AC-LGAD sensor Optimization and Consideration

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2025-02-20

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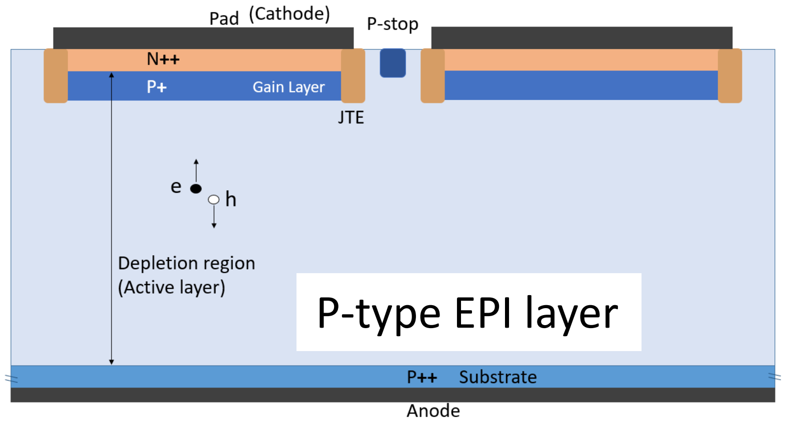
- DC-LGAD and AC-LGAD structure
- AC-LGAD capacitance
  - Impact to sensor performance and power consumption
  - Components of Device Capacitance
  - How to improve?
- AC-LGAD strip length
  - Impact to sensor performance
    Transmission loss, charge sharing
  - How to improve?
- Summary

LGAD and AC-LGAD

- **Low gain avalanche detector** be demonstrated to have timing resolution <35ps and will be used to provide precise timing information in ATLAS HGTD and CMS ETL for address pile-up issues.

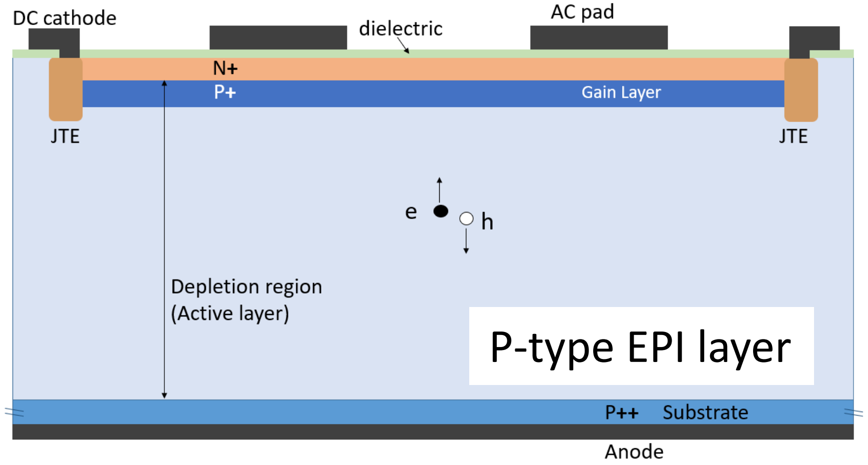
- **AC-LGAD**, a 4D detector, provides both timing and position information at the same time.

LGAD (Low-Gain Avalanche Diode)



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

AC-LGAD (AC-coupled LGAD)



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

Timing performance

The timing resolution of an LGAD is determined by the accuracy with which it can measure the time of arrival of particles.

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

б$_{Timewalk}$	The term "time walk" refers to the phenomenon where the time of signal arrival varies depending on the amplitude of the detected signal.	恒比定时 TOT correction constant fraction discriminator (CFD) method
б$_{Landau}$	Variations in carrier trajectories due to Landau levels can introduce additional timing jitter, reducing the overall timing resolution.	EPI thickness
б$_{jitter}$	$\propto t_{rise}/(S/N)$ t_{rise}, rising time, S/N, Signal to noise ratio,	Electrical field and EPI thickness Signal【EPI thickness and gain】, Noise【capacitance】

Capacitance

- Capacitance impact

  4pF for HGTD → 10pF for CEPC OTK

  - Timing resolution worse

    Rise time and noise increase, sensor timing performance worsen

  - Power consumption increase

    To keep the timing performance, ASIC power consumption 20mW/channel

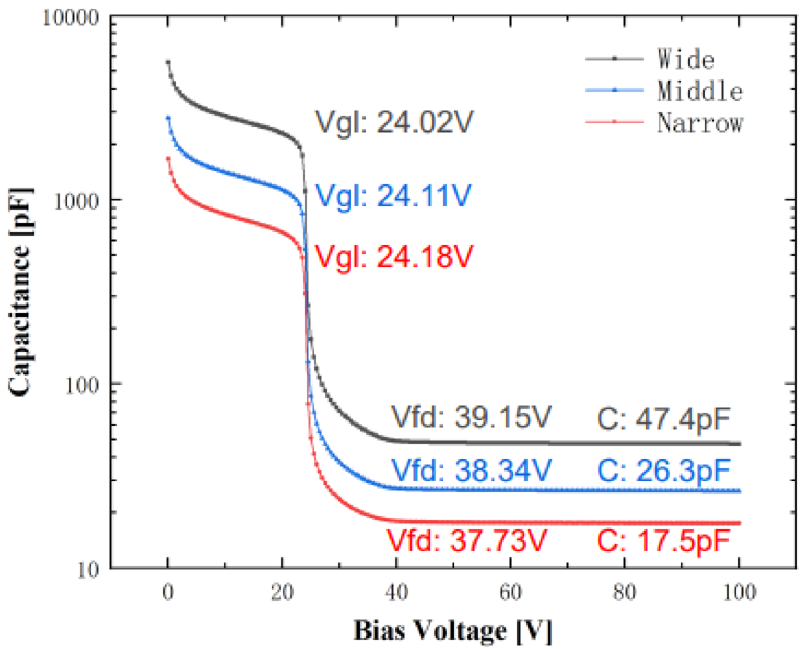
Capacitance impact

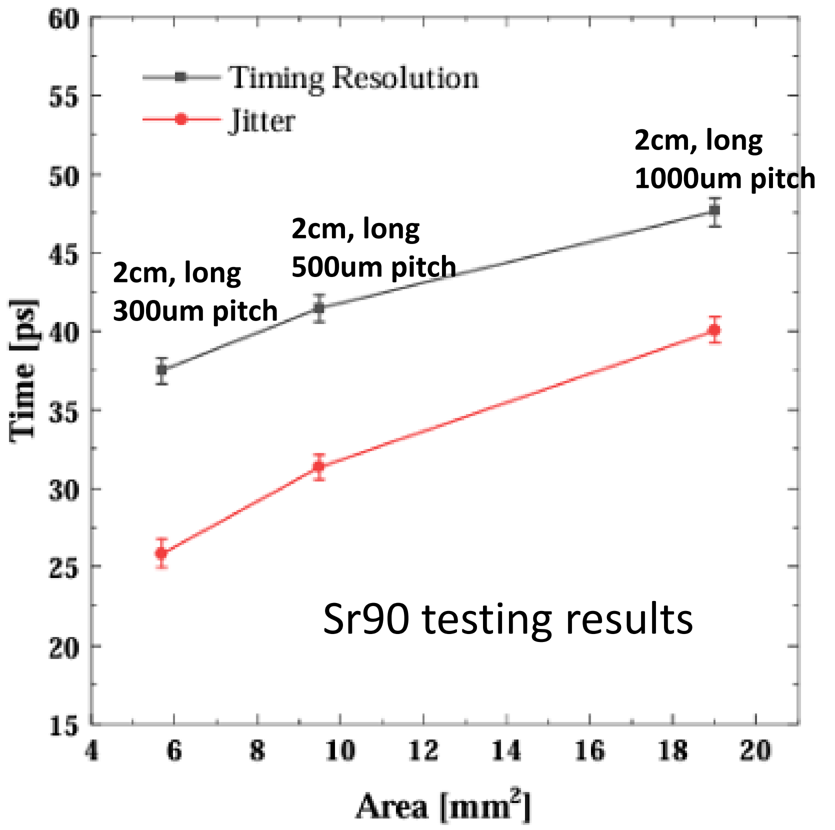
- **Capacitance impact to timing performance:**

S/N ∝ (1/Capacitance), $б_{jitter} \propto t_{rise}/(S/N)$ ⟶ **$б_{jitter} \propto$ Capacitance**

area	Capacitance	Timing performance
1.9 cm x 300 um	17.5pF	37.5ps
1.9 cm x 500 um	26.3pF	42ps
1.9 cm x 1000 um	47.4pF	48ps

DC-LGAD(50um thick) with long strip(1.9cm) and large capacitance





Capacitance impact

Sensor capacitance impact to power consumption:

Timing performance:
Jitter part of ASIC

$$\sigma_{\text{jitter}} = \frac{e_n C_d}{Q_{\text{in}}} \sqrt{t_d}.$$

$$e_n = \sqrt{2kT/g_{m1}}.$$

$$g_{m1} = q \times I_d / 2kT$$

C_d is capacitance from sensor
I_d is the current of amplifier

In order to keep same timing performance (jitter from ASIC):

C_d increase by 2 times, Id need to increase 4 times, Power consumption: V_{dd} x I_d **4 times**

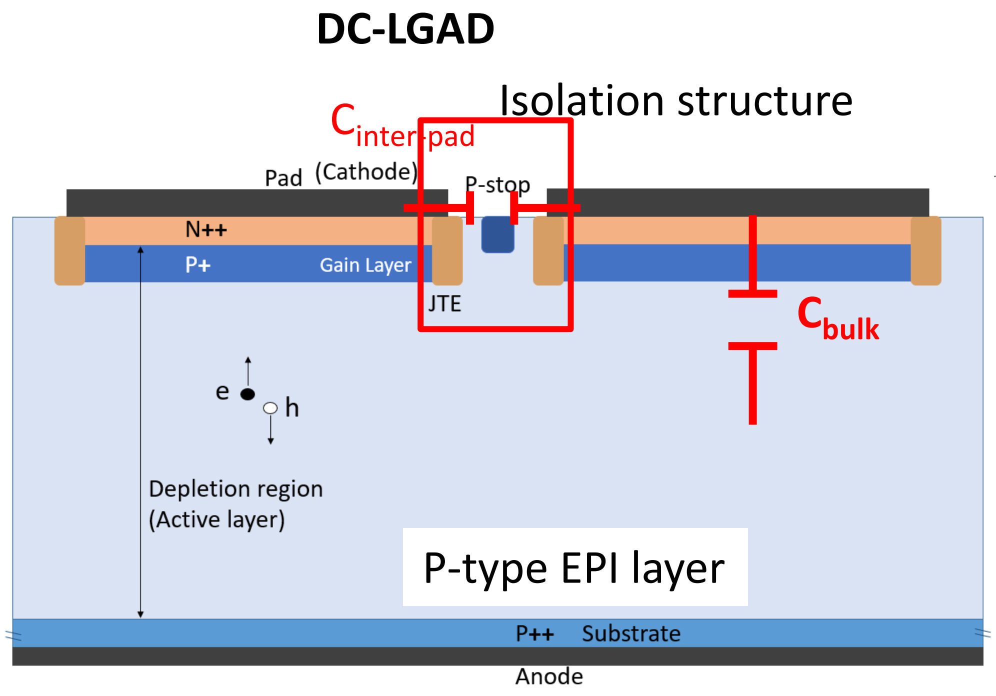
	LGAD capacitance	FEE power consumption
HGTD (Altiroc)	4.2pF	2.7mW/channel
CEPC OTK (Juloong)	10pF	**15mW/channel**

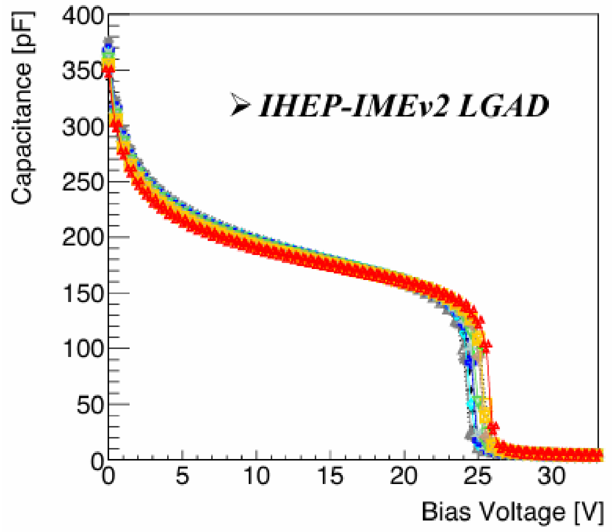
Very large!
To keep ASIC timing performance as 30ps

Capacitance impact

→Which parameter of AC-LGAD affect the sensor’s capacitance？
→How to improve?

Capacitance for DC-LGAD





$C = \varepsilon_0 * \varepsilon_r * A / d$

C : Capacitance 电容
ε_0 : Vacuum permittivity, 真空介电常数
ε_r : Relative permittivity, Dielectric constant介电常数
A: Capacitor area 面积, d: distance between plates 距离

- **DC-LGAD**
  - C_{bulk}: Bulk capacitance, PN junction capacitance
  - $C_{inter-pad}$: pixel size and isolation structure(<0.5pF testing result)

- Depletion capacitance: C_{bulk}
  - EPI thickness: 50um
  - Size: 1.3mm x 1.3mm

Calculation results：电容计算结果：

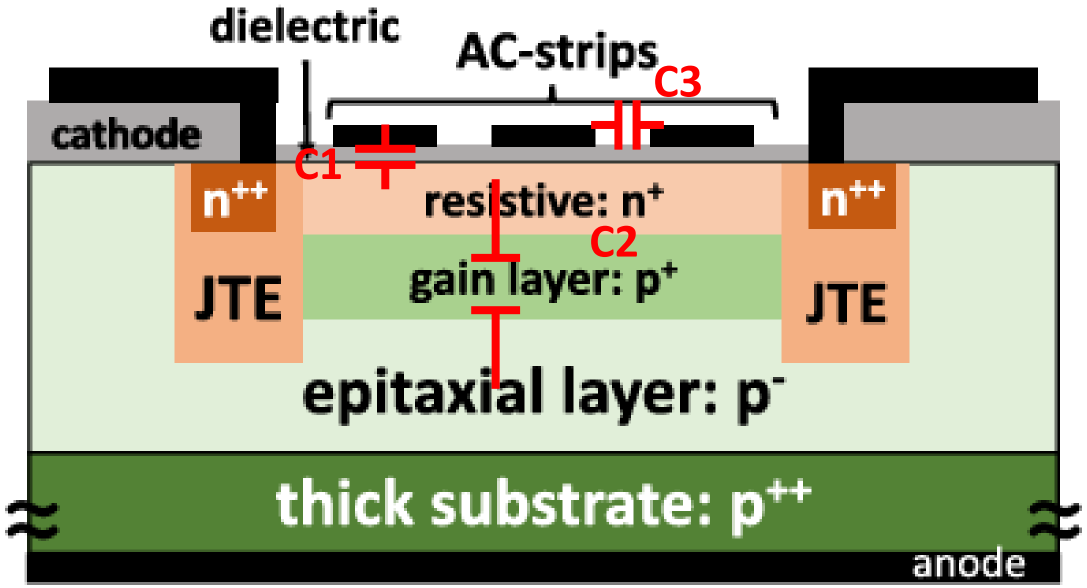
8.85e-12 x 11.9 x 1.3x1.3x1e6/ 50e-6 = 4.38pF

ε_0 ε_r A d

Testing results：电容测试结果：4.2pF

Capacitance for AC-LGAD

- AC-LGAD capacitance



C1: capacitance between AC metal and n+ layer (MIS)

metal length and width, dielectric thickness and material

HPK: 1cm long, 50um wide, 600pF/mm^2 ,
capacitance: 300pF

IHEP: 5.65mm long, 100um wide, 300pF/mm^2 ,
oxide thickness:150nm
capacitance: 170pF

100pF Magnitude

C2: capacitance PN junction (PN)

Strip length and pitch, strip group(isolated), EPI layer thickness

IHEP: EPI 50um thick, 1.3mm x 1.3mm
capacitance: 4.2pF

10pF Magnitude

C3: capacitance between strips (MIM)

Strip length and pitch, isolation method [1pF Magnitude]

Capacitance along the signal path: C1 and C2, Series Connect

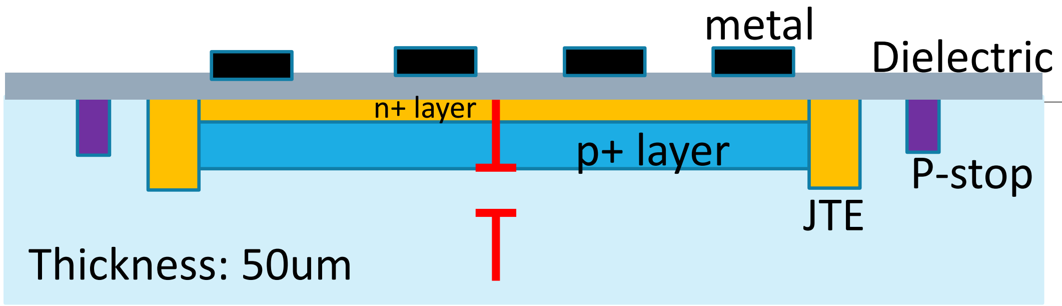
$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

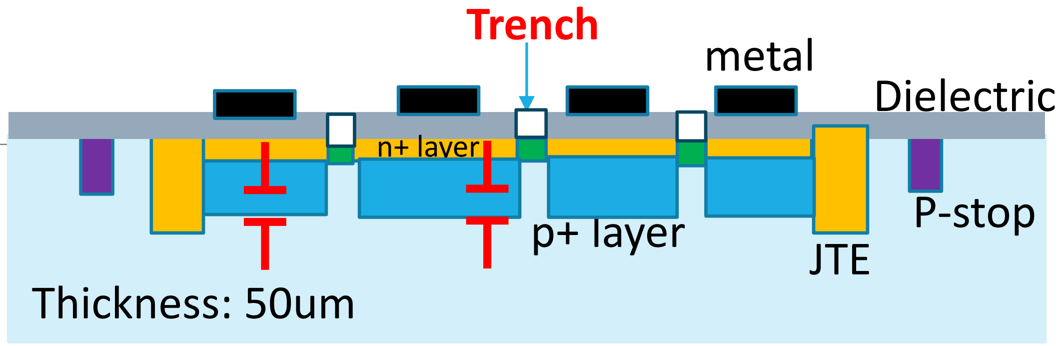
$$C = \frac{C_1 C_2}{C_1 + C_2}$$

C2 smaller, decide the capacitance

Capacitance for AC-LGAD

1、 Reduce capacitor area





$$C = \varepsilon_0 * \varepsilon_r * A\downarrow / d$$

C_2 area: Strip length, pitch, number of strip

HGTD LGAD results:

Bulk capacitance:

50um thick, 1.3mm x 1.3mm=1.69mm^2

Capacitance: 4.2pF

Isolation structure: reduce this number of strips to one

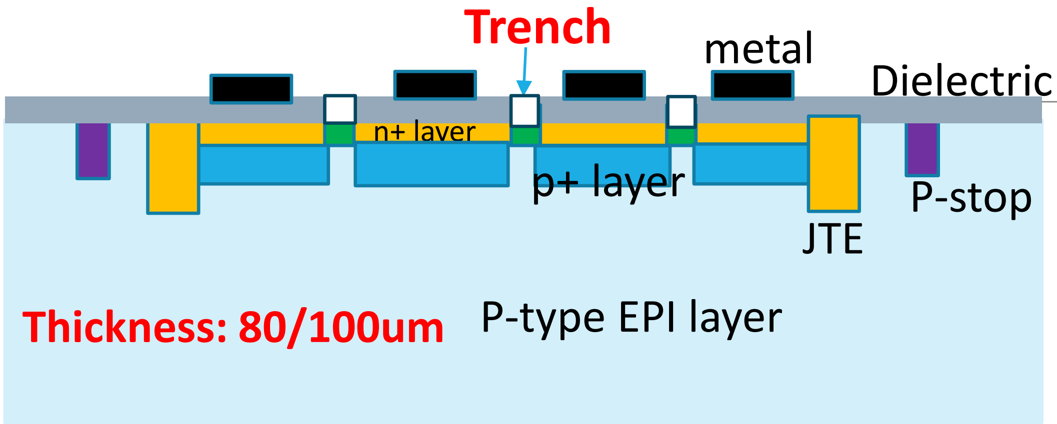
Isolated AC-LGAD: one strip

The capacitance is proportional to [strip length X pitch]

length	pitch	Two strip EPI thickness(50um)	One strip EPI thickness(50um)
4cm	100um	~20pF	4/1.69 x 4.2=~10pF
	200um	40pF	20pF
2cm	100um	10pF	5pF
	200um	20pF	10pF

Capacitance for AC-LGAD

2、 Increase EPI thickness



$C = \varepsilon_0 * \varepsilon_r * A / \mathbf{d} \uparrow$

HGTD LGAD results:
Bulk capacitance: C_2
50um thick, 1.3mm x 1.3mm
Capacitance: 4.2pF

Isolated AC-LGAD: one strip

length	pitch	EPI thickness (50um)	EPI Thickness（80um）	EPI thickness (100um)
4cm	100um	4/1.69 x 4.2=~10pF	6.25pF	**~5pF**
	200um	20pF	12.5pF	**10pF**
2cm	100um	5pF	3pF	**2.5pF**
	200um	10pF	6.25pF	**5pF**

	length	pitch	Capacitance
Before	**7cm**	100um	10pF

EPI thickness and Timing performance

The timing resolution of an LGAD is determined by the accuracy with which it can measure the time of arrival of particles.

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

б$_{\text{Timewalk}}$ The term "time walk" refers to the phenomenon where the time of signal arrival varies depending on the amplitude of the detected signal

恒比定时 TOT correction

constant fraction discriminator (CFD) method

б$_{\text{Landau}}$

Landau affect

Variations in carrier trajectories due to Landau levels can introduce additional timing jitter, reducing the overall timing resolution.

☹ EPI thickness ↑ б$_{\text{Landau}}$ ↑

б$_{\text{jitter}}$ t_{rise}/(S/N)

t_{rise}, rising time, electrical field and EPI thickness

☹ EPI thickness ↑ t_{rise} ↑

S/N, Signal to noise ratio, EPI thickness(MIP, 70-80e/um)

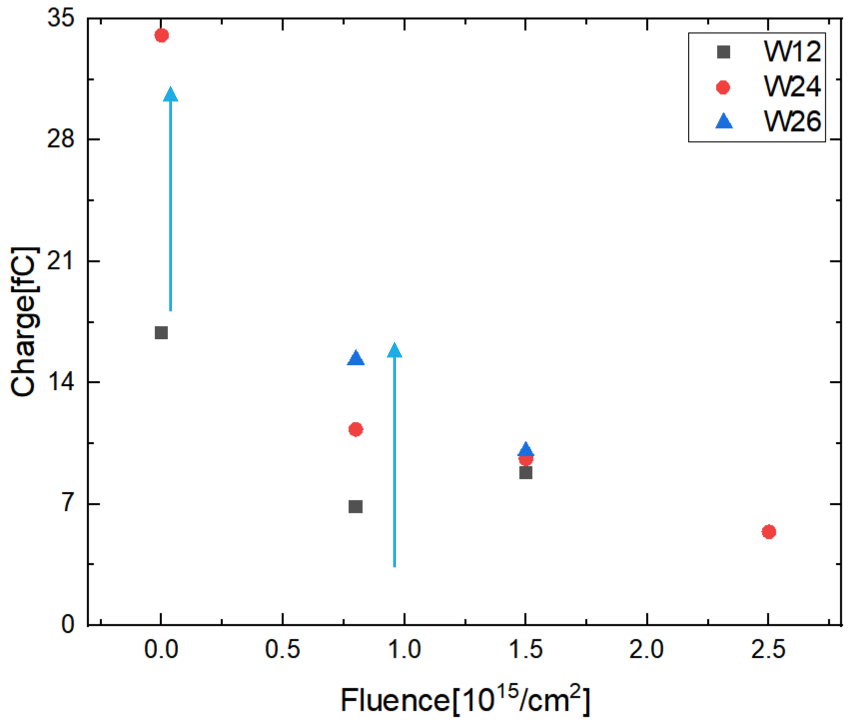
☺ EPI thickness ↑ MIP charge ↑

$$\sigma_{\text{jitter}} = \frac{e_n C_d}{Q_{\text{in}}} \sqrt{t_d}$$

☺ EPI thickness ↑ Cd ↓

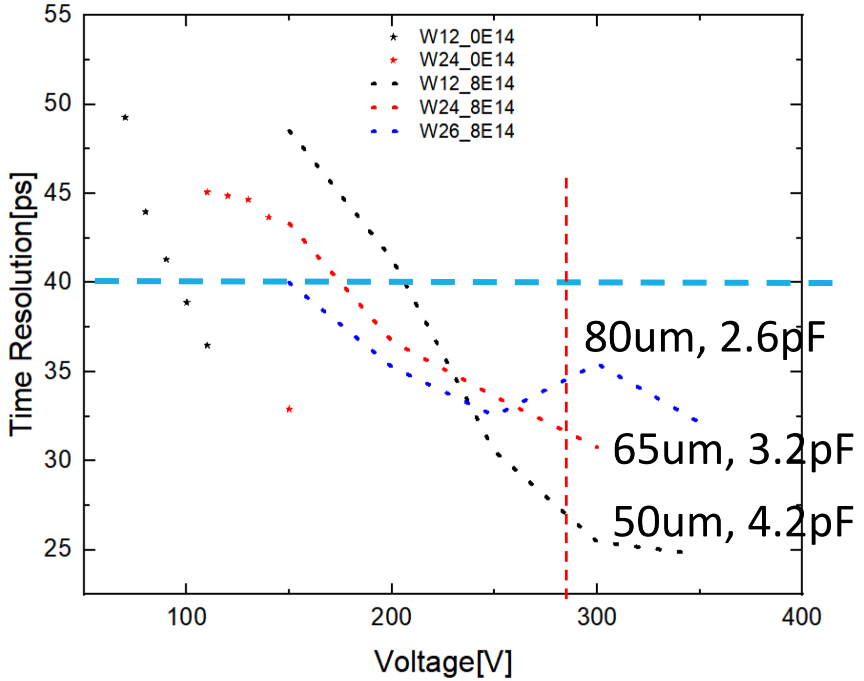
EPI thickness and timing performance

During IHEPV3, Sensors with same size, different EPI thickness: 50um(W12), 65um(W24), 80um(W26) be fabricated. Testing results be got recently.



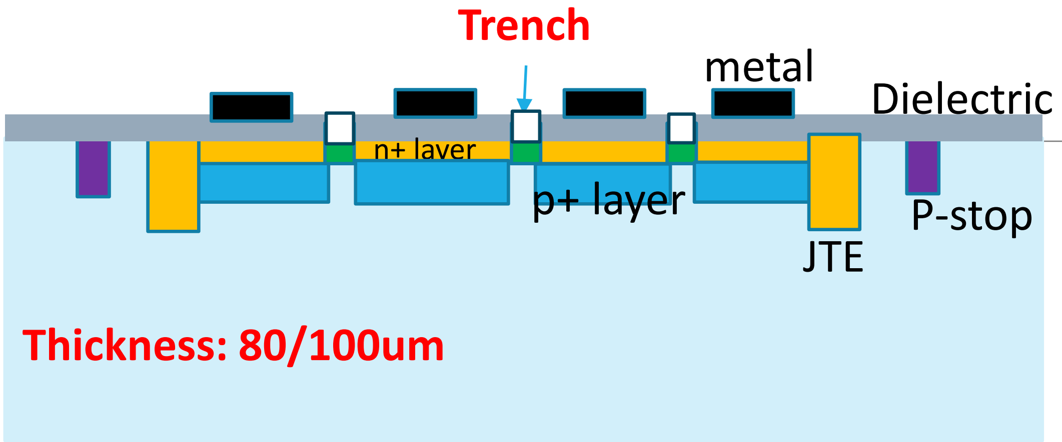
EPI thickness increase, charge increase

Sr 90 testing results



- **Timing resolution <40ps**
- **EPI thickness 80um, capacitance reduce, worse resolution. (10ps worse)**

Power consumption VS EPI thickness



length	pitch	EPI thickness (50um)	EPI Thickness（80um）	EPI thickness (100um)
4cm	100um	4/1.69 x 4.2=~10pF	6.25pF	**~5pF**
	200um	20pF	12.5pF	**10pF**
2cm	100um	5pF	3pF	**2.5pF**
	200um	10pF	6.25pF	**5pF**

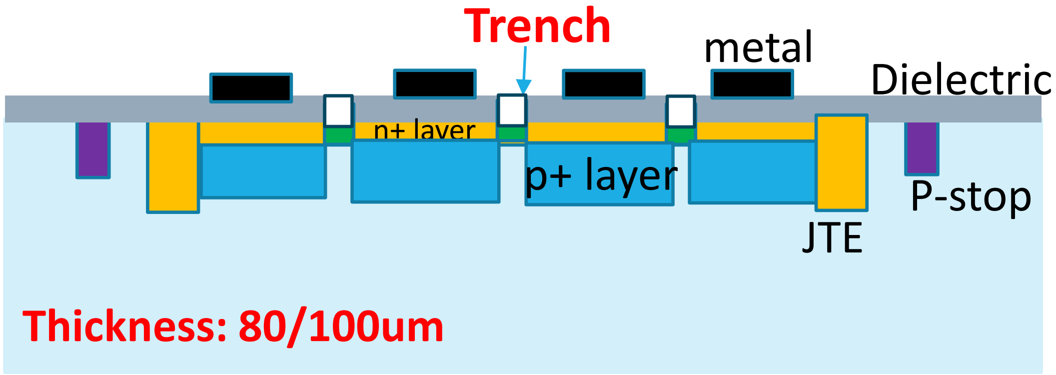
Power consumption calculation (per channel)

4cm length, 100um pitch

	LGAD capacitance	FEE part	TDC part	Clock system and other digital part	ASIC total
HGTD (Altiroc)	**4.2pF**	**2.7mW**	**Static 11mW**	**1mW**	
CEPC OTK (Juloong)	**10pF (EPI: 50um)**	**15mW**	**3mW**	**2mW**	**20mW/channel**
CEPC OTK (Juloong)	**5pF (EPI: 100um)**	**3.8mW**			**8.8 mW/channel**

With EPI thickness increasing from 50um to 100um, readout power consumption decreases from 20mW/channel to 8.8mW/channel.

Capacitance Optimization method



➢Capacitance

Method to improve:

- Change area: **Add isolated structure**, [JTE+Pstop, Trench, dielectric layer separate]
- Change EPI thickness: **Increase EPI thickness** [50um to 80/100um], without changing length

By using these methods, the capacitance can be reduced from 10pF to 5pF, and the readout power consumption reduce from 20mW/channel to 8.8 mW/channel.

➢Timing performance

- Sensor timing performance will be from 25ps to 35ps (when EPI thickness: 50um—>80um)
- How does the total timing resolution impact physical analysis when it varies from 40 ps to 50 ps, or even worse?

➢Spatial resolution

- With EPI thickness increasing, spatial resolution will be better (MIP generate more charge)

Strip length impact

Strip length: bad impact ☹

- Signal transmission loss: signal amplitude reduce which will affect timing performance

  2cm to 4cm

- Charge sharing

  Strip length increases signal sharing among more strips, the signal-to-noise ratio decreases, leading to worse timing performance

Strip length: good impact ☺

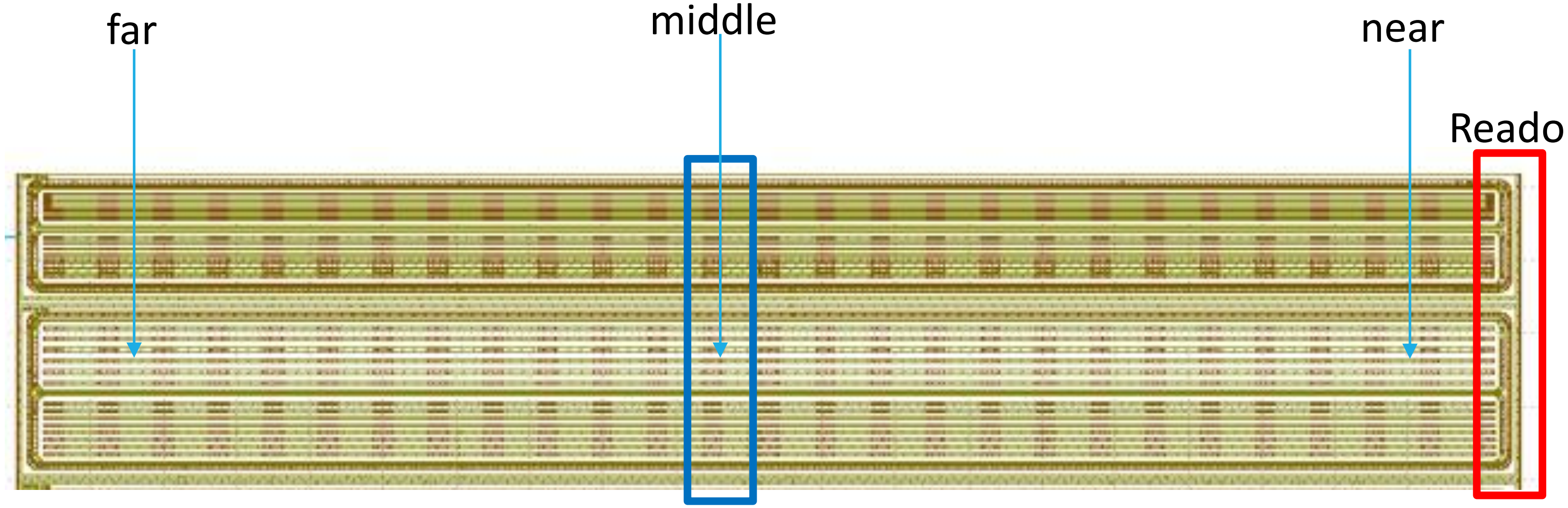
- Reduce the readout channels
- Easy for module assembly, enough room to accommodate supporting electronics(DC-DC, etc)

Strip length affect

➢ **Signal transmission**: signal amplitude reduce? Timing performance worse

Results got by Yunyun (testing of FBK 2cm sensors)

Readout from end, and inject laser from near, middle and far. The signal amplitude decrease, and the timing performance get worse(from 25ps to 40ps) as increasing the length of readout line.



When the signal transmit along the strip, some charge will be lost. →S/N ↓ Why?

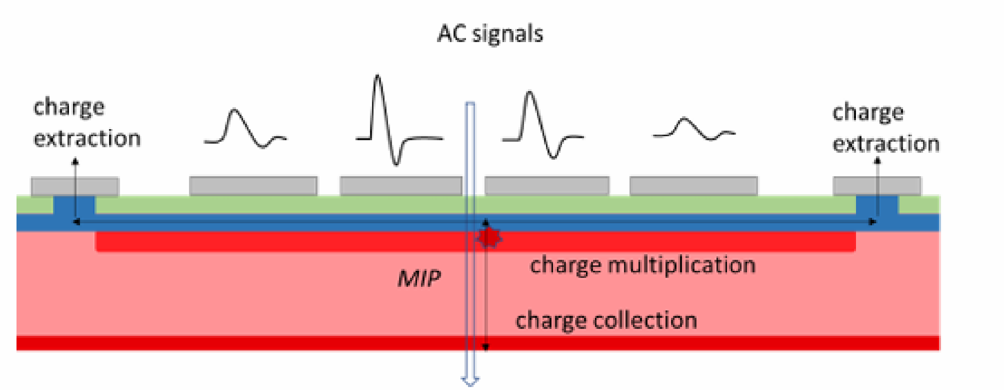
➢ Method to improve: **Readout the signal from middle instead of end**

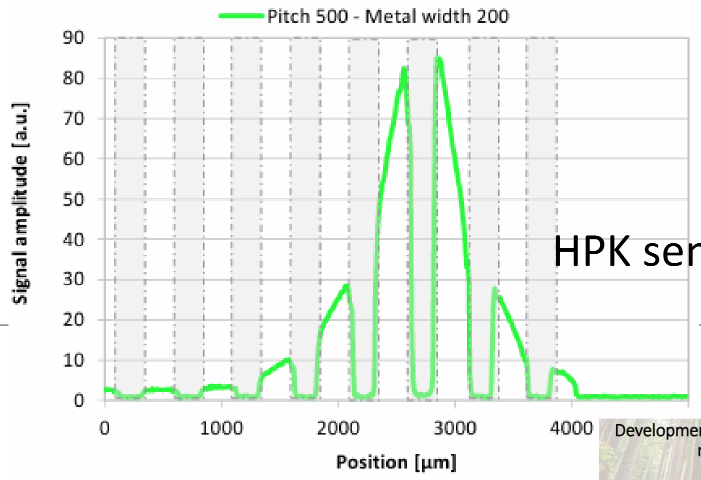
Strip length affect

- **charge sharing**

  Strip length increases charge sharing, worse timing expected

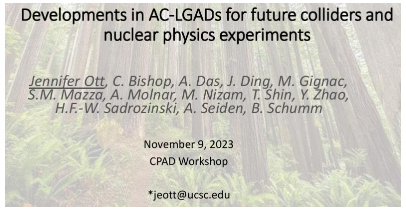
  signal from primary strip decrease





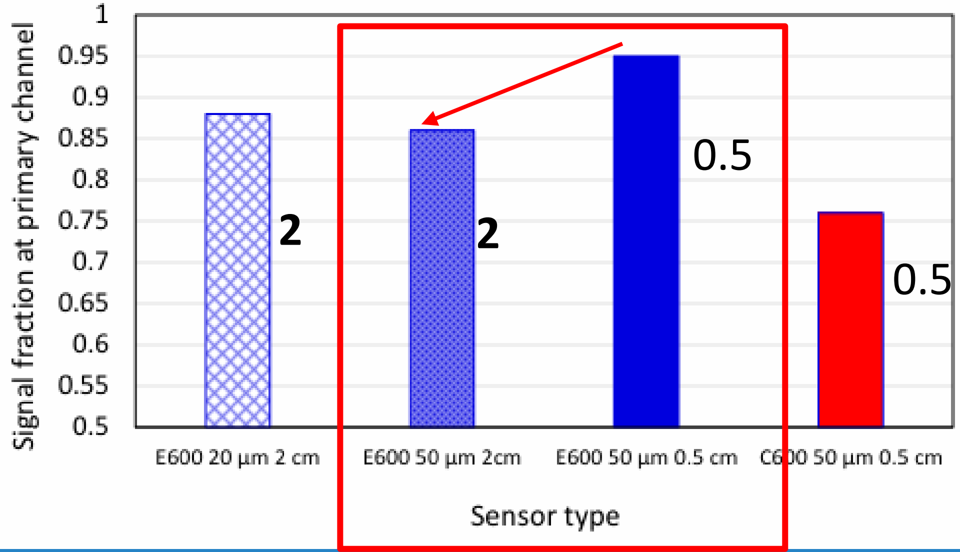
HPK sensors

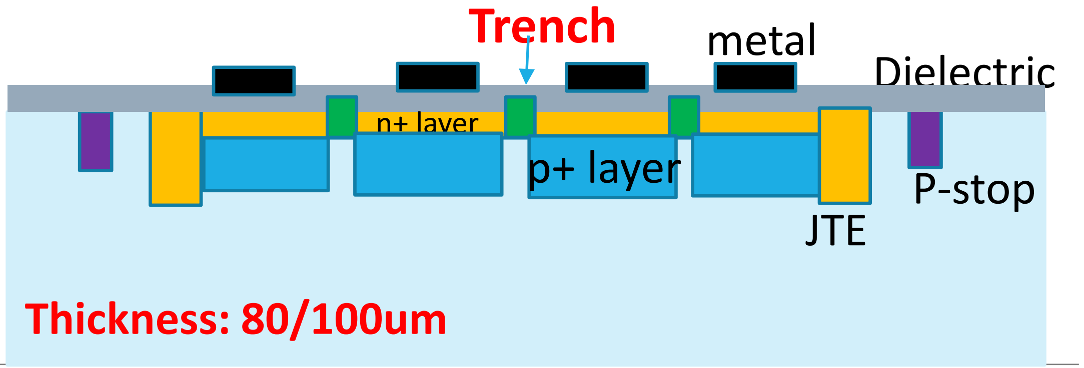
Older 2.5 cm strip sensor



HPK long strip AC-LGAD results

ONLY Length from 0.5cm to 2cm





Sensor parameters that can be changed to decrease charge sharing:

1、increase the pitch size, reduce capacitance between strips

Change pitch size larger, sharing reduce. Timing and spatial resolution?

2、increase resistance between strips

By increasing the resistivity of n+ layer. Timing and spatial resolution?

3、 Isolation (not mentioned here)

1、Increasing pitch size

Capacitance between pixel reduces, charge sharing be reduced

1cm long

80um pitch， 60um metal

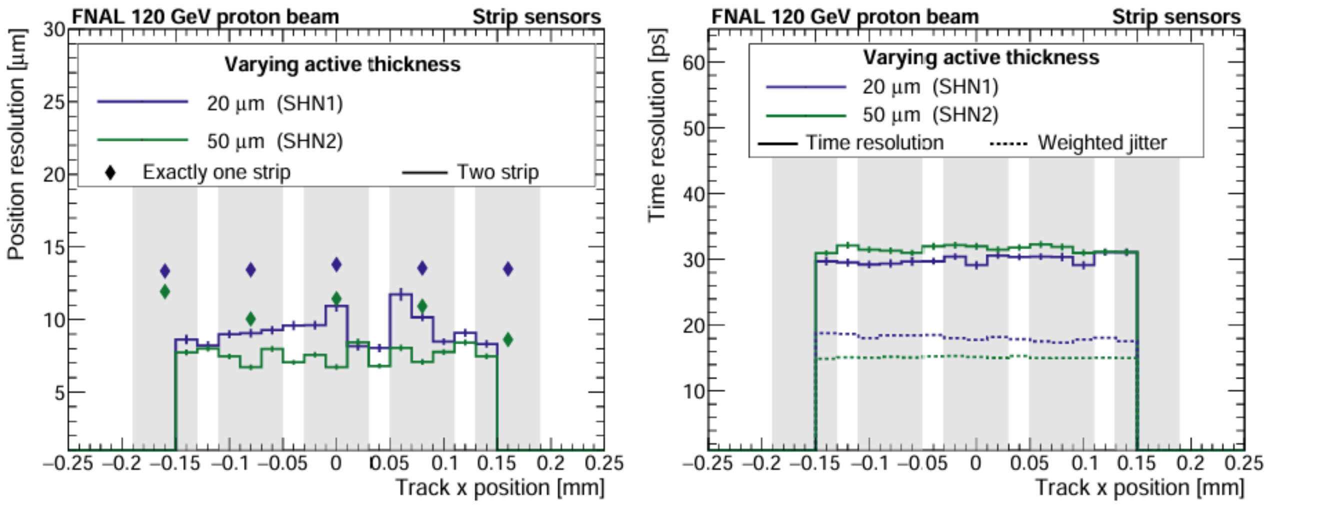


Figure 11: Position (left) and time (right) resolution as functions of the x position for strip sensors of different active thickness. The sensors presented have 80 µm pitch, 60 µm strip width, 1600 Ω/□ sheet resistance, and 240 pF/mm^2 coupling capacitance. Spatial resolution values have a tracker contribution of 5 µm removed in quadrature. Time resolution values have a reference contribution of 10 ps removed in quadrature.

1cm long

500um pitch， 50um metal

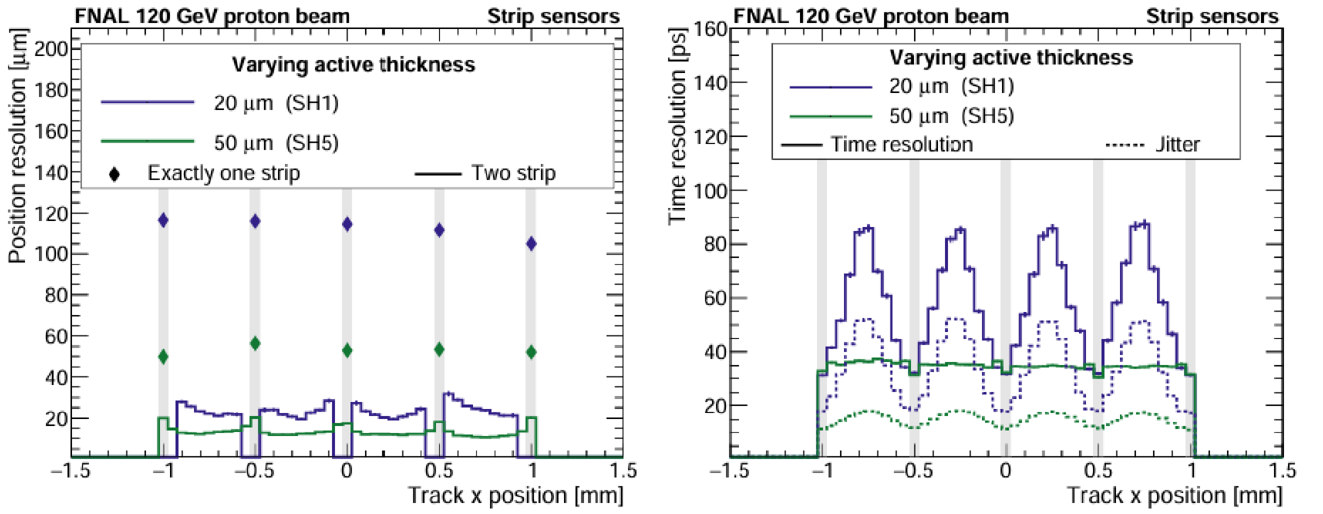


Figure 9: Position (left) and time (right) resolution as functions of x position for strip sensors of different active thicknesses. The sensors presented have 500 µm pitch, 50 µm strip width, 1600 Ω/□ sheet resistance, and 600 pF/mm^2 coupling capacitance. Spatial resolution values have a tracker contribution of 5 µm removed in quadrature. Time resolution values have a reference contribution of 10 ps removed in quadrature.

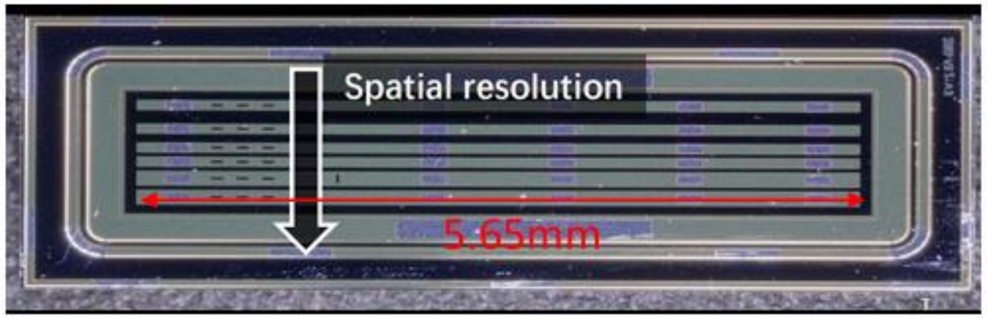
Increasing pitch size will worsen both spatial resolution and timing resolution

For the method: consider both charge sharing and time-position resolution

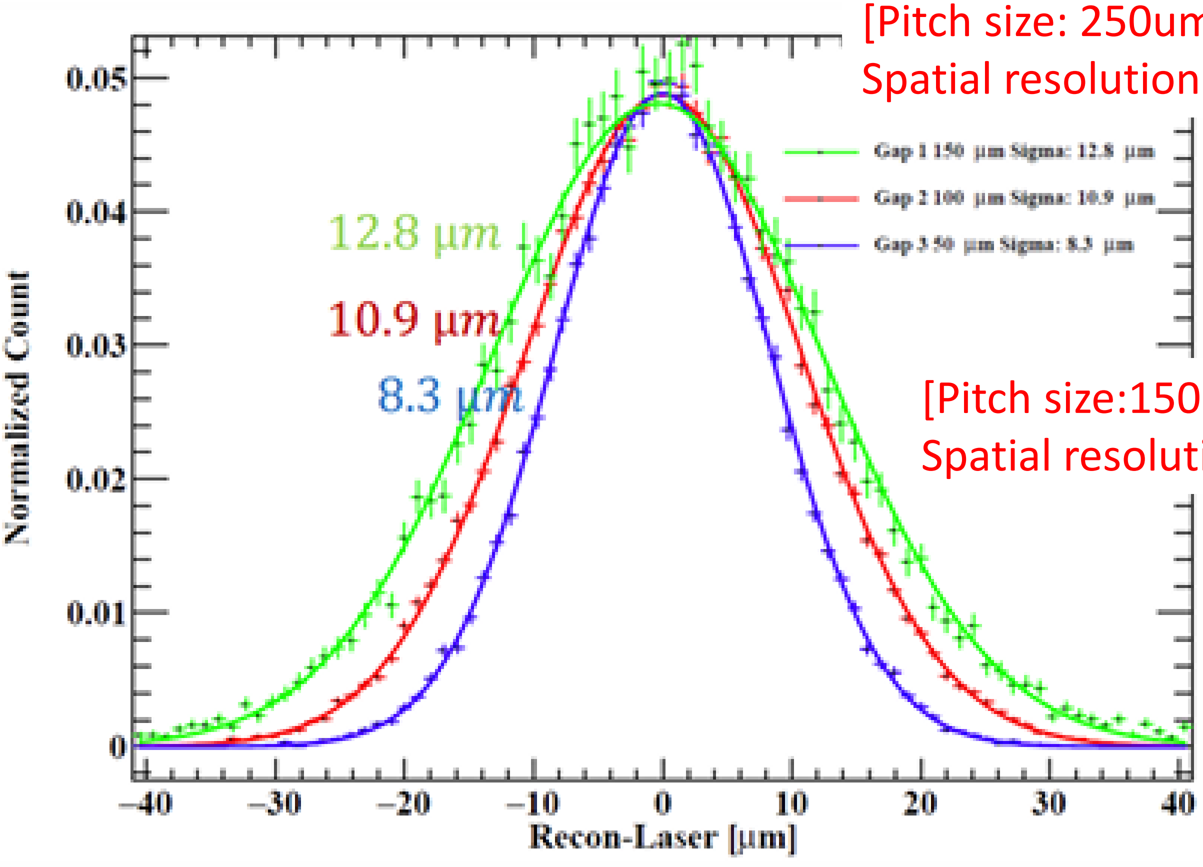
Results for pixel and strip centimeter-scale AC-LGAD sensors with a 120 GeV proton beam, Fermilab, BNL, HPK, July 16, 2024

IHEP AC-LGAD R&D

1、 Increasing pitch size



Strip length: 5.65mm
Pitch size: 250um, 200um, 150um

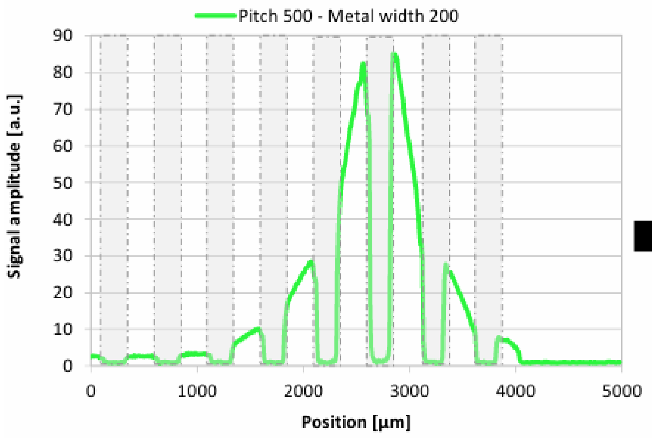


Increasing pitch size will worsen spatial resolution

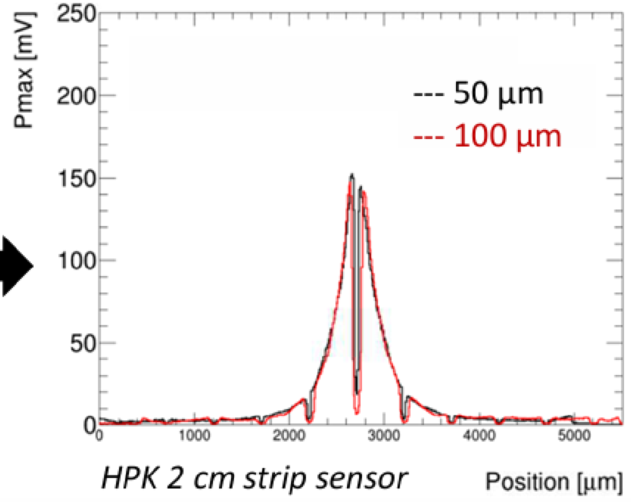
For the method:
consider both charge sharing and position resolution

2、Increasing the n+ resistivity

Charge sharing can be decreased!



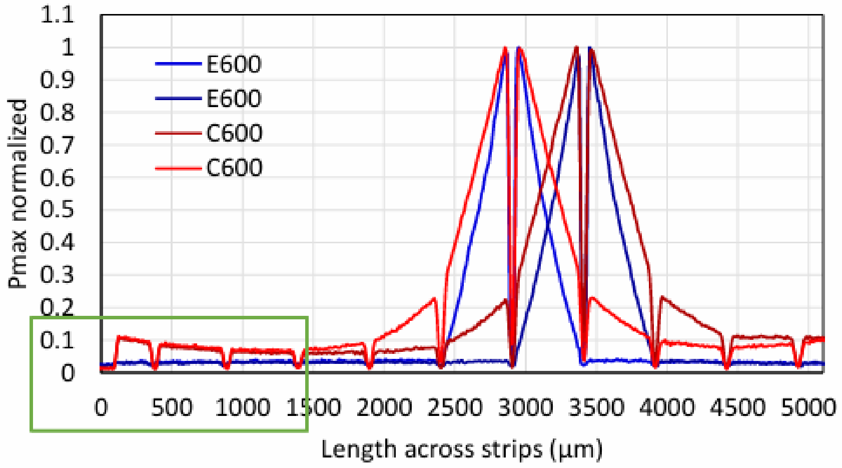
Older 2.5 cm strip sensor

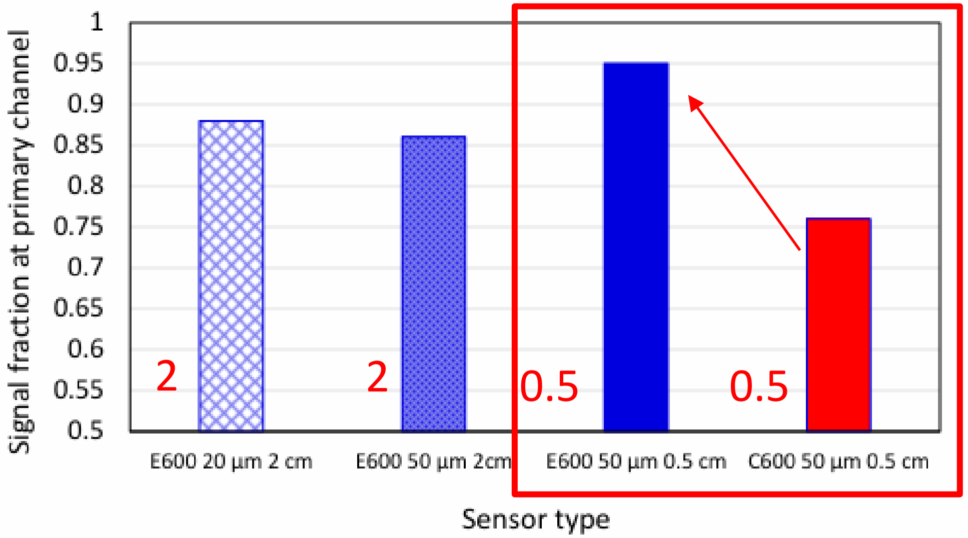


HPK 2 cm strip sensor
Amplitude normalized

Before: more charge sharing to far strips

Now: less charge sharing to far strips





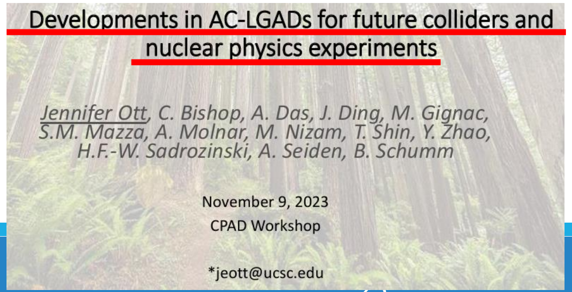
How?

What is the difference for E600 and C600?

Increase resistivity of n+ layer!

In terms of signal sharing / signal amplitude:

- Signal sharing is strongly impacted by the n-layer resistivity – almost 20 % more for lower resistivity, as well as different long-range behavior



2、Increasing the n+ resistivity

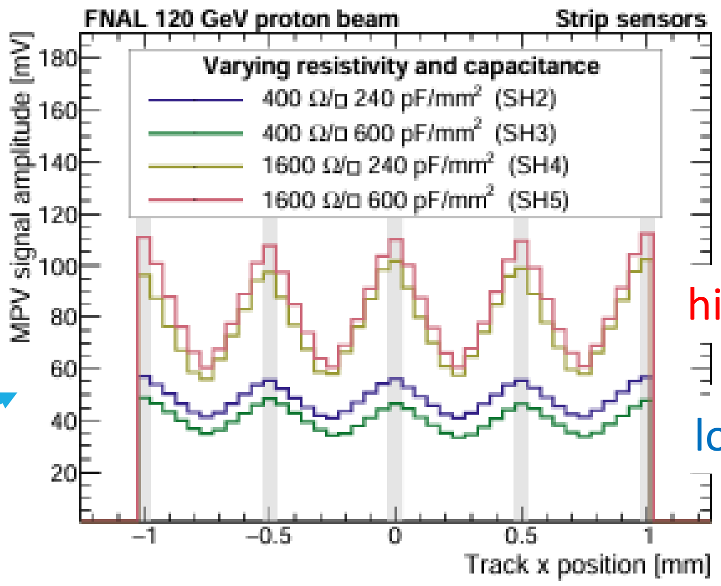
HPK sensors

Higher n+ resistivity, better spatial resolution

Sensors with higher n+ resistivity have large signal amplitude

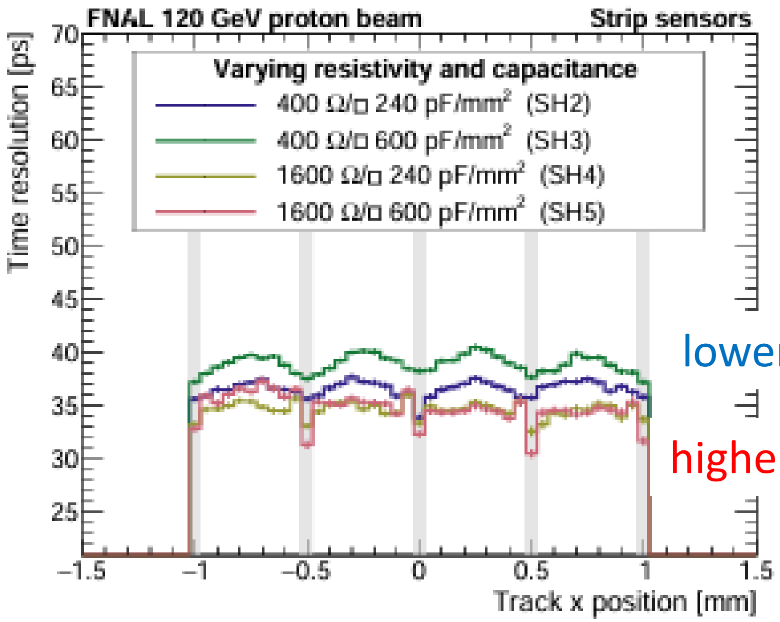
And signal amplitude change fast as position changing

Higher n+ resistivity, comparable timing resolution



higher n+ resistivity

lower n+ resistivity



lower n+ resistivity

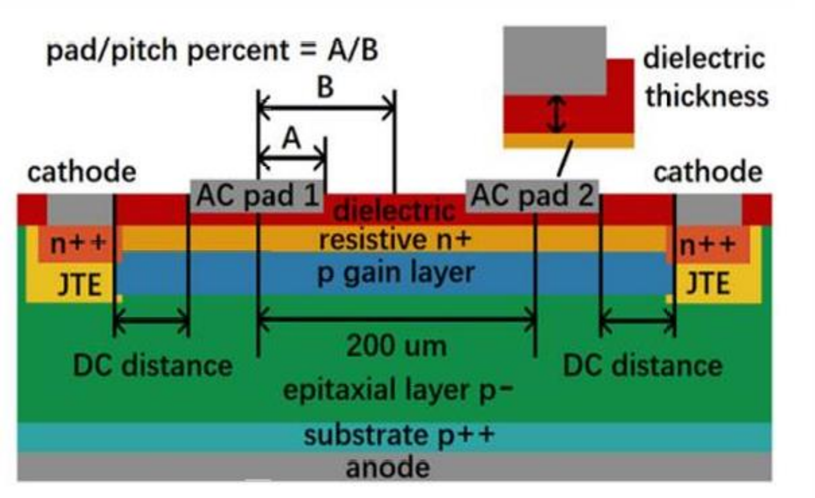
higher n+ resistivity

SH2, SH3, less n+ resistivity

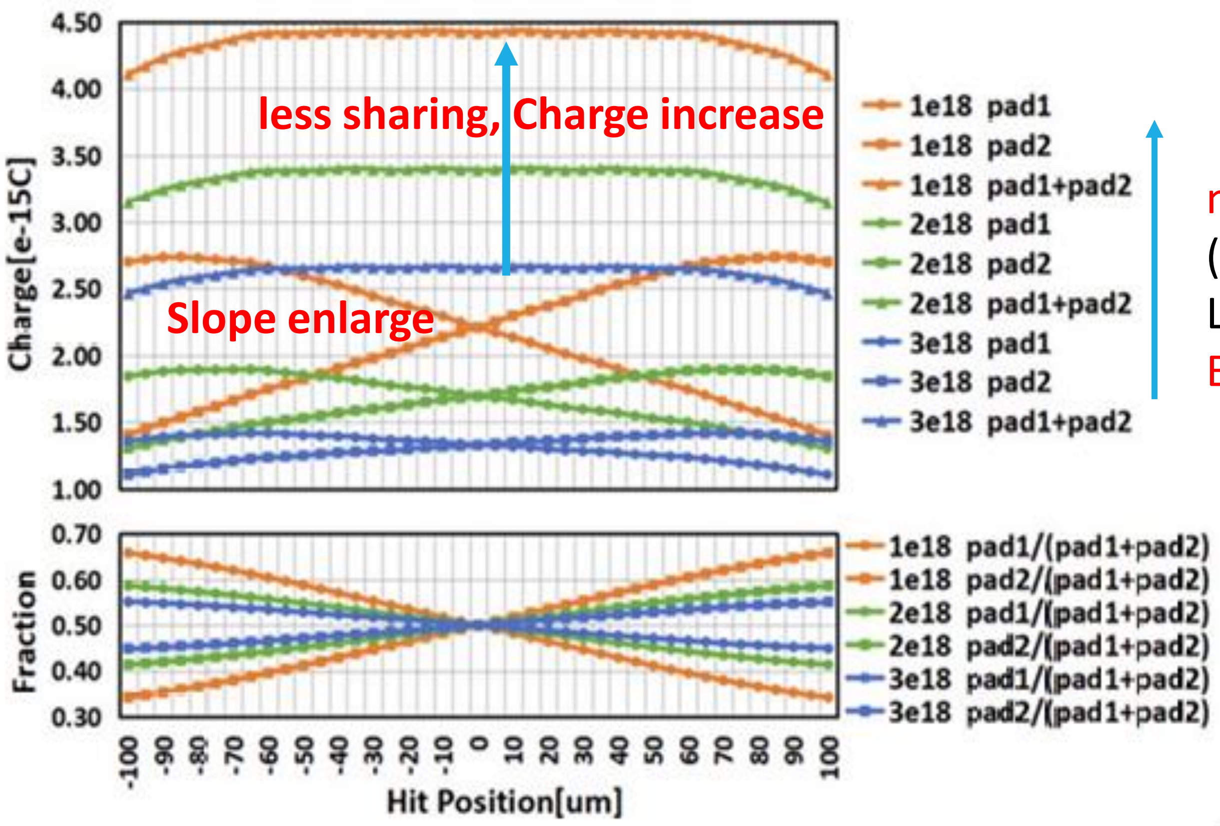
SH4, SH5, high n+ resistivity

2、Increasing the n+ resistivity

IHEP simulation



TCAD model of AC-LGAD for simulation

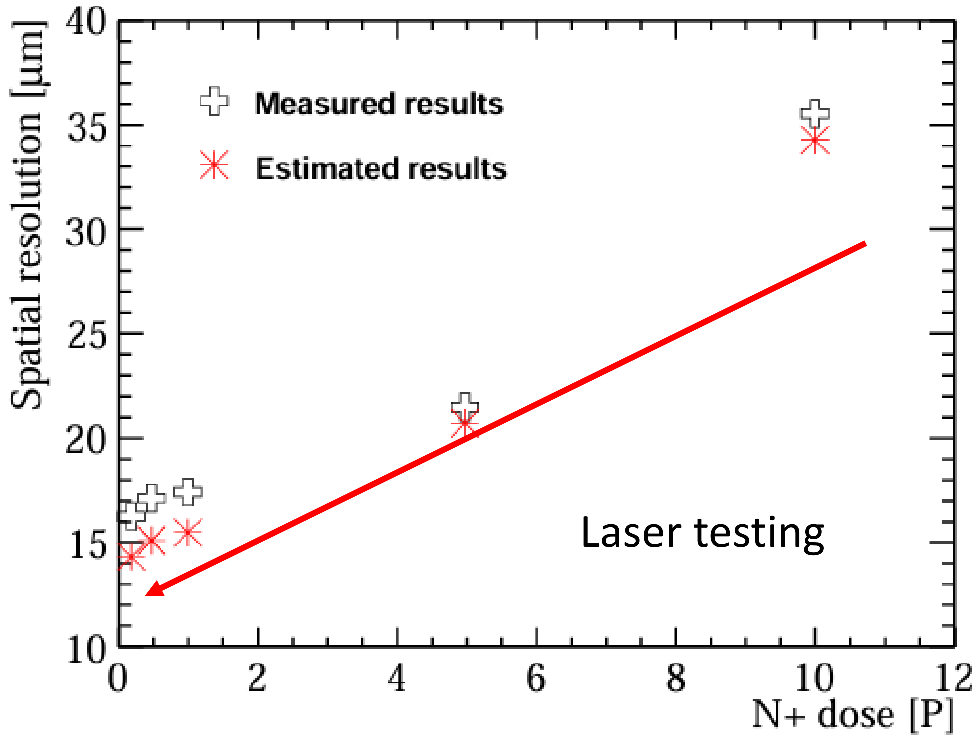


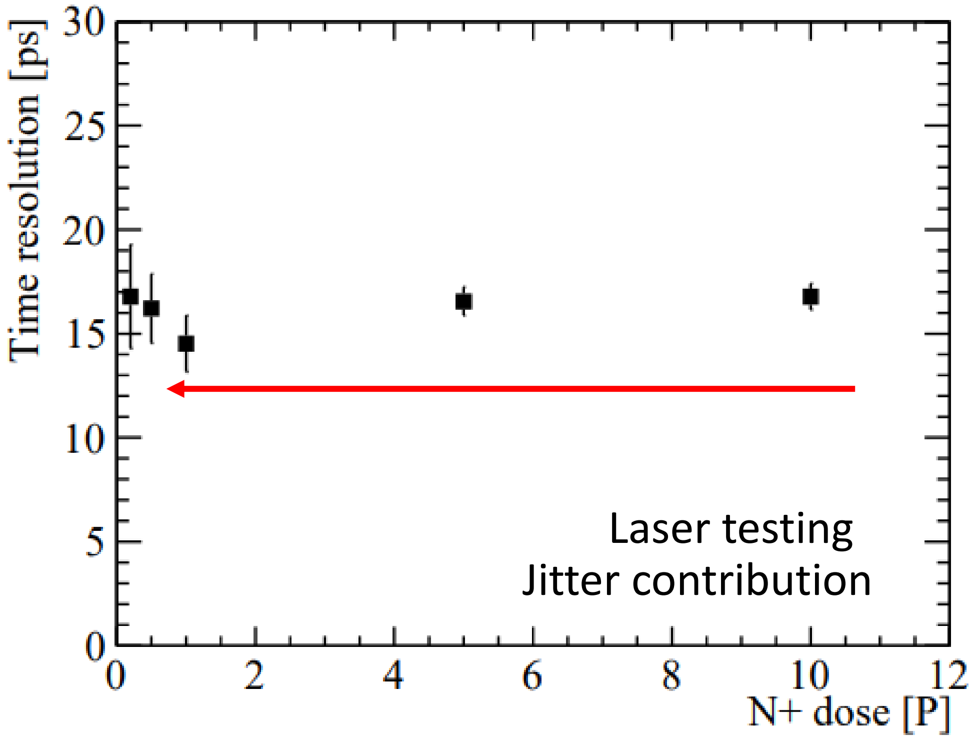
n+ dose decrease
(Higher n+ resistivity)
Less charge sharing
Better spatial resolution

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

2、 Increasing the n+ resistivity

IHEP AC-LGAD results





When n+ dose decreases(higher n+ resistivity), spatial resolution is improved.
While the corresponding timing resolution is similar

Strip length impact

Strip length: bad impact

- Signal transmission loss: signal amplitude reduce which will affect timing performance
  Method to improve: Readout the signal from middle instead of end

- Charge sharing
  Strip length increases signal sharing among more strips, the signal-to-noise ratio decreases, leading to worse timing performance
  Methods to improve:
  1、**increase the pitch size**, while the spatial resolution worsen(10um→15um, 20um).
  2、**increase the n+ resistivity**, spatial resolution is better, and timing resolution is comparable.
  [cannot be very high(lower n+ dose change PN junction properties)]

Compromise consideration, trade-off

New submission

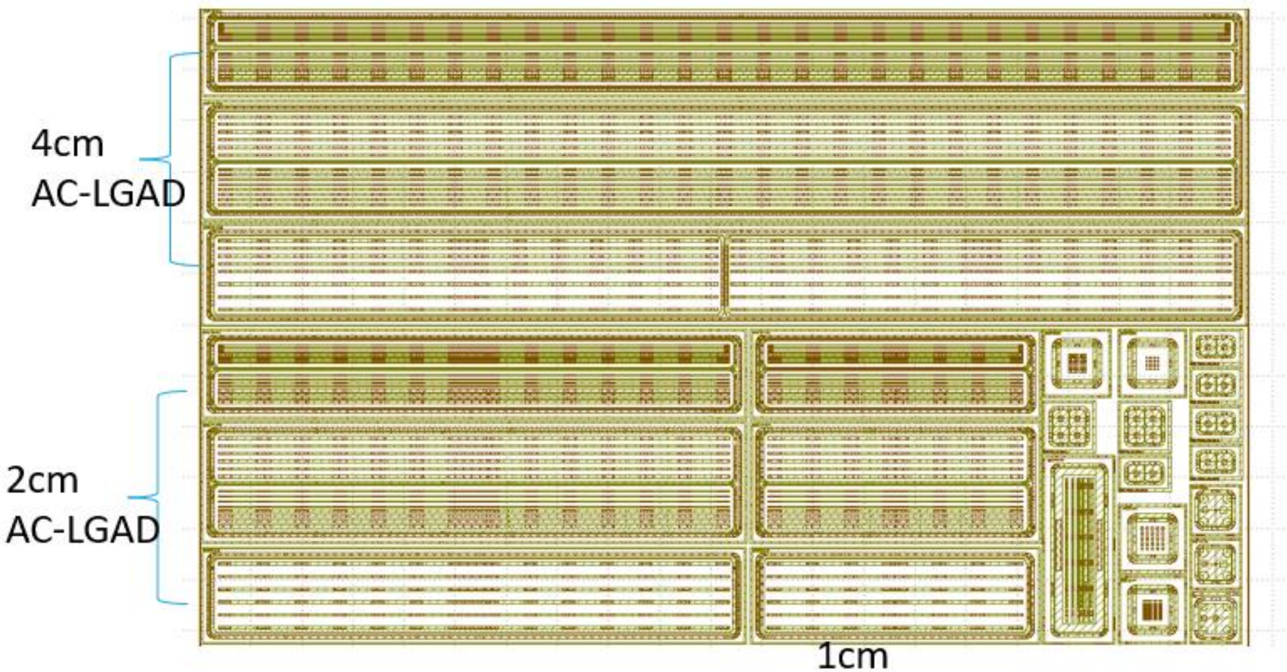
New submission: several optimization methods have been implemented

Strip AC-LGAD with different length and pad-pitch size, [1cm, 2cm, 4cm] [100um, 200um, 500um]

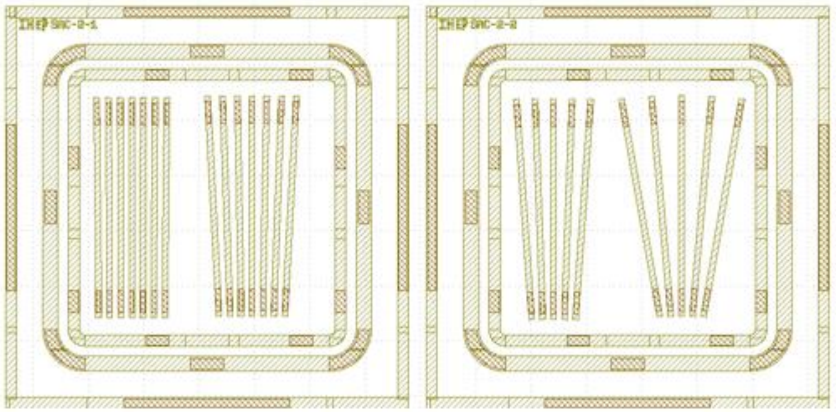
Strip AC-LGAD **with EPI layer of different thickness(50um, 65um, 80um)** — Reduce capacitance, increase signal

Strip AC-LGAD with different isolation structure — Reduce both capacitance and charge sharing

Strip AC-LGAD with different process parameters: reduce **n+ dose(resistivity)** — Reduce charge sharing and improve spatial resolution



- Sector, Fan shape AC-LGAD for Endcap



Yield

- **Yield** depends on sensor size (not only strip length)

  2cm x 2cm, or 4cm x 4cm 【Yield will be too bad for large sensor size: 8cm x 9cm, 14cm x 14cm】

- Larger sensor size, worse yield!

  From the point of yield, 2cm x 2cm is more preferred than 4cm x 4cm.

- But smaller sensor requires more readout channels, results in larger dead area and smaller place for electronics. **More studies are needed to address following issues:**

  the impact of more readout channels

  the impact of small sensor size to module assembly(ASIC, readout board, and so on)

  the impact of the dead area to physics

- The advantage of large sensor is obvious.

Let's focus on improving the performance and yield first!

Summary

- **Capacitance:** impact both power consumption and timing resolution
  - bulk capacitance

    Methods to improve: **adding isolation structure, increasing the EPI thickness**

    Sensor timing performance be a little worse(25ps→35ps) because of the thick EPI layer

- **Strip length:**
  - Transmission, impact signal amplitude(rise time)
    - Method to improve: **readout pads placed at the middle of strips**
  - Charge sharing, impact to signal amplitude and timing performance
    - Method to improve: **increasing pitch size, reducing the n+ layer dose,**

- **Let's do more work**

  1、Simulation and testing, find methods to improve capacitance \charge sharing \sensor performance

  Need manpower and support!

  2、Improve the yield

  3、A backup design with 2cmx 2cm sensor will be implemented in Ref-Tdr

Plan

➢Simulation: (2025.2-2025.6)

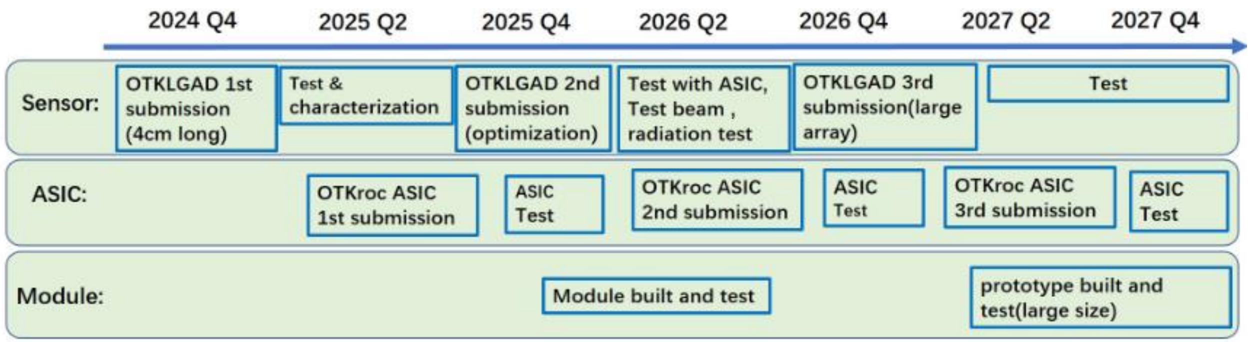
- Simulate sensor performance with long strip
  - TCAD software + spice model
- Simulate process and structure parameters to improve sensor capacitance and performance
  - N+ resistivity, isolation structure

➢Testing: (2025.2-2025.5)

- Radiation performance of available sensors(TID)
- Testing of sensors from FBK
- Timing and spatial resolution(Beam test)

➢Submission: (2025.2-2025.5)

- Layout ready, adding new isolated structure ongoing
- Process parameter chosen based on simulation



Backup

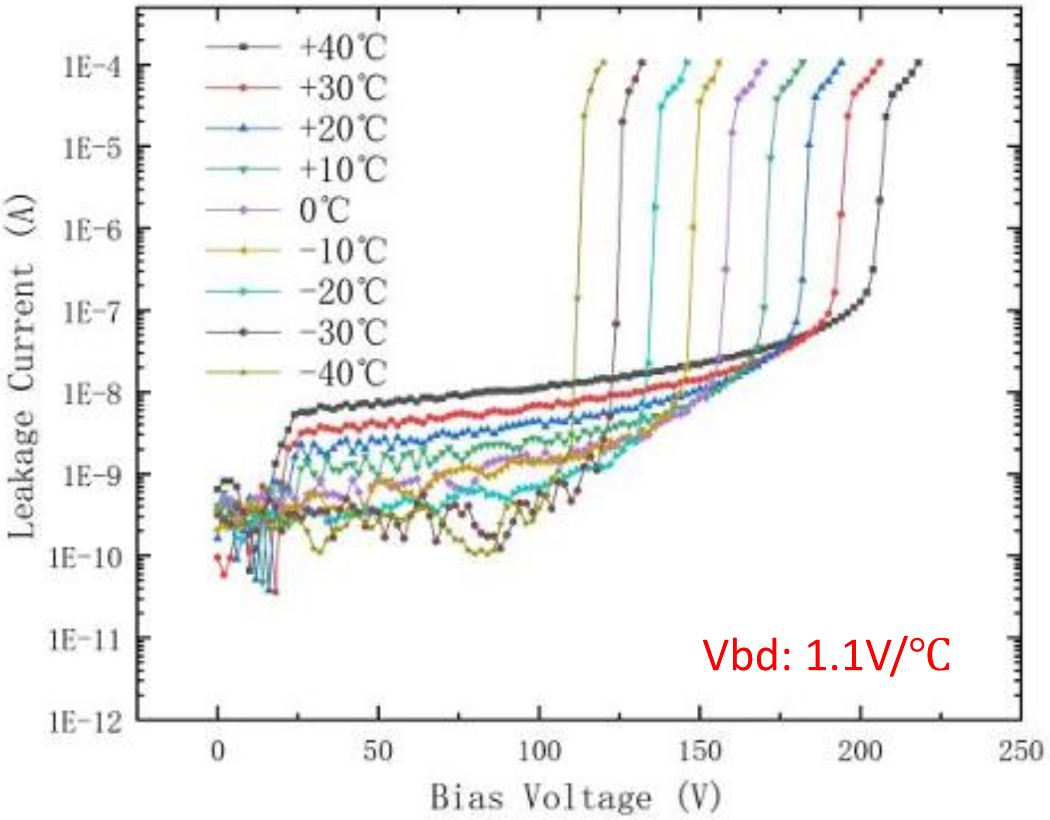
Plan

Long term plan

time	work
2025	• Testing the sensors from first submission, clarify the sensors performance and requirement (include Test beam and radiation test) • Find out how to optimize the sensor performance(structure and process) • Submission 2 Based on the results from first version and more simulation sensors with strip length ~4cm
2026	• Test of sensors from submission 2(basic properties and together with ASIC and BEE?) • Submission 3 large area sensor design and fabrication
2027	• Submission 4 if needed • module: sensor + ASIC module built and test

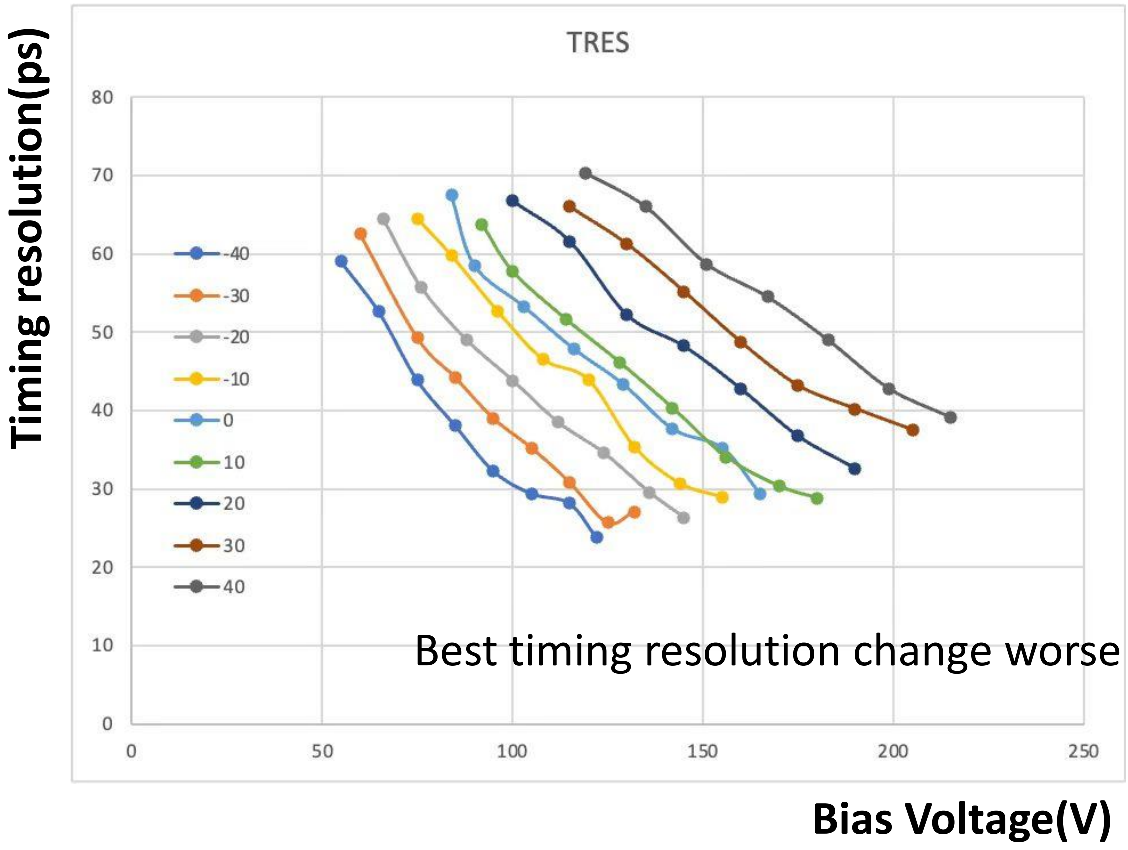
Backup

LGAD performance with operation temperature changing(before radiation)

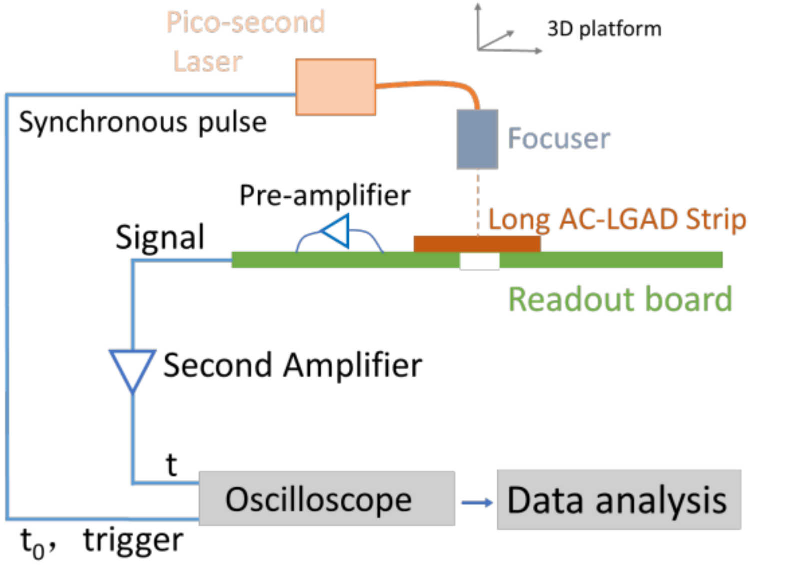


Need to change operation voltage

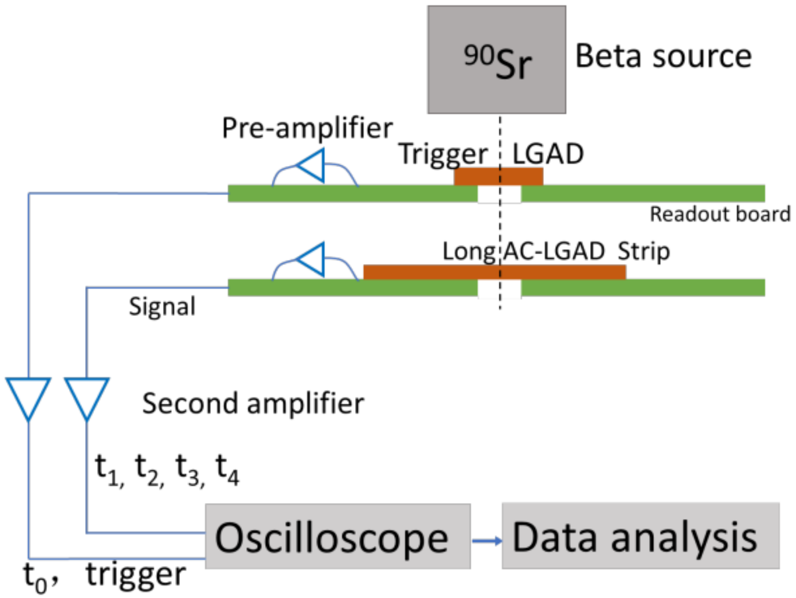
Sr90 testing results



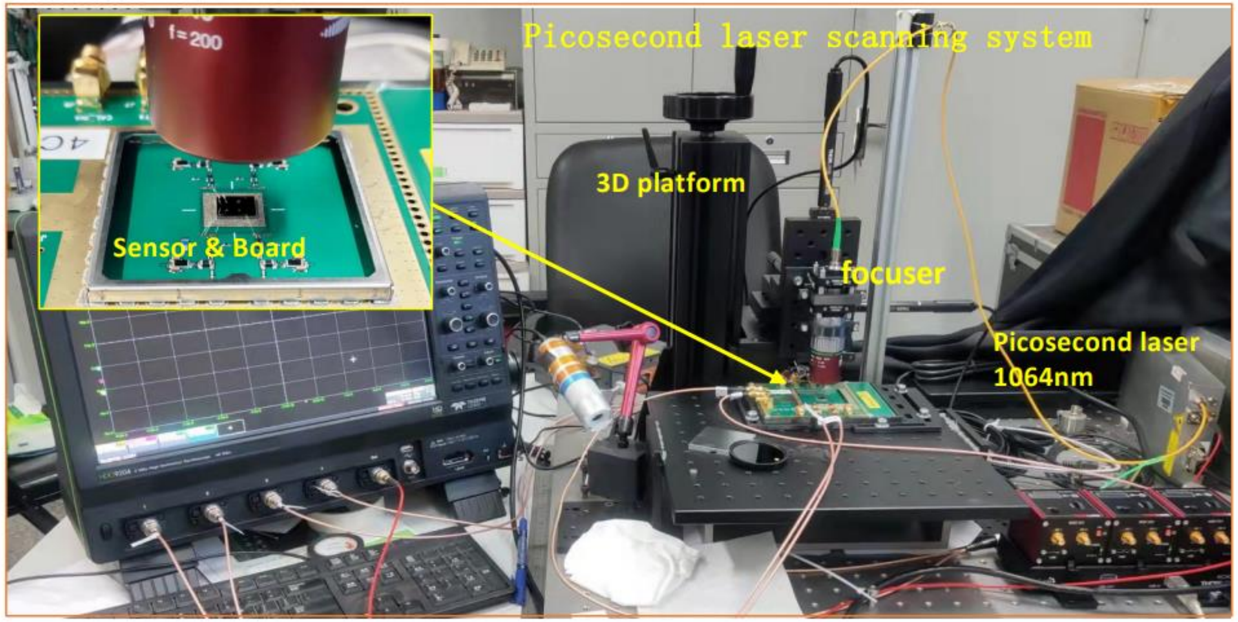
Testing setup



(a)



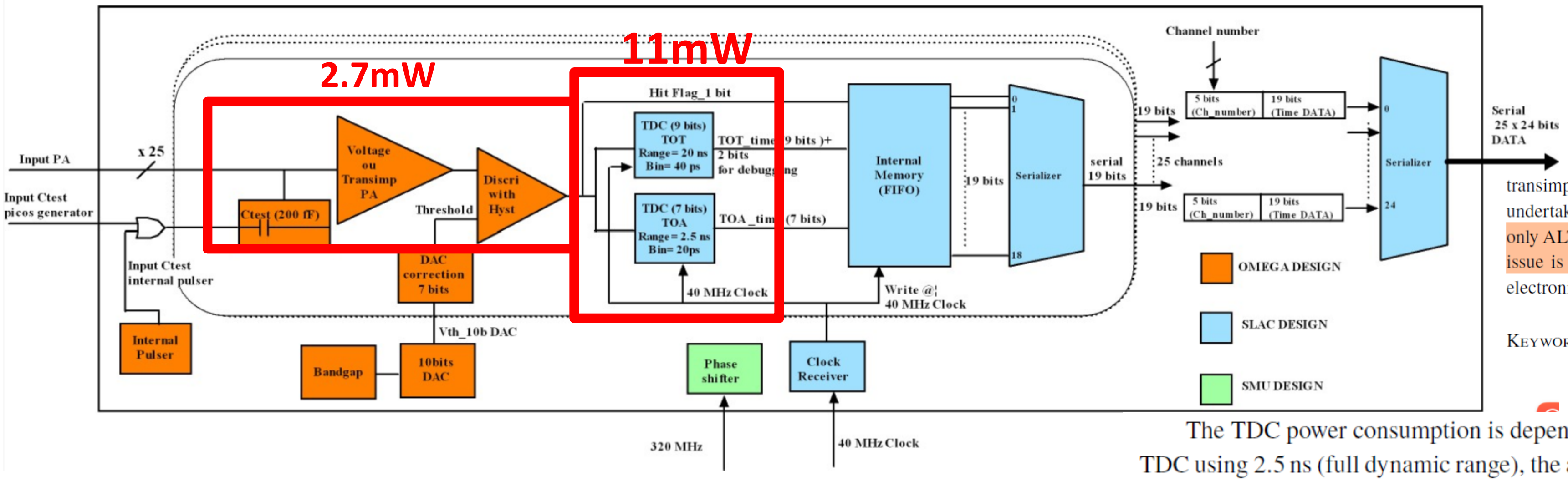
(b)



Picosecond laser scanning system

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

ALTIROC power consumption



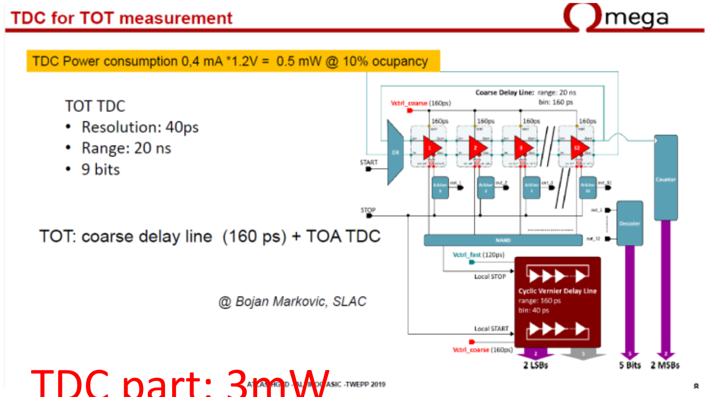
By Xiongbo Yan

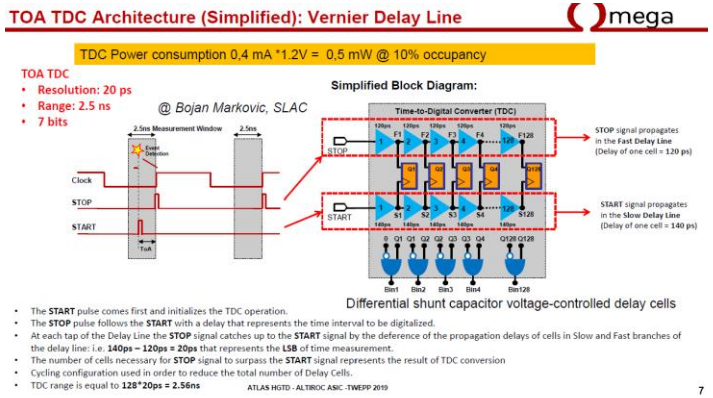
transimpedance preamplifiers. Beam test measurements with a pion beam at CERN were also undertaken to evaluate the performance of the module. The best time resolution obtained using only ALTIROC TDC data was 46.3 ± 0.7 ps for a restricted time of arrival range where the coupling issue is minimized. The residual time-walk contribution is equal to 23 ps and is the dominant electronic noise contribution to the time resolution at 15 fC.

KEYWORDS: Front-end electronics for detector readout; Timing detectors

The TDC power consumption is dependent on the time-interval being measured. For the TOA TDC using 2.5 ns (full dynamic range), the average power consumption over the 25 ns measurement period is about 5.2 mW. It is only 3.5 mW for a time-interval equal to half the dynamic range. Thanks to the reverse START-STOP operation, the power consumption of the TDC is much lower in the absence of a hit over threshold. This results in an average power consumption per channel of 1.1 mW for both TDCs, assuming a time interval uniformly distributed (1.25 ns average) and a maximal channel occupancy of 10%.

Both preamplifiers are built around a cascoded common source NMOS amplifier to ensure high bandwidth (see figure 2). The drain current (I_d) of the input transistor is adjustable between 200 µA and 1 mA. The transistor size is optimized to operate close to weak inversion while keeping its capacitance small compared to that of the sensor. The operating current is chosen to minimize the series noise while not dissipating too much power (< 2.25 mW/ch for the analog part). A PMOS follower is added to isolate the load from the discriminator. The total preamplifier power consumption is 0.85 mW using a nominal current I_d = 600 µA in the input transistor. A bank of seven capacitors (from 0 to 3.5 pF) can be connected by slow control to the preamplifier input to emulate the sensor capacitance when measuring the ASIC alone. They are not used when the ASIC is connected to the LGAD sensor array.





TOA measurement. Each discriminator output is sent to a sampling cell to generate a "Hit Flag" bit, that is equal to 1 in case of a hit or to 0 in case of no hit. The discriminator's power consumption is slightly less than 0.4 mW.

ALTIROC Cd：4pF

OTK Cd：10pF

FEE power consumption: 15mW

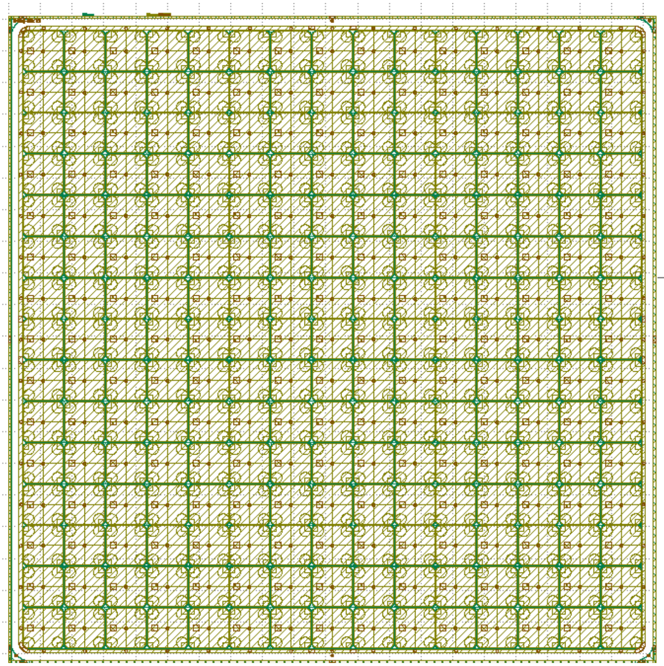
$$\sigma_{\text{jitter}} = \frac{e_n C_d}{Q_{\text{in}}} \sqrt{t_d}.$$

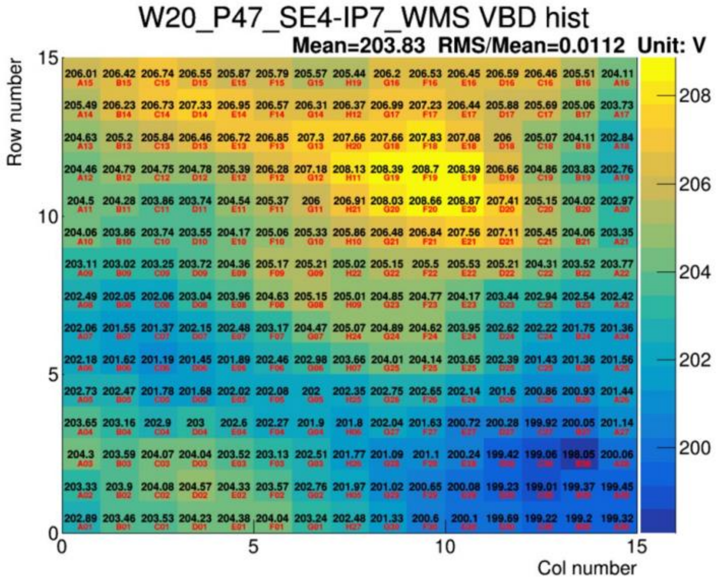
$$e_n = \sqrt{2kT/g_{m1}}.$$

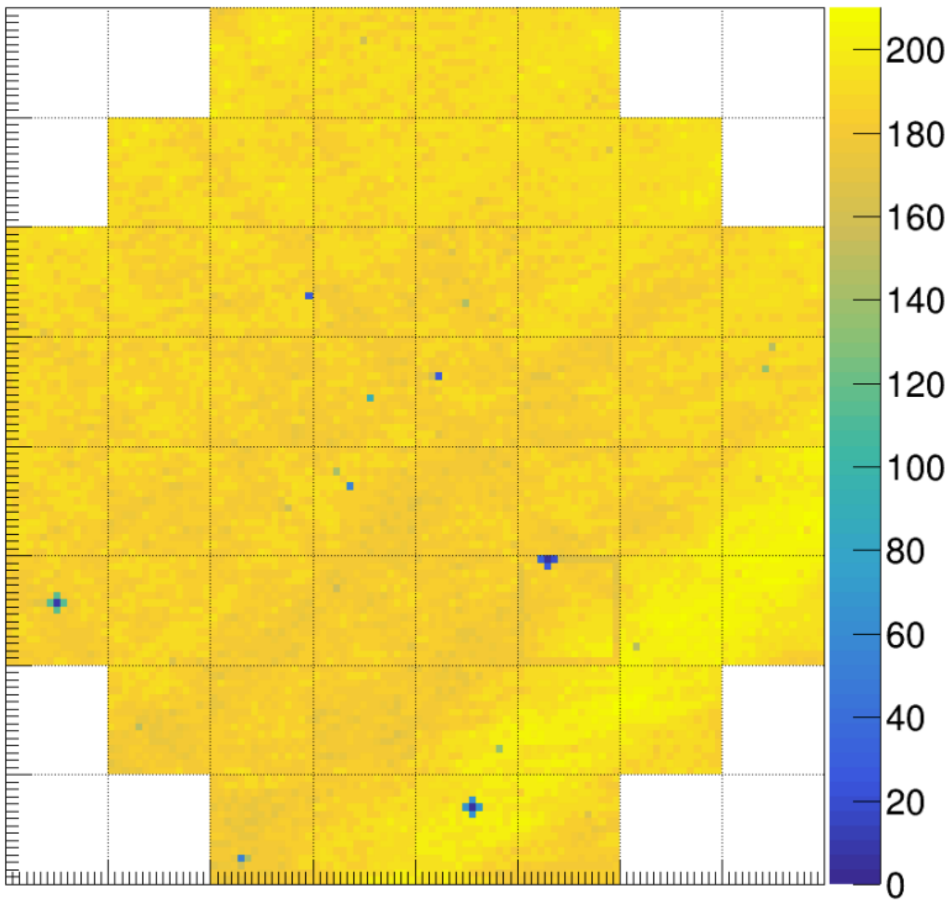
$$g_{m1} = q \times I_d/2kT$$

TDC part: 3mW

Not include Clock system and other digital part







V_{BD} Map

2cm x 2cm DC-LGAD
15x15 array
Pixel size: 1.3mm x 1.3mm

$$
\begin{cases}
X = X_0 + k_x m \\
Y = Y_0 + k_y n \\
m = \frac{q_1+q_2-q_3-q_4}{q_1+q_2+q_3+q_4} \\
n = \frac{q_1+q_4-q_2-q_3}{q_1+q_2+q_3+q_4}
\end{cases}
$$

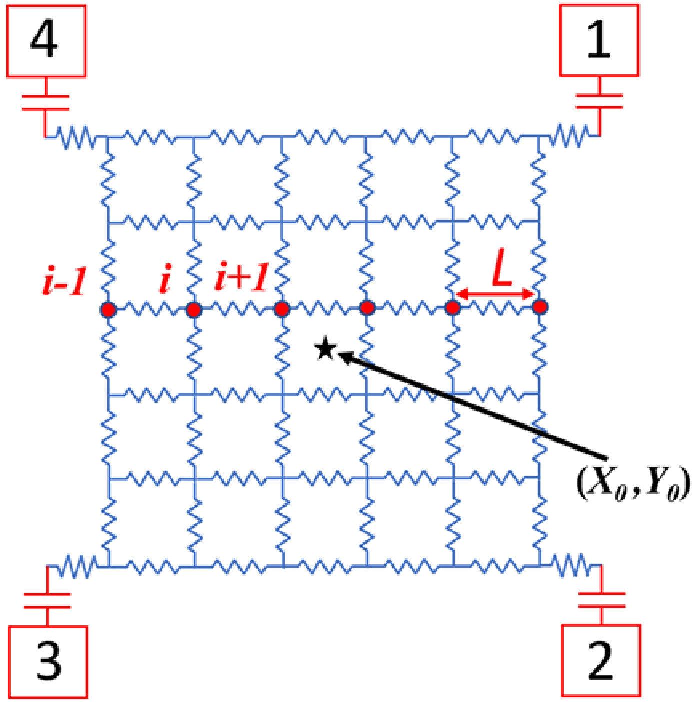


Fig. 6. The discretized positioning circuit representation of an AC-LGAD [14].

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

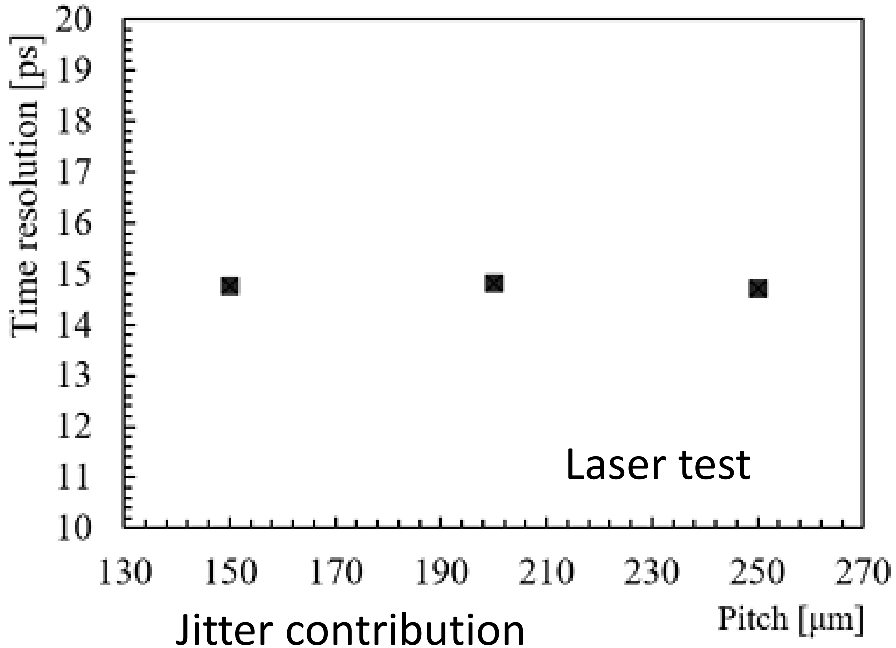
Strip AC-LGAD R&D

Strip AC-LGAD: Strip length:5.65mm

pad-pitch size: 100-250um, 100-200um, 100-150um

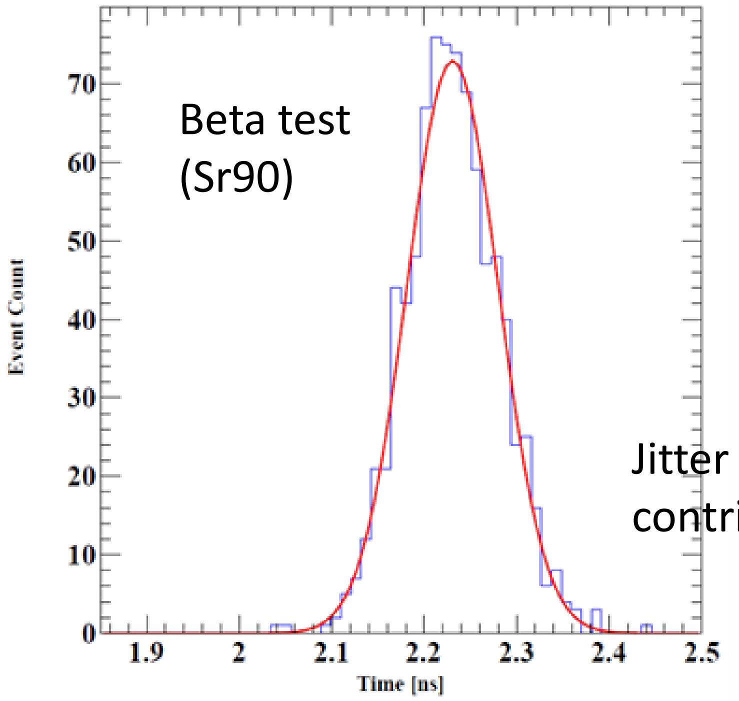
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$

constant fraction discriminator (CFD) method



Jitter contribution

The timing resolution: 15~17ps



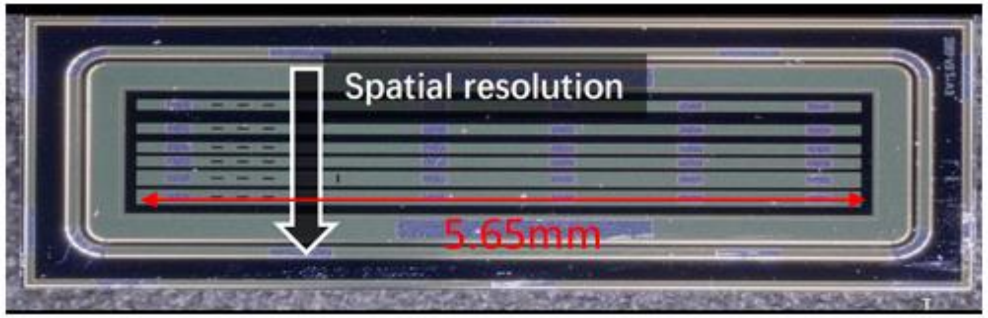
Jitter and Landau contribution

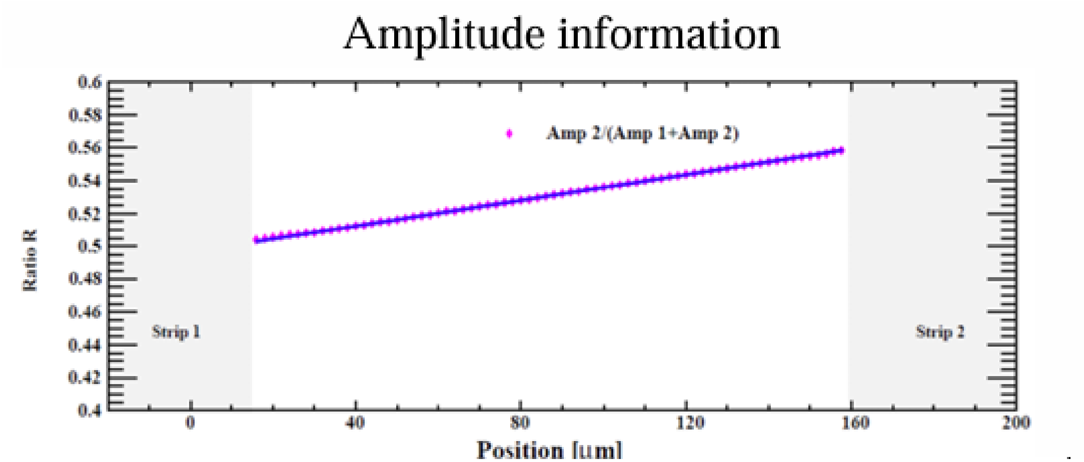
Time residual sigma: 47.1ps
Time resolution: 37.5ps

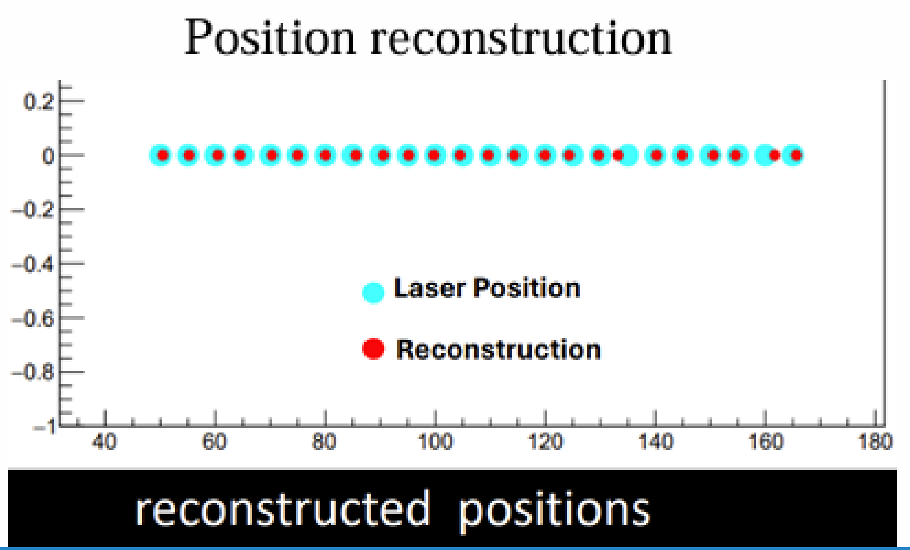
Strip AC-LGAD R&D

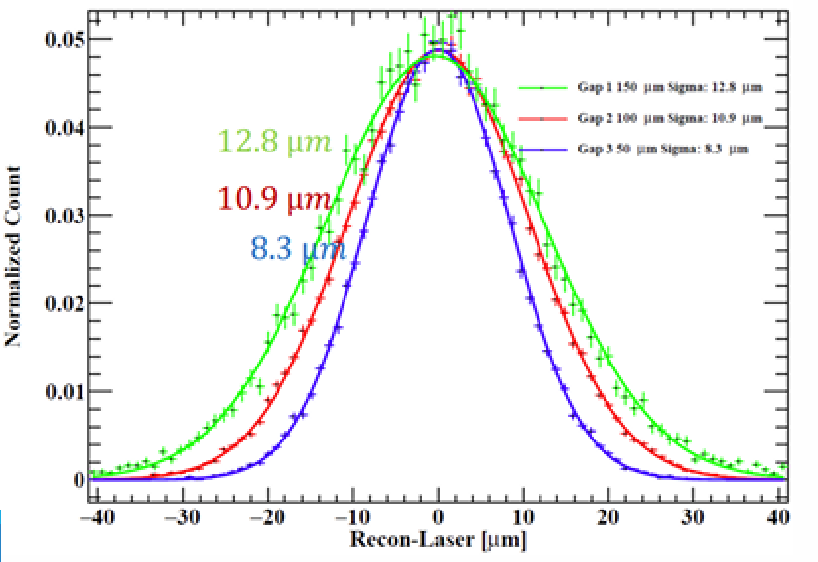
Strip AC-LGAD: Spatial resolution(Laser testing)

Amplitude information of two electrodes → position reconstruction → Spatial resolution



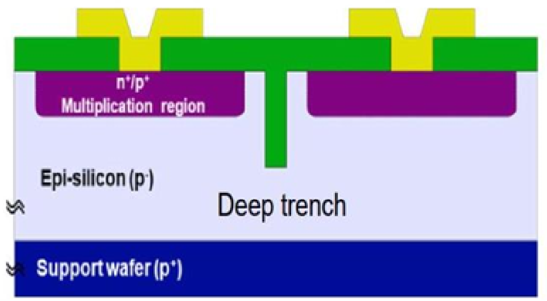






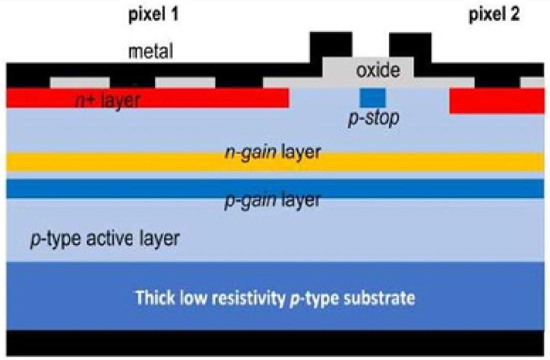
Best result: 8.3um
[Pitch size:150um]

LGAD types



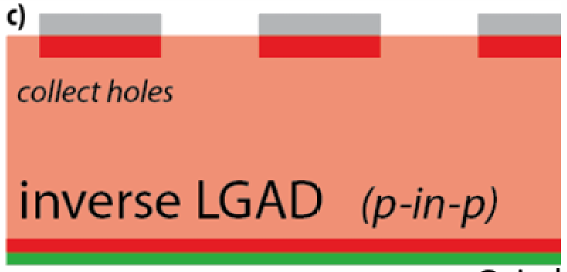
Ti-LGAD

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



DJ-LGAD

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

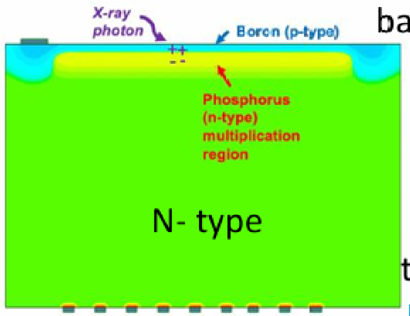


Gain layer

- inverse-LGADTo increase fill factor

Thin Entrance Window LGADs

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



backside

topside

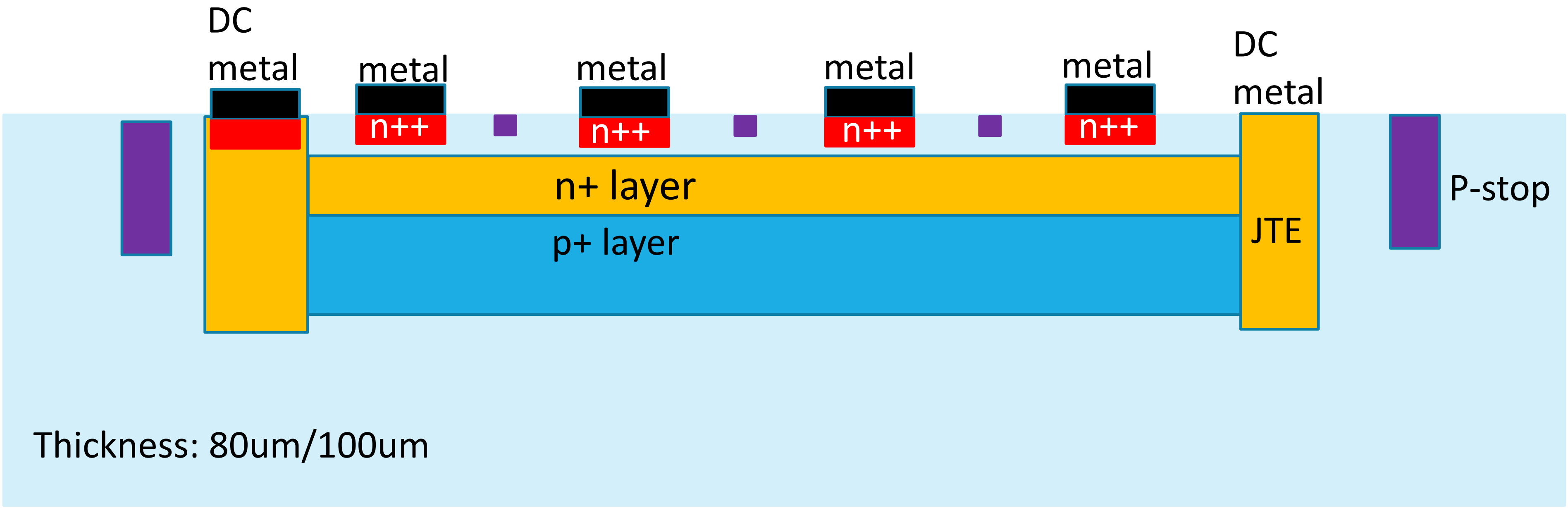
Monolithic LGAD

Considerations regarding future colliders

- Standalone timing layers or integration into 4D (5D) Trackers?
  - Integration of gain layer in CMOS sensors…
- Occupancy:
  - Challenging for resistive layers
  - AC-coupling may not be ideal or necessary: DC-coupled resistive detectors? (in production at FBK)
- Radiation hardness: similar problems related to gain layer radiation hardness as other LGADs, potentially additional features
  - Partially compensated boron doping
- Segmentation
  - AC-LGADs can achieve better position resolution through charge sharing – may come at expense of timing performance
  - Deep-junction LGAD or deep gain layer

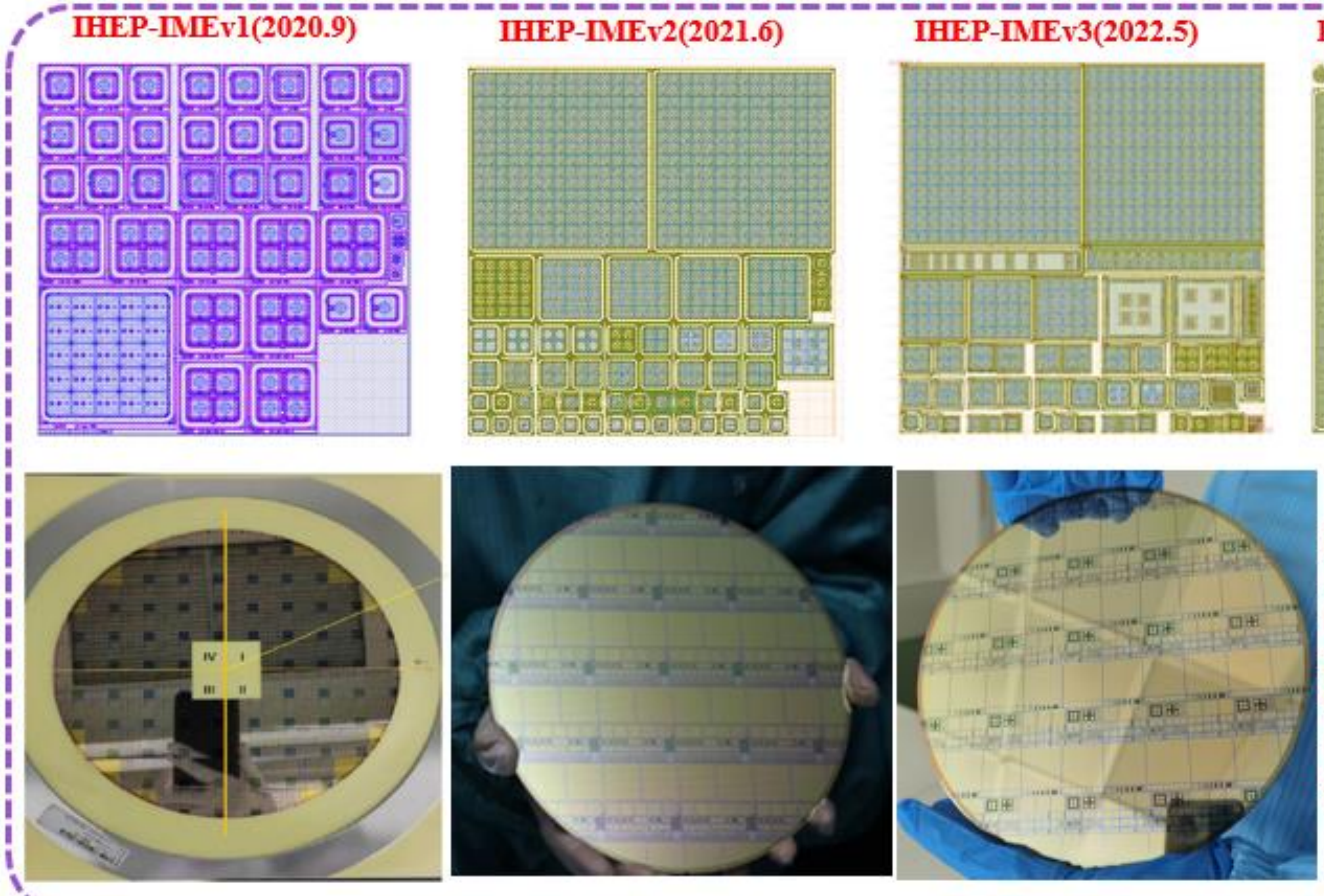
RSD, resistance sensitive LGAD

Adding a small capacitance



LGAD研究进展

高能所团队进行了多版器件的研发，改善其抗辐照性能。



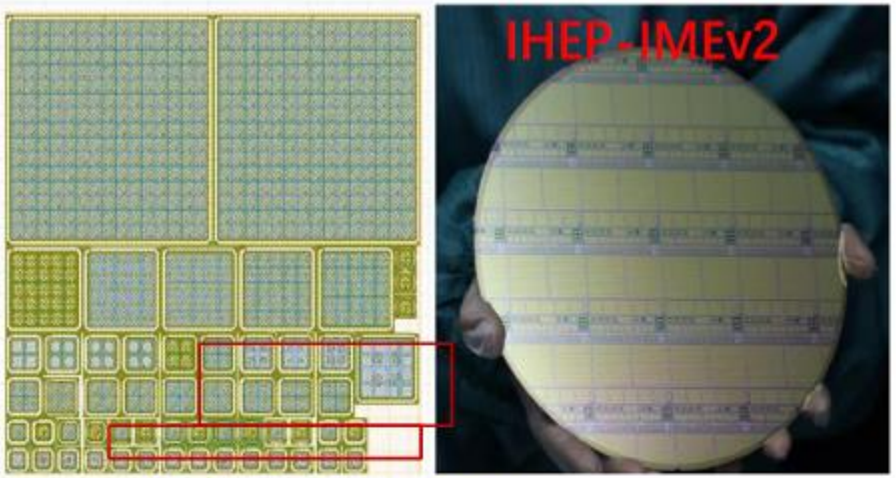
高能所研发的LGAD器件于2023年参与ATLAS HGTD CERN采购部分的市场调研，并因性能优良获得CERN的全部采购份额

部分的全部份额。

8片晶圆　　10片晶圆　　16片晶圆

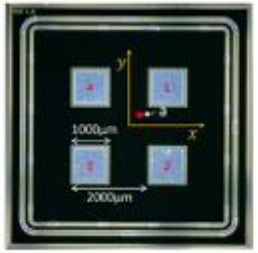
AC-LGAD development

2022



AC-LGAD R&Dv1:

Pixelated AC-LGAD One wafer

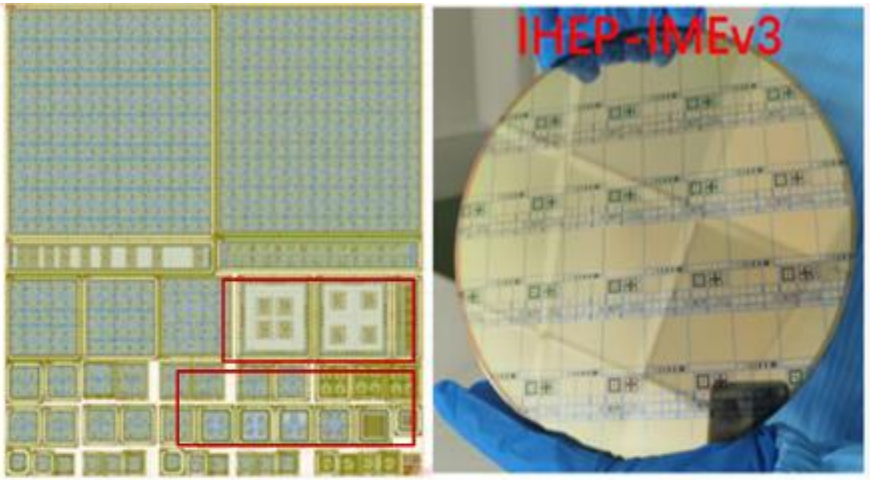


- With different pad-pitch size
  1000-2000um
  100-500um
  100-200um
  50-100um
- wafers: with different n+ dose: 10P to 0.2P

Process parameters be studied.

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

2023



AC-LGAD R&Dv2: One wafer

Pixelated and strip AC-LGAD

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

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

C. *The time resolution*

The arrival time of particle or laser (t_{arrived}) is defined as the mean value of the cross-threshold time of four AC pad signals:

$$t_{\text{arrived}} = (t_1 + t_2 + t_3 + t_4)/4 \tag{4}$$

where t_1, t_2, t_3, t_4 are the cross-threshold time of four AC pads obtained according to the constant fraction discriminator (CFD) method. In this experimental setup, the spread of arrival time is mainly composed of the time resolution of AC-LGAD (σ_{ACtime}) and the jitter of the trigger t_0 (σ_{t_0}):

$$\sigma^2_{(t_1+t_2+t_3+t_4)/4} = \sigma^2_{ACtime} + \sigma^2_{t_0} \tag{5}$$

To avoid the jitter of t_0, $(t_1 + t_2 - t_3 - t_4)/4$ is used to calculate the time resolution of AC-LGAD sensors:

$$\sigma_{ACtime} = \sigma_{(t_1+t_2-t_3-t_4)/4}. \tag{6}$$

Figure 10 shows the distribution of $(t_1 + t_2 - t_3 - t_4)/4$, with a time resolution of 15.6 ps. The time resolution here is based on laser tests and includes only the jitter component [1], [2], which is evaluated by the mean value of the jitter component of 36 test positions. Figure 11 shows the jitter component of the time resolution of AC-LGAD with different N+ doses. The jitter component of the time resolution varies slightly, about 15-17 ps with different N+ doses.

Given the large length of these sensors, a position-dependent delay is introduced in the mean arrival times of the signal based on the impinging location of the proton. To correct for this, the first strategy uses the external tracker to determine the proton hit position as a function of x and y, and creates a reference map of correction values depending on the location of the hit. The second correction strategy utilizes the signals from the leading and sub-leading channels on the sensor and re-defines the *multi-channel timestamp* as defined in [13], is given by:

$$t = \frac{a_1^2 t_1 + a_2^2 t_2}{a_1^2 + a_2^2}, \tag{1}$$

where subscript 1 (2) refers to the leading (subleading) channel: $t_{1(2)}$ is the time of arrival and $a_{1(2)}$ is the amplitude of the leading (subleading) channel respectively.

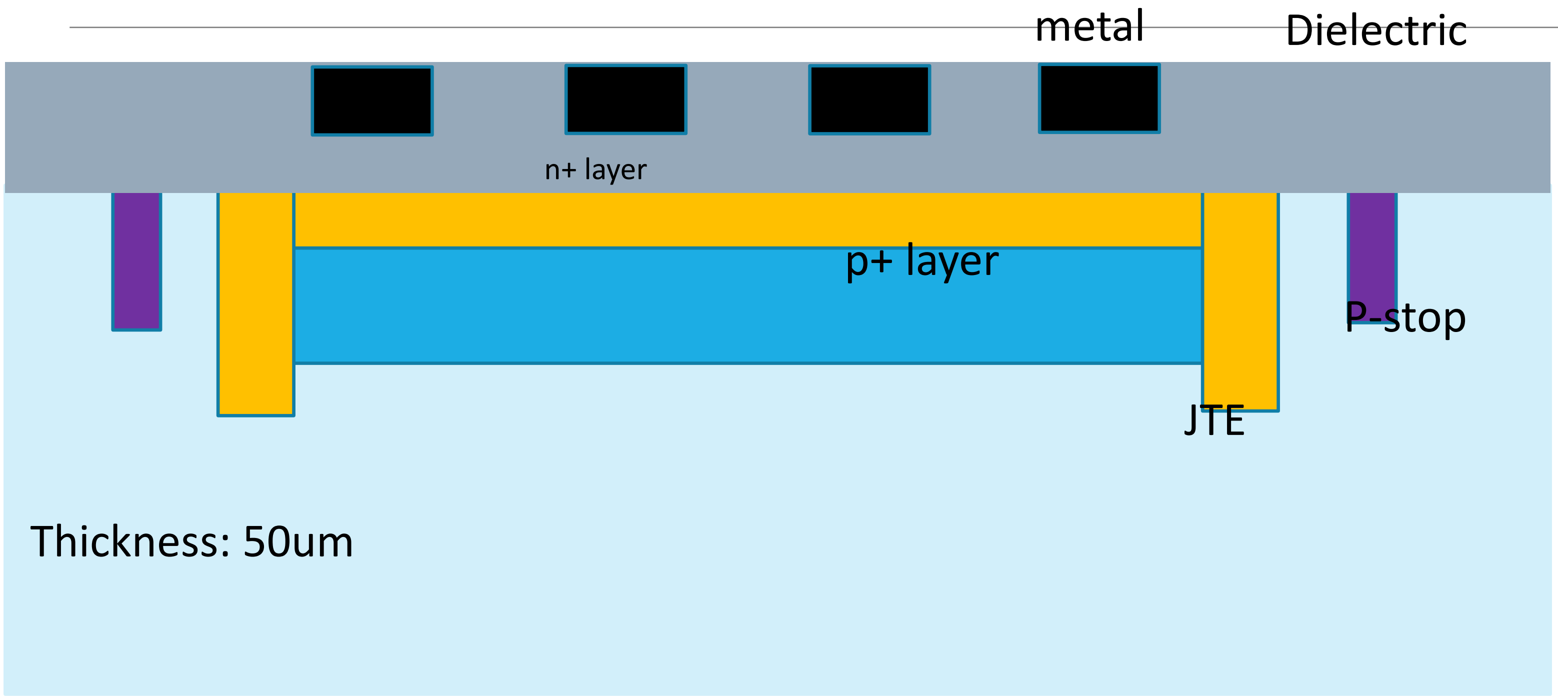
The jitter from one channel is given by $\sigma_{\text{jitter}} = \text{N}/\frac{\text{dV}}{\text{dt}}$, where N is the baseline noise and $\frac{dV}{dt}$ is the signal slew rate, for events throughout the sensor. However, since the aim is to calculate the contribution of the jitter to the time resolution arising from multiple channels, a "weighted jitter" method is implemented as follows:

$$\sigma_{t,\text{jitter}} = \sqrt{\frac{a_1^4 \sigma^2_{t_1,\text{jitter}} + a_2^4 \sigma^2_{t_2,\text{jitter}}}{(a_1^2 + a_2^2)^2}} \tag{2}$$

where $\sigma_{t,\text{jitter}}$ is the weighted jitter from the AC-LGAD signal, and $\sigma_{t_1,\text{jitter}}$ and $\sigma_{t_2,\text{jitter}}$ are the jitter from the leading and subleading channels, respectively.

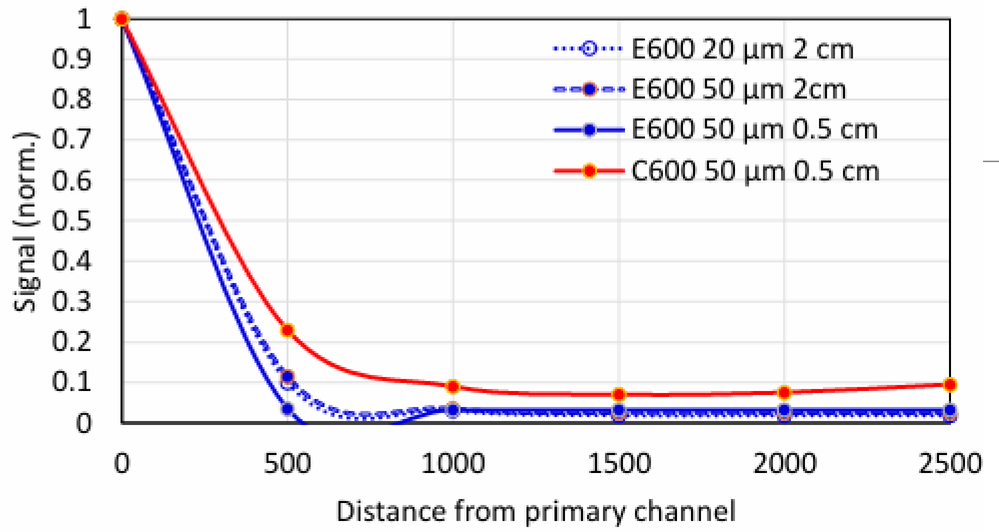
All time resolution numbers quoted in this paper remove the MCP reference contribution of 10 ps in quadrature.

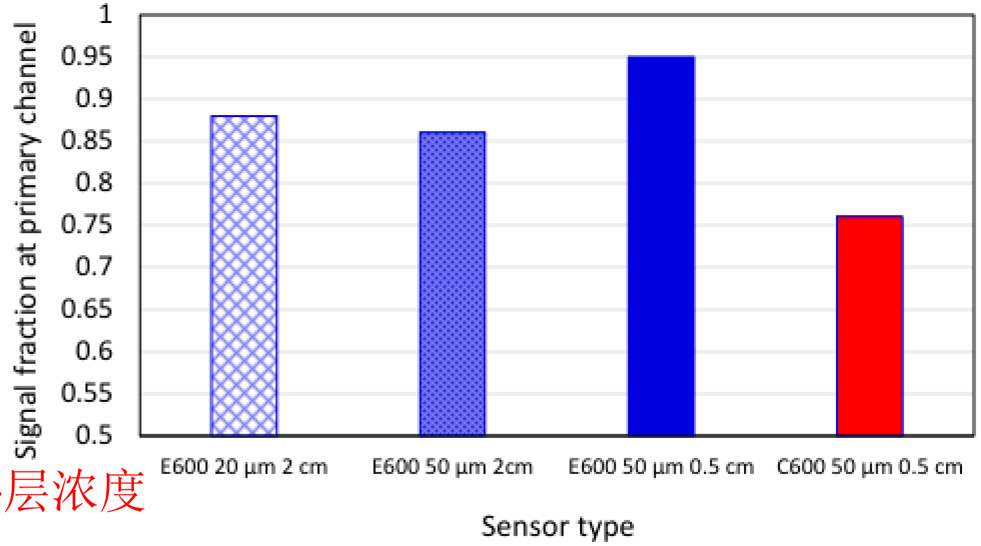
The design used now



In terms of signal sharing / signal amplitude:

- Signal sharing is strongly impacted by the n-layer resistivity – almost 20 % more for lower resistivity, as well as different long-range behavior
- Strip length increases signal sharing, but signal from primary channel decreases down to ~10% at the next neighbor
- Roles of sensor bulk thickness, strip width, dielectric capacitance are less significant

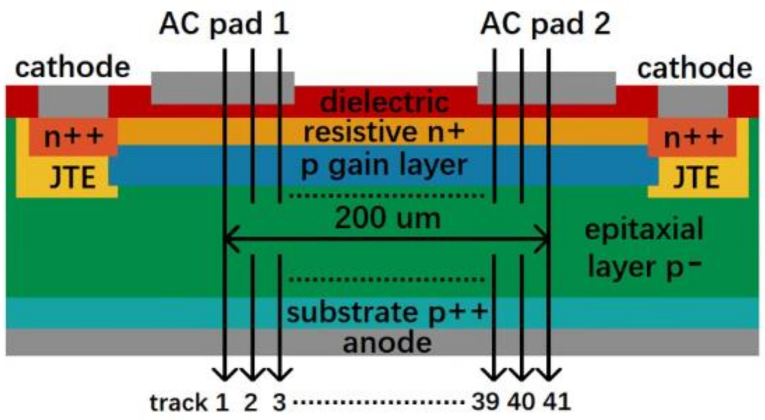




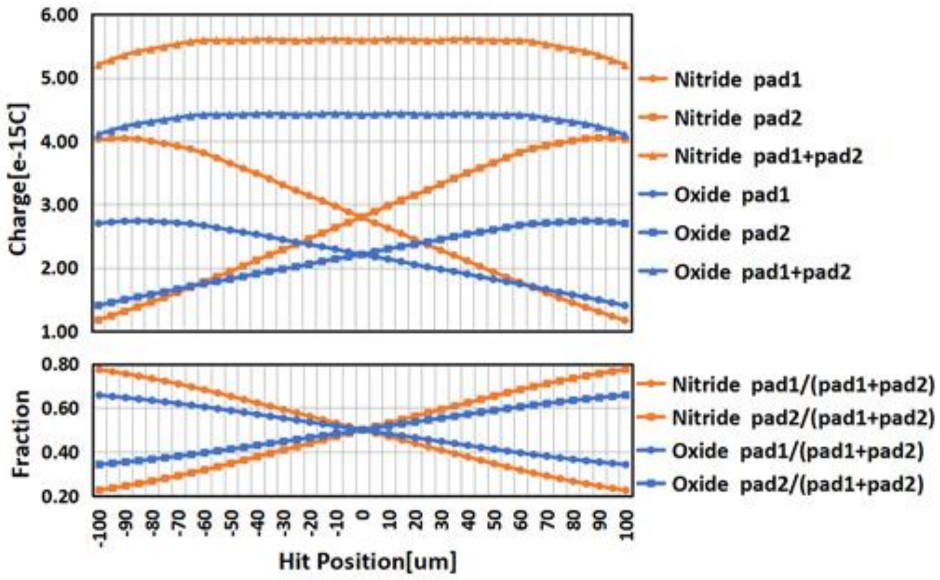
电荷共享最重要的影响因素是n+层浓度

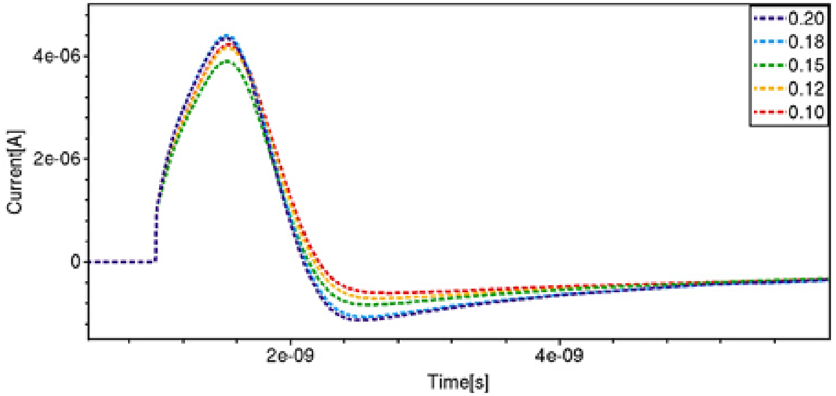
耦合电容

材料和厚度



不变厚度，变材料





结论：2、耦合电容越大(氮化硅介电常数大)，位置分辨越好

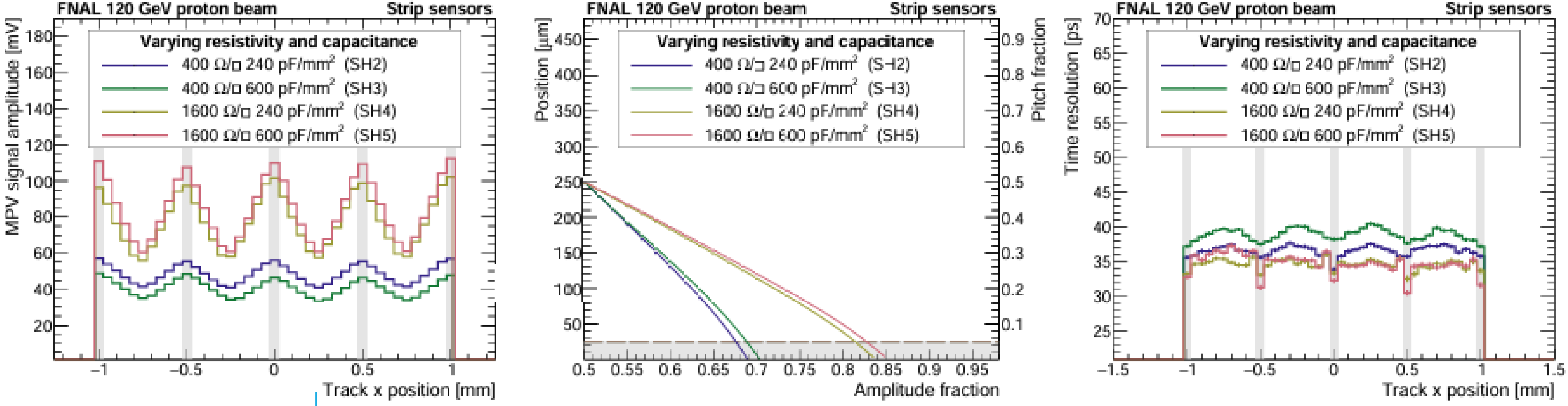


Figure 7: MPV amplitude as a function of x position (left), position reconstruction fit results (center), and time resolution as a function of x position (right) for HPK strip sensors of different coupling capacitance and sheet resistance values. The sensors presented here have a 50 μm active thickness and a 50 μm strip width.

N+电阻率变大
信号变化量大
影响大

电容增大，位置分辨
变好(变化量)
影响较小

时间分辨，电阻率大
仍可到35ps