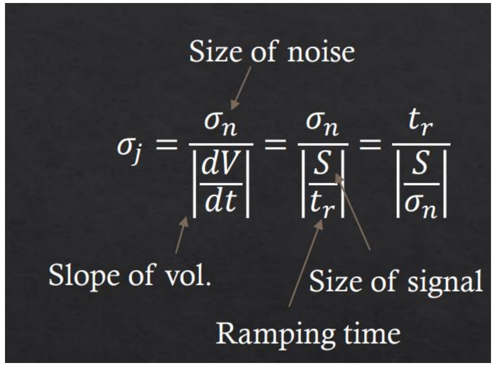
LGAD detector

- **Low Gain Avalanche Detectors (LGAD)** is a silicon detector technology that has timing resolution <35ps.
- Compared with PIN, a gain layer between P and N++ is added:
  - Work in a linear mode, Gain:10~50
  - Good Signal/Noise ratio without self triggering
  - Thin depleted region to decrease t_{rise} (fast timing)
  - Types of LGAD: DC-LGAD, AC-LGAD, Ti-LGAD

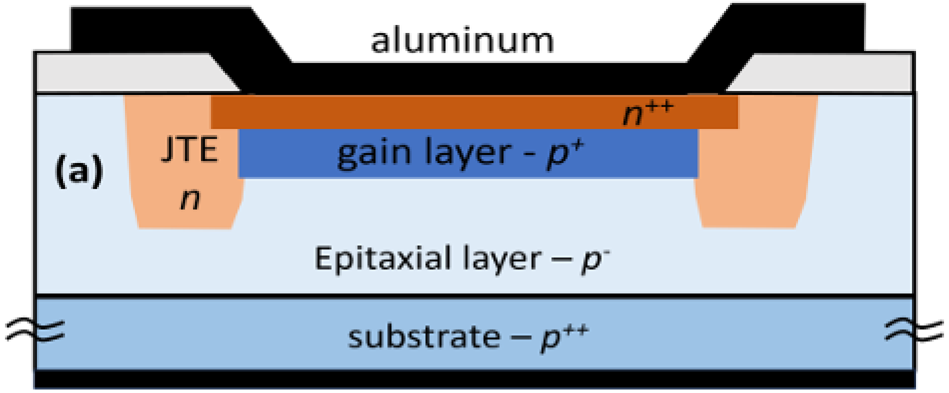
    Inversed LGAD, Monolithic LGAD…

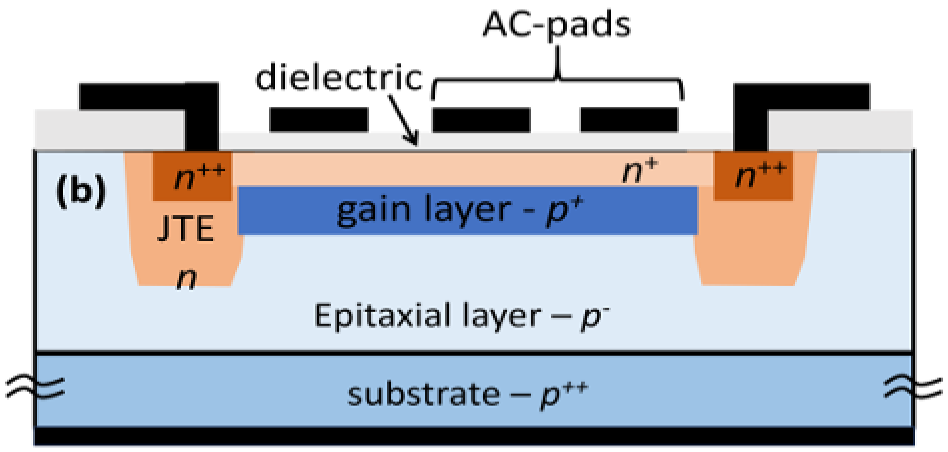


- Owning to its good performance, LGAD technology is chosen as timing detector for ATLAS HGTD and CMS ETL project.
- And have good potential for other applications(future collider, X-ray detection, iCT etc)



Types of LGAD





DC-LGAD

- The read-out electrode is placed and connected to the N++ layer.
- Large pixel size and dead zone between pixels(JTE, Pstop)

Timing performance:<35ps
Position resolution: pixel size/√12
1.3mm/ √12
Dead area: JTE, P-stop

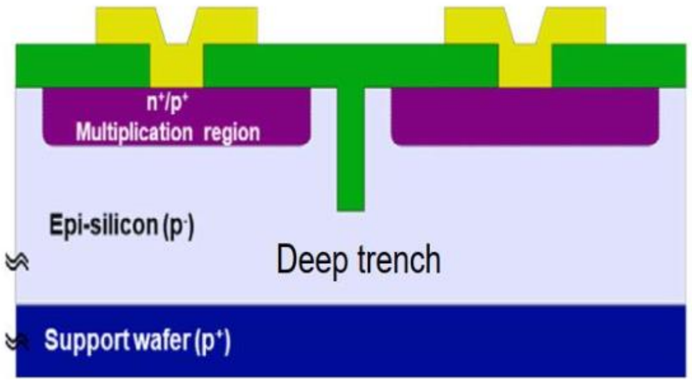
AC-LGAD

- metal AC readout electrode and a thin dielectric layer (Si_3N_4, SiO_2) above the N+ layer
- Less dead area and better position resolution

AC-coupled LGADs, n++ implant well is replaced by a more resistive n+ layer, with electrodes that are AC coupled to it via a thin dielectric layer

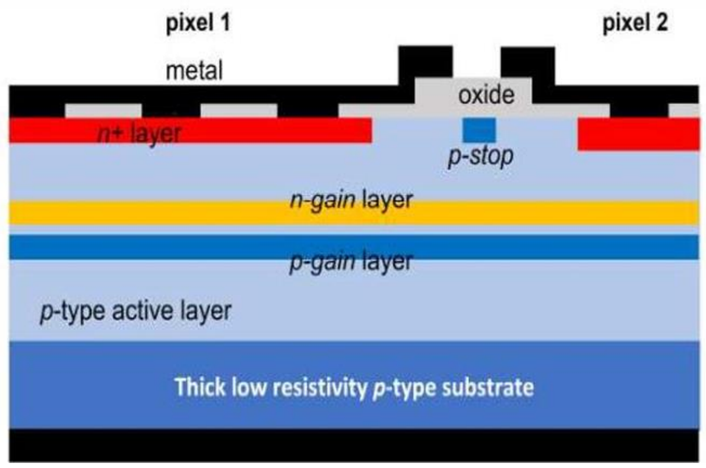
- Research institute: FBK, HPK,INFN, BNL, CNM, USTC, IHEP…

Types of LGAD



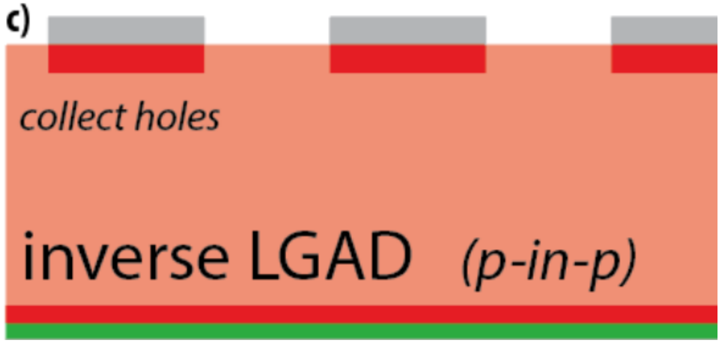
Ti-LGAD

- isolation structures (p-stop and JTE) are replaced by a deep trench, less than a µm wide
- Increasing the fill factor



DJ-LGAD

- A deep junction be made by a large area of uniform n+ and p+ gain implants. and n+ DC coupled electrodes are placed a few microns from the surface.
- To increase fill factor and improve radiation hardness



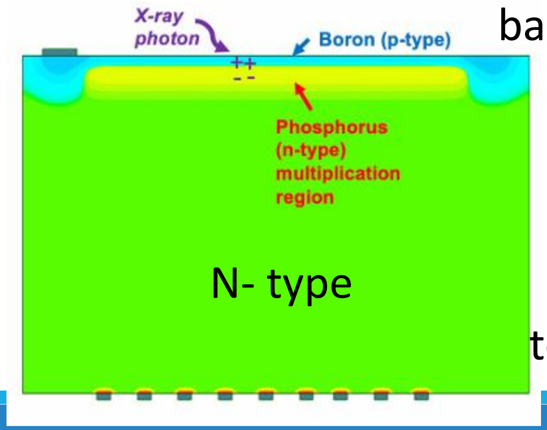
Gain layer

- inverse-LGAD To increase fill factor

Thin Entrance Window LGADs

For soft X-rays with energies as low as 250 eV

backside



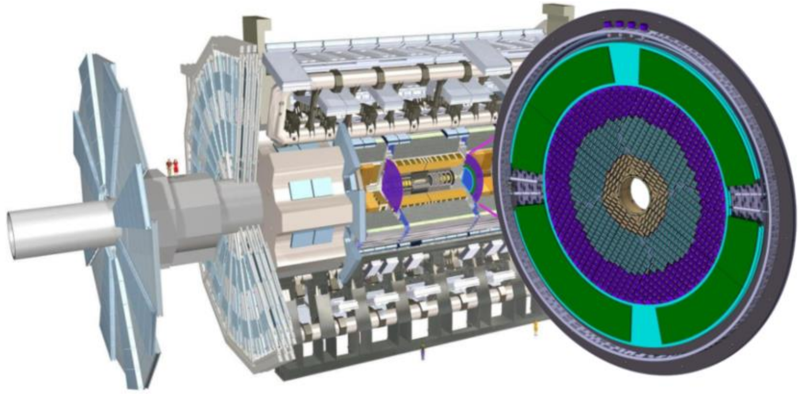
topside

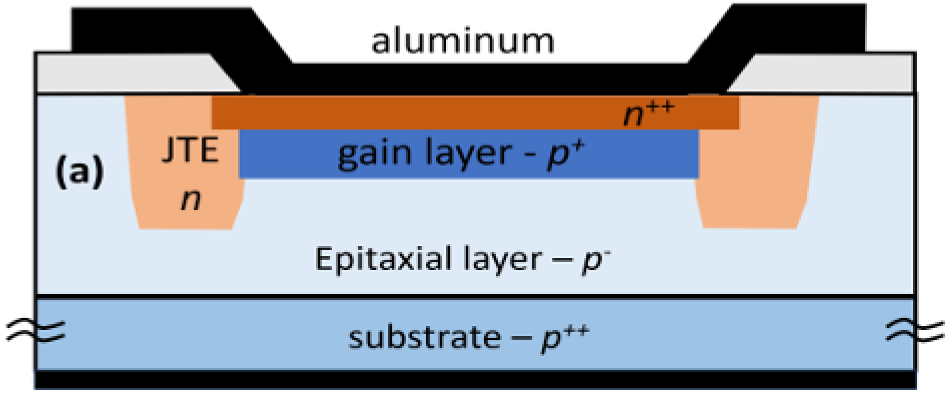
Monolithic LGAD

DC-LGAD development

For ATLAS HL-LHC upgrades

ATLAS High Granularity Timing Detector (HGTD)





➢ to provide precise timing information to mitigate pile-up in HL-LHC.

➢ ~21,000 LGAD sensors for HGTD project

➢ Requirements:

•Size: 15x15 array, 1.3x1.3 mm^2 pixel size

•Active thickness: 50 um(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: $2.5 \times 10^{15}\ n_{eq}/cm^2$

Total Ionizing Dose (TID): 2 MGy at the end of HL-LHC (4000 fb^{-1})

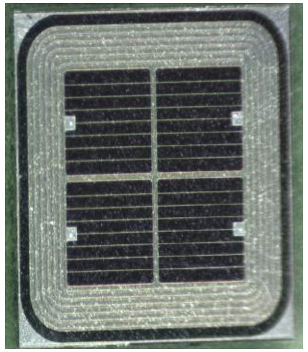
•Time resolution: 35 ps (start), 70 ps (end) per hit, while 30 ps (start), 50 ps (end) per track

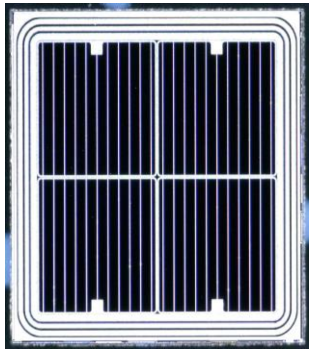
•Collected charge per hit >4 fC (minimum charge needed by the ASIC to hold good time resolution)

•Hit efficiencies of 97% (95%) at the start (end) of their lifetime

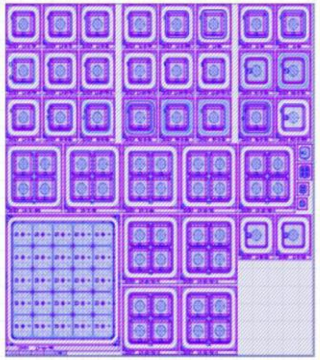
LGAD Development at IHEP

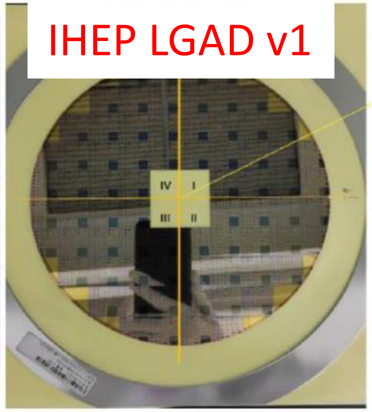
IHEP-NDL(2019)



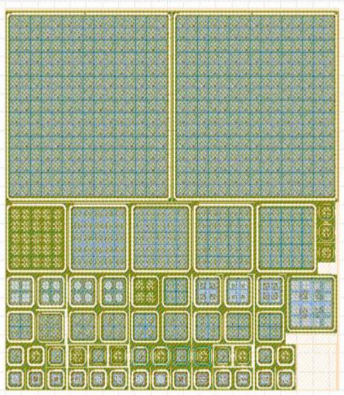


IHEP LGAD v1 (2020.9)

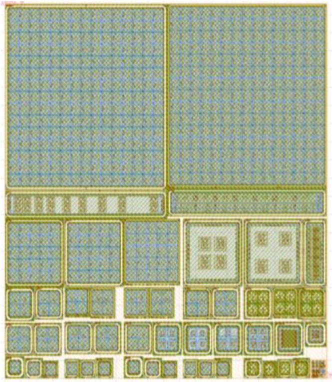


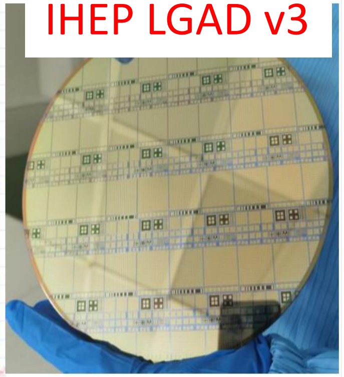


IHEP LGAD v2 (2021.6)

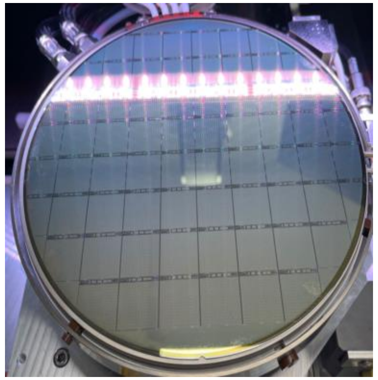


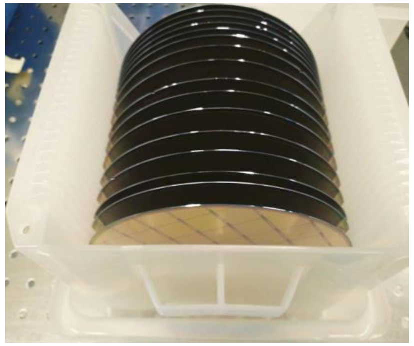
IHEP LGAD v3 (2022.5)



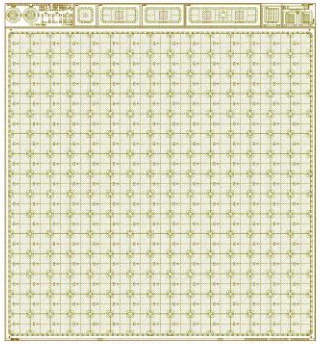


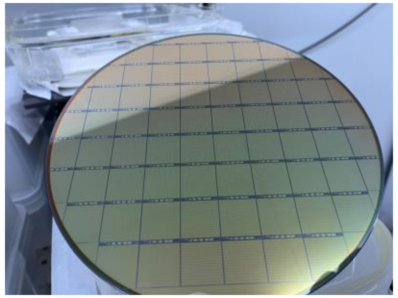
Pre-production for ATLAS (2023.7)

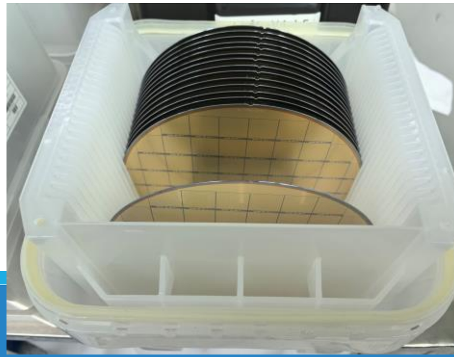




Mass production for ATLAS (2024.8)





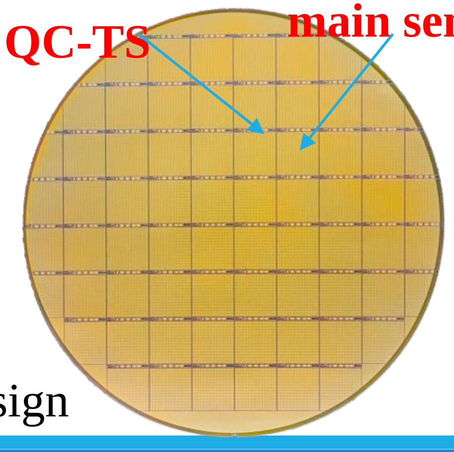


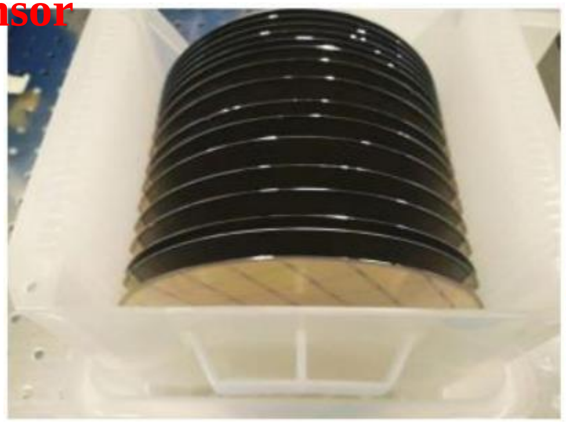
For ATLAS HGTD

- LGAD sensors for HGTD project: ~21,000
  - IHEP design:90%
  - USTC design:10%
- In 2023, IHEP design LGAD sensors be selected in the HGTD sensor tendering process.
- Pre-production started at June 2023. Sensor pre-productions finished in 2023 – produced comfortably enough sensors for HGTD needs.
- HGTD group testing results show that the IHEP and USTC sensors properties fulfill HGTD specification.
- PRR passed at July 2024, and final production started after it. Some wafers(~20) already be fabricated.

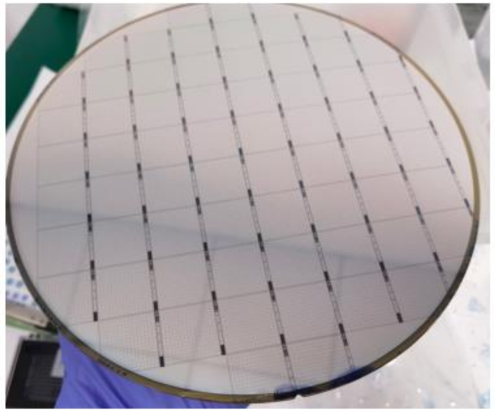
vendor		Percent
IHEP design	CERN	54%
	China in-kind	24%
	Spain in-kind	12%
USTC design	China in-kind	10%

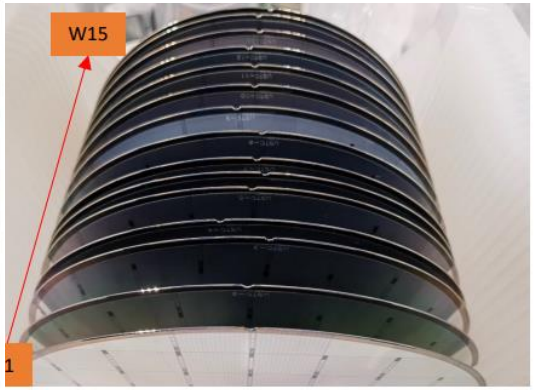
	Wafer number	Good sensors
IHEP design	58	~1,700
USTC design	9	~200





IHEP design



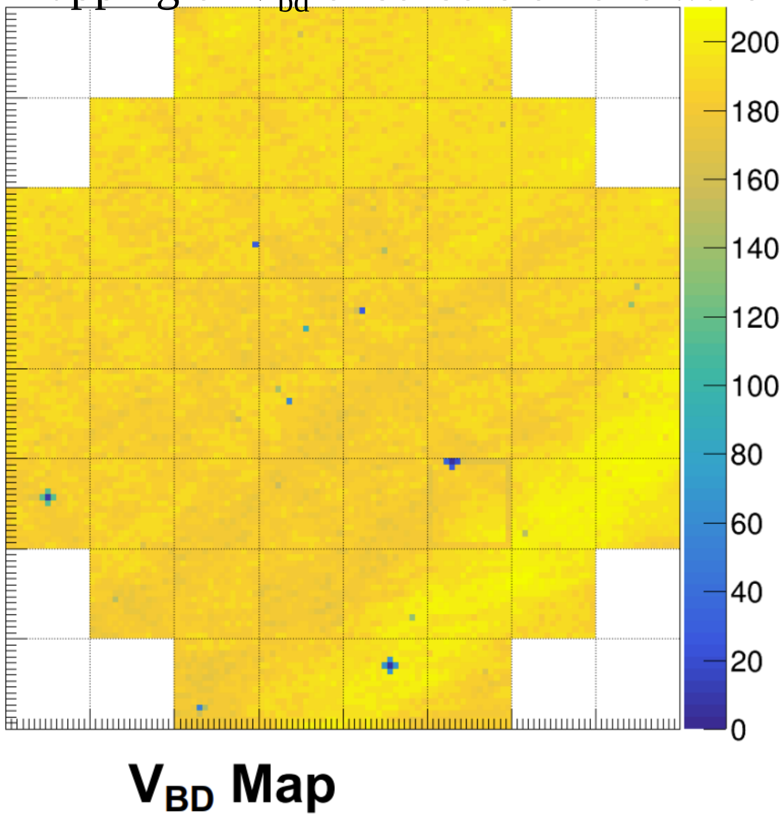


USTC design

For ATLAS HGTD

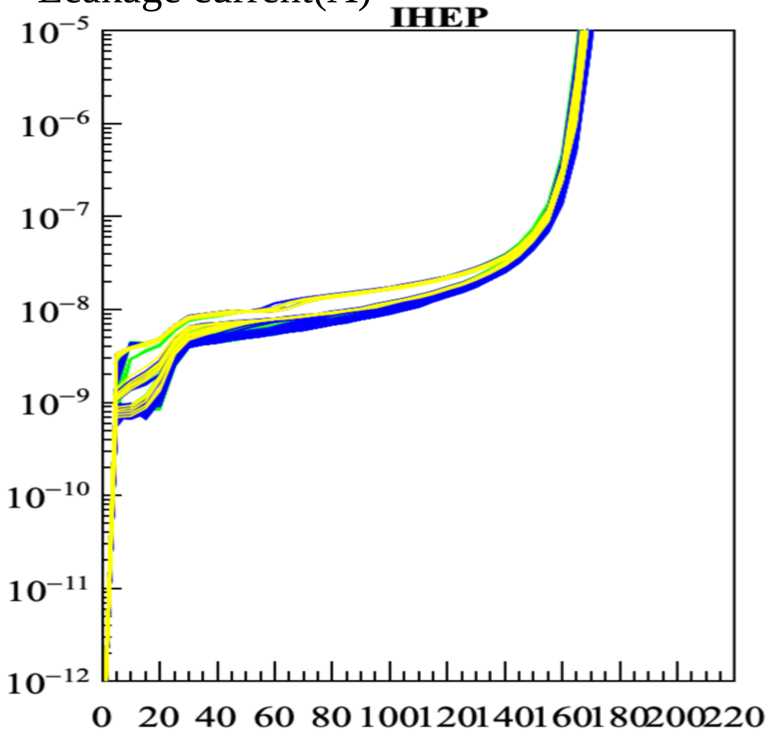
- **The 15x15 array sensors have good IV performance and uniformity**
  Breakdown voltage deviation for 225 pads is less than 5% ： RMS($V_{bd,pad}$)/<$V_{bd,pad}$> < 5%
  The ratio of the maximum and minimum leakage current is less than 3 (Pad leakage current spread at 0.8V_{bd}) ,peak to peak within a factor of 3X.
- **Yield**： pad yield: >99%, sensor yield: ~64%

Mapping of V_{bd} of sensors on one wafer



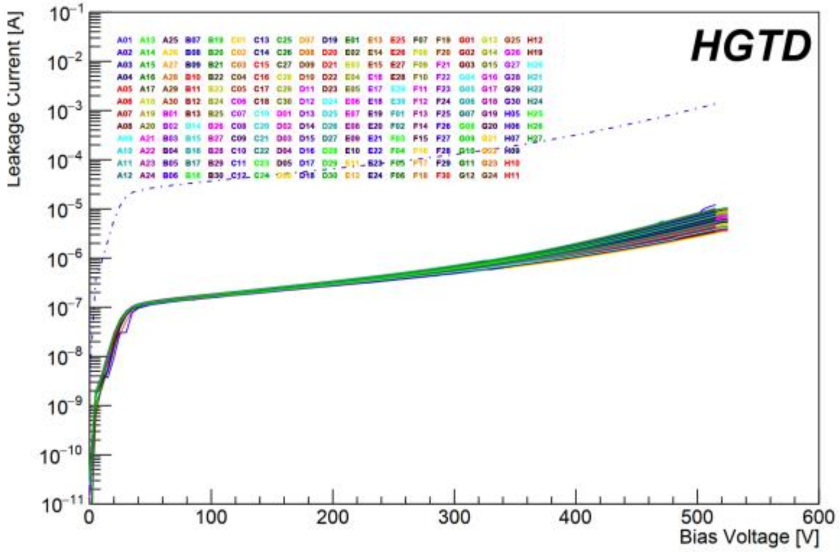
Good IV uniformity before and after irradiation

Leakage current(A)



Bias voltage(V)

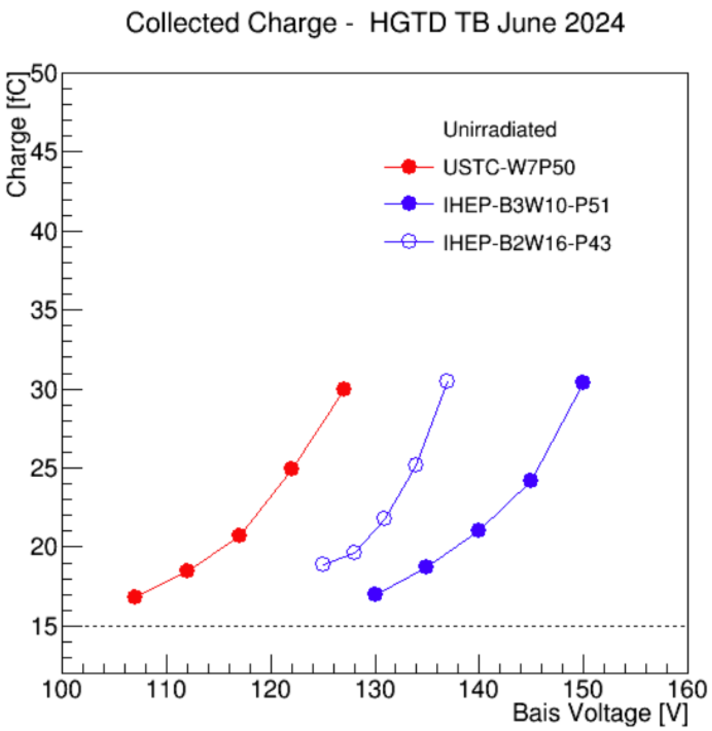
IHEP LGAD sensors after 2.5e15 n_{eq}/cm^2



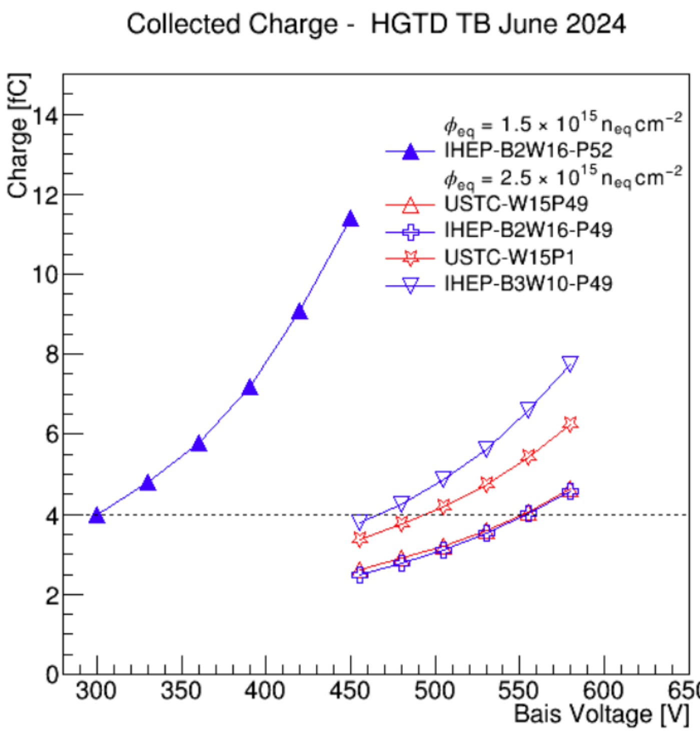
For ATLAS HGTD

Performance of pre-production sensors: Beam test results

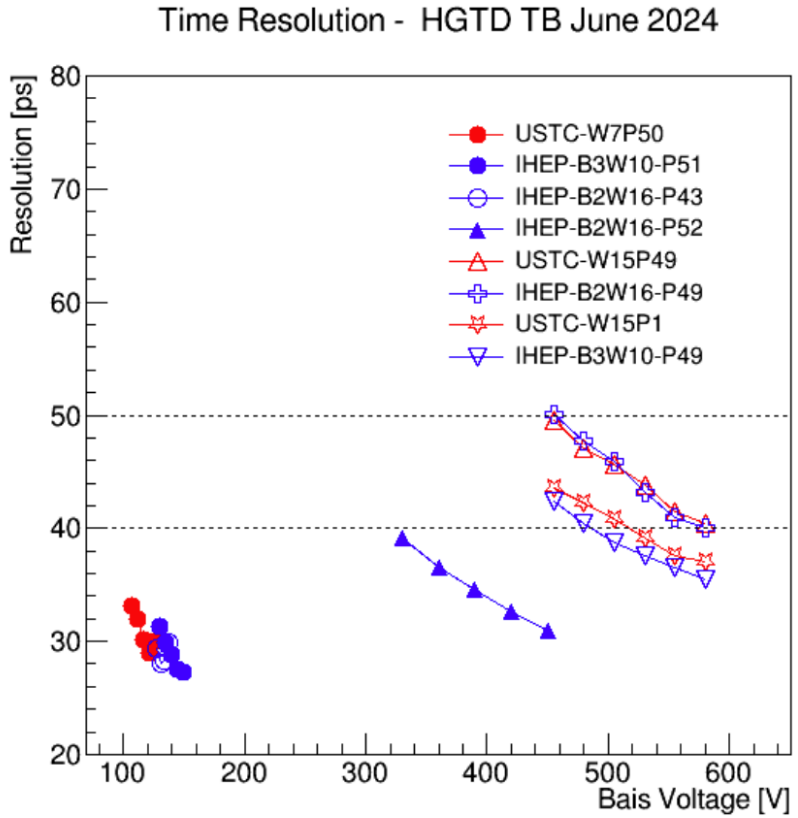
- Collected charge： The sensors can collect more than 15 fC charge before irradiation and >4 fC charge after irradiation at bias voltage <550 V (SEB limit)
- Timing resolution: The timing resolution is better than 35 ps (50 ps) before(after) irradiation(fluence 2.5×10^{15} n_{eq}/cm^2)
- The collected charge and timing performance of sensors from pre-production fulfills HGTD requirement.



unirradiated sensor

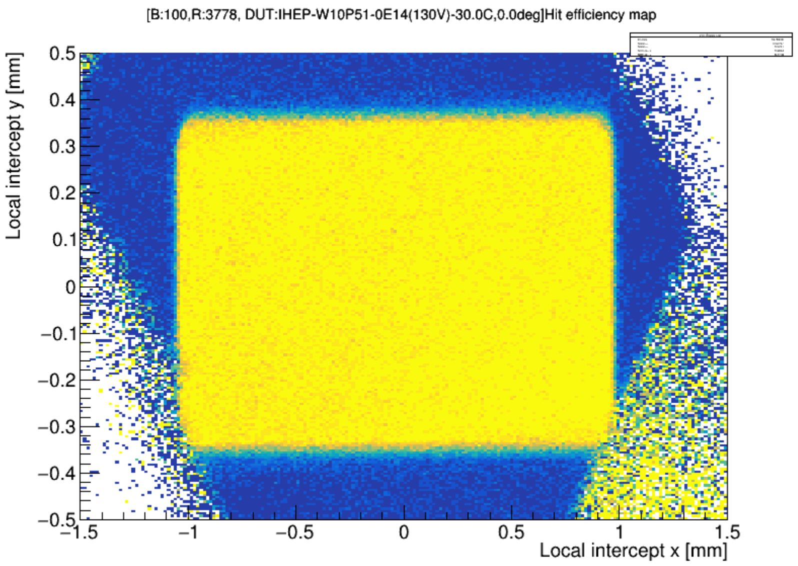


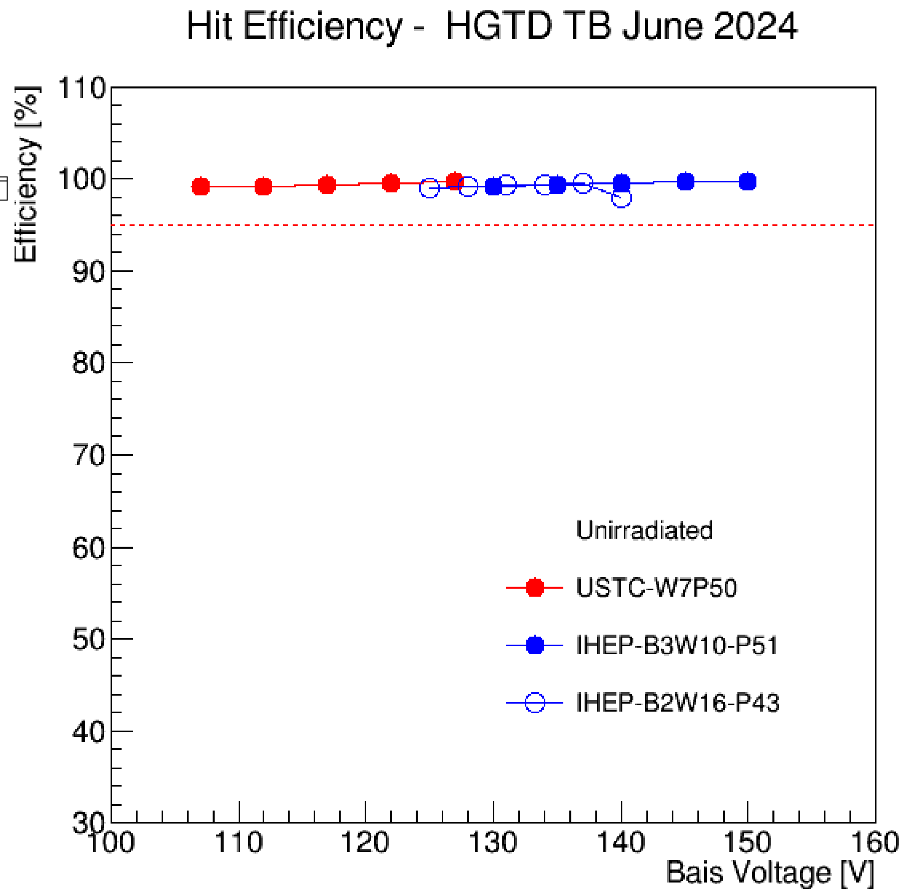
irradiated sensor

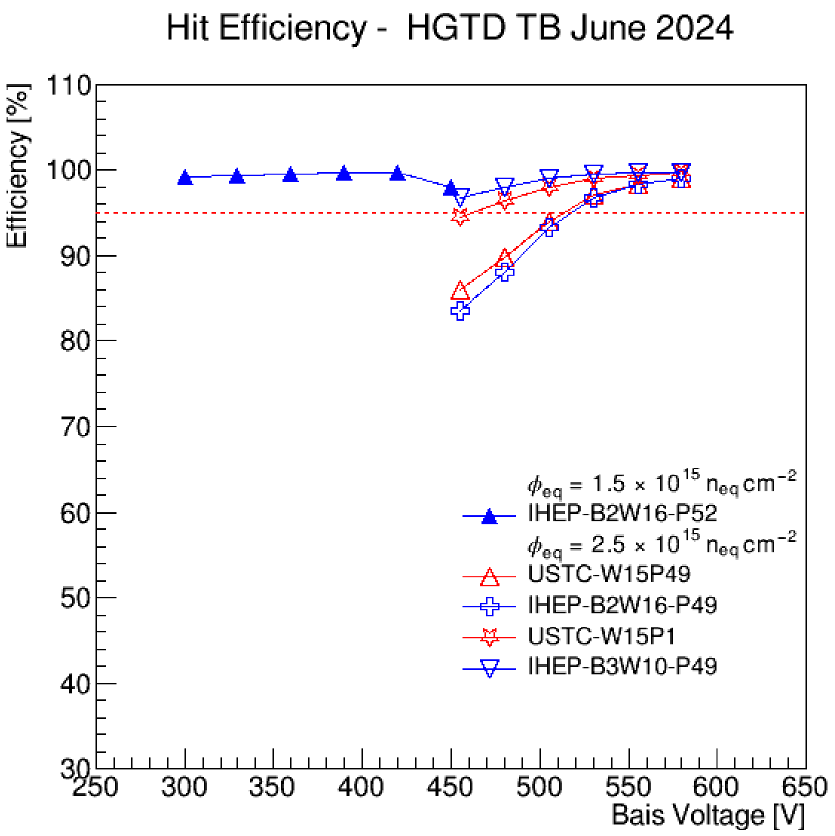


For ATLAS HGTD

- **Performance of pre-production sensors: Beam test results**
- **Efficiency : 95%~100% for sensors before and after irradiation, fulfills HGTD project requirement**

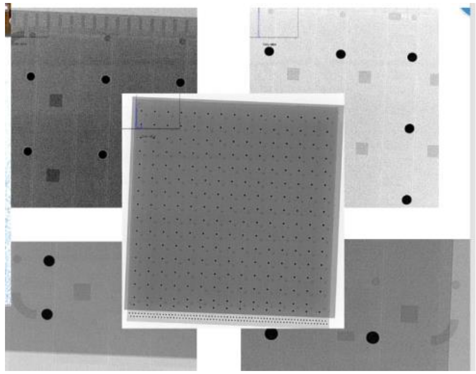


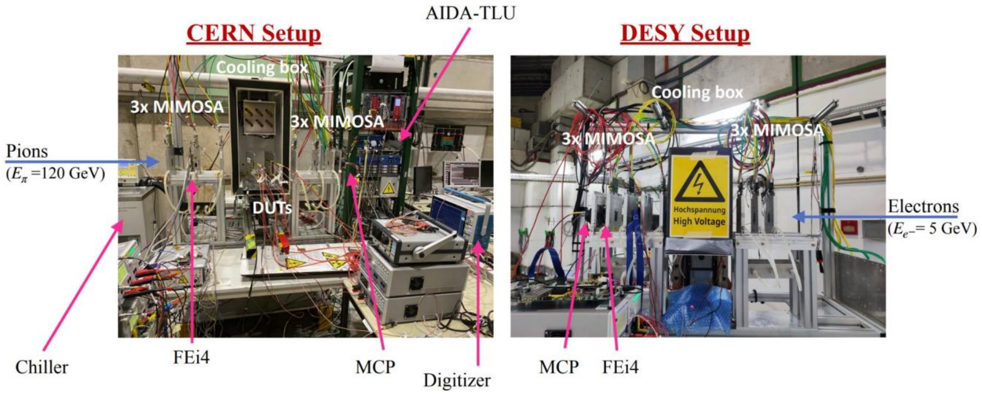


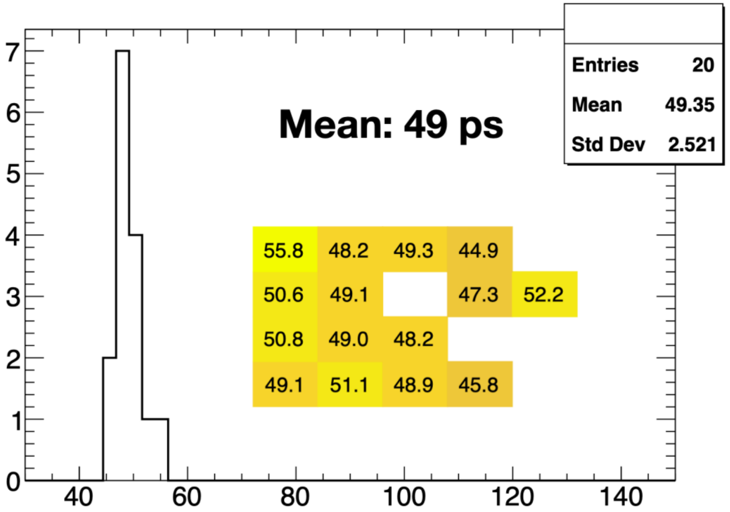


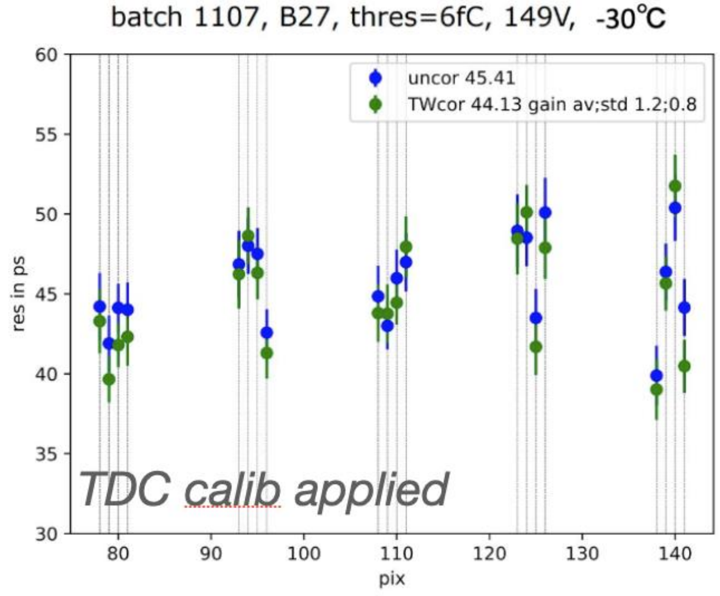
For ATLAS HGTD

- **IHEP Pre-production sensors with ASIC(Altiroc3): Beam test results**
- **Timing resolution can reach 50 ps for the sensor/ASIC module**
- **The efficiency is larger than 98%**

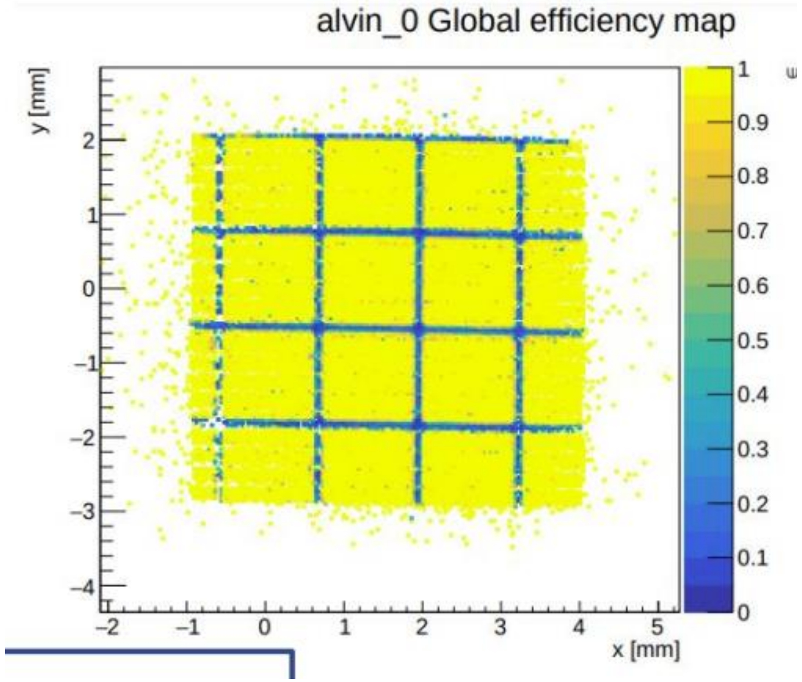






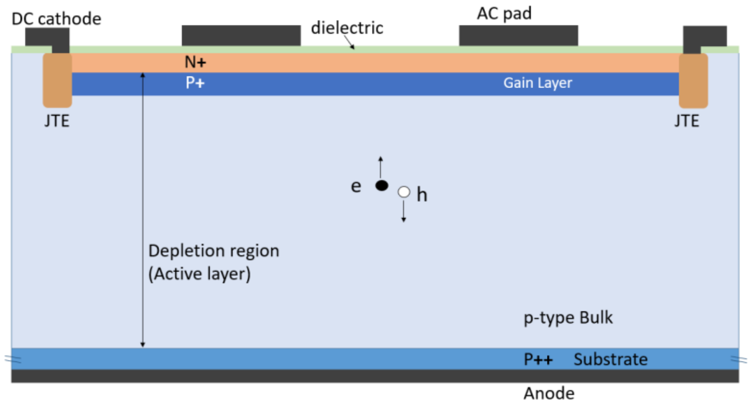


~45 ps after calibration and time walk correction



AC-LGAD development

- **AC-LGAD sensor is the choice for future collider OTK & TOF detector to provide both spatial resolution and timing resolution.**



- metal AC readout electrode and a thin dielectric layer (Si_3N_4, SiO_2) above the N+ layer
- Less dead area and better position resolution
- Research institute: FBK, HPK,INFN, BNL, CNM, USTC, IHEP…

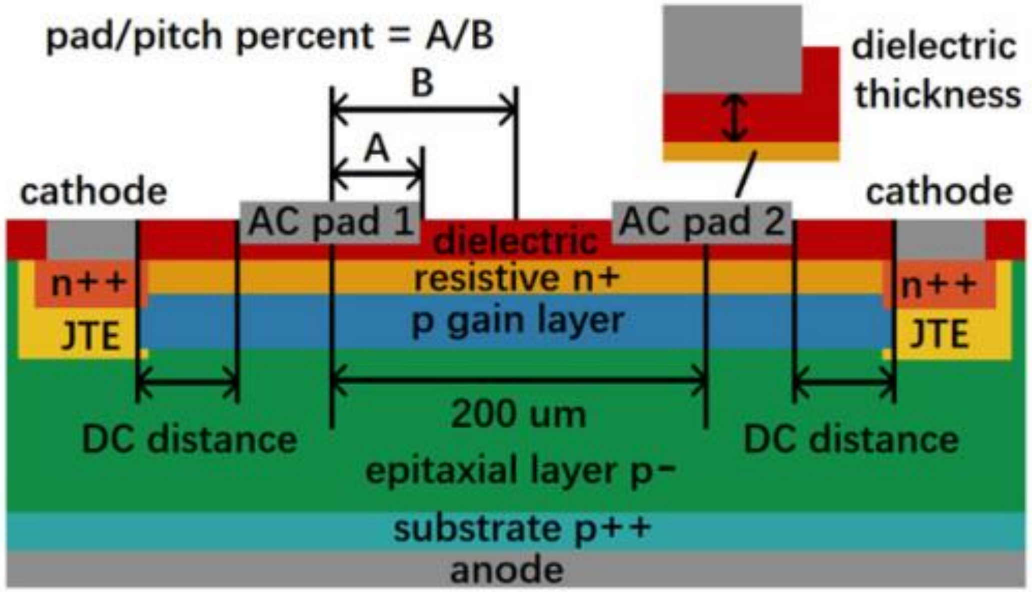
- Spatial resolution: 10 μm Time resolution: 30-50 ps

AC-LGAD R&D at IHEP

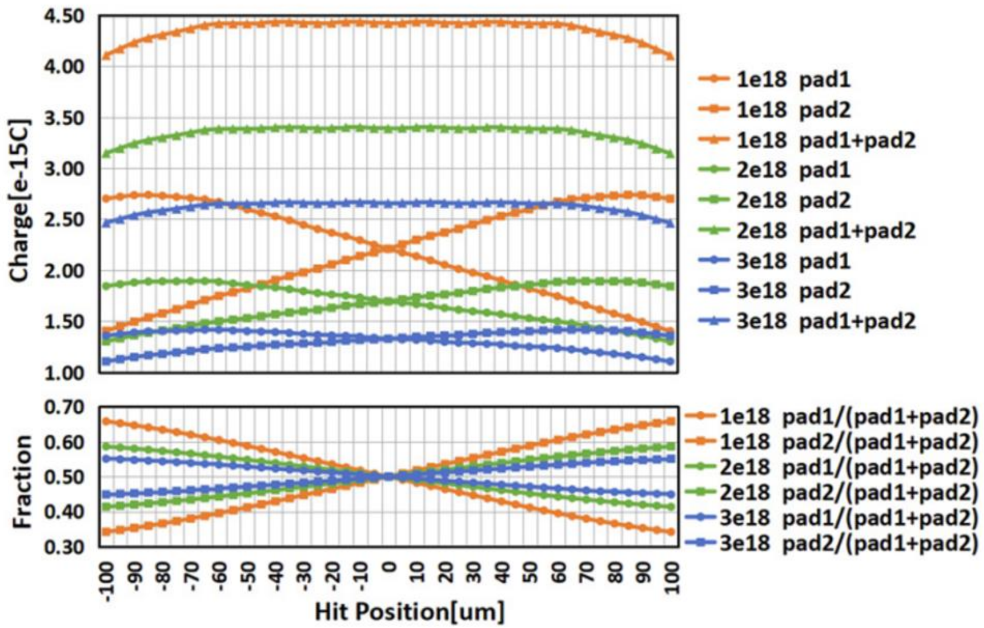
◆**AC-LGAD sensor simulation**： **Optimization of process and structure parameters**

Process parameter: n+ layer dose, AC dielectric material and thickness

Structure parameter: pad shape, pad-pitch size



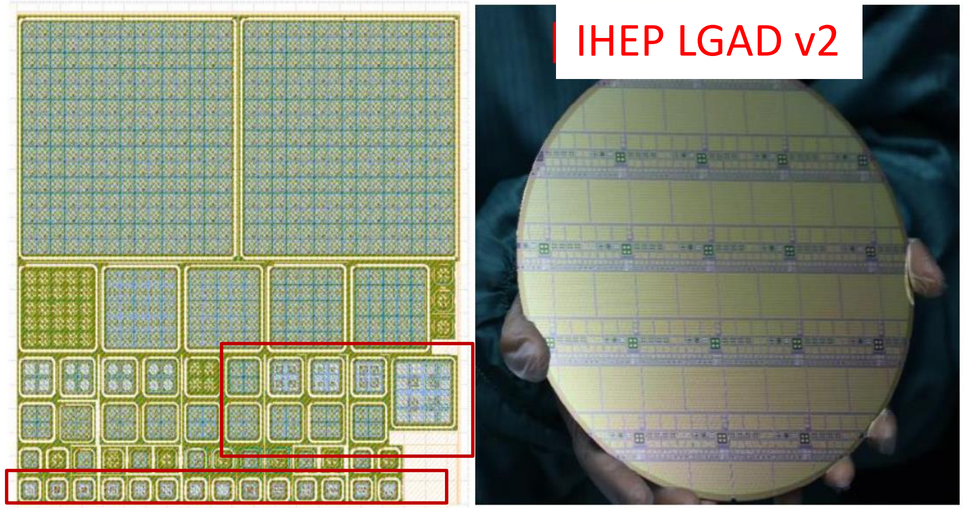
TCAD model of AC-LGAD for simulation

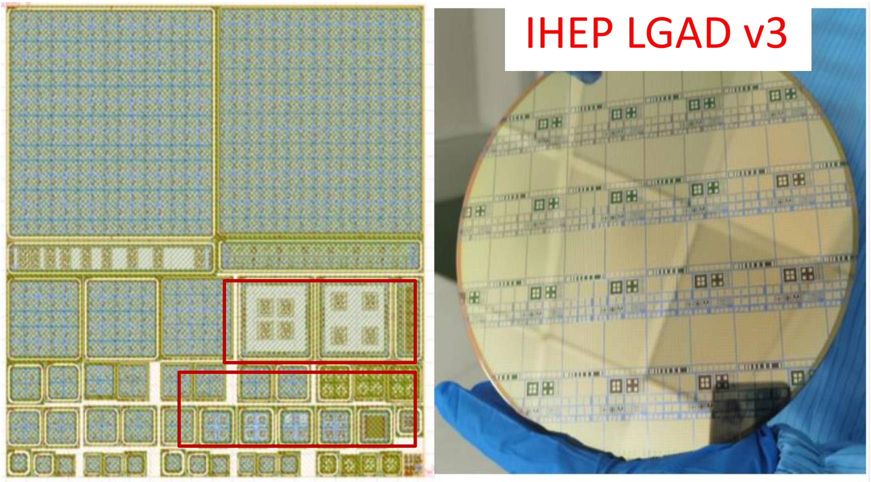


Lower n+ dose→ Large resistivity →good spatial resolution

Design of AC-coupled low gain avalanche diodes (AC-LGADs): a 2D TCAD simulation study, JINST, 2022.9, DOI:10.1088/1748-0221/17/09/C09014

AC-LGAD R&D at IHEP

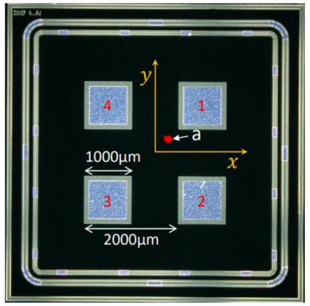




AC-LGAD R&Dv1:

Pixelated AC-LGAD

- With different pad-pitch size
  1000-2000um
  100-500um
  100-200um
  50-100um



- wafers: with different n+ dose: 10P to 0.2P

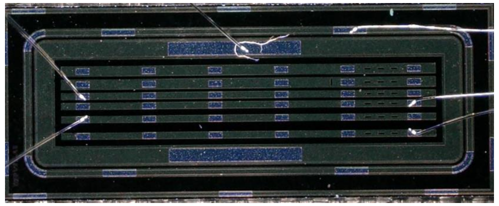
Process parameters(n+ dose) be studied.

The performance of large-pitch AC-LGAD with different N+ dose， Trans. Nucl. Sci.， 2023.6

AC-LGAD R&Dv2:

Pixelated and strip AC-LGAD

- With different pad-pitch size
  1000-2000um pixel
  100-250um strip
  100-150um strip
  50-100um strip

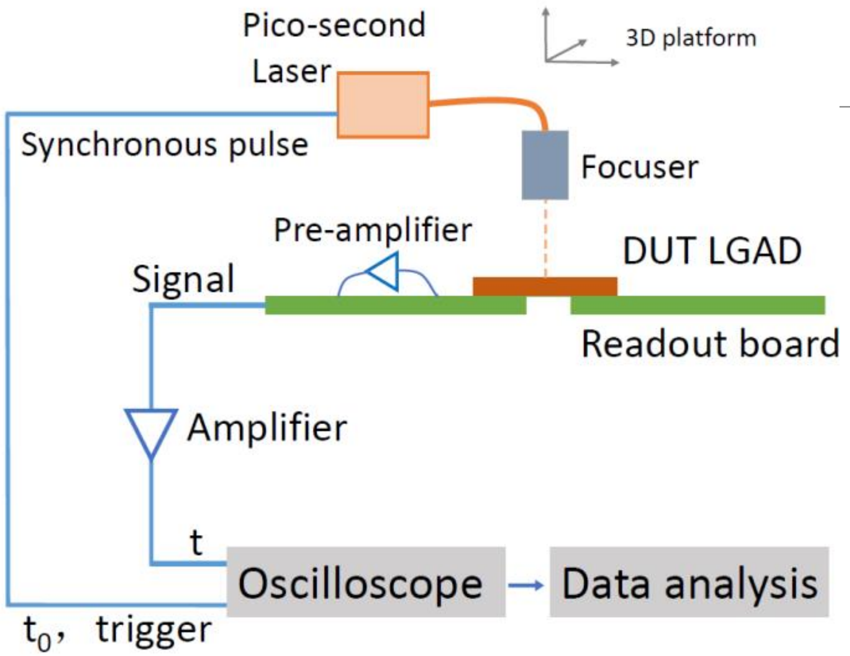


- wafers: with different n+ dose:0.2P to 0.01P

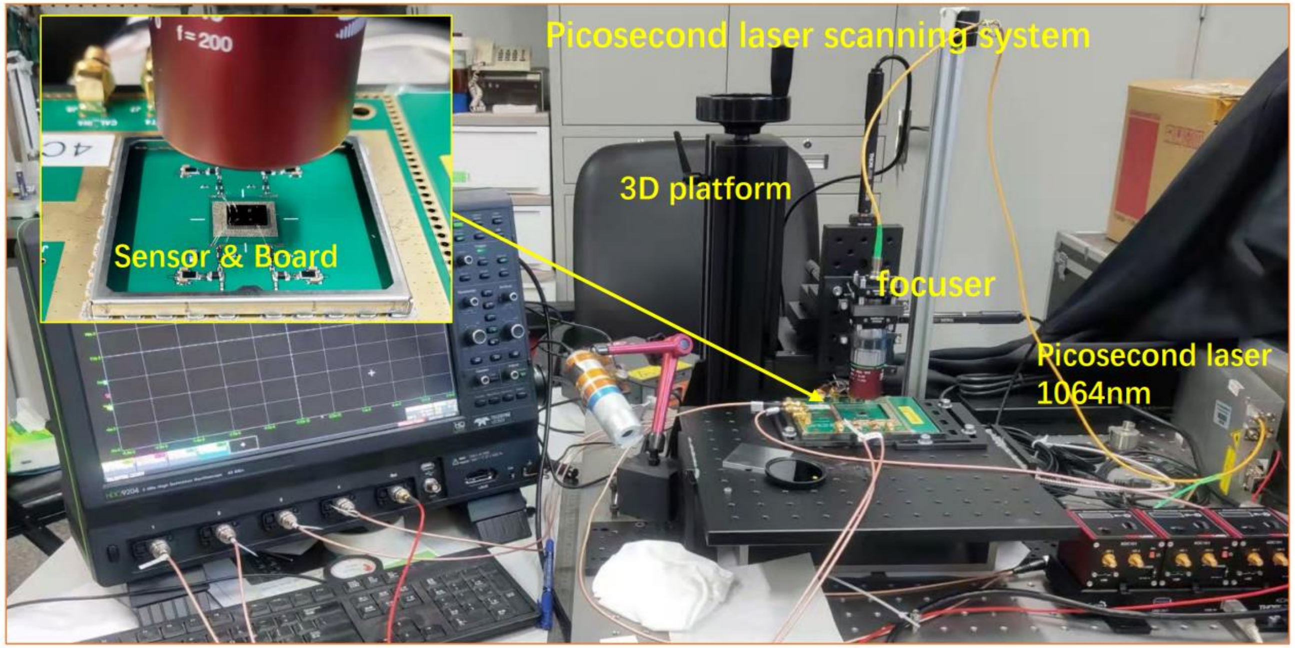
The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

AC-LGAD testing setup

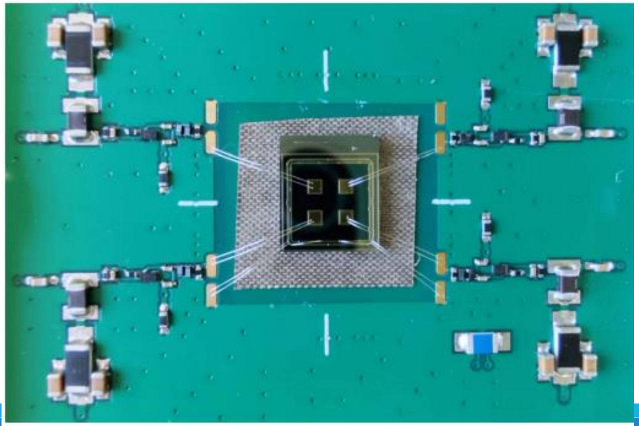
◆AC-LGAD sensor testing system



Pico-second laser testing system for AC-LGAD



4 channels readout board with fast amplifiers

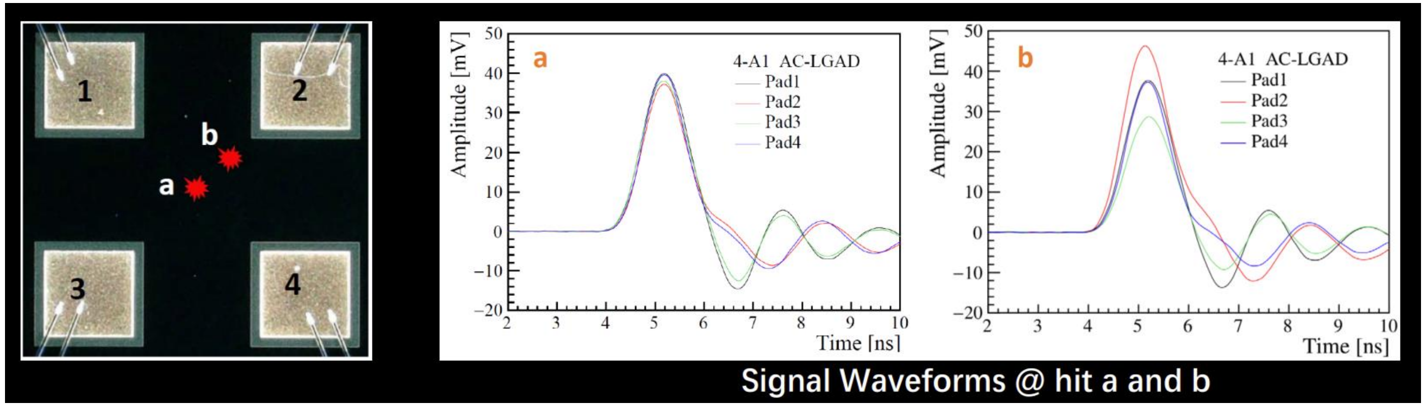


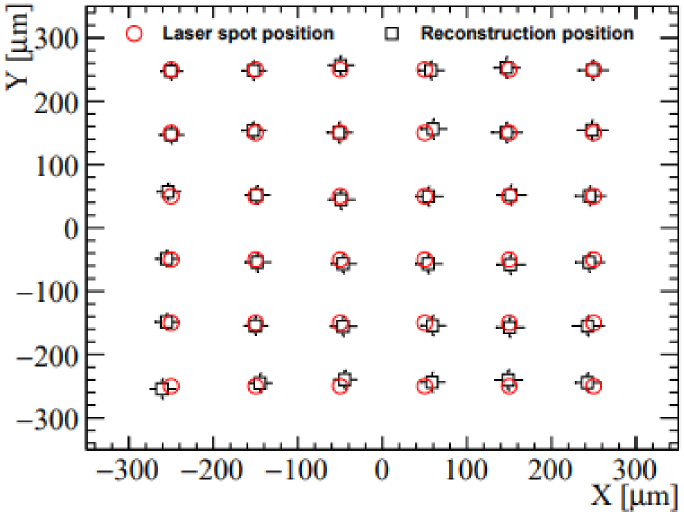
Picosecond laser testing system

- Automated scanning
- Displacement accuracy： 1 μm
- Picosecond laser： 1064nm
- Laser spot size： 2~5 μm

Position reconstruction, spatial resolution and timing performance of AC-LGAD be calculated based on the results from 4 pads.

AC-LGAD development

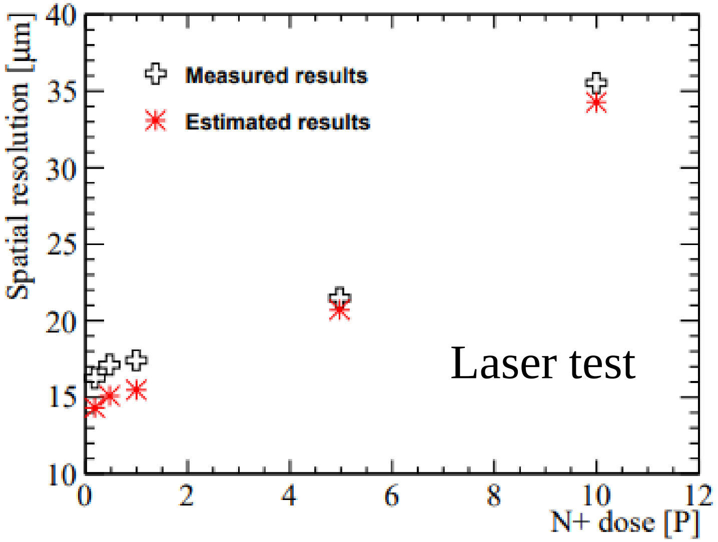


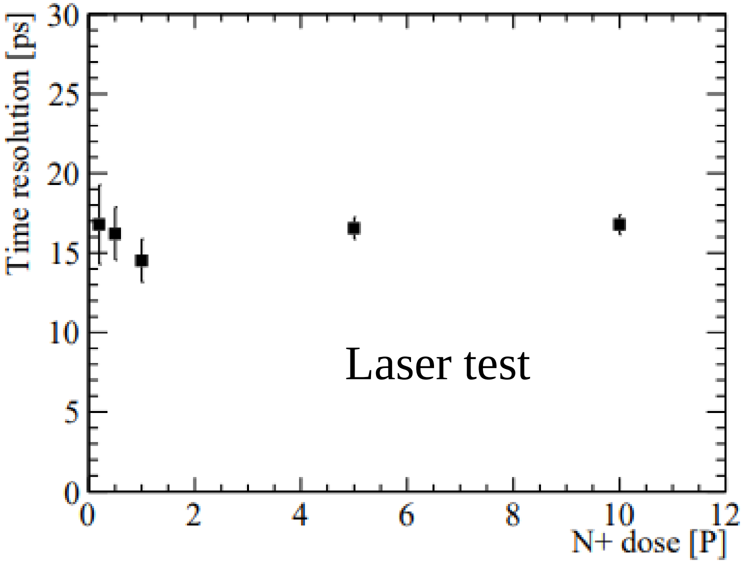


Pixel size: 2000um
Pad size: 1000um

Pixelated AC-LGAD：

- Best spatial resolution~15um (laser test)
- Timing resolution: 15-17ps
- N+ dose and other process parameters be studied.

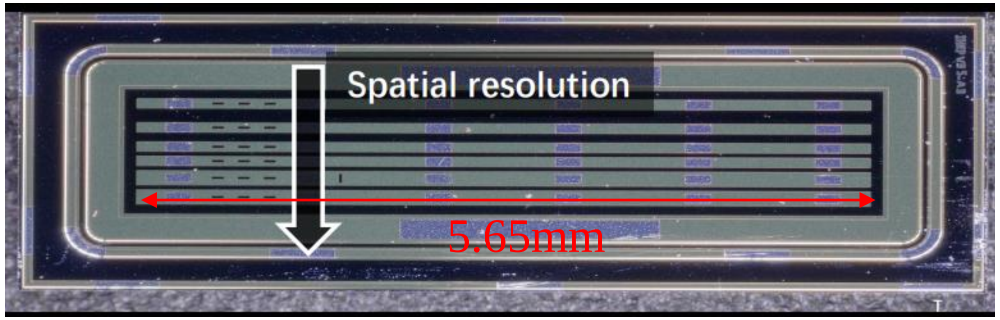




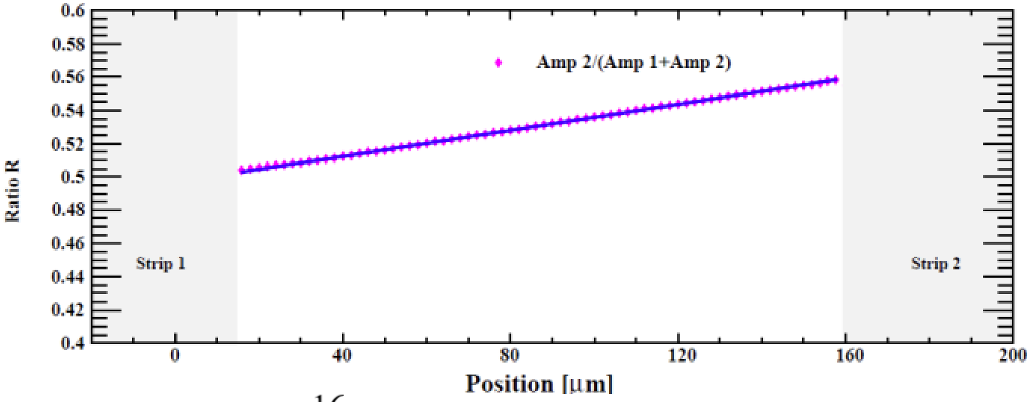
AC-LGAD development

Spatial resolution: Laser testing

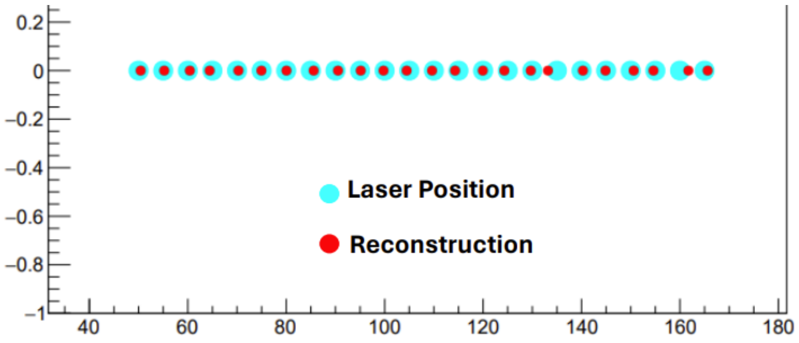
- Strip length 5.65mm
- pad-pitch size:
  100-250 um
  100-200 um
  100-150 um

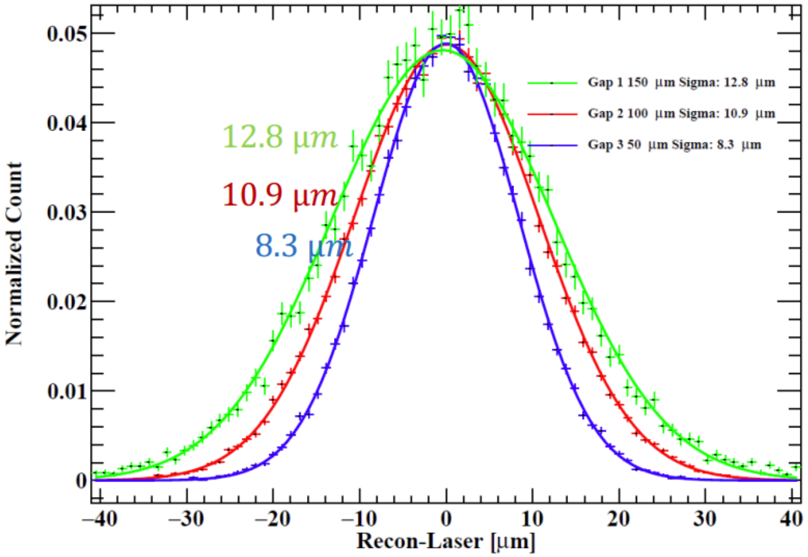


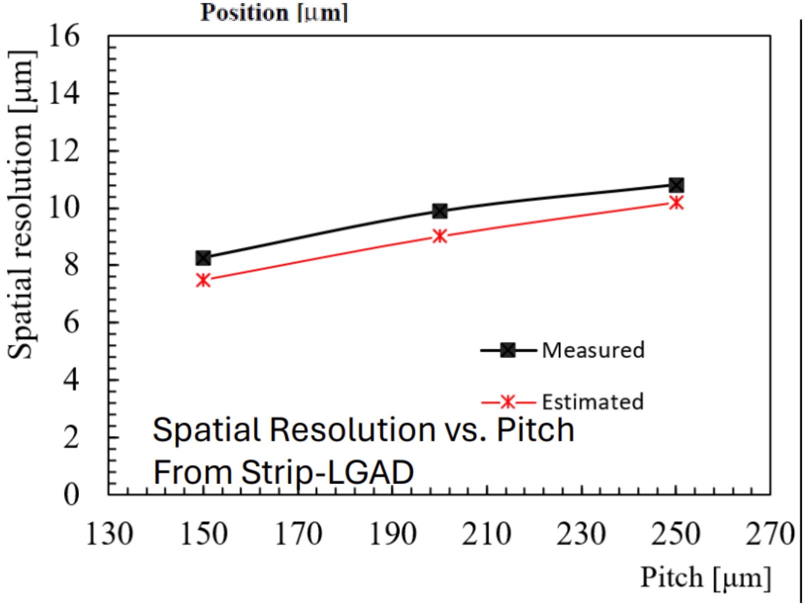
Amplitude information



Position reconstruction







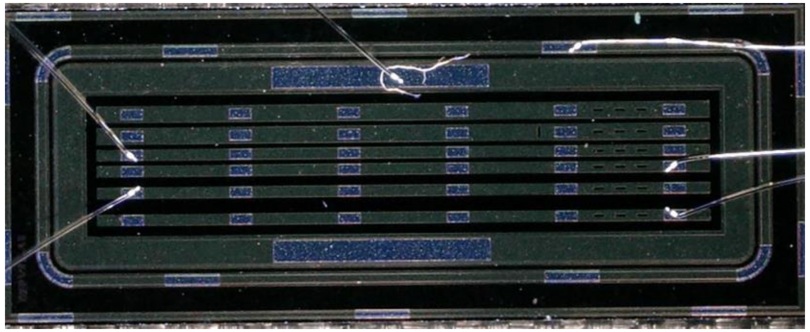
AC-LGAD with Pitch as 150um：Best spatial resolution~8um (laser test)

The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

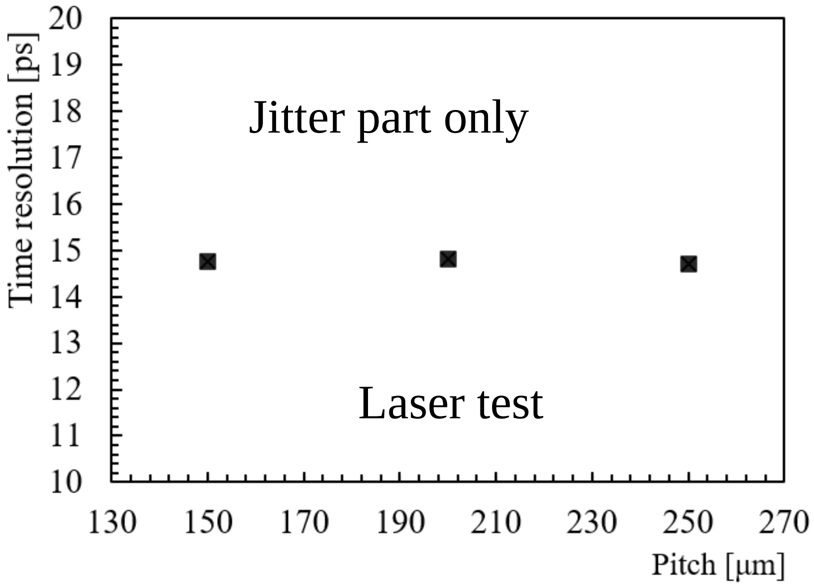
AC-LGAD development

Timing resolution

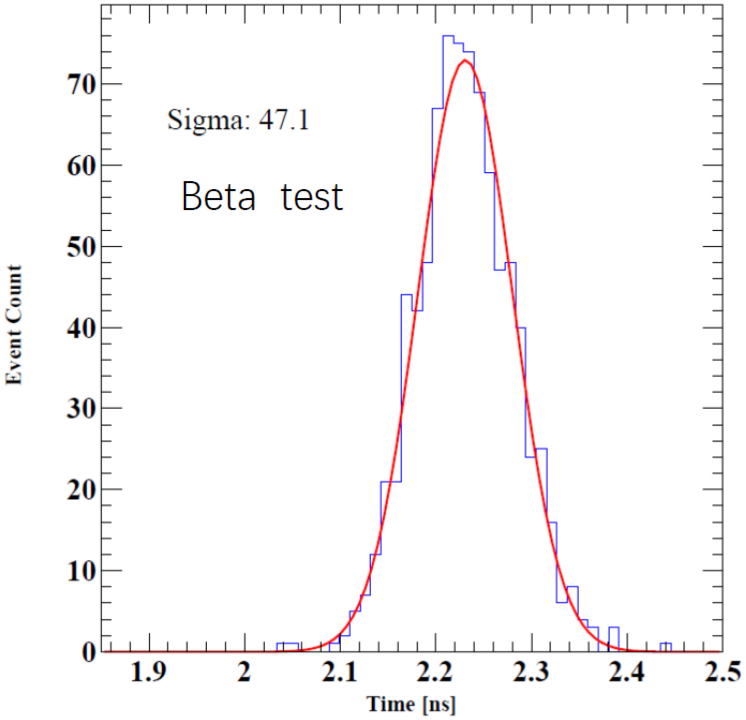
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$



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



The time resolution does not change significantly, ~15-17 ps.



Time resolution： 37.5 ps

Landau and jitter contribution

$$\sigma_{AC-LGADStrip} = \sqrt{\sigma_{\Delta T}^2 - \sigma_{Trigger}^2}$$

Trigger: 28.5ps

LGAD application for X-ray detection

LGAD for X-ray detection

Advantage:

Low Gain Avalanche detector could improve signal-to-noise for soft x-ray sensors, with good spatial resolution

- In photon science, the gain provided by LGAD sensors can boost the signal-to-noise ratio of the detector system, effectively reducing the x-ray energy threshold of photon counting detectors and the minimum x-ray energy where single photon resolution is achieved in charge integrating detectors.
- This can improve the hybrid pixel and strip detectors for soft and tender x-rays by only changing the sensor element of the detector system.

Research institute and status

PSI, Diamond, IHEP, USP, UCSC, SLAC and SINTEF..
Foundry: CNM, FBK, HPK…

Low energy: 250eV, fast timing:<100ps

PSI: Development of LGAD sensors with a thin entrance window for soft X-ray detection

a game changer for several resonant diffraction and spectromicroscopy applications.
LGAD could be used for soft X-rays experiments at XFELs in combination with a CI readout, improving the single photon resolution

Diamond: Low Gain Avalanche Diode Sensors for Time Resolved Synchrotron Applications

- exploit the circa-100-ps timing capability of the Timepix4+LGAD to perform highly time-resolved experiments;
- an LGAD sensor to couple to a hybrid such as the Timepix4 to image X-rays at energies as low as 250 eV by making use of the sensor's built-in amplification.

LGAD design for X-ray

➢For X-ray detection：

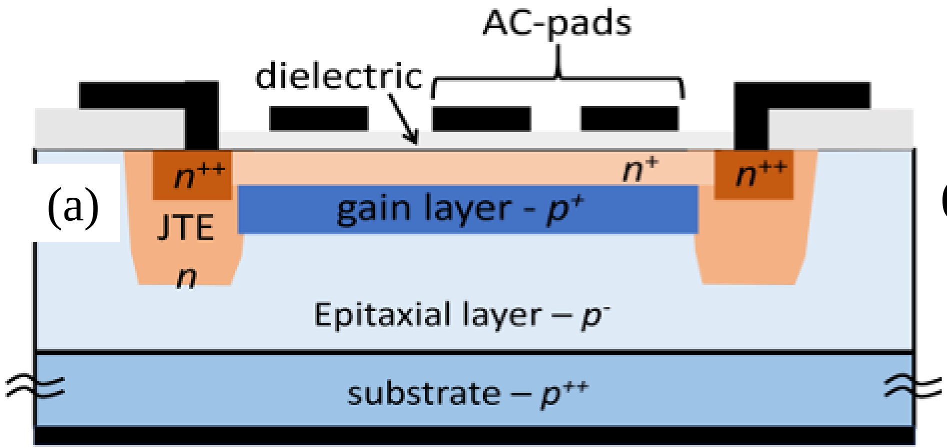
LGAD structures need to be optimized for several aspects relevant to photon science applications.

- The placement of the gain structure on quantum efficiency, the active thickness
- The sensors’ signal characteristics and its compatibility with available readout chips

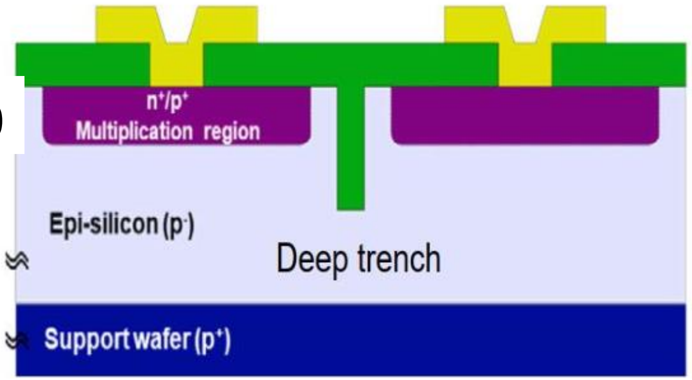
➢ For 50-100um pixel size X-ray image application: small pixel size with good fill factor

- AC-coupled LGAD, trench-isolated LGADs(Ti-LGAD), inversed LGADs
- Its compatibility with available readout chips also need to be considered.

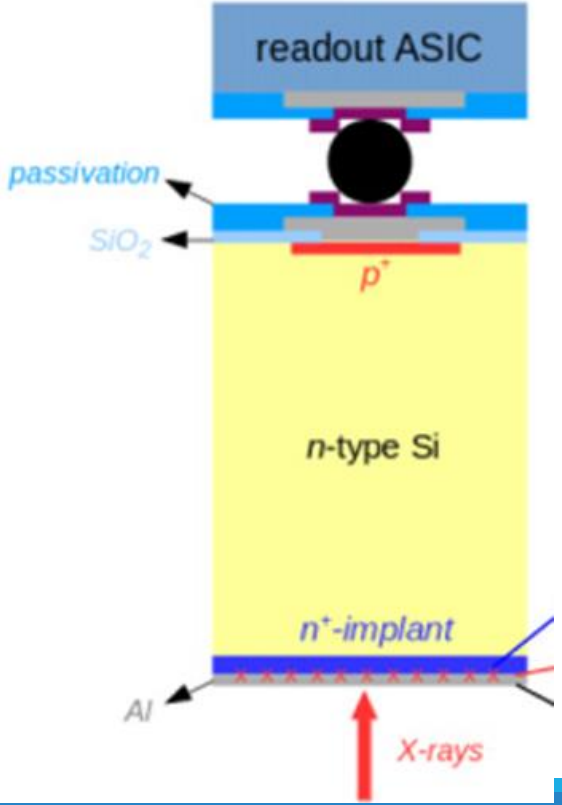
(a)



(b)



(c)

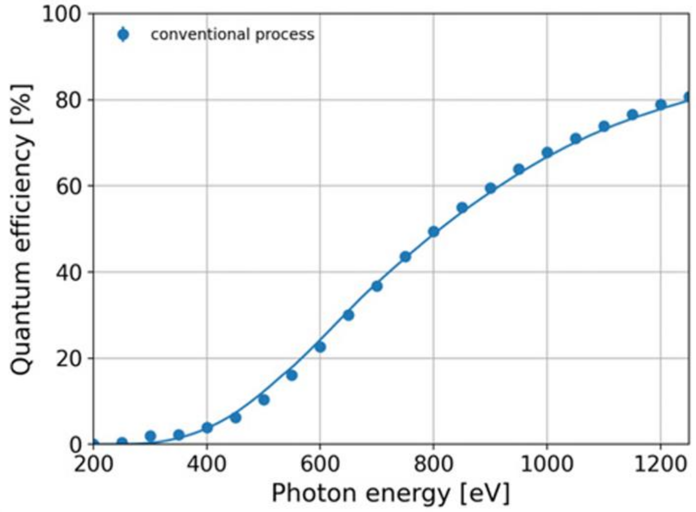


LGAD design for X-ray

➢For X-ray detection：

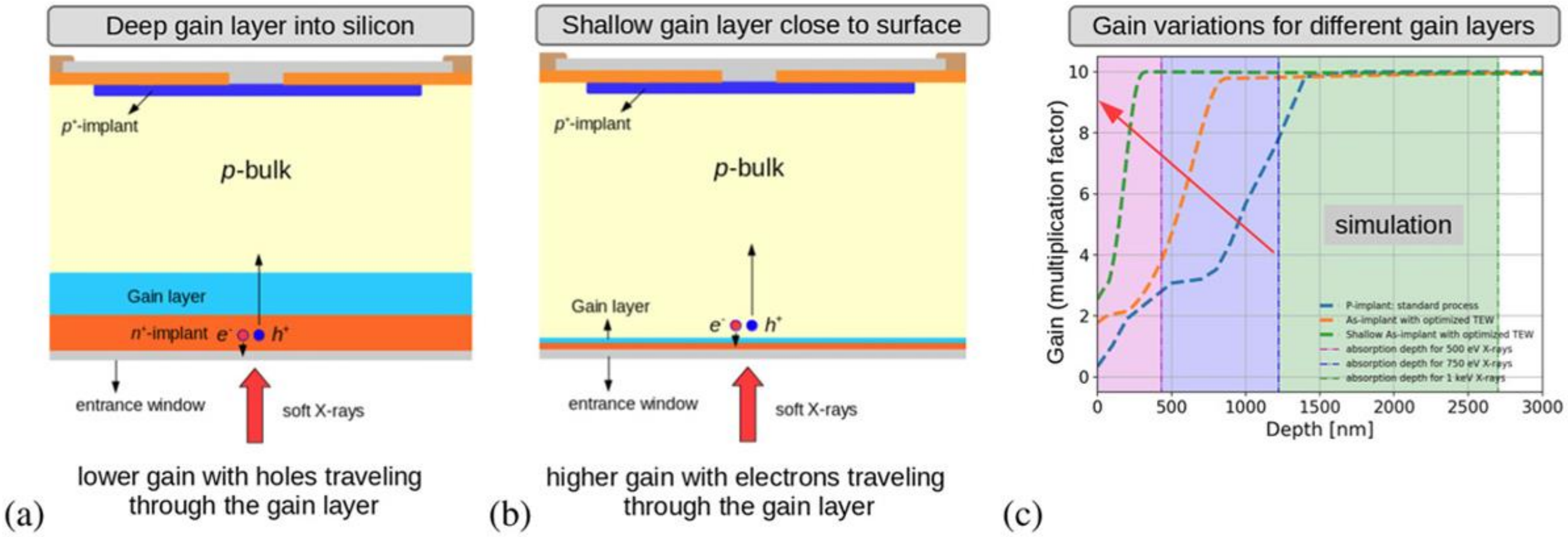
- For low energy X-ray detection, the conventional LGAD structure is not compatible with thin-entrance window (<50nm).

   Inversed LGAD with thin-entrance window



The measured (dots) and simulated (line) QE for a conventional silicon sensor

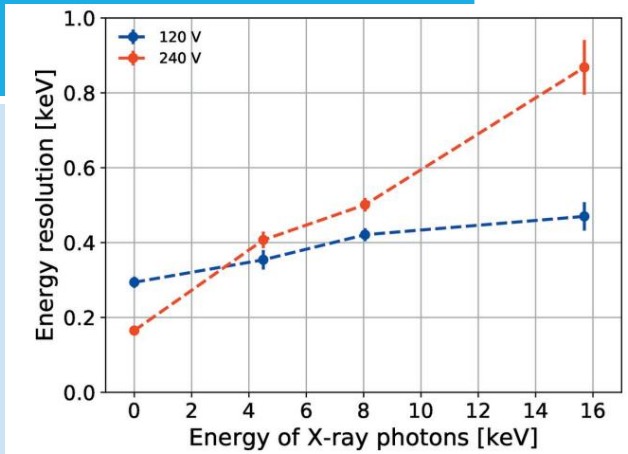
At 400eVthe QE is less than 5%



PSI: Development of LGAD sensors with a thin entrance window for soft X-ray detection

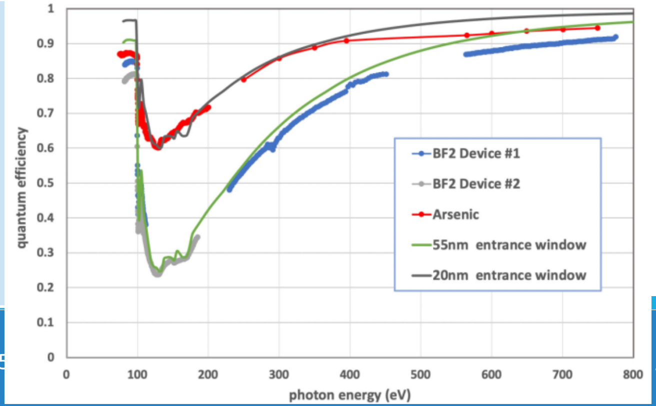
LGAD testing results (X-ray)

Institute	Sensors type	X-ray source	performance
PSI, FBK	FBK(50um)	X-ray energy range (2–4 keV) installed at the PHOENIX beamline of the Swiss Light Source	The average energy resolution for all channels at 2.1 keV is 0.310±0.024 keV RMS.
USP, UCSC	HPK LGAD type 3.1, type 3.2 (50um) BNL LGAD (20um)	Stanford Synchrotron Radiation Light source SSRL 11-2 beamline	More details in Marco's talk next
SLAC, SINTEF (HSTD 13)	New Thin-Entrance window LGAD	Not tested yet	QE simulation gain = 7.0
free electron lasers, SLAC's LCLS-II			



For 35 keV X-ray:

	HPK PIN	HPK3.1		HPK3.2		BNL 20um	
Bias V	200 V	150 V	230 V	80 V	130 V	50 V	100 V
Energy Resolution	14 %	6 %	17 %	10 %	20 %	6 %	16 %
Energy Response	19 mV	75 mV	185 mV	68 mV	211 mV	66 mV	147 mV
σ_t CFD	78 ps	141 ps	123 ps	371 ps	171 ps	69 ps	65 ps

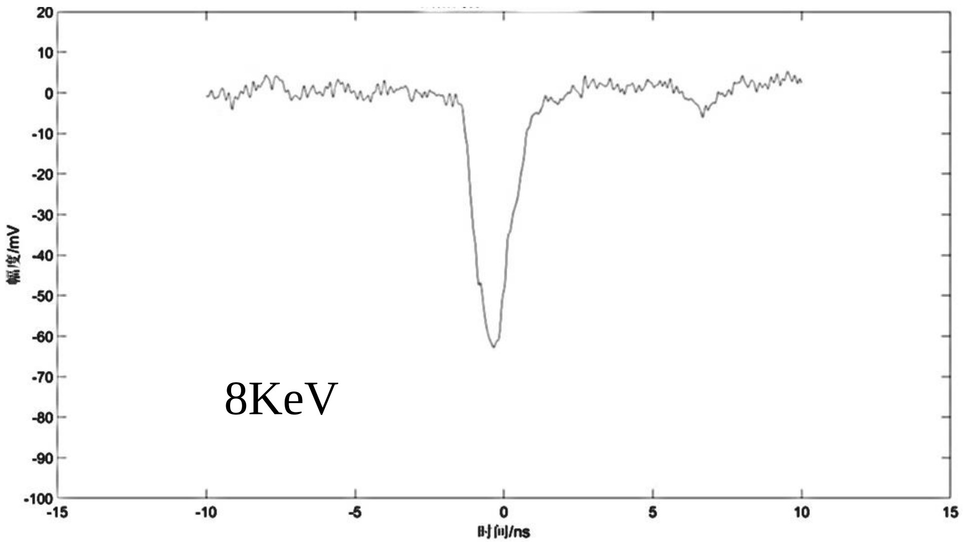


LGAD testing results(X-ray)

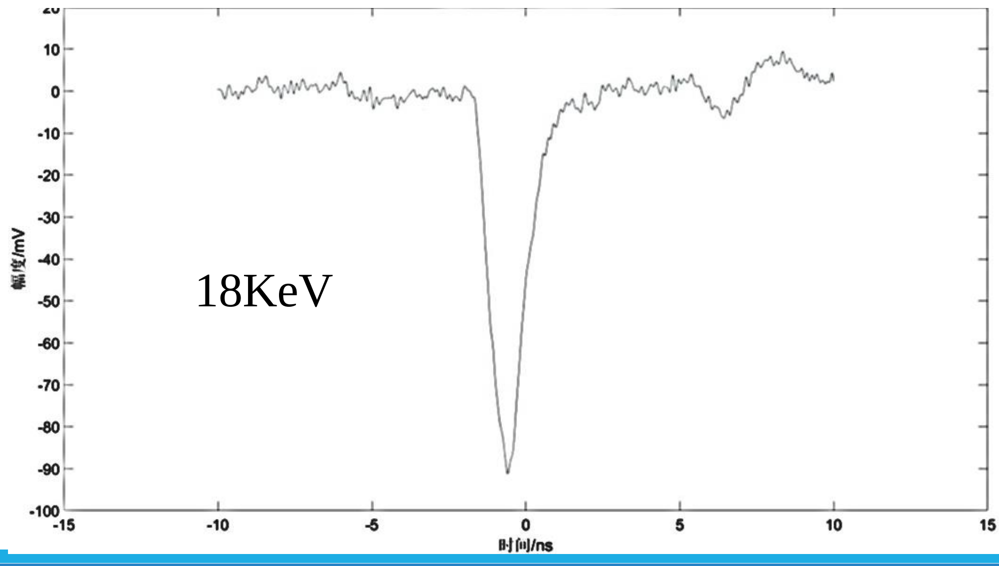
Sensor type: IHEP LGAD version3 sensors: W25

	size	capacitance	Active thickness
Single LGAD	1.3mm x 1.3mm	4.2pF	80um

Sensor be wire bonded to readout board,
gain of readout board(two stage amplifiers): 100.
X-ray source at BSRF be used for testing.



	X-ray energy	Noise (RMS)	Signal amp mV	Rise time
Single LGAD	8KeV	2.8mV	70	1.2ns
	18KeV		70-130	0.9ns



LGAD design (for X-ray)

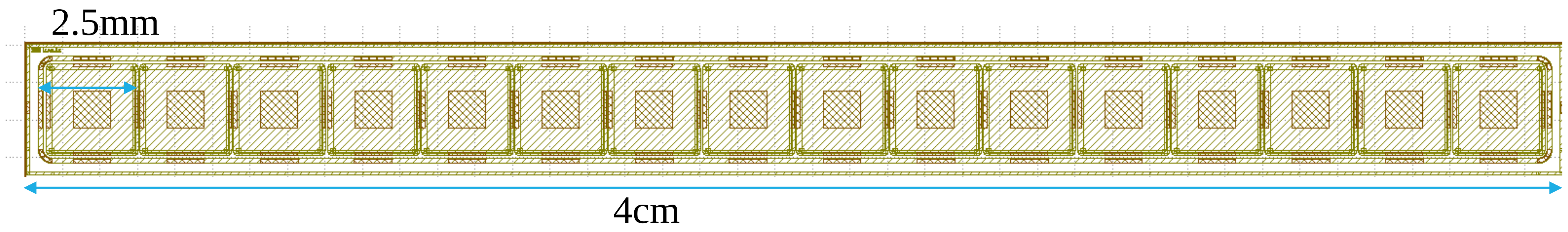
New run be submitted, sensors be finished mid of this year.

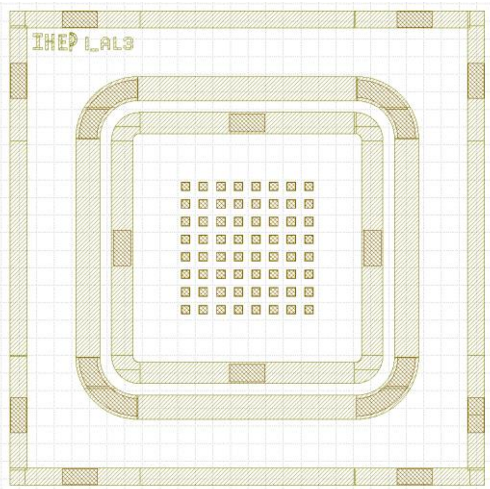
DC-LGAD:

	Pixel size	Active thickness
Single LGAD	1.3mm x 1.3mm	50um 80um 300um
1x16 LGAD	2.5mm x 2.5mm	50um 80um 300um

AC-LGAD:

	Pixel size	Pixel array	Active thickness
LGAD 55	55um x 55um	5x5	50um 80um 300um
LGAD 100	100um x 100um	8x8	50um 80um 300um





Check the basic performance of LGAD for X-ray detection.
More simulation and design need to be done to optimize LGAD structures for X-ray application.

Summary

- DC-LGAD has timing resolution <35ps, be chosen as timing detector to solve pile-up issues for ATLAS HGTD project. Now IHEP LGAD sensors' pre-production is finished, and sensors fulfills the project requirement. PRR Review passed and final production started.
- IHEP AC-LGAD R&D chip has been designed and studied. Spatial resolution: <10um, timing resolution: <40ps
- LGAD has potential for X-ray detection due to its good timing performance and S/N advantage for low energy x-ray, be studied by many light sources.
- Studies need to be done to optimize the LGAD sensor performance, make it more suitable for X-ray application. (Simulation, design, fabrication, testing, readout board and ASIC, bonding…)

    Small pixel size, efficiency, low energy → new design of AC-LGAD and inversed LGAD

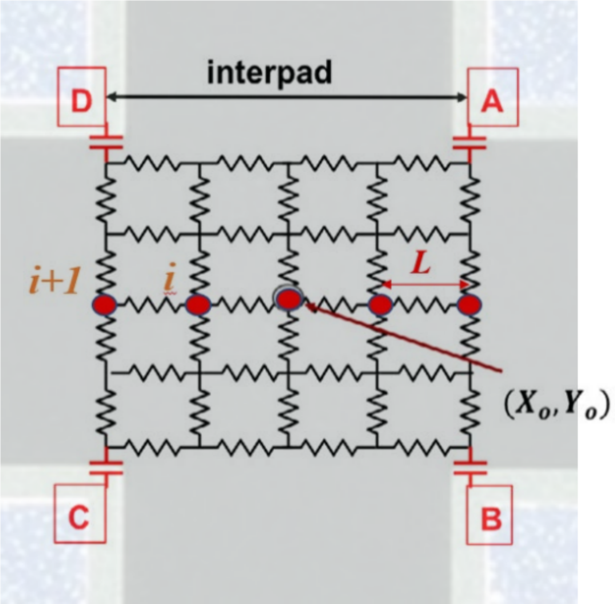
    Sensor bonding with ASIC, its performance

Collaboration is warmly welcome.

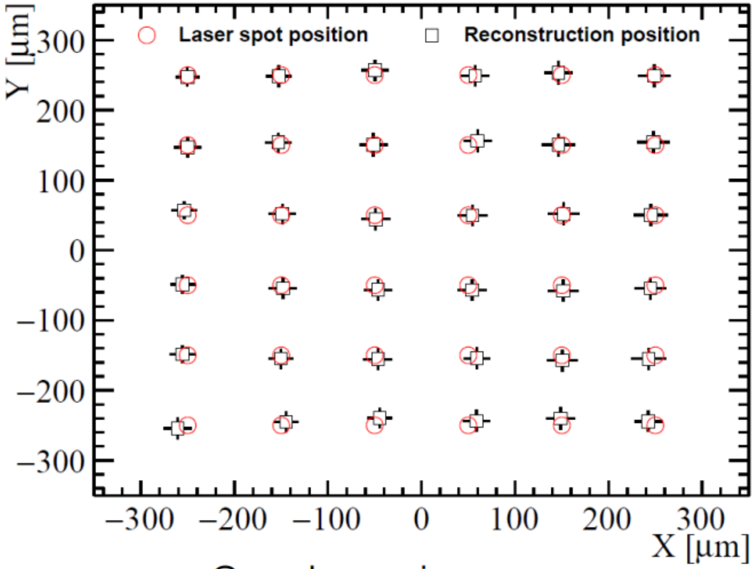
Mei Zhao, zhaomei@ihep.ac.cn

Backup

ASIC： TWEPP 2024 Topical Workshop on Electronics for Particle Physics (30 September 2024 - 4 October 2024): An ASIC for ToF-PET application with MCP-PMTs · Indico

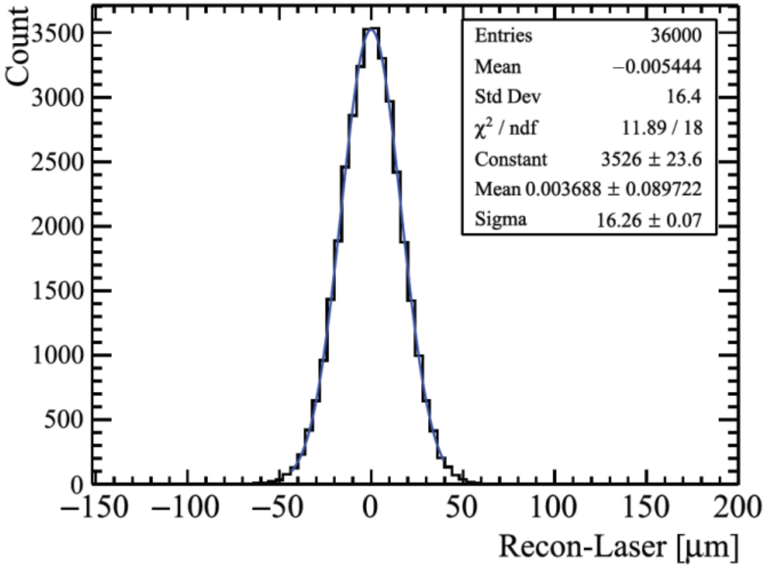


reconstructed 6x6 positions



Good consistency

Spatial resolution：reconstruction - laser



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

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

Correction factor: k_x k_y

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

Discretized Positioning Circuit model (DPC)

Spatial resolution：

- the sigma of the difference between the laser and the reconstructed position

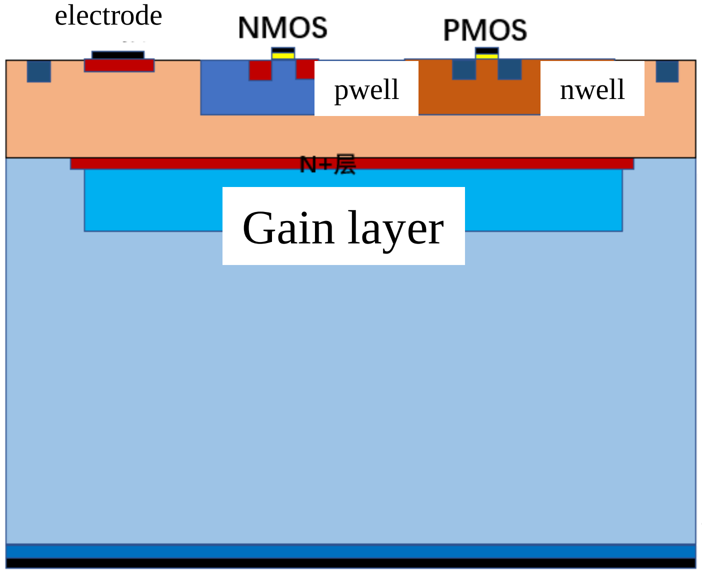
$$\sigma_{spatial} = \sigma_{reconstruction-laser}$$

Discretized Positioning Circuit model
Machine learning method ongoing

Monolithic LGAD

- Monolithic LGAD: Fermilab, University of Geneva, CERN, INFN, CNM, FBK…

MAPS detector timing information: 10ns→ < 50ps **Bonding cost, and also material budget reducing**



EPI layer
Electronic circuit

LGAD sensor for charge multiplication and sensing

Backside p+ layer, metal

Monolithic silicon sensors with very high time resolution will enable making 4D measurements better and in a single and cost-effective silicon tracker, and will also influence how future particle-physics experiments will be designed and constructed.

---G. Iacobucci et al 2022 JINST **17** P10040

- Monolithic LGAD:

	sites	node	Pixel size	Timing
MonPicoAD	University of Geneva, CERN	130nm SiGe	25x25 um^2	25ps
miniCACTUS	IRFU, IFAE	150nm Si	0.5x1 mm^2	65ps
Madpix	INFN	110nm Si	250 x 100 μm^2	75ps