具有高空间分辨率的低增益雪崩探测器研究

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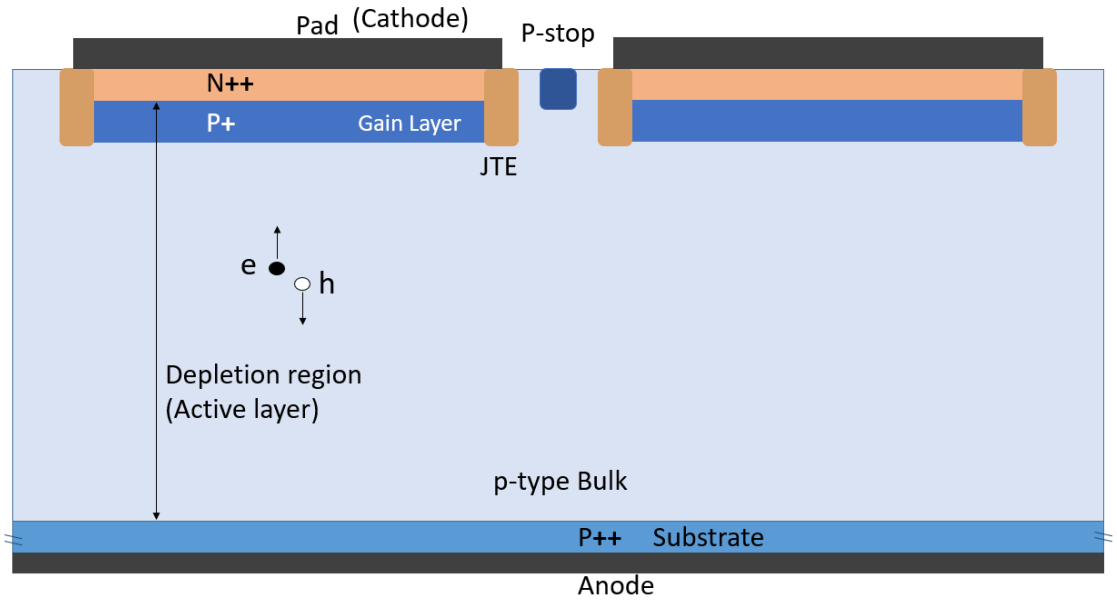
2023年10月22日 广西·南宁

1. Introduction of AC-LGAD



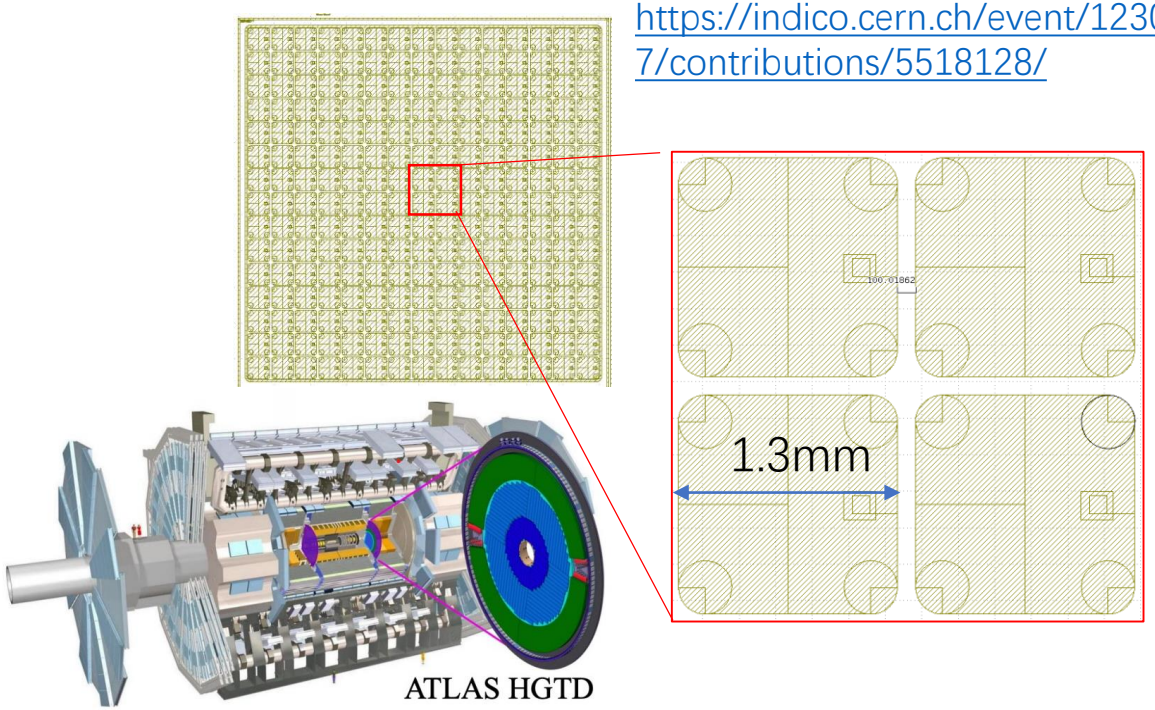
2 pixels LGAD (Low-Gain Avalanche Diode)

The readout pad is connected to n++ layer

- Gain 10-50
- Time resolution ~ 30ps
- Radiation hardness: 2.5e15 n_{eq}/cm^2
- **Position resolution:** pixel size/$\sqrt{12}$
- **Dead zone : p-stop and JTE**

15×15 LGAD for ATLAS HGTD project

https://indico.cern.ch/event/1230837/contributions/5518128/



- **Pixel size: 1.3mm**
- **Dead zone : 0.05~0.1mm**

Better position resolution
-> Reduce pixel size
-> Lower fill factor
-> More readout channels

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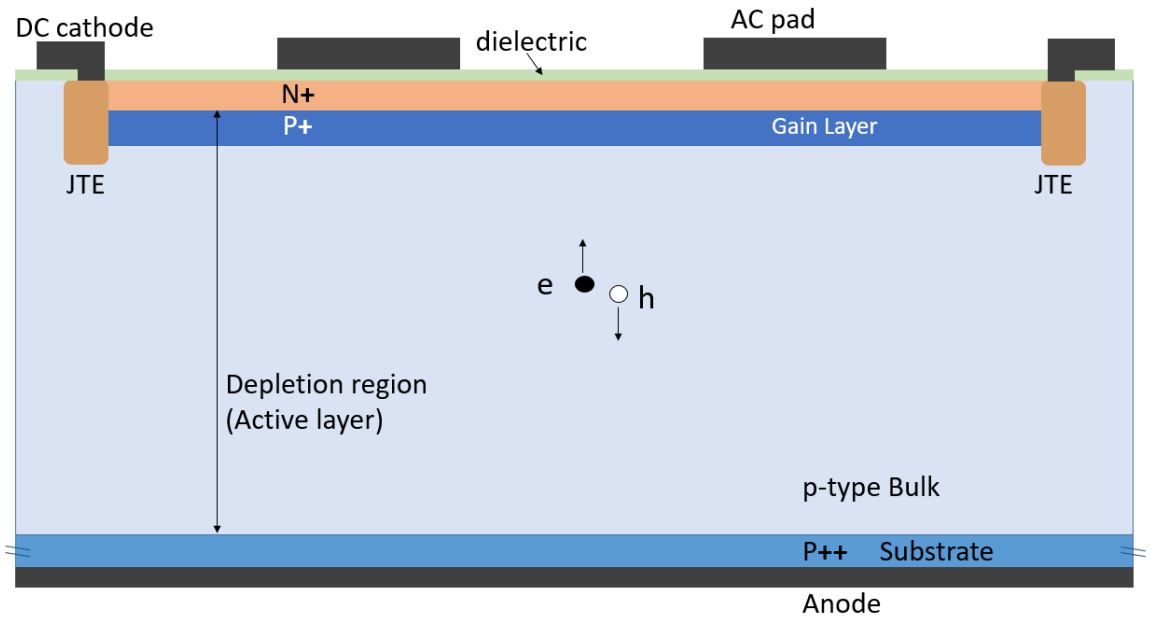
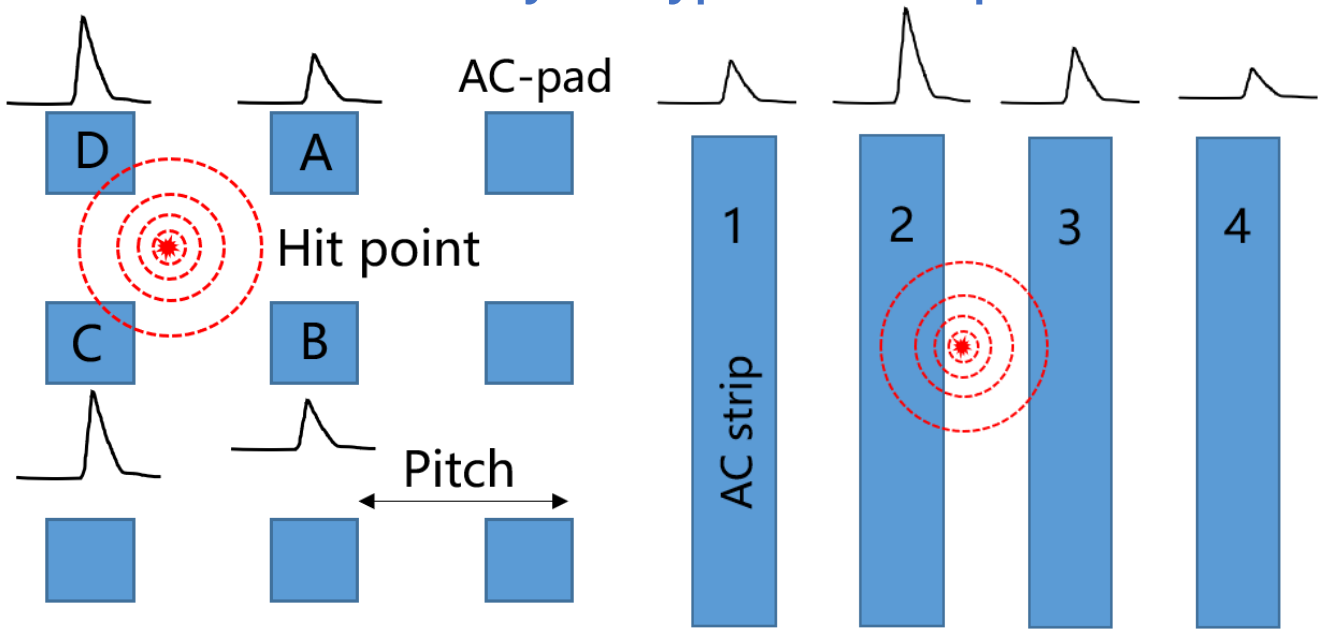
1. Introduction of AC-LGAD



AC-LGAD (AC-coupled LGAD)

- Metal AC-pads separated from the n+ layer by a thin dielectric (SiO_2, Si_3N_4)
- **No dead zone (100% fill factor)**
- **Position resolution: 5~10 um**
- **Time resolution ~ 30ps**
- Radiation hardness: same as LGAD

AC-LGAD: two layout types for AC-pads



Pixels AC-LGAD:
- Position information: **X** and **Y**
- Bump bonding to ASIC

Strips AC-LGAD:
- Position information: **X** or **Y**
- Lower readout density, wire bonding (easy)

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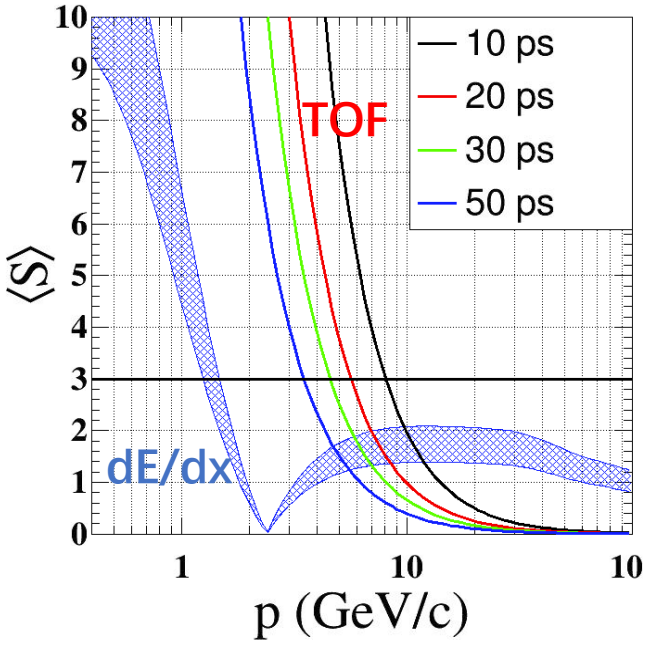
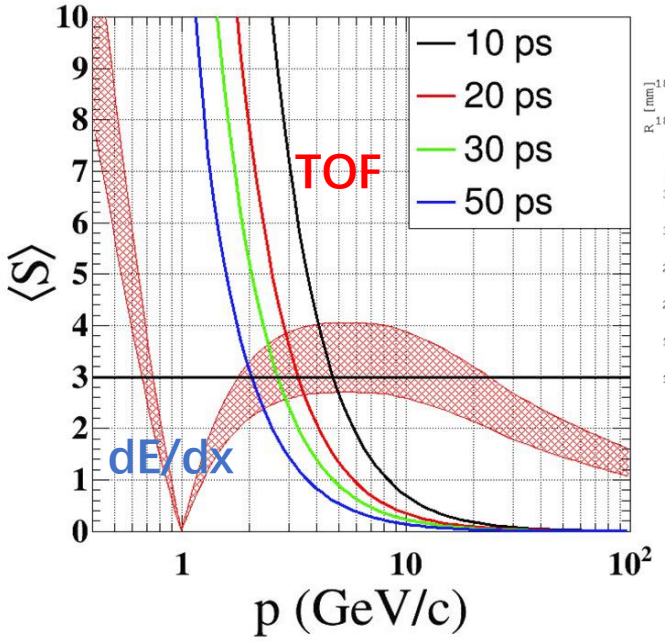
2. AC-LGAD的应用：CEPC 时间探测器

- **CEPC will produce 10^{12} Z boson at Z pole: Rich flavor physics program**
- **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 tracker)
- **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
- **Concept design:** Offer the time and spatial information (4D tracker) Close to / replace SET tracker

K/p separation

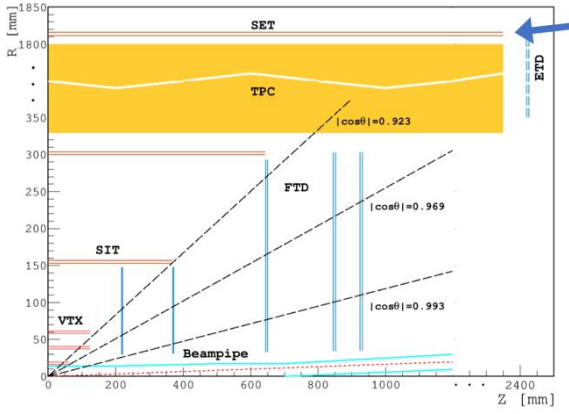


K/pi separation

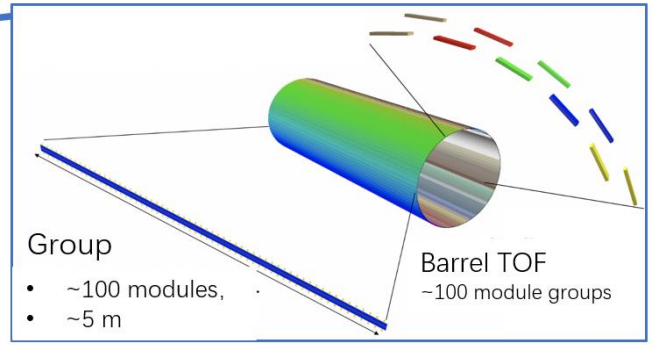


CEPC LGAD timing detector concept designs

Baseline detector concept in CDR



LGAD timing detector in Barrel region



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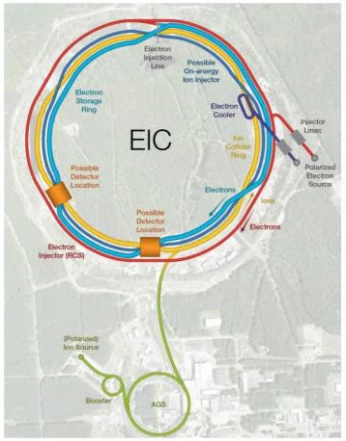
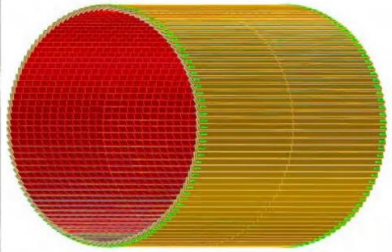
2. AC-LGAD的应用

电子离子对撞机EIC：Timing-tracker

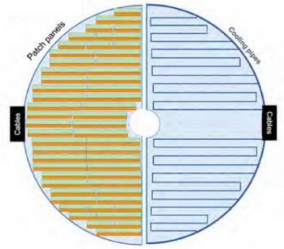


Barrel AC-LGAD detector



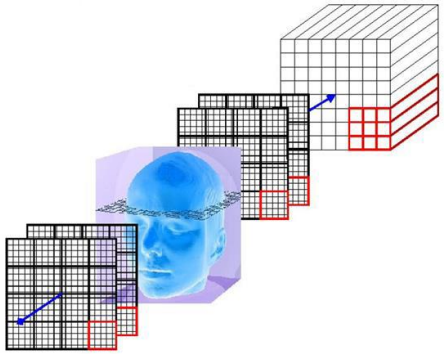
10.9 m^2

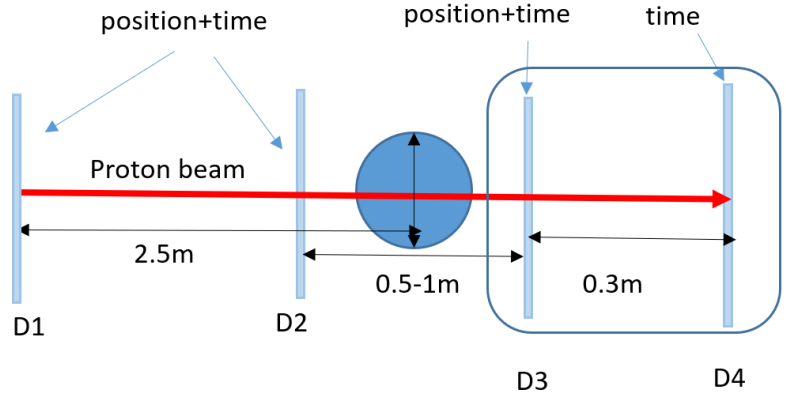
Hadron endcap AC-LGAD detector



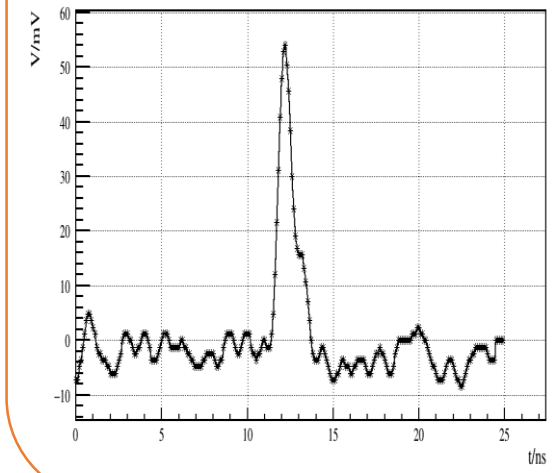
2.22 m^2

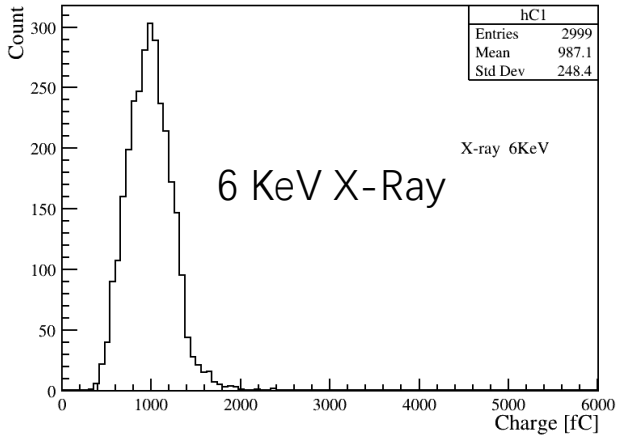
核医疗设备如：质子治疗 与 质子CT中的探测器





先进光源中**X射线探测器**





其它应用

- 束流测试平台的束流望远镜
- 激光定位与导航：激光雷达
- 其他粒子物理与核物理实验中径迹与时间探测器
- ……

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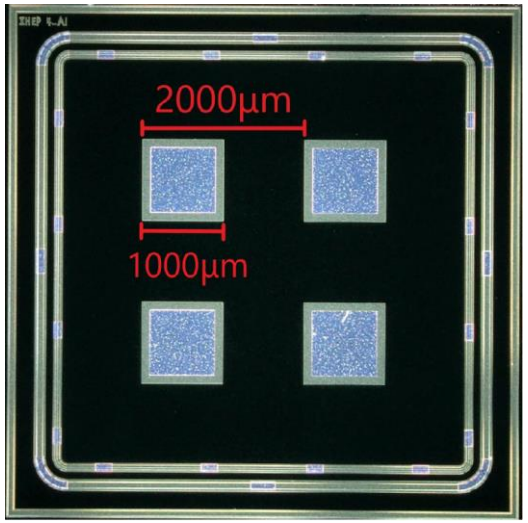
3. 高能所 IHEP AC-LGAD 探测器设计

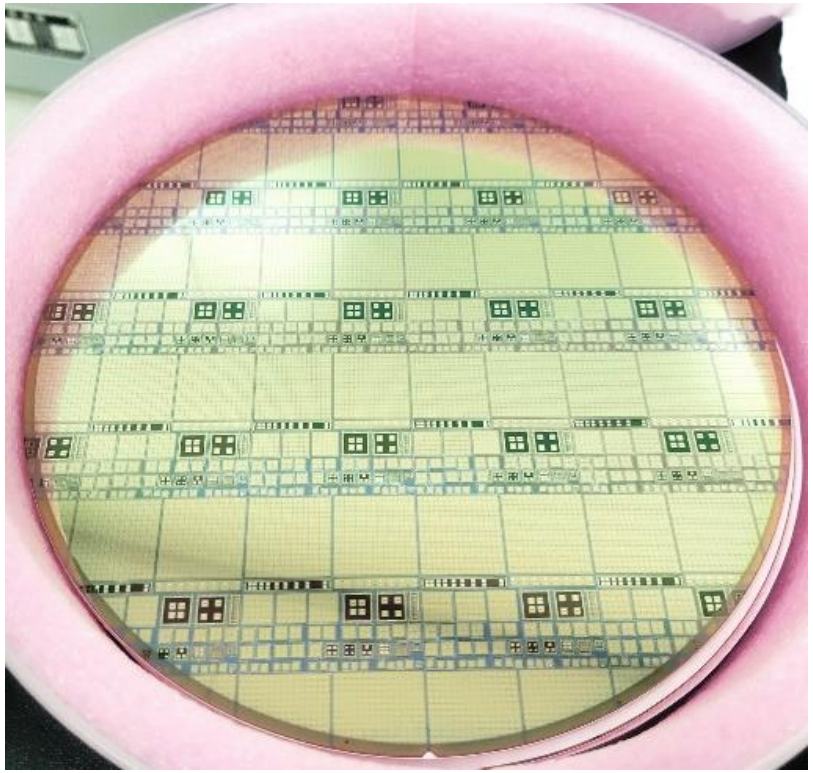
Pixels AC-LGAD:

- Pitch size 2000um, pad size 1000um
- **Different N+ dose：**
  - **10P (phosphorus)，5P，1P，0.5P，0.2P**

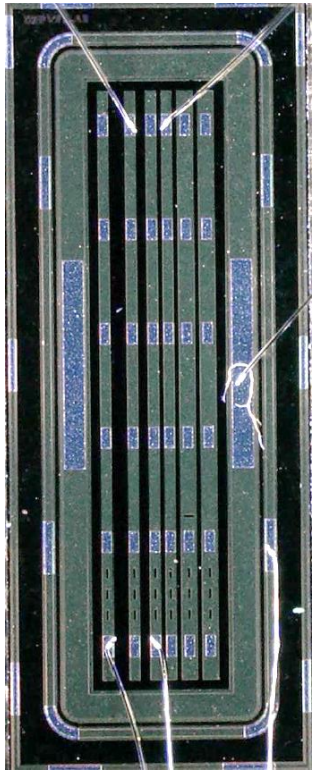
Strips AC-LGAD：

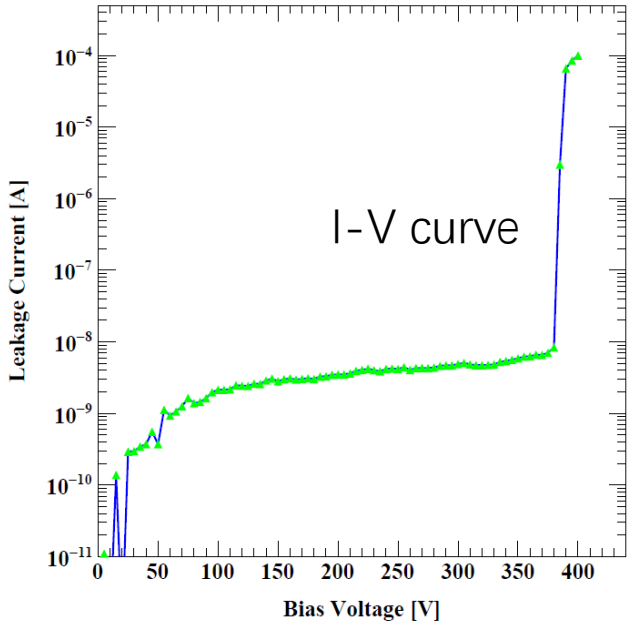
- AC-pad length 5.6mm, width 100um
- **Different Pitch size：**
  - **150um，200um，250um**





IHEP LGAD wafer: 8 inch





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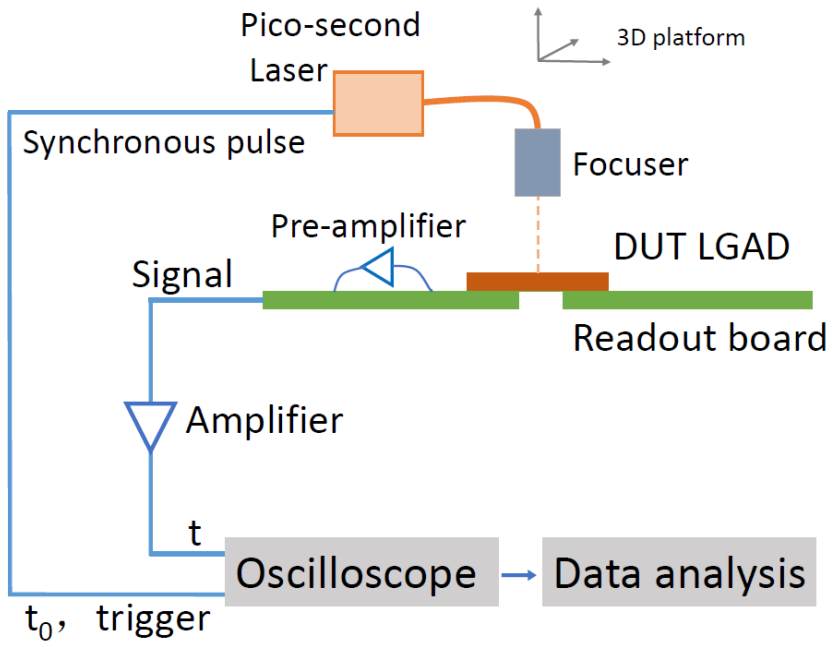
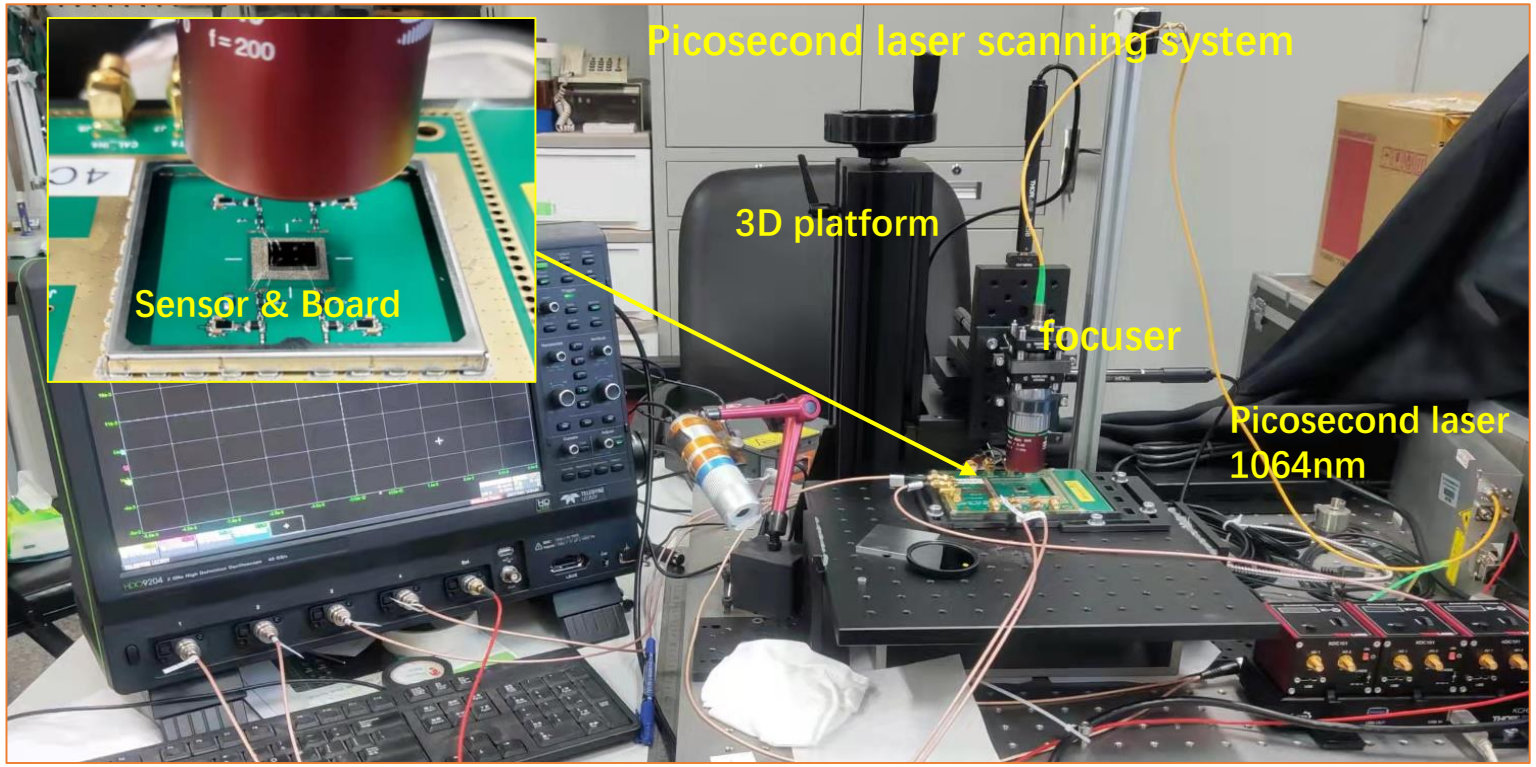
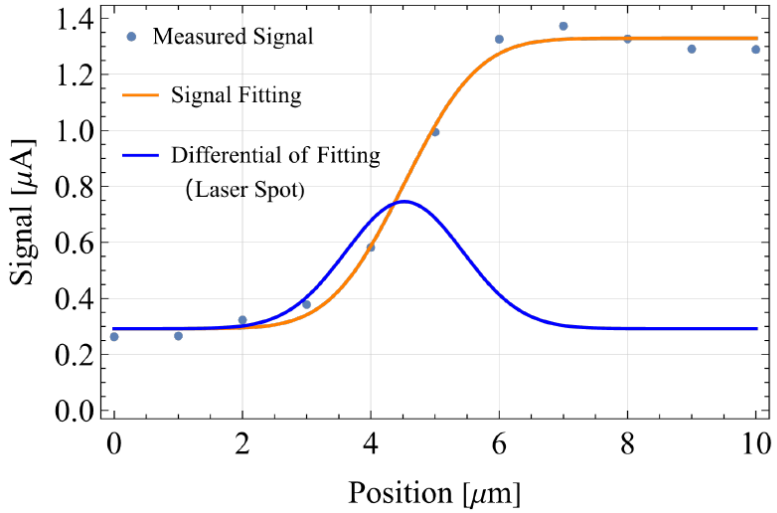
4. 皮秒激光测试：测试系统

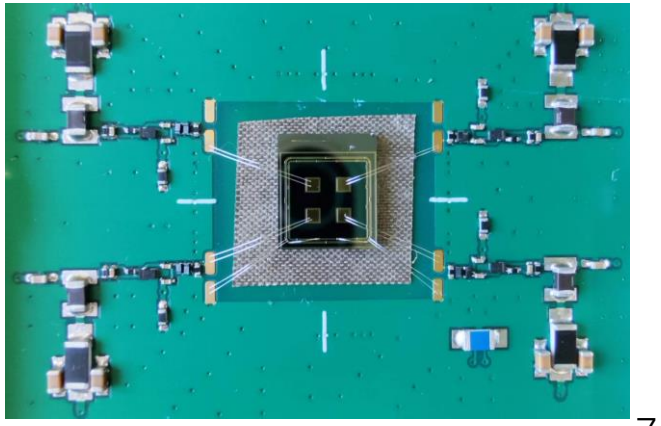






Picosecond laser scanning system

- Displacement accuracy 1 μm
- Automated scanning
- Picosecond laser 1064nm
- Laser pulse energy ~ 1 pJ
- Laser spot size 2~5 μm



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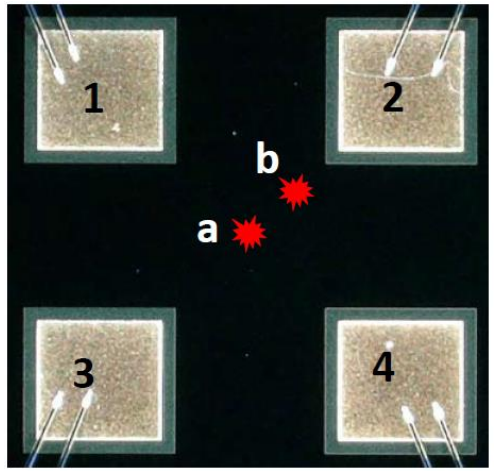
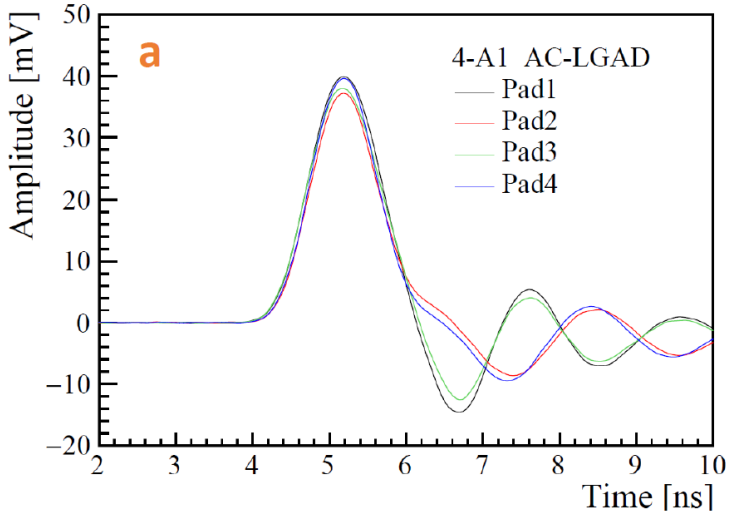
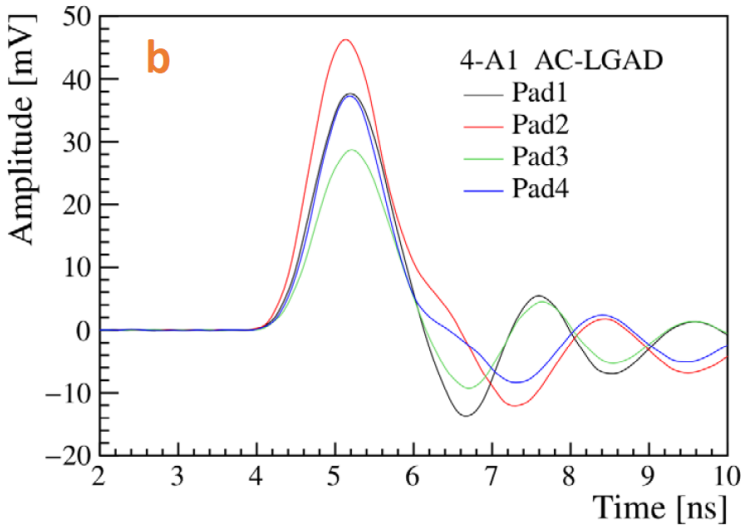
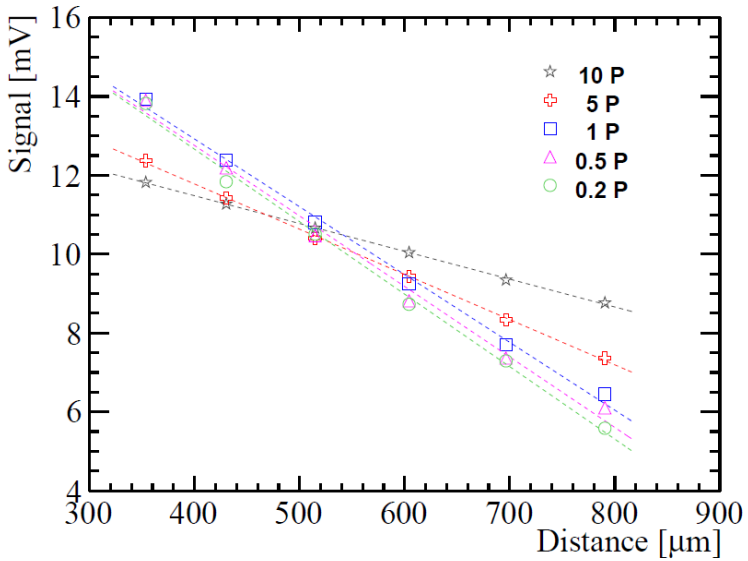
4. 皮秒激光测试：信号特征



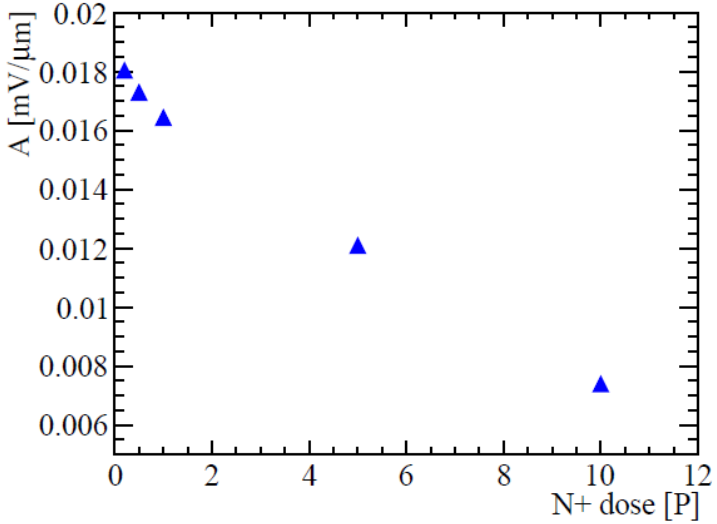




signal amplitude vs. distance



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**

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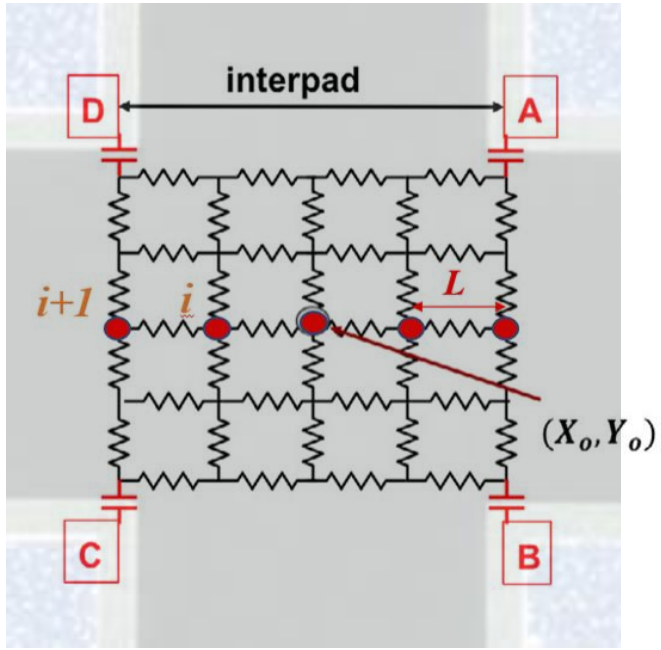
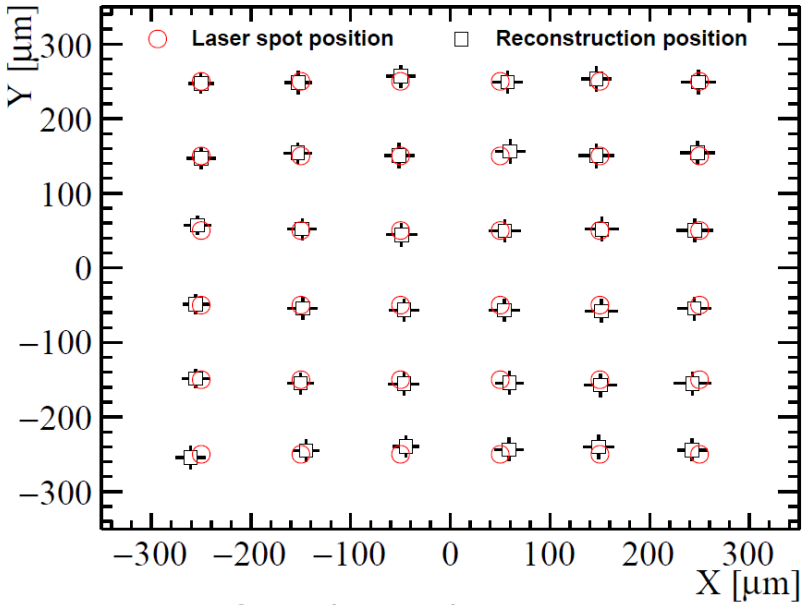
5. 位置信息重建：pixels AC-LGAD

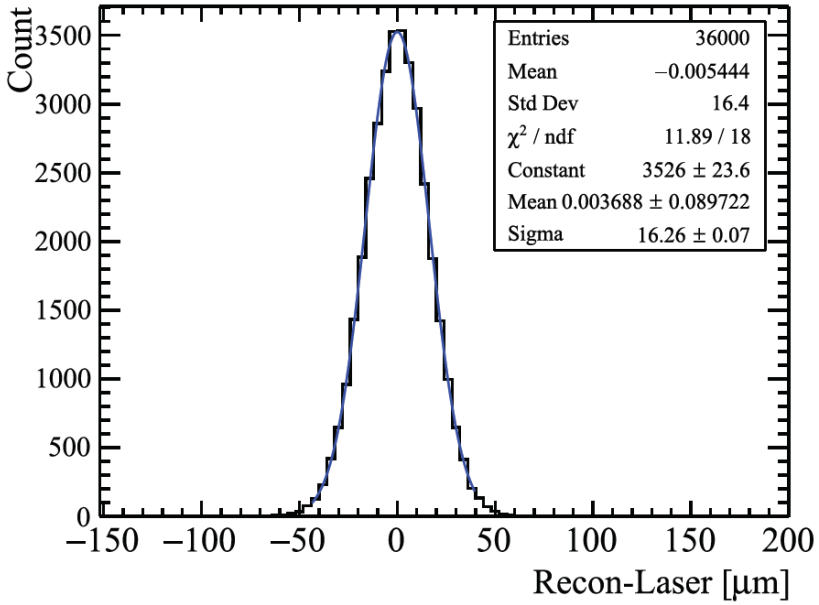


reconstructed 6x6 positions



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

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

刚发表在 *IEEE Transactions on Nuclear Science* https://doi.org/10.1109/TNS.2023.3289032

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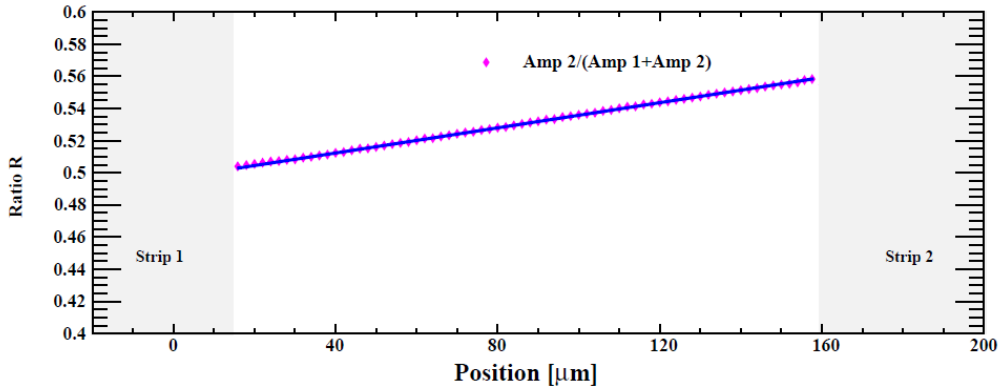
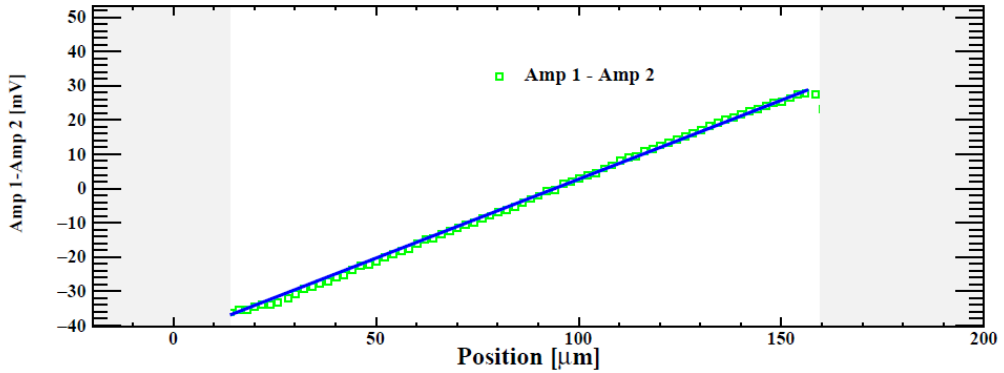
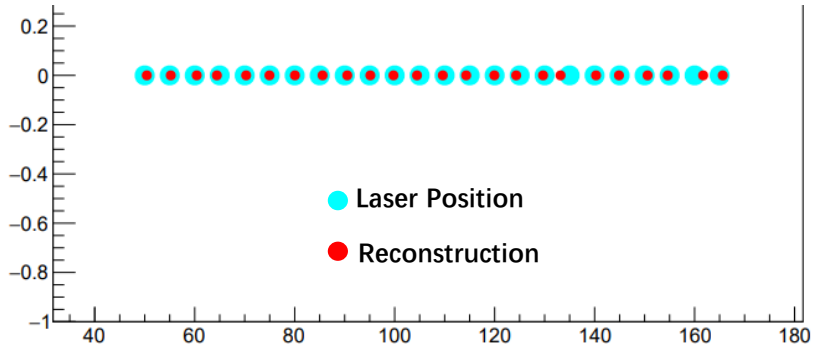
5. 位置信息重建：strips AC-LGAD





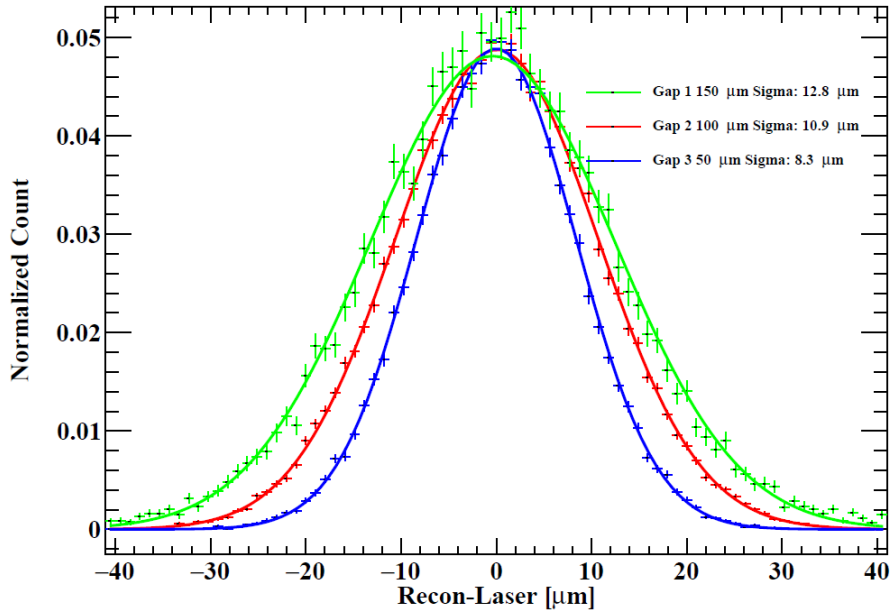


reconstructed positions

reconstructed position

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

$$x = \frac{R - c}{k_R}$$



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**

已投稿 *IEEE Transactions on Nuclear Science*

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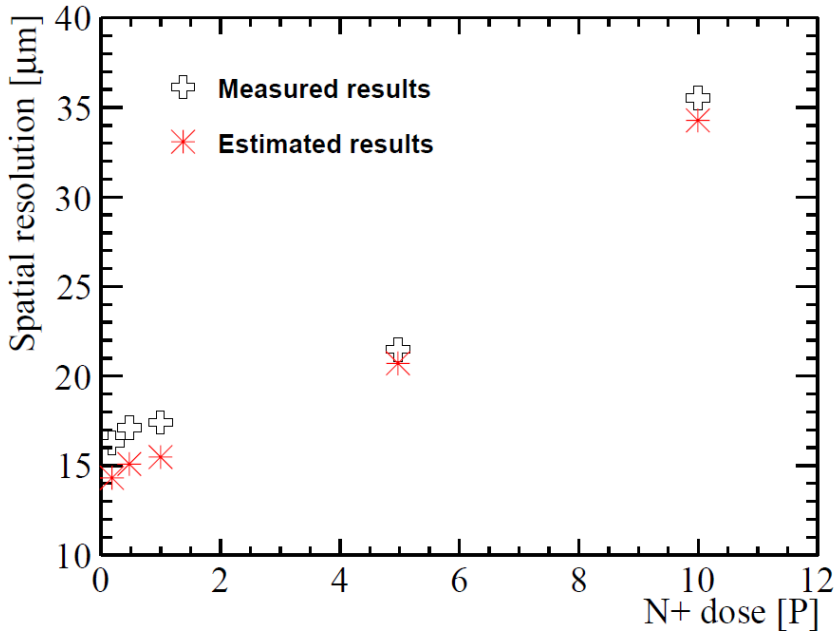
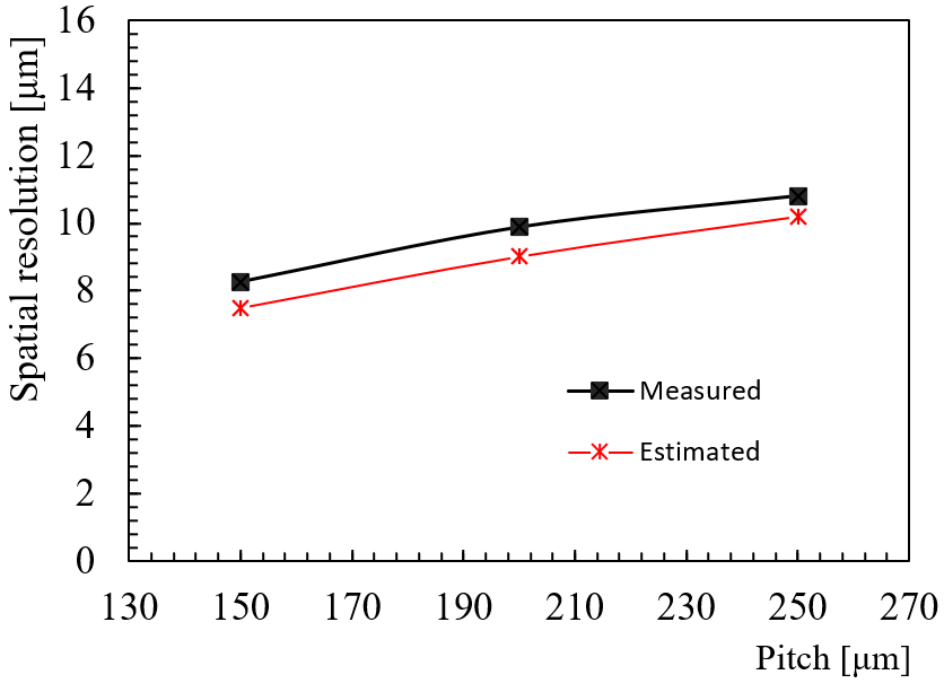
7. N+剂量与单元尺寸对空间分辨率的影响

Spatial resolution Vs. N+ dose



Spatial resolution Vs. pitch size



Resolution estimation:

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

A: signal attenuation factor

N: noise RMS (sensor + electronics)

- N+ dose 10 P⟶0.2 P, spatial resolution 36 -> 16 μm.
- **Lower N + dose** has higher resistivity and larger attenuation factor, ->**better spatial resolution**.
- Pitch size 250um ⟶ 150um, spatial resolution 11 -> 8 μm.
- **Smaller pitch sizes** result in faster signal attenuation and larger attenuation factor, ->**better spatial resolution**

Spatial resolution can also be evaluated according to signal attenuation factor and noise level.

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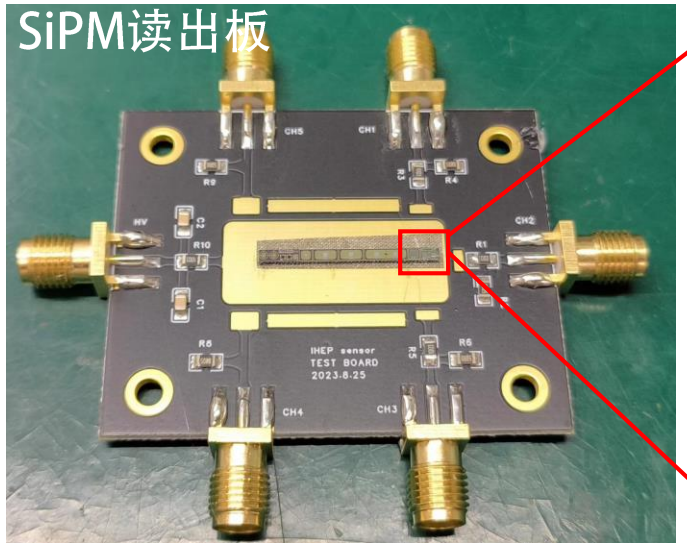
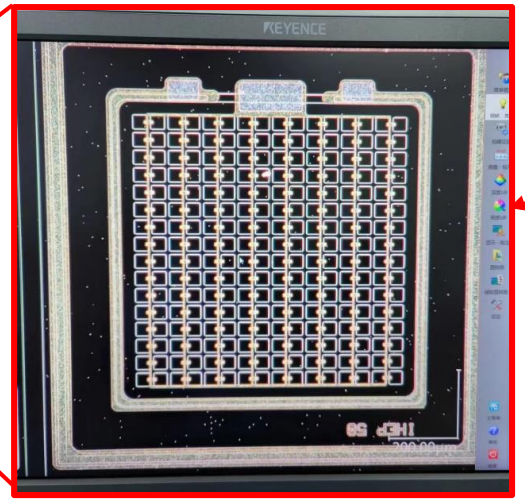
8. IHEP自研 SiPM 进展

自研抗辐照SiPM可用于CEPC、HERD、 LACT等项目

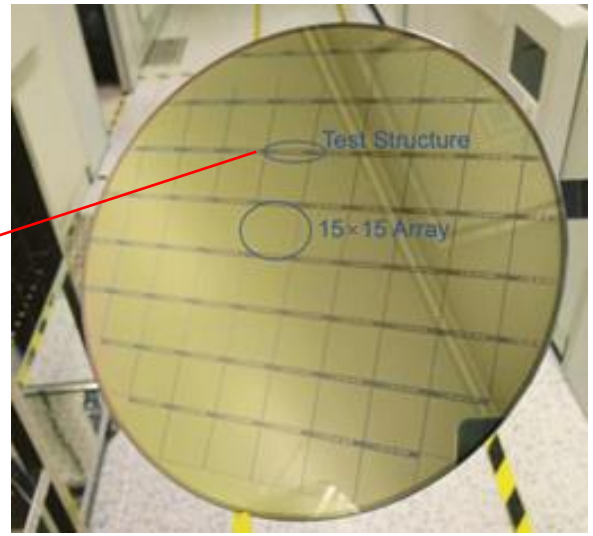
SiPM读出板



IHEP SiPM 样品

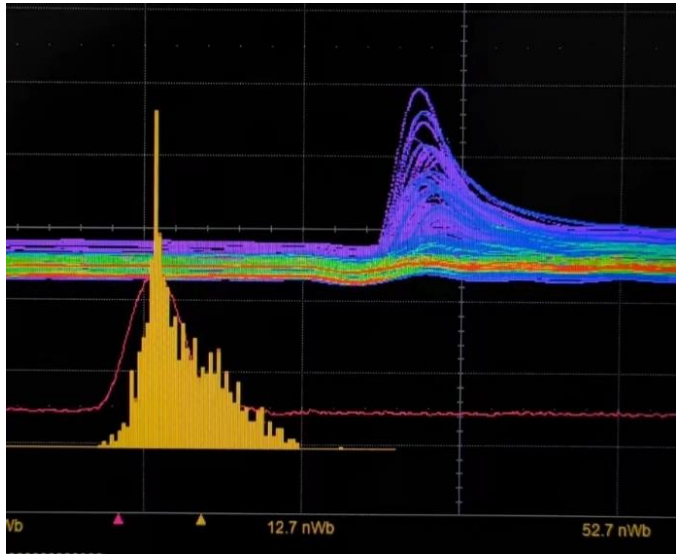


ATLAS LGAD 预生产晶圆



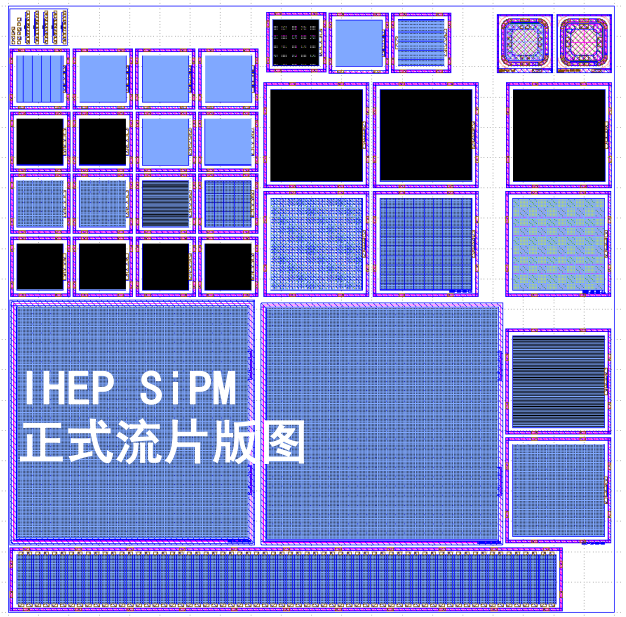
随LGAD 预生产的SiPM样品

- 部分结构与工艺初步验证
- Pixel size： 50μm
- 16 x 16 pixels
- 9月份收到



SiPM样品信号

- SiPM的结构设计和部分工艺得到验证
- 能量分辨率有待优化



正式流片计划：

- 10月底提交设计版图
- 年底完成第一版流片

SiPM器件尺寸：

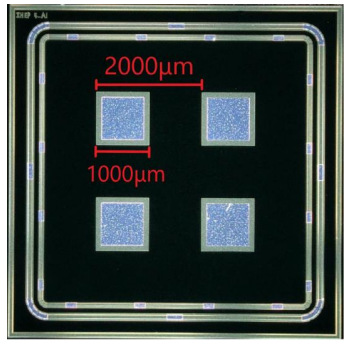
- 7.6 mm X 7.6 mm
- 3.0 mm X 3.0 mm
- 1.5 mm X 1.5 mm

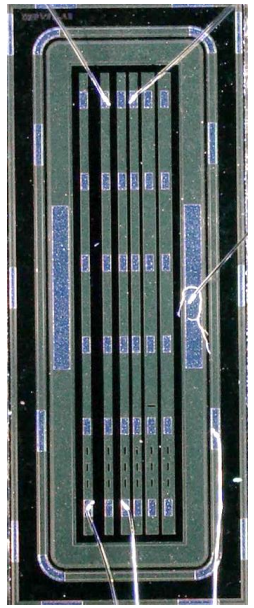
像素尺寸：

- 100um、50um、20um、10um

9. 总结

- AC-LGAD is a new 4D detector （position + time）
- IHEP has designed pixels and strips AC-LGAD sensors
- **The best spatial resolution of strips AC-LGAD ~8μm**
- **The best spatial resolution of pixels AC-LGAD ~16μm**
- **Low N+ dose (high resistivity) and small pitch size have better spatial resolution**
- **The signal attenuation factor and noise level are the main parameters for estimating the spatial resolution**





The next plan of IHEP AC-LGAD

- Test beam
- Optimize n+ p+ layers and AC-electrodes
- Longer (~40 mm) strips AC-LGAD
- Advanced algorithms for the reconstruction
- Ultra Low Noise Electronics
- ASIC and monolithic integration
- ……

IHEP自研SiPM

- **随LGAD预生产的SiPM样品，结构设计和部分工艺得到验证**
- **正式流片计划：10月底提交设计版图，年底完成第一版流片**

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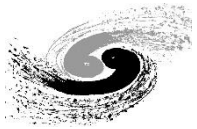

Thanks