Development and Performance of Centimeter-Scale AC-LGAD Detectors for the CEPC Outer Silicon Tracker

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On be half of CEPC OTK group

2026-10-22

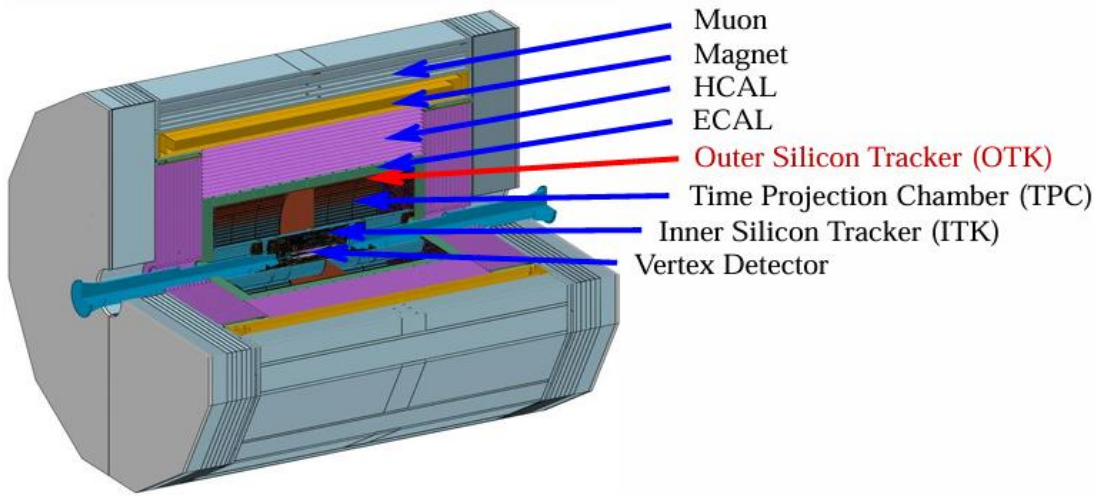
CEPC

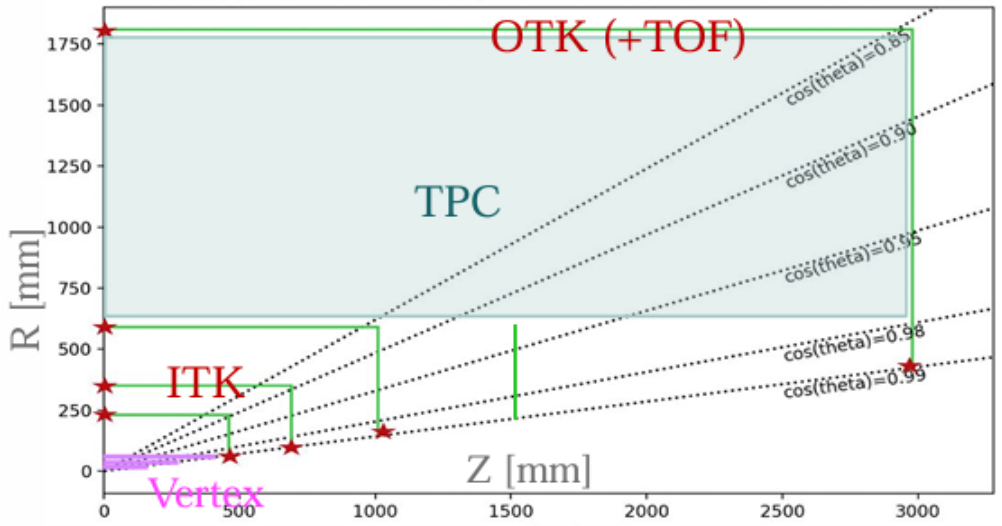
CIRCULAR ELECTRON POSITRON COLLIDER

AGORA

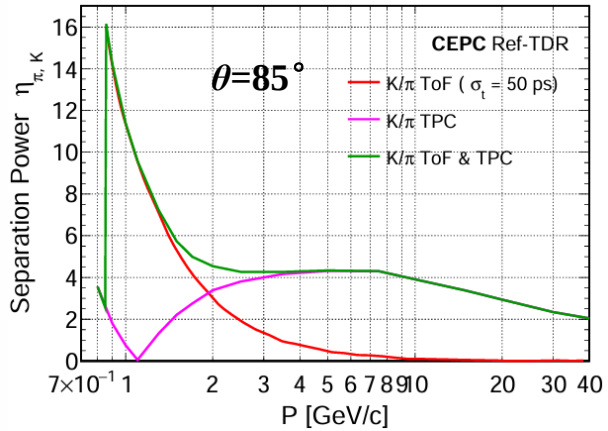
ADVANCED GLASS OPTIMIZED RESEARCH APPARATUS

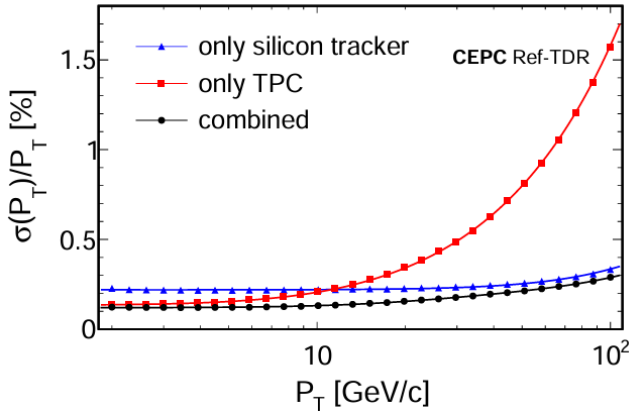
CEPC Outer Silicon Tracker





- **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:
  0-4 GeV for K/π separation, 0-8 GeV for K/p separation
  Improve momentum measurement
- **Barrel: 65 m², Endcap: 20 m²**
- **Requirement for detector： timing resolution~50ps, spatial resolution~10μm**

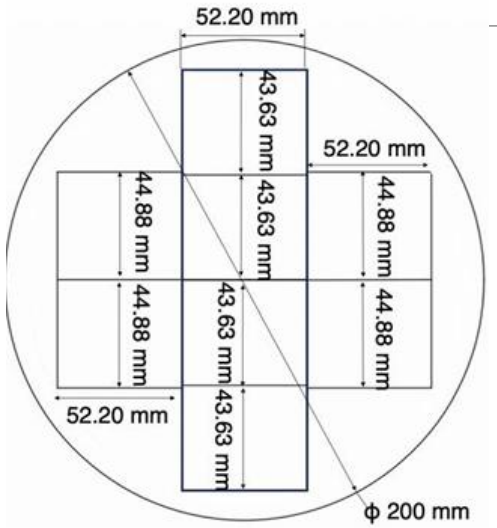


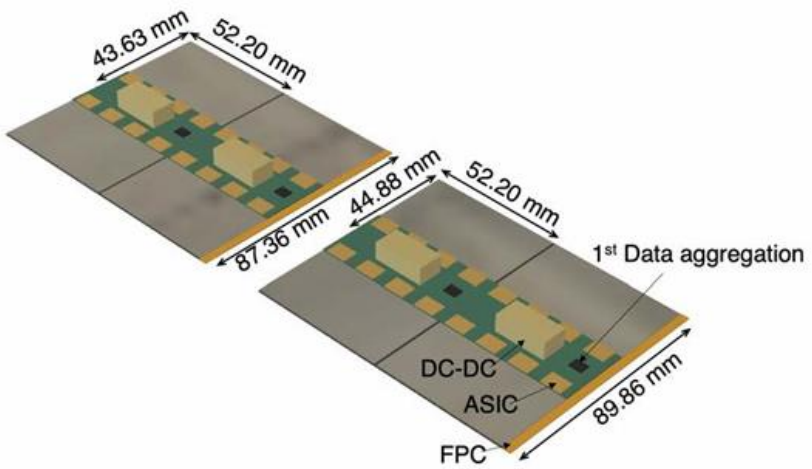


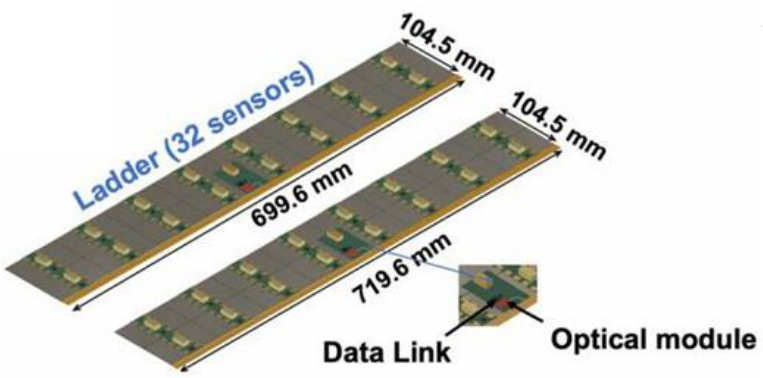
[1] **CEPC Technical Design Report -- Reference Detector**
https://doi.org/10.48550/arXiv.2510.05260

CEPC Outer silicon tracker

- **AC-LGAD strip sensor is the choice for CEPC OTK baseline since it can provide both high-precision timing information for particle identification and spatial resolution for momentum measurement.**







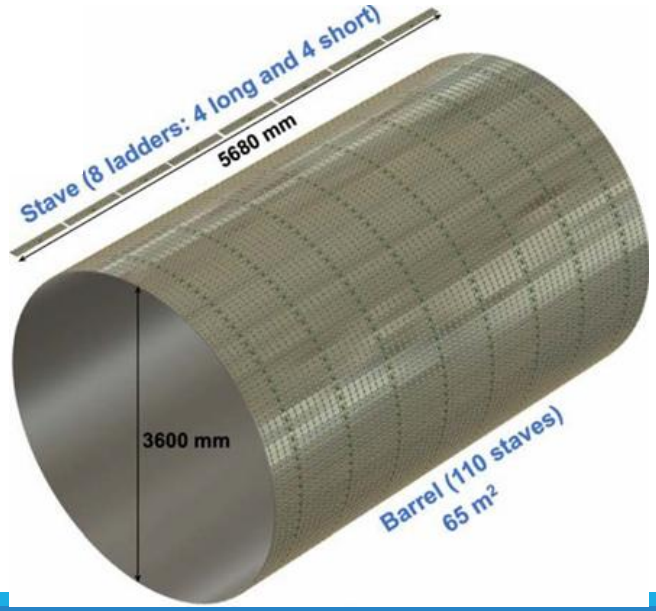
- **CEPC outer silicon tracker utilizes AC-LGAD**

For barrel:

Sensor size:4.34 cm × 5.22 cm, 4.34 cm × 5.22 cm **Large size**

Strip number per sensor: 512; Strip pitch size:100μm

Timing resolution: 50ps; Spatial resolution: 10μm **4D detector**



Outline

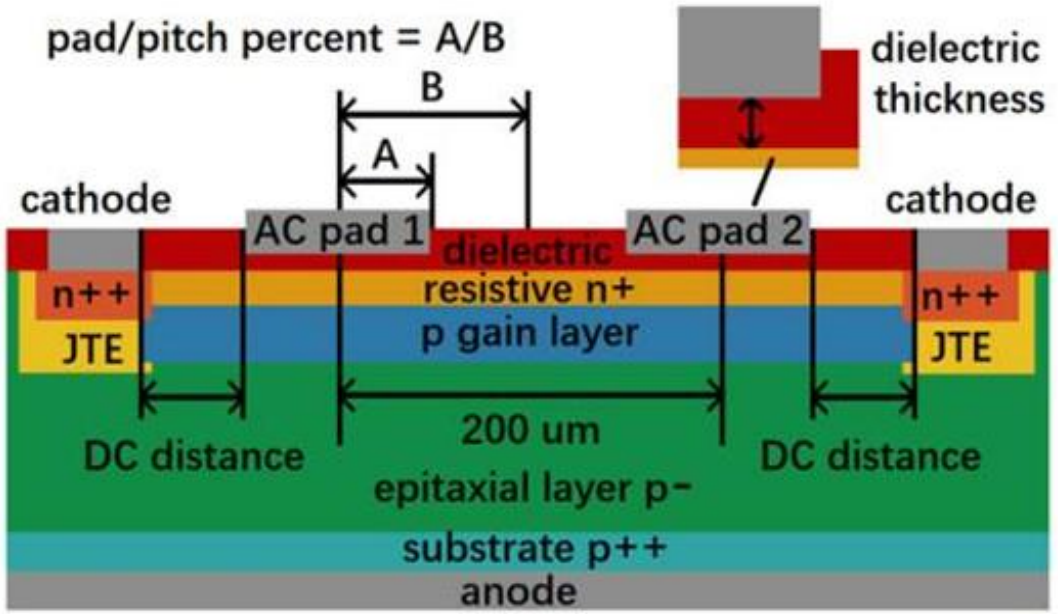
- **AC-LGAD sensor simulation, design and fabrication**
- Strip AC-LGAD sensor: timing and spatial resolution
  - N+ dose: 1P VS 0.1P, Length: 2cm, pitch~100μm, electrode pad:50μm
  - N+ dose: 0.1P, Length: 2cm, pitch~100μm VS 200μm, electrode pad:50μm
  - N+ dose: 0.1P, Length: 2cm, pitch~100μm, electrode pad:25um VS 50μm
  - N+ dose: 0.1P, Length: 2cm VS 1cm, Pitch~200um, electrode pad:50μm
- Pixelated AC-LGAD sensor's performance
- Readout ASIC: LATRIC
- Summary

AC-LGAD sensor simulation

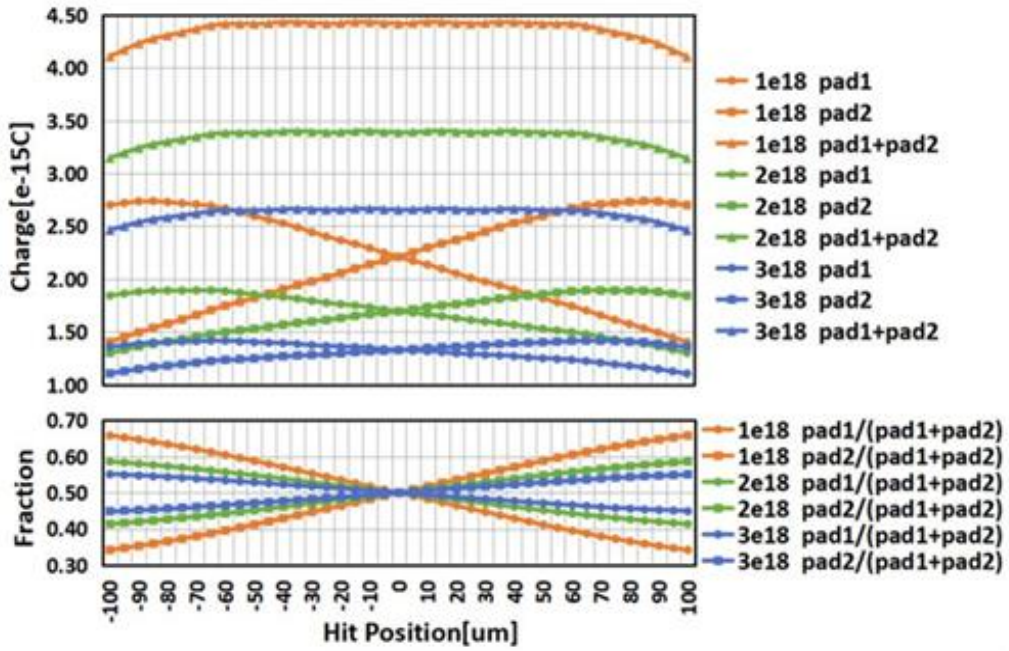
AC-LGAD sensor simulation: Optimization of process and structure parameters

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

Structure parameter: pad shape, pad-pitch size



TCAD model of AC-LGAD for simulation

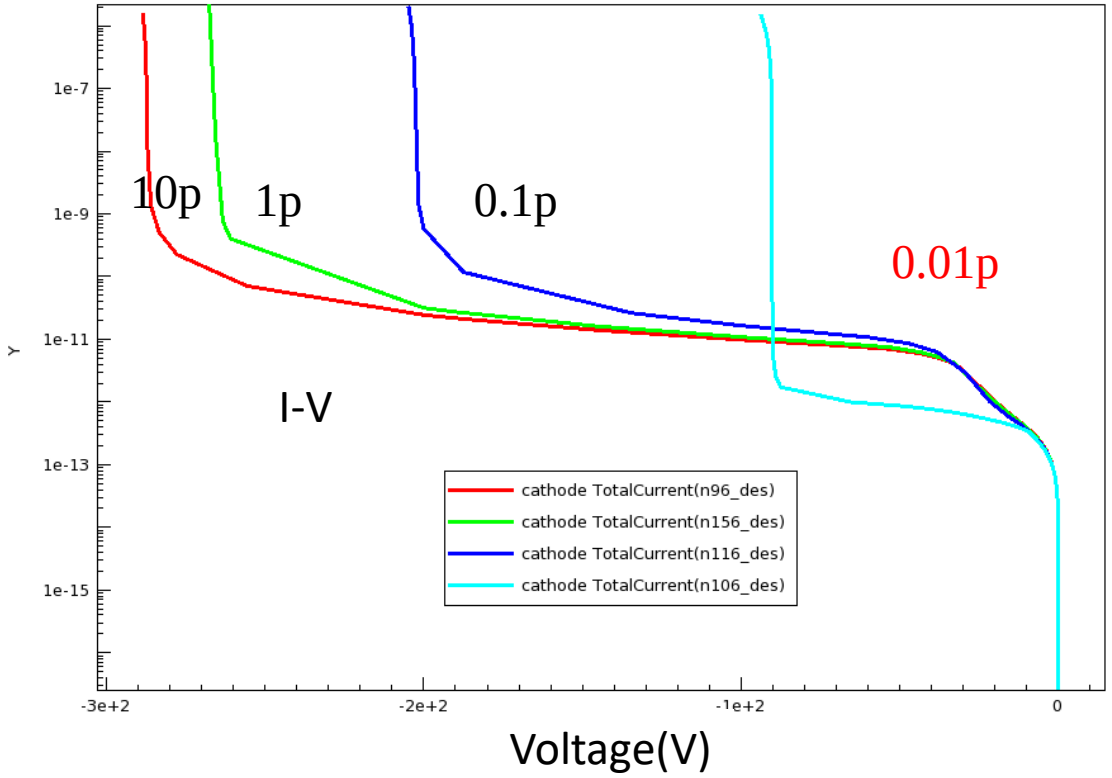


Lower n+ dose→ Large resistivity →good spatial resolution

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 sensor simulation

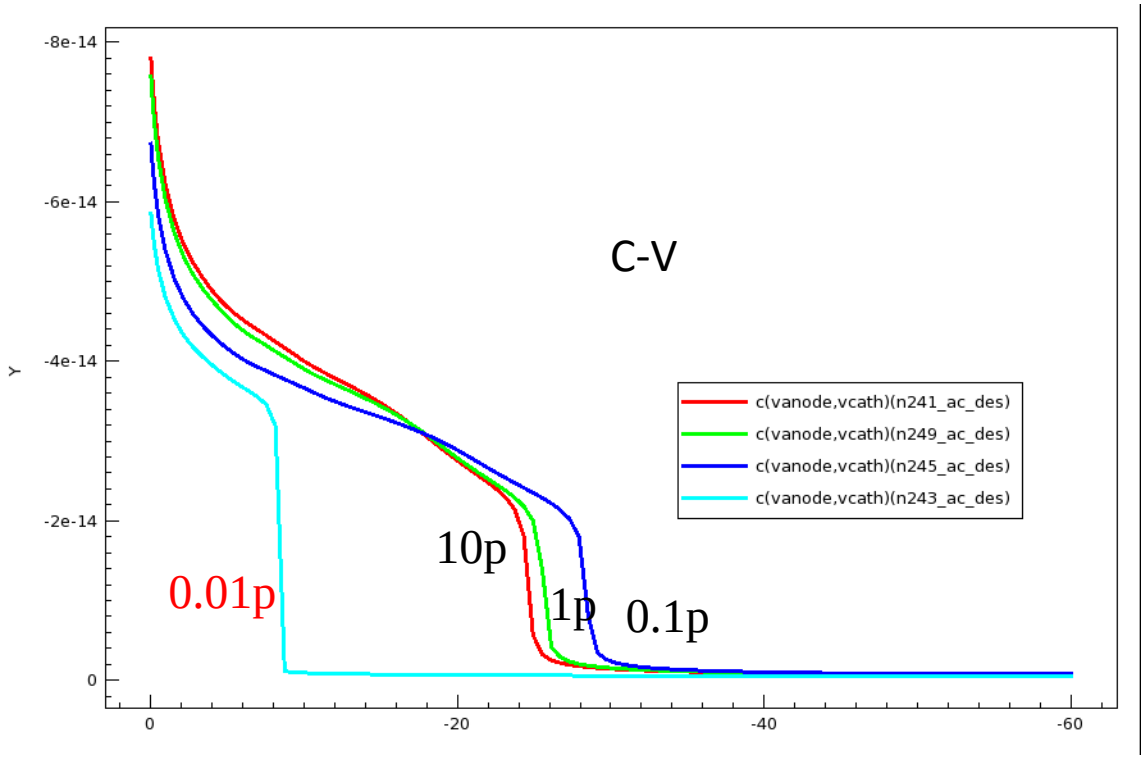
With the p-layer dose kept constant, the breakdown voltage (BV) decreases as the N^+ layer dose is reduced.



With the p-layer dose kept constant, the Vgl increases as the N^+ dose is reduced.

[V_{gl}[gain layer depletion voltage]~26V for 1p; Vgl~30V for 0.1p]

But if N+ layer dose too low, the V_{gl} will be very small,~10V



AC-LGAD sensor R&D

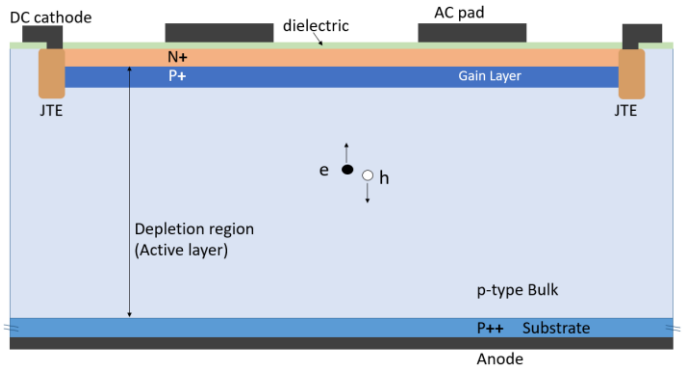
- AC-LGAD sensor has been submitted for fabrication in April 2025

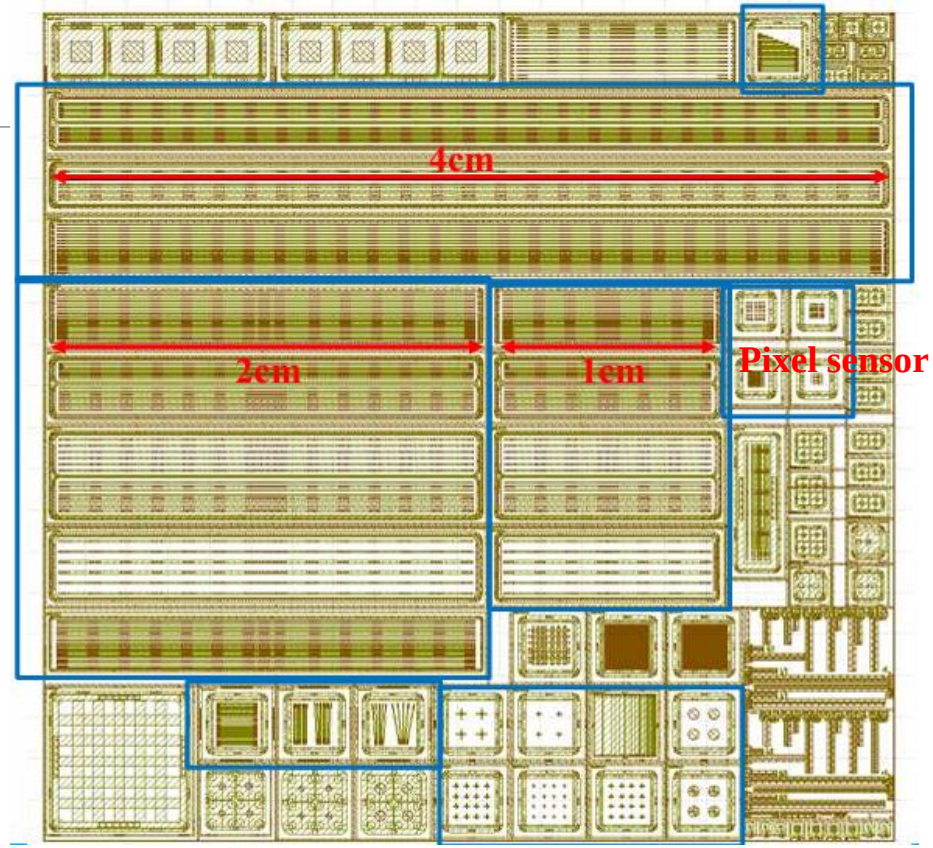
➢ Strip lengths: 1 cm, 2 cm, and 4 cm

➢ Strip pitch sizes: 100 μm, 200 μm, and 500 μm

➢ Electrode widths: 25 μm, 50 μm, and 100 μm

➢ Pixel sensor: pixel size, 55μm,100μm,150μm, 200μm

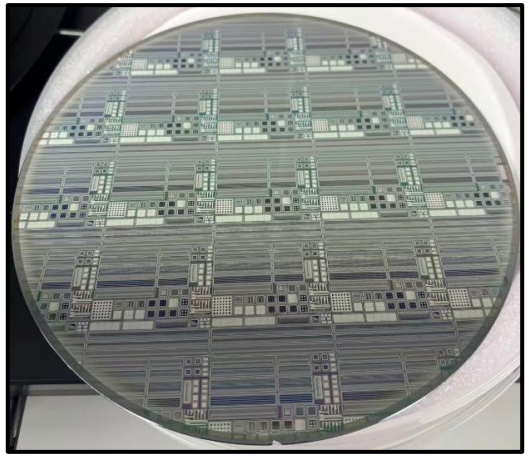




➢ Isolated structure design and EPI thickness (50 μm, 80 μm) to reduce sensor capacitance

➢ Process design optimization: N+ doping concentration

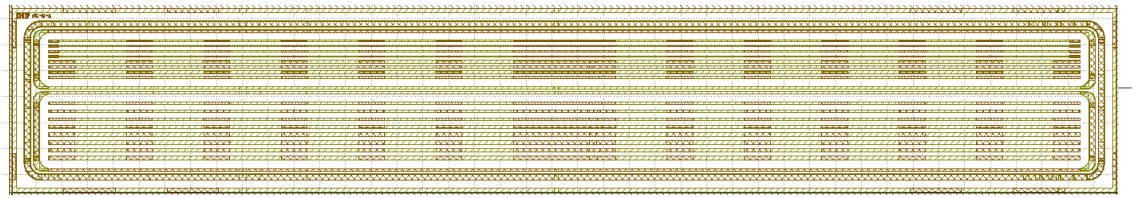
Wafer	EPI thickness	N+ dose	AC coupling	carbon	status
1	50μm	10p	SiO_2	Yes	delivered
2	50μm	10p	SiO_2	Yes	delivered
3	50μm	0.01p	SiO_2	No	delivered
7	80μm	10p	SiO_2	Yes	delivered
8	80μm	0.01p	SiO_2	No	delivered
4	50μm	1p, 0.1p	SiO_2	No	delivered
9	80μm	1p, 0.1p	SiO_2	No	delivered
6	50μm	0.05P	SiO_2	No	Ongoing
7	50μm	0.05P	Si_3N_4	No	Ongoing

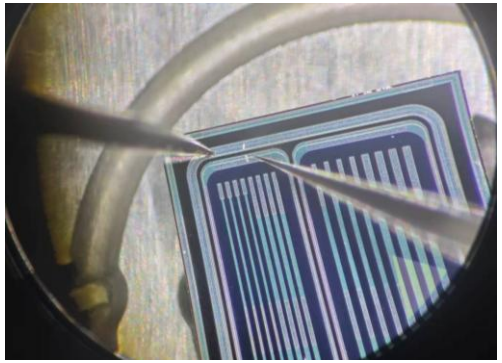


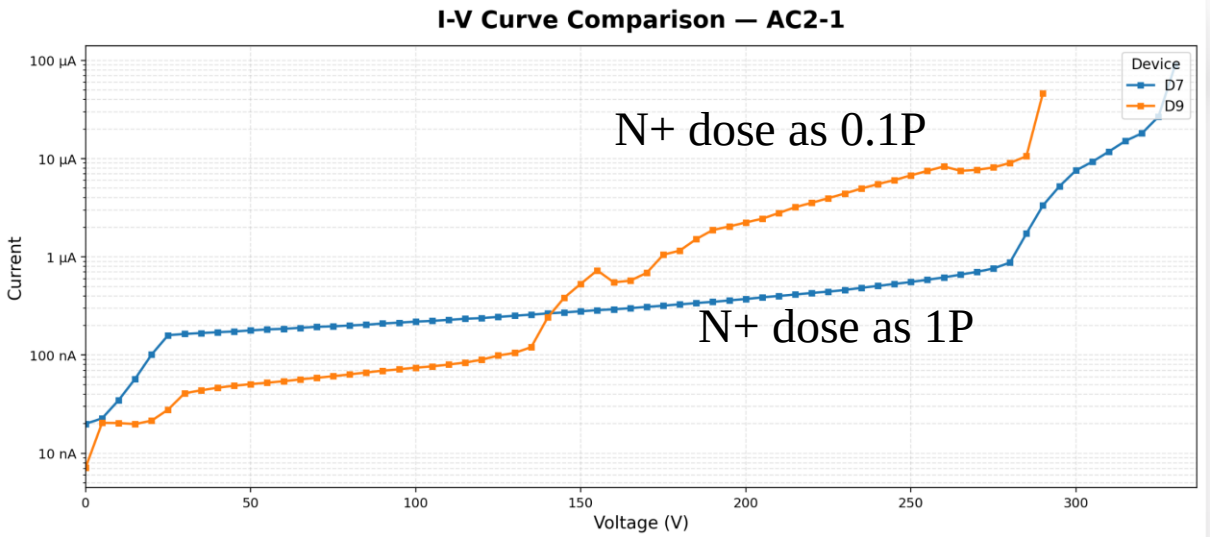
Testing has been done on wafer 1, wafer 3, wafer 4.
I-V, C-V, spatial and timing performance laser system

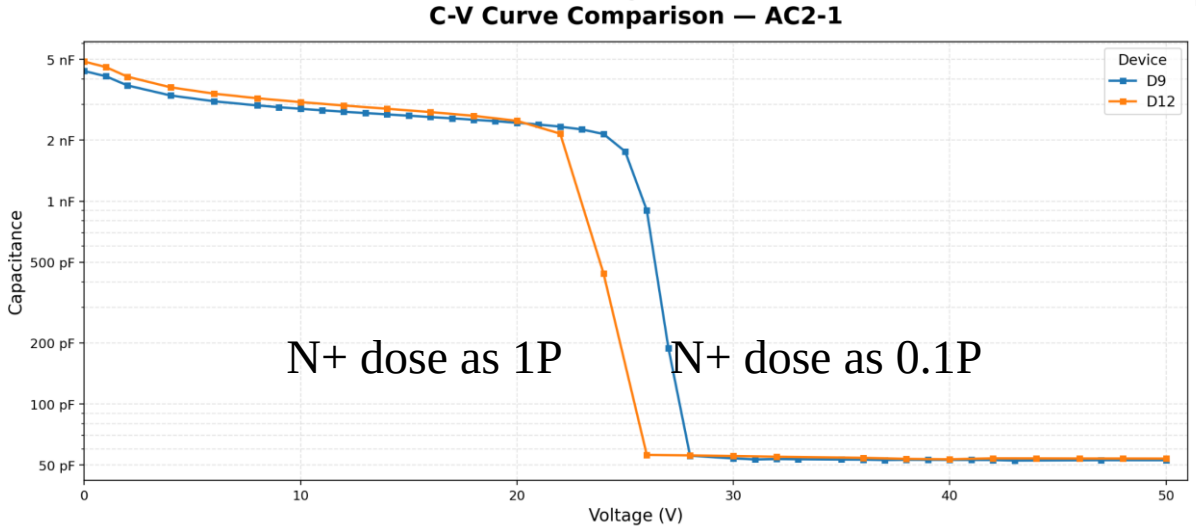
AC-LGAD sensor R&D

AC-LGAD with 2cm long strip









- **I-V results** of AC-LGAD with different N+ dose

  Breakdown voltage: V_{bd}~340V for N+ dose as 1p

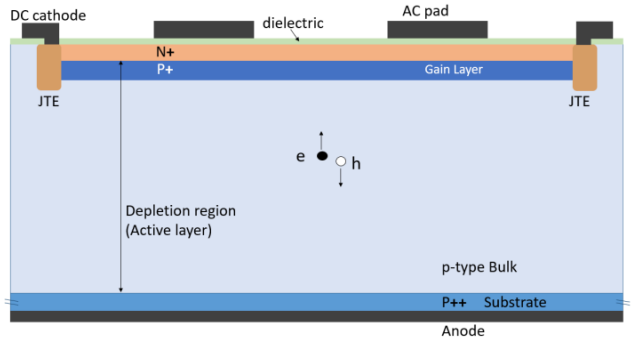
  V_{bd}~280V for N+ dose as 0.1p

- **C-V results** of AC-LGAD with different N+ dose

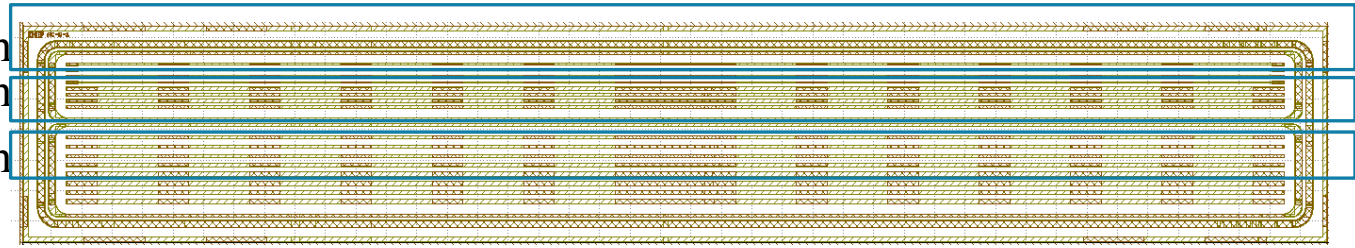
  These are from DC electrode, bulk capacitance of 8 strips

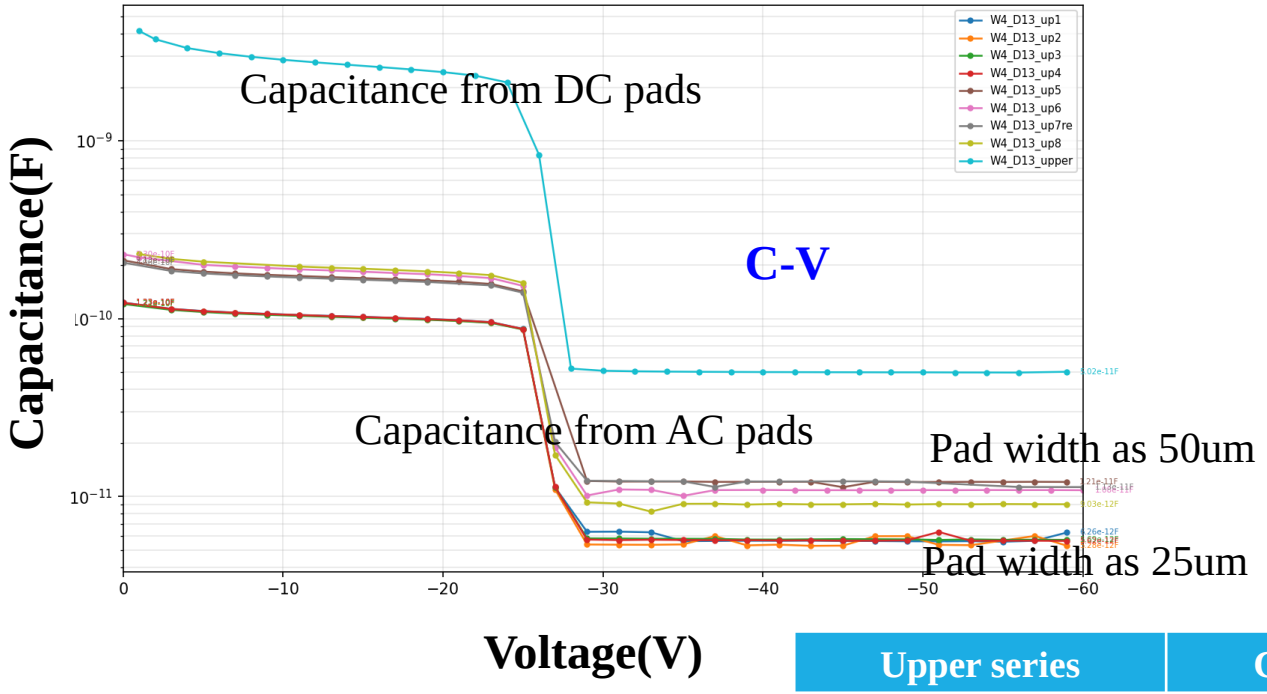
Gain layer depletion voltage:V_{gl}~23V for 1p; V_{gl}~27V for 0.1p

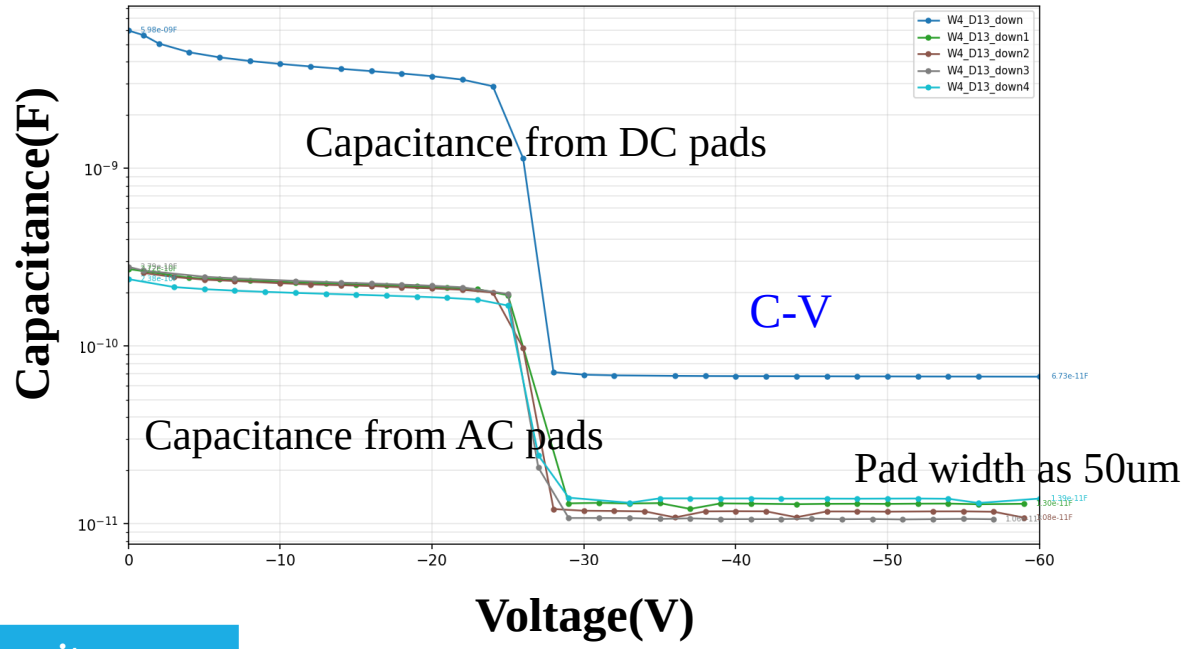
AC-LGAD sensor R&D



Pad-pitch: 25-100μm
Pad-pitch: 50-100μm
Pad-pitch: 50-150μm





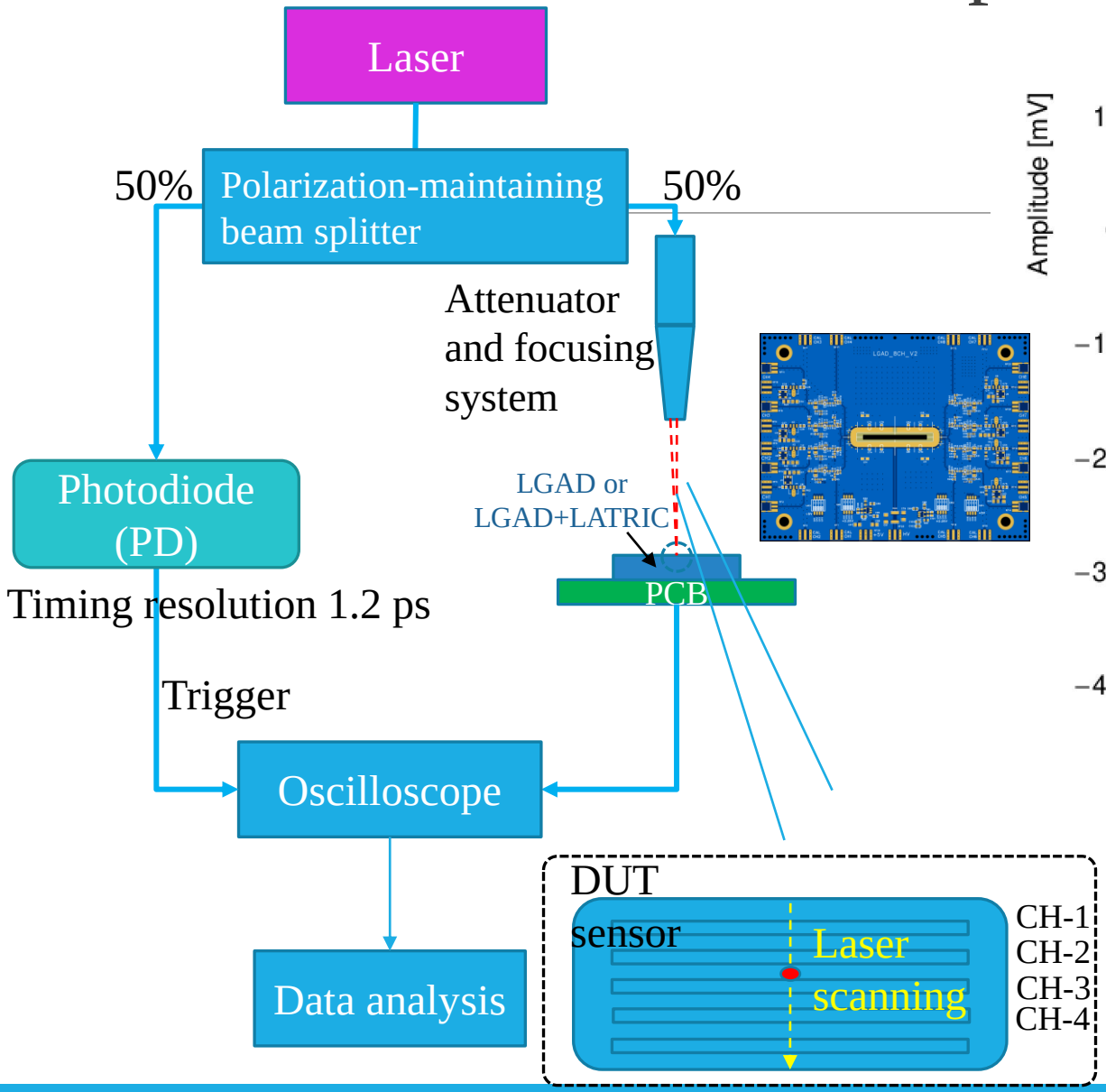


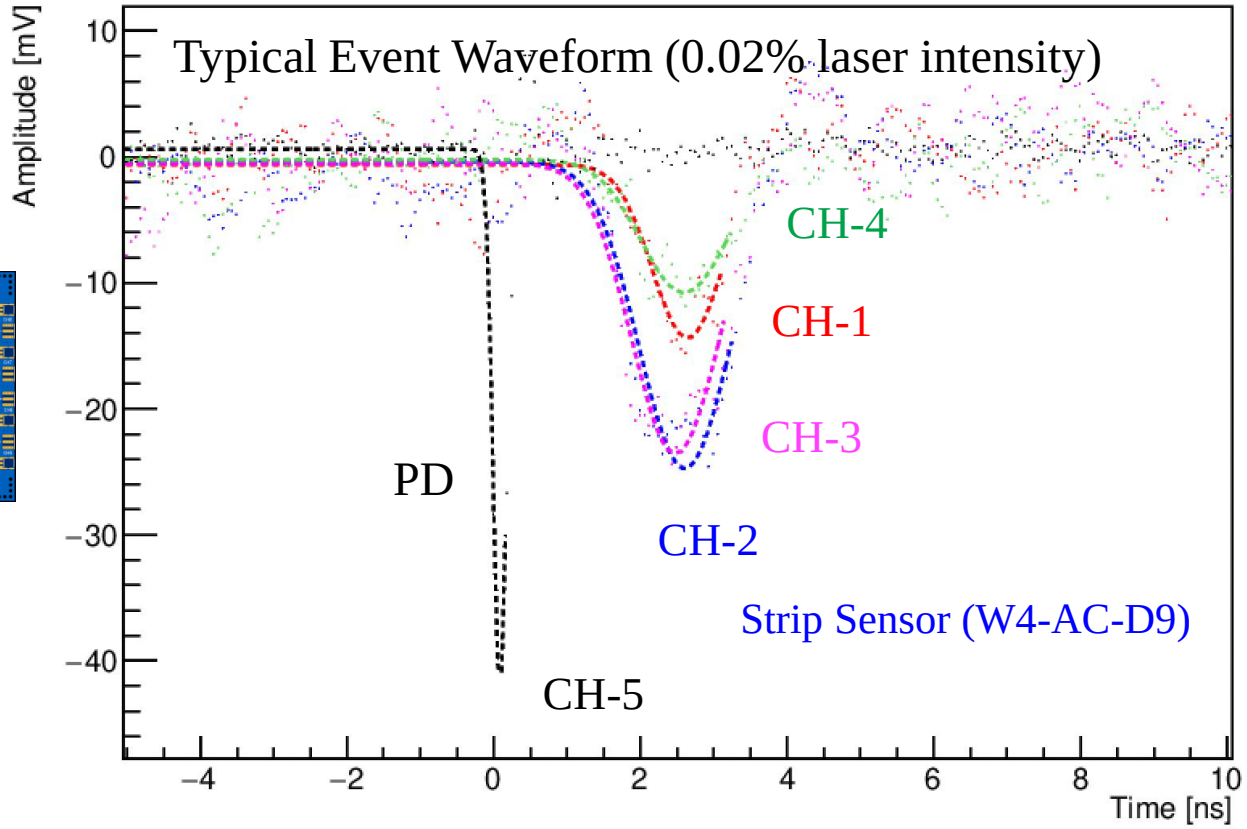
Sensors with same DC capacitance, Capacitance from AC pad is less for sensors with narrow electrode pad.

Upper series	Capacitance
DC	50PF
50um AC pad	9-12pF
25um AC pad	5-6 PF

Down series	Capacitance
DC	68PF
50um AC pad	10-13pF

Laser TCT setup for Sensor Characterization





Laser density:0.02%, collected charge equal to MIP

See Jiajian TEOH's report

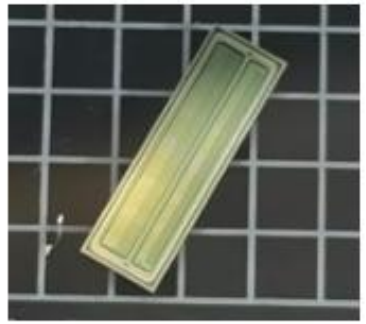
Outline

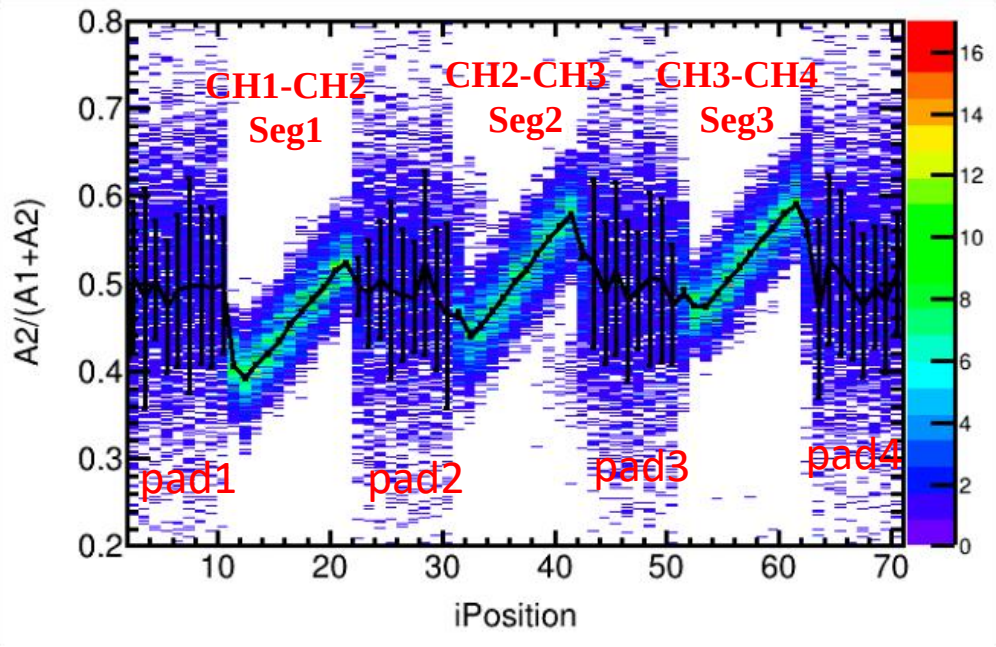
- AC-LGAD sensor simulation, design and fabrication
- **Strip AC-LGAD sensor: timing and spatial resolution**
  - N+ dose: 1P VS 0.1P, Length: 2cm, pitch~100μm, electrode pad:50μm
  - N+ dose: 0.1P, Length: 2cm, pitch~100μm VS 200μm, electrode pad:50μm
  - N+ dose: 0.1P, Length: 2cm, pitch~100μm, electrode pad:25um VS 50μm
  - N+ dose: 0.1P, Length: 2cm VS 1cm, Pitch~200um, electrode pad:50μm
- Pixelated AC-LGAD sensor's performance
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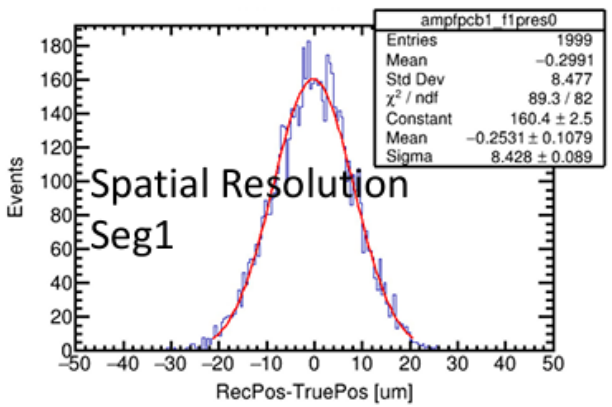
Strip AC-LGAD sensor

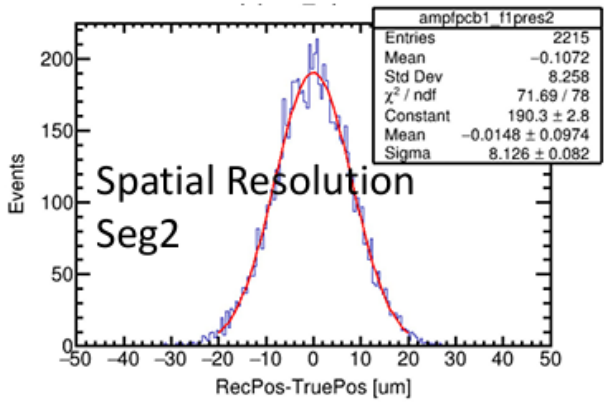
Strip sensor (W4-AC2-1-D9, 2 cm long strip, pitch 100 μm, 50 μm electrode width, and n^+ dose = 0.1 p)

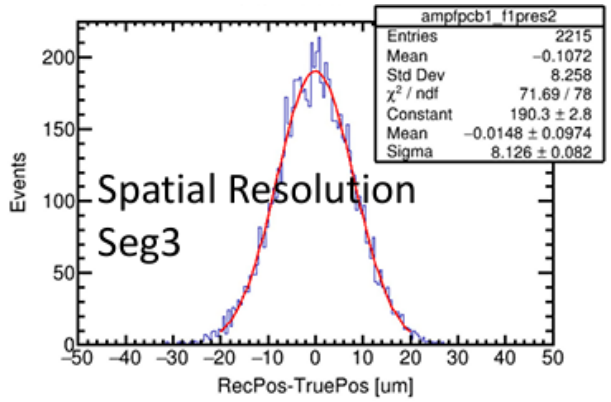








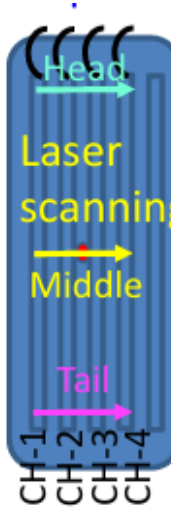




2cm long strip sensor (W4-AC2-1-D9: 2 cm, pitch 100 μm, 50 μm electrode width, and n^+ dose = 0.1 p) achieved a spatial resolution of ~8 μm.

Strip AC-LGAD sensor

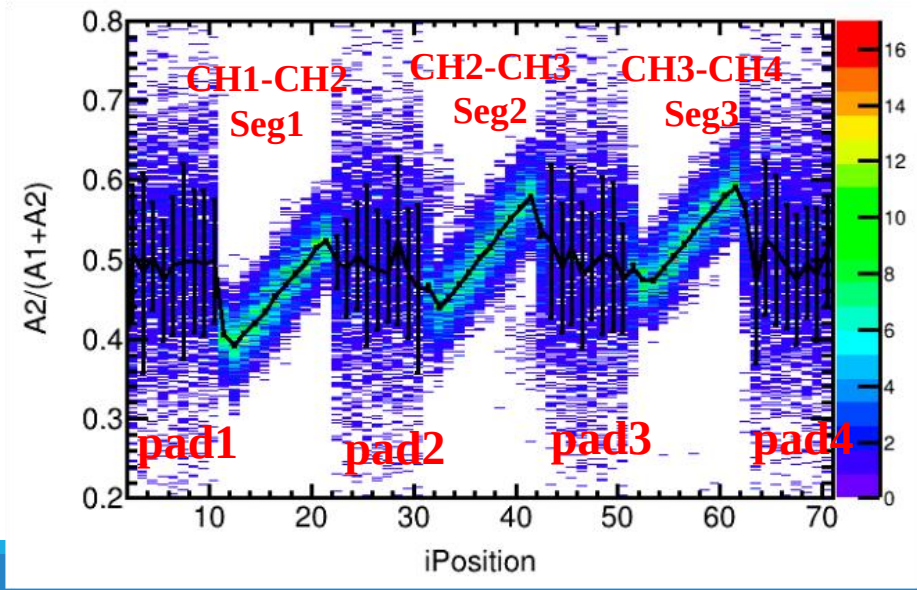
Changing laser hit position：



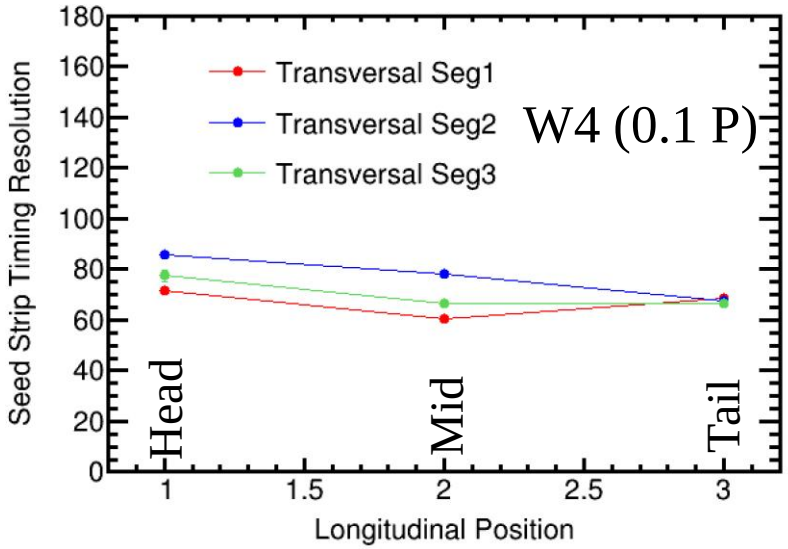
Head： Near readout wire

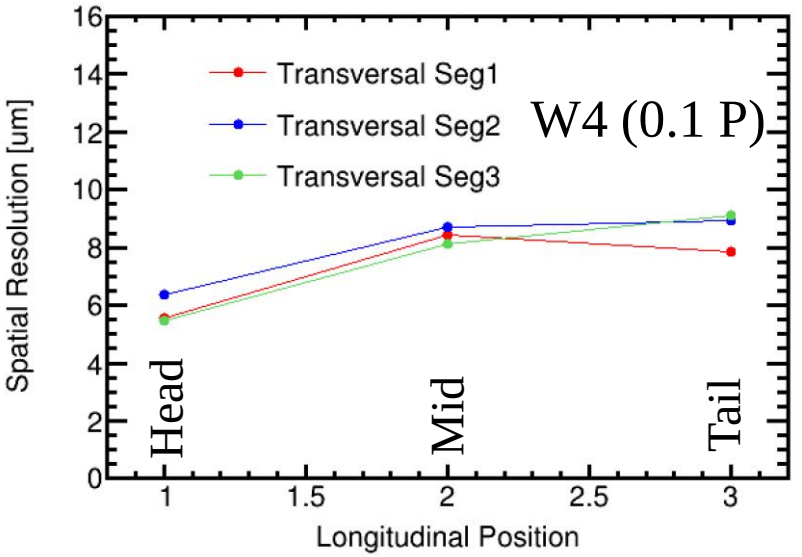
Middle: middle of sensor

Tail: far from readout wire



W4-AC2-1-D9 (290 V)
(2cm long, pitch 100um, electrode 50 um)

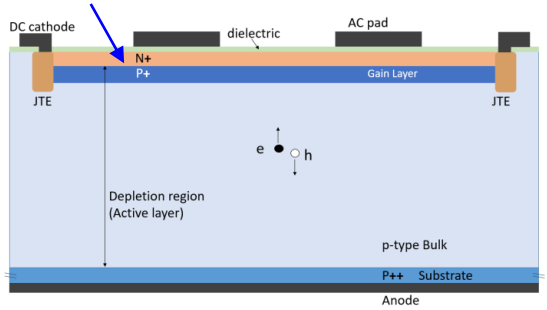




- 2cm long strip sensor (W4-AC2-1-D9: 2 cm, pitch 100 μm, 50 μm electrode width, and n^+ dose = 0.1 p) achieved a timing resolution of 60-80ps
- Spatial resolution of 6~8 μm.
  Spatial resolution change worse when laser hit Tail part

Strip AC-LGAD sensor

Changing n+ dose



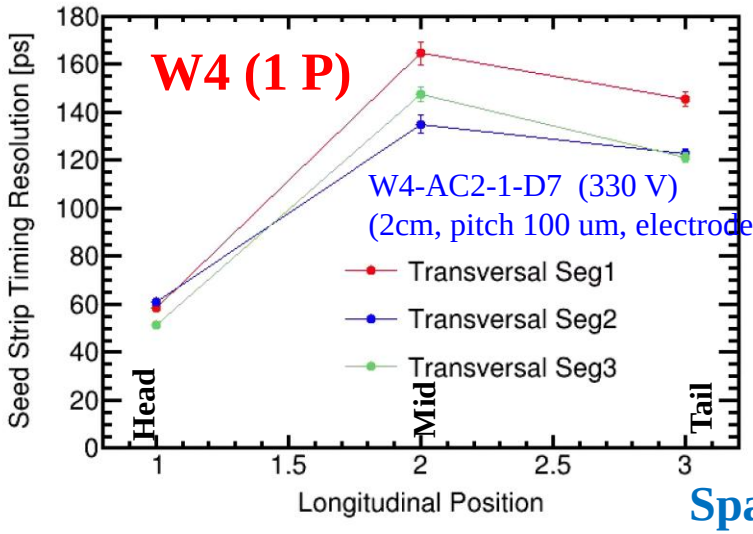
As reducing n+ dose from 1P to 0.1P,
Improving Timing and spatial resolution

- Timing resolution: 60-160ps → 80ps
- Spatial resolution: >10um →6-8um
- Reason: larger collected charge for A1+A2 , Improved charge sharing

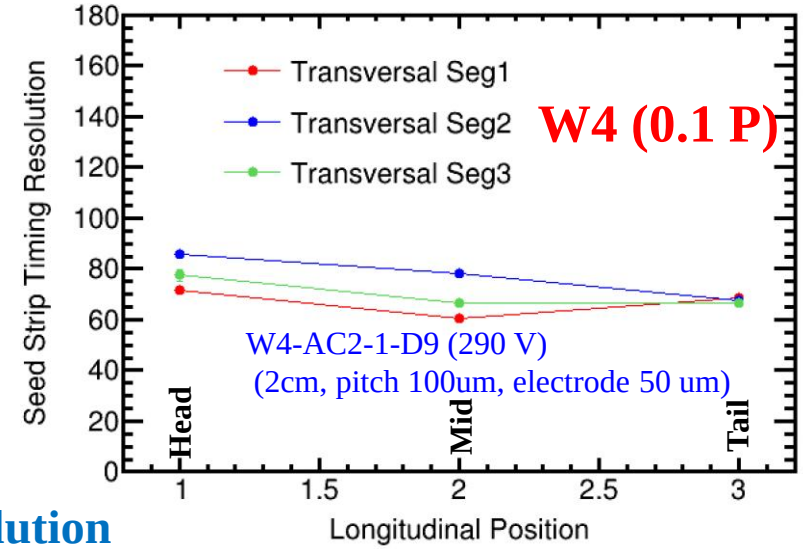
Laser density:0.02%, collected charge equal to MIP

N+ dose as 1P

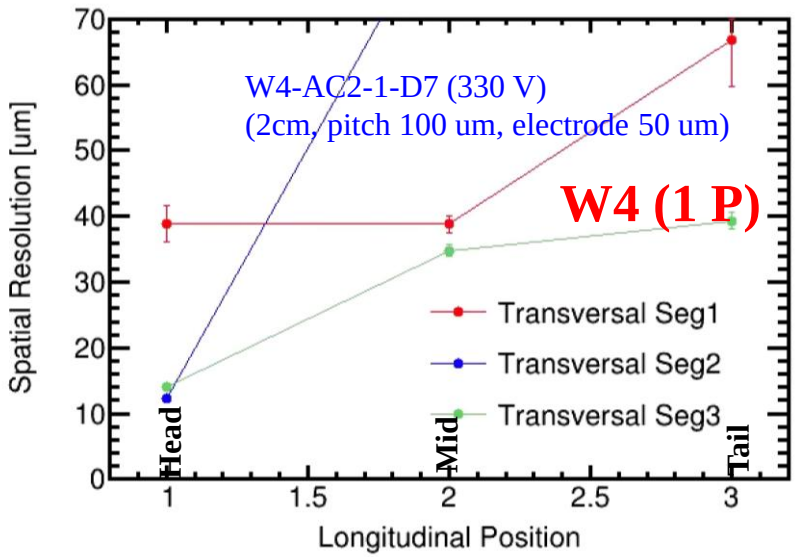
Timing resolution

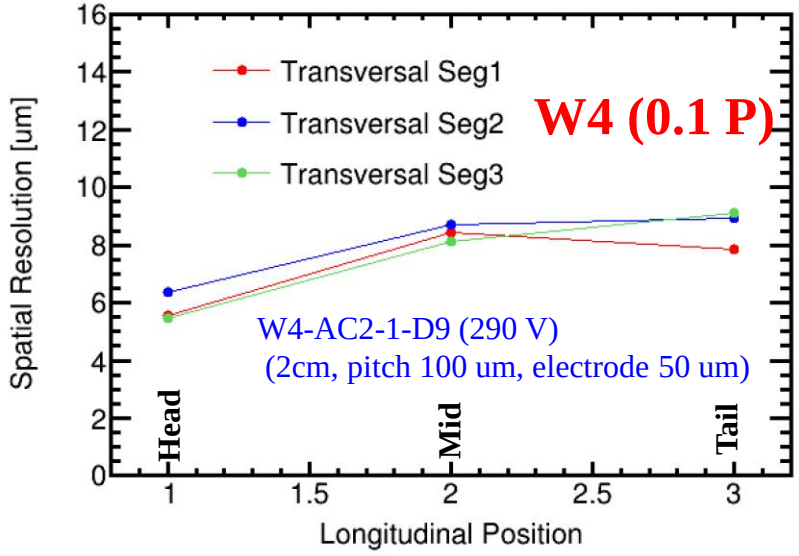


N+ dose as 0.1P



Spatial resolution

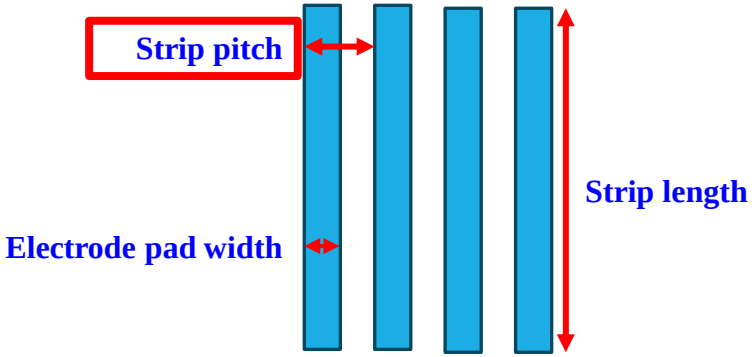




Strip AC-LGAD sensor

N+ dose as 0.1P

Changing strip pitch size： 100→200um



Larger pitch size, better timing performance, similar spatial resolution

- Timing resolution:

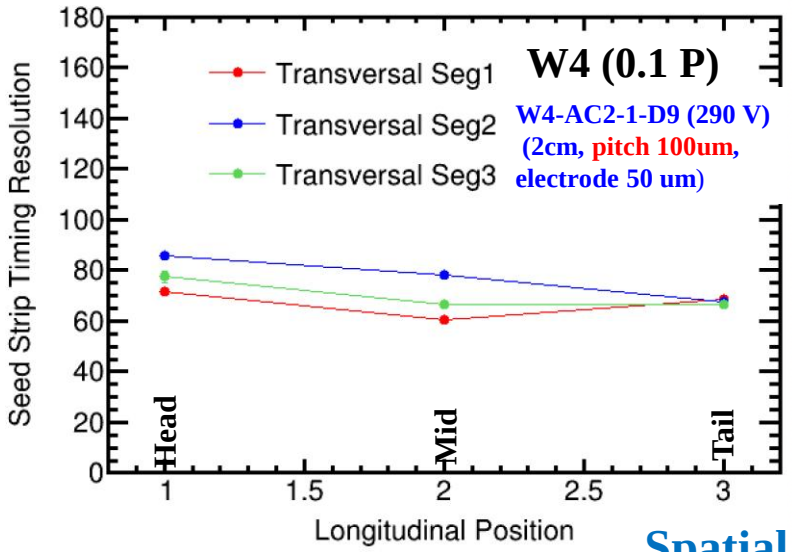
  70-100ps(100um)→40ps(200um)

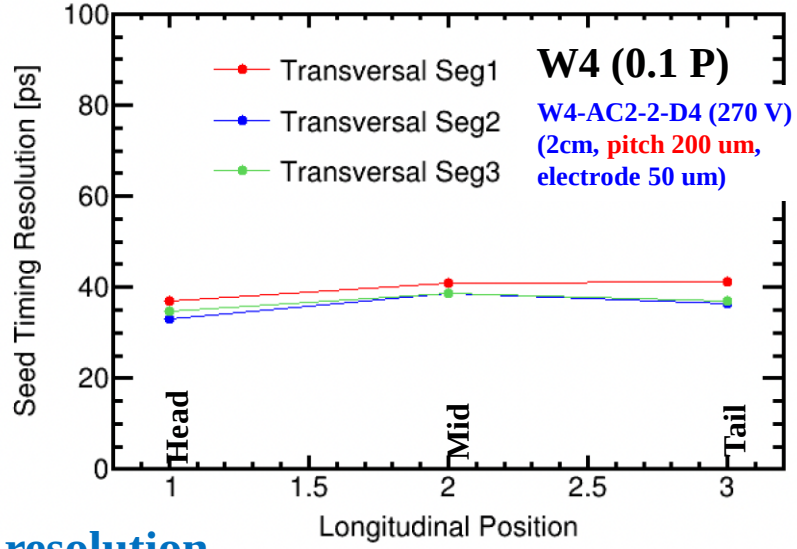
- Spatial resolution:
  6-8um(100um)→6-8um(200um)

Reason: larger collected charge for A1+A2

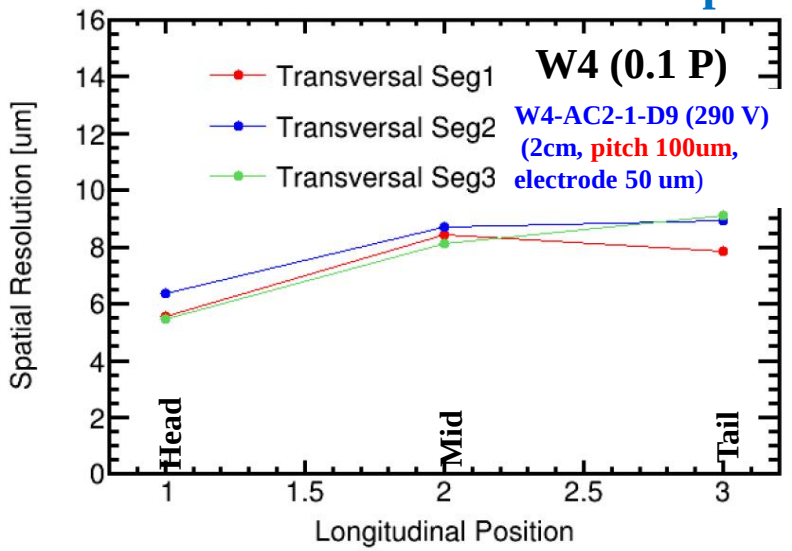
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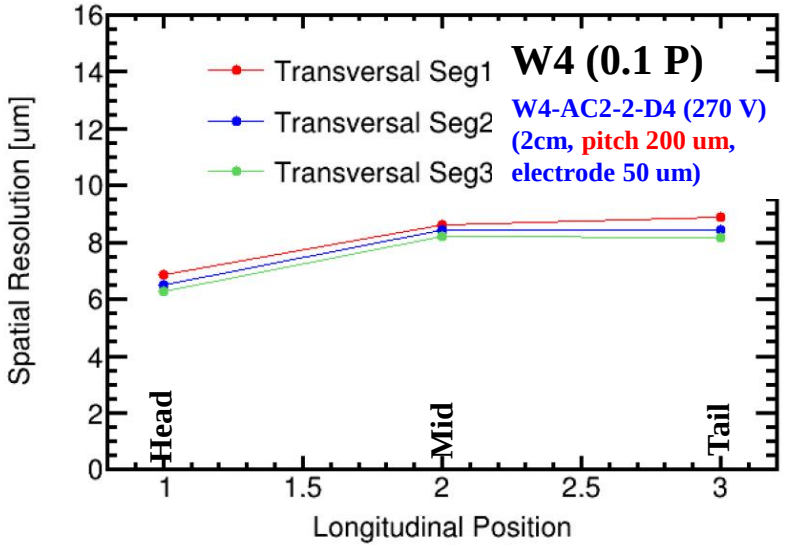
pitch size as 100um **Timing resolution** **pitch size as 200um**





Spatial resolution



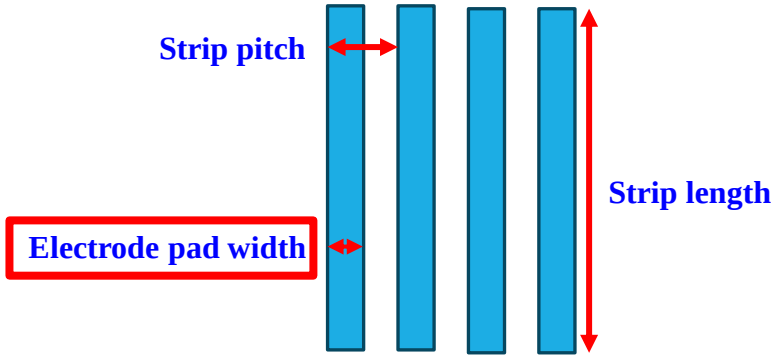


Strip AC-LGAD sensor

N+ dose as 0.1P

Changing electrode pad width：

From 100um to 50um



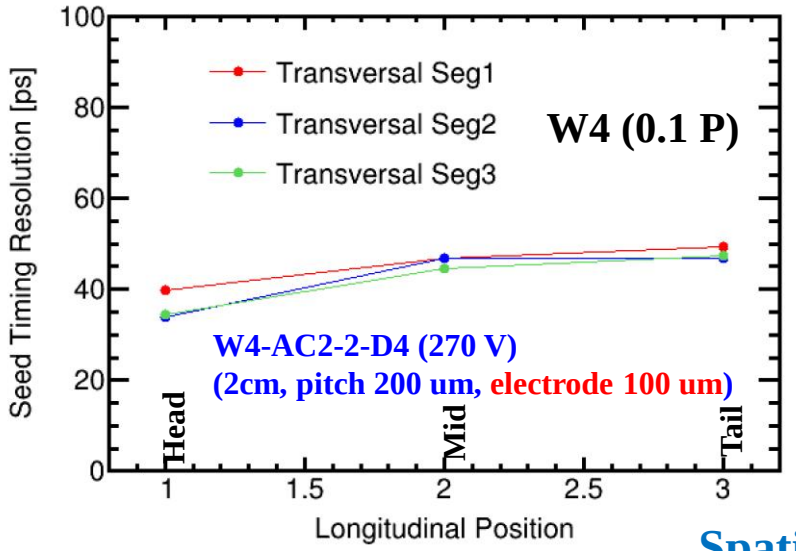
As reducing electrode pad width, Improve the timing performance, but worse spatial resolution

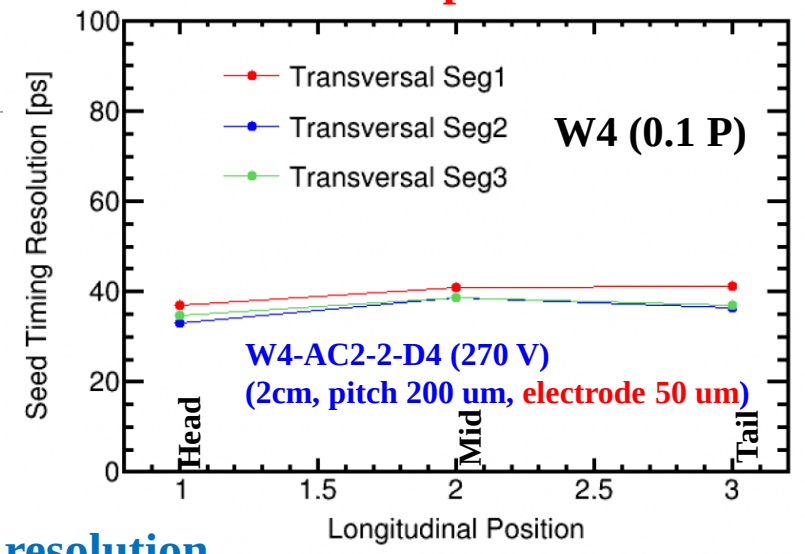
Timing resolution:
~50ps(100um) → ~40ps (50um)

Spatial resolution:
5-9um (100um) →6-9um (50um)

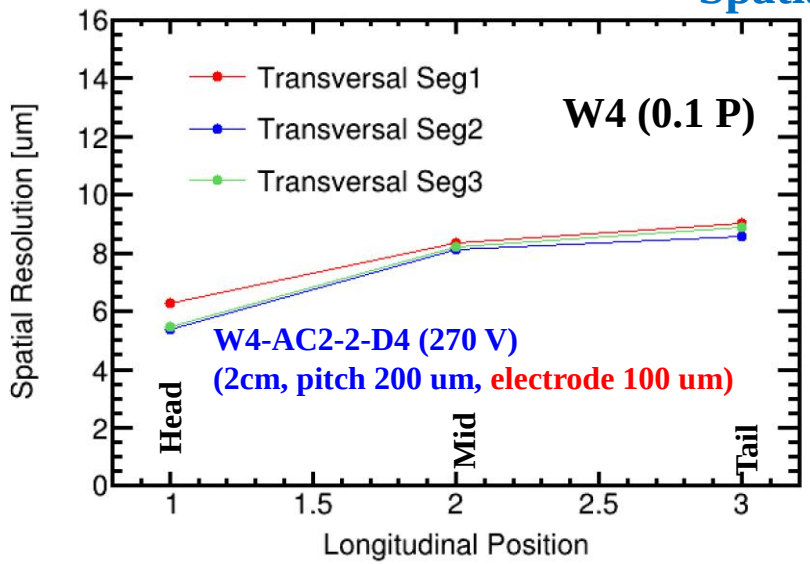
Laser density:0.02%, collected charge equal to MIP

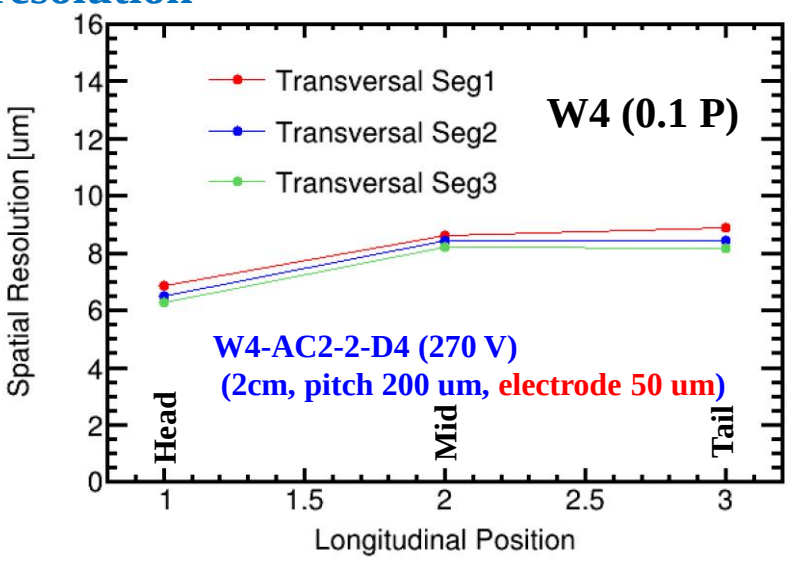
electrode pad width as 100um **Timing resolution** **electrode pad width as 50um**





Spatial resolution

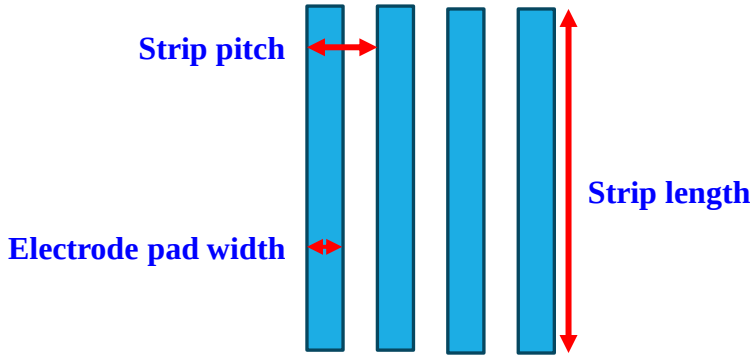




Strip AC-LGAD sensor

Changing strip length

From 1cm to 2cm



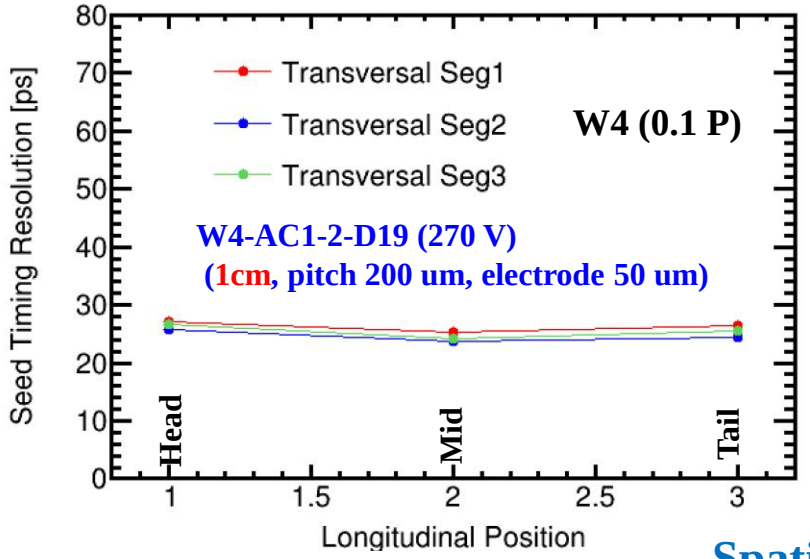
- Worse timing and spatial resolution all less than 40ps, 10um
- Reason: larger capacitance → worse timing and spatial resolution

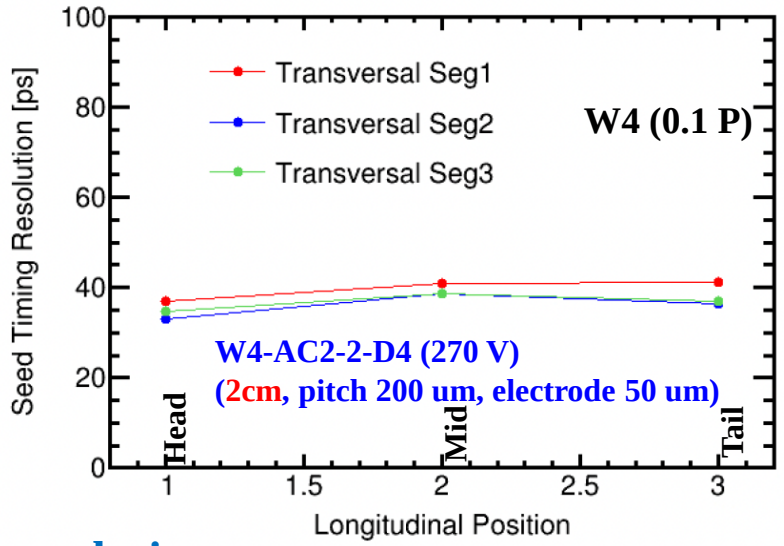
But Short strip length

→More readout channels

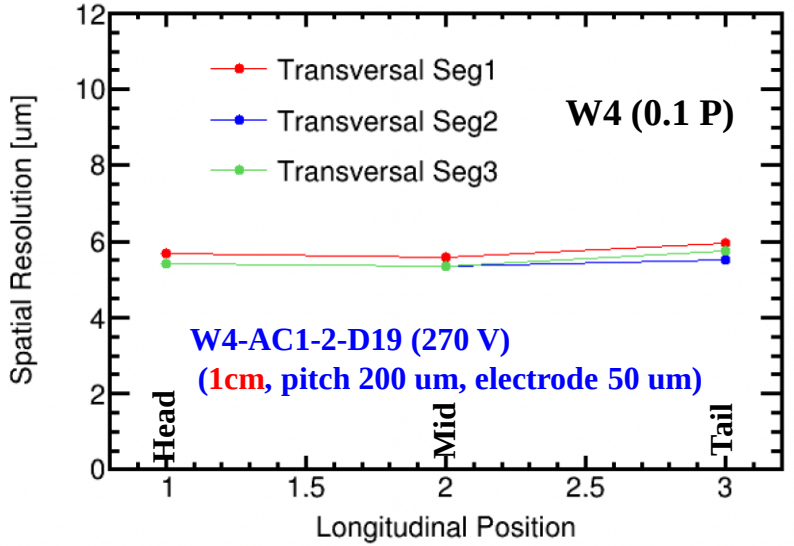
Laser density:0.02%, collected charge equal to MIP

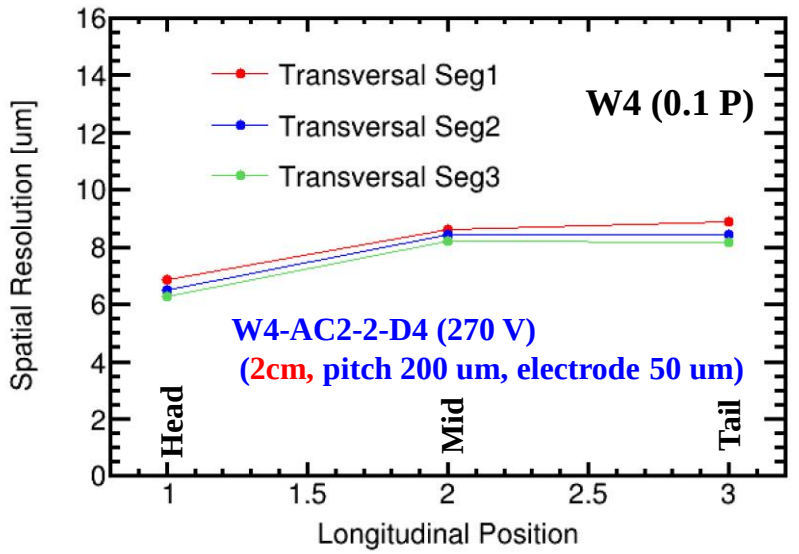
Strip Length as 1cm **Timing resolution** **Strip Length as 2cm**





Spatial resolution



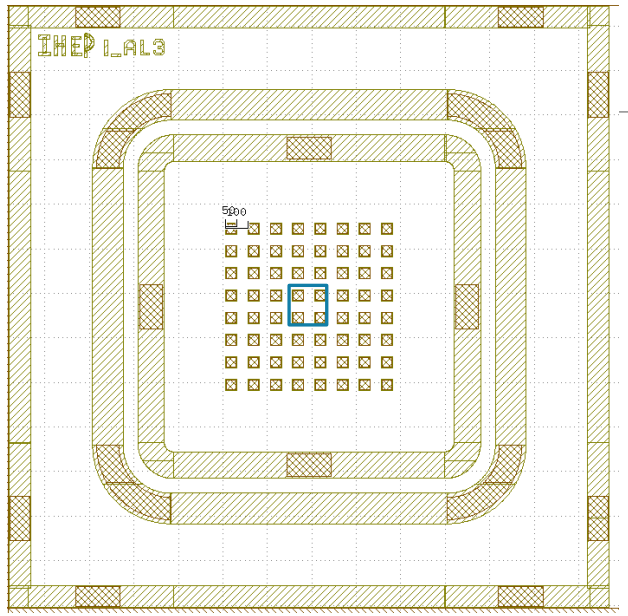


Outline

- AC-LGAD sensor simulation, design and fabrication
- Strip AC-LGAD sensor: timing and spatial resolution
  - N+ dose: 1P VS 0.1P, Length: 2cm, pitch~100μm, electrode pad:50μm
  - N+ dose: 0.1P, Length: 2cm, pitch~100μm VS 200μm, electrode pad:50μm
  - N+ dose: 0.1P, Length: 2cm, pitch~100μm, electrode pad:25um VS 50μm
  - N+ dose: 0.1P, Length: 2cm VS 1cm, Pitch~200um, electrode pad:50μm
- **Pixelated AC-LGAD sensor's performance**
- Readout ASIC: LATRIC
- Summary

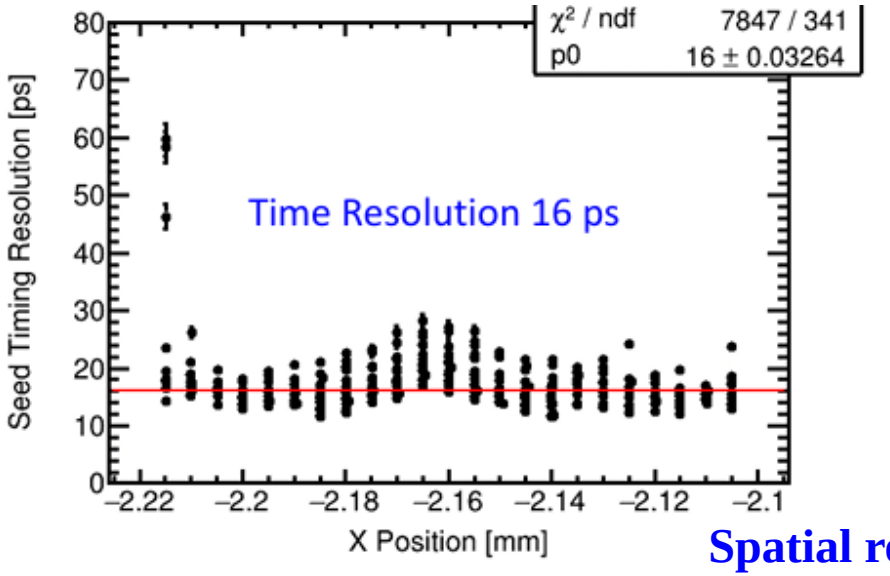
Pixelated AC-LGAD performance

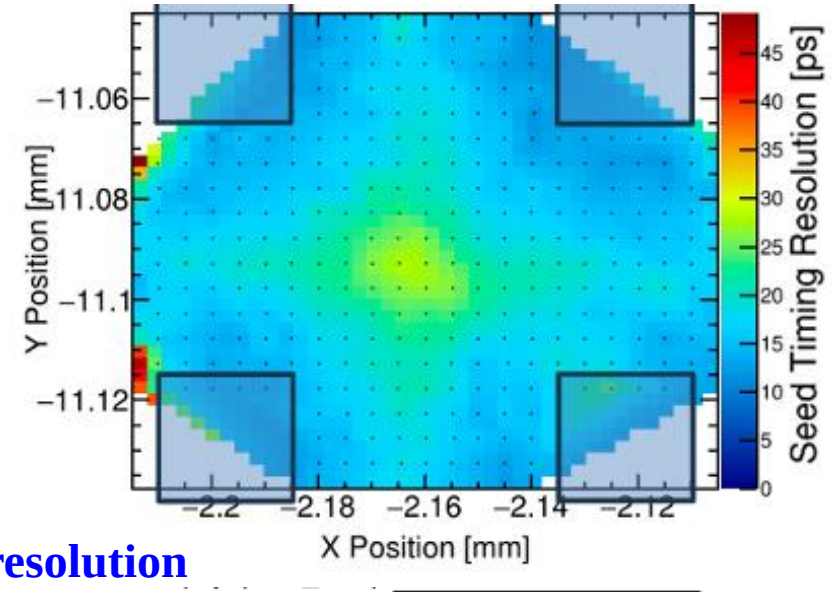
Laser density:0.02%, collected charge equal to MIP



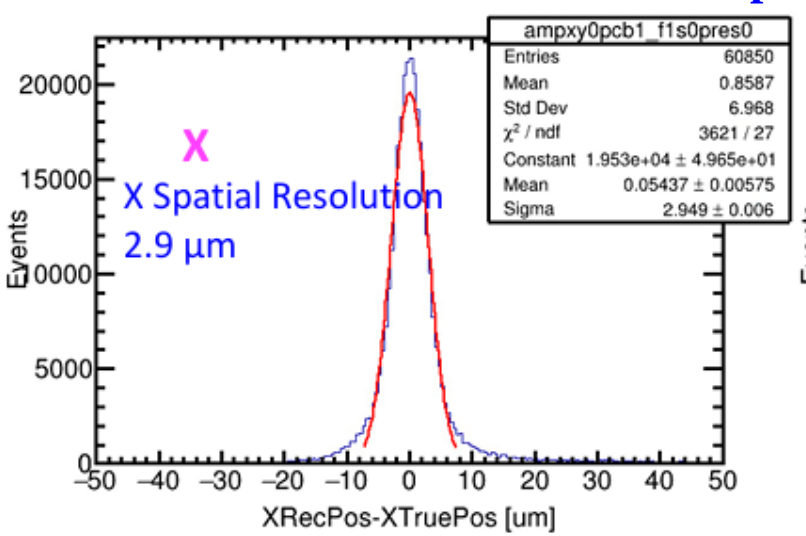
➢Pixelated AC-LGAD sensors: 100um pitch, 50um pad size

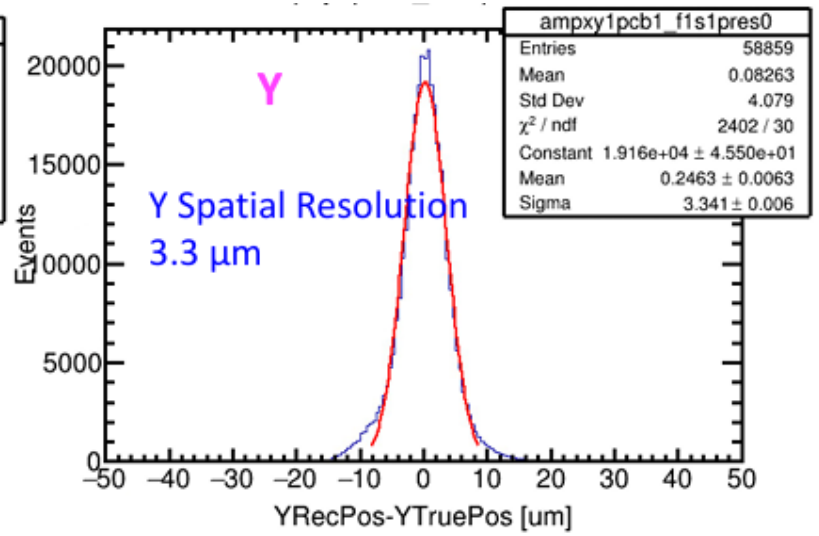
Time resolution





Spatial resolution





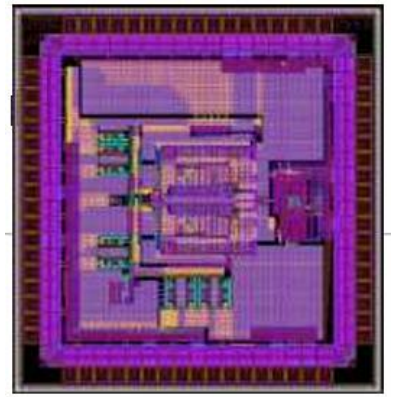
Outline

- AC-LGAD sensor simulation, design and fabrication
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  - N+ dose: 1P VS 0.1P, Length: 2cm, pitch~100μm, electrode pad:50μm
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- Pixelated AC-LGAD sensor's performance
- **Readout ASIC: LATRIC**
- Summary

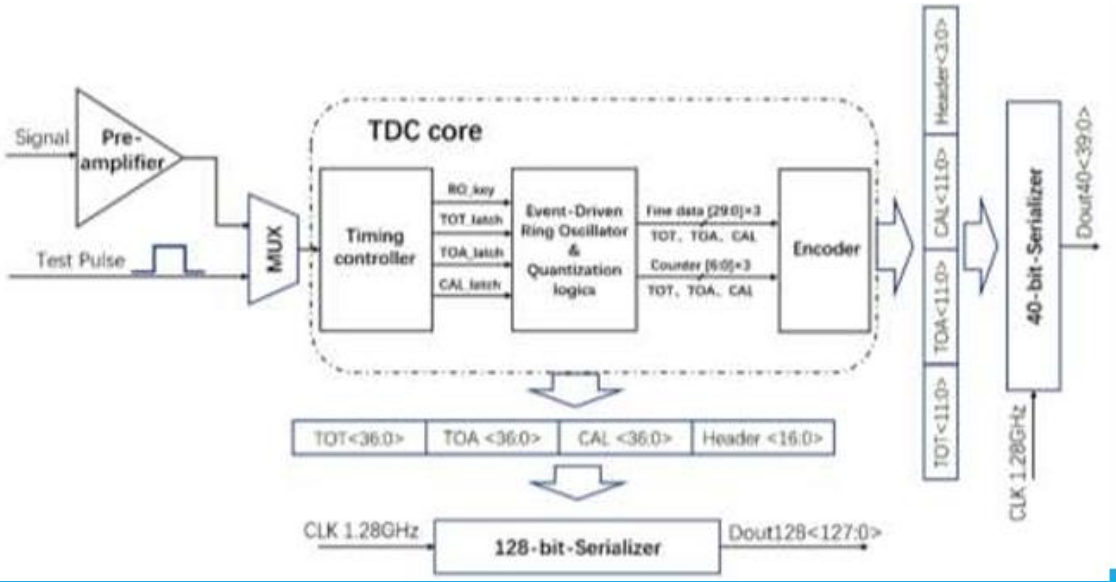
Read out ASIC

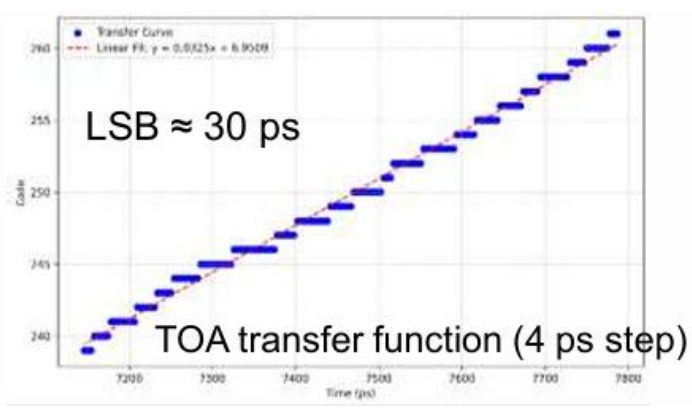
The first LGAD readout ASIC prototype, LATRIC-V0, submitted for tape-out in April, was delivered in August 2025

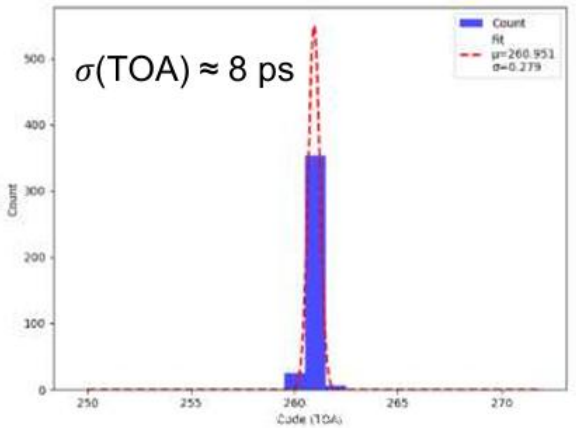
- The ASIC integrates a pre-amplifier, a discriminator, a TDC, and a serializer for data output. o
- The LSB is 29.8 ps, meeting the 30 ps design goal.
- TDC power consumption is 0.1 mA (1.2 V) @ 0.5 MTPS (Mega-Trigger Per Second), 0.3 mA @ 1 MTPS, and 0.5 mA @ 2 MTPS.





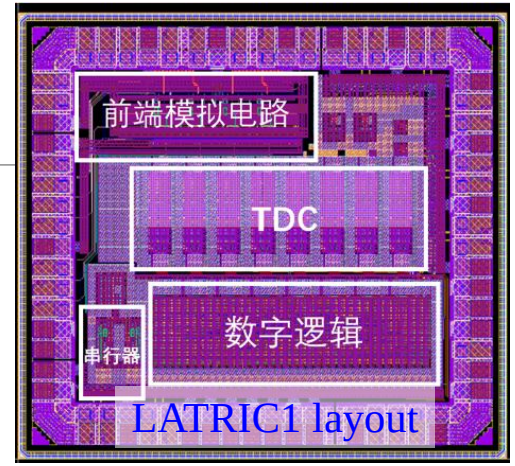






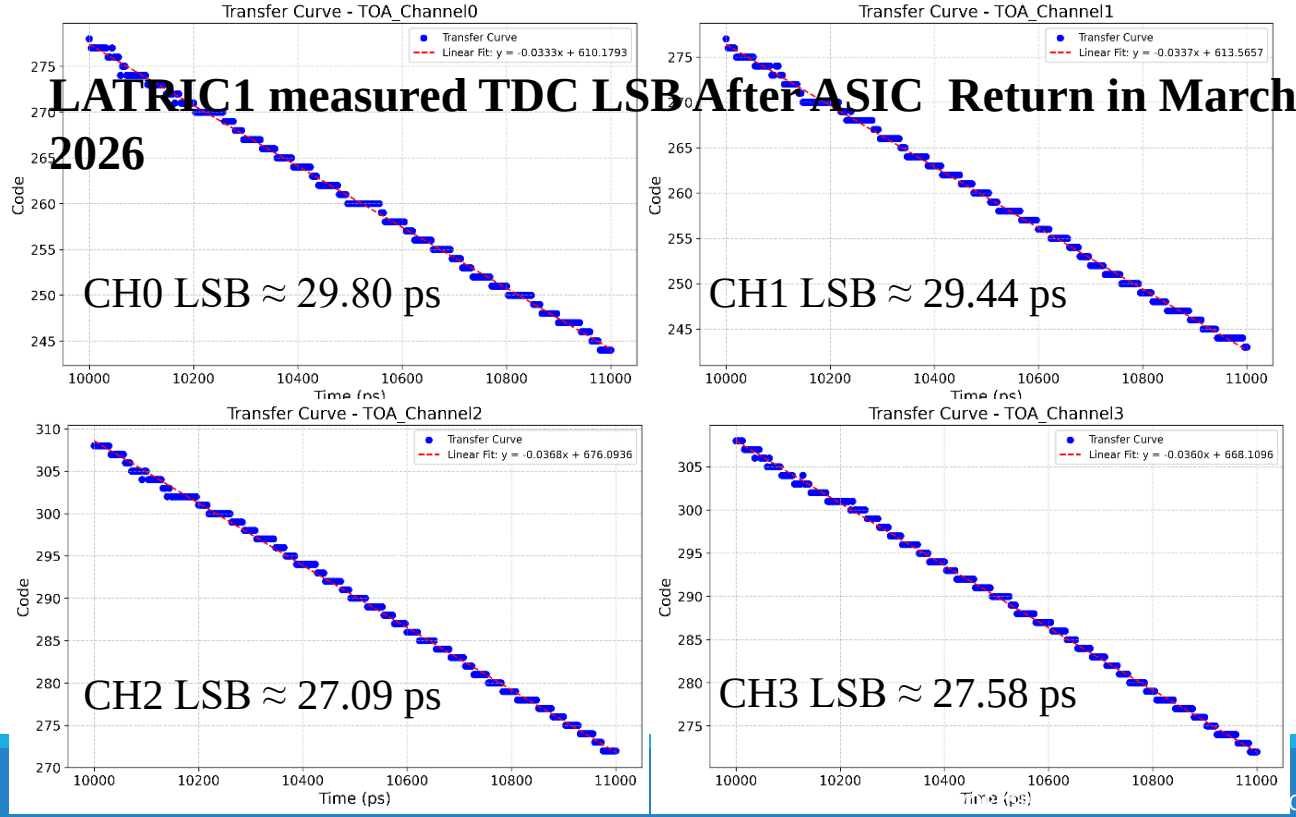
Readout ASIC

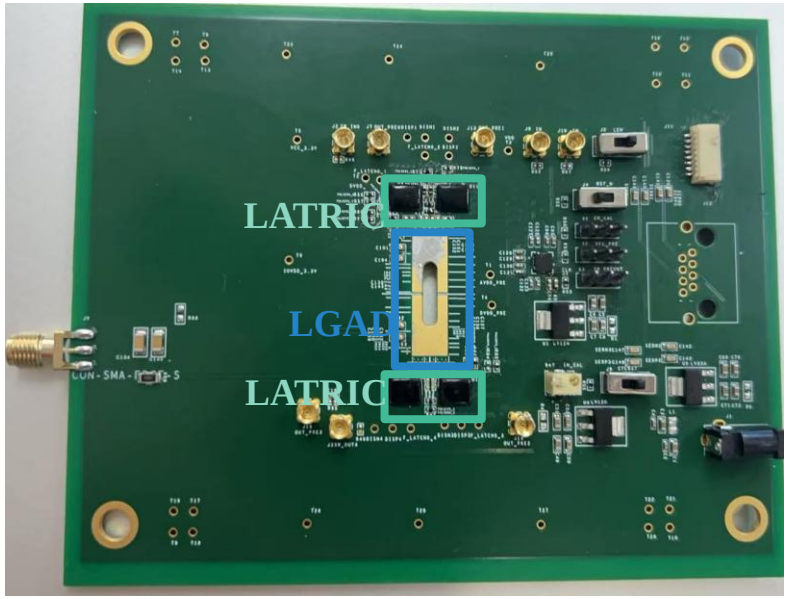
- The second version readout ASIC, LATRIC1, adopts an 8-channel was designed and submitted for tape-out in October 2025.
  - The channel pitch is **100 μm.** Four channels integrate the analog front-end and TDC. The other four channels consist of TDCs connected to differential pulse receivers.
- Performance optimizations include:
  - An enhanced analog front-end with increased preamplifier gain to improve the signal-to-noise ratio.
  - Refined encoder logic. Addition of an event builder and timestamp functionality, etc.



LATRIC1 layout

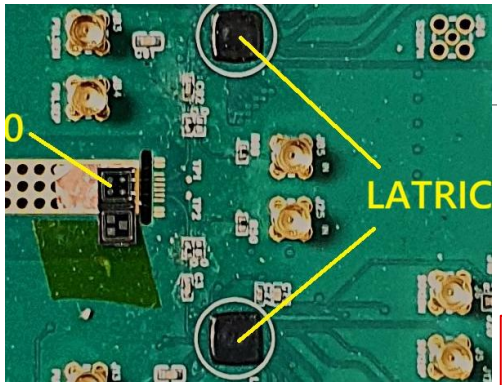
LATRIC1 measured TDC LSB After ASIC Return in March 2026

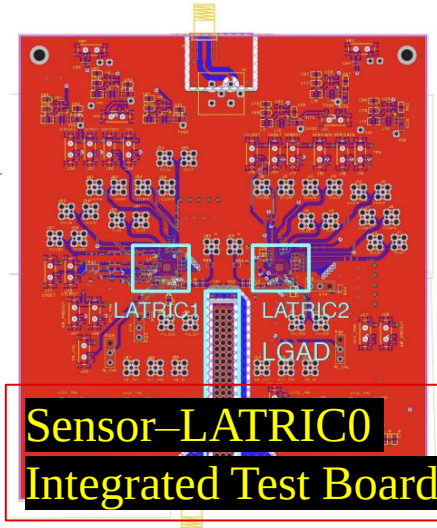




The latest designed LATRIC1-Sensor Integration Test Board

LATRIC0 (Single Channel) and Sensor Combined Test

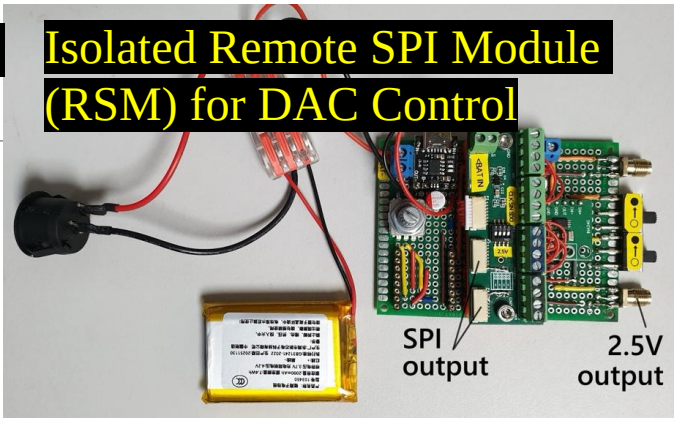




Sensor–LATRIC0 Integrated Test Board

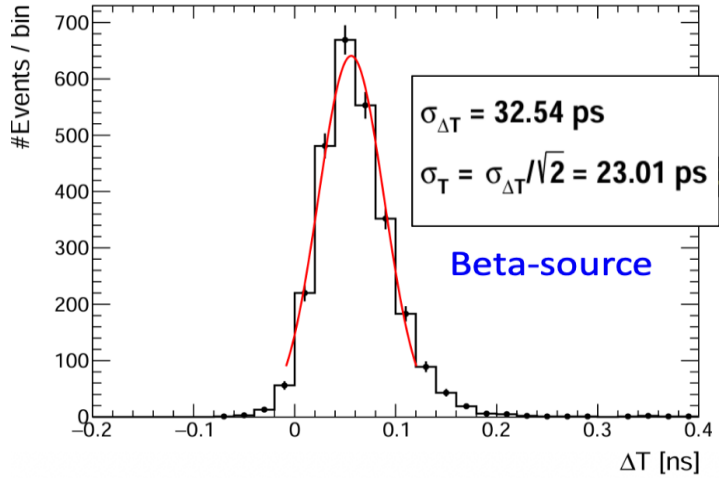


Developed DAC Controller "PicoCalc

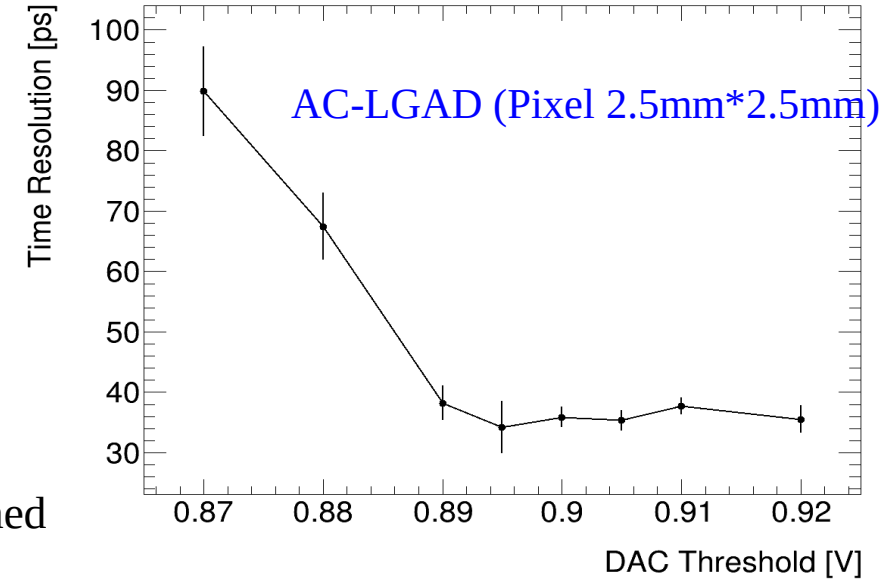


Isolated Remote SPI Module (RSM) for DAC Control

Time difference measured with two LATRIC0 chips



A time resolution of 23 ps was measured for the combined LGAD+LATRIC at Beta source system



At MIP-equivalent laser intensity, the time resolution improves with increasing threshold and stabilizes at about 36 ps in the 0.89–0.92 V range.

Summary

- CEPC outer tracker system requires high timing and spatial resolution for PID and tracking.
- **Towards CEPC Outer tracker, R&D of AC-LGAD sensor, readout ASIC, combined test is ongoing; Meanwhile, beam test preparation and Mechanical Design and Fabrication R&D also are ongoing [see Jiajian TEOH's talk and Xiaohui Qian's talk]**
- Sensors with different n+ dose, pitch size, electrode pad width, strip length, Impact to sensor performance is clear

Laser density:0.02%,
collected charge equal to MIP

- **Strip AC-LGAD sensors:**
  - **2cm long strip sensors: timing resolution: ~40ps, Spatial resolution: 6-9um**
  - **1cm long strip sensors: timing resolution: ~30ps, Spatial resolution: 5-6um**

N+ dose	Strip length	Pitch size	Electrode pad width	Timing resolution	Spatial resolution
1P	2cm	100	50	60-160ps	>10um
0.1P	2cm	100	50	60-80ps	6-8um
	2cm	200	100	~50ps	5-9um
	2cm	200	50	~40ps	6-9um
	1cm	200	50	~30ps	5-6um

- Readout ASIC: LATRIC0[1-channel] and LATRIC1[8-channel],TOA and TOT resolution~30ps
- Plan： More study will be done about strip sensors with lower n+ dose, with the pitch size as 300um and 500um, pixelated sensors

  Beam test will be done for strip AC-LGAD sensors

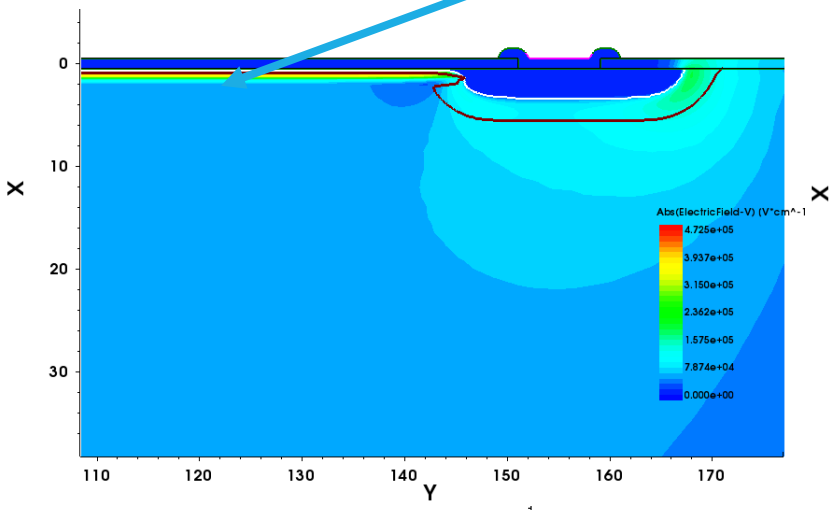
  AC-LGAD sensors with ASIC test will be done.

  Next submission of AC-LGAD sensor is planned in November, 2026

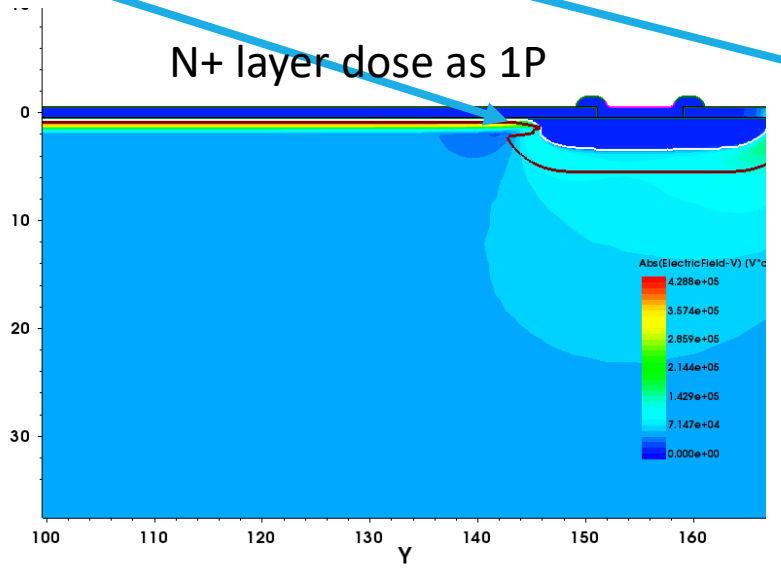
Backup

High electrical field region

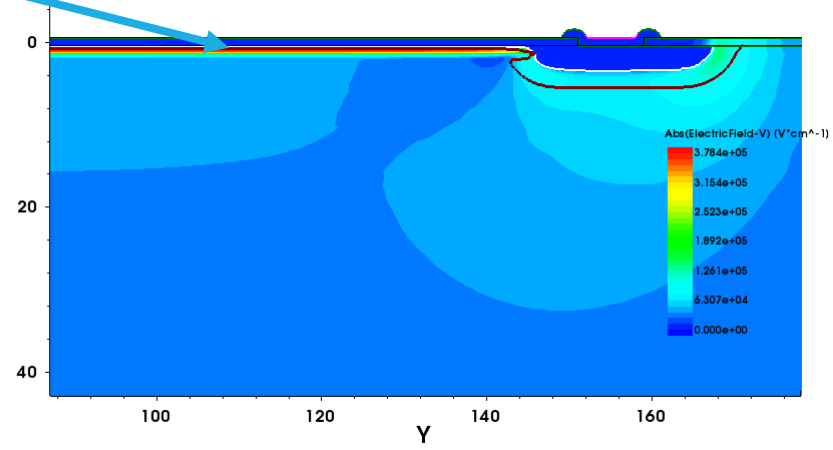
N+ layer dose as 10P



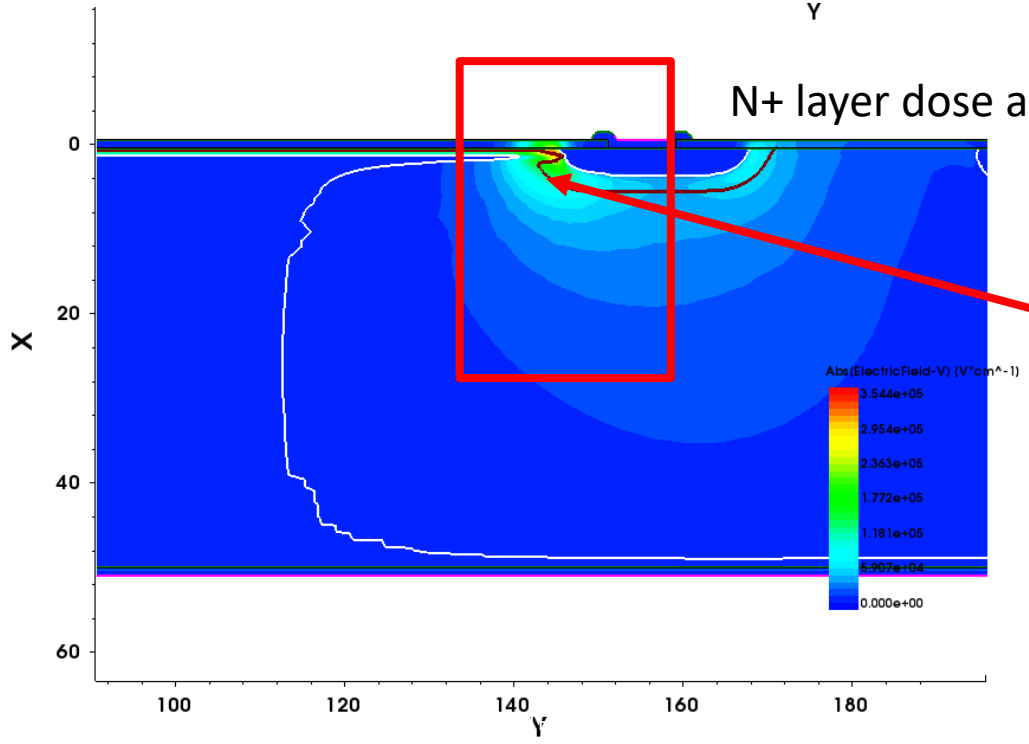
N+ layer dose as 1P



N+ layer dose as 0.1P



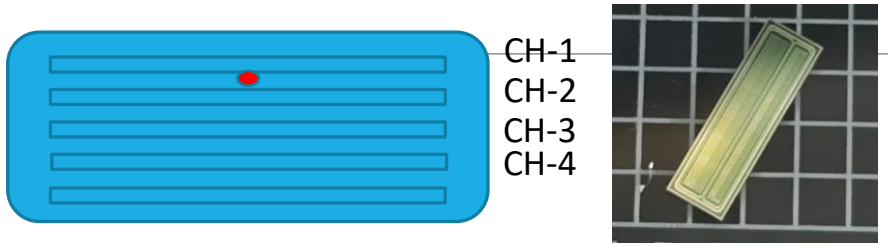
N+ layer dose as 0.01P



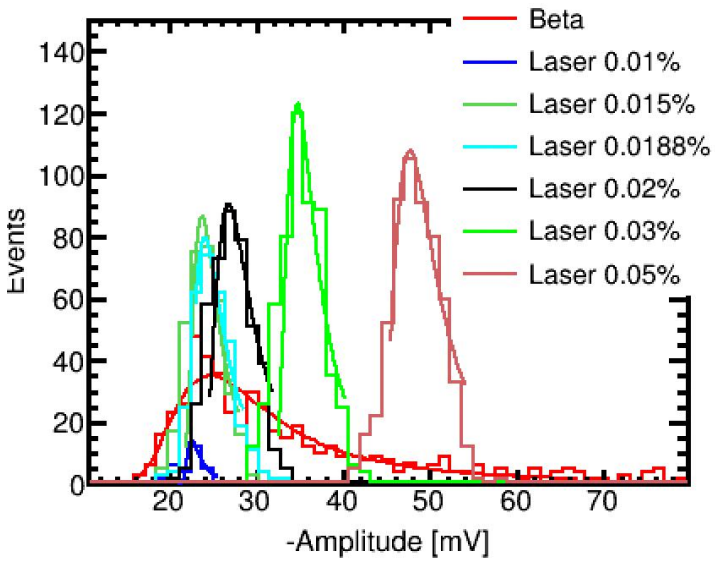
Early breakdown happens near the JTE not from the Gain layer

MIP-Equivalent Laser Tuning (W4-AC2-1-D7)

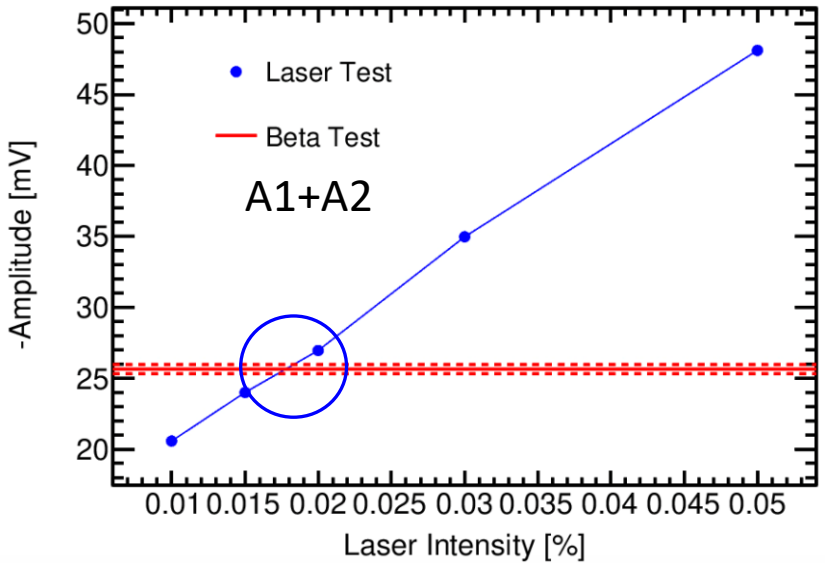
DUT sensor (W4-AC2-1-D7, 2 cm)

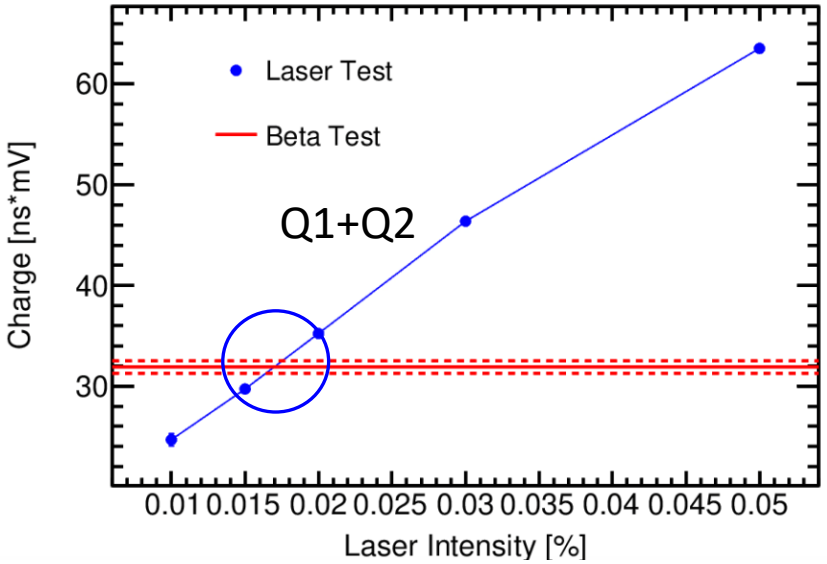


A1 and A2 are the waveform amplitudes of the seed (maximum amplitude) strip and the second strip, respectively.
Q1 and Q2 are the integral charge (negative polarity) of the corresponding waveforms.



W4 (1 P)





The laser intensity of ~0.02% matches the MIP response in both amplitude and integrated charge.