Research of radiation-resistant LGAD sensors for ATLAS High Granularity Timing Detector

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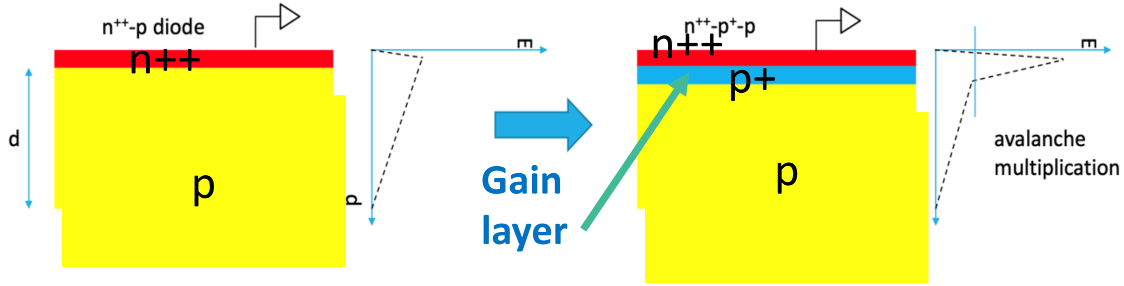
Content

- LGAD & ATLAS HGTD
- IHEP-IME LGAD sensor R&D
- Outlook & Summary

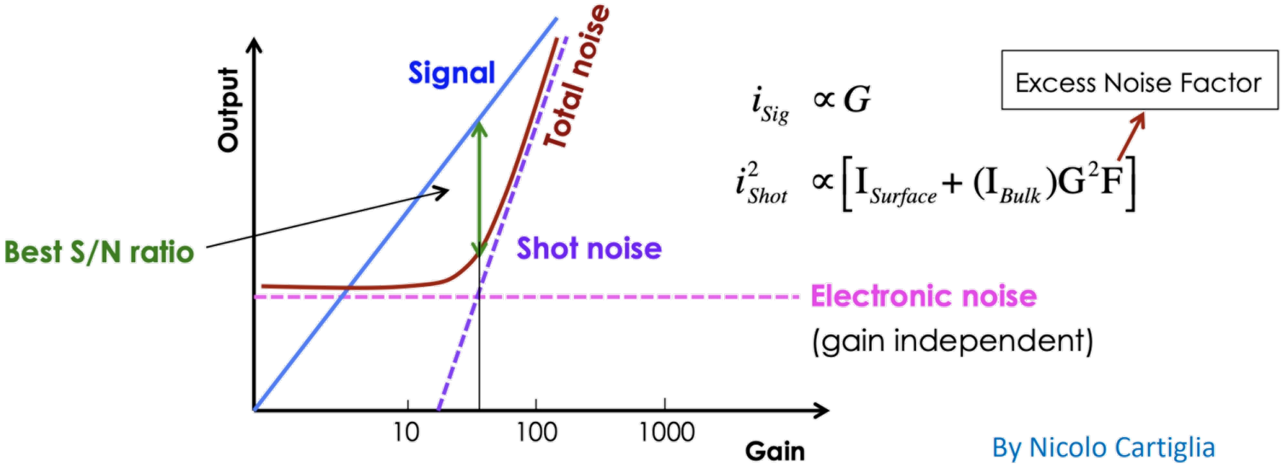
LGAD detector

- **Low Gain Avalanche Detectors (LGAD)** is a silicon detector technology developed recently, that could measure the particle time at ps precision (~30ps).

- 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)



- **Owning to its good performance, LGAD technology is chosen as detector for ATLAS HGTD and CMS ETL project.**



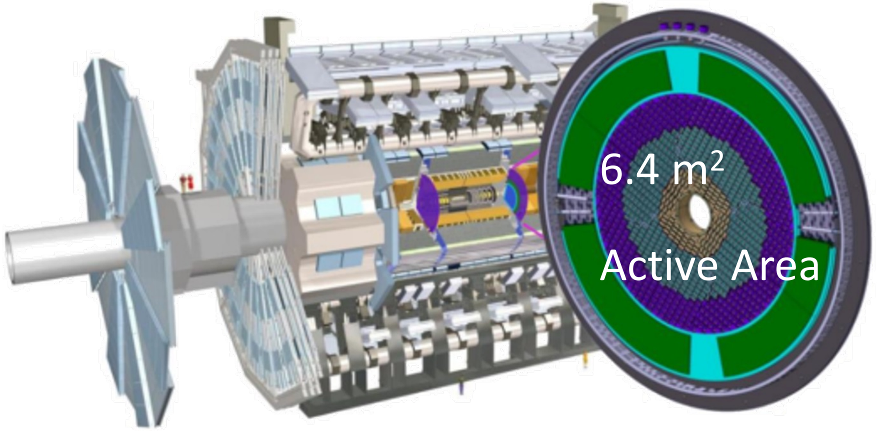
Noise increases faster than then signal

→ the ratio S/N becomes worse at higher gain

https://doi.org/10.1201/9781003131946

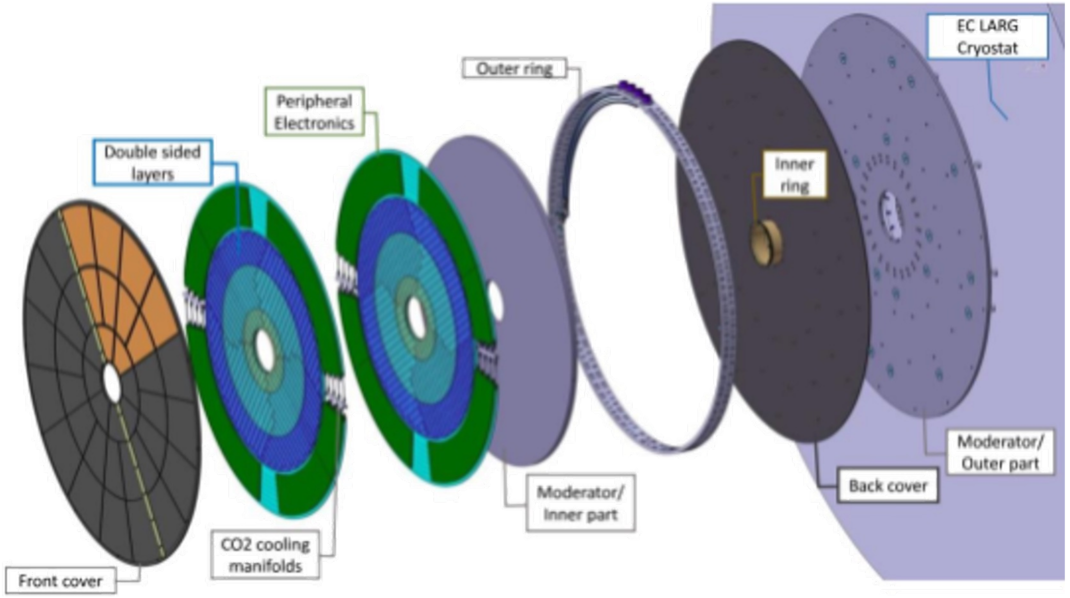
HGTD detector

- At High Luminosity –LHC:
  - Instantaneous luminosity up to **7.5×10^{34} cm^{-2}s^{-1}**
  - **Pileup**: $<\mu>$= 200 interactions per bunch crossing ~1.6 vertex/mm on average
- Timing information can be used to reduce pile-up and improve object reconstruction
- A High Granularity Timing Detector (HGTD) is proposed in front of the Liquid Argon end-cap calorimeters for pile-up mitigation
  - Combining HGTD high-precision time measurement and ITk position information (vertices longitudinal impact parameter)
  - Will improve performance in the forward region
  - In addition, will provide a direct measurement on the luminosity



- ~3.6 million 1.3$\times$1.3 mm^2 pixels(channels)
- Time resolution target
  - 30-50 ps /track
  - 35-70 ps/hit up to 4000fb^{-1}

- **Two end-caps**
  - z ≈ ±3.5 m, Total radius: 11 cm < r < 100 cm
  - Active detector region: 2.4 < |η| < 4.0



LGAD sensor for HGTD

- ~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})

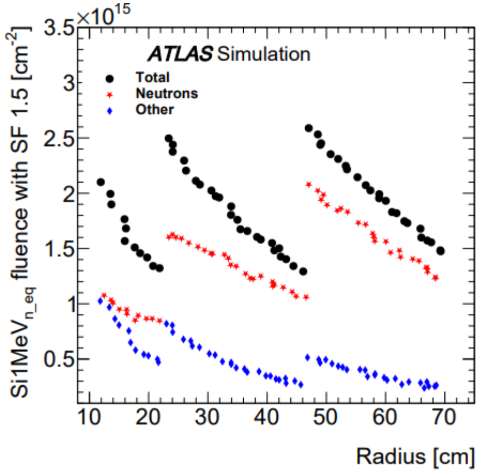
•Time resolution: 35 ps (start), 70 ps (end) per hit, while 30 ps (start), 50 ps (end) per track

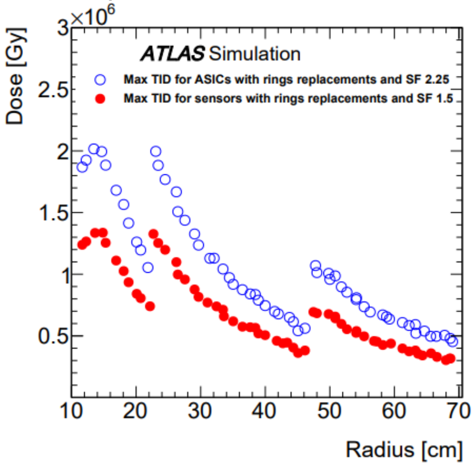
•Collected charge per hit >4 fC (minimum charge needed by the ASIC to hold good time resolution)

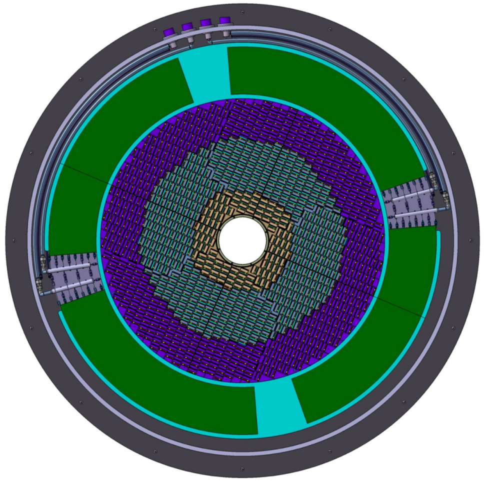
•Hit efficiencies of 97% (95%) at the start (end) of their lifetime

Replacement of inner ring every 1,000 fb^{-1} and middle ring at 2,000 fb^{-1}

Maximum fluence with replacements

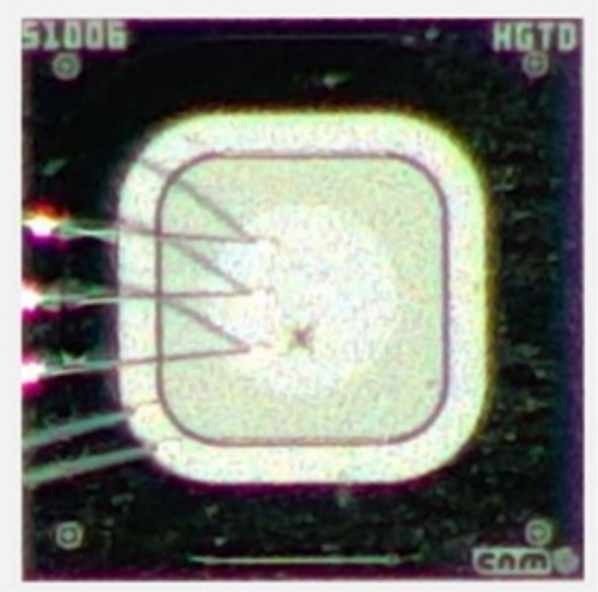




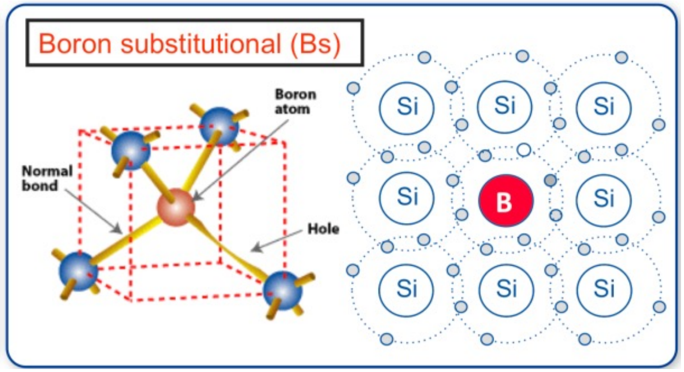


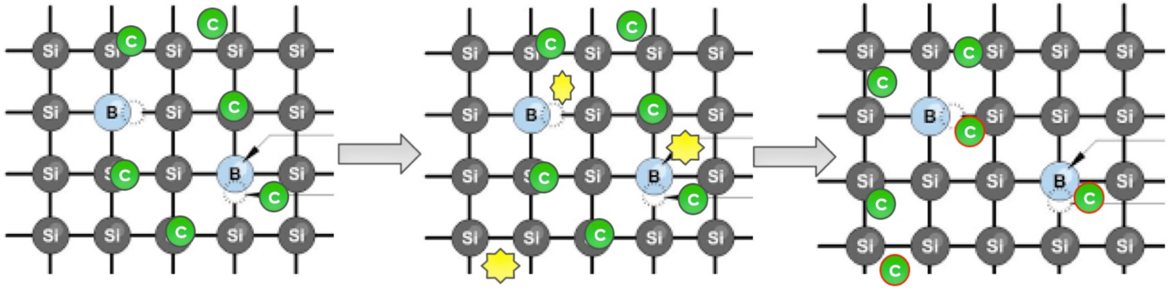
LGAD sensor for HGTD

- To improve the irradiation hardness of LGAD sensors
- IHEP USTC FBK: optimized the doping concentration
  adding the Carbon to gain layer
- Requirement of charge collection and time resolution is determined, and gets better with the increase of bias voltage
- Carbon enriched sensors show very low acceptor removal coefficient($1\text{-}2\times10^{-16}\ cm^2$),which would reduce the required voltage for enough charge collection and avoid the SEB



Single Event Burnout (SEB)
At high working voltage





Irradiation Hardness Reinforcement by Carbon Doping：

✓ LGAD forms defects after irradiation, and the boron in the gain layer moves

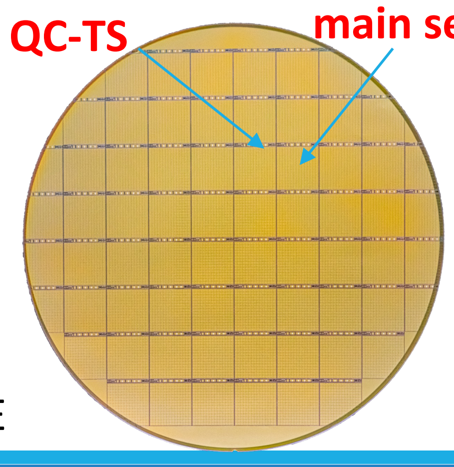
✓ Carbon is more active than boron, carbon fills the defective area, boron is not easily lost

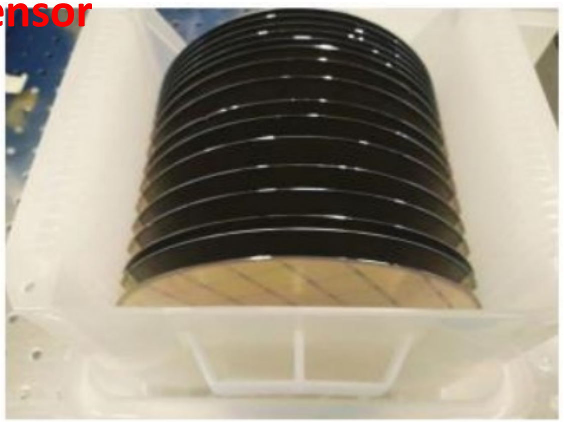
ATLAS HGTD sensor status

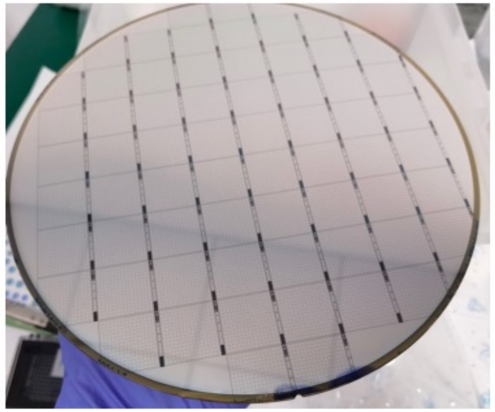
- LGAD sensors for HGTD project: ~21,000
  - IHEP design:90%
  - USTC design:10%

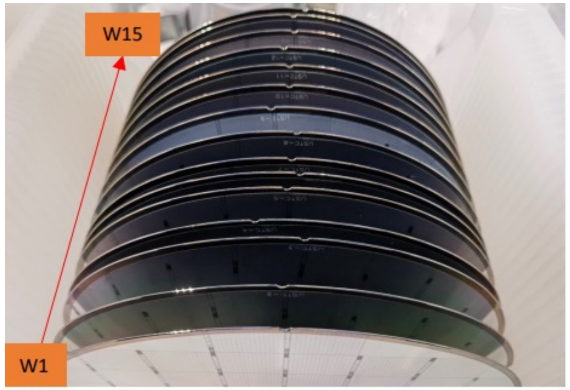
Vendor		Percent
IHEP-IME	CERN	54%
	China in-kind	24%
	Spain in-kind	12%
USTC-IME	China in-kind	10%

- 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 sensors properties fulfill HGTD specification.









IHEP-IME

USTC-IME

ATLAS HGTD sensor status Pre-Production

- Acceptance of sensors has been set up based on pre-production results
- 117 wafers have been fabricated
- About 1000 good sensors are checked in this phase
- Production Readiness Review passed on July 25,2024
- Final production started after the PRR

Table 4: Required electrics properties of produced Sensors at room temperature (applies also to irradiated sensors, ¤for irradiated sensors at -30°C)*

Pad leakage current (V_{bd} condition)	< 500 nA
Break-down voltage (V_{bd})	$V_{bd} > V_{fd} + D \cdot 2$ V/µm
Device total leakage current	< 20 µA/cm^2 at bias voltage $< V_{bd}$
$V_{gl,pad}$ spread over the Sensor*	$RMS(V_{gl,pad})/\langle V_{gl,pad}\rangle < 0.005$
$V_{bd,pad}$ spread over the Sensor*,¤	$RMS(V_{bd,pad})/\langle V_{bd,pad}\rangle < 0.05$
Pad leakage current spread at $0.8 \cdot V_{bd}$	Peak-to-Peak within a factor of 3x
Variation of the V_{fd} between different sensors	±10% from the average V_{fd}
Variation of the V_{gl} between different sensors	±1% from the average V_{gl}
Variation of the V_{bd} between different sensors	±8% from the average V_{bd}

Over one sensor (Break-down voltage through $V_{bd,pad}$ spread)

Among sensors (Pad leakage current spread through Variation of the V_{bd})

Pre-production	Wafers		Sensors		
	IHEP-IME	USTC-IME	IHEP-IME	USTC-IME	Total
Fabricated	90	27	4680	1404	6084
Passing preproduction requirements	52	13	1702	208	1910
Pre-production with UBM, diced and tested by HGTD	23	5	789	118	907

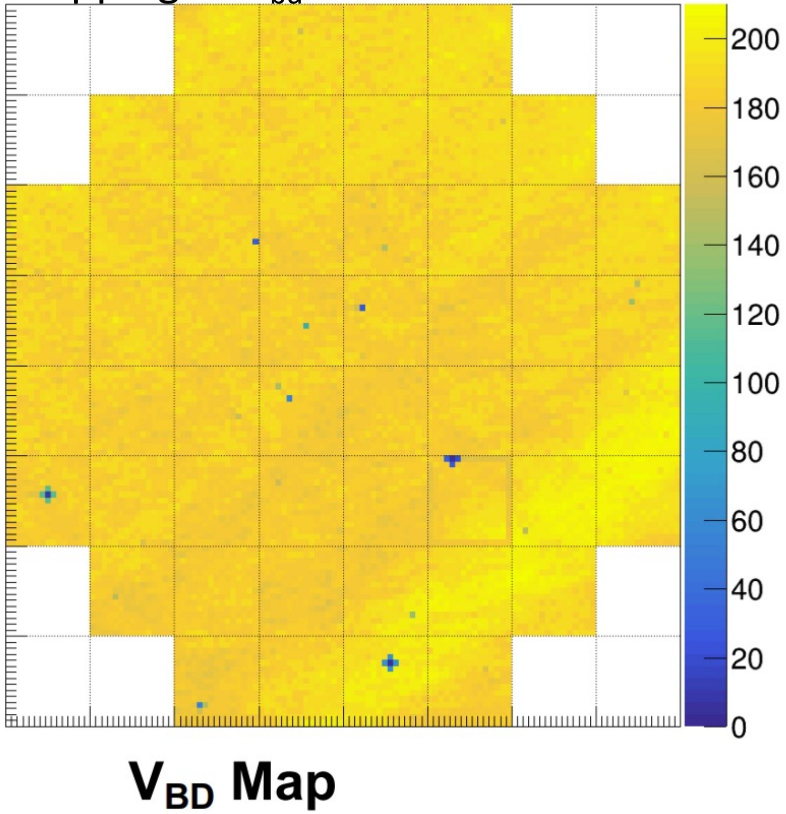
ATLAS HGTD sensor status

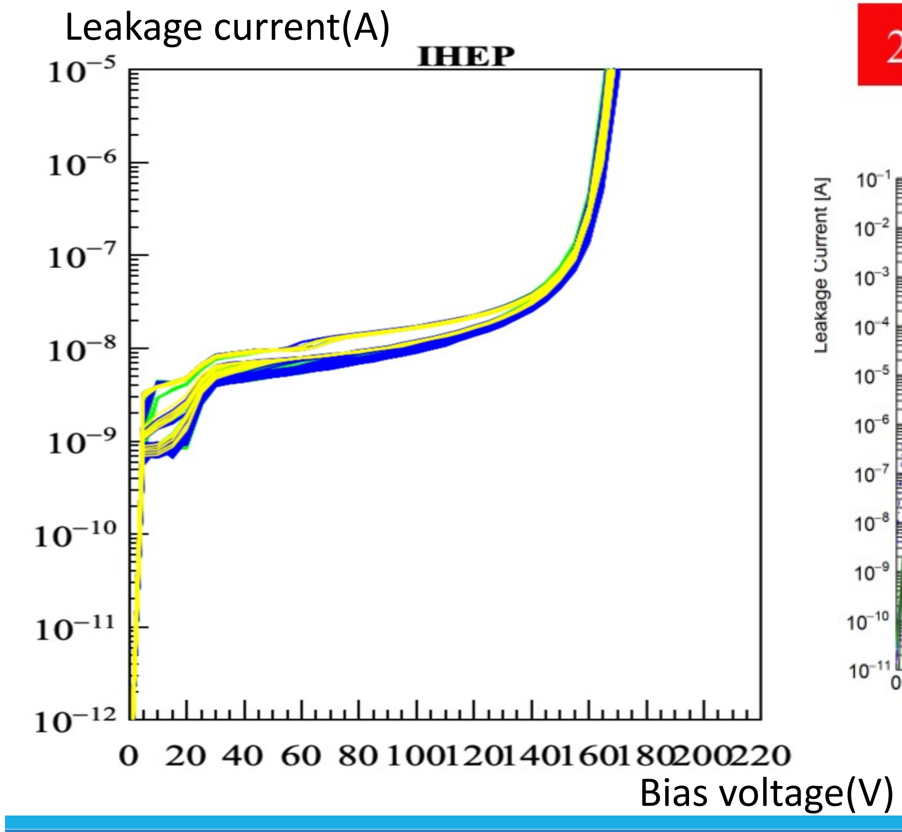
- **The 15x15 array sensors have good IV performance and uniformity**

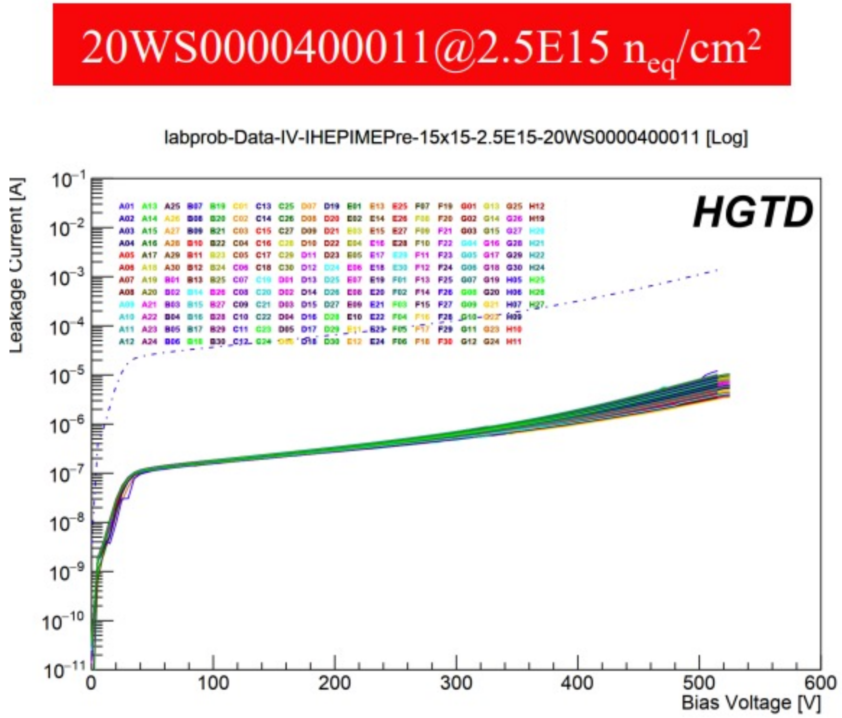
  Breakdown voltage deviation for 225 pads is less than 5%： RMS($V_{bd,pad}$)/<$V_{bd,pad}$> < 5%

  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



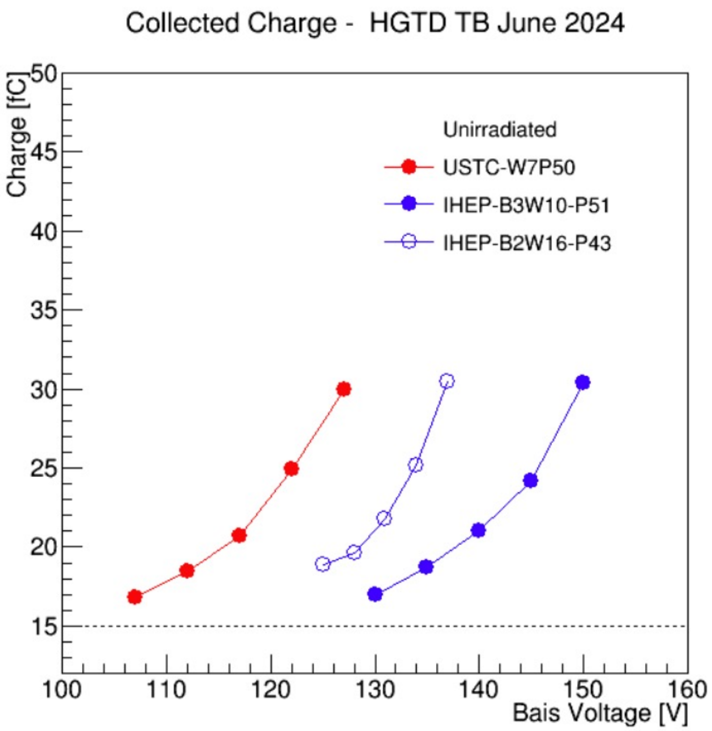




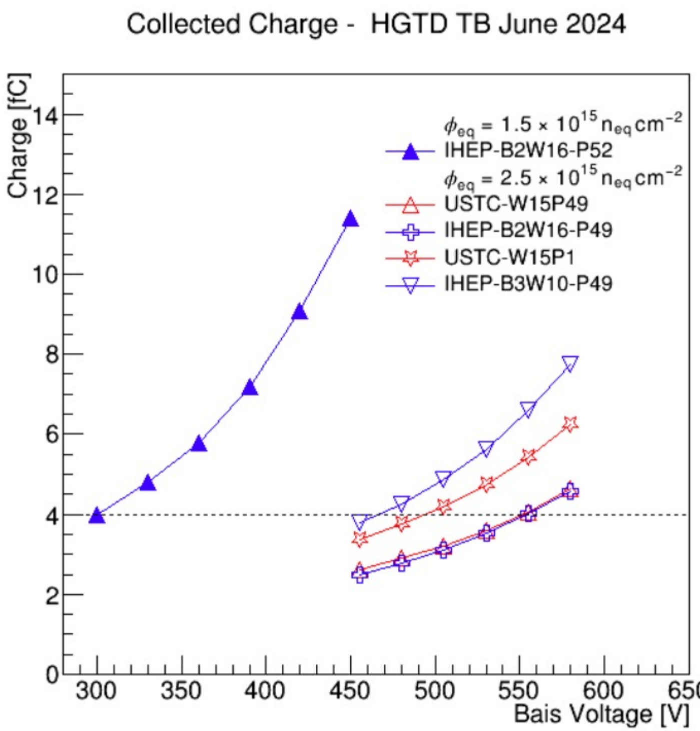
ATLAS HGTD sensor status

Performance of pre-production sensors: Beam test results

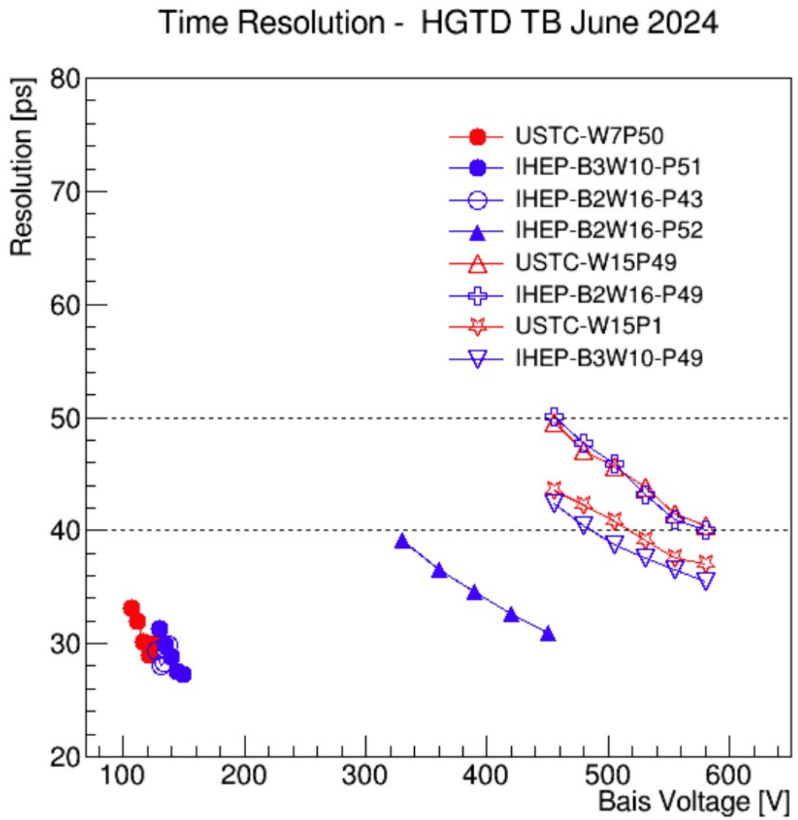
- Collected charge： The sensors can collect more than 15 fC charge before irradiation and >4 fC charge after irradiation at bias voltage <550 V (SEB limit)
- Timing resolution: The timing resolution is better than 35 ps (50 ps) before(after) irradiation(fluence 2.5×10^{15} n_{eq}/cm^2)
- The collected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



unirradiated sensor

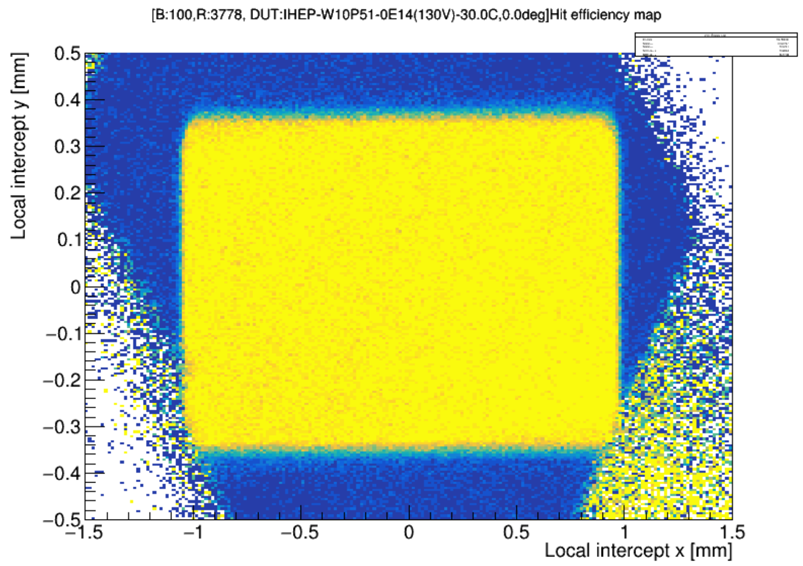


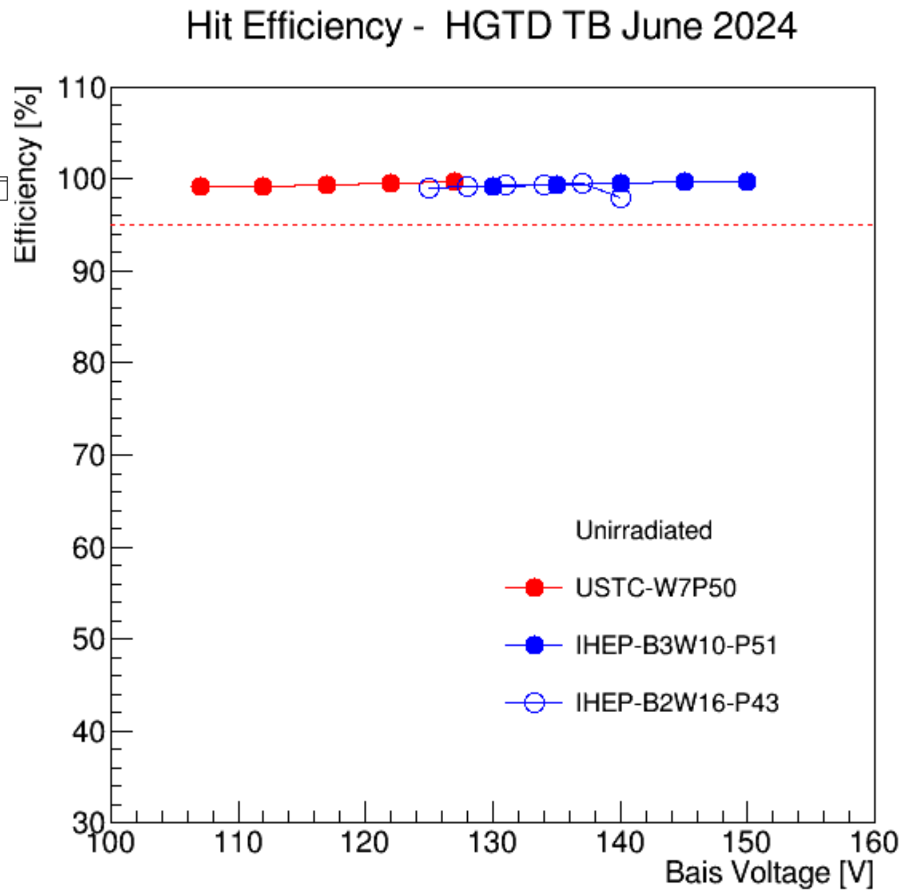
irradiated sensor

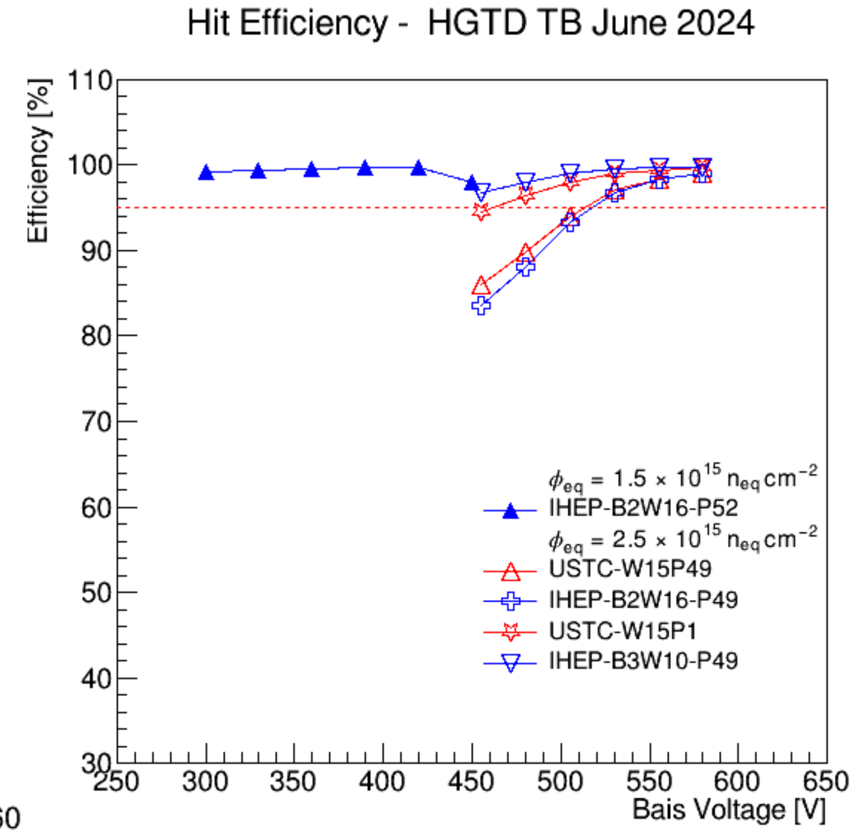


ATLAS HGTD sensor Beam Test

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

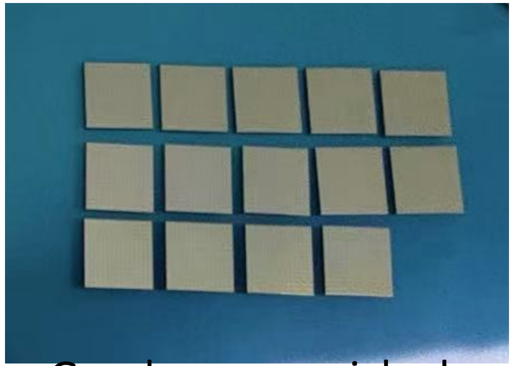




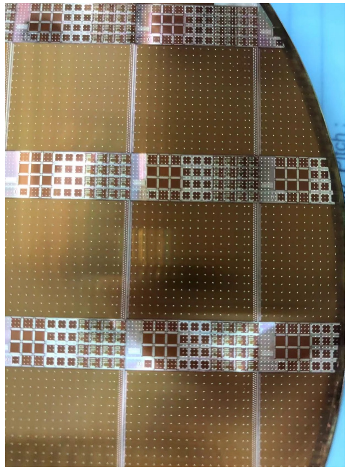


ATLAS HGTD sensor status (Module)

- LGAD sensors are connected with ASIC (Altiroc) chip using bump bonding
- Then two hybrids are placed on module flex(one module), the module is supported by support unit

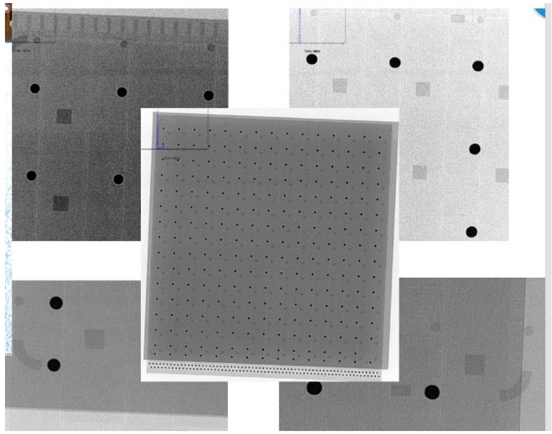


Good sensors picked



Altiroc wafer with ball for bump bonding

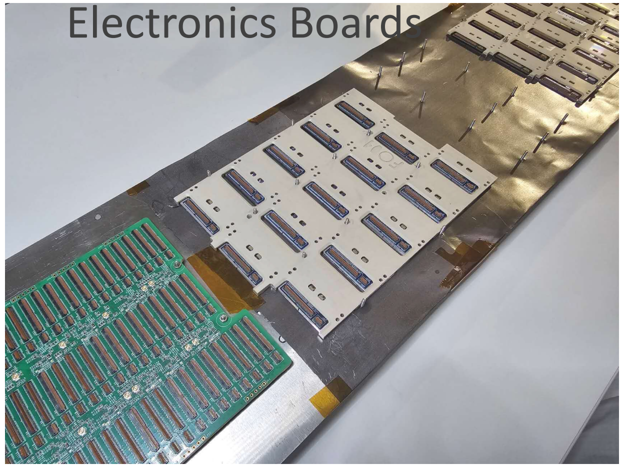
X-ray image of hybrid

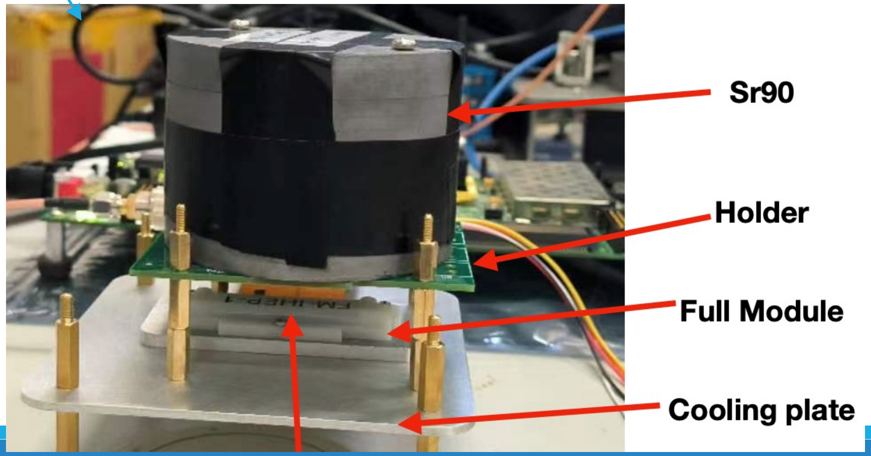


Module flex

Module on support unit

Connected to Peripheral Electronics Boards

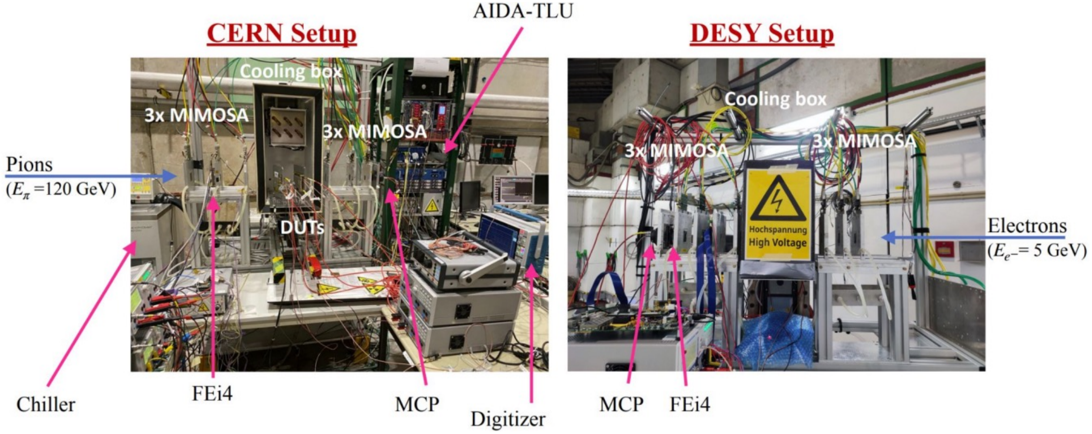


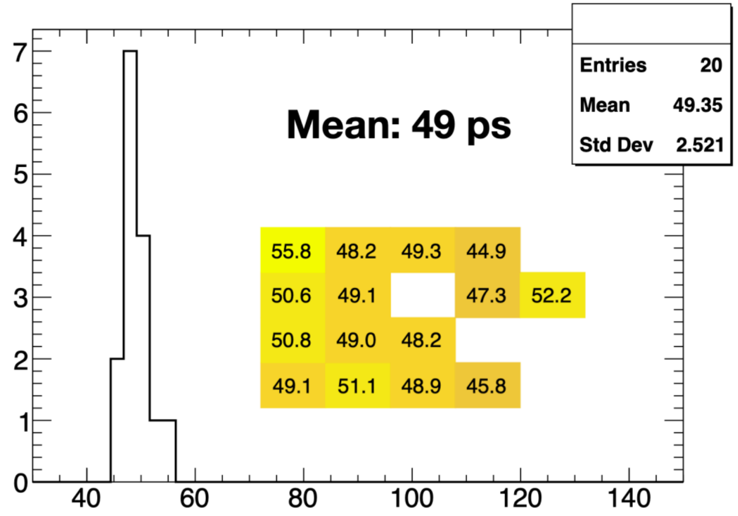


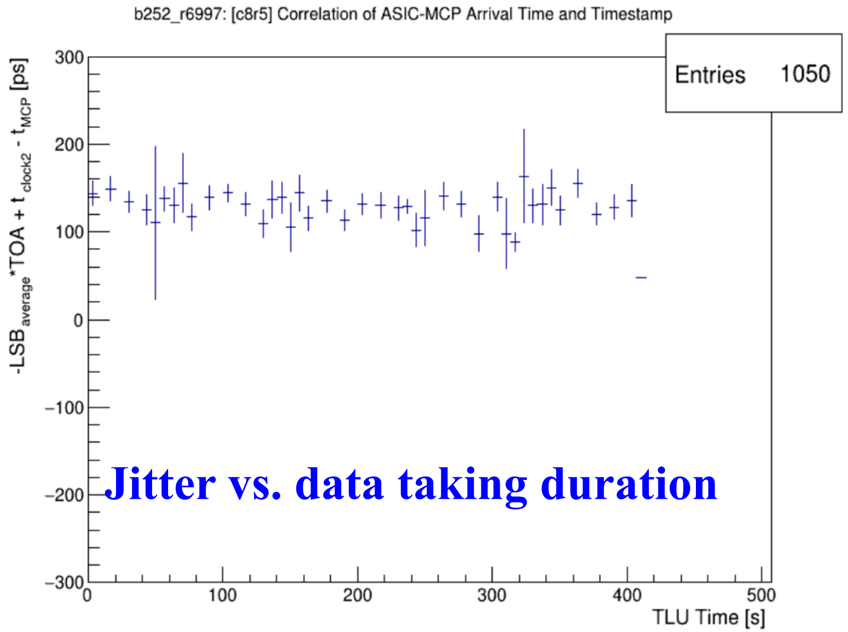
ATLAS HGTD sensor Beam Test

Pre-production LGAD Sensor + ALTIROC-A (ASIC) hybrids Tested at SPS

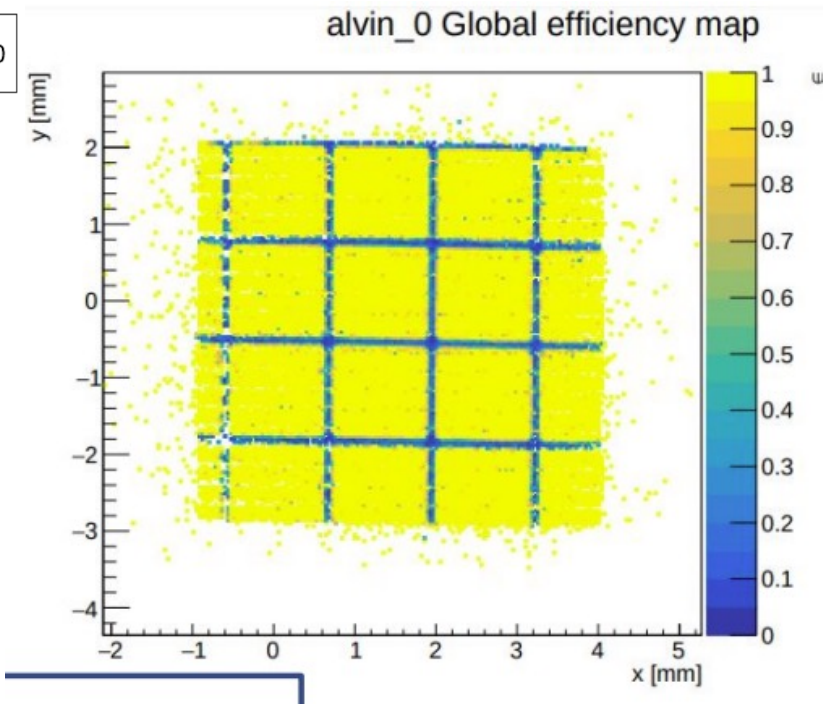
- **Timing resolution can reach 50 ps for the sensor/ASIC module**
- **The efficiency is larger than 98%**
- **Long term stability is proved**



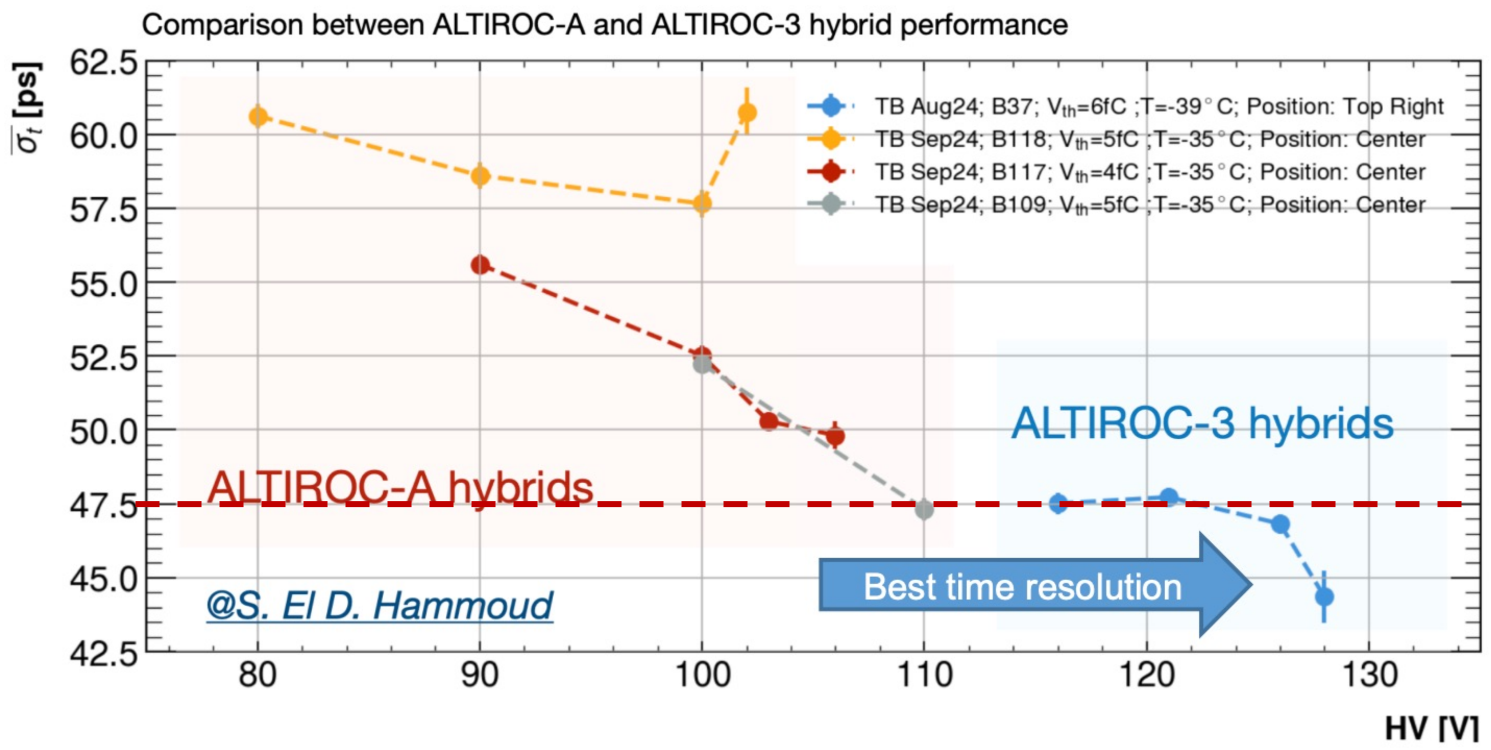


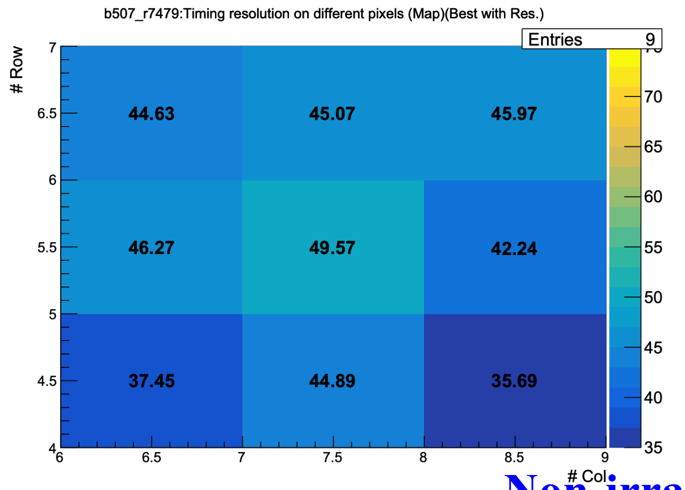


Jitter vs. data taking duration

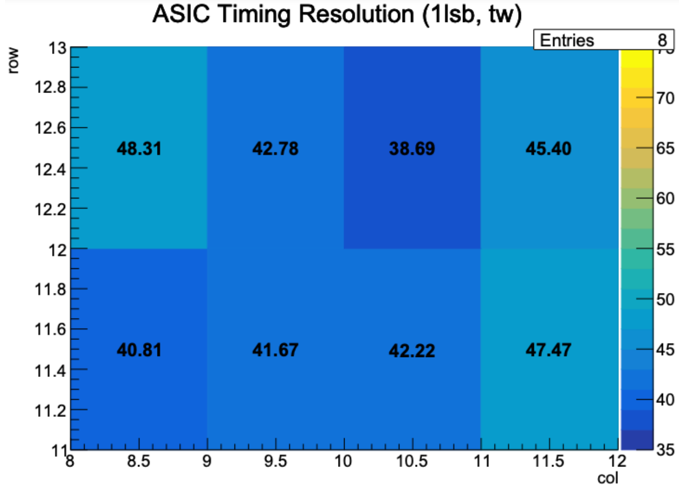


ATLAS HGTD sensor Beam Test





Non-irradiated

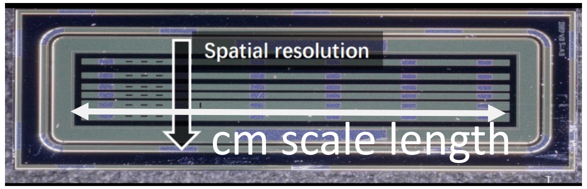


2.5E15 Neutron irradiation

- 47.5 ps of timing resolution is achieved !
- Good homogeneity among modules
- No significant change is observed after irradiation

And beyond: AC-LGAD as timing detector

AC-LGAD microstrip sensor is the choice for CEPC OTK baseline to provide both spatial resolution (bending direction) and timing resolution.

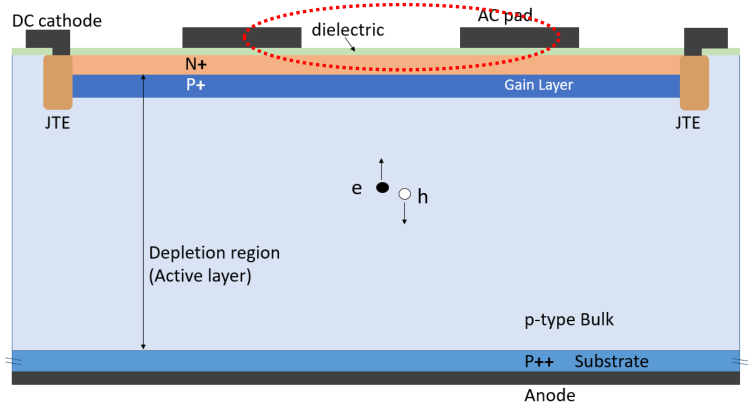


The outer silicon tracker (OTK) requirement：

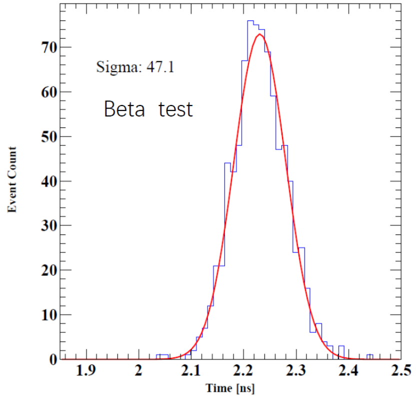
- Spatial resolution: 10 µm (with a strip pitch of 100 µm)
- Time resolution: 30-50 ps

AC-LGAD (AC-coupled LGAD)

Continuous gain layer

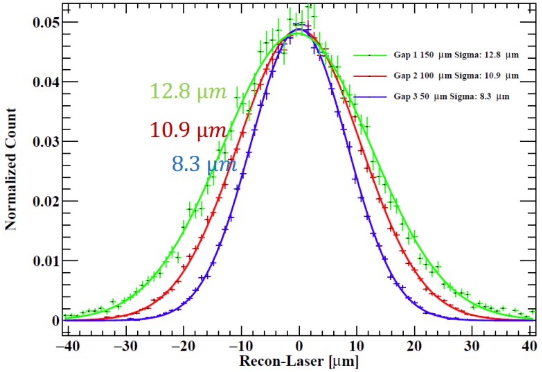


- metal AC readout electrode and a thin dielectric layer (Si_3N_4, SiO_2) above the N+ layer
- Less dead area and better position resolution
- Research institute: FBK, HPK,INFN, BNL, CNM, USTC, IHEP…



Time residual sigma: 47.1 ps

Time resolution： 37.5 ps



Pitch 150um：
Best spatial resolution
~8um

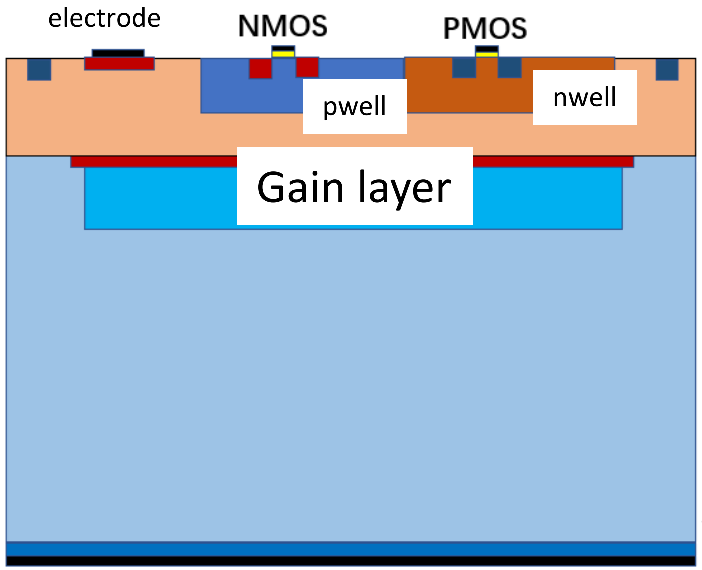
Summary

- LGAD is chosen as detection sensors for HGTD project as it has good time resolution <30ps to improve pile-up.
- Carbon enriched LGAD sensors show good radiation performance. The sensors fill the HGTD requirement, including charge collection, time resolution and hit efficiency.
- For ATLAS HGTD project, LGAD sensors' pre-production is finished, and sensors fulfills the project requirement. Review passed and final production started. Final production is in progress.
- The beam test of module (sensor + asic) reaches a timing resolution of better than 50 ps.
- Further study of AC-LGAD as well as application on the future colliders is ongoing, to make it a 4D detector.

Backup

And beyond: Monolithic LGAD?

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



EPI layer
Electronic circuit

LGAD sensor
for charge
multiplication
and sensing

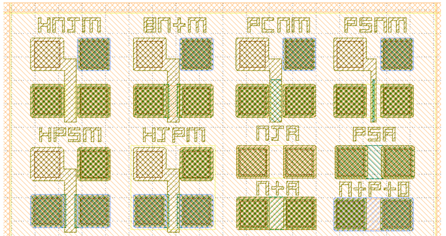
Backside p+ layer, metal

MAPS detector timing information: 10ns→ < 50ps

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

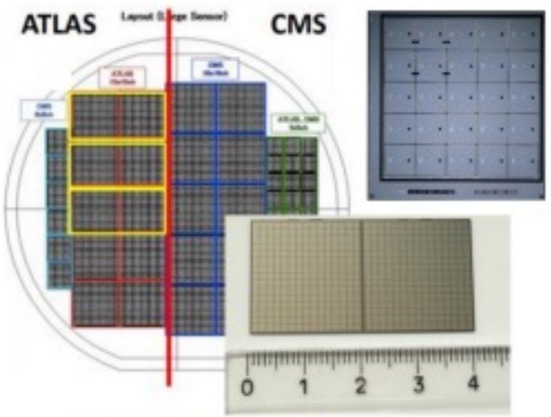
- Researches at IHEP:
  - Simulation by using TCAD tools is ongoing.
  - LGAD with MOSFET transistor be fabricated and tested. Amplifier design ongoing.



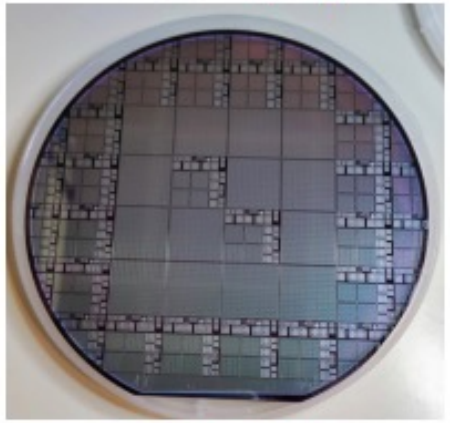
LGAD sensor for HGTD

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

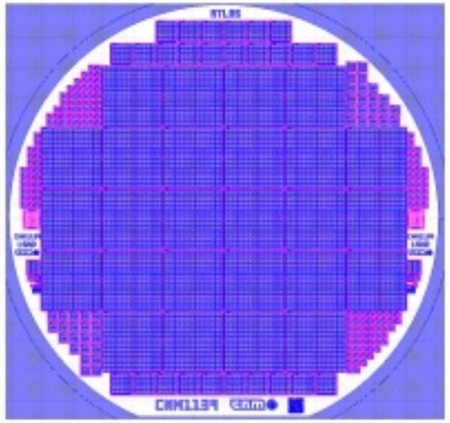
HPK-P2 (2022)



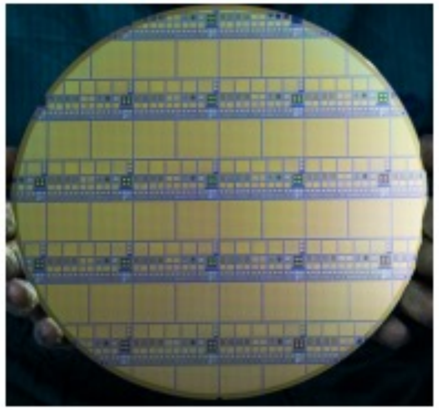
FBK-UFSD 4.0 (2022)



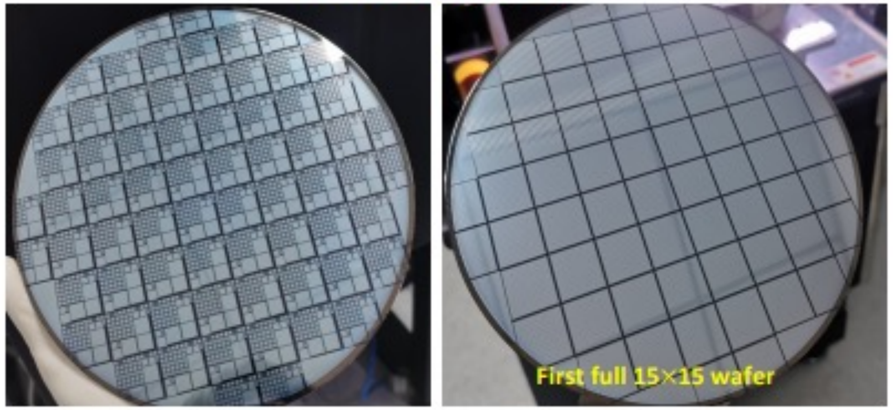
CNM Run 15973 (2022)



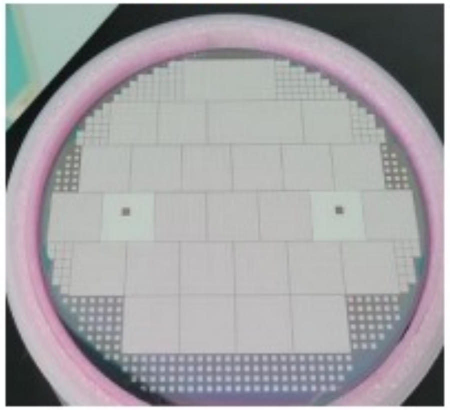
IHEP-IME-v2 run (07/2022)



USTC-IME-v2 (14/2021)



NDL-v4 (2021)

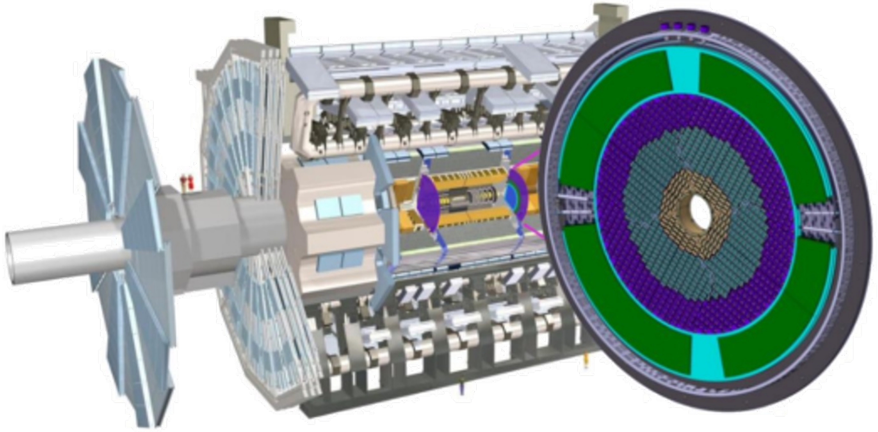


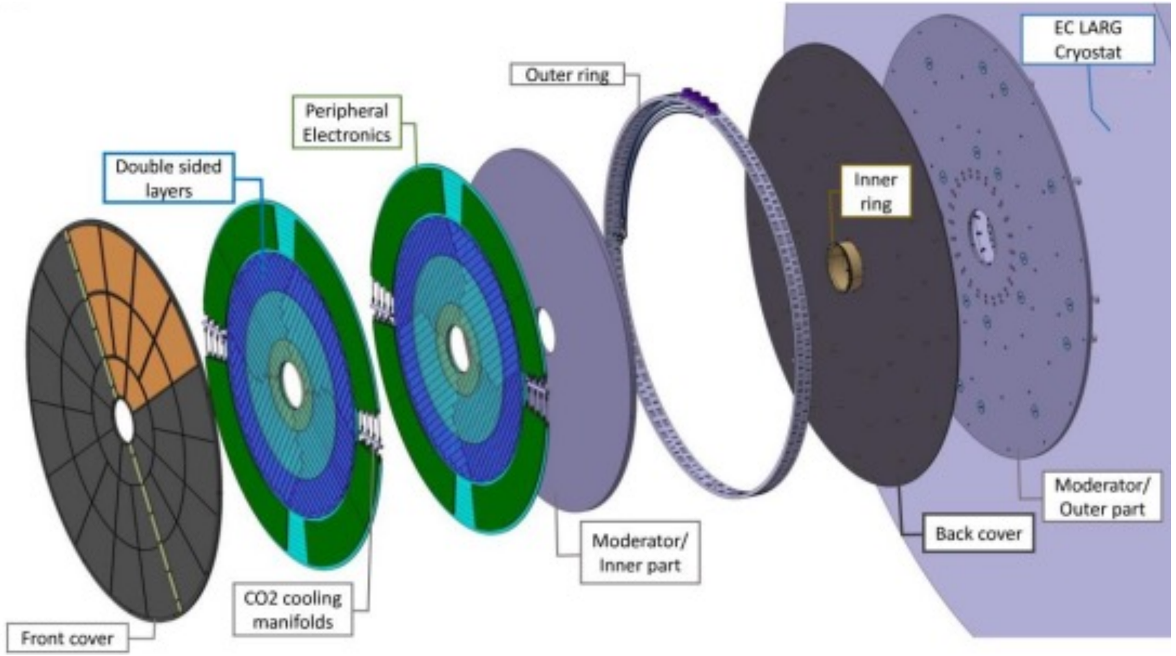
HGTD detector

- The High Granularity Timing Detector (HGTD) is designed to provide precise timing information to mitigate pile-up in HL-LHC.
  - ~3.6 million 1.3×1.3 mm^2 pixels(channels)
    - 6.4 m^2 active area
  - Time resolution target
    - 30-50 ps /track
    - 35-70 ps/hit up to 4000fb^{-1}
  - Luminosity measurement
    - Count number of hits at 40 MHz (bunch by bunch)
    - Goal for HL-LHC: 1% luminosity uncertainty

- **Two end-caps**
  - $z \approx \pm 3.5$ m from the nominal interaction point
  - Total radius: 11 cm < r < 100 cm
  - Active detector region: $2.4 < |\eta| < 4.0$

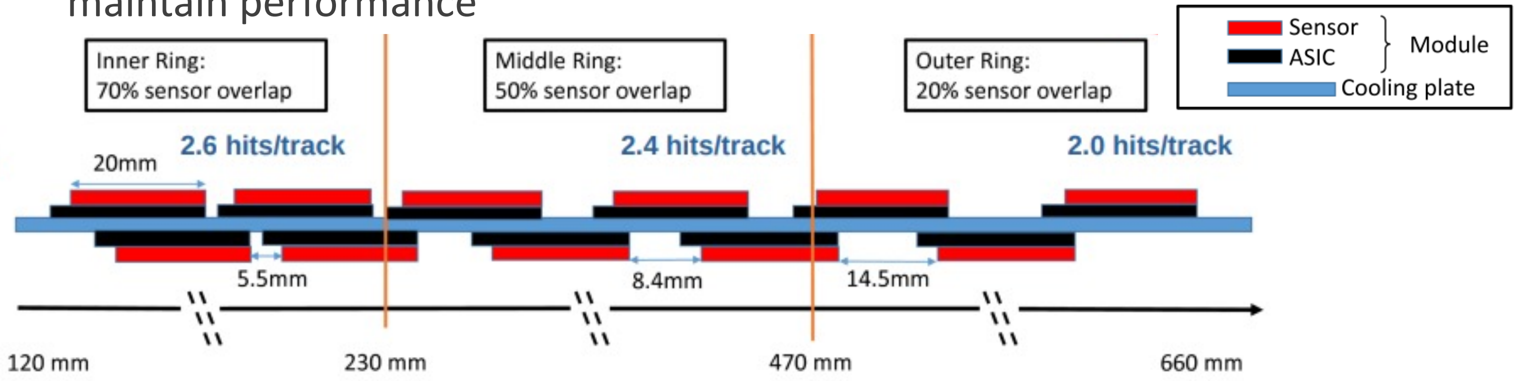
- Each end-cap
  - Two instrumented disks, rotated by 15° for better coverage

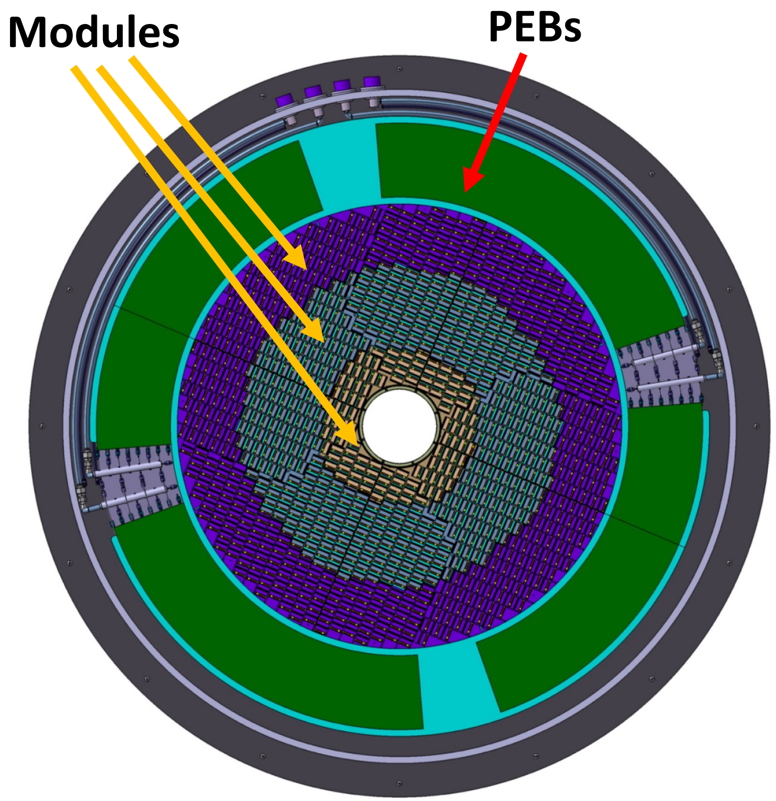




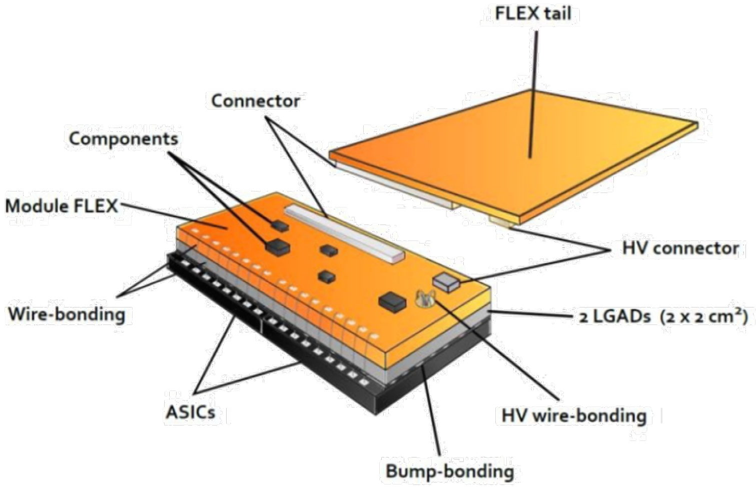
HGTD detector

- **2 disks, each Disk:**
  - Double-sided layers mounted on a cooling plate
  - 3 rings layout regarding to the fluence received
    Overlap between modules on inner, middle and outer ring
  - Replacement of inner ring every 1000 fb^{-1} and middle ring at 2000 fb^{-1} to maintain performance



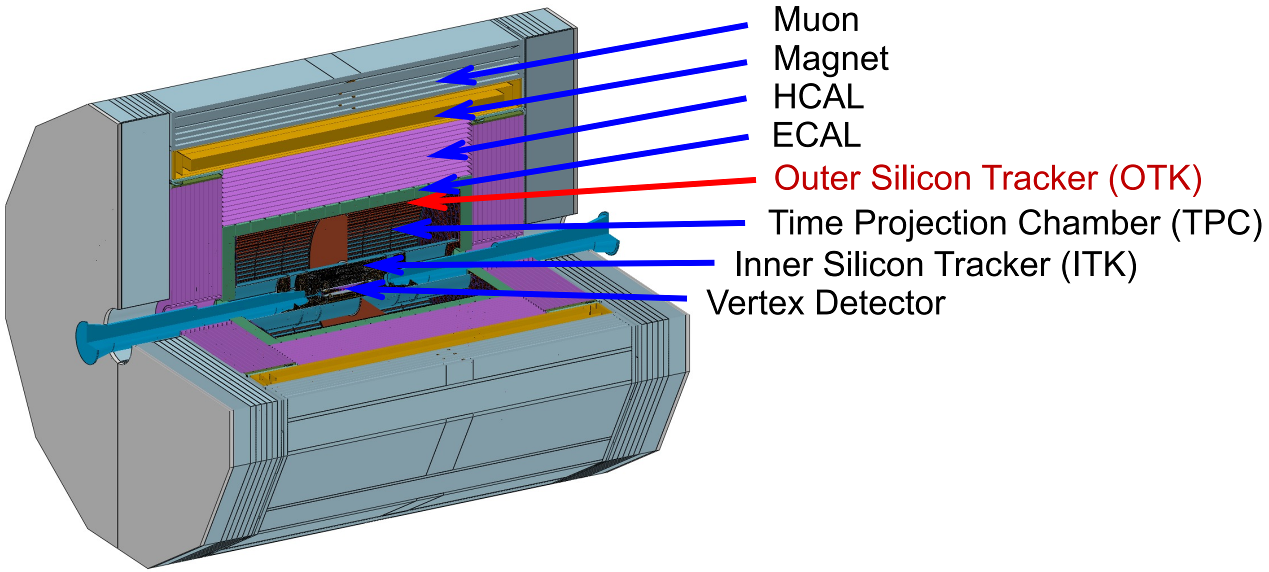


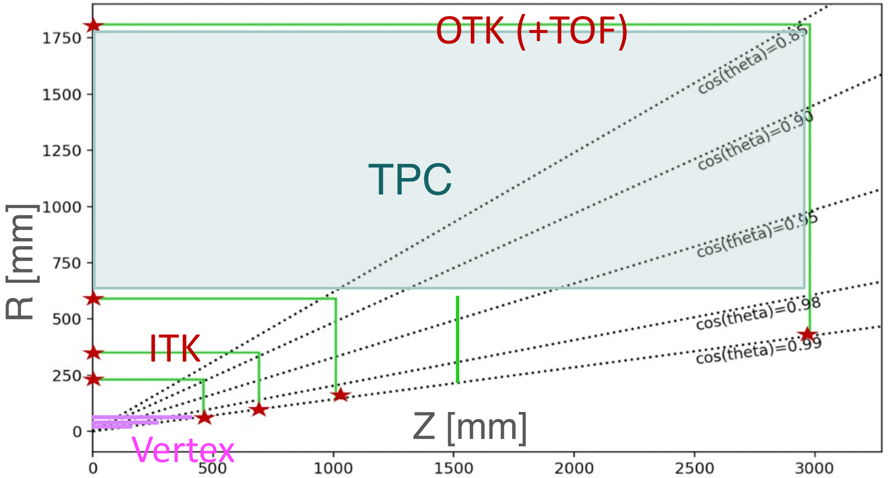
- **8032 modules, each module:**
  - consists of two hybrids
    (2 sensors+ 2 ASICs)
  - 2x4 cm^2, 15x30 channels



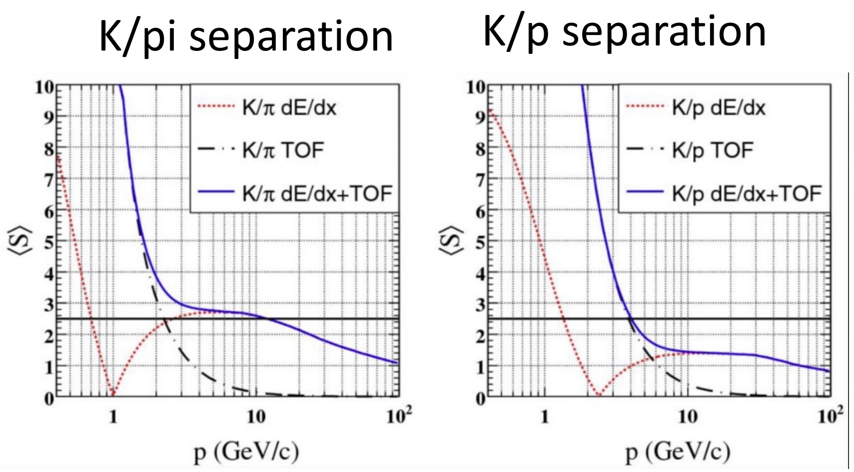
- Two bare modules be connected with one module FLEX
- Module Flex be connected via flex tails, arranged in rows, to the Peripheral Electronics Boards (PEB) @ 660 < r < 920 mm

Future collider: CEPC





- **CEPC**--huge measurement potential for precision tests of SM: Higgs, electroweak physics, flavor physics, QCD/Top
- Produce 10^{12} Z boson at Z pole: Rich flavor physics program
- **The LGAD based OTK (+TOF) detector** will be placed between TPC and ECAL
- 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
- Barrel : 70 m², Endcap 20 m²



AC-LGAD as timing detector

AC-LGAD microstrip sensor is the choice for CEPC OTK baseline to provide both spatial resolution (bending direction) and timing resolution.

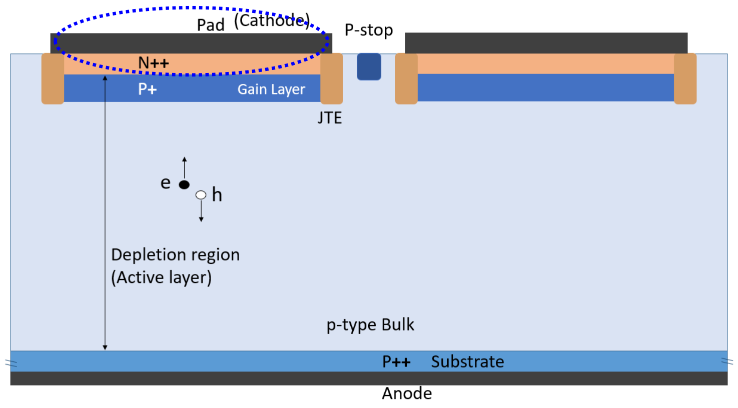
The outer silicon tracker (OTK) requirement：

- Spatial resolution: 10 μm (with a strip pitch of 100 μm)
- Time resolution: 30-50 ps

5cm-9cm length

LGAD (Low-Gain Avalanche Diode)

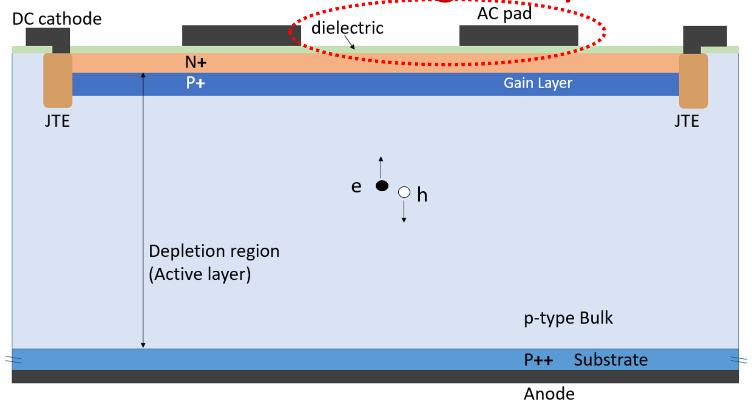
Segmented gain layer



- The read-out electrode is placed and connected to the N++ layer.

AC-LGAD (AC-coupled LGAD)

Continuous gain layer



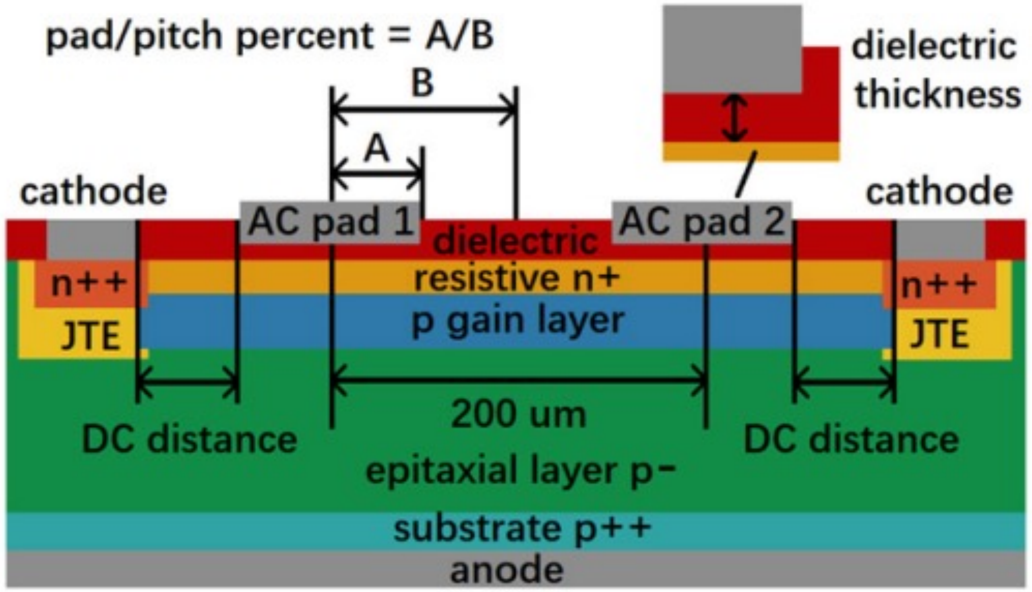
- metal AC readout electrode and a thin dielectric layer (Si_3N_4, SiO_2) above the N+ layer
- Less dead area and better position resolution
- Research institute: FBK, HPK,INFN, BNL, CNM, USTC, IHEP…

AC-LGAD R&D

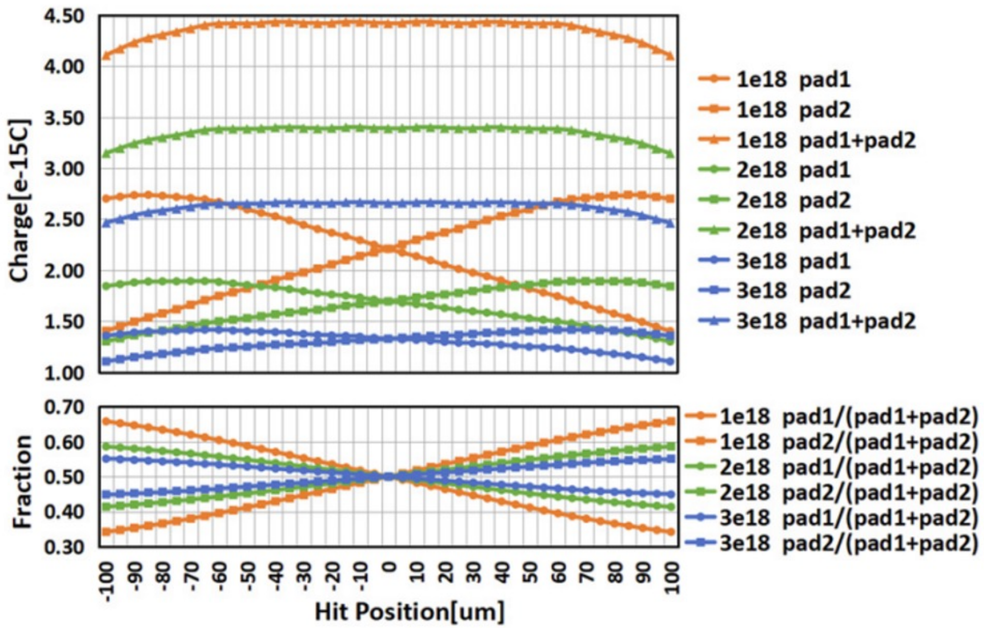
◆ AC-LGAD sensor simulation： **Optimization of process and structure parameters**

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

Structure parameter: pad shape, pad-pitch size



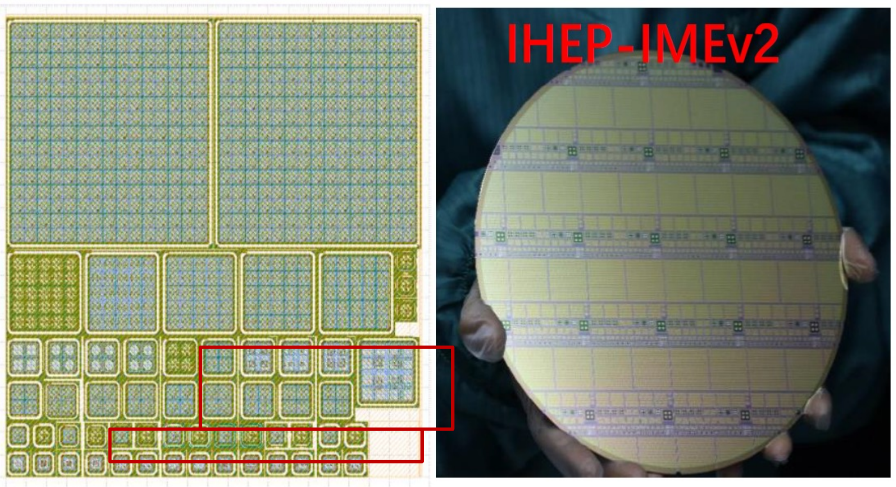
TCAD model of AC-LGAD for simulation

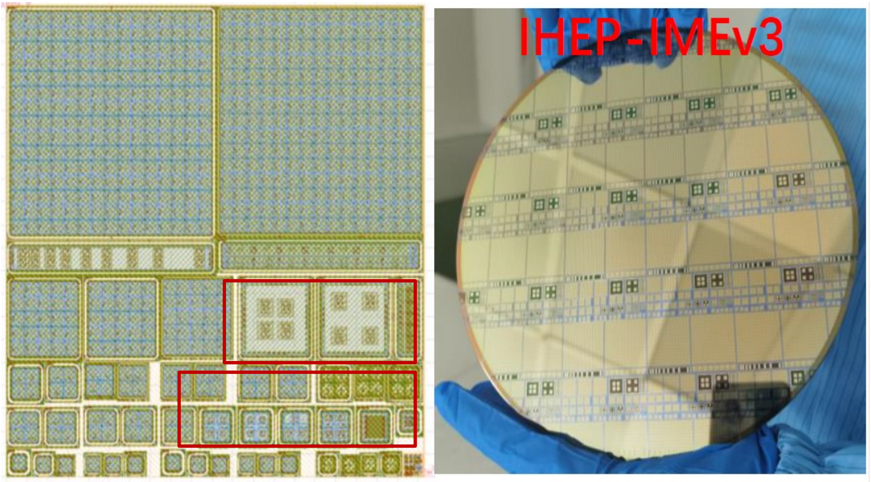


Lower n+ dose→ Large resistivity →good spatial resolution

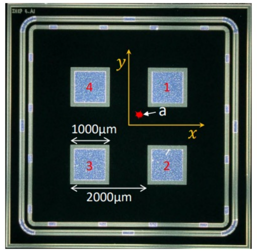
Design of AC-coupled low gain avalanche diodes (AC-LGADs): a 2D TCAD simulation study, JINST, 2022.9, DOI:10.1088/1748-0221/17/09/C09014

AC-LGAD development at IHEP





AC-LGAD R&Dv1:



Pixeled AC-LGAD

- With different pad-pitch size
  1000-2000um
  100-500um
  100-200um
  50-100um
- wafers: with different n+ dose: 10P to 0.2P

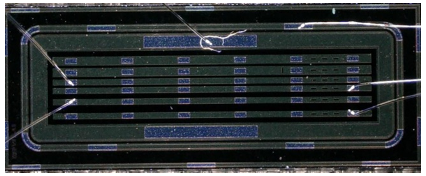
Process parameters be studied.

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

AC-LGAD R&Dv2:

Pixeled and strip AC-LGAD

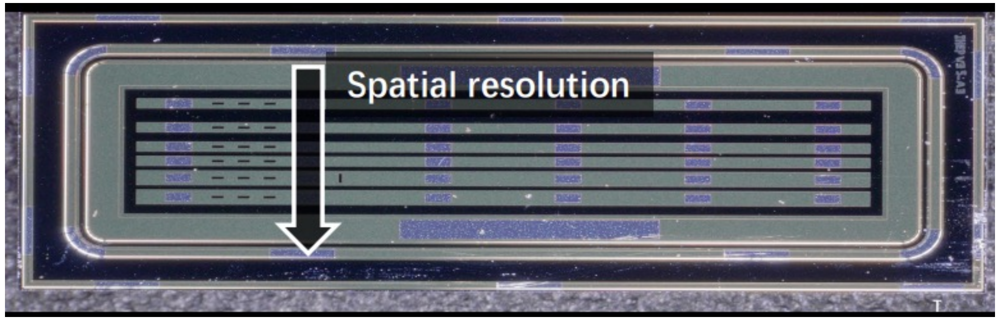
- With different pad-pitch size
  1000-2000um pixel
  100-250um strip
  100-150um strip
  50-100um strip
- wafers: with different n+ dose:0.2P to 0.01P



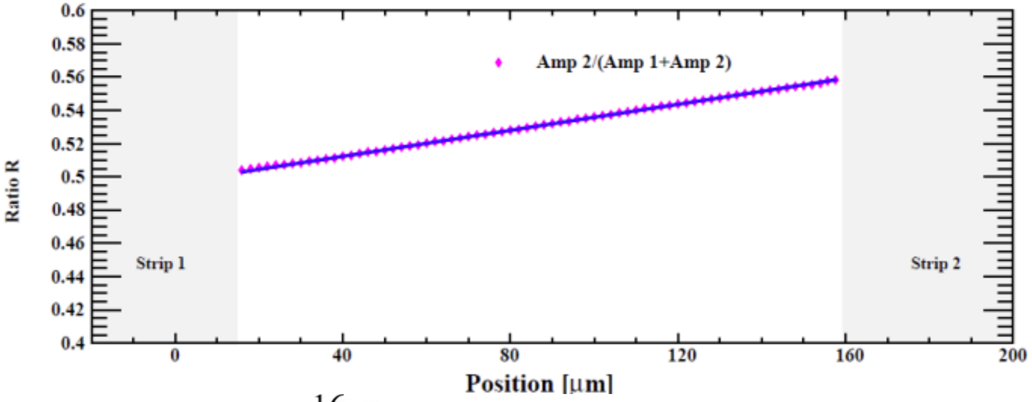
The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

AC-LGAD R&D

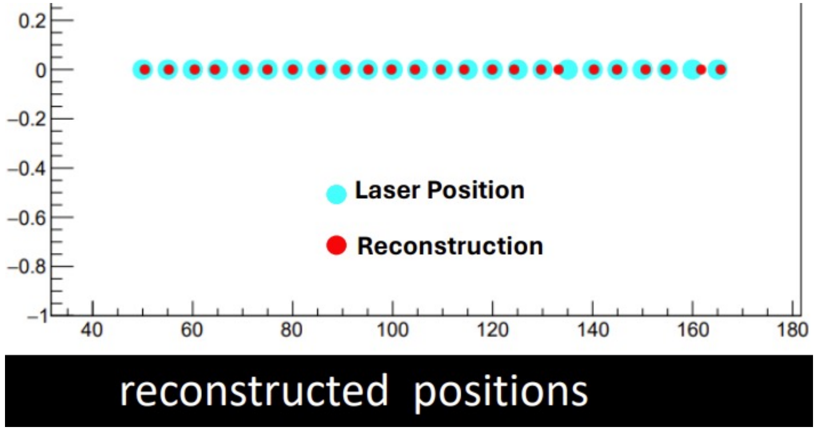
Spatial resolution: Laser testing

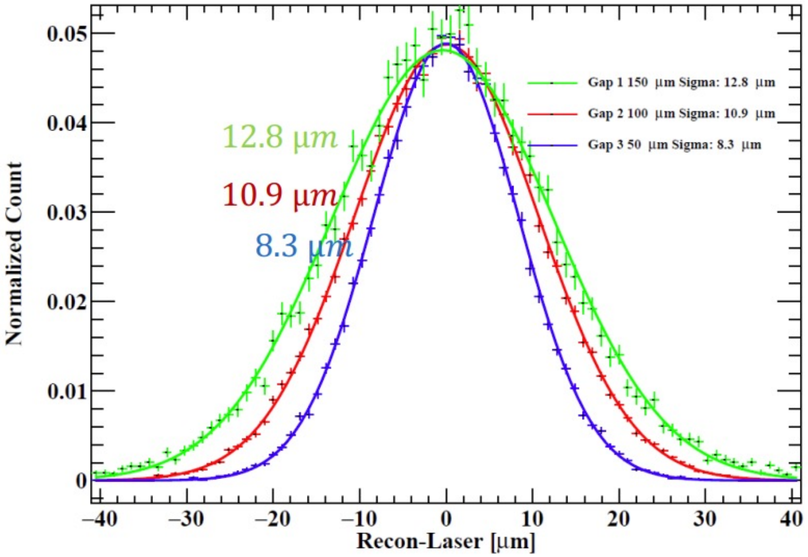


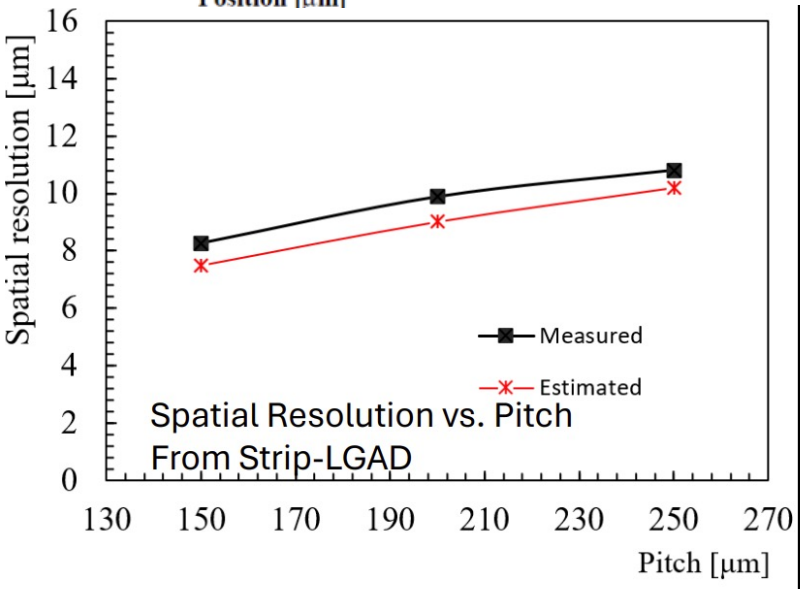
Amplitude information



Position reconstruction





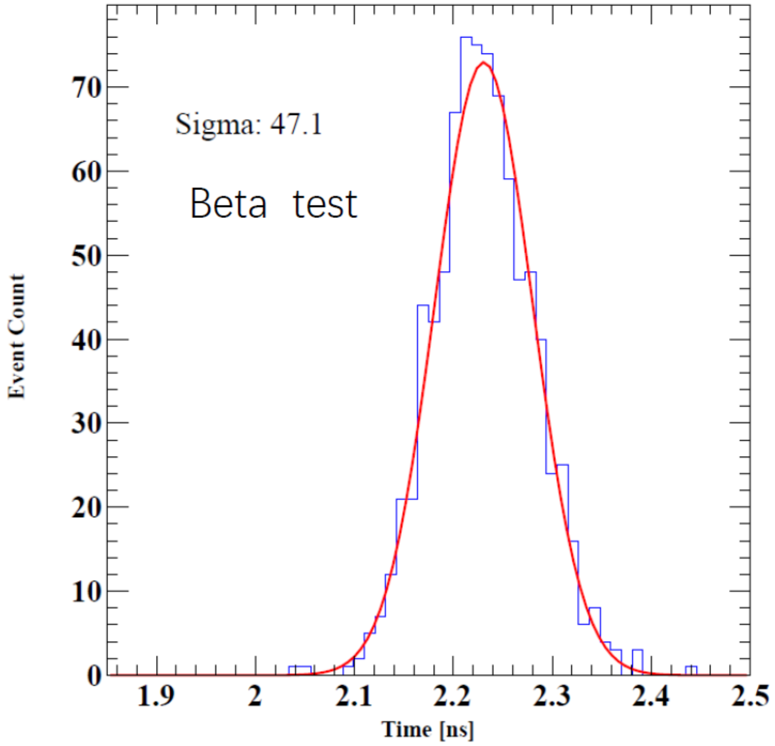


Pitch 150um： Best spatial resolution~8um

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

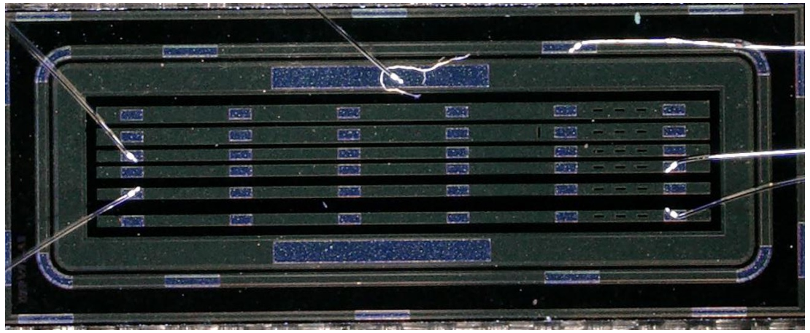
AC-LGAD R&D

Timing resolution



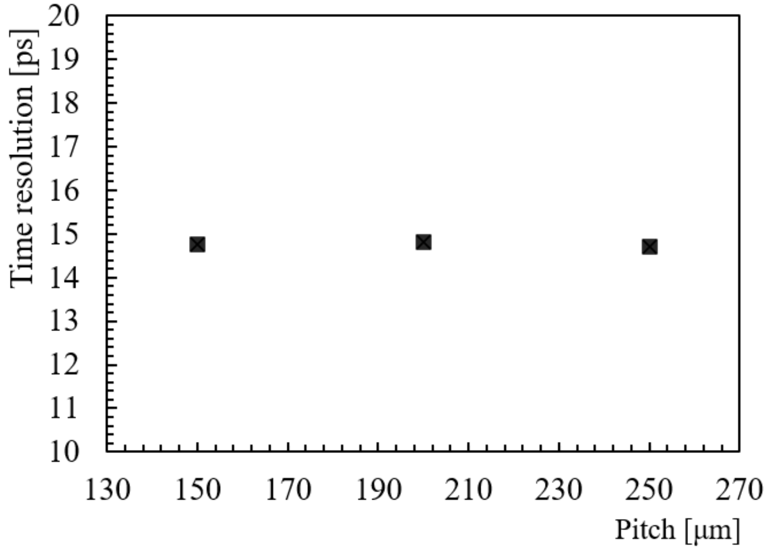
Time residual sigma: 47.1 ps

Time resolution: 37.5 ps



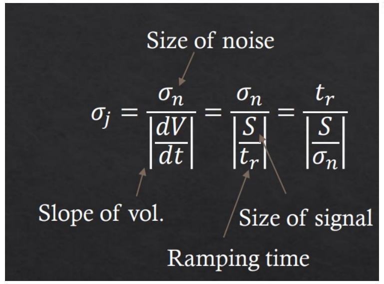
- Strip length 5.6mm
- pad-pitch size:
  100-250 um
  100-200 um
  100-150 um

Timing resolution:



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

AC-LGAD R&D

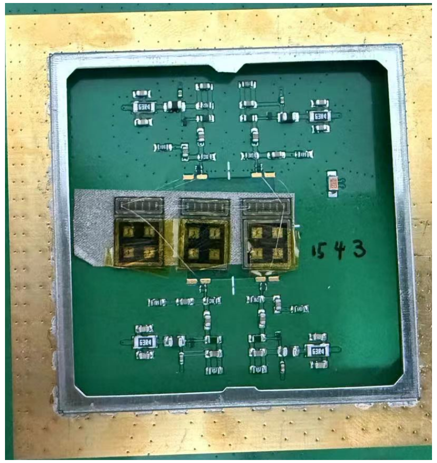


- **Beam testing for spatial resolution:** low noise board design ongoing
- **Timing performance of LGAD with long strip:**

  Large capacitance: effect to the timing resolution and power consumption

  Long transmission lines: signal delay, impedance, capacitance between strips

  Process control and yield

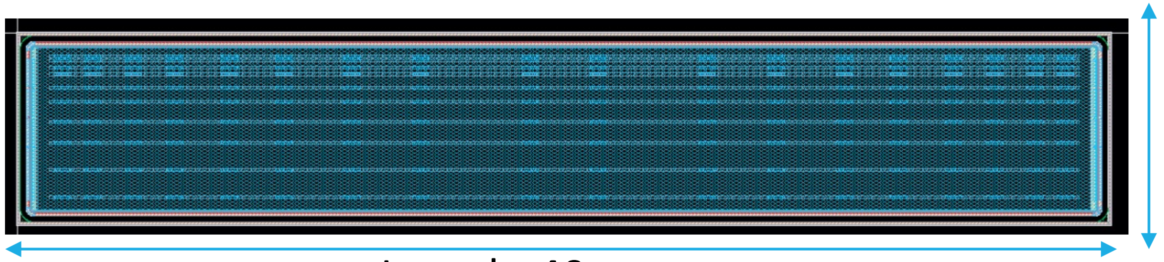


- **Prototype design for the CEPC application:**

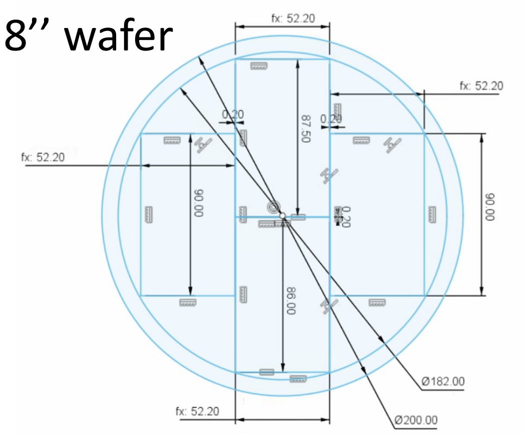
✓Pitch as 50 um, 75 um, 100 um, 200 um, and the strip length as 1cm, 2cm, and 4cm..

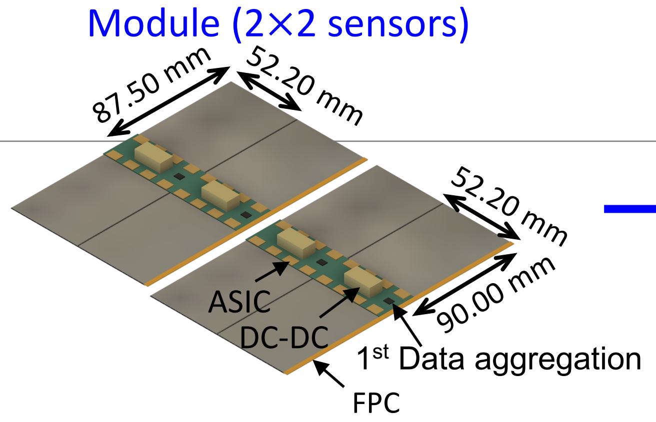
✓ optimized design for reduction of the sensor capacitance

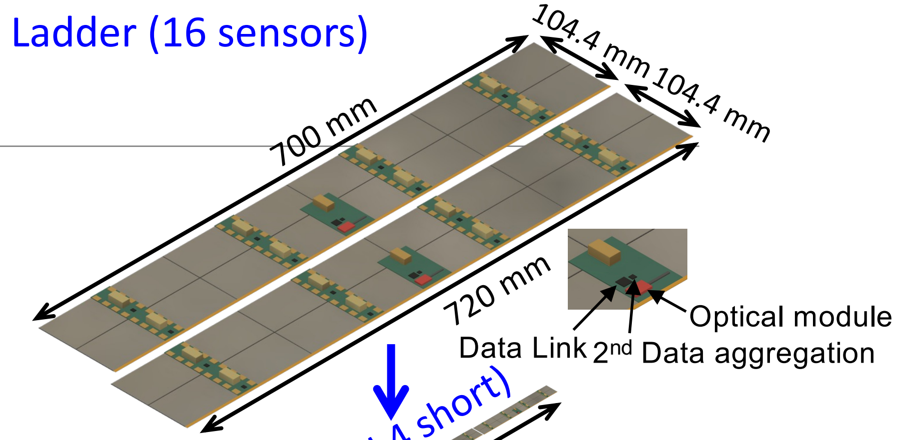
✓Process design for better spatial resolution

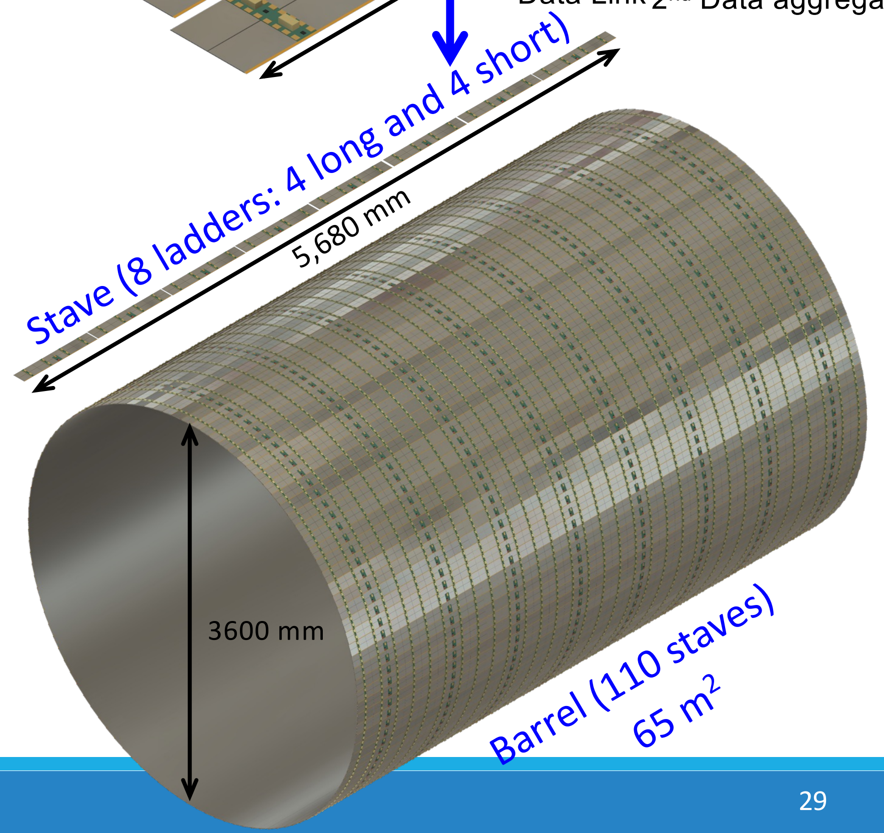


CEPC OTK Barrel Design (AC-LGAD Strips)







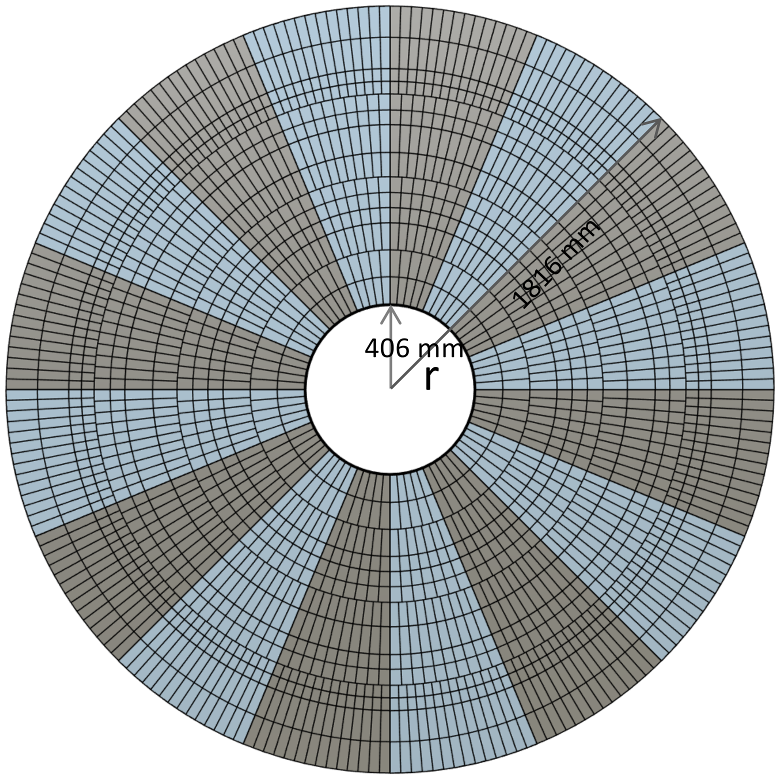


- CEPC outer silicon tracker (OTK) utilizes AC-LGAD (Low Gain Avalanche Detector) developed by IHEP-IME:
  - Sensor size: 8.75 cm × 5.22 cm
    9.00 cm × 5.22 cm
  - Strip number per sensor: 512
  - Strip pitch size: 100 μm
  - Spatial resolution: 10 μm
  - Time resolution: 50 ps
  - Power consumption: ~300 mW/cm^2

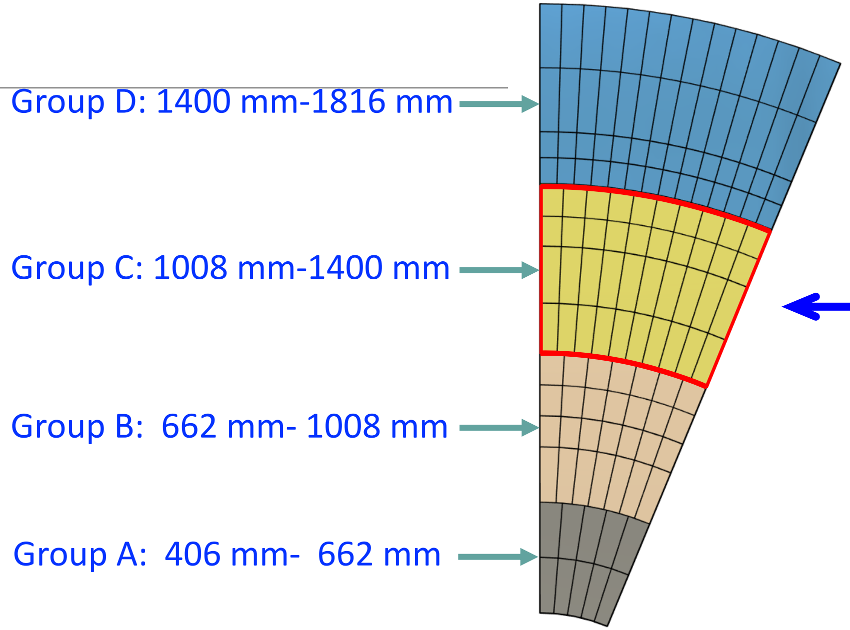
Maximum usage of silicon wafers for OTK barrel: a total 3,520 wafers, with 15% higher efficiency compared to a conventional single-piece sensor cut from a wafer.

CEPC OTK Endcap Design (AC-LGAD Strips)

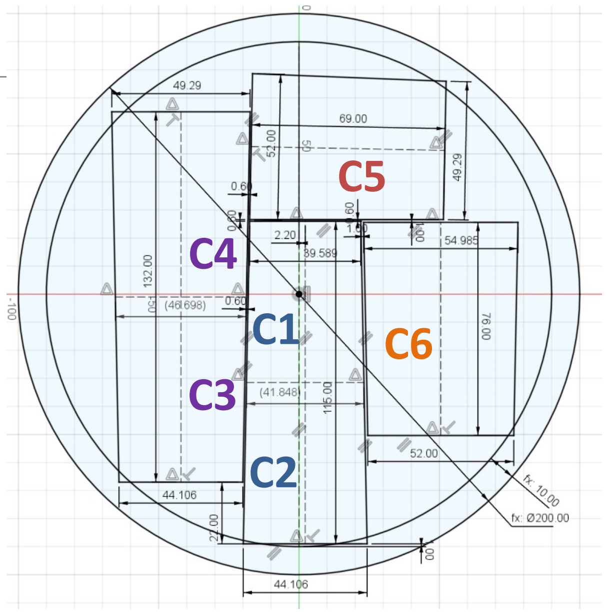
Endcap (16 sectors, 10 m^2):



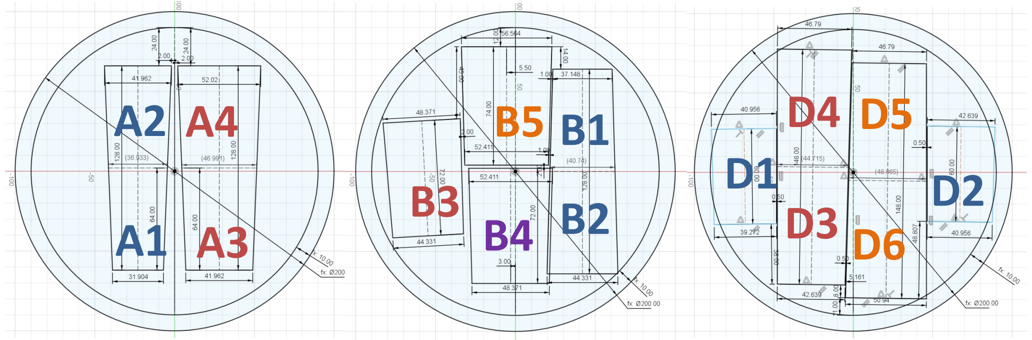
1/16 Sector:



Sensor: 8'' wafer (group C sensors)



8'' wafer (group A, B, D sensors)

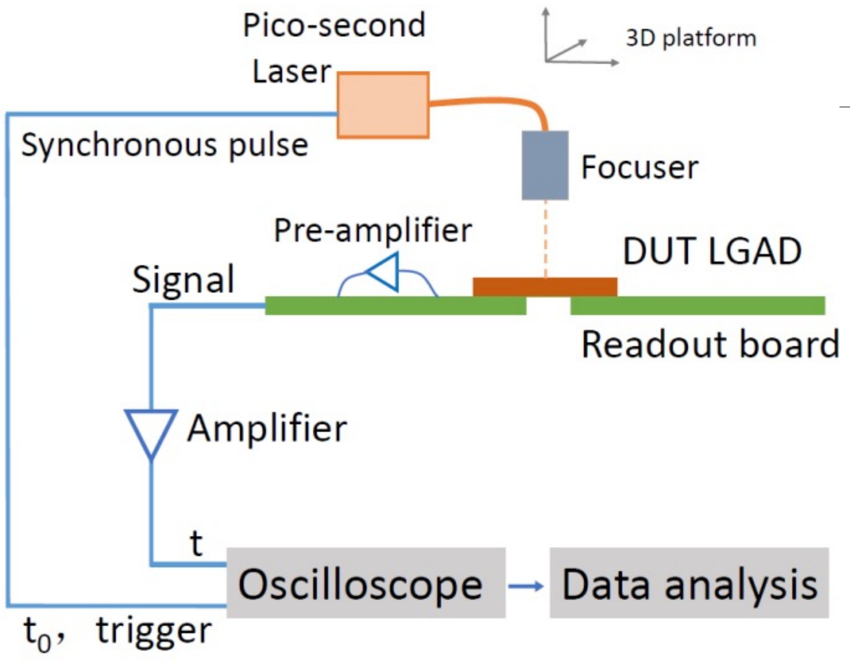


- OTK endcap consists of 14 rings, arranged into 4 groups.
- Each group contains 2-4 types of trapezoid sensors, which can be fitted to one 8'' silicon wafer.
- Each group of sensors is aligned to a 1/16 sector.
- The long sensor contains 2 sets of short-strip sensors.

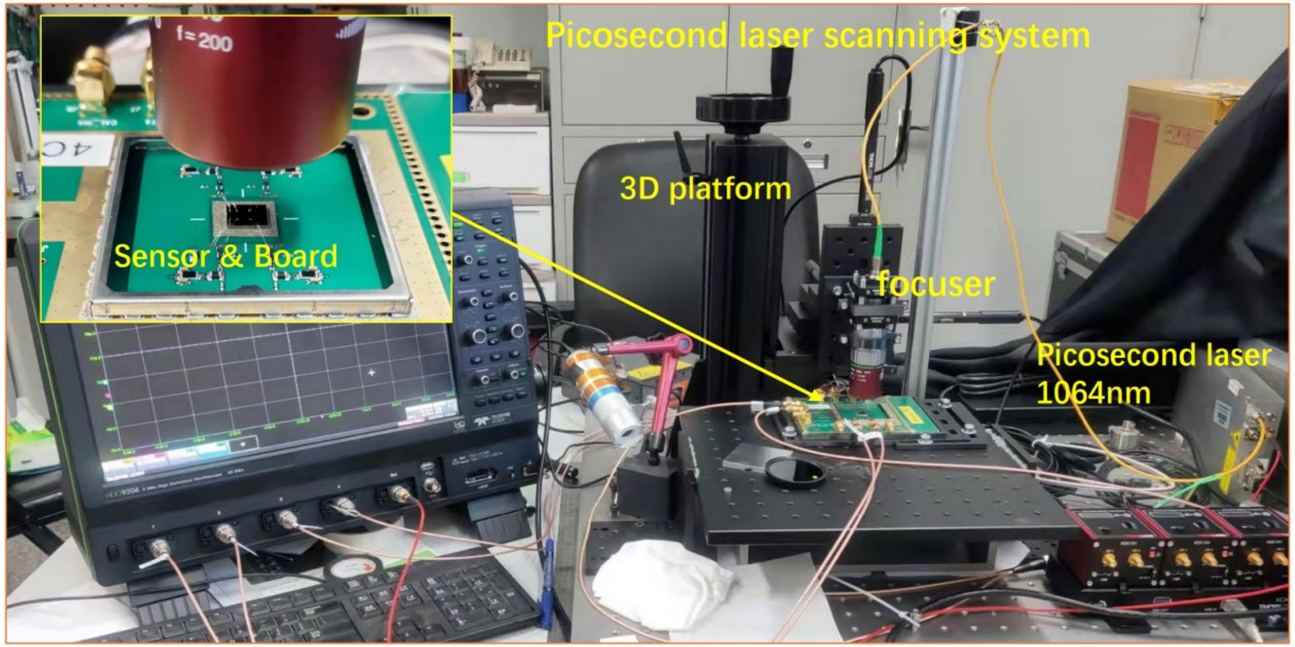
Maximize the use of silicon wafers and facilitate detector assembly.

Backup

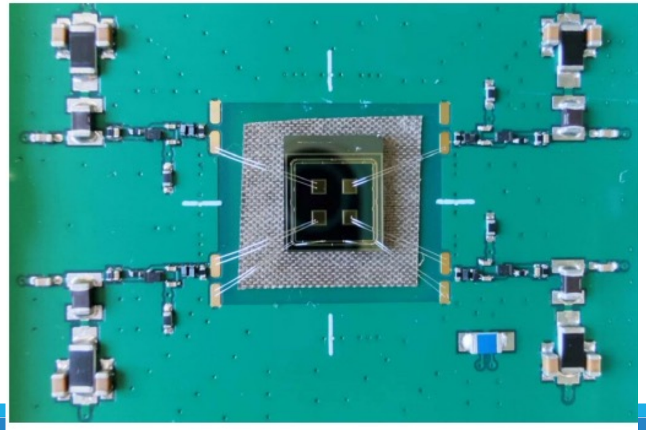
◆AC-LGAD sensor testing system



Pico-second laser testing system for AC-LGAD



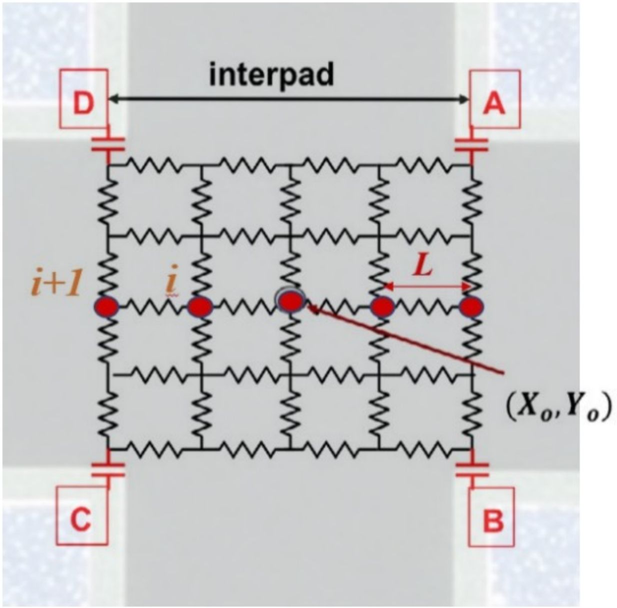
4 channels readout board with fast amplifiers



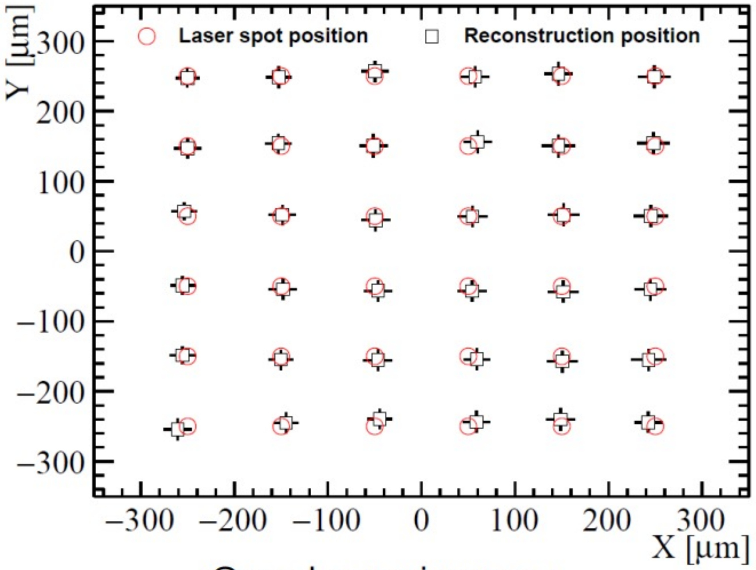
Picosecond laser testing system

- 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.

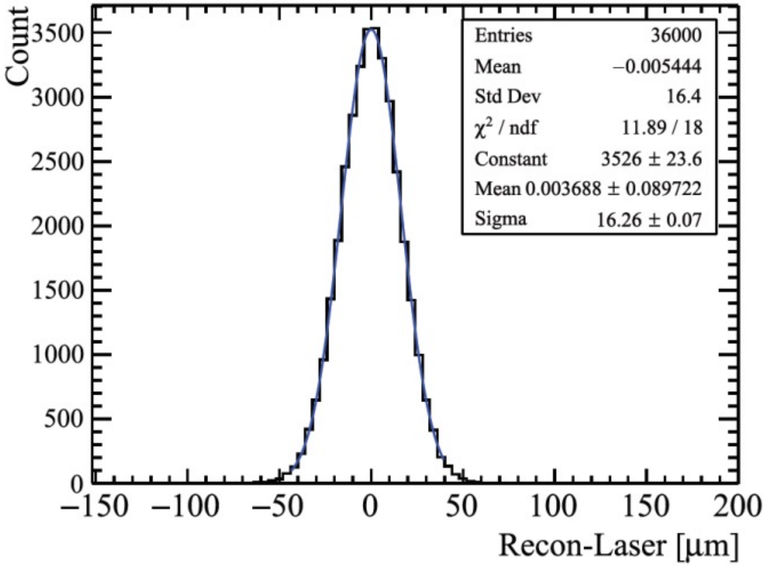


reconstructed 6x6 positions



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)

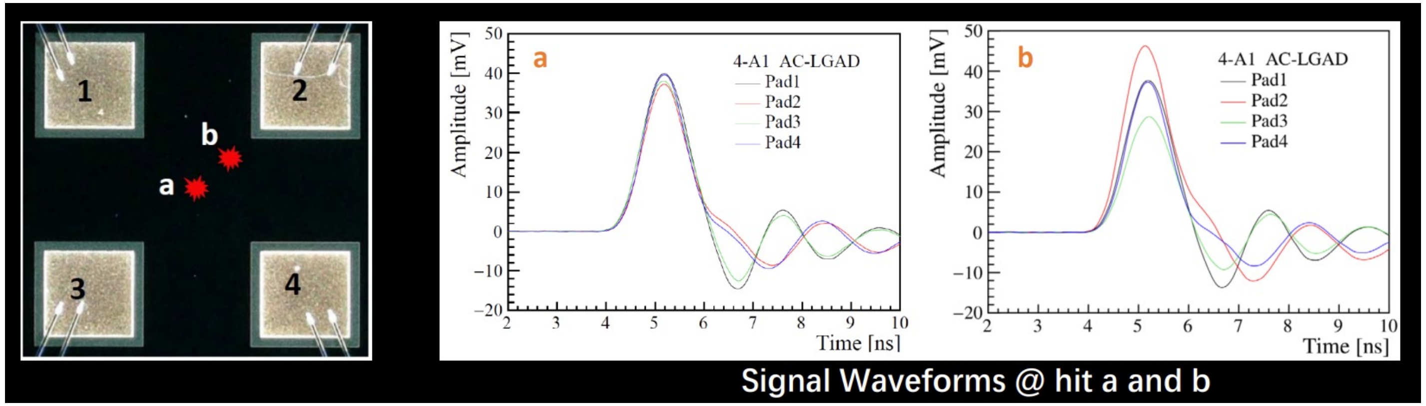
Spatial resolution :

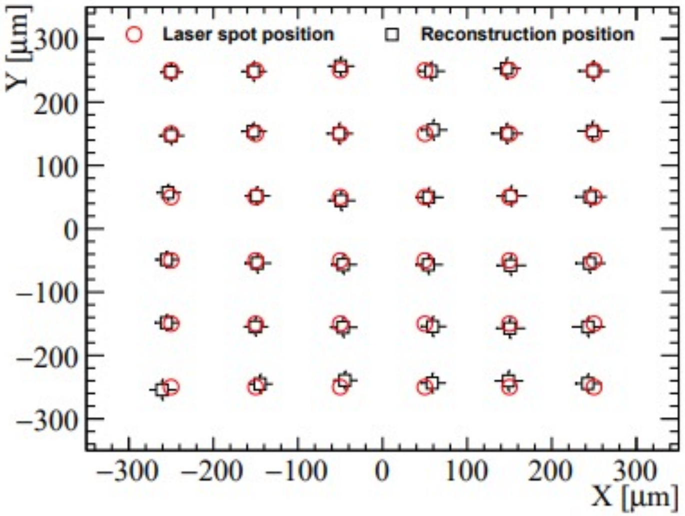
- the sigma of the difference between the laser and the reconstructed position

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

Discretized Positioning Circuit model
Machine learning method ongoing

IHEP AC-LGAD

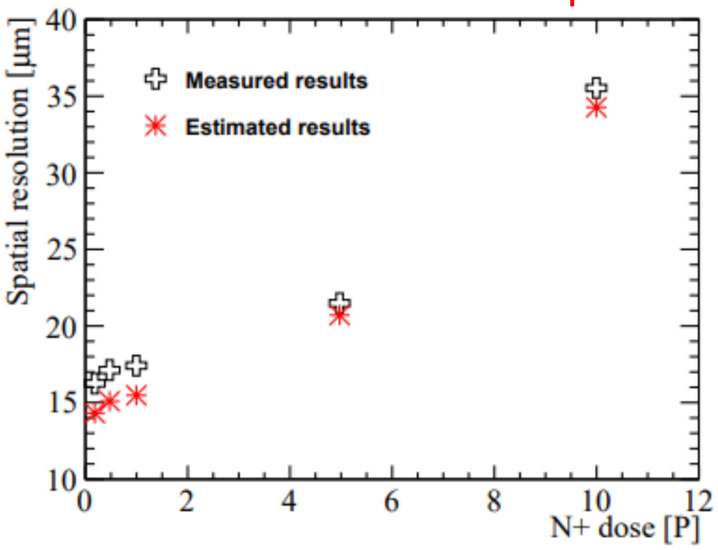




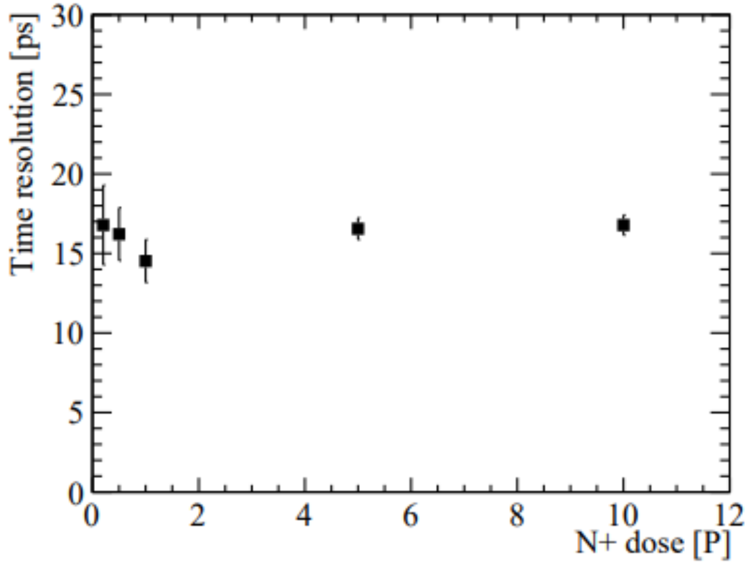
Position reconstruction

Pixel AC-LGAD

Pad-pitch： 1000-2000um



Position resolution as n+ dose changing



Timing resolution(laser testing): 15ps

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