

Time of flight detector based on LGAD technology for the Circular Electron Positron Collider

42ND INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

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Motivation: Time of Flight for CEPC

- CEPC: huge measurement potential for precision tests of SM (Higgs, electroweak physics, **flavor physics**, QCD/Top)

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

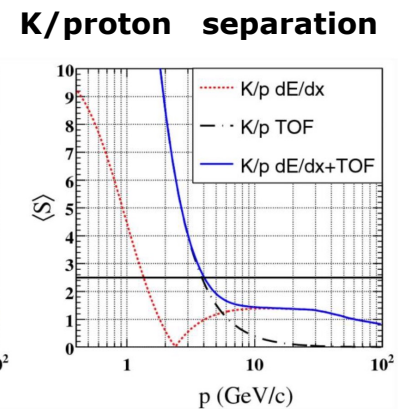
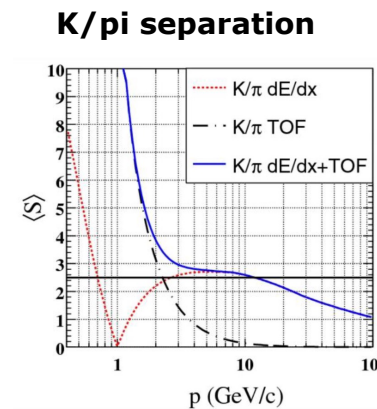
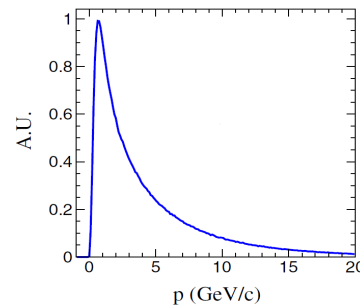
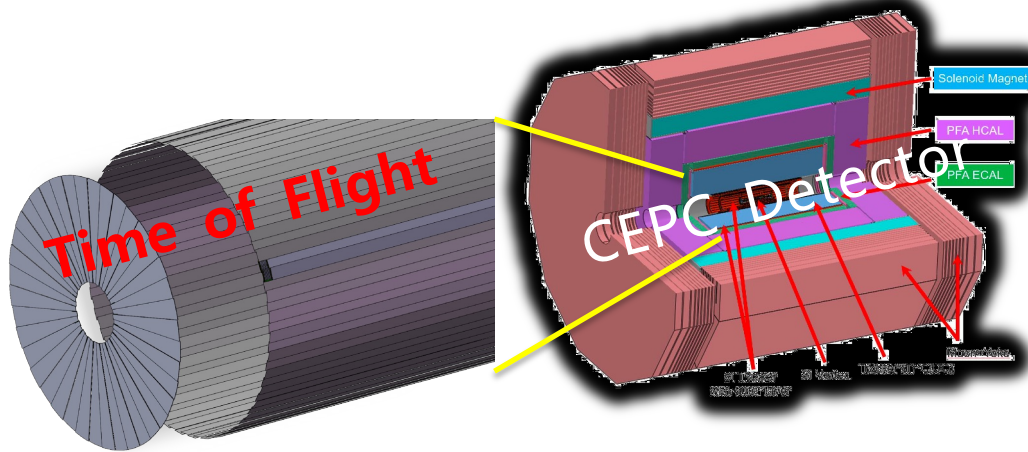
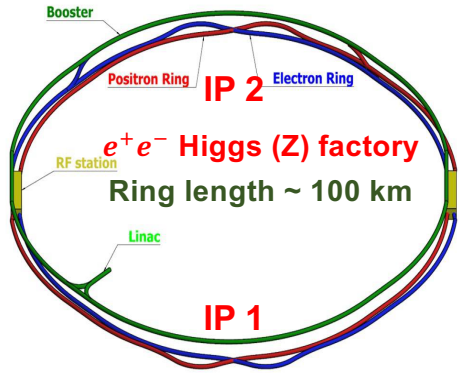
- 0.5-2 GeV for K/pi separation, >1.5 GeV for K/p separation

- 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

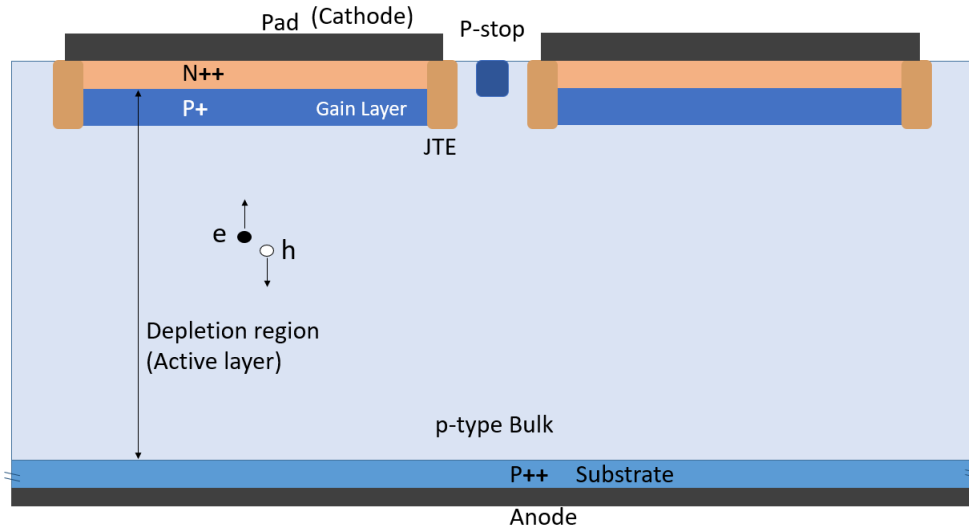
0 - 4 GeV for K/pi separation, 0 – 8 GeV for K/p separation



4D sensor AC-LGAD: time & spatial

LGAD (Low-Gain Avalanche Diode)

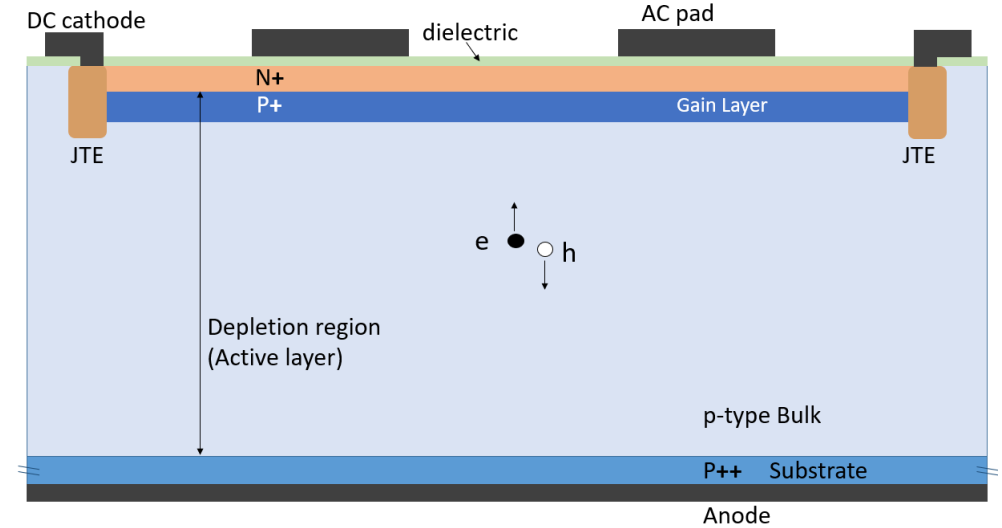
Segmented gain layer



- The read-out electronics is connected to n++ layer
- Time resolution $\sim 30\text{ps}$
- Position resolution: $\text{pixel size}/\sqrt{12}$
- Radiation hardness: $10^{15} \sim 10^{16} n_{\text{eq}}/\text{cm}^2$

AC-LGAD (AC-coupled LGAD)

Continuous gain layer



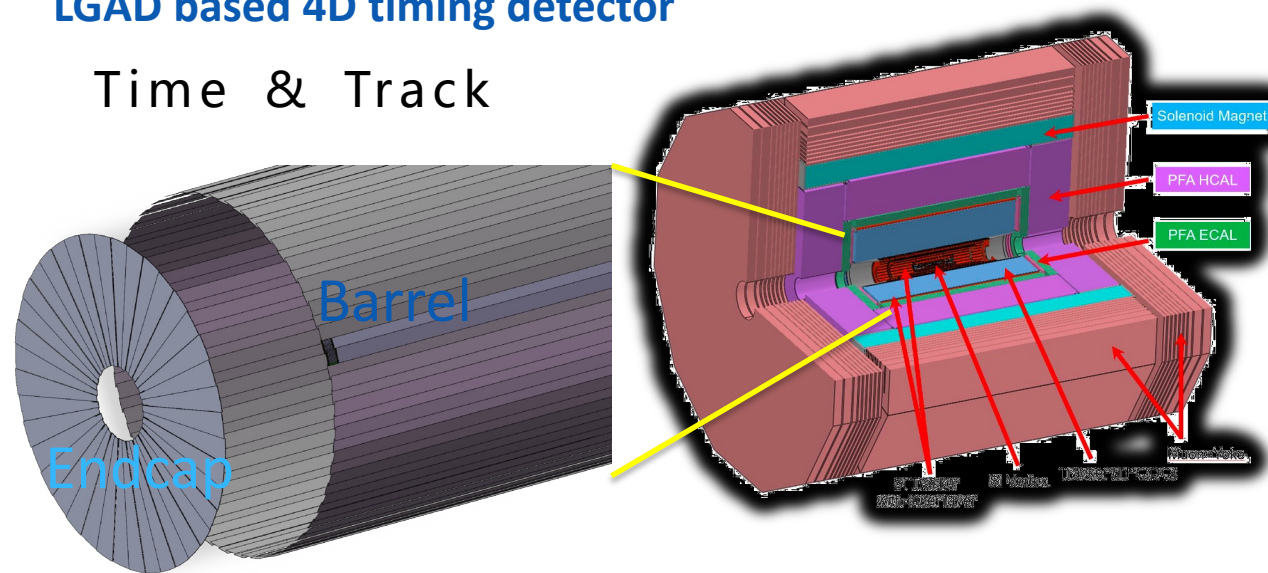
- Metal AC-pads separated from the n+ layer by a thin dielectric (Si_3N_4 , SiO_2)
- Time resolution $\sim 30\text{ps}$
- Position resolution: $5 \sim 10 \mu\text{m}$

Review of the ToF of CEPC

- **Develop LGAD based strip silicon sensors and detector modules**
 - spatial resolution better than **10 μm (R-phi direction)**
 - timing resolution in the range of **30-50 ps**.
- **Barrel & endcap: 70 m², 20 m²**
- **Sensor technology: AC-LGAD**

LGAD based 4D timing detector

Time & Track

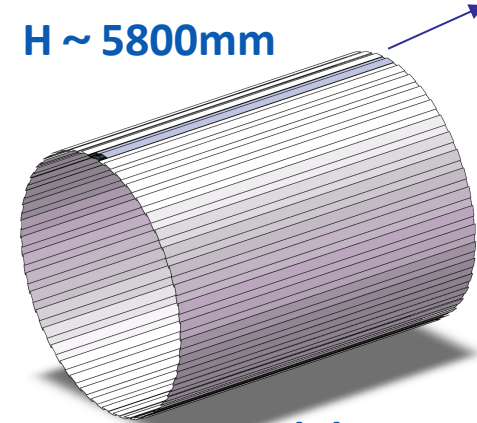
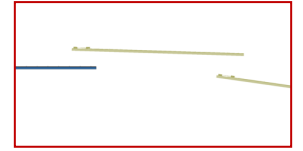


Reference TDR of CEPC

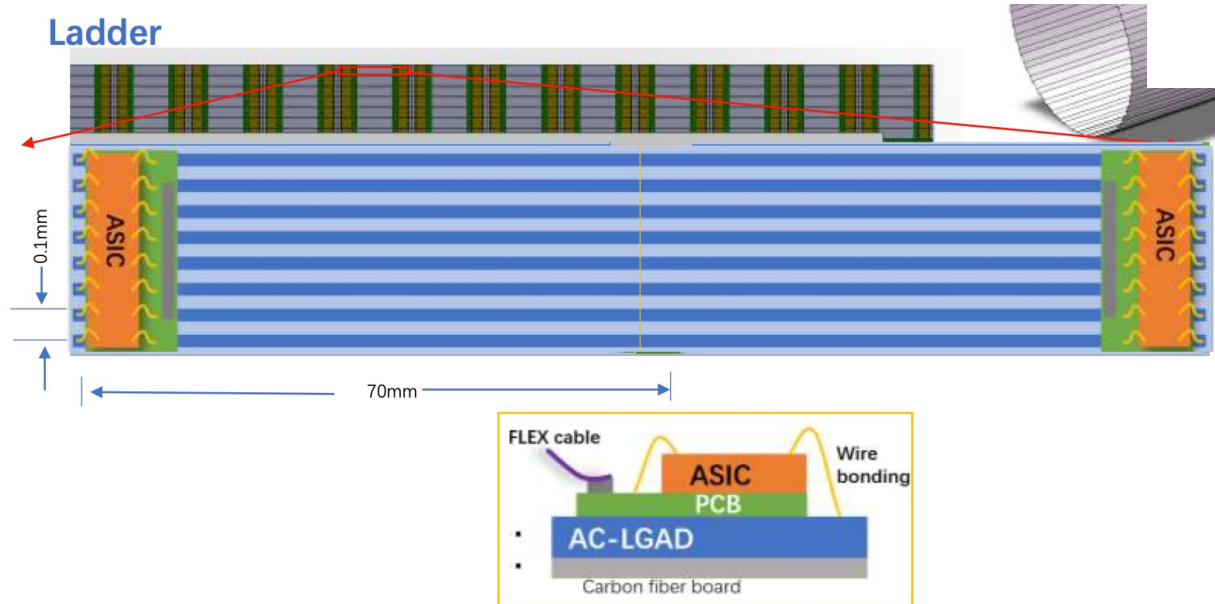
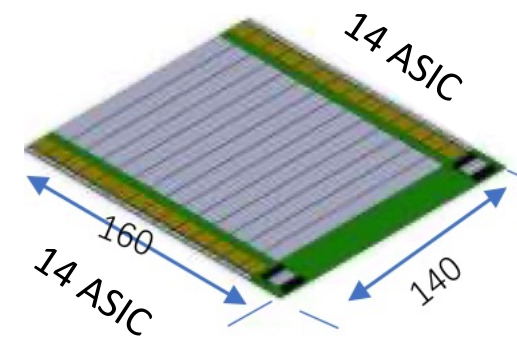
Arrangement of the ToF with strip LGAD: Barrel

- **One layer: 70 m², 3780 modules**
90 ladders, 45 ladders each side,
✓ 42 modules/ladder, 28 ASIC/module, 128 Channel/ASIC
- **Very challenging:**
 - Long ladder: **2900 mm ladder**
 - Large area ToF : 70 mm long strip/ module
 - High timing precision ASIC...

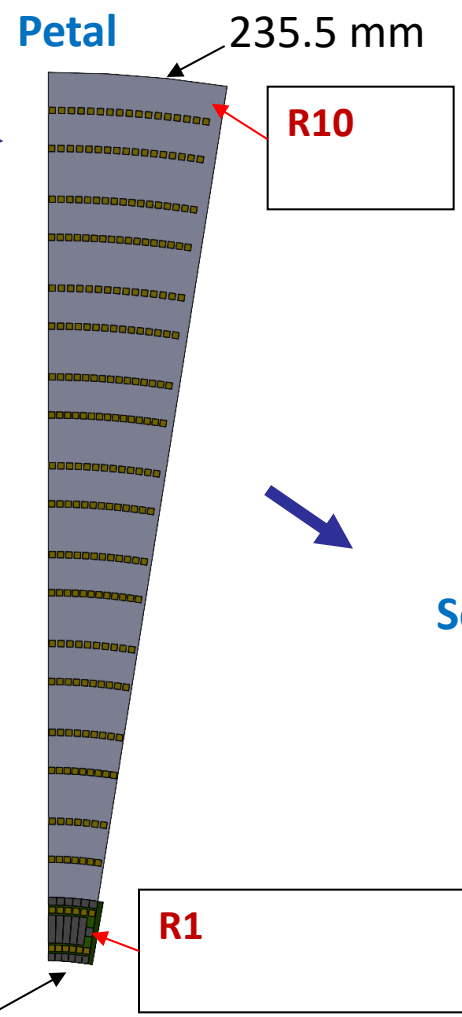
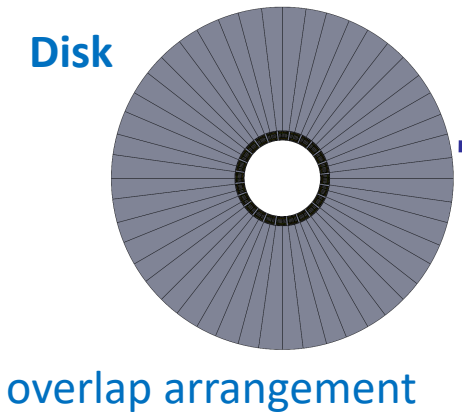
One layer ToF
R= 1800 mm
H ~ 5800mm



Module
140mm x 160mm

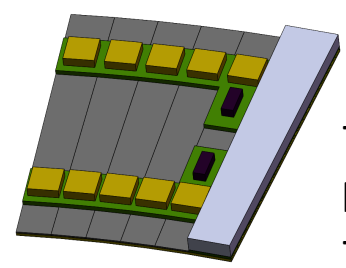


Endcap Design



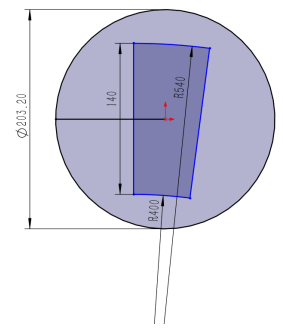
- Double layers to reduce the dead area
 - ✓ 24 petals/layer
 - ✓ 10 rows/petal,
 - ✓ 7.5° per row,
 - ✓ Overlap 0.5°/petal
- 140 mm / row at R direction

Sector Module per row



70 mm
R1: 52.36mm-
70.69mm

Sector/wedge shape sensor in the 8 inch wafer



Challenges for the LGAD based ToF & Out tracker

- ✓ **4D LGAD based sensor**
 - 30-50 ps and 10 μm
 - Long strip: 70 mm
 - Sector strip sensor for endcap
 - 50 μm
- ✓ **High time precision ASIC**
 - 40-48 bit TDC
 - Low power consumption
 - Fast timing
- ✓ **Large module:**
 - Long ladder: 2900 mm
 -

CEPC requirement for the sensor and ASIC

	CEPC TOF barrel	CEPC TOF endcap
Area (m ²)	~ 70	~19.4
Granularity	70mm \times 0.1mm	70mm \times 0.1mm
Capacitance	~10 pF	~10 pF
Charge	>15fC	>15fC
Channel number	~ 1\times10⁷	~ 2\times10⁶
Module assembly	Wire bonding at strip	Wire bonding at strip
MIP Time resolution	~30-50 ps	~30-50 ps
Spatial resolution	~ 10 μm	~ 10 μm (r- ϕ)
Number of channels per module	2816	2816
Data size	16 bit (9 TOT, 7 TOA) + channel(7bit, 128) +bunch ID(8bit) + chip ID (4-5 bit) ~40-48 bits	16 bit (9 TOT, 7 TOA) + channel(7bit, 128) +bunch ID(8bit) + chip ID (4-5 bit) ~40-48 bits

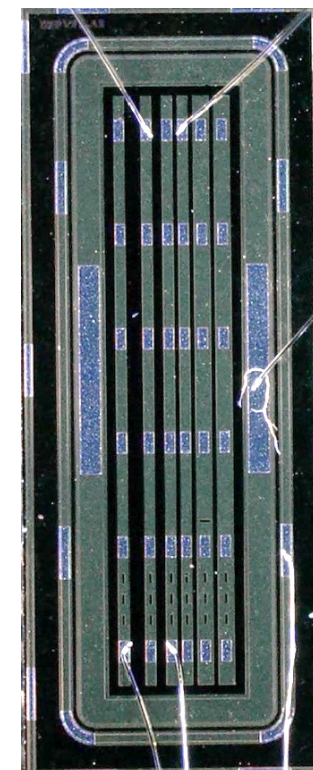
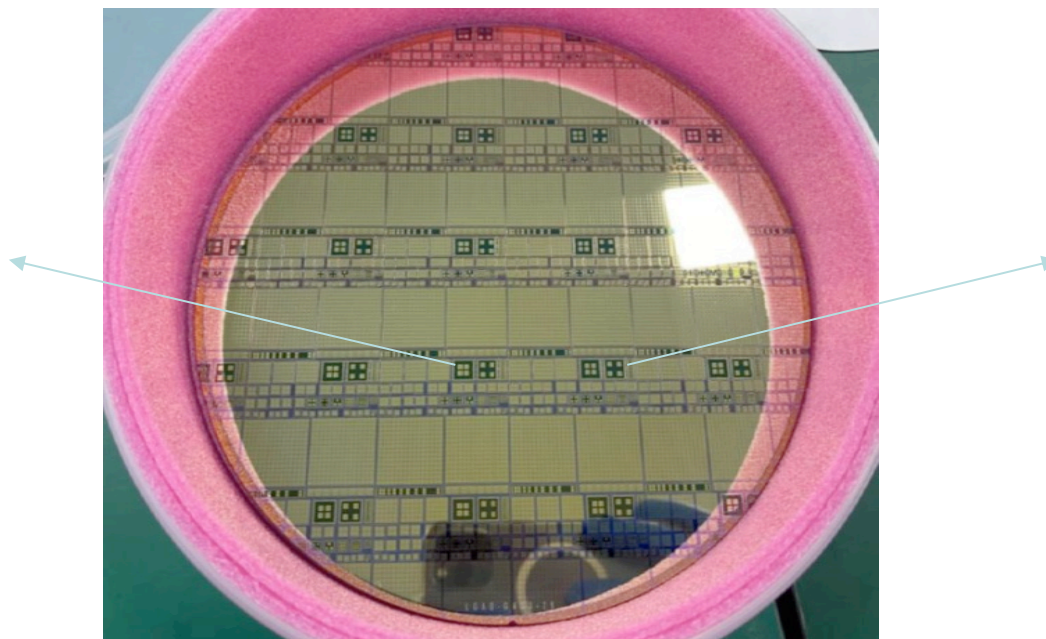
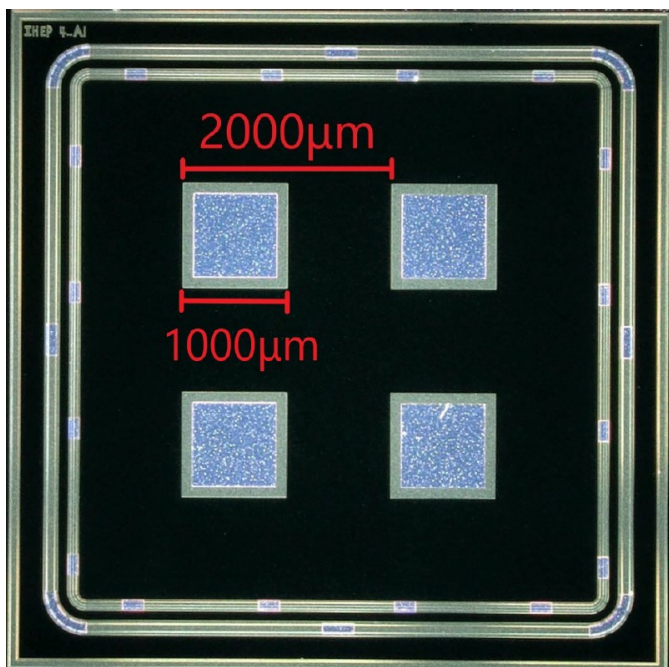
AC-LGAD sensors development at IHEP

Pixels AC-LGAD:

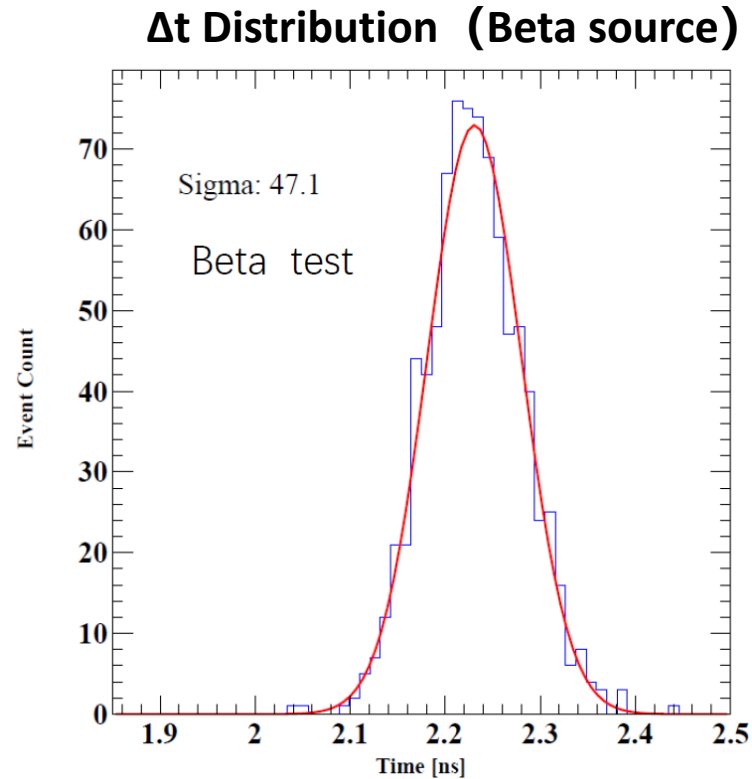
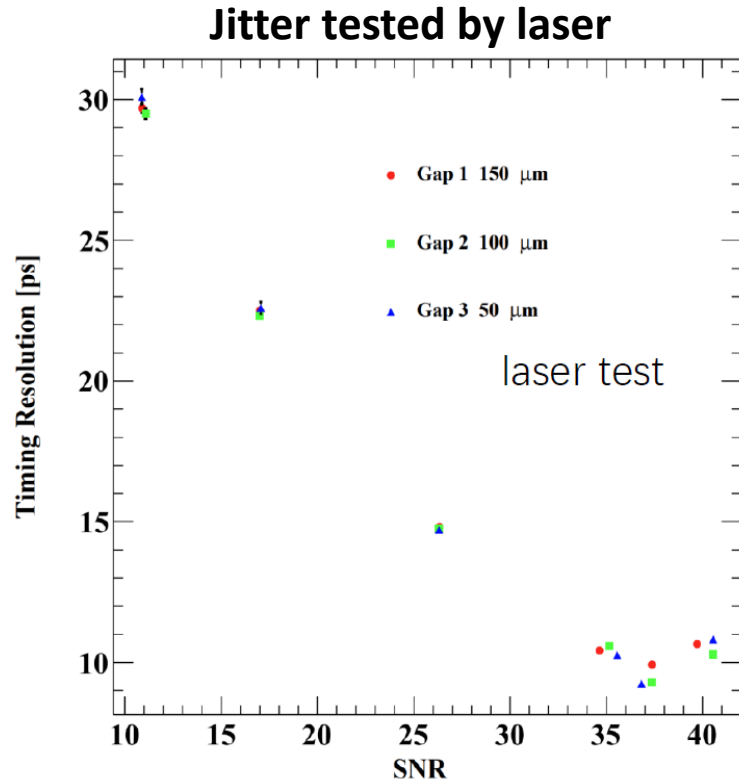
- Position information: 1 layer
- Pitch size 2000um, pad size 1000um
- Different N+ dose :
 - 10P, 5P, 1P, 0.5P, 0.2P

Strips AC-LGAD:

- Position information: 2 layer
- Strip length 5.6mm, width 100um
- Different Pitch size:
 - 150um, 200um, 250um



Performance of AC-LGAD: Time Resolution



Timing resolution of Trigger

$$\Delta T = T_{trigger} - \frac{\sum_i a_i^2 T_i}{\sum_i a_i^2}$$

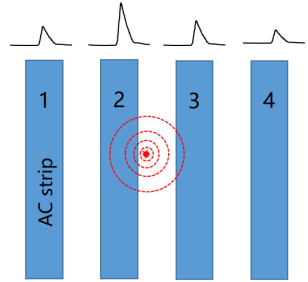
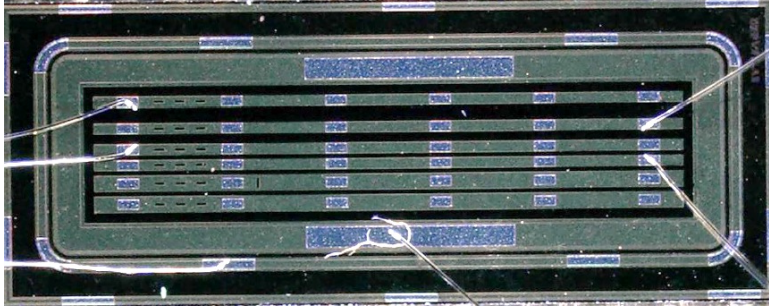
Weighted timing resolution of three strip electrodes

Sigma $\Delta t = 47.1$ ps

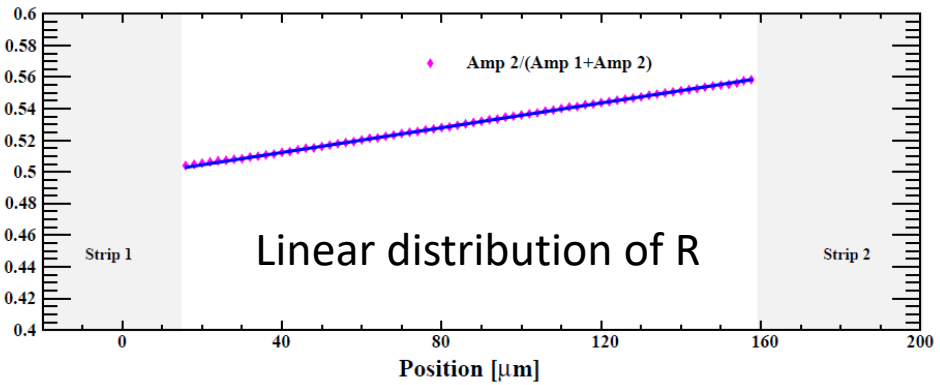
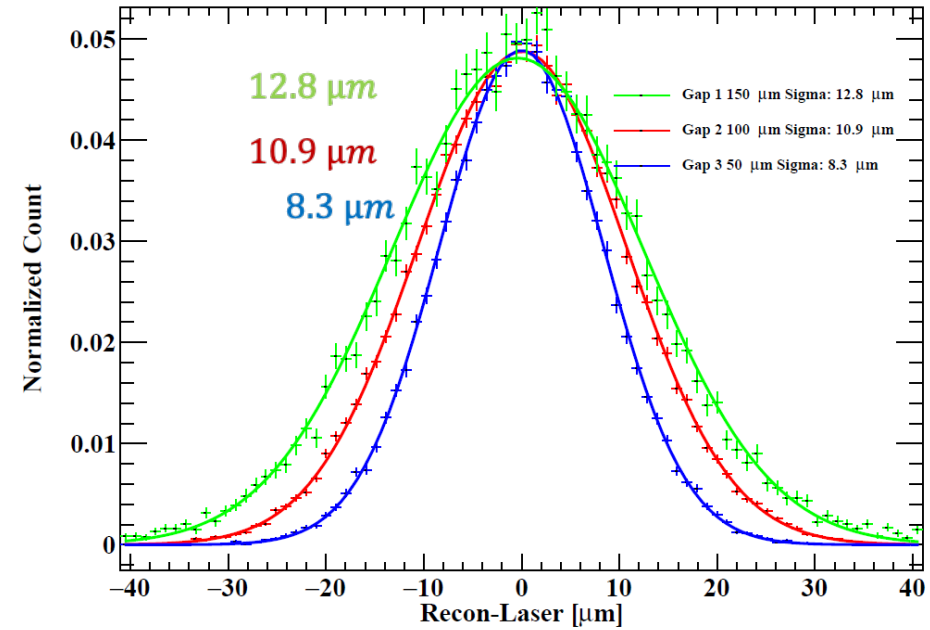
AC-LGAD strip : 37.5 ps

- No significant change in timing resolution was observed among different pitches
- Saturation may be observed, ~ 10 ps.
- **37.5 ps timing resolution**, via Beta source test.

Performance of AC-LGAD: Spatial Resolution



Spatial resolution :
8.3 μm
with 150 μm pitch



$$R = \frac{Amp_2}{Amp_1 + Amp_2}$$

Position reconstruction:

- The fraction of the signal (R) changes linearly with the movement of the laser.
- Good consistency between the reconstruction position and the laser position
- The smaller the pitch size, the better the spatial resolution

AC-LGAD: Spatial Resolution

- **Spatial resolution Vs. Pitch size**
 - ✓ Pitch size 250 μm \rightarrow 150 μm
 - ✓ Spatial resolution 11 \rightarrow 8 μm (Strip).
- **Smaller pitch sizes \rightarrow better spatial resolution**

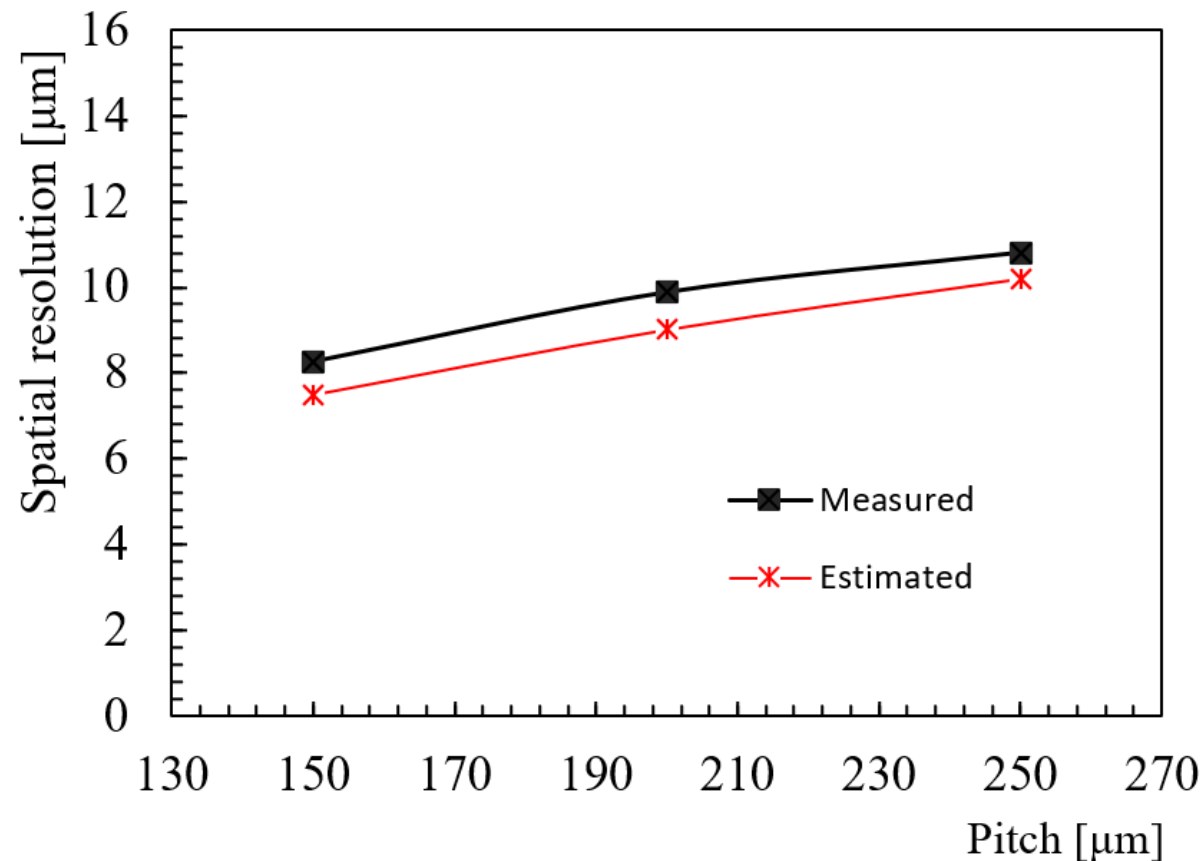
Resolution estimation:

$$\sigma_{\text{spatial}} \approx \frac{N}{A}$$

A: signal attenuation factor

N: noise RMS (sensor + electronics)

Spatial resolution Vs. pitch size



Milestones, deliverables and timeline

	Deliverable/Milestone Title	DRD /WG	Institute	Type	Dessemination Level	Due Data
M1	Report on LGAD based 4 D ToF for CEPC	WG2, WG5	IHEP...	Report	DRD3 report	Month 6 (Q4 2024)
D1	20 mm long strip and sector LGAD based 4 D sensor design, fabrication, beam test, ASIC	DRD7, WG5	IHEP, IME, STU...	Prototype	Manual/Presentation	Month 28 (Q1 2026)
M2	Report on demonstration Sensor performance	WG2, WG5	IHEP...	Report	Publication	Month 34 (Q3 2026)
D2	40mm long strip and sector LGAD based 4 D sensor design, fabrication, beam test	WG2, DRD7, WG5	IHEP, IME, STU...	Prototype	Manual/Presentation	Month 46 (Q1 2027)
M3	Report on demonstration Sensor performance	WG2, WG5	IHEP	Report	Publication	Month 52 (Q3 2027)
D3	70 mm long strip and sector sensor , ASIC full module	WG2,DRD7, WG5	IHEP, IME, STU	Prototype	Manual/Presentation	Month 67 (Q1 2030)
M4	Report on demonstration module performance	WG2, WG5	IHEP	Report	Publication	Month 78 (Q4 2030)

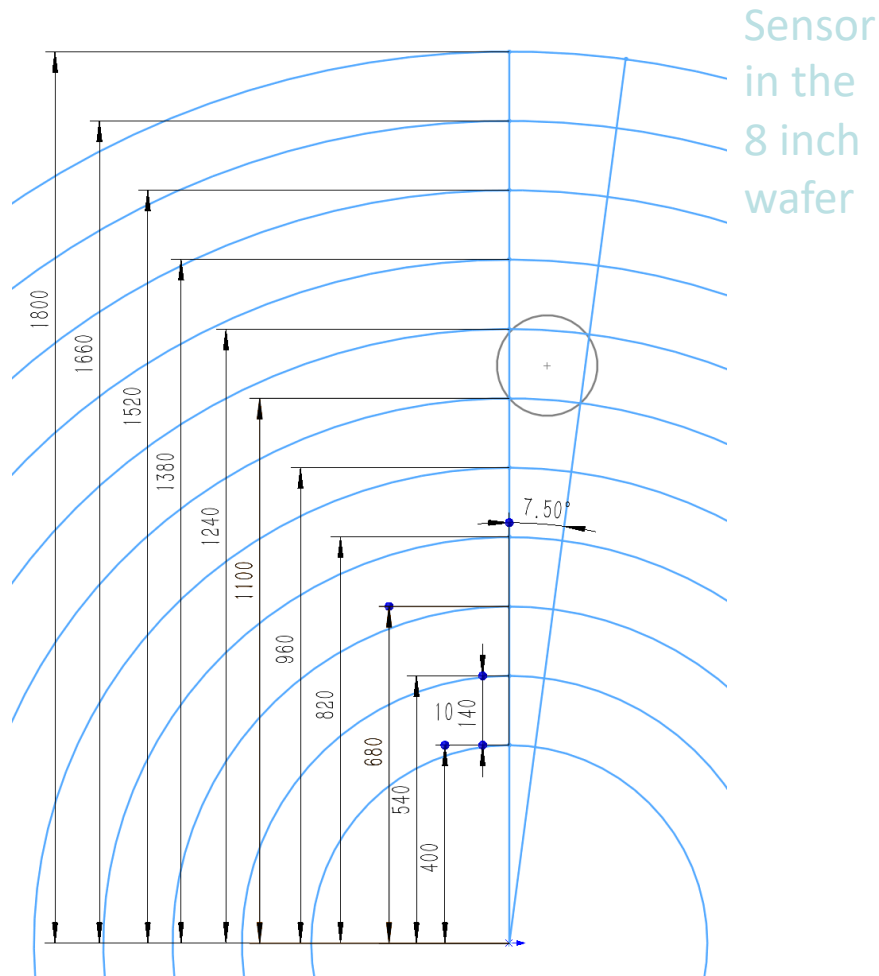
Summary

- **LGAD based Timing tracker development for the CEPC**
 - Important for flavor physics of CEPC
 - Improve the k/pi,k/p separation at low energy part
 - Total area: 70 m² (Barrel) + 20 m² (Endcap)
 - Readout channels 10⁶
- **Very challenge!**
 - 4 D track, 30-50 ps and 10 μm (**R-phi direction**)
 - Large area, sector strip, long strip
 - High precision time resolution electronics readout

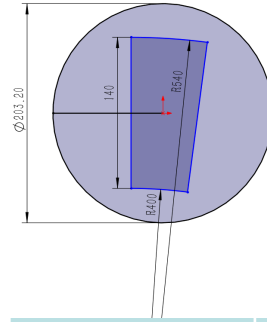
**Thank you for your
attention !**



Sensor Arrangement and the readout channel



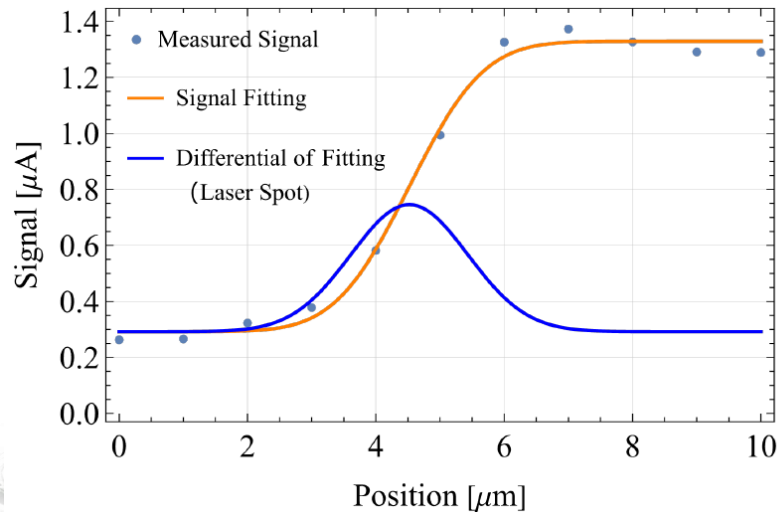
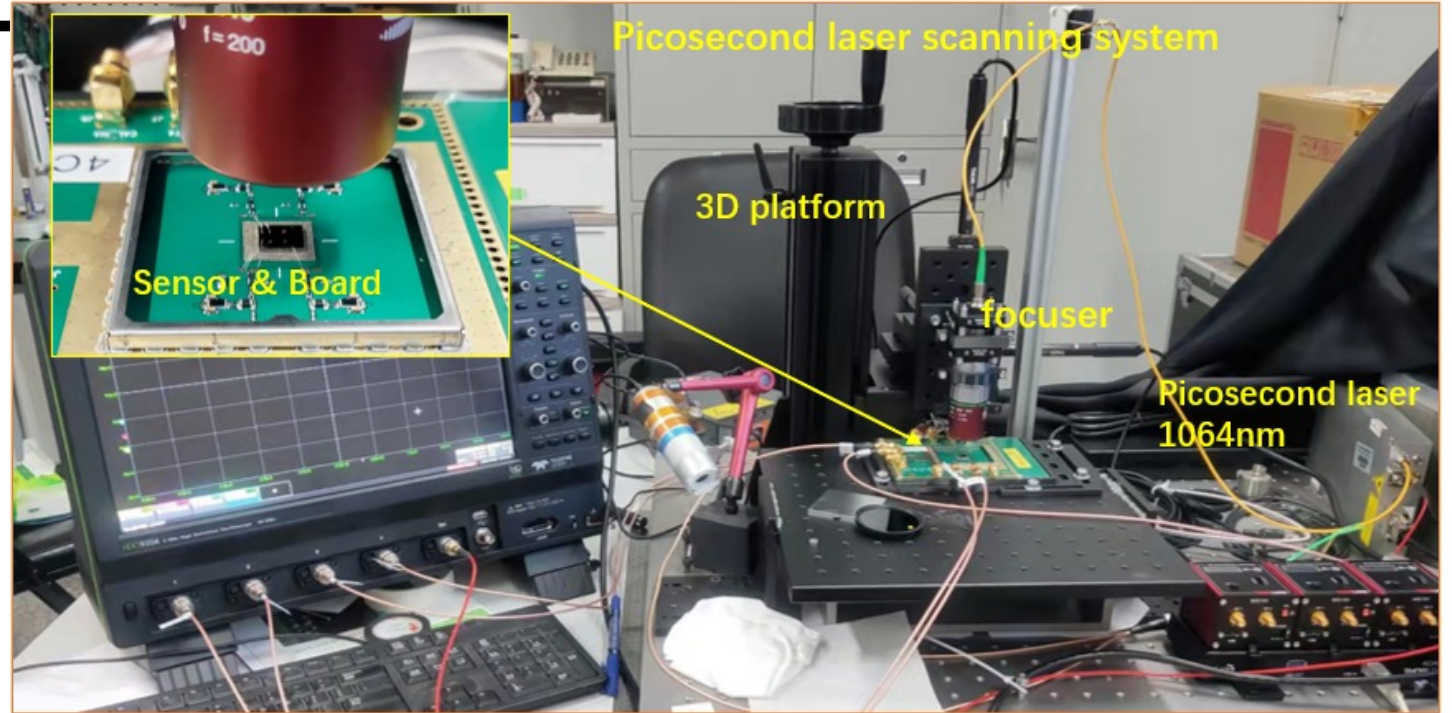
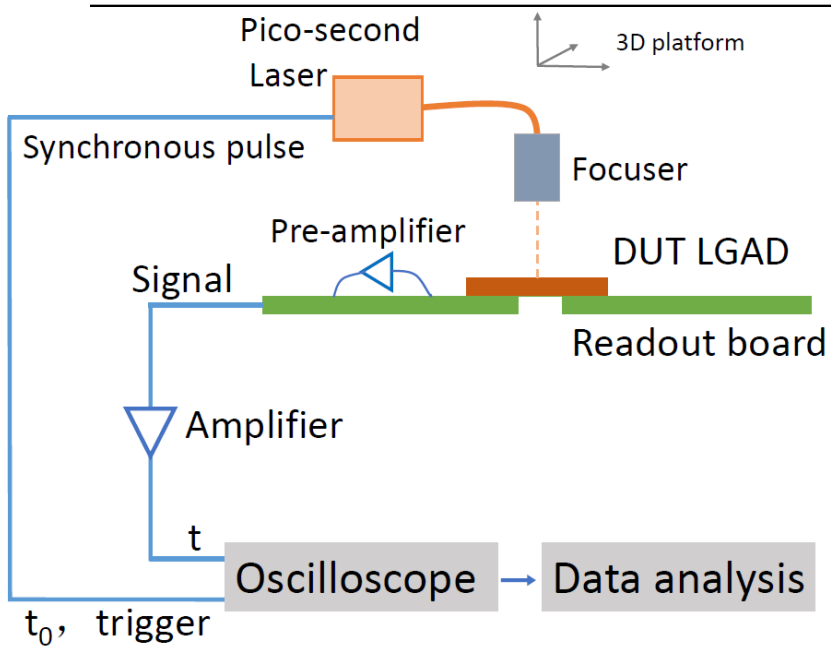
Sensor in the 8 inch wafer



位置分辨: 10 um (最大pitch 100 um)

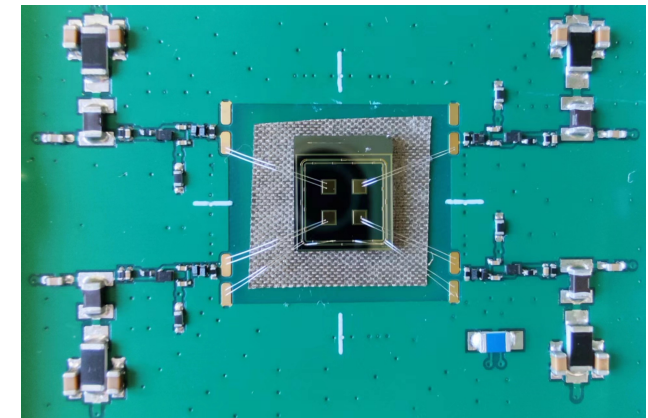
		Maximum Arc (mm)	Readout channel number	Sensor number	Old number	Hit Rate Hz/cm ²
R0 (400-540)	52.36	70.686	707	1		10 ⁵
R1: 540-680	70.69	89.012	891	1		10 ³
R2: 680-820	89.012	107.338	1074	1		10 ²
R3:		125.664	1257	1		20
R4	125.664	143.990	1440	1		20
R5		162.316	1624	2		20
R6		180.642	1807	2		20
R7		198.968	1990	2		20
R8		217.294	2173	2		20
R9: 1660-1800		235.620	2357	2		20

4.1 AC-LGAD sensor test : Picosecond laser test

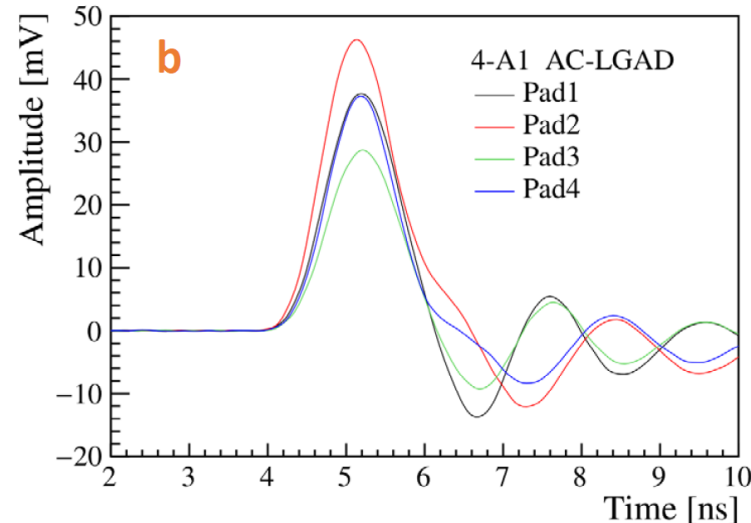
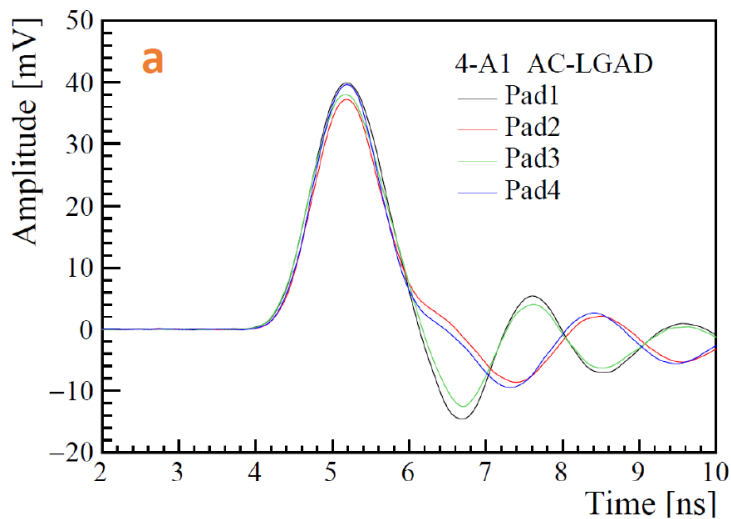
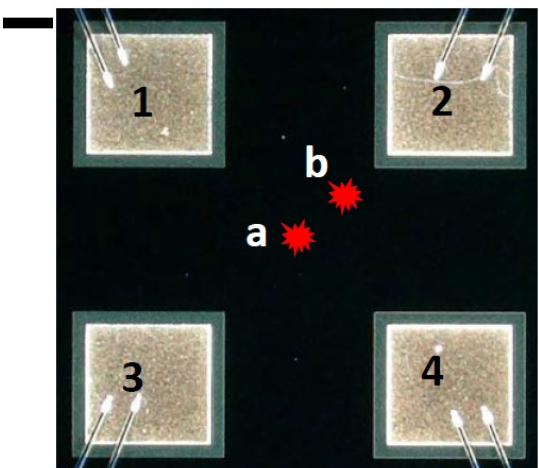


Picosecond laser scanning system

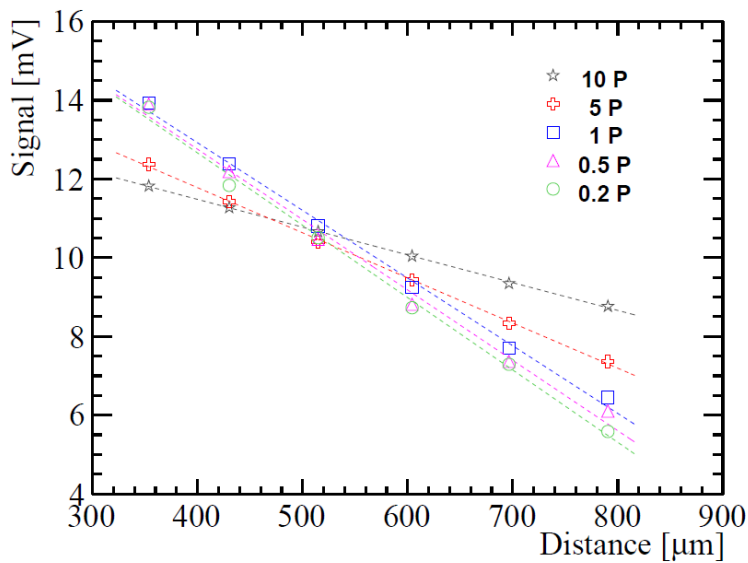
- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Spot size 2~5 μm



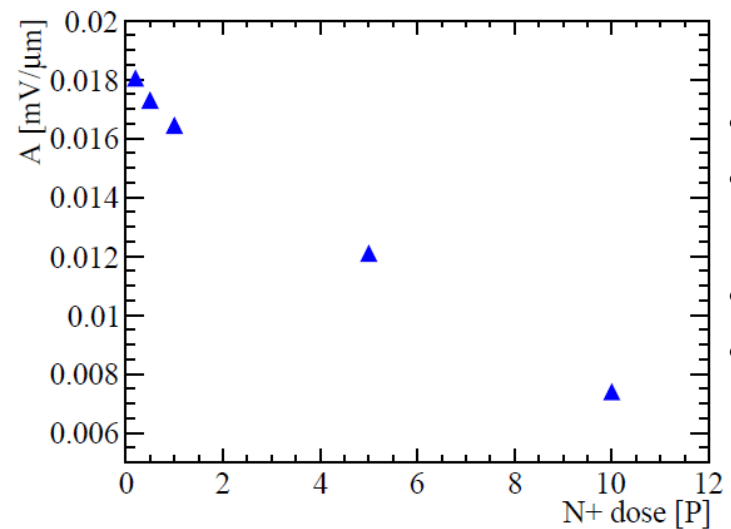
4.2 AC-LGAD sensor test: Signal attenuation



signal amplitude vs. distance



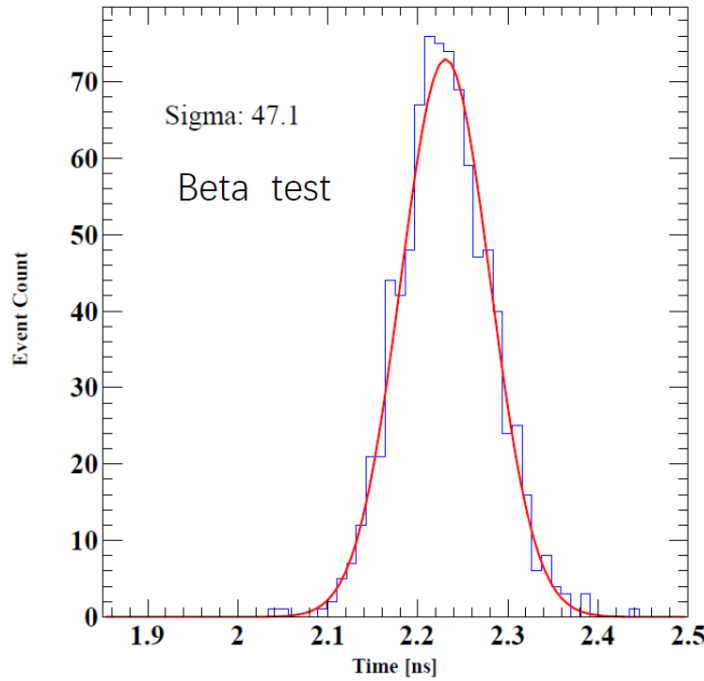
attenuation factor A



- The signal decreases with distance
- The factor A is obtained by the linear fit
- The A decreases with the increase of N+ dose
- Low N + dose means high resistivity

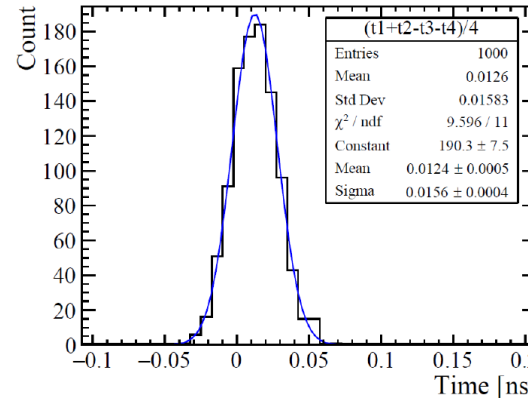
III Performance of AC-LGAD | Timing Resolution

Time resolution



Sigma $\Delta t = 47.1$ ps

Sigma AC-strip : 37.5 ps



Time Resolution

$$\Delta T = T_{trigger} - \frac{\sum_i a_i^2 T_i}{\sum_i a_i^2}$$

Time resolution of trigger

Weighted time resolution of AC-LGAD

Area (m²)

~ 70 m²

Radius

1.8m

Length

5.8m

Granularity

**70mm × 0.1mm
(10cm², 128channel/chip)**

Channel number

~ 1 × 10⁷ channels

MIP Time resolution

~50 ps

Spatial resolution

~ 10 μm (R-Φ)

~ 1 mm (R-Z direction)

LGAD Sensor Area

14cm*14cm

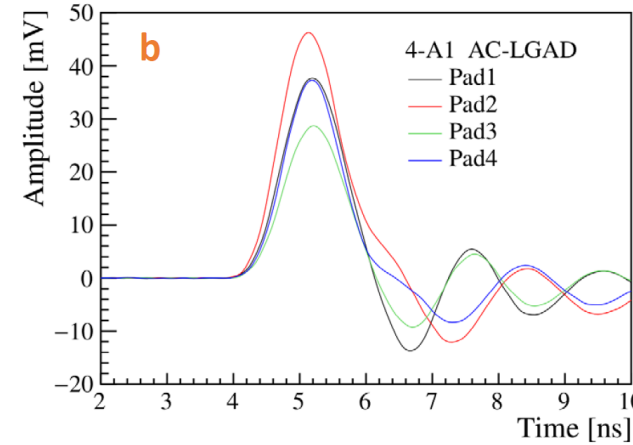
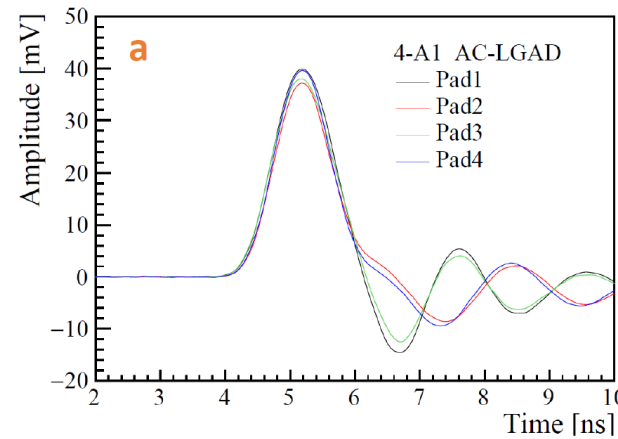
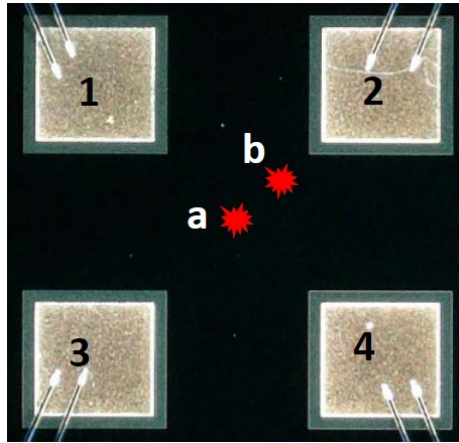
**Number of channels
per module**

2816 (22 chip, 128channel/chip)

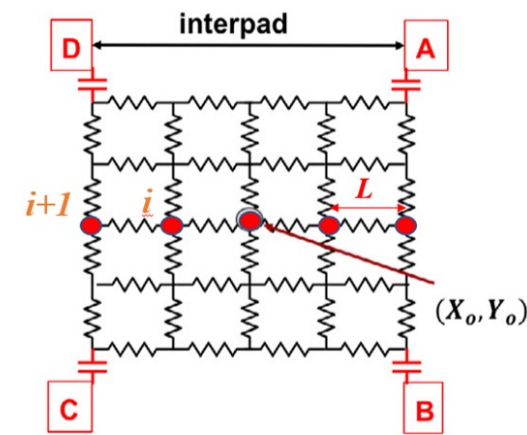
- No significant change in timing resolution was observed among pixel and strip LGADs.
- Timing resolution improves as increasing in SNR, same trend as in spatial resolution.
- Saturation may be observed in jitter, ~ 10 ps.
- 37.5 ps timing resolution, via Beta source test.

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

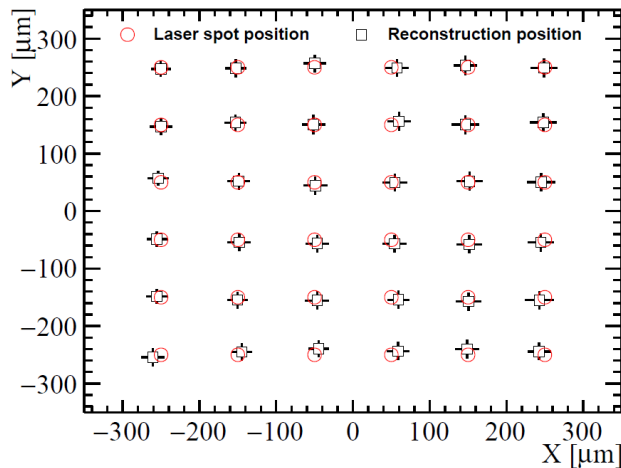
III Performance of AC-LGAD | Spatial Resolution--Pixel



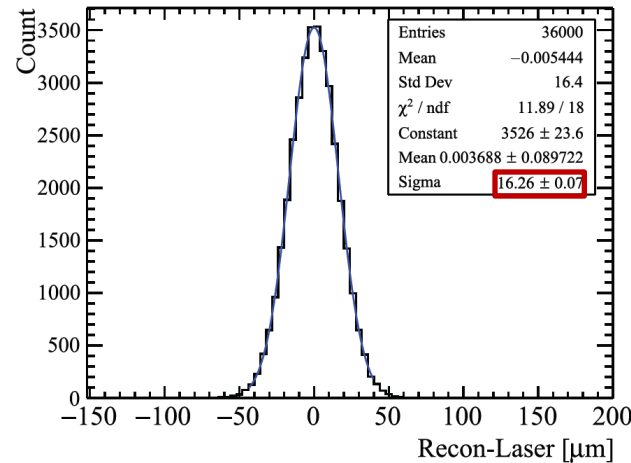
Signal Waveforms @ hit a and b



Discretized Positioning Circuit model (DPC)



Reconstructed 6x6 positions



Difference between reconstruction and laser

Barrel Spatial Resolution Target $\sim 10 \mu\text{m}$ (R- Φ)
 $\sim 1 \text{ mm}$ (R-Z direction)

Spatial resolution

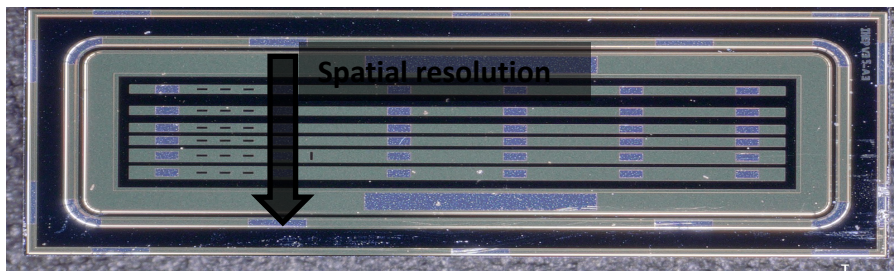
$16 \mu\text{m}$ with 2mm x 2mm pitch

Spatial resolution :

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

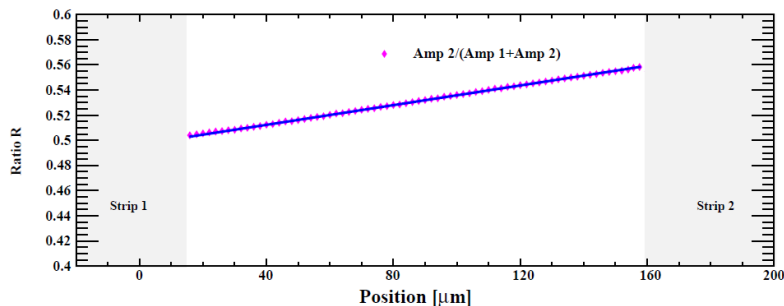
$$\sigma_{\text{spatial}} = \sigma_{\text{reconstruction-laser}}$$

III Performance of AC-LGAD | Spatial Resolution--Strip

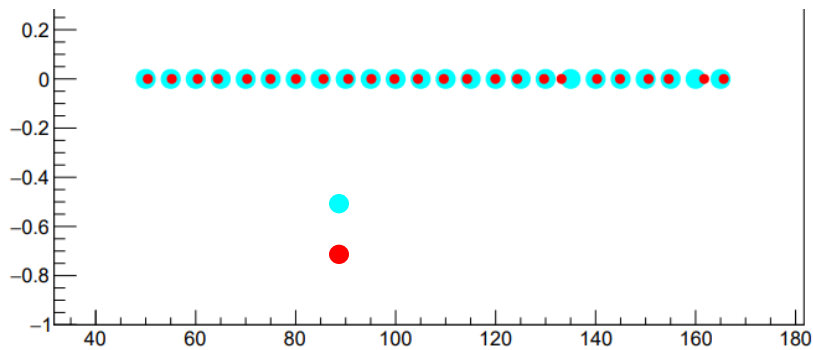


$$R = \frac{Amp_2}{Amp_1 + Amp_2}$$

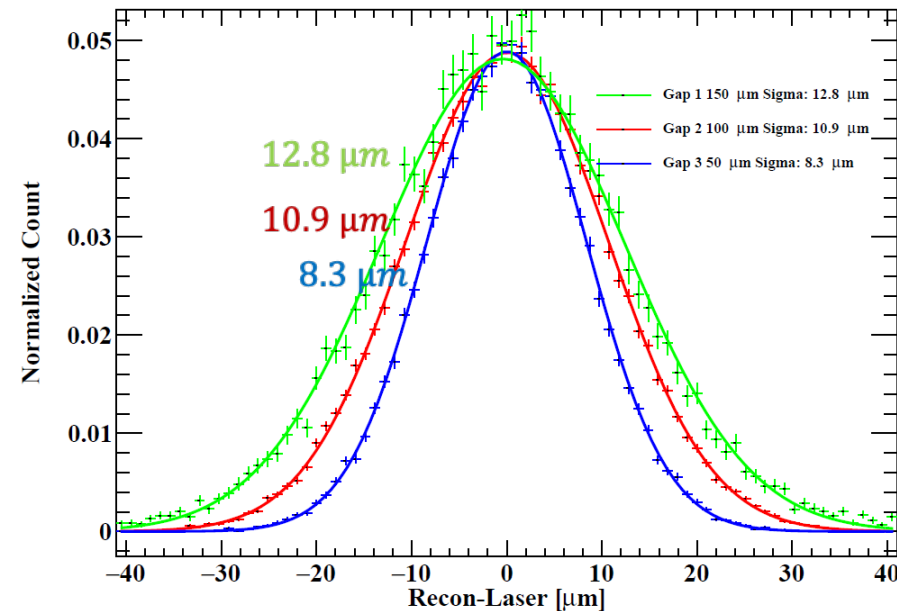
Spatial resolution :
8.3 μm
 with 150 μm pitch



Linear distribution of R



reconstructed positions

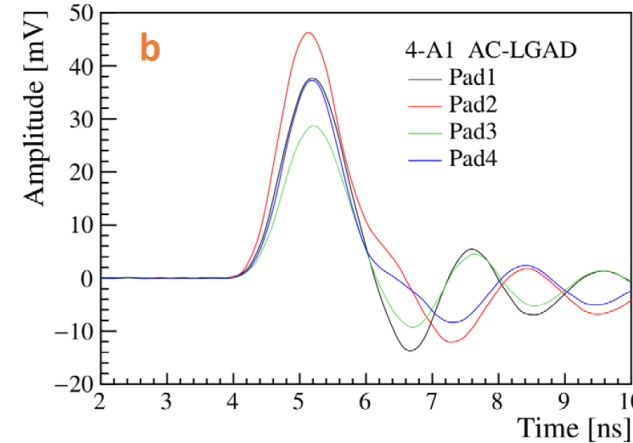
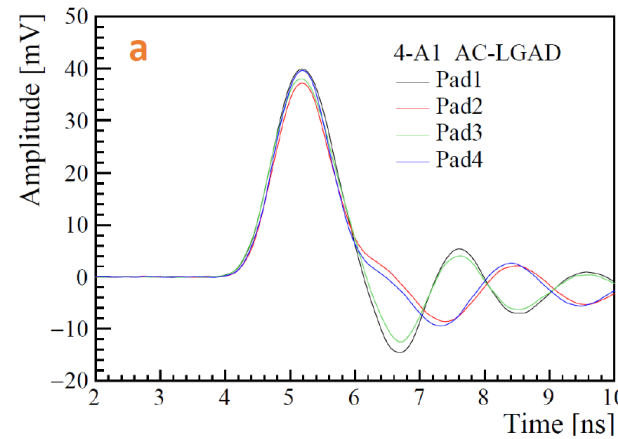
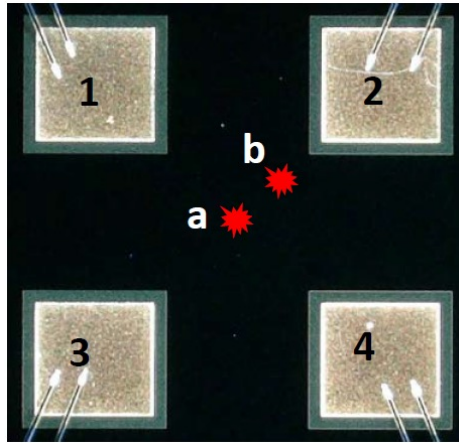


Barrel Spatial Resolution Target $\sim 10 \mu m$ (R- Φ)
 $\sim 1 \text{ mm}$ (R-Z direction)

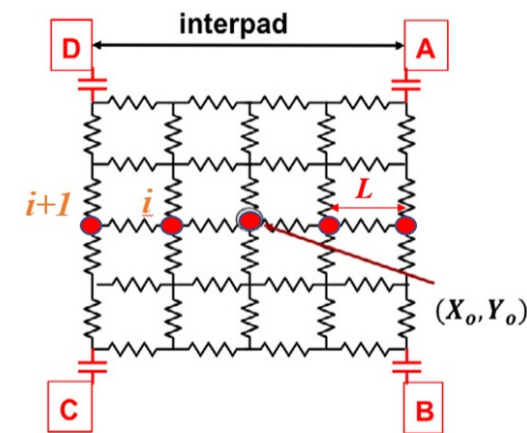
Position reconstruction:

- The fraction of the signal (R) changes linearly with the movement of the laser.
- Good consistency between the reconstruction position and the laser position
- The smaller the pitch size, the better the spatial resolution

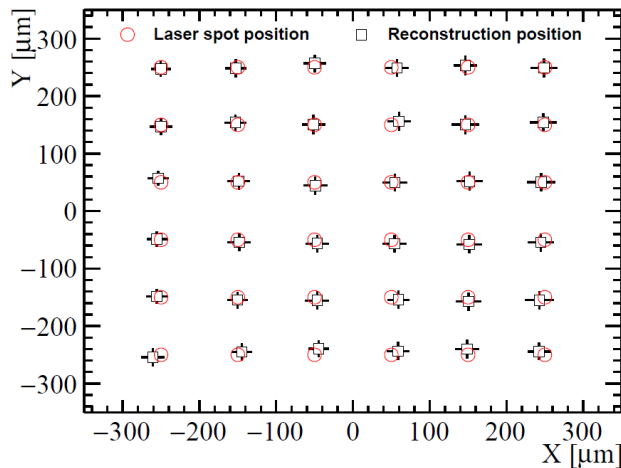
III Performance of AC-LGAD | Spatial Resolution--Pixel



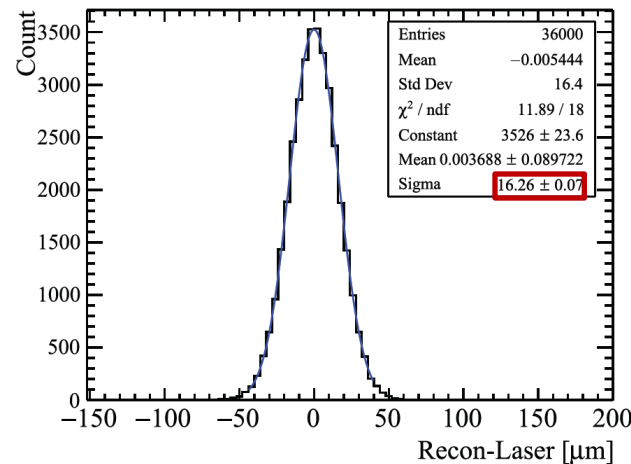
Signal Waveforms @ hit a and b



Discretized Positioning Circuit model (DPC)



Reconstructed 6x6 positions



Difference between reconstruction and laser

Barrel Spatial Resolution Target $\sim 10 \mu\text{m}$ (R- Φ)
 $\sim 1 \text{ mm}$ (R-Z direction)

Spatial resolution

16 μm with 2mm x 2mm pitch

Spatial resolution :

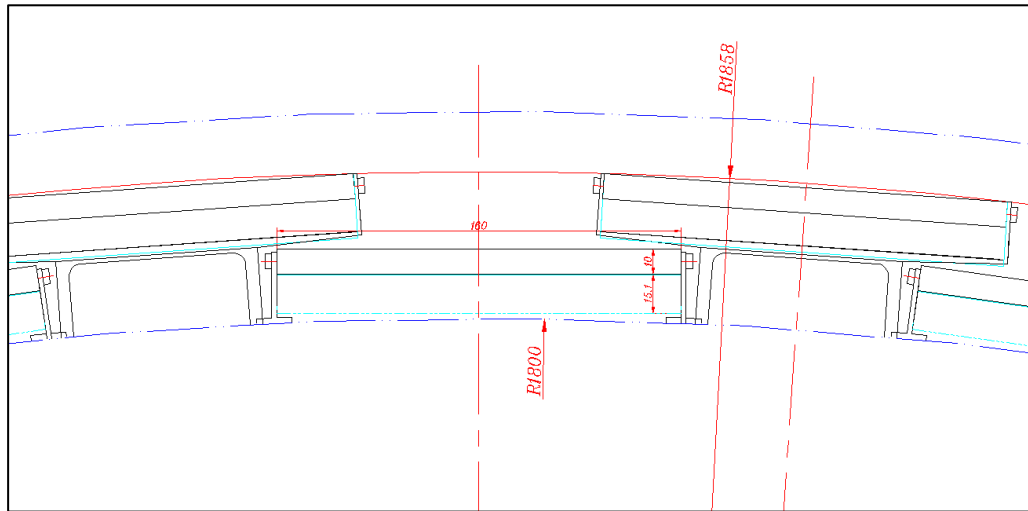
- the sigma of the difference between the laser and the reconstructed position

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

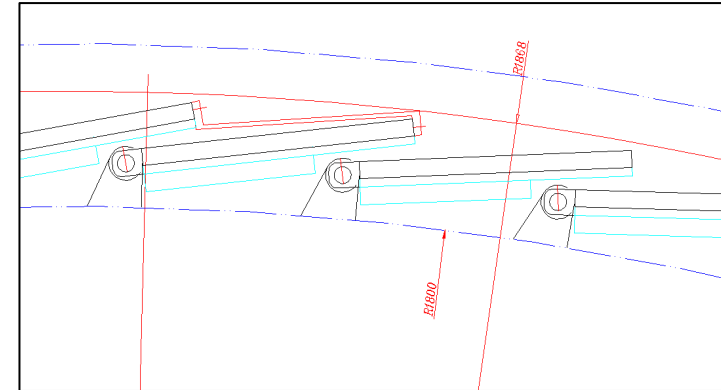
Optimization of the Barrel Design

- Three arrangement of the ladder

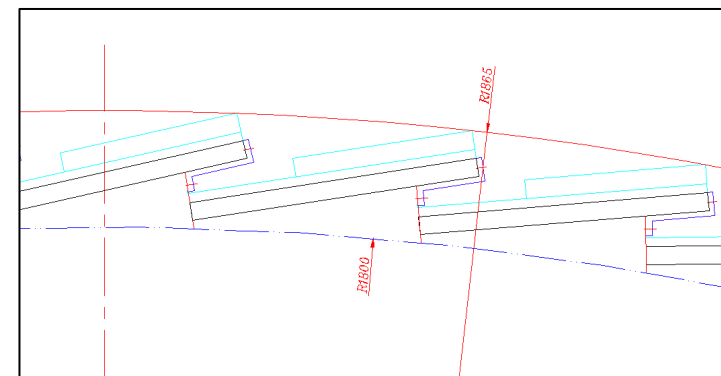
G1: $\Delta R = 58$ mm (**The Best arrangement**)
Sensor towards the IP



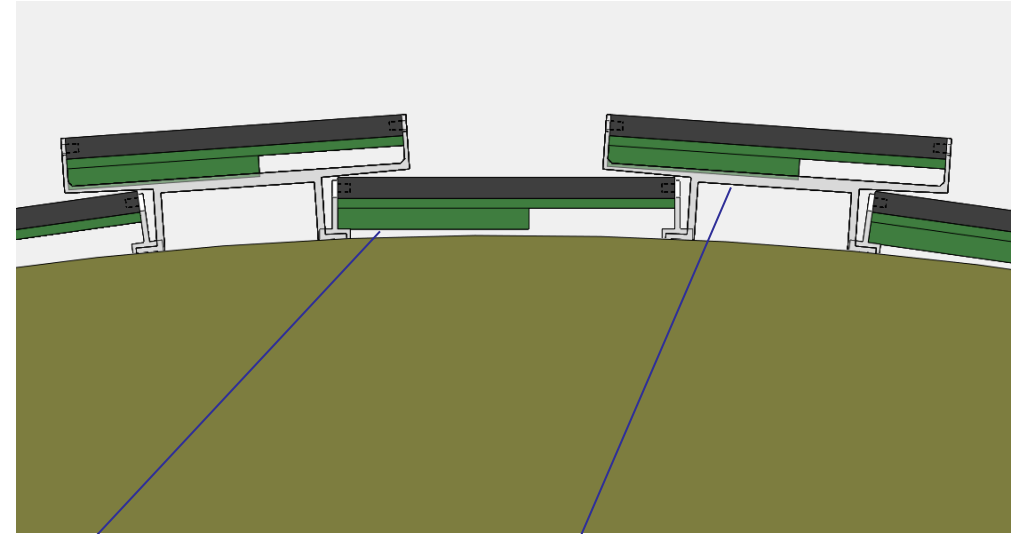
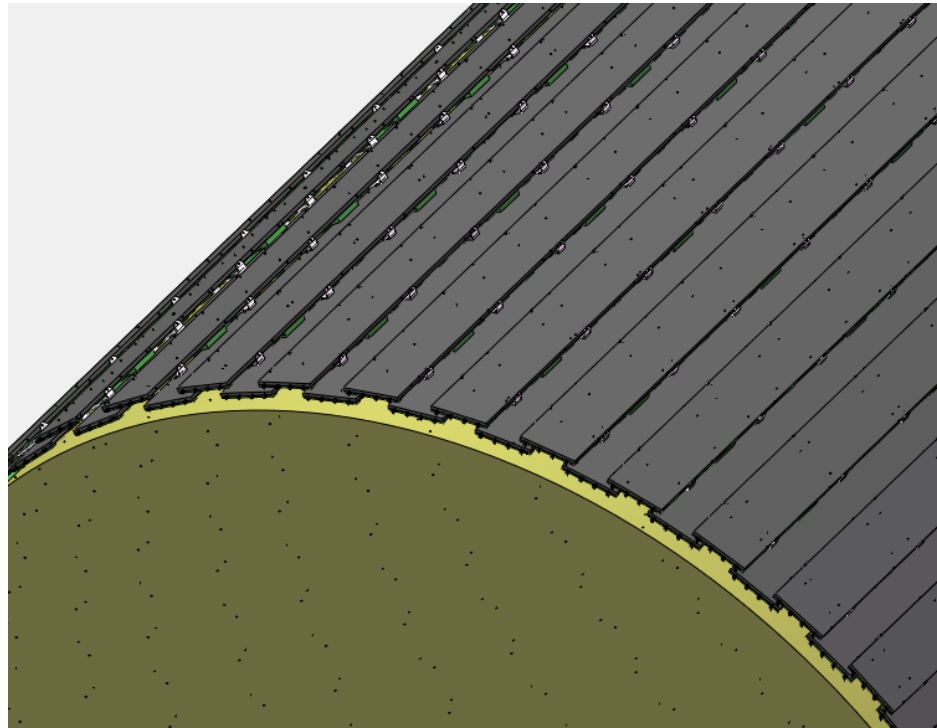
G2: $\Delta R = 68$ mm



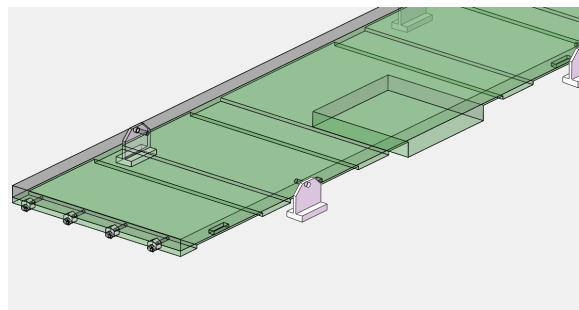
G3: $\Delta R = 65$ mm



3D module of the Barrel



Higher Ladder



Lower Ladder

