LGAD based 4D outer tracker and time of flight

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Outline

- CEPC and LGAD introduction
  - CEPC requirement
  - LGAD and AC-LGAD
- Status of LGAD R&D
  - LGAD and AC-LGAD
- LGAD 4D detector design for CEPC
- Future R&D

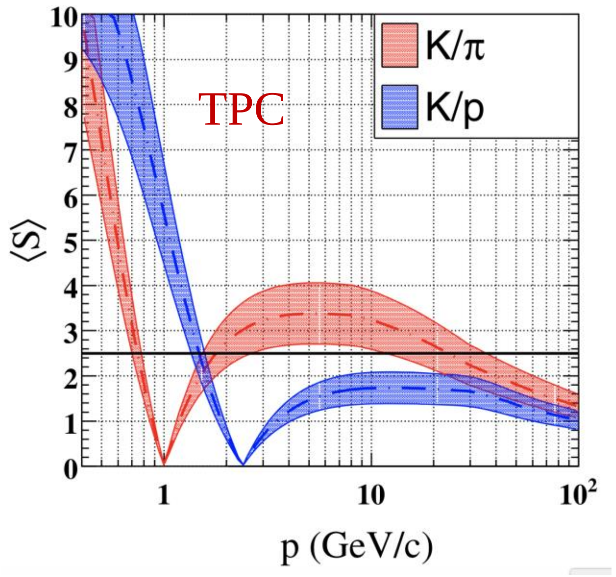
Physics requirement

CEPC will produce 10^{12} Z boson at Z pole: Rich flavor physics program

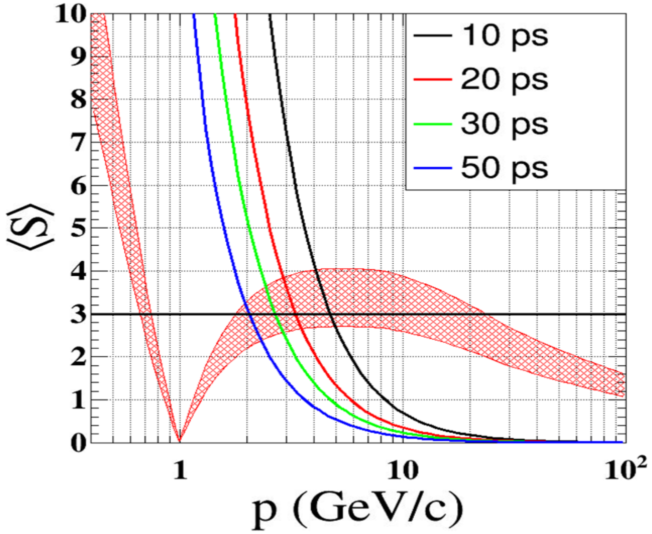
- **Particle separation** of Gas detector (dE/dx) for CEPC flavor physics:

  0.5-2 GeV for K/π separation, >1.5 GeV for K/p separation
- **Combined gas detector with Timing detector(resolution<50ps):**

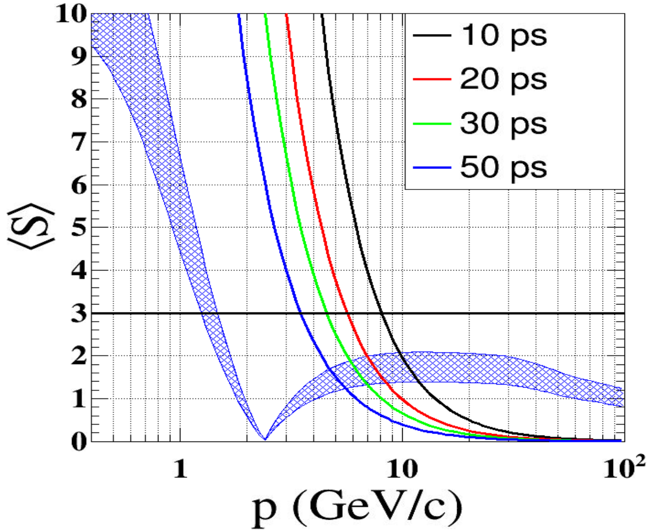
  0 - 4 GeV for K/π separation, **0 – 8 GeV** for K/p separation, especially for 3 sigma K/π separation below 2GeV
- **LGAD (having precise timing information) based 4D outer tracker be proposed and aim to provide good timing and spatial resolution(50ps and 10um)**



k/π Separation



k/p Separation

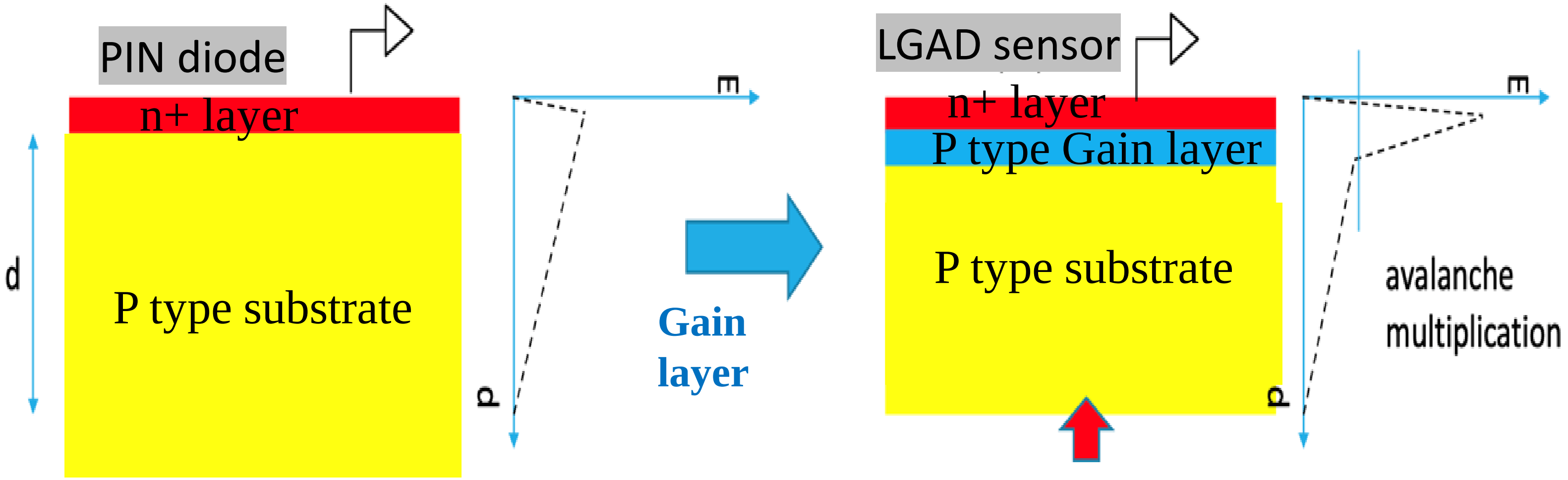


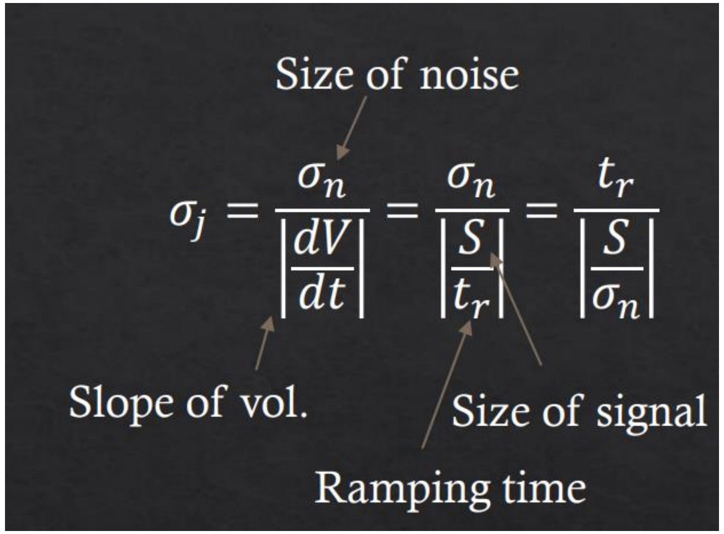
LGAD sensor

◆Low Gain Avalanche Detectors (LGAD) :

- Avalanche diode, having gain layer between n+ layer and p sub, work in linear mode
- Gain: 10~50, higher signal as compared with PIN
- Thin depleted region(~50um) to decrease t_{rise} (fast ramping time)
- Good Signal/Noise ratio, no self triggering as compared with SiPM
- Be used in ATLAS HGTD and CMS project for timing information

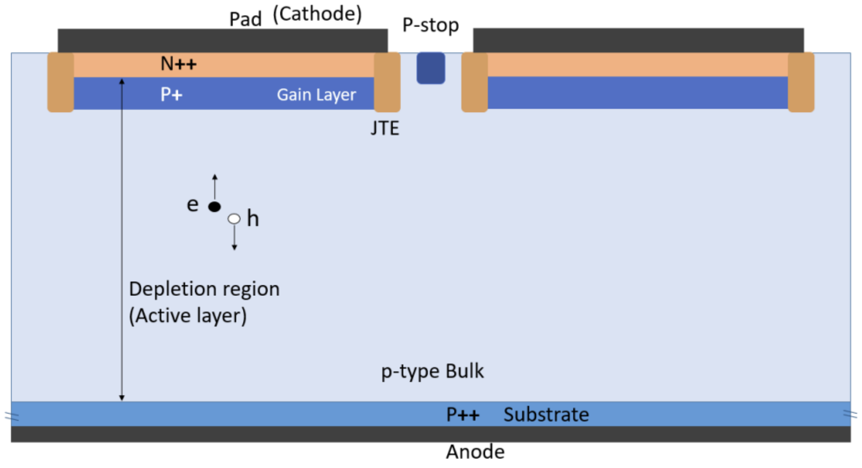
➤good timing resolution(<30ps)

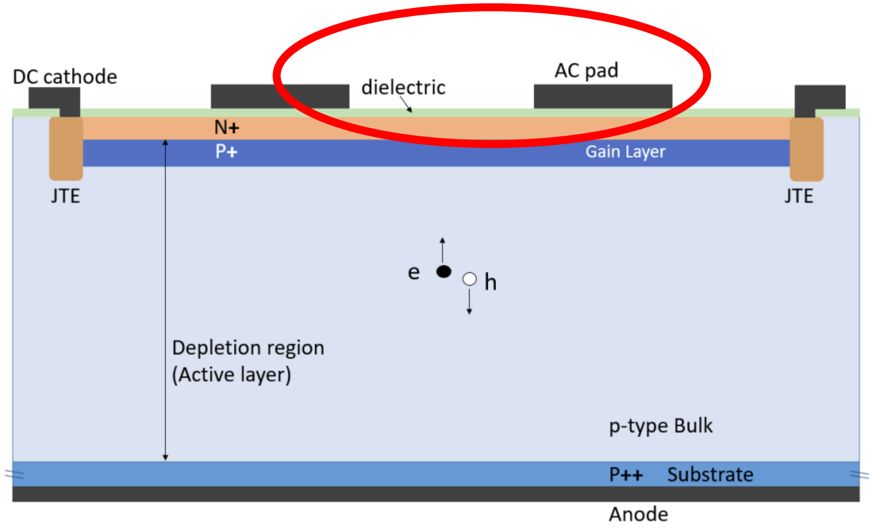




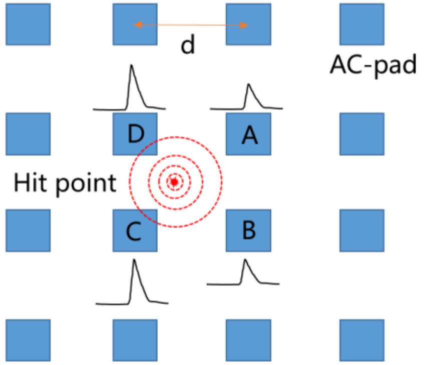
Koji Nakamura (KEK), https://indico.ijclab.in2p3.fr/event/9730/

LGAD and AC-LGAD





Signal of AC-LGAD



◆ Standard LGAD

Metal pads is connected to N++ layer
Time resolution: <30ps
Position resolution: pixel size/$\sqrt{12}$
With dead zone: Junction termination extension(JTE) and p-stop

Application:

ATLAS upgrade: HGTD, CMS

◆ AC-LGAD

Uniform gain layer with AC-Coupled electrode
No dead zone (100% fill factor)
Position resolution: 5~10 um
Time resolution: ~ 30ps

Application:

Electron-Ion Collider (EIC)：Central detector，Far-Forward detector

Signal shared on neighboring electrodes. The coupled signal or collected charge from the 4 pixels is closely related to the position of the laser injection.

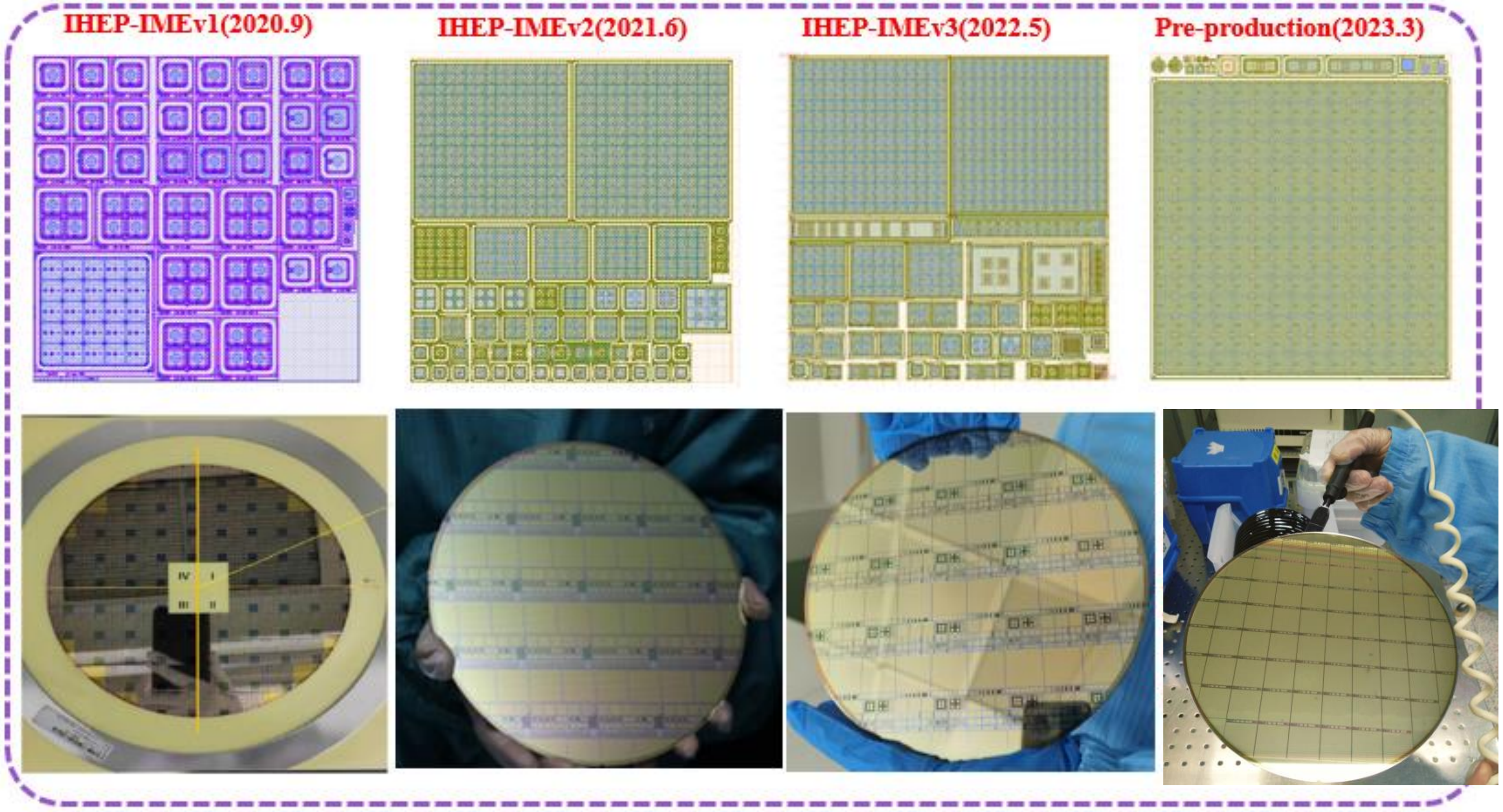
LGAD and AC-LGAD R&D

status of LGAD

IHEP LGAD sensor be designed by IHEP and produced by IME, 3 versions of sensors be studied from 2020.

Pre-production of LGAD for HGTD project started in 2023.

- In 2023, IHEP LGAD got all the share of the order from CERN tendering
  > 10,000 LGAD (54%, **will be produced by IME according to IHEP design**)
- Contribution of the LGAD sensors in HGTD project
  IHEP-IME: 90%
  UCSC-IME: 10%
- 2023-2024: Pre-production almost finish: >2000 sensors produced
- Final production will start around June this year, 21000 sensors

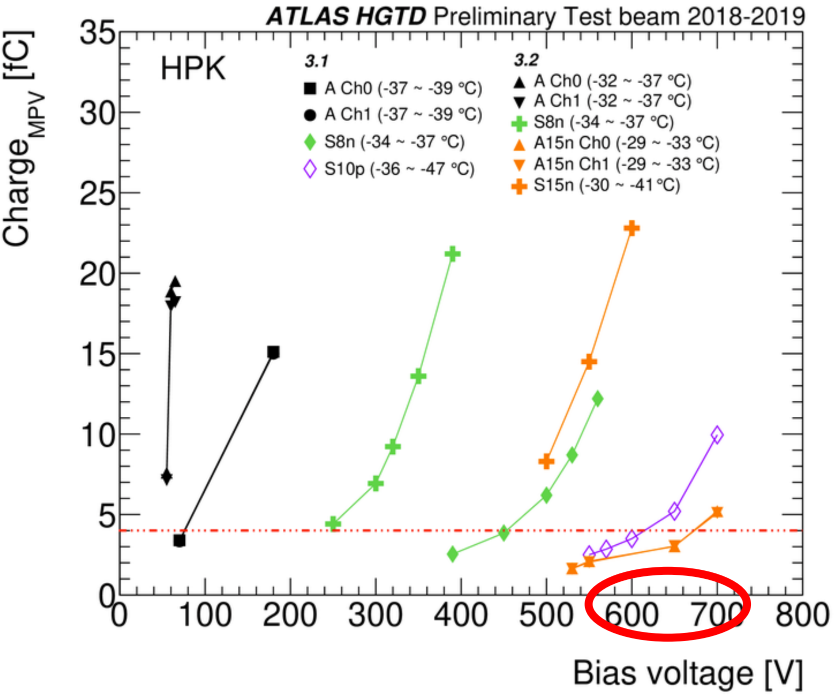


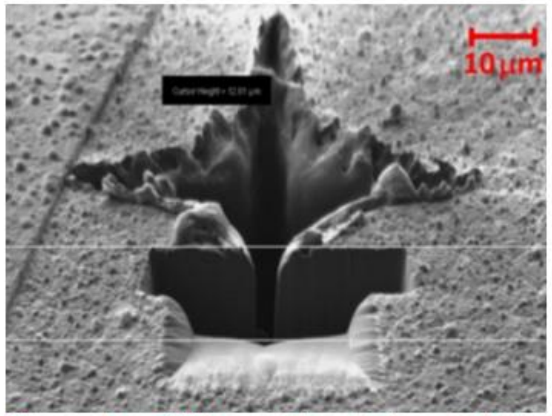
Status of LGAD

◆ **Main challenge of LGAD for HGTD: Radiation Hardness**

➢Boron doping in gain layer became less active after irradiation（**acceptor remove**）

➢Irradiated sensors require higher bias voltage to maintain performances. Single Event Burnout (SEB) occur when irradiated sensors 2.5×10^{15} n_{eq}/cm^2) operated with high bias voltage.

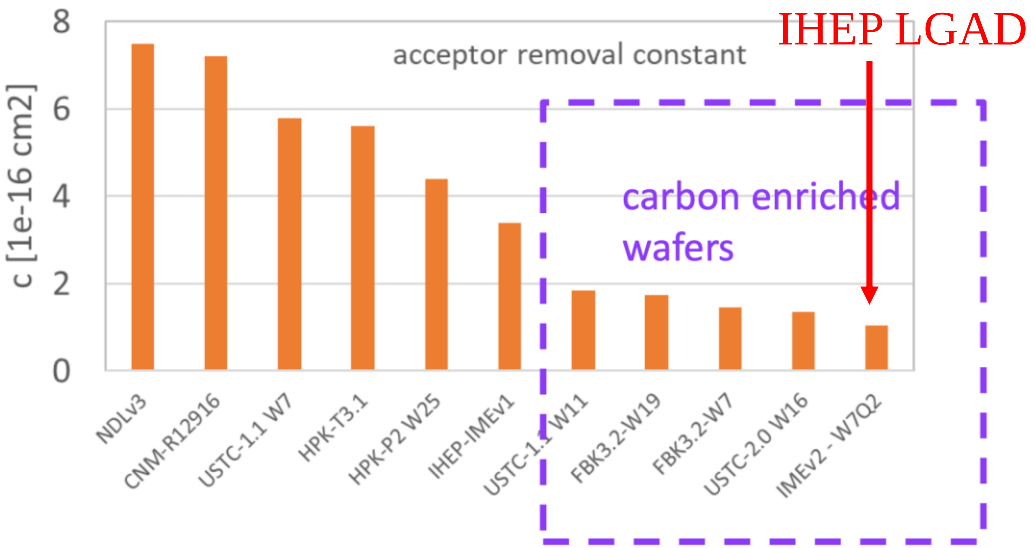




Burn mark on a CNM sensor after proton beam irradiation in Fermilab in 2018 (picture produced by CNM)

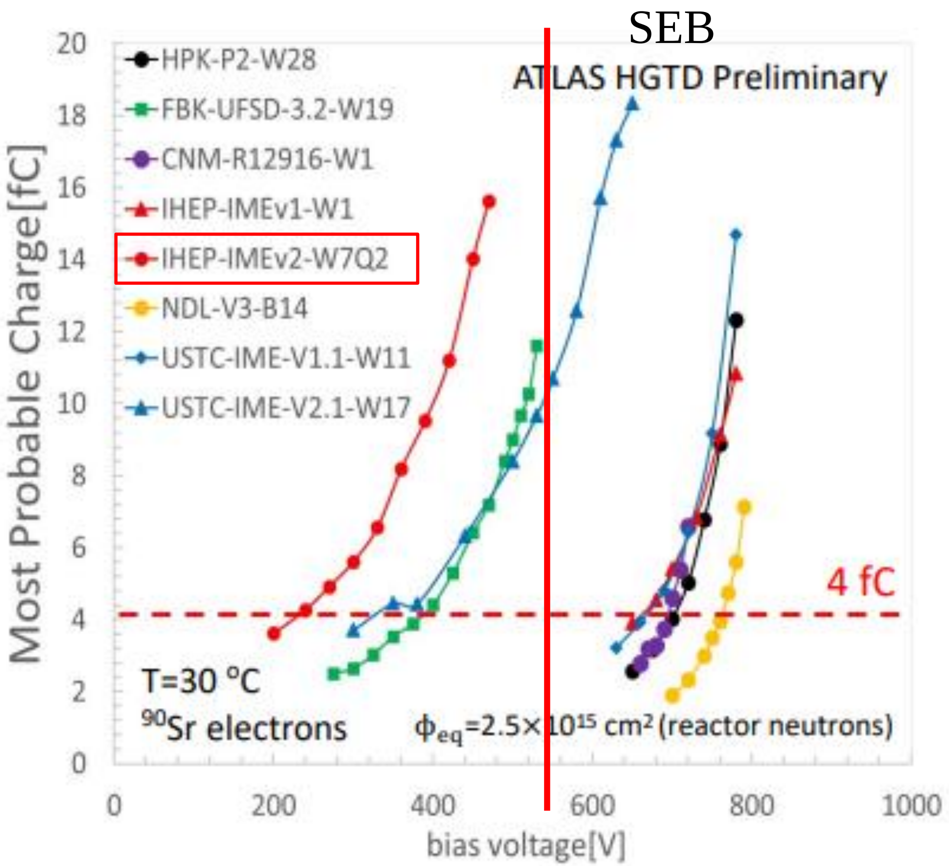
- RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam.

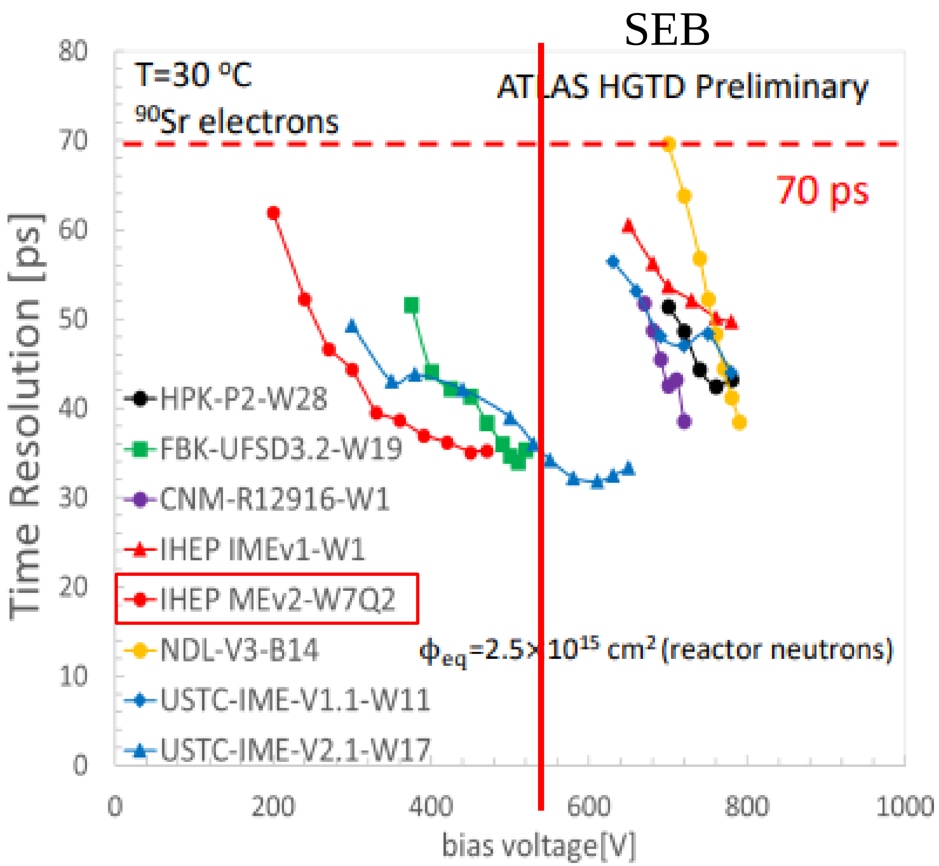
➢ IHEP LGAD Sensors with carbon enrichment show very low acceptor removal coefficient(1-2×10^{-16} cm^2), which means they have good radiation hardness



Status of LGAD

- ➢IHEP LGAD sensors with carbon enrichment show good **charge collection/timing performance after 2.5×10^{15} n_{eq}/cm^2** at voltage less than SEB requirement.
- ➢ These sensors performs good enough over the entire lifetime of the ATLAS HGTD experiment.



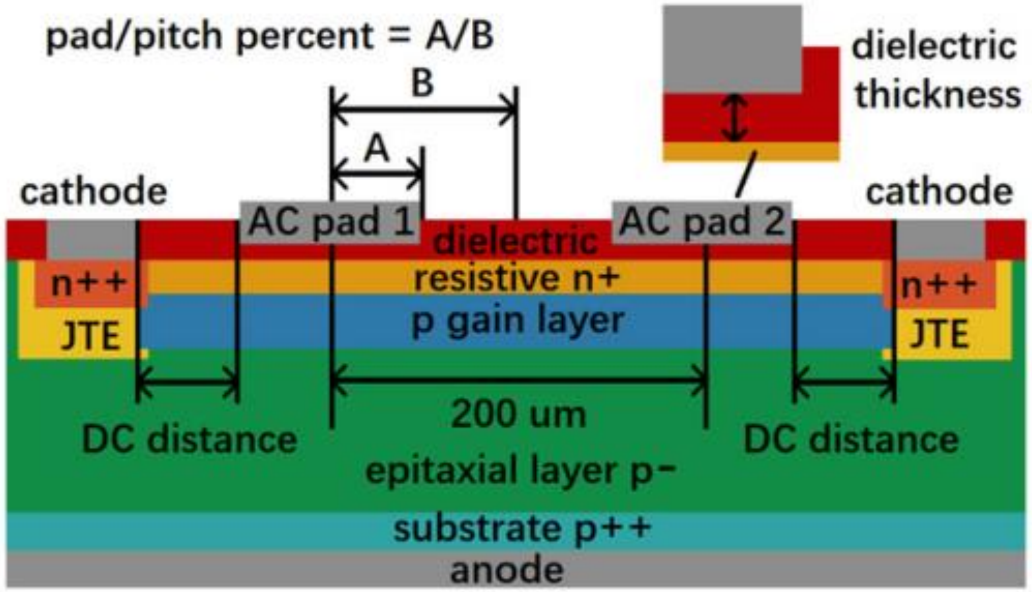


AC-LGAD R&D

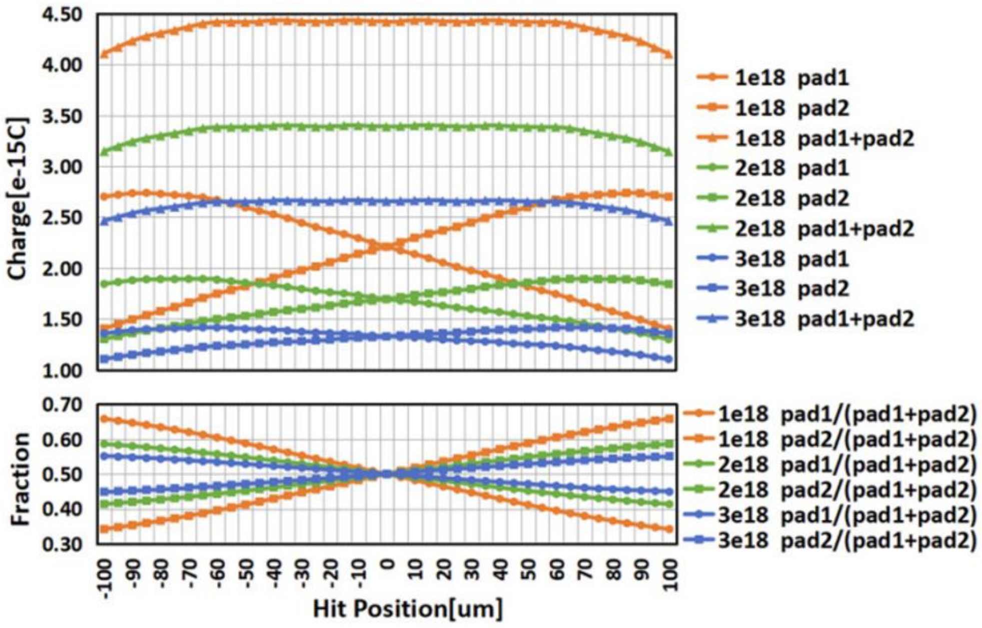
◆ **AC-LGAD sensor simulation：** Optimization of process and structure parameters

Process parameter: n+ dose, dielectric material and thickness

Structure parameter: pad shape, pad-pitch size



TCAD model of AC-LGAD for simulation



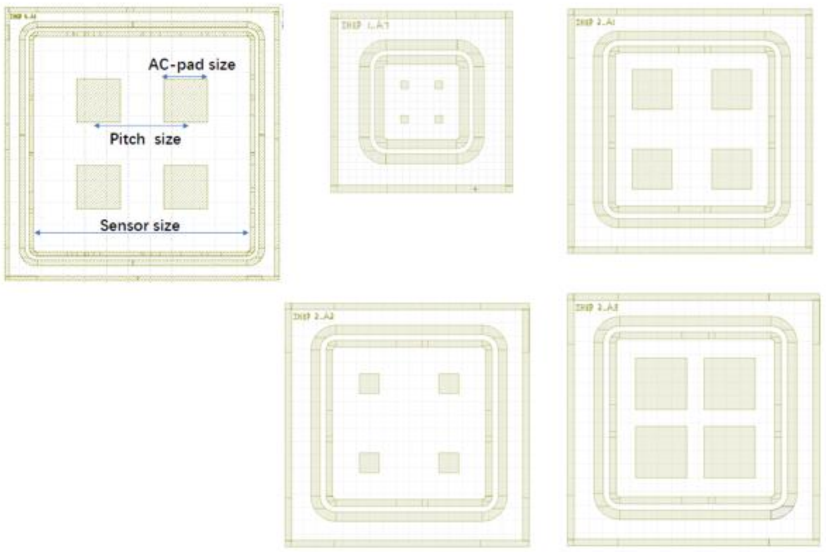
Lower N+ dose→ Large N+ resistivity →good spatial resolution

Paper: 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

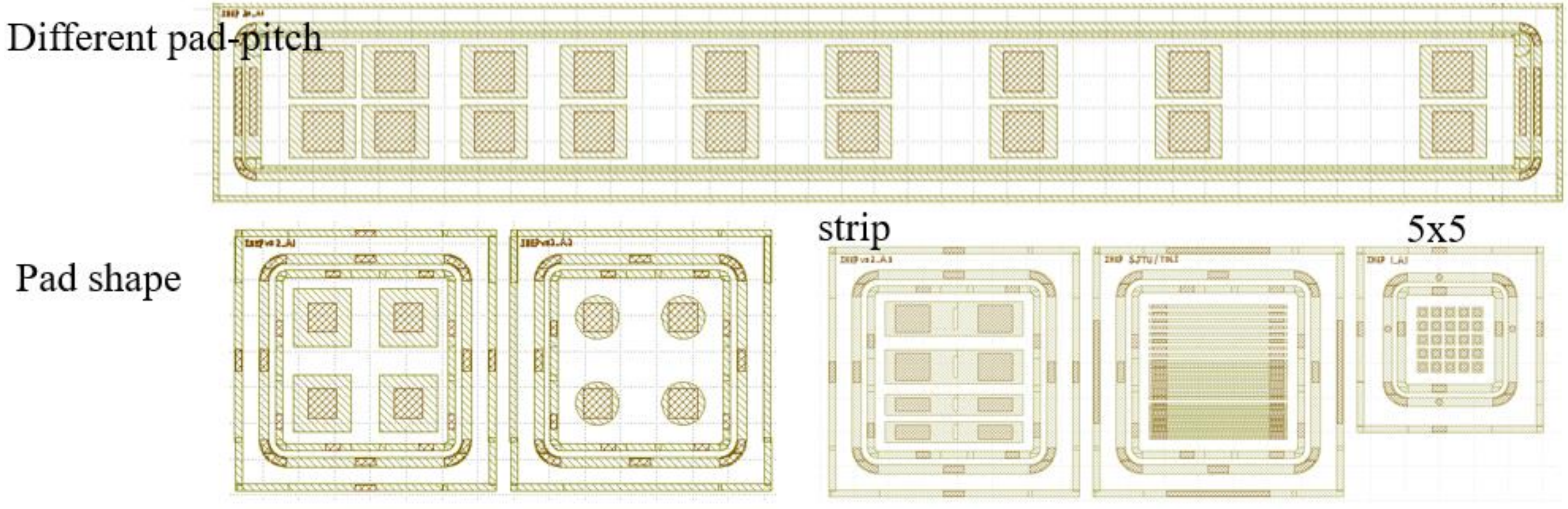
◆AC-LGAD sensor design, fabrication and testing

IHEP AC-LGAD v1: 2021.6-2021.11



Pixelated LGAD

IHEP AC-LGAD v2: 2022.9-2023.2



strip LGAD

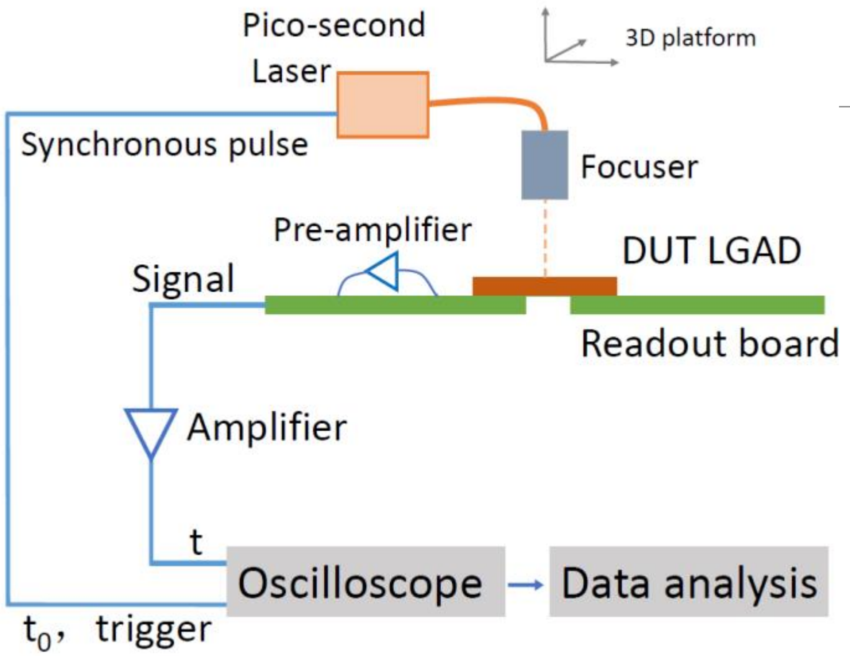
For more details:

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

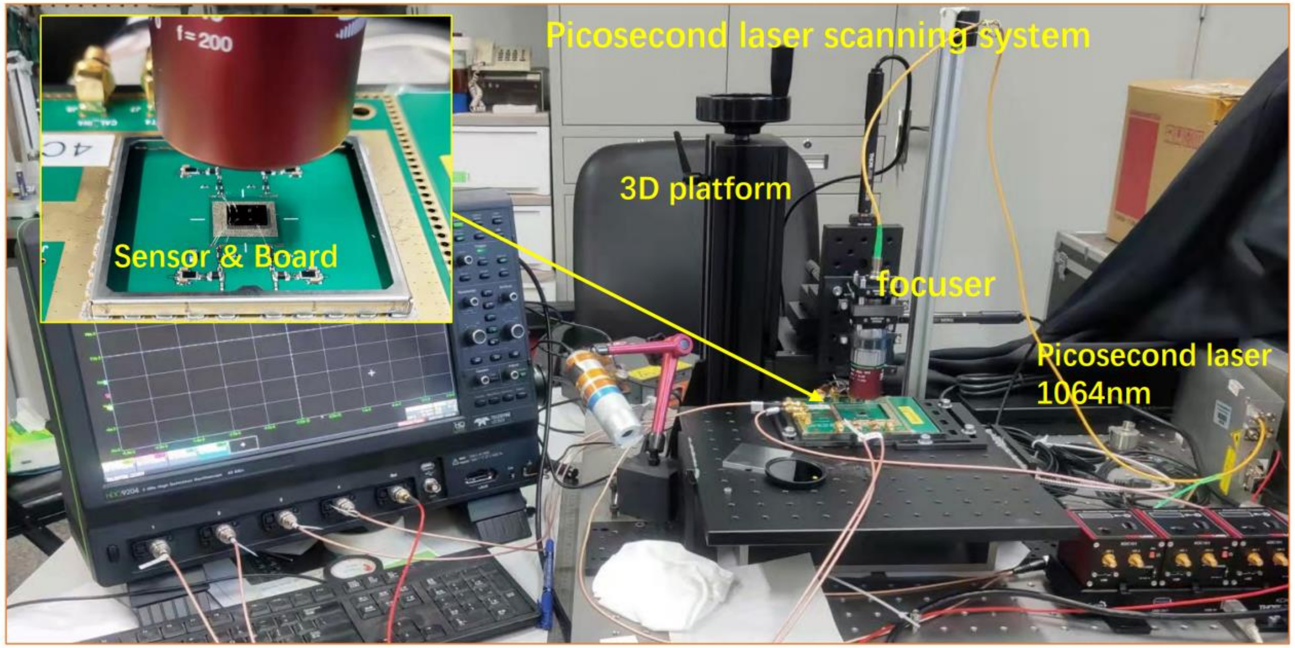
The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

AC-LGAD R&D

◆AC-LGAD sensor testing system

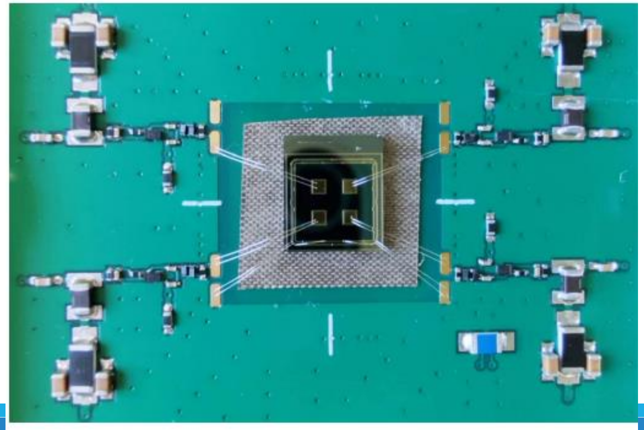


Pico-second laser testing system for AC-LGAD



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

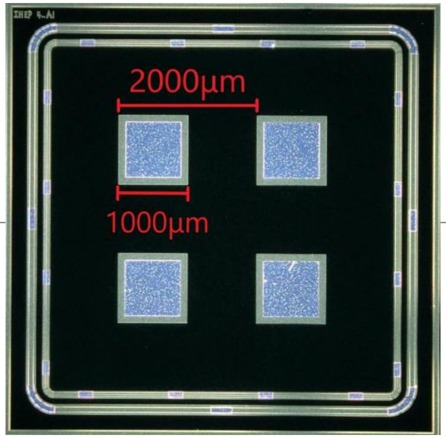
4 channels readout board with fast amplifiers



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

AC-LGAD R&D

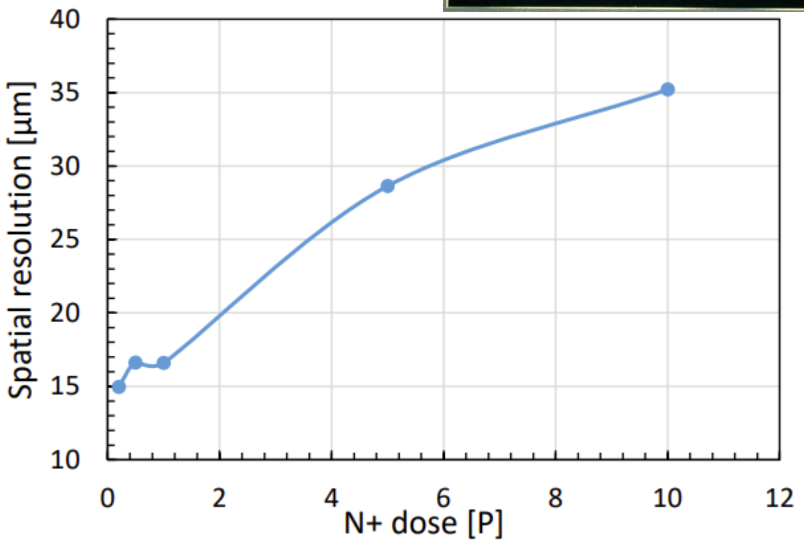
Study of process parameter n+ dose



Sensors	N+ dose	AC-pad size [μm]	Pitch size [μm]
W7Q1	10.0 P	1000	2000
W5Q1	5.0 P	1000	2000
W5Q2	1.0 P	1000	2000
W5Q3	0.5 P	1000	2000
W5Q4	0.2 P	1000	2000

Different n+ dose

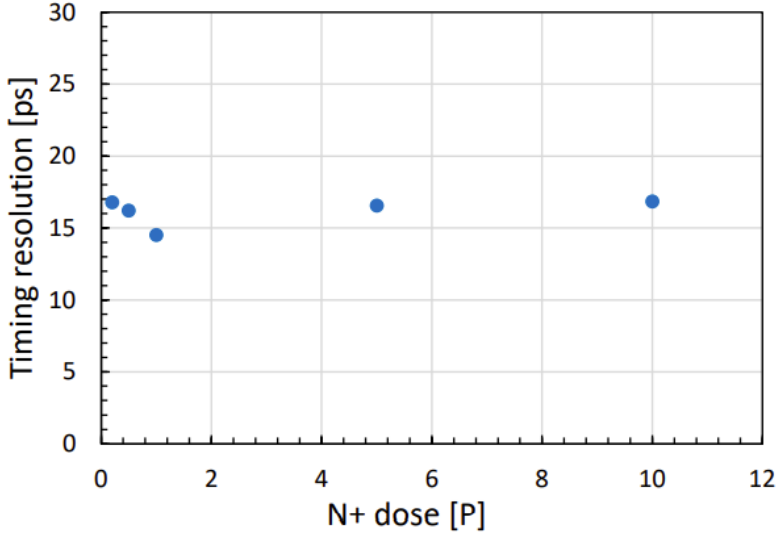
Spatial resolution:



Lower N+ dose→ Large N+ resistivity →good spatial resolution

The doping dose is from 10 P to 0.2 P, and the spatial resolution is from 35μm becomes better to 15 μm.

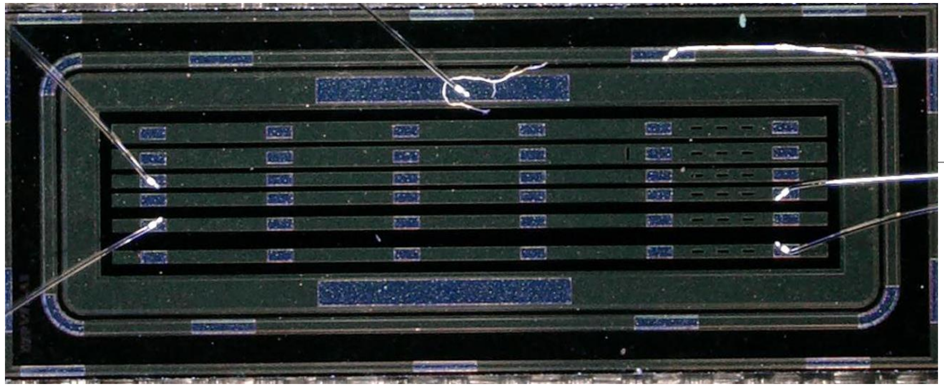
Timing resolution:



The time resolution does not change significantly at different N+ doping doses, which is about 15-17 ps.

AC-LGAD R&D

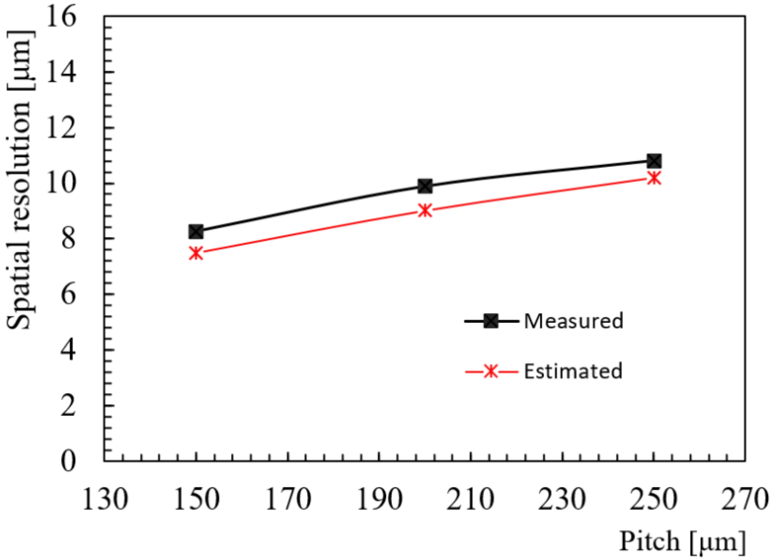
Study of Strip design



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

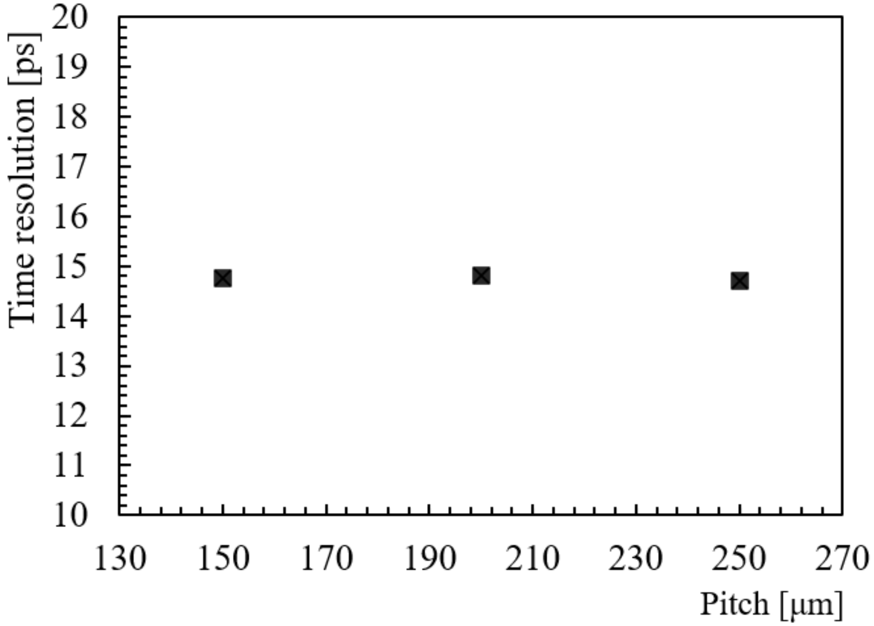
N+ dose(phosphorus): 0.2P to 0.01P

Spatial resolution:



Smaller pitch → good spatial resolution, but more readout channel

Timing resolution:



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

AC-LGAD R&D

Size of noise

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

Slope of vol.

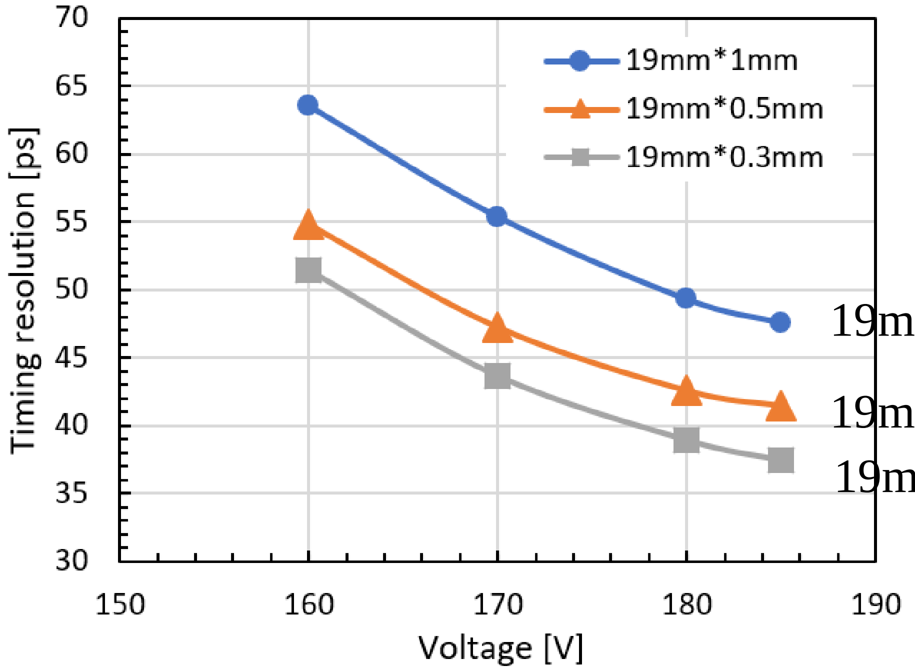
Size of signal

Ramping time

- Timing performance of LGAD with large size:

Large size→ large Capacitance → worse S/N→ worse timing performance

By connecting some sensors together using wire bonding, timing performance of sensors with large size by tested



19mm*1mm=19mm^2

19mm*0.5mm=8.5mm^2

19mm*0.3mm=5.7mm^2

From testing results of LGAD with large size, the timing performance still can be better than 50ps.

For CEPC outer tracker and TOF

For CEPC outer tracker and TOF

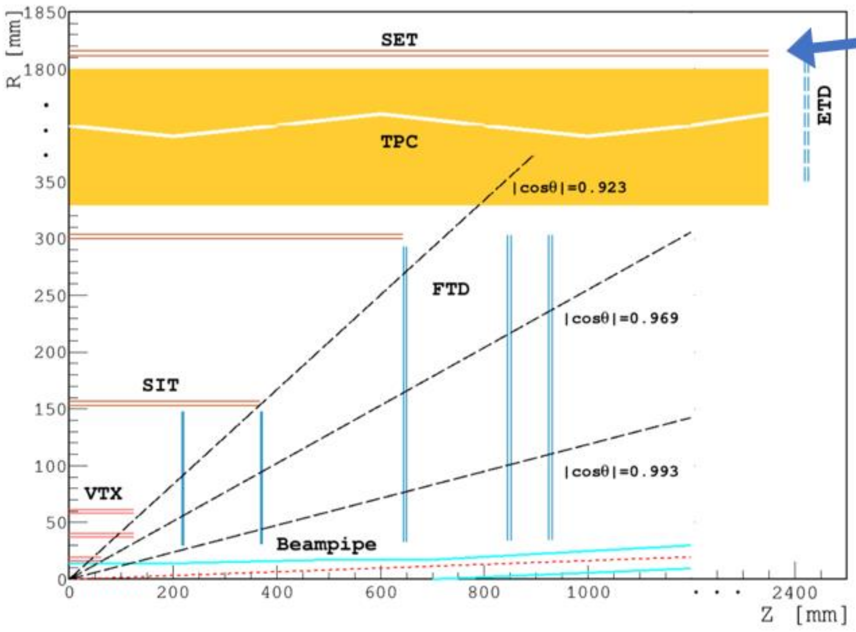
◆ LGAD based 4D outer tracker concept design：

- Be part of SET (silicon wrapper layer outside TPC or drift chamber)
- Serve as Timing detector and part of the tracker
- Barrel : 50 m^2 , Endcap 20 m^2
- Strip AC-LGAD be used for 4D detecting:

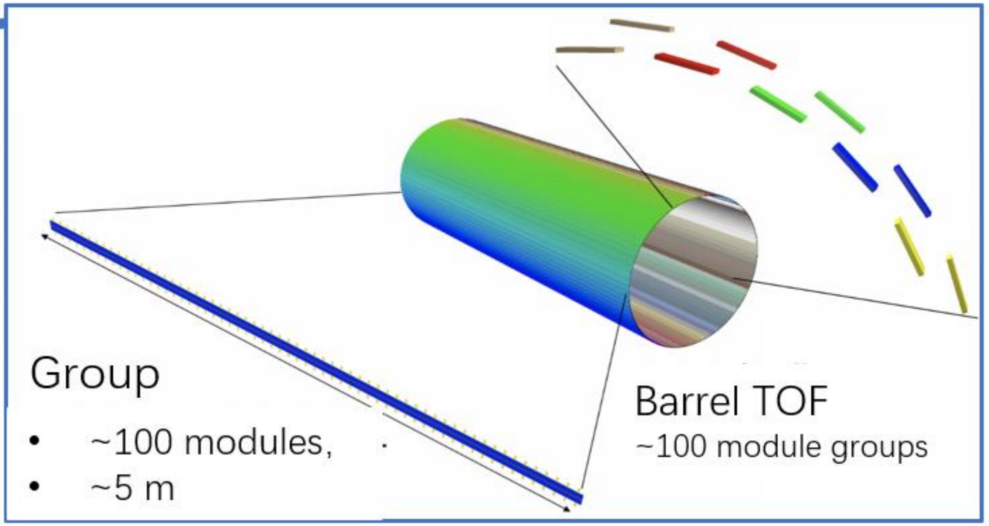
  Timing resolution: 30-50 ps

  Position resolution: ~ 10 μm @ R-phi direction • ~ 1mm @ z direction

Baseline detector concept in CDR



LGAD timing detector in Barrel region



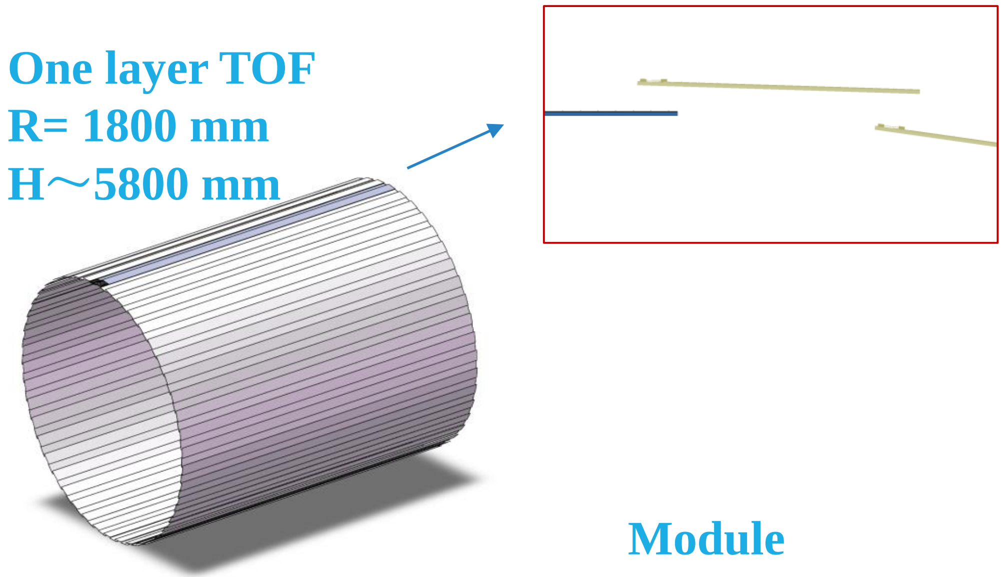
For CEPC outer tracker and TOF

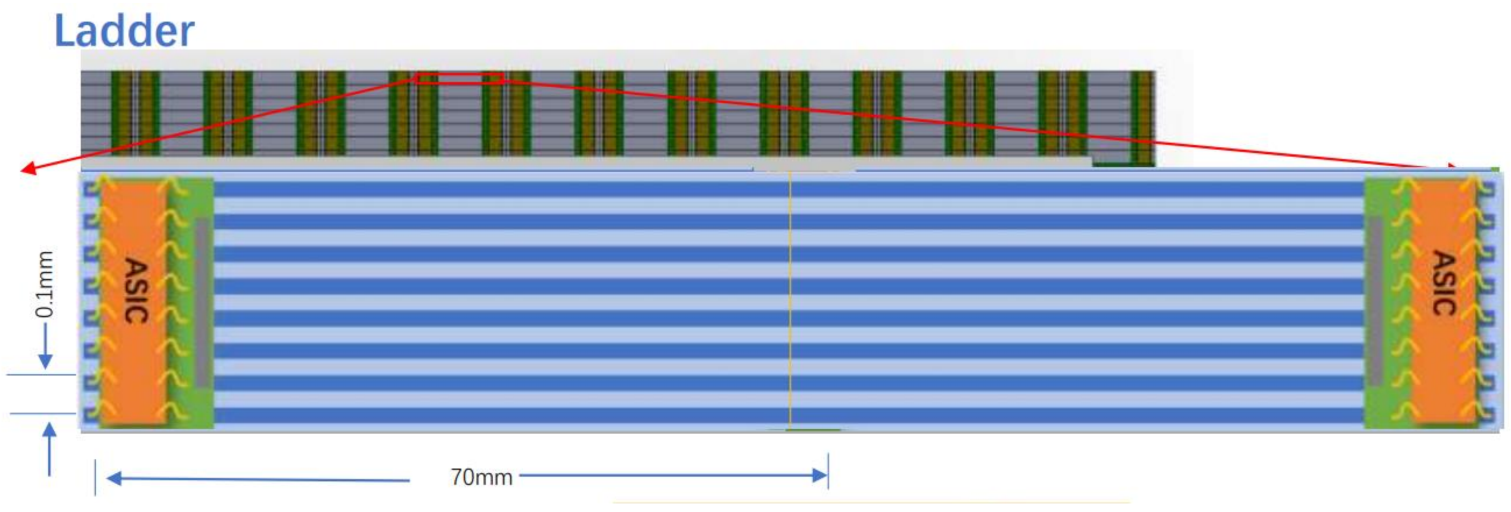
◆Arrangement of the TOF with strip LGAD

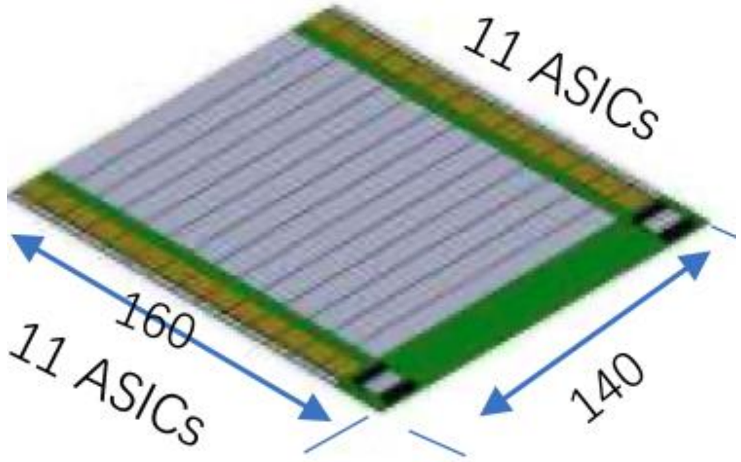
One layer TOF:

- R=1800 mm, H~5800 mm
- Double sided, 45 ladders each side, totally 90 ladders

  42 modules/ladder
- • Total modules needed： 45 *2*42 = 3780 modules







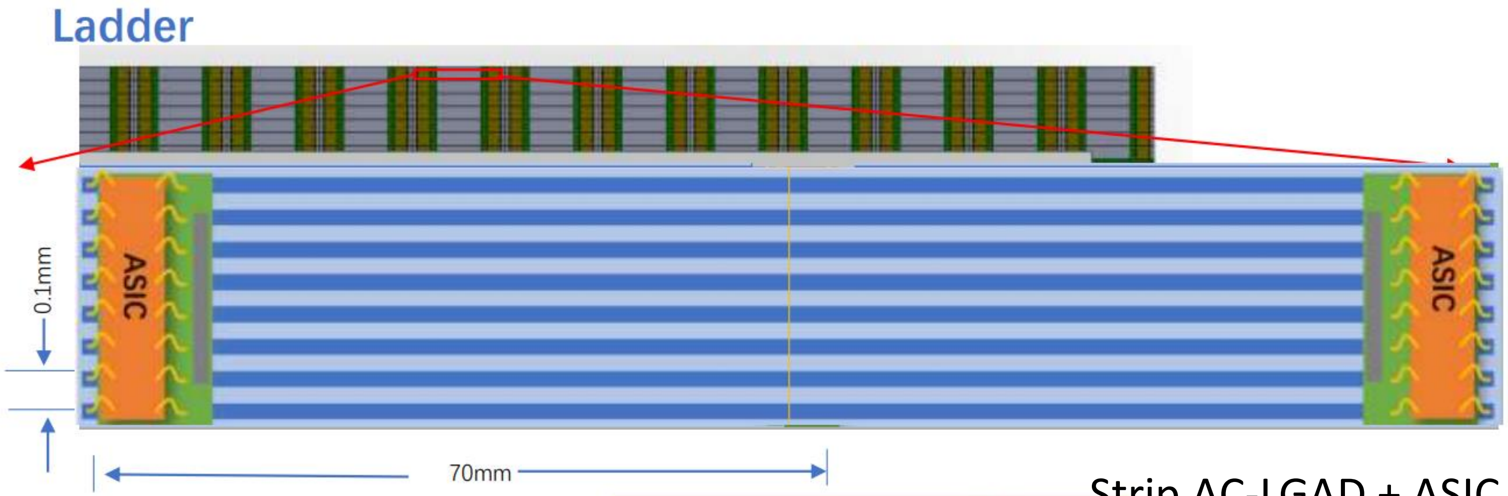
For CEPC outer tracker and TOF

◆ Per module:

- 22 ASIC/module，128 Channel/ASIC
- Sensor strip size: 70mm*0.1mm

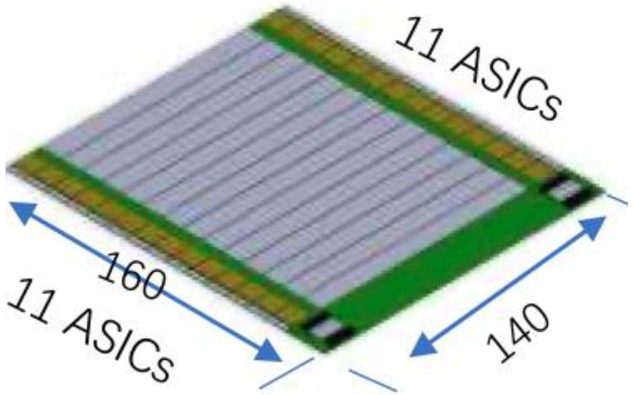
•Strip LGAD and ASIC be connected through wire bond

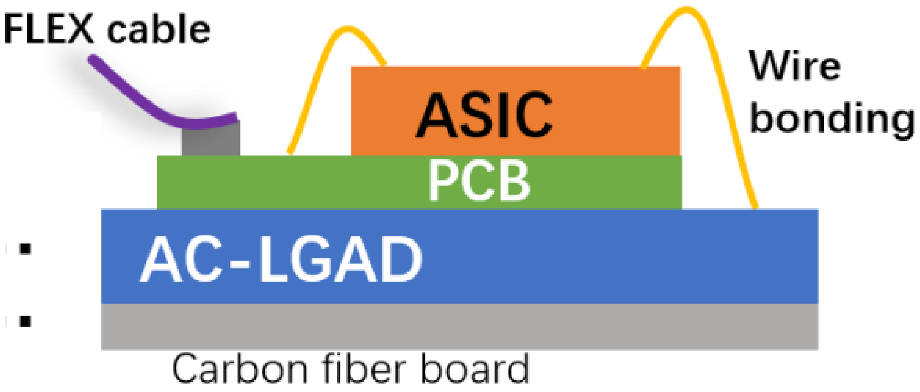
•Out signals from ASIC to readout PCB, then be sent out from FLEX cable



Strip AC-LGAD + ASIC

Module
140mm x 160mm





More details of electric readout scheme in Wei’s talk bout Elec-TDAQ framework for the CEPC

LGAD future R&D

Towards 4D outer tracker and time of flight

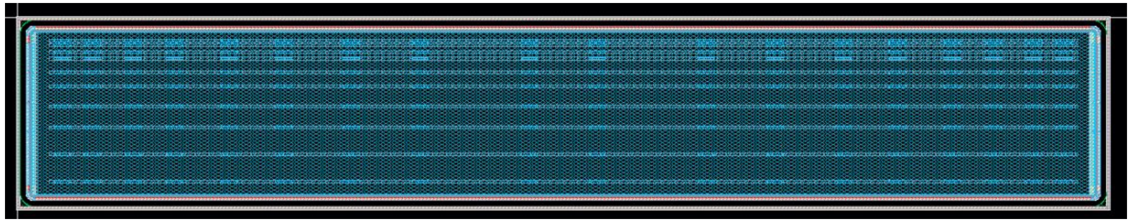
1、**AC-LGAD new design**, fabrication and testing—5.2024

New design

process parameter: active thickness, dielectric materials thickness, implantation parameters

structure design: Large size prototype, strip width and gap between strips

Prototype：40mmx0.1mm



Pitch: 0.1 mm-0.5mm

Length: 40 mm

2、**Beam testing** of AC-LGAD

low noise PCB board—design on going

evaluation

3、**radiation testing** of AC-LGAD

CEPC TOF: less radiation level

4、 **ASIC for AC-LGAD**

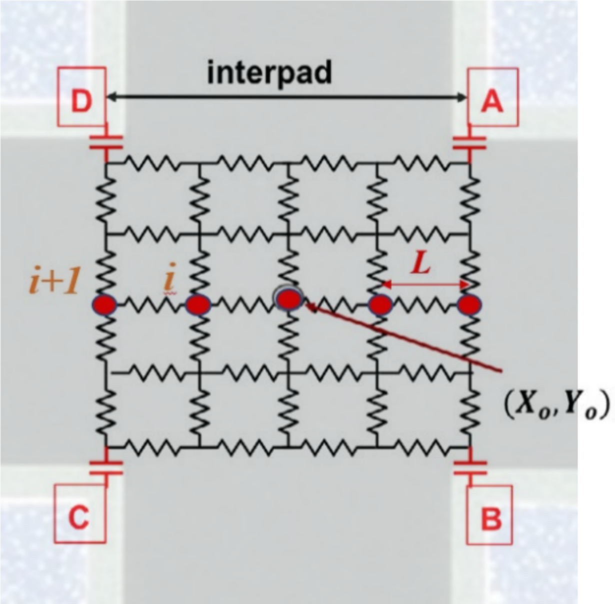
EICROC, H2GCROC… like ASIC

ASIC

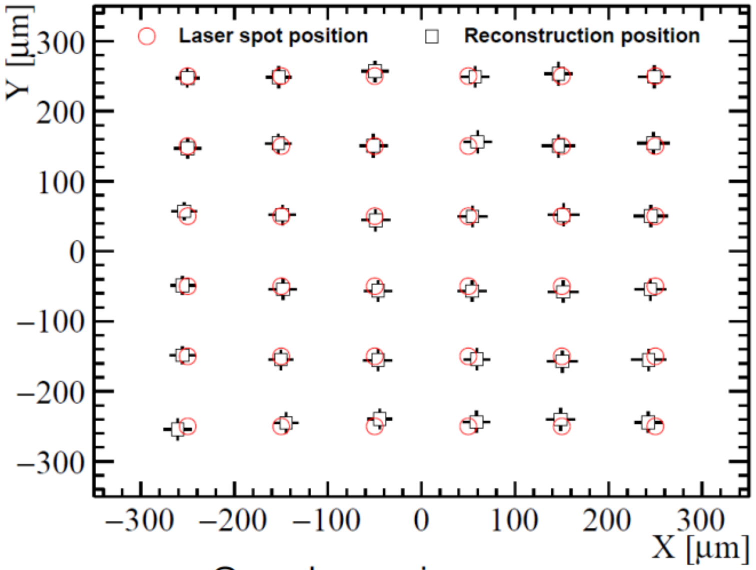
own ASIC chip(FPMROC)designed by IHEP electrical group

Thanks

Questions & Comments

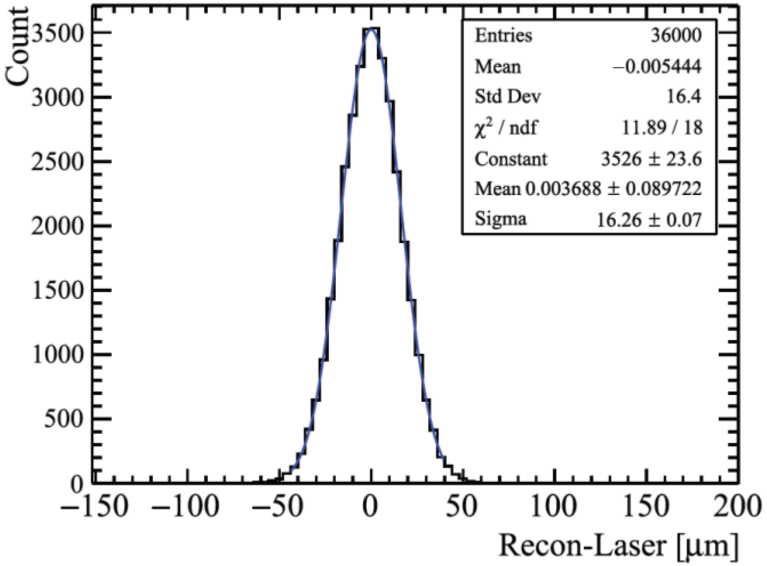


reconstructed 6x6 positions



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