Ref-TDR内部评审: AC-LGAD chip R&D

赵梅

中科院高能所 电子学组

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5.4.1.1 AC-LGAD sensor R&D

LGAD与AC-LGAD简介

- LGAD：因时间分辨性能优良被HGTD，CMS采用作为时间探测器解决pile-up问题
- IHEP LGAD 时间与收集电荷性能
  - 图5.59：Sr 90测试结果（HGTD合作组）
  - 图5.60 束流测试结果（辐照前后）
- 从Standard LGAD到AC-LGAD
  - 图5.61，两种器件的结构示意图
- 各个章节的具体内容

Extensive R&D efforts have been undertaken at IHEP to advance the development of AC-LGADs. The process and structural parameters of AC-LGAD devices have been extensively simulated by using TCAD software. These simulations explore the impact of various process parameters and structures on AC-LGAD performance. The details of these simulations are described in Subsection 5.4.1.1.1. Two types of prototypes have been fabricated and studied: pixelated AC-LGADs with varying process parameters and strip AC-LGADs with different pad-pitch sizes. Testing setups using TCT laser scans and Beta tests have been established, as outlined in Subsection 5.4.1.1.2. The pixelated AC-LGAD prototypes are used to evaluate fabrication process parameters and their effects on sensor performance, including charge collection and timing. This is discussed in Subsection 5.4.1.1.3. The strip AC-LGAD prototypes are designed to study the influence of pad-pitch size on spatial and timing resolution, detailed in Subsection 5.4.1.1.4.

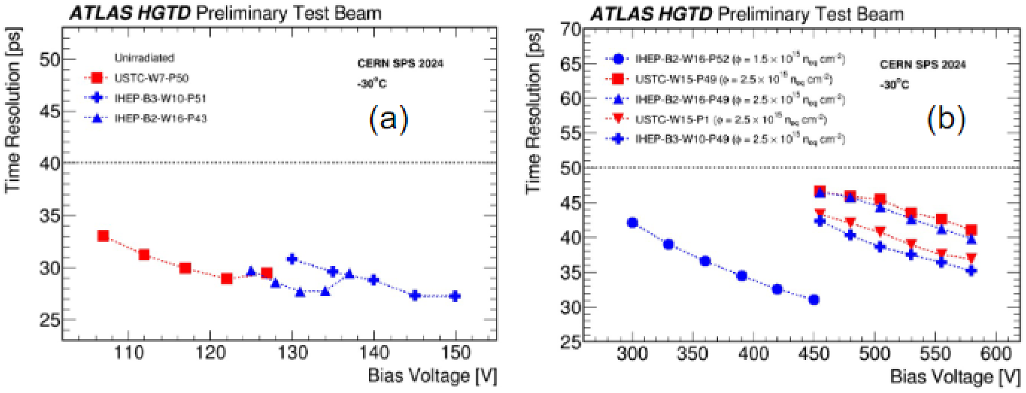


Figure 5.60: Timing resolution before and after irradiation (test beam results from ATLAS HGTD group)

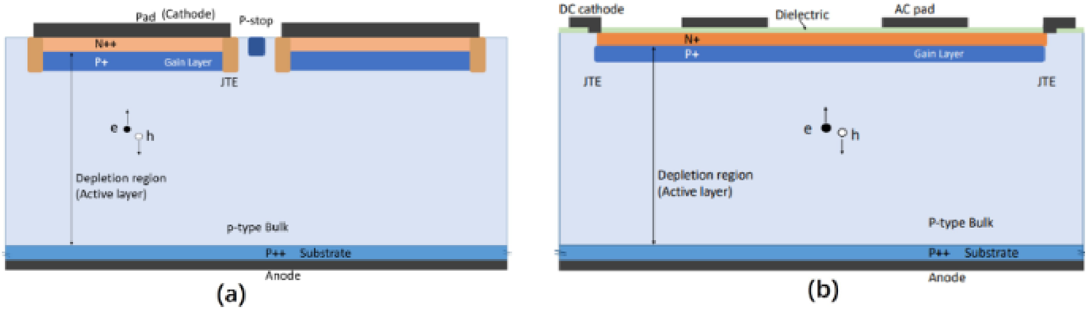


Figure 5.61: structures of (a) standard LGAD and (b) AC-LGAD

AC-LGAD Simulation

节5.4.1.1.1

介绍AC-LGAD TCAD仿真模型与关键工艺与结构参数的仿真结果

包括：耦合电容的材料与厚度，n+层的浓度，金属电极的间距等

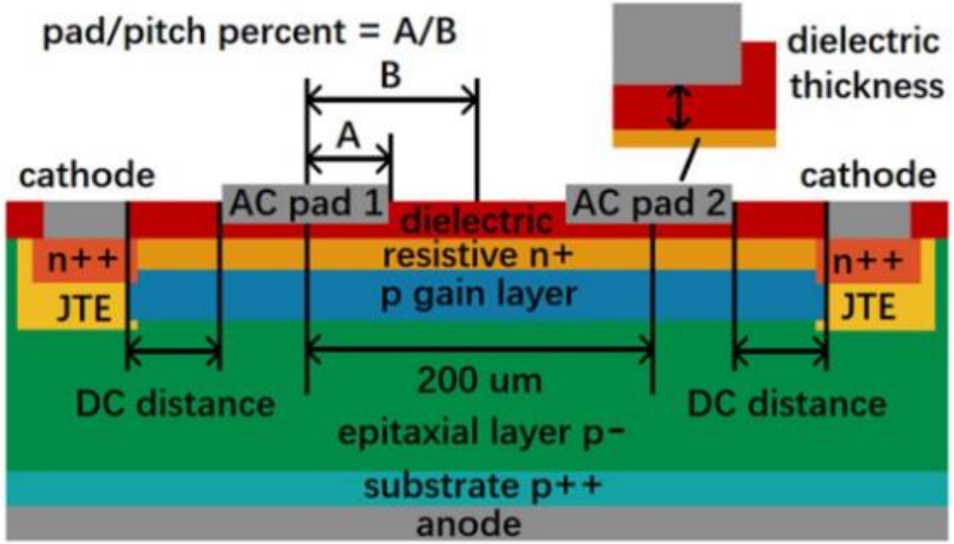


Figure 5.62: Sketch of AC-LGAD with 2 AC pads

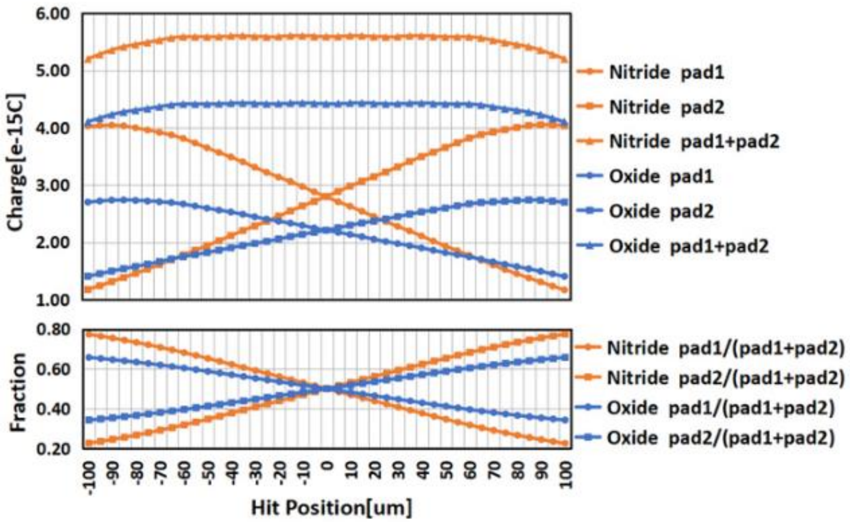


Figure 5.63: Charge collection of two pads for 2 different dielectric materials: oxide and nitride

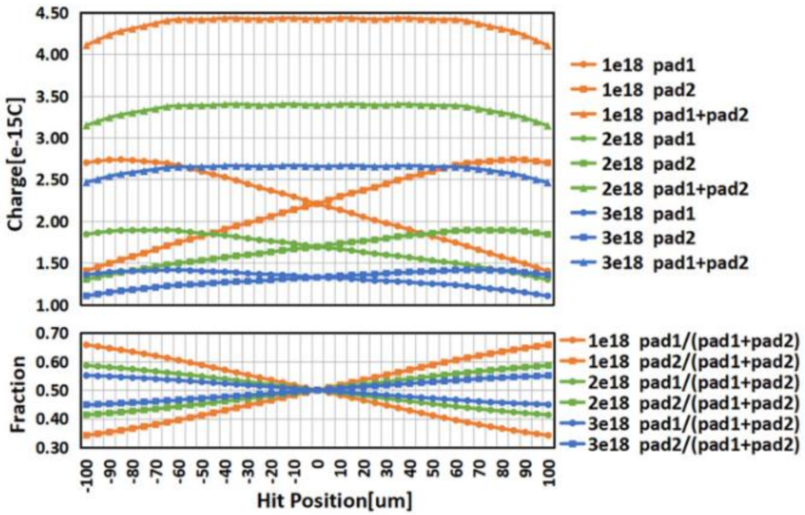


Figure 5.64: Charge collection of two pads for 5 different values of n+ dose: 1×10^{18} cm^{-2}, 2×10^{18} cm^{-2} and $3 \times 10^{18} cm^{-2}$

5.4.1.1.2 Testing setup

介绍了测试系统，时间与位置分辨测试与分析方法

节5.4.1.1.2

5.4.1.1.2 Testing setup The testing platforms, utilizing TCT laser scans and Beta tests, are illustrated in Figs. 5.65 and 5.66. These setups include readout boards, amplifiers, oscilloscopes (Teledyne LeCroy HDO9204 with 2 GHz bandwidth and 20 G/s sampling rate), laser sources, and Beta sources. Signals from AC-LGAD electrodes are processed through preamplifiers and recorded by the oscilloscope.

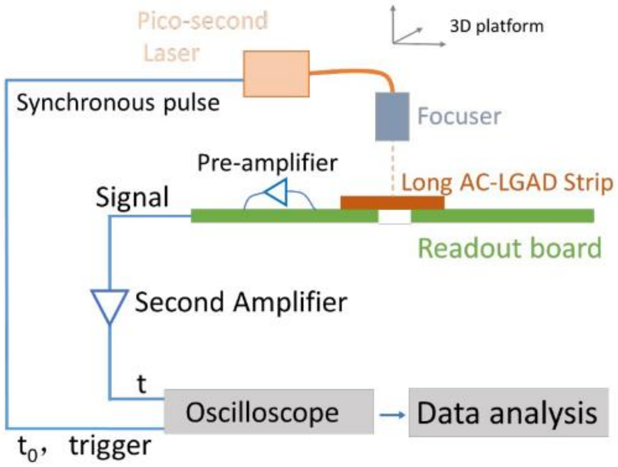
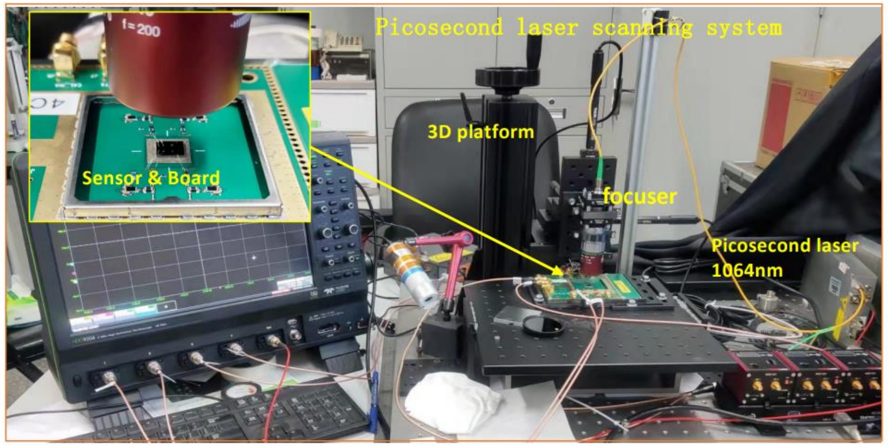


Figure 5.65: The schematic of the TCT testing platform



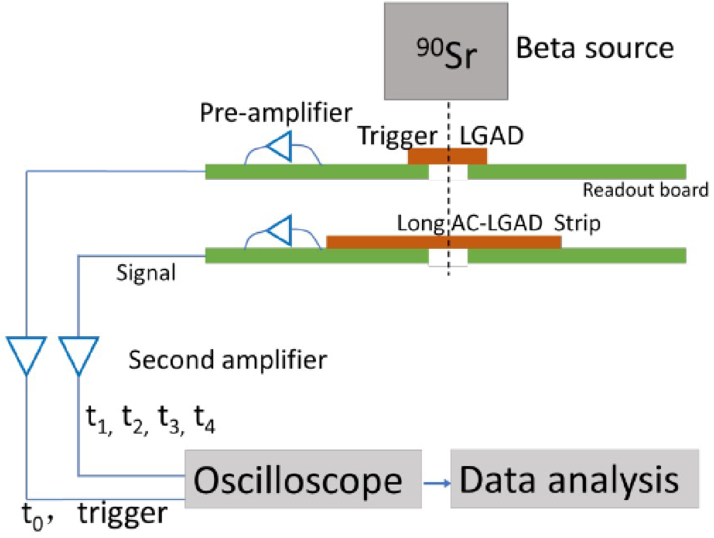


Figure 5.66: The schematic of the Beta testing platform

时间分辨 $\sigma_t^2 = \sigma_{\mathrm{TimeWalk}}^2 + \sigma_{\mathrm{Landau}}^2 + \sigma_{\mathrm{Jitter}}^2$

位置分辨：改变激光入射位置，记录电极波形，重建激光入射位置，重建位置和实际位置的偏差即为位置分辨率

5.4.1.1.3 Pixelated AC-LGAD prototypes

节5.4.1.1.3

1： Prototype描述

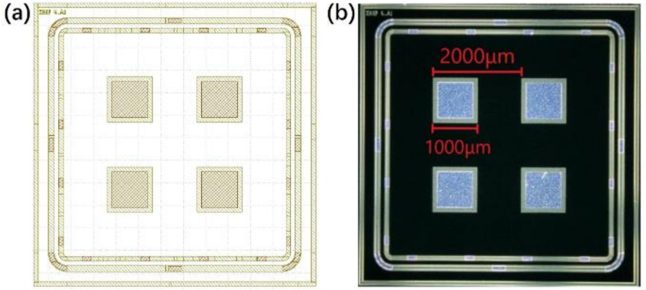


Figure 5.67: Pixelated AC-LGAD prototype

The pixelated AC-LGADs are fabricated on 8-inch wafers with a 50 μm P-type epitaxial layer and a 725 μm substrate. These AC-LGADs include four square AC pads for AC-coupled signalreadout, as illustrated in Fig. 5.67. The innermost ring serves as the DC ring (DC-cathode), while the second ring is aguard ring. The DC-cathode can be utilized for DC-coupled signal readout or grounded during testing.

The AC pads havea size of 1000 μm, with a pitch size of 2000 μm.

To investigate the effects of N+ dose on spatial and timing resolution, five types of sensors were designed with varyingdoses: 10.0 P, 5.0 P, 1.0 P, 0.5 P, and 0.2 P. Here, ” P” represents the phosphorus dose unit specific to the IHEP AC-LGAD.

2： Timing performance测试结果

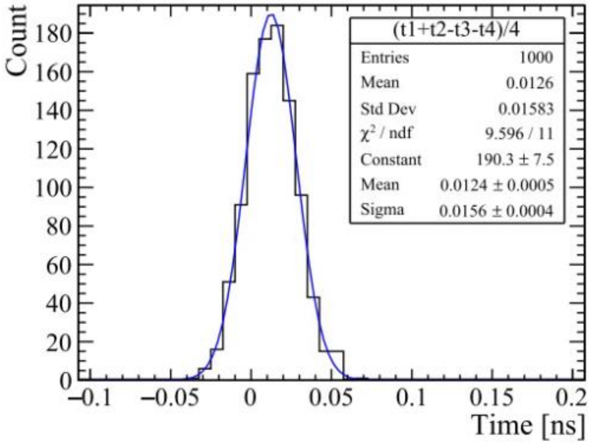


Figure 5.68: Distribution of $(t_1 + t_2 - t_3 - t_4)/4$ at one position in 6×6 laser test array

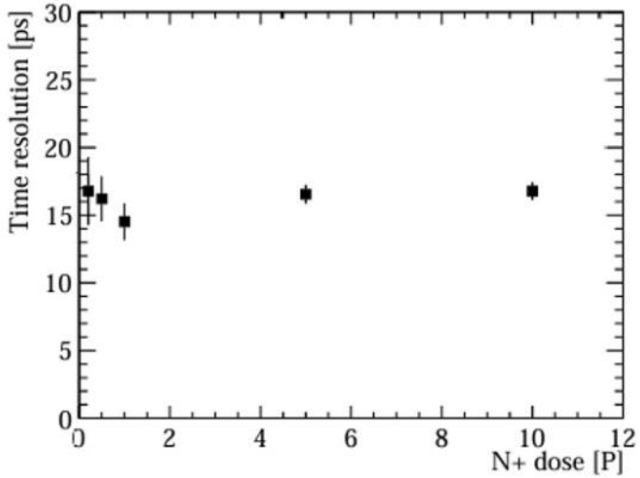


Figure 5.69: The jitter component of the time resolution with different N+ doses

3： Spatial resolution测试结果

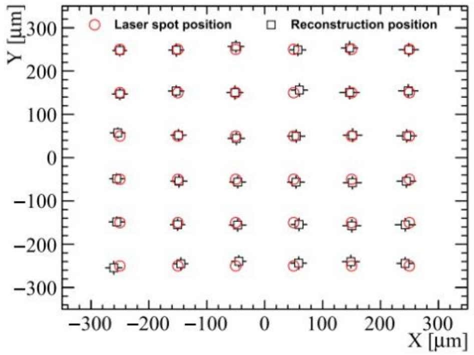


Figure 5.70: Reconstruction position of 6×6 laser test array of sensor with dose 0.2 P (black squares) and the laser spot position as measured by the TCT stage (red circles)

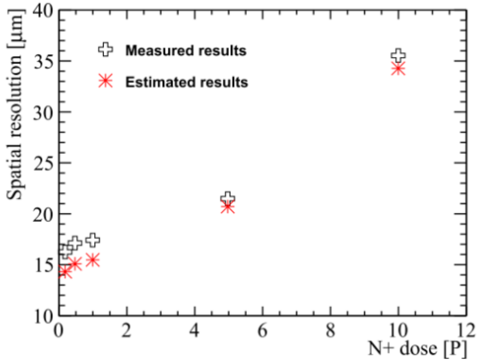


Figure 5.71: The measured spatial resolution (black marks) and estiamted spatial resolution (red marks) at different N+ doses.

5.4.1.1.4 Strip AC-LGAD prototypes

节5.4.1.1.4

1： Prototype描述

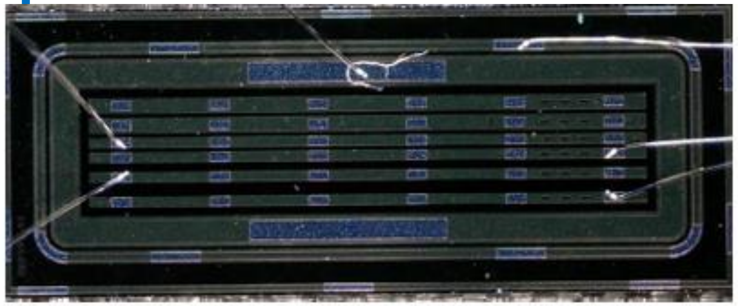


Figure 5.72: Strip AC-LGAD prototype

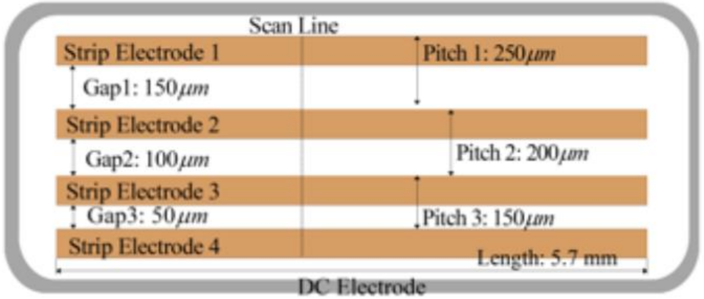


Figure 5.73: Schematic diagram of the AC-LGAD prototype structure

三种类型的器件：pitch 分别是250um，200um，150um

2： Timing performance 测试结果

Timing performance from Laser testing 激光测试

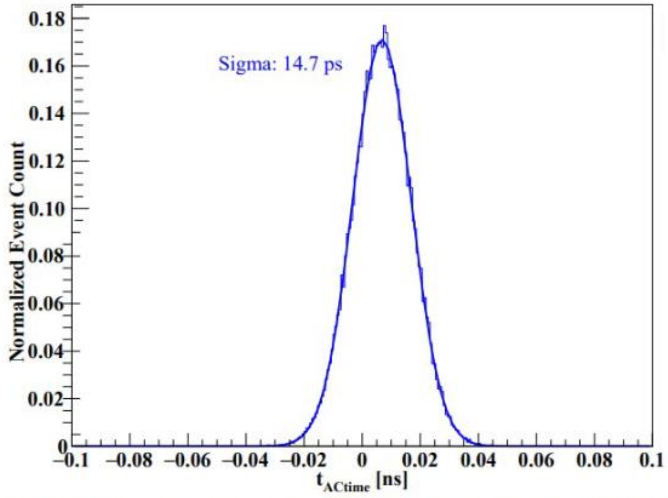


Figure 5.74: Distribution of $t_{ACtime} = (t_1 - t_2)/2$. The sigma of the distribution is 14.7 ps.

Timing performance from Beta source testing Sr90 测试

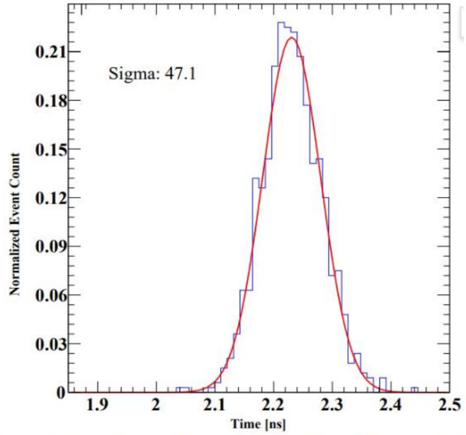


Figure 5.75: Distribution of ΔT of strip electrode 2 (strip with pitch as 200 µm). The sigma of the distribution is 47.1 ps.

3： Spatial resolution测试结果

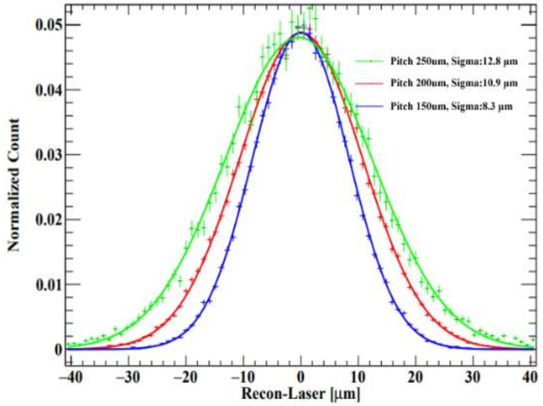


Figure 5.76: Spatial resolution of strip LGAD with different pad-pitch size,the resolutions of gap 1, gap 2, and gap 3 are 12.8 µm, 10.9 µm, and 8.3 µm, respectively.

三种类型的器件：pitch 分别是250um，200um，150um
位置分辨率，分别为12.8um，10.9um，8.3um（激光测试结果）

5.4.5 Prospects and plan

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5.4.5.1 Development of AC-LGAD strip sensor for CEPC

5.4.5.2 Development of AC-LGAD readout ASIC

5.4.5.3 Development of mechnical and cooling system

5.4.5.4 Summary

5.4.5.1 Development of AC-LGAD strip sensor for CEPC

LGAD technology has developped rapidly in recent years and is now being used in major HEP experiments, such as the ATLAS HGTD. However, the development of high-performance long strip AC-LGAD sensors for CEPC as out tracking layer is still ongoing. The impact of strip length to timing and spatial resolution is still not clear and need to be studied.

Sensor Development and Testing: Development will focus on simulating, fabricating, and testing AC-LGAD strip sensors.

Using TCAD tools, models of AC-LGAD with various strip lengths and process parameters will be developed to study the impact of strip length on signal quality and to optimize spatial and timing performance of strip AC-LGAD. Prototypes with strip lengths of 1 cm, 2 cm, and 4 cm will be fabricated and tested. Meanwhile, sensors with one strip length will also have prototypes with differnet n+ dose and coupled capacitance. Testing will cover current-voltage, capacitance-voltage, spatial resolution, and timing performance, with subsequent radiation and beam tests.

Design Adjustments: Based on test results, the strip length and pitch size may be modified to balance performance, yield, and readout requirements. One of our backup plans includes reducing the strip length from 4 cm to 2 cm and increasing the pitch size from 100 μm to 200 μm to maintain similar readout channels and power consumption. The final decision will be made based on the performance and yield.

A detailed tap-out plan for the CEPC AC-LGAD strip sensor, along with the testing schedule, is summarized in Fig. 5.107.

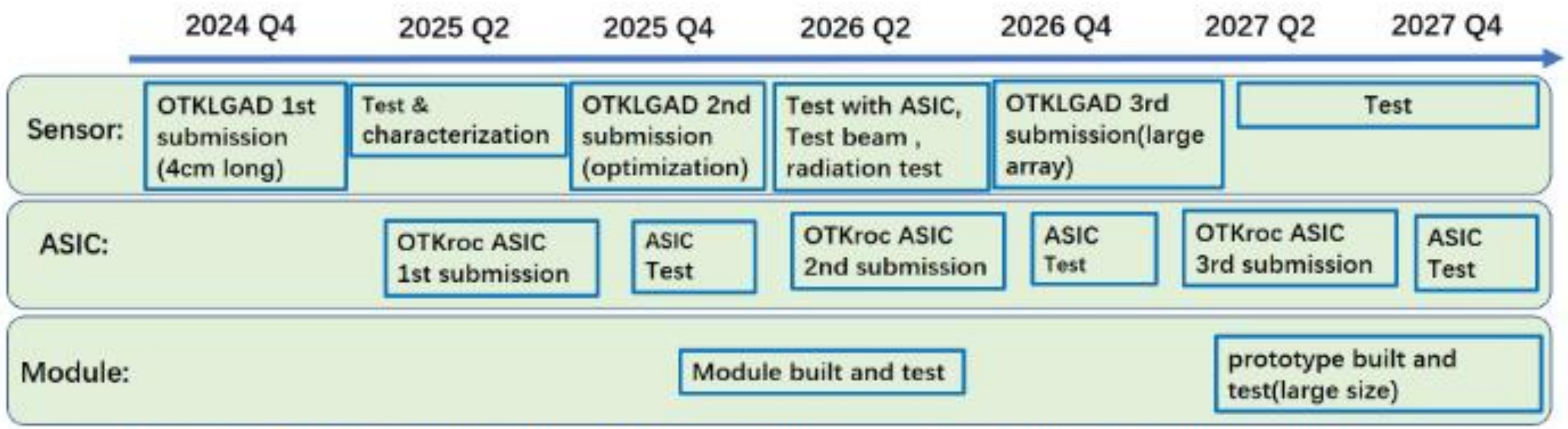

Figure 5.107: Timeline for OTK, including sensor, ASIC, mechanics and so on

具有不同strip长度的器件设计，Ref-TDR发布之前若有新的结果可对R&D内容进行补充

Summary

径迹探测器Ref-TDR撰写：

5.4.1.1 AC-LGAD sensor R&D

- LGAD性能
- AC-LGAD介绍
- 仿真模型与结果
- 测试平台与时间位置分辨率分析方法
- 两种Prototype与测试结果

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5.4.5 Prospects and plan

AC-LGAD sensor研究计划(3年期)

Backup

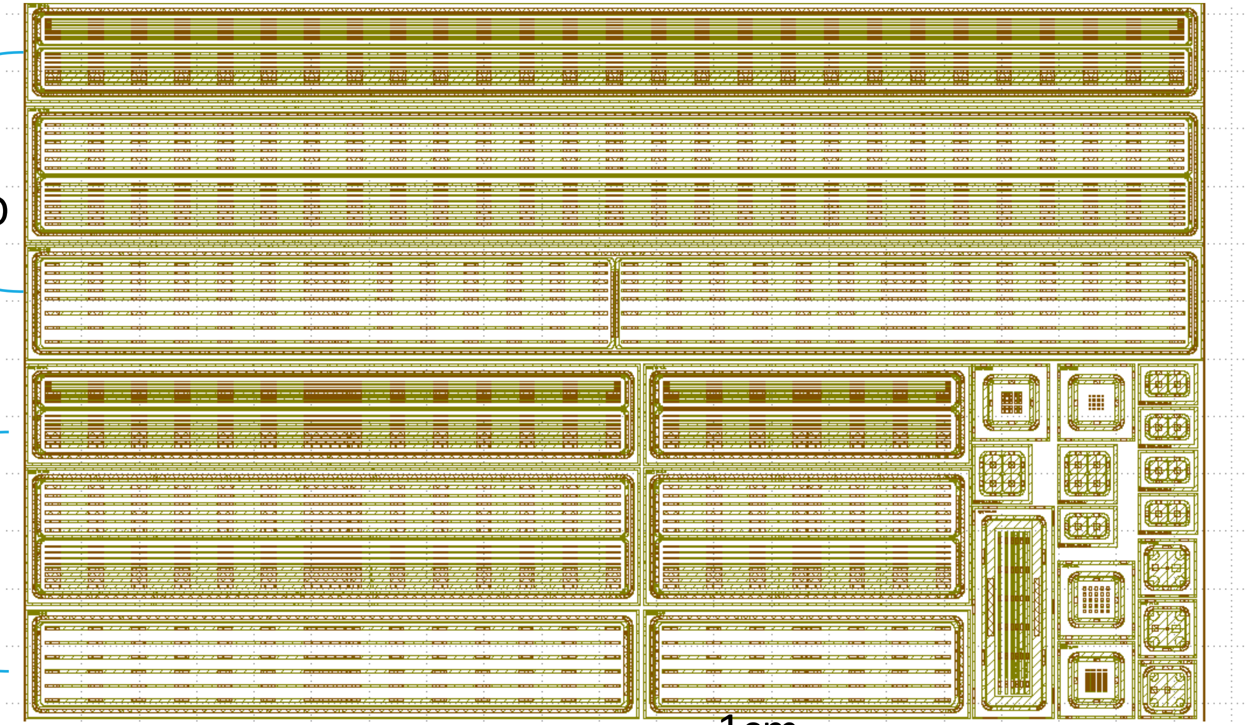
AC-LGAD R&D

➢IHEP AC-LGAD New Prototype design for the CEPC OTK&TOF application:

- The strip length as 1cm, 2cm, and 4cm and Pitch size as 100 um, 200 um, to 500um.
- Optimized isolated structure design for reduction of the sensor capacitance
- Process design for better spatial resolution(n+ layer dose)

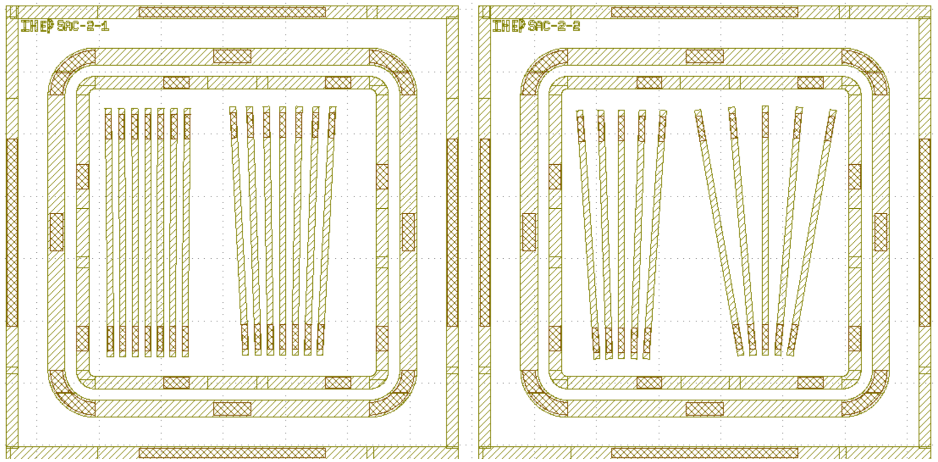
4cm AC-LGAD

2cm AC-LGAD



1cm AC-LGAD

- Sector, Fan shape AC-LGAD for Endcap

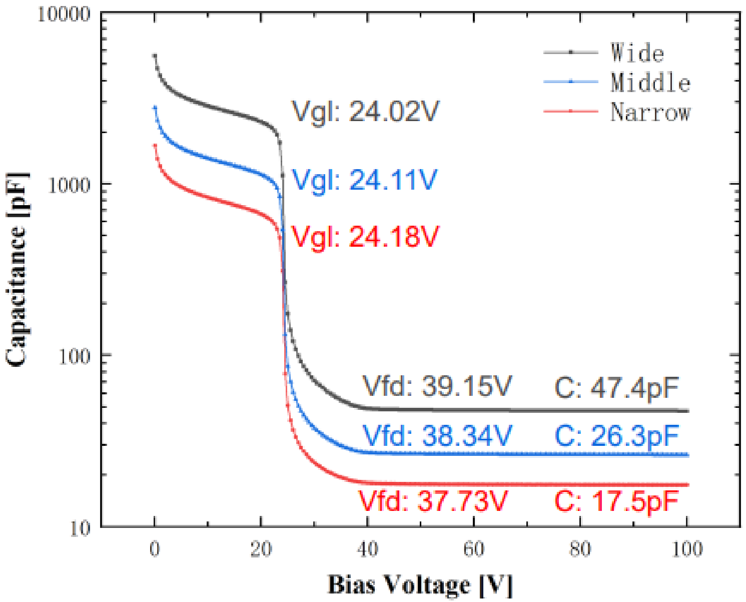


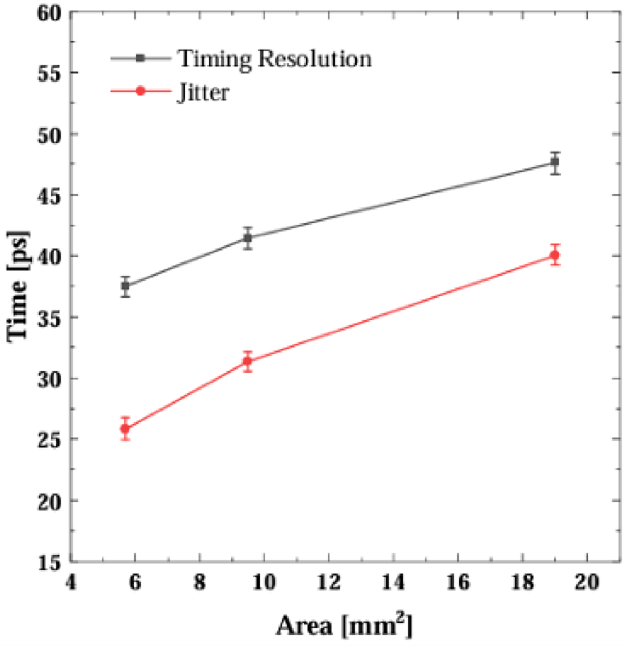
AC-LGAD R&D

➢Issues：Performance of LGAD with long strip

- Large capacitance: worse S/N, effect to the timing resolution and power consumption
- Long readout lines: signal delay(t_{rise}), impedance, charge sharing between strips
- Process control and yield

LGAD with large capacitance:



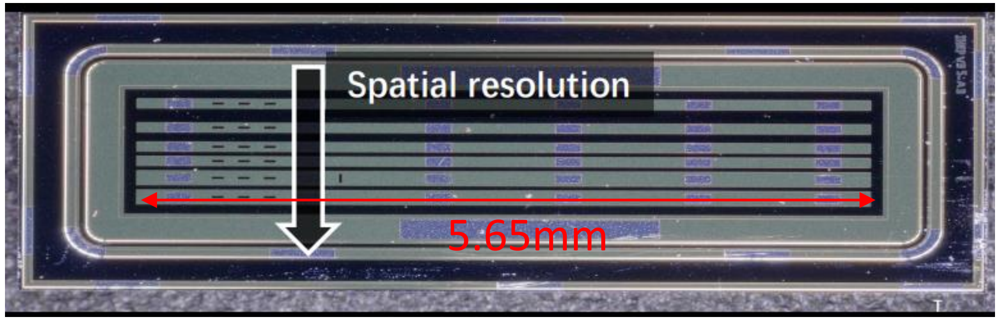


Sr90 testing results

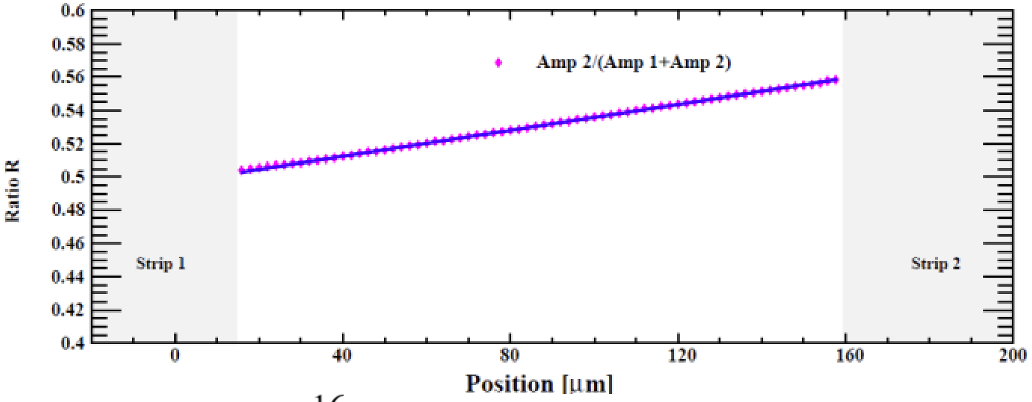
AC-LGAD R&D

Spatial resolution: Laser testing

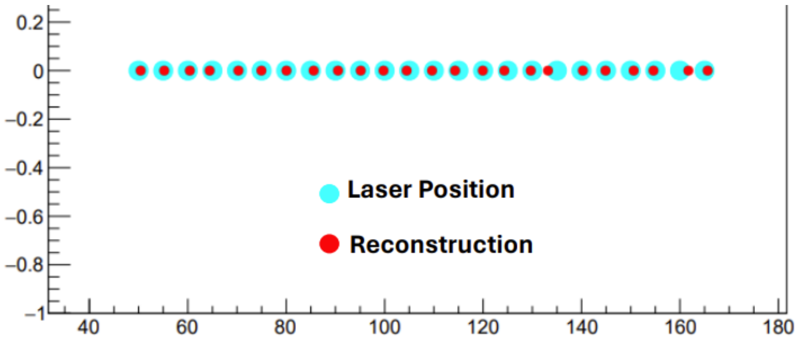
- Strip length 5.65mm
- pad-pitch size:
  100-250 um
  100-200 um
  100-150 um

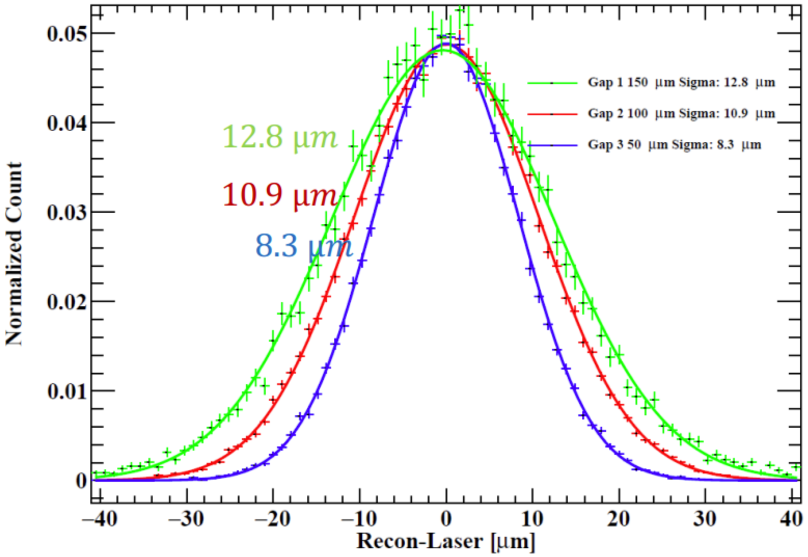


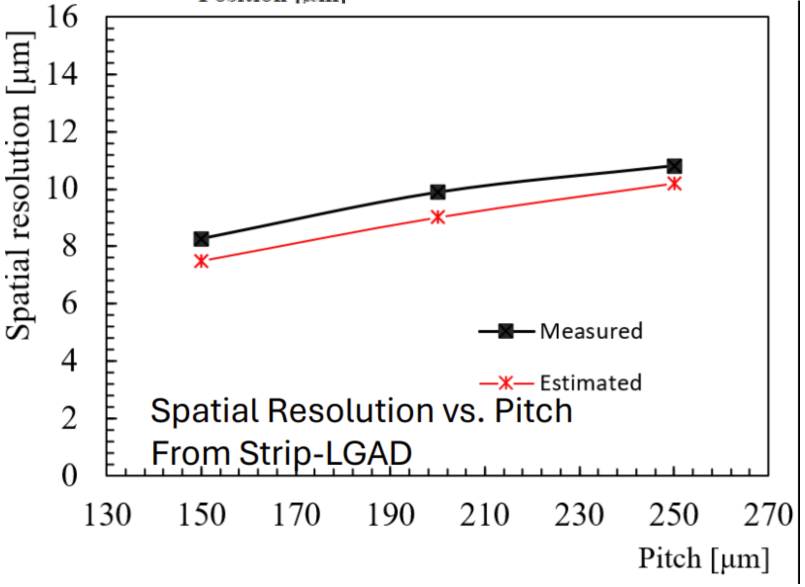
Amplitude information



Position reconstruction







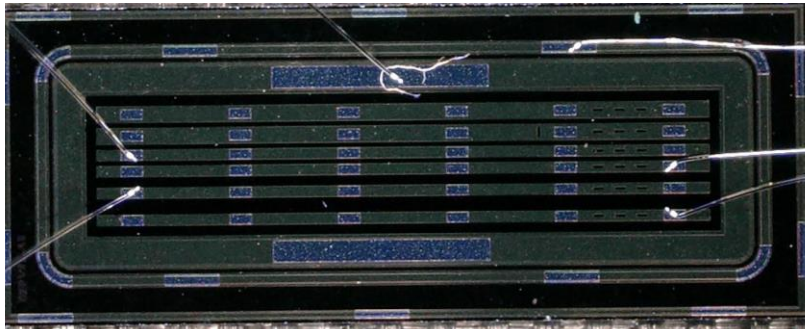
AC-LGAD with Pitch as 150um：Best spatial resolution~8um (laser test)

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

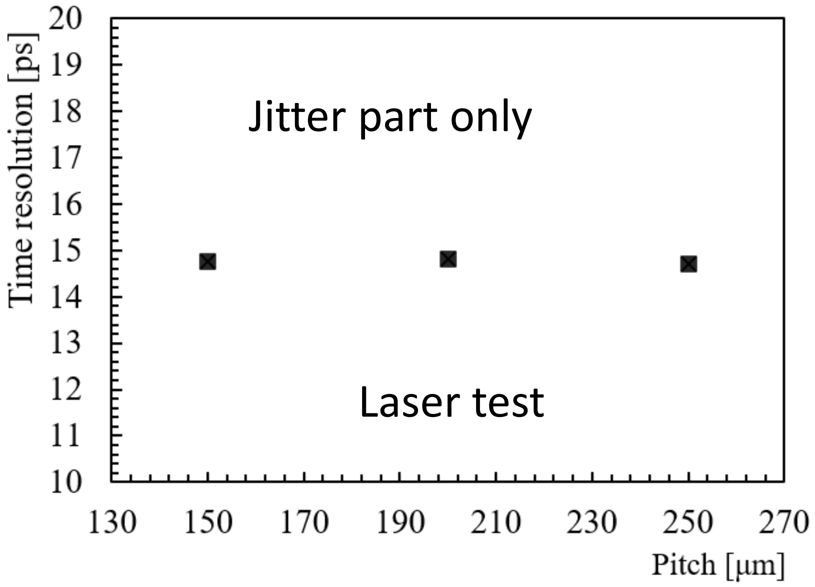
AC-LGAD R&D

Timing resolution

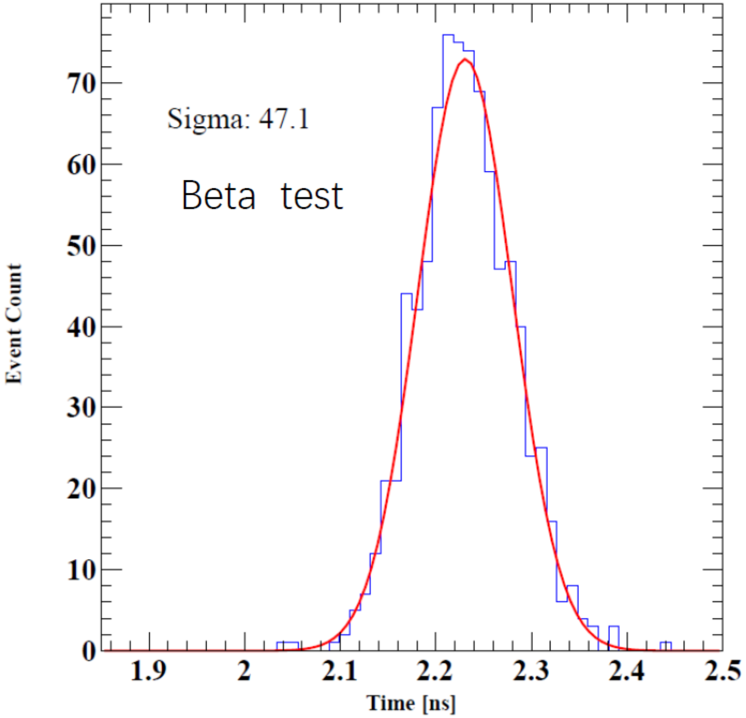
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{Landau}^2 + \sigma_{Jitter}^2$$



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



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

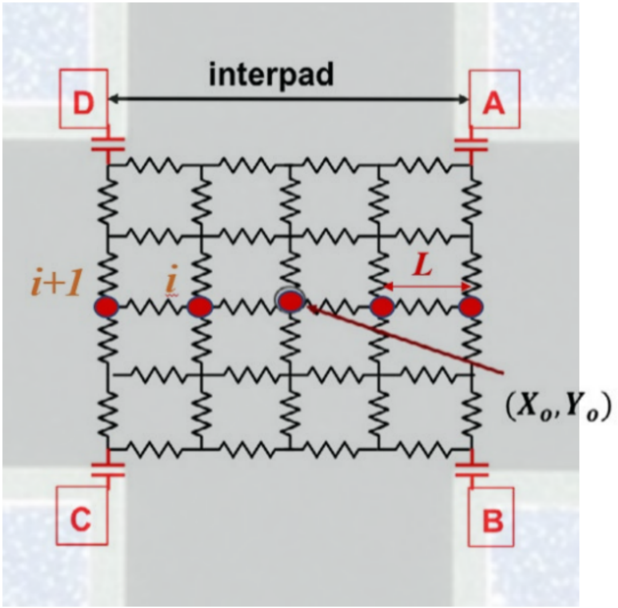


Time resolution： 37.5 ps

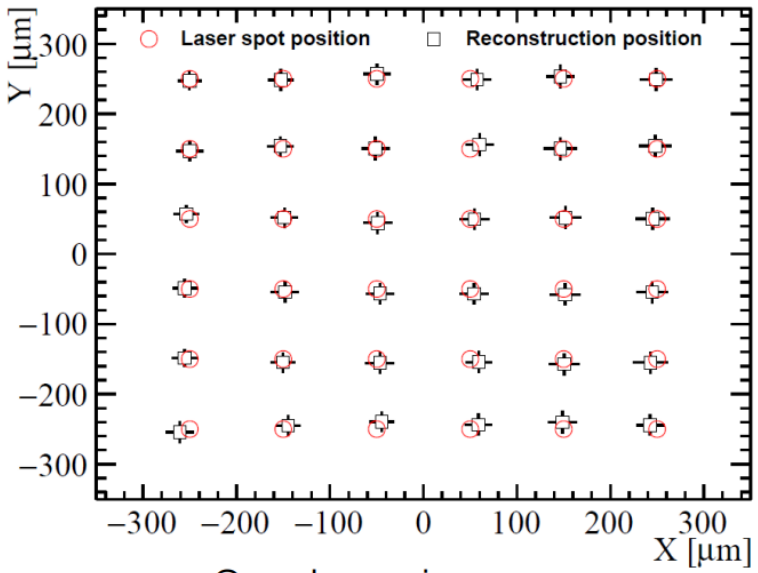
Landau and jitter contribution

$$\sigma_{AC-LGADStrip} = \sqrt{\sigma_{\Delta T}^2 - \sigma_{Trigger}^2}$$

Trigger: 28.5ps

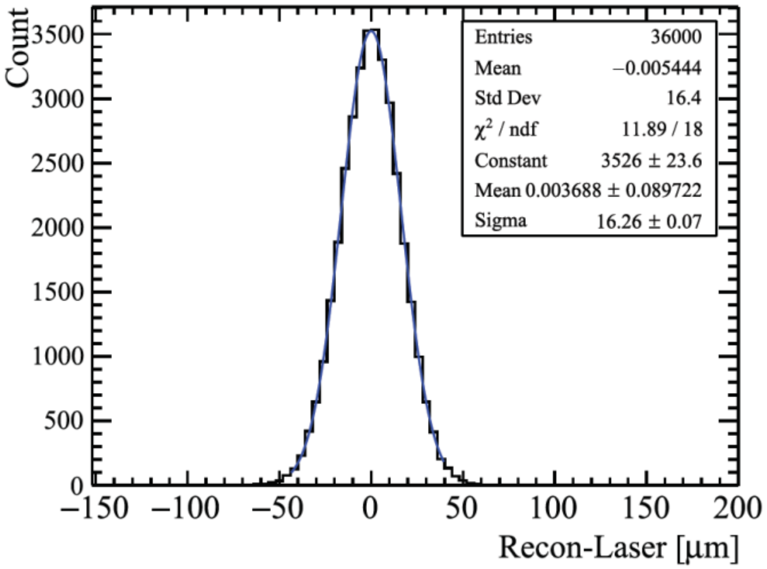


reconstructed 6x6 positions



Good consistency

Spatial resolution：reconstruction - laser



$$X = X_0 + k_x\left(\frac{q_A + q_B - q_C - q_D}{q_A + q_B + q_C + q_D}\right) = X_0 + k_x m$$

$$Y = Y_0 + k_y\left(\frac{q_A + q_D - q_B - q_C}{q_A + q_B + q_C + q_D}\right) = Y_0 + k_y n$$

Correction factor：k_x k_y

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

Discretized Positioning Circuit model (DPC)

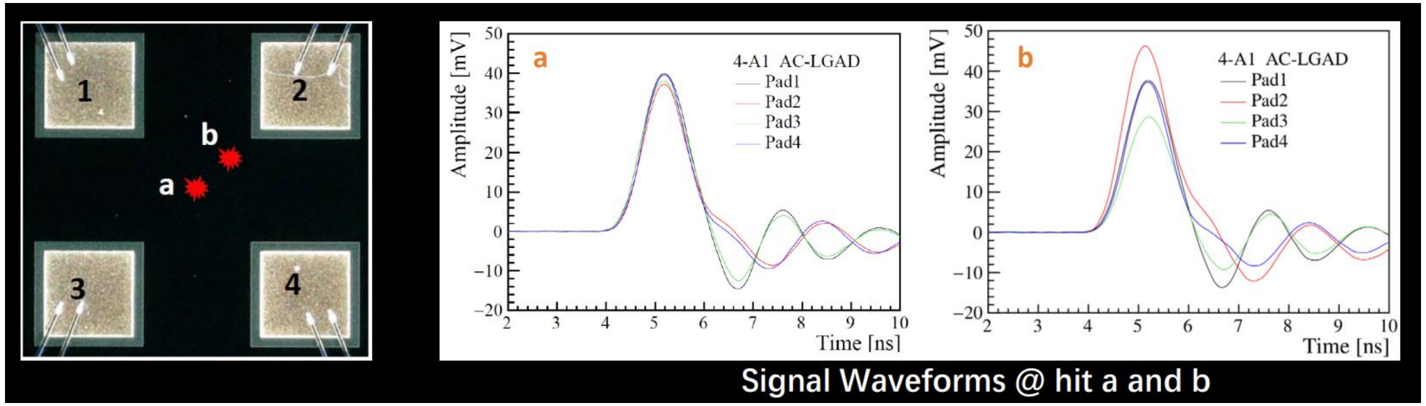
Spatial resolution：

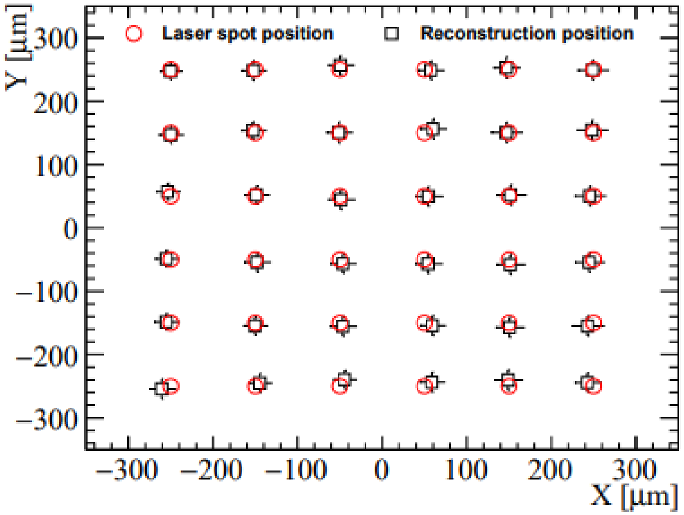
- the sigma of the difference between the laser and the reconstructed position

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

Discretized Positioning Circuit model
Machine learning method ongoing

IHEP AC-LGAD

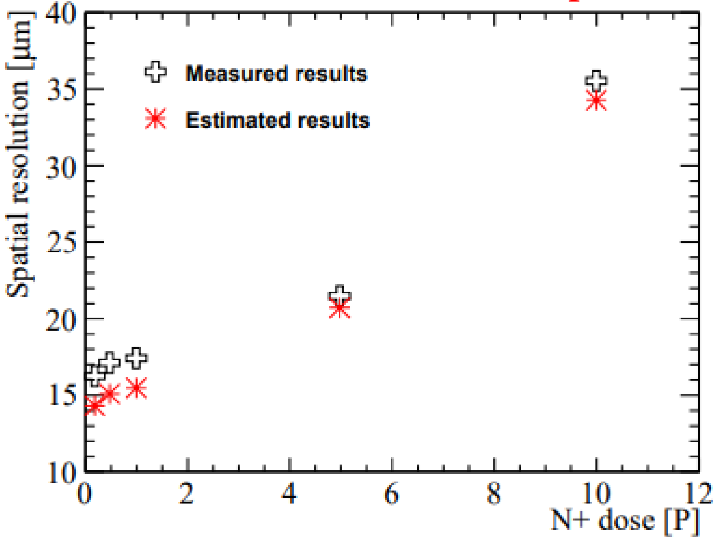




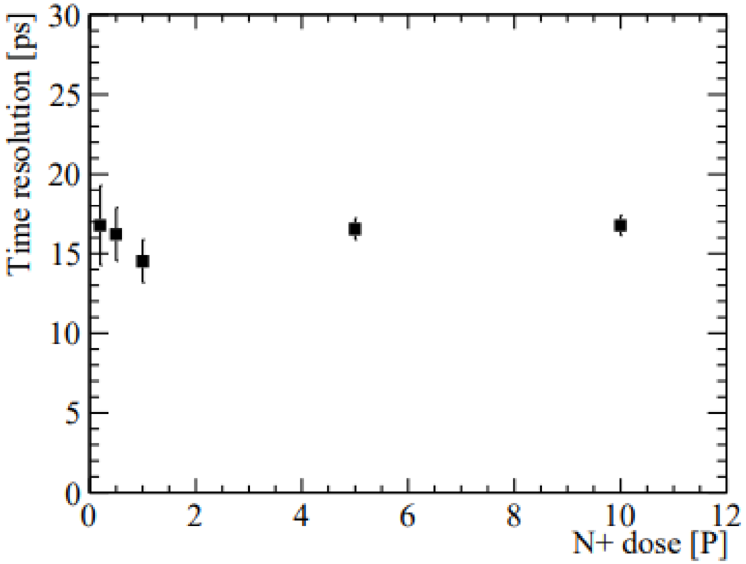
Pixel AC-LGAD

Pad-pitch： 1000-2000um

Position reconstruction



Position resolution as n+ dose changing



Timing resolution(laser testing): 15ps

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