CEPC timing detector R & D
--AC-coupled LGAD for 4D tracking

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on behalf on IHEP-HGTD team
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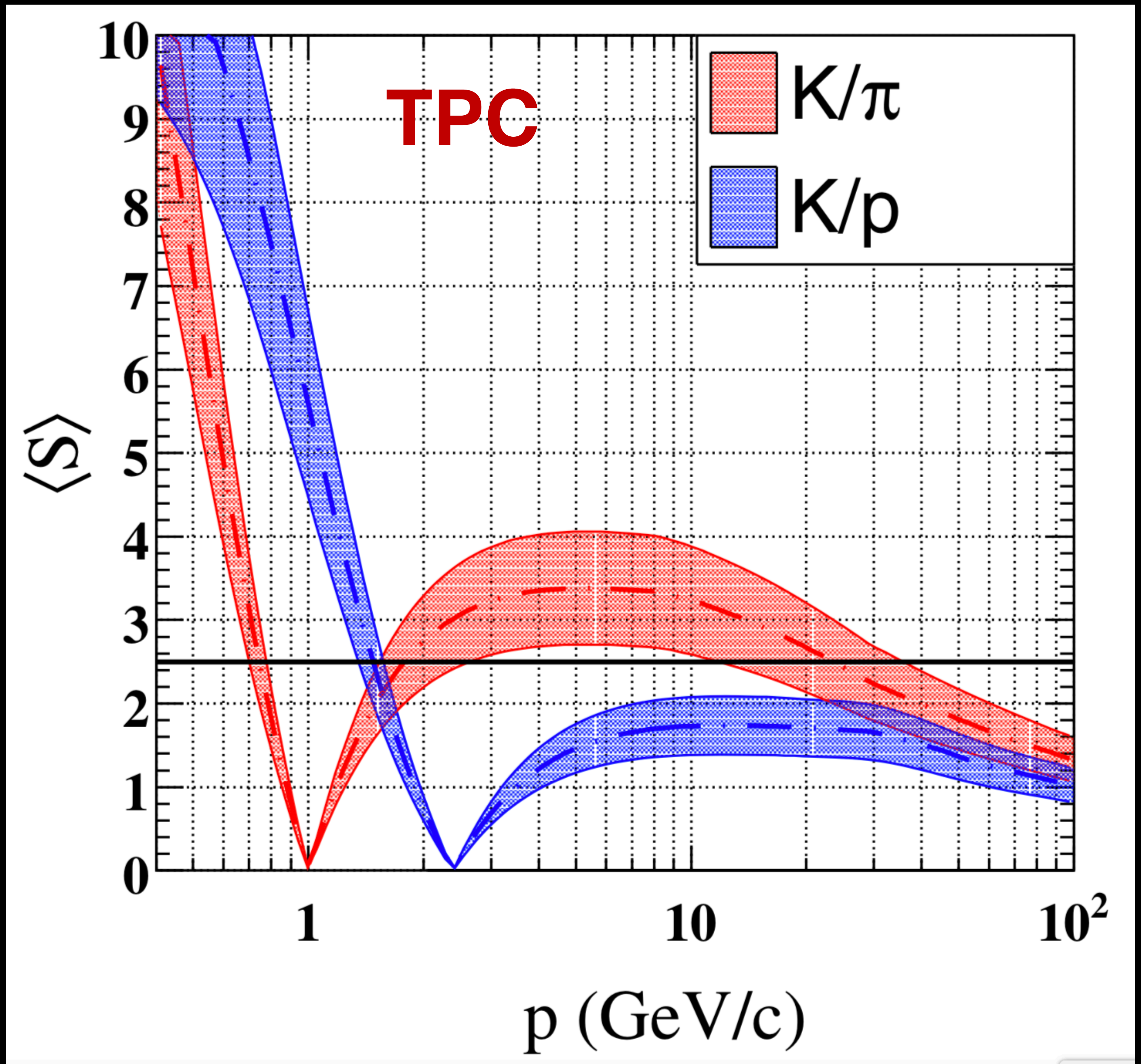
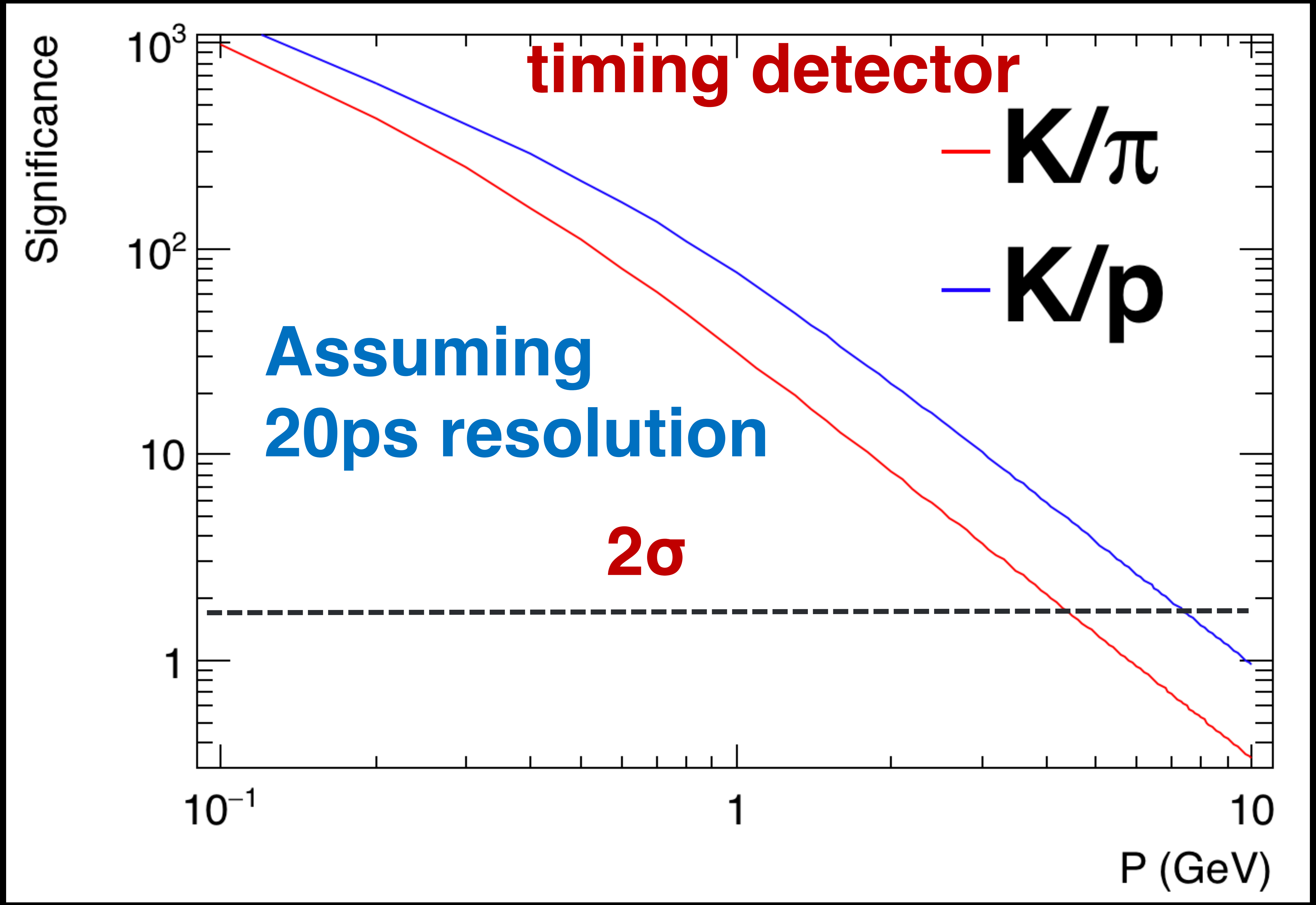
CEPC timing detector : motivation

- **CEPC will produce 10^{12} Z boson at Z pole → Rich flavor physics program**
- **CEPC International Advisory Committee: one of the key recommendations**

→ Precision timing detector should be determined as a matter of urgency

- **Gas detector is responsible for particle identification in flavor (dE/dx)**
  → Challenge: 0.5-2GeV for K/pi separation, >1.5GeV for K/p separation
- **Timing detector is complementary to gas detector**
  → 0-4GeV for K/pi separation, 0-8GeV for K/p separation

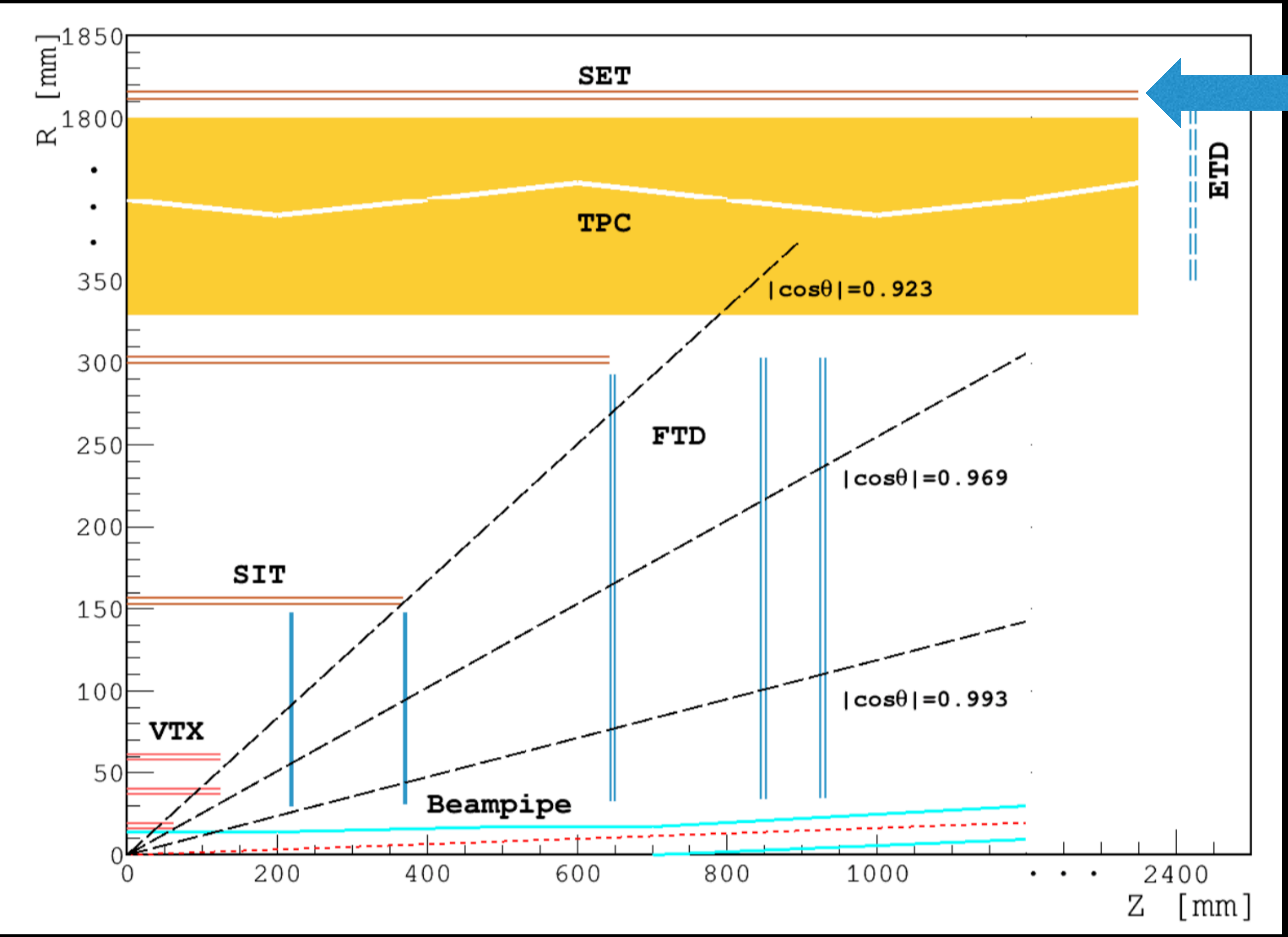




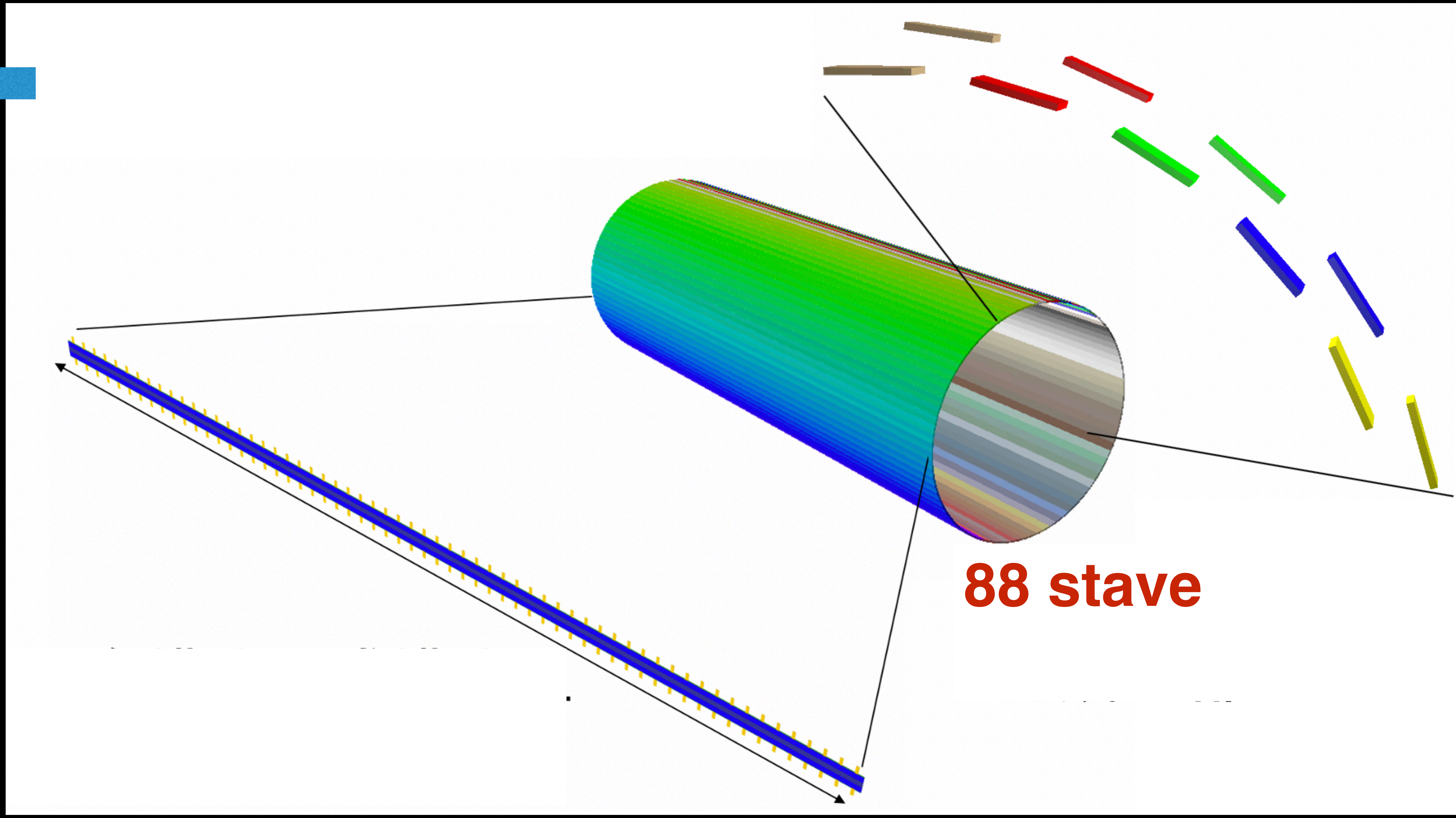
CEPC timing detector : Concept

- Timing detector: Between tracker and calorimeter
- → **TOF** Close to **SET** tracker, Radius **~1.8m**
- Target time resolution: **50 pico-second(ps)**
- Area of detector (Barrel : ~$50m^2$, Endcap: ~$20m^2$)

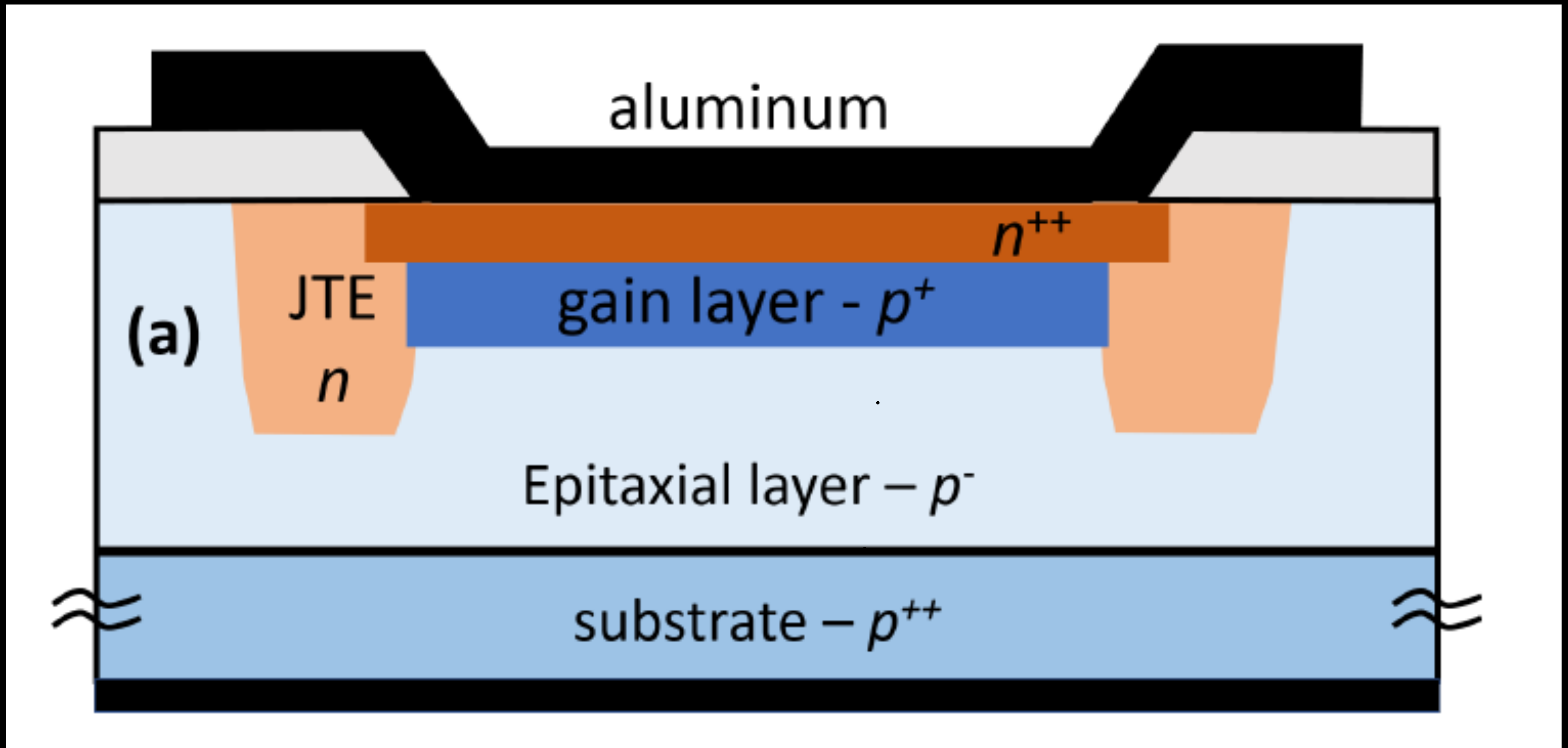
Baseline detector concept in CDR



Timing detector in Barrel region



Introduction of Low-Gain Avalanche Detectors (LGAD)



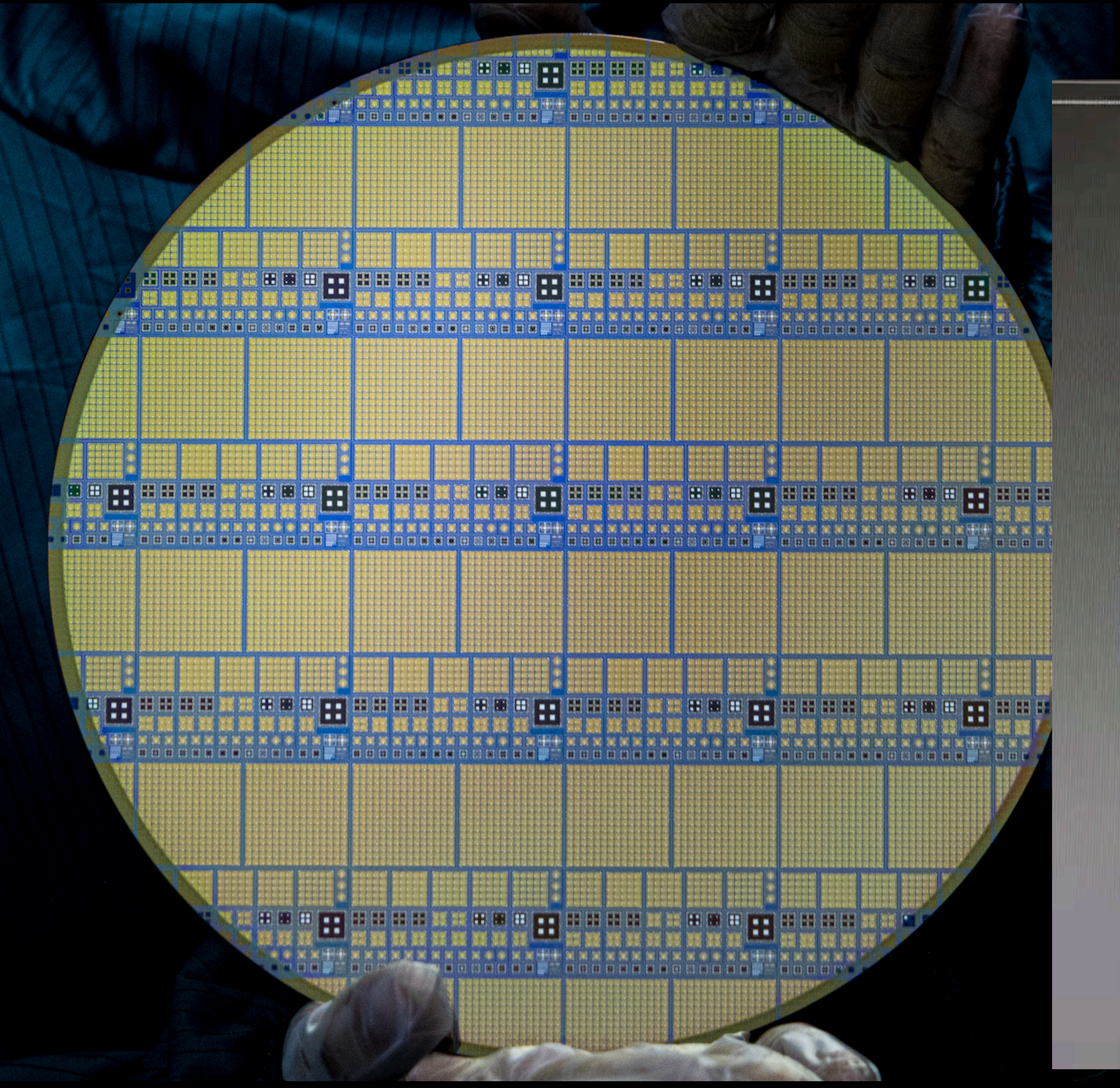
DC-LGAD

- **CEPC application: TOF**
- **The DC readout**
- **Time resolution ~ 30ps**
- **Position resolution: ~1mm**
- **Dead zone : ~ 0.1mm**

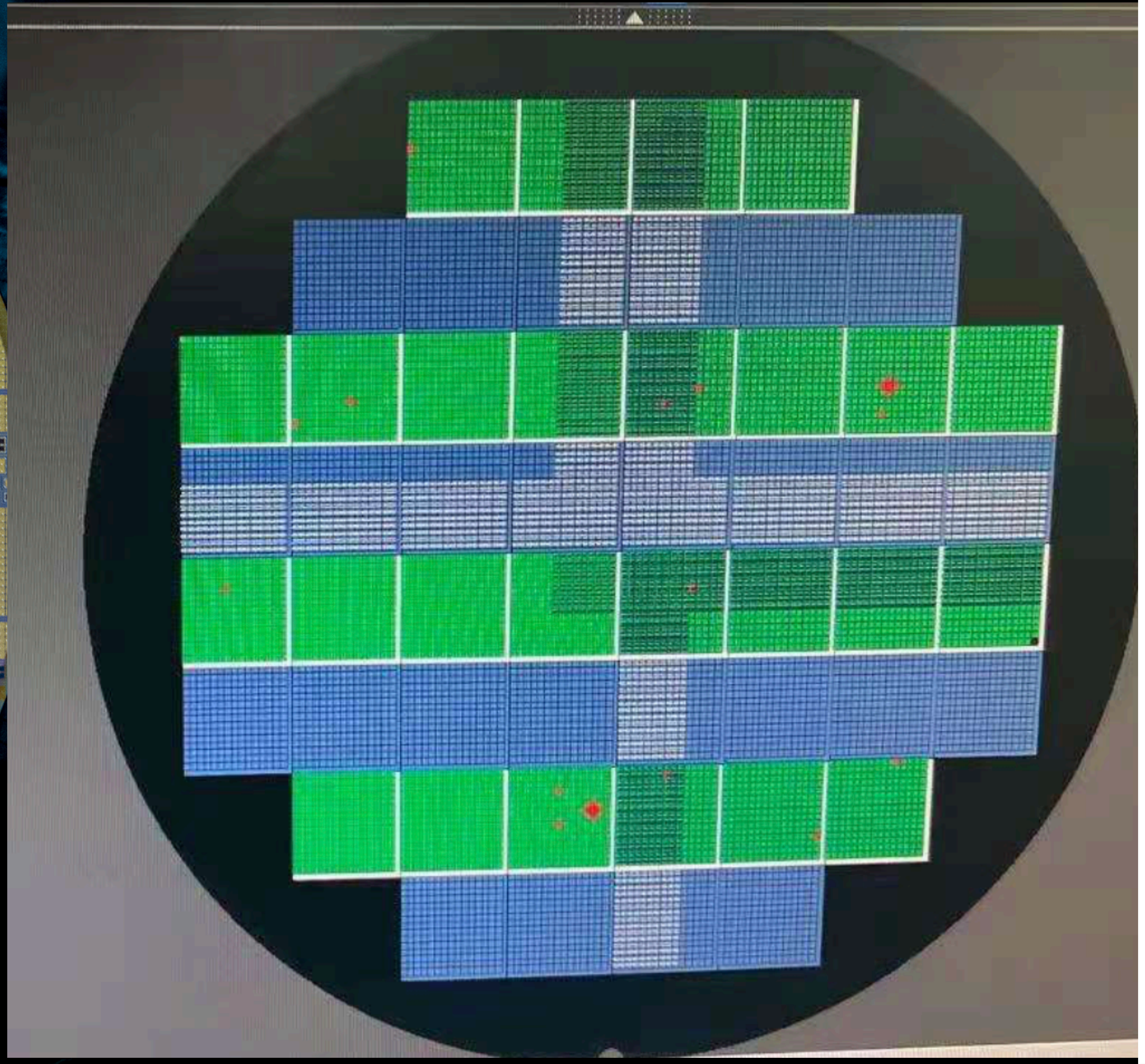
Progress in DC-LGAD for CEPC

- IHEP team collaborated with Institute of micro-electronics (IME)
- **IHEP team designed and IME fabricated**
- **Managed to fabricated 8-inch LGAD prototype wafer with good yield**
  - **>99.3%** yield for single pad
  - **>50%** yield for 15 × 15 channels LGAD (2 × 2 cm)

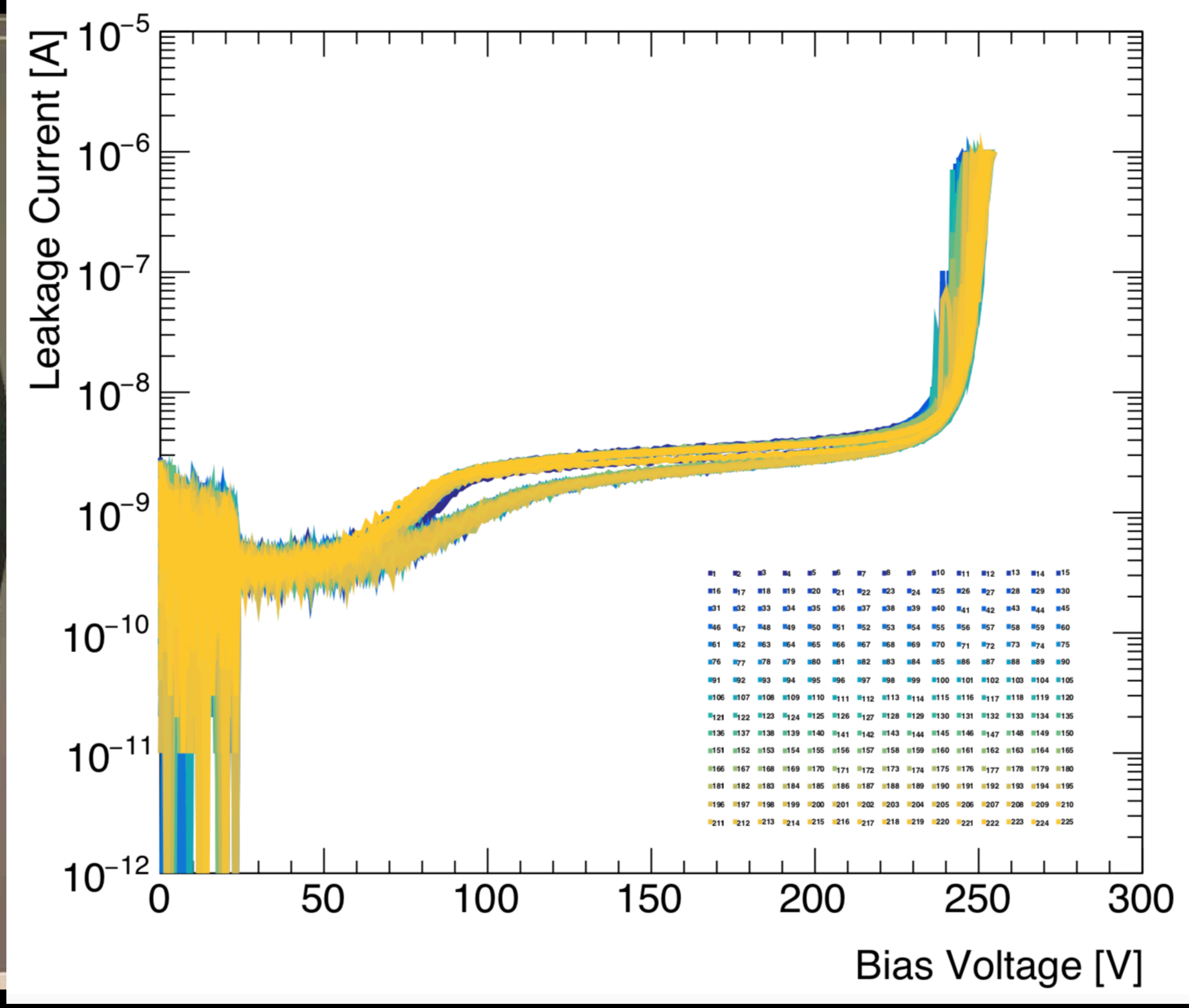
IHEP-IME LGAD wafer



IHEP-IME LGAD wafer
Good yield

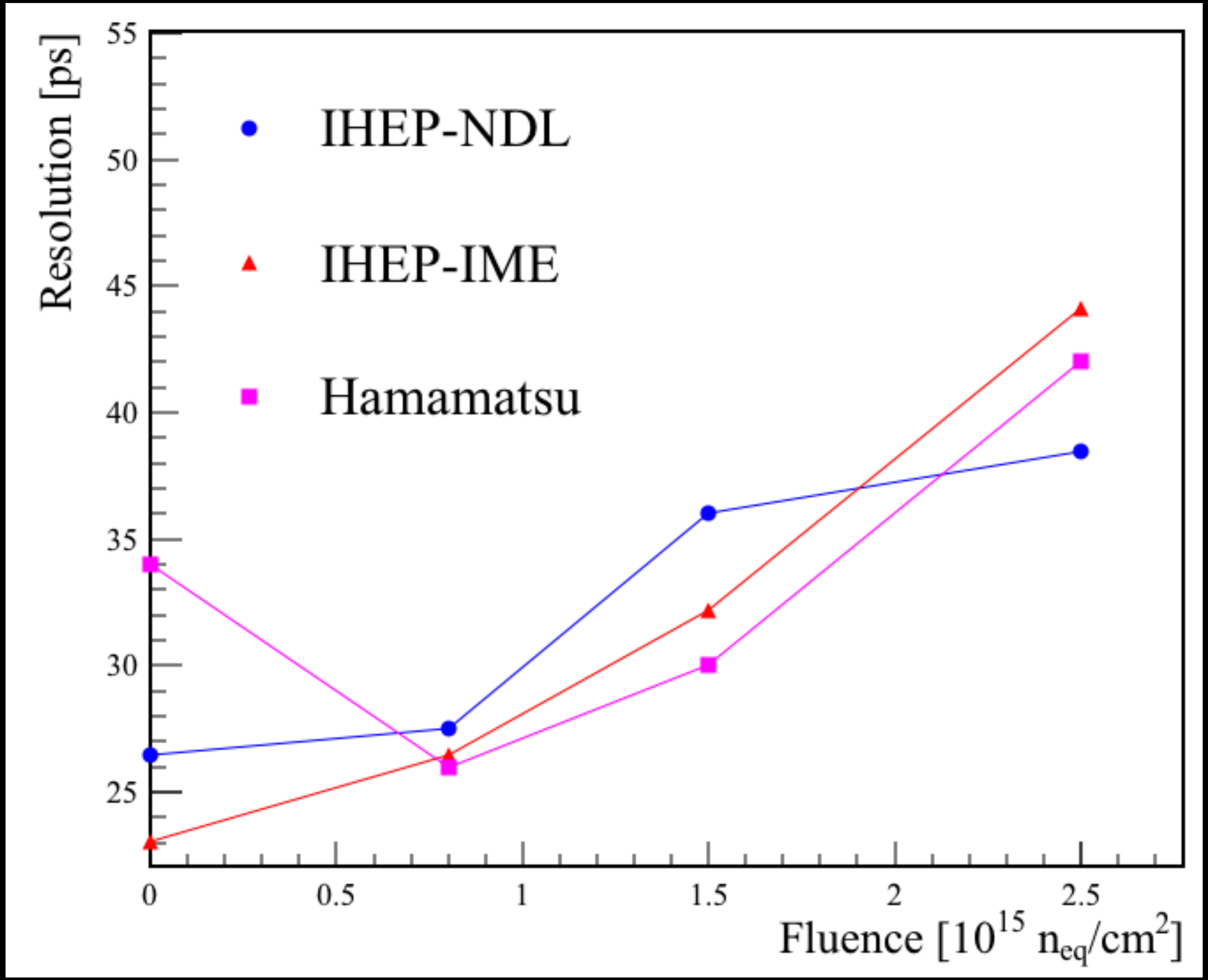


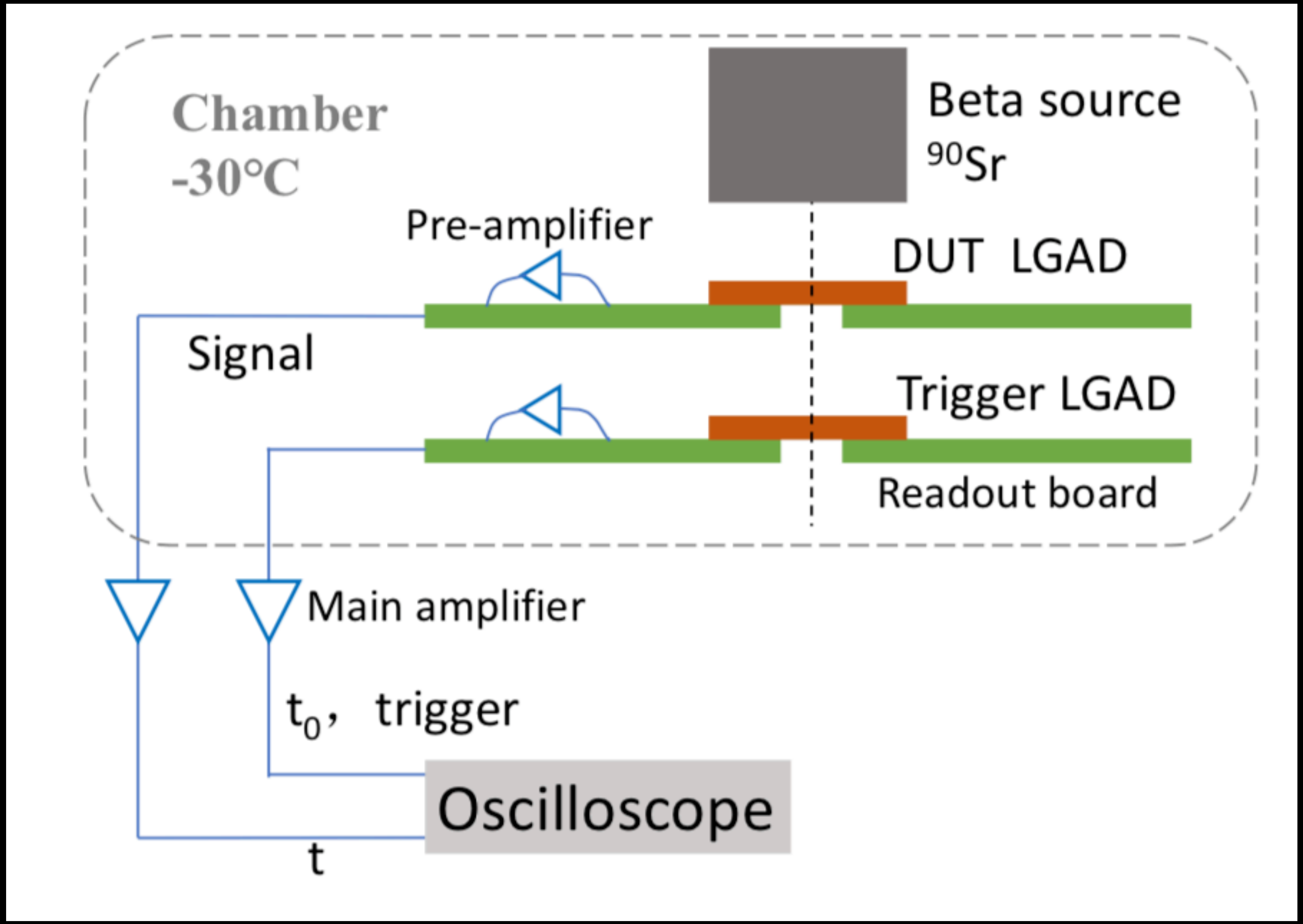
I-V curve for 15*15 LGAD
Good uniformity



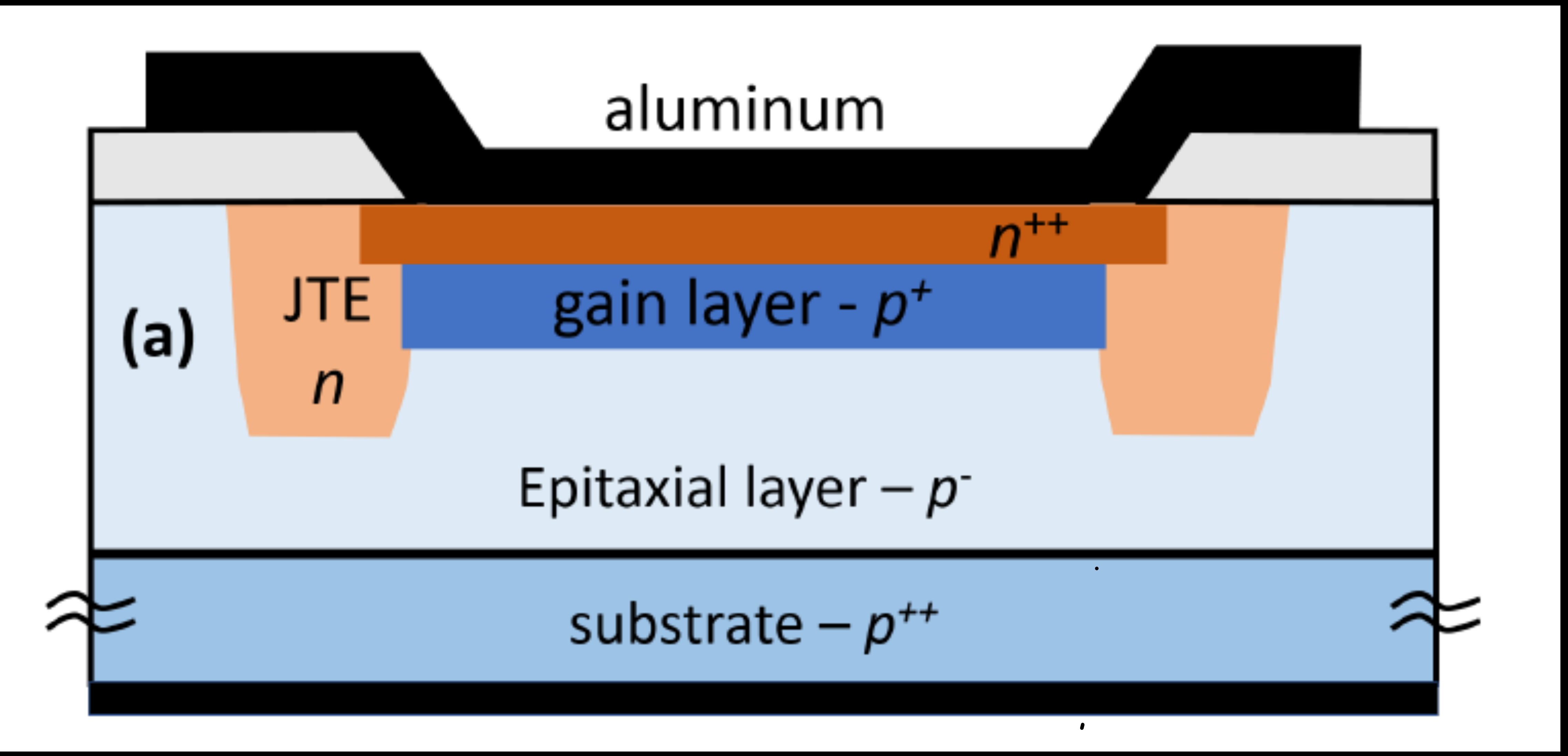
Performance of DC-LGAD developed by IHEP

- Two type of LGAD developed by IHEP (joint R & D for CEPC and ATLAS)
- Can reach 30 ps timing resolution in beta tests before irradiation
- Below 50ps after irradiation after 2.5×10^{15} fluence (HL-LHC requirement)



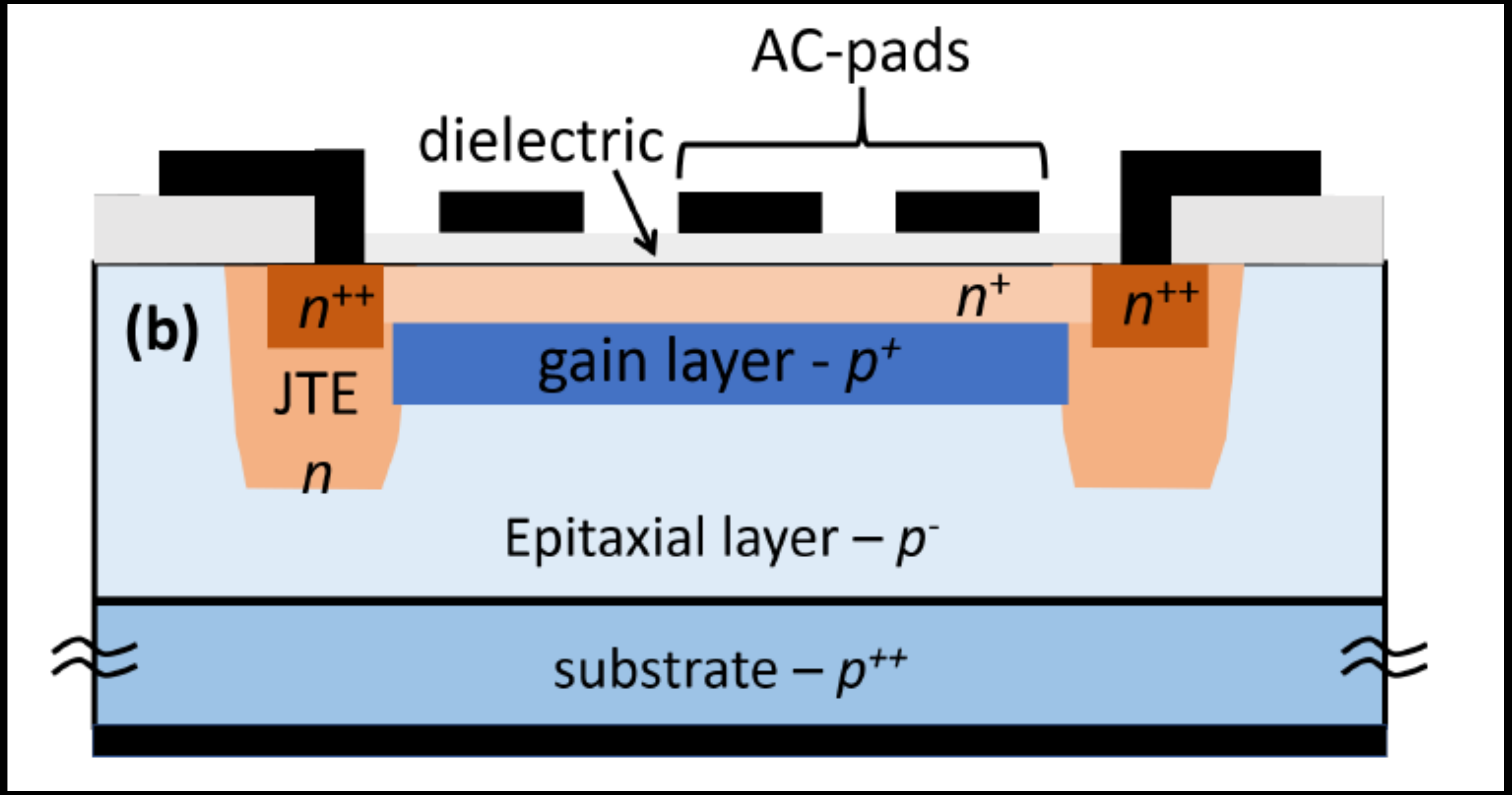


Introduction of Low-Gain Avalanche Detectors (LGAD)



DC-LGAD

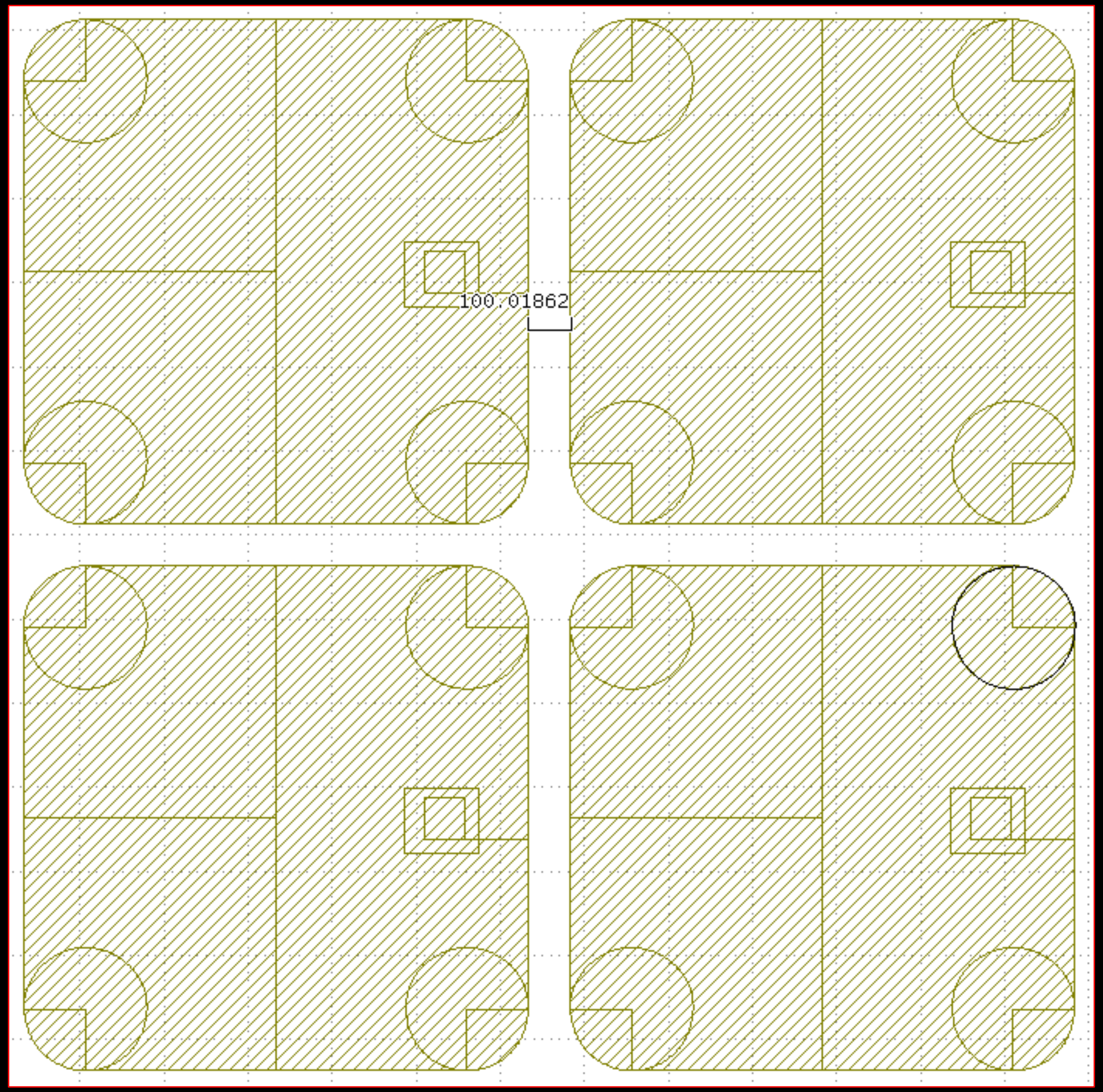
- aAplication: **LHC, CEPC TOF**
- The DC readout
- Time resolution **~ 30ps**
- Position resolution: **~1mm**
- Dead zone : **~ 0.1mm**

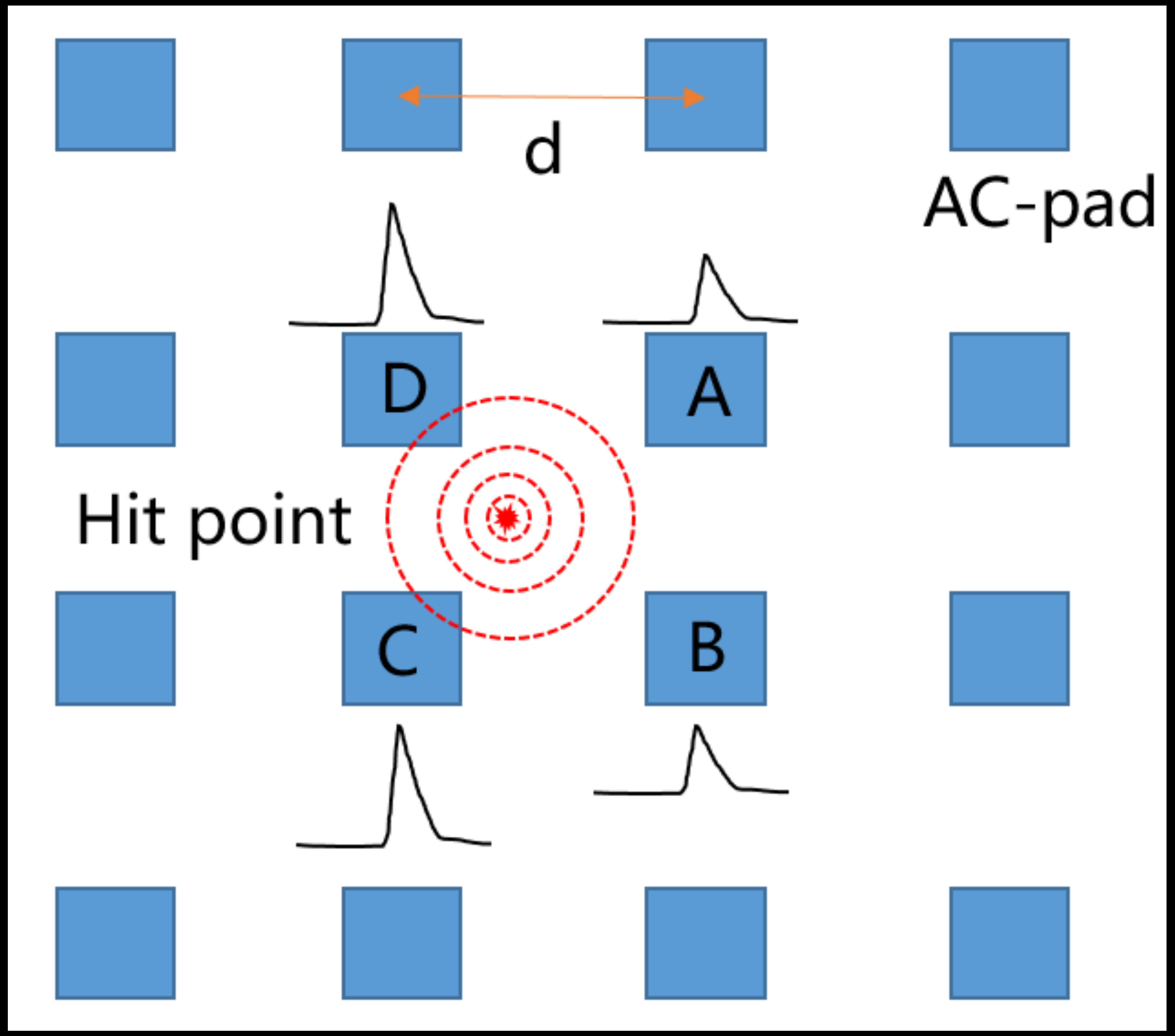


AC-LGAD

- Application: **CEPC TOF +SET (4D tracker)**
- AC coupled readout
- Time resolution **~ 30ps**
- Position resolution: **10-50 um**
- Dead zone : **0 mm (no dead zone)**

Introduction of AC-LGAD (2)





DC-LGAD

- CEPC application: **TOF**
- Cross-talk: no
- Dead zone : **~0.1mm**

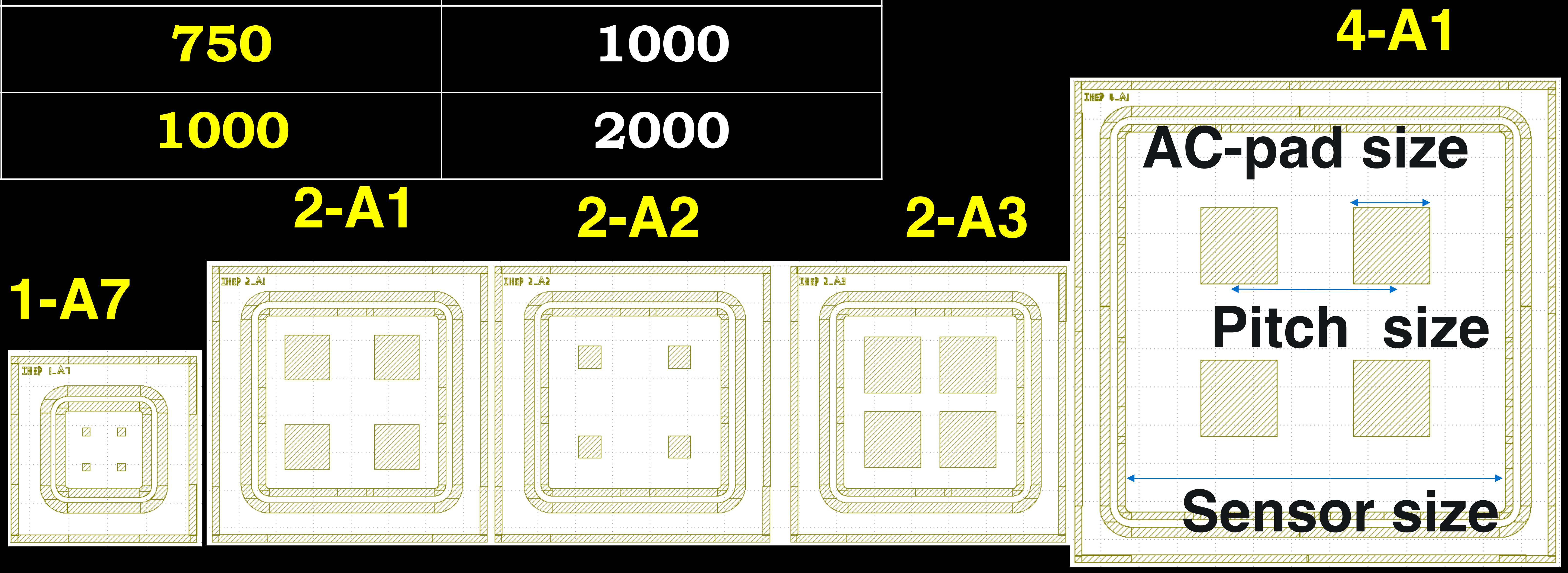
AC-LGAD

- CEPC application: **TOF +SET (4D tracker)**
- Cross-talk: can be adjusted
- Dead zone : **0 mm (no dead zone)**

AC-LGAD prototype for CEPC

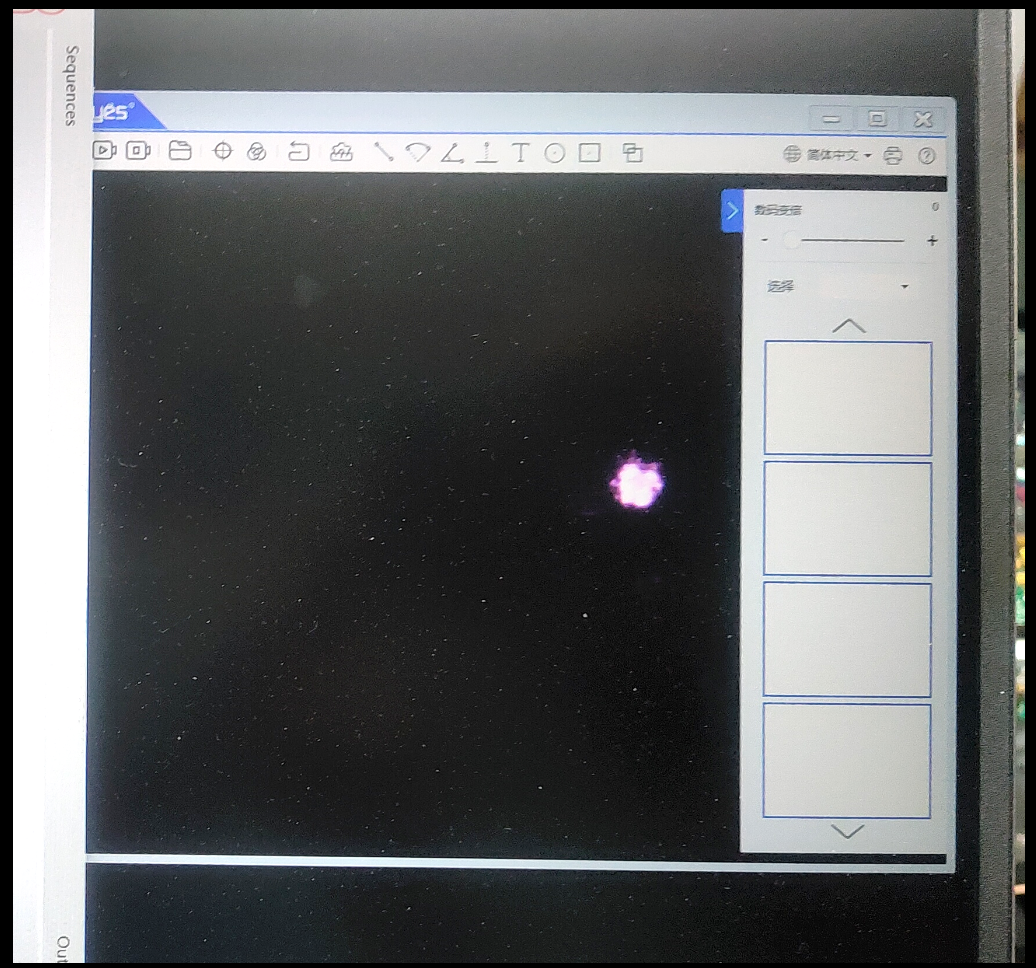
- AC-LGAD first proposed by INFN in RD50, and first fabricated by FBK.
- First AC-LGAD prototype in China by IHEP-IME in 2021.
- Try different sensor geometry

Sensors	Sensor size [μm]	AC-pad size [μm]	Picth size [μm]
1-A7	1000	100	450
2-A2	2000	300	1200
2-A1	2000	600	1200
2-A3	2000	750	1000
4-A1	4000	1000	2000

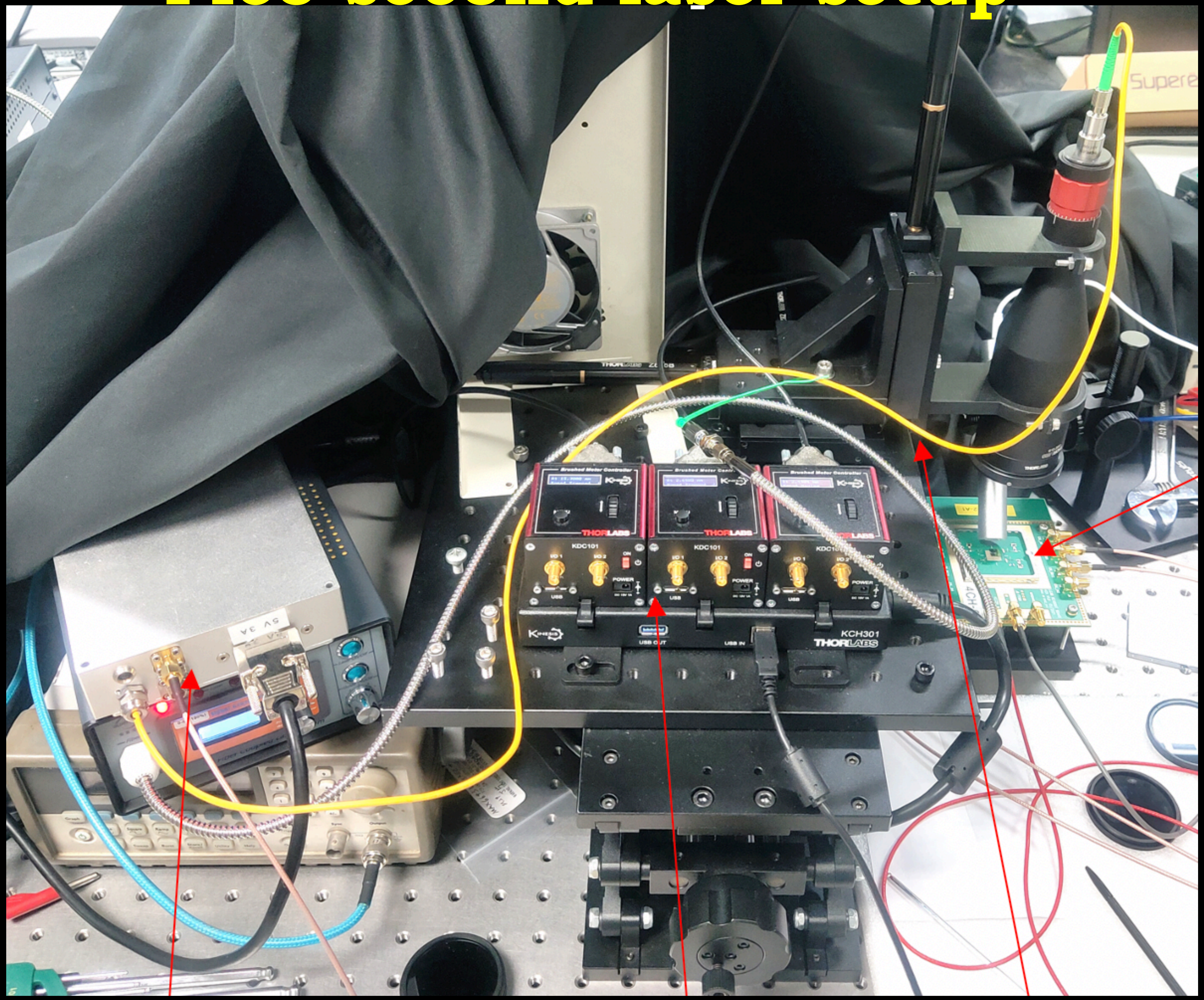


Laser testing for AC-LGAD

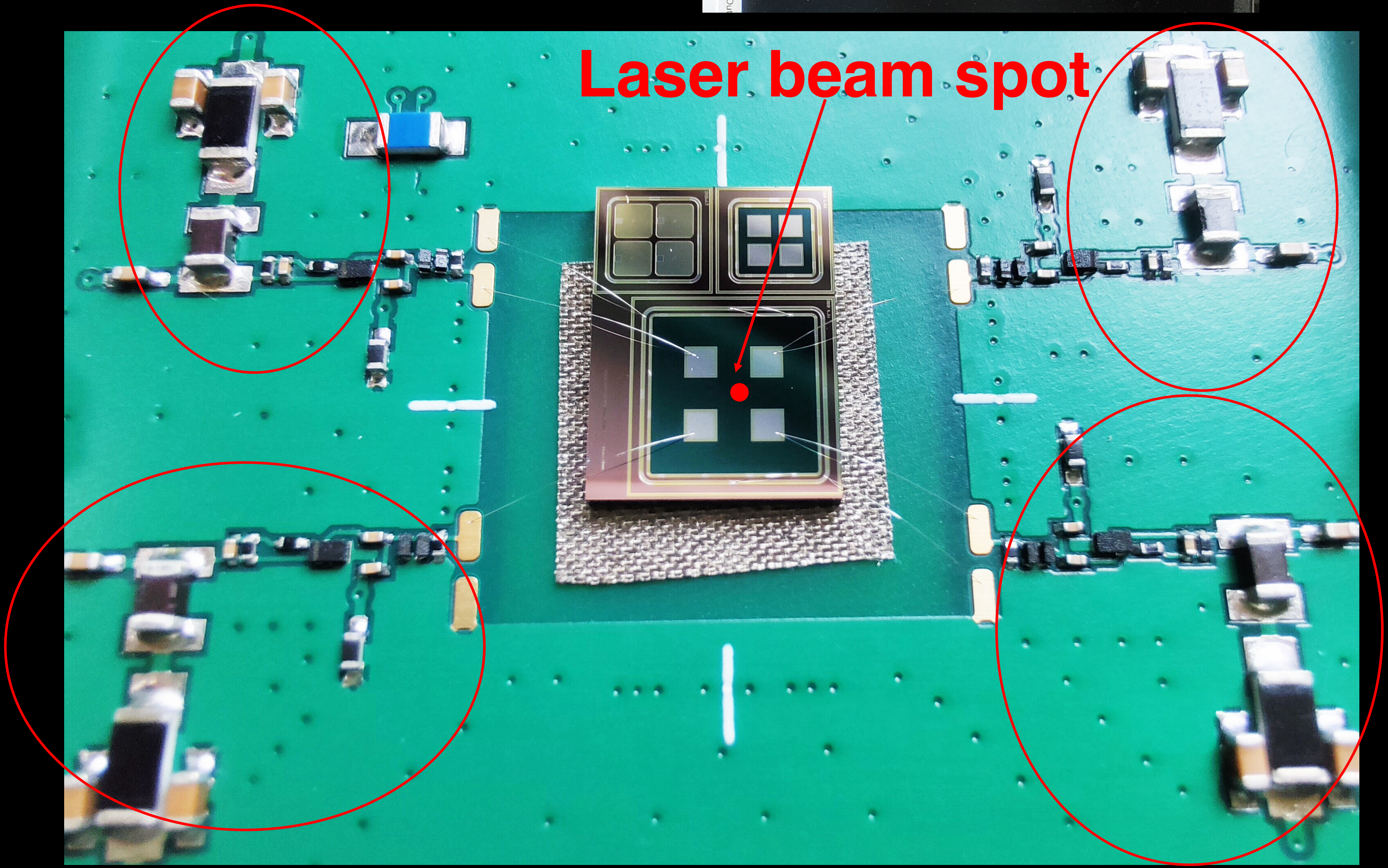
- **Pico-second laser testing for AC-LGAD**
- **4 channels readout board with fast amplifiers (~2GHz)**
- 3D X-Y-Z stage platform (precision : ~1um)



Pico-second laser setup



X-Y-Z platform



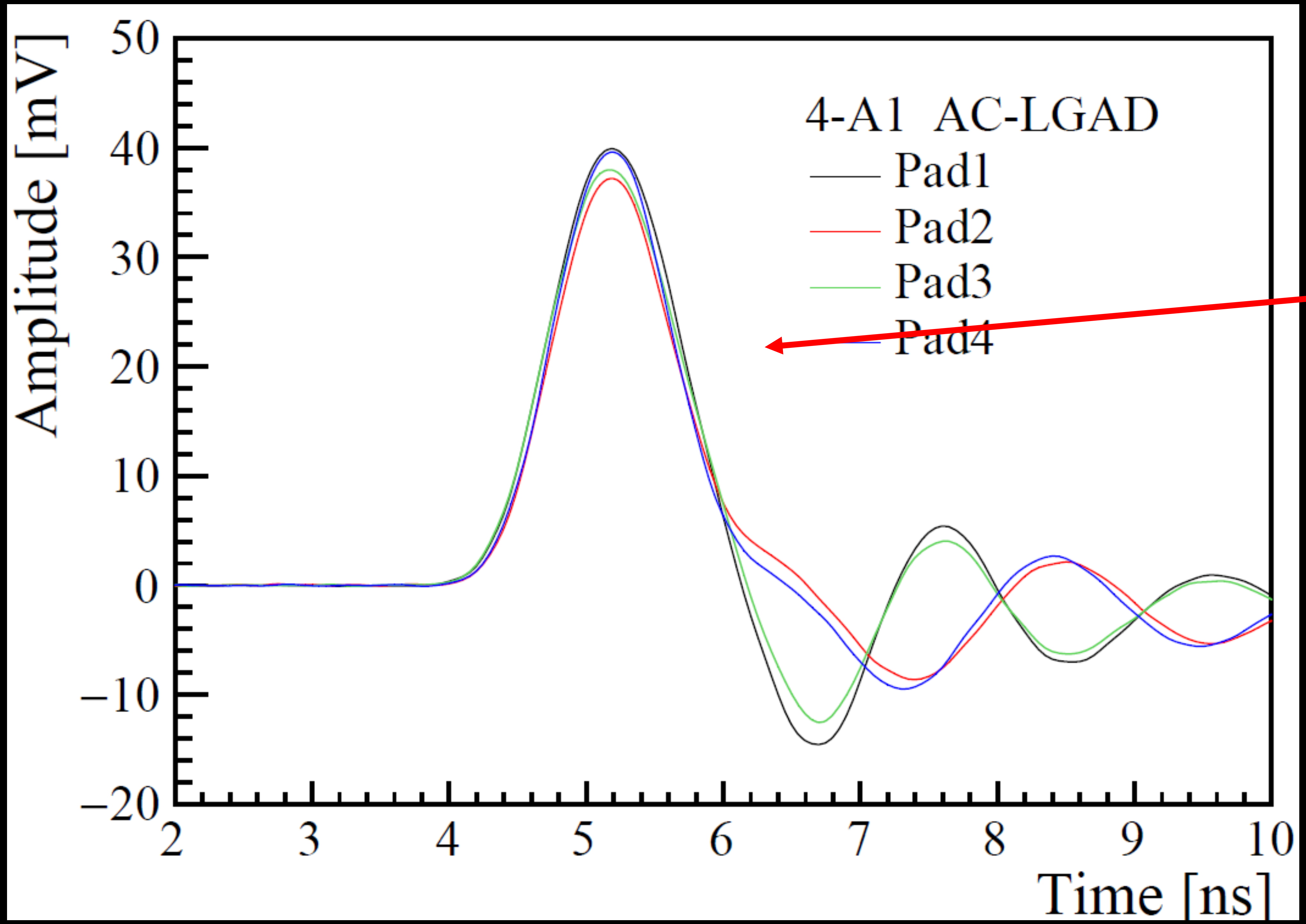
4 channels fast readout board

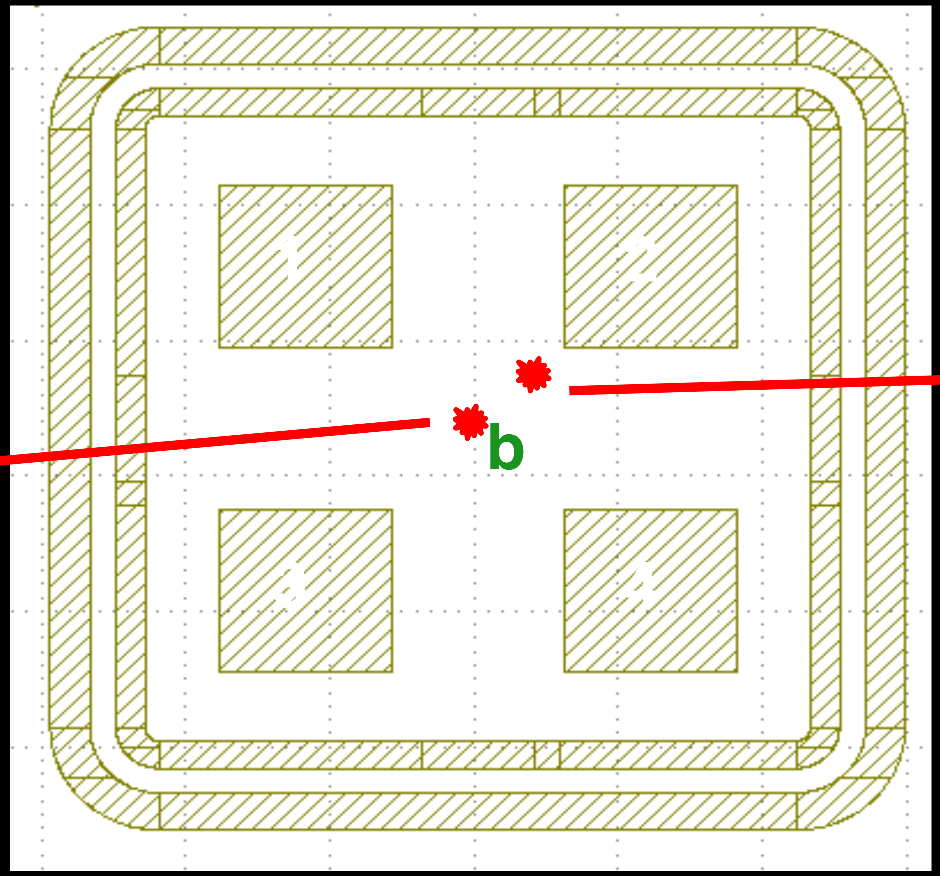
Laser testing for AC-LGAD

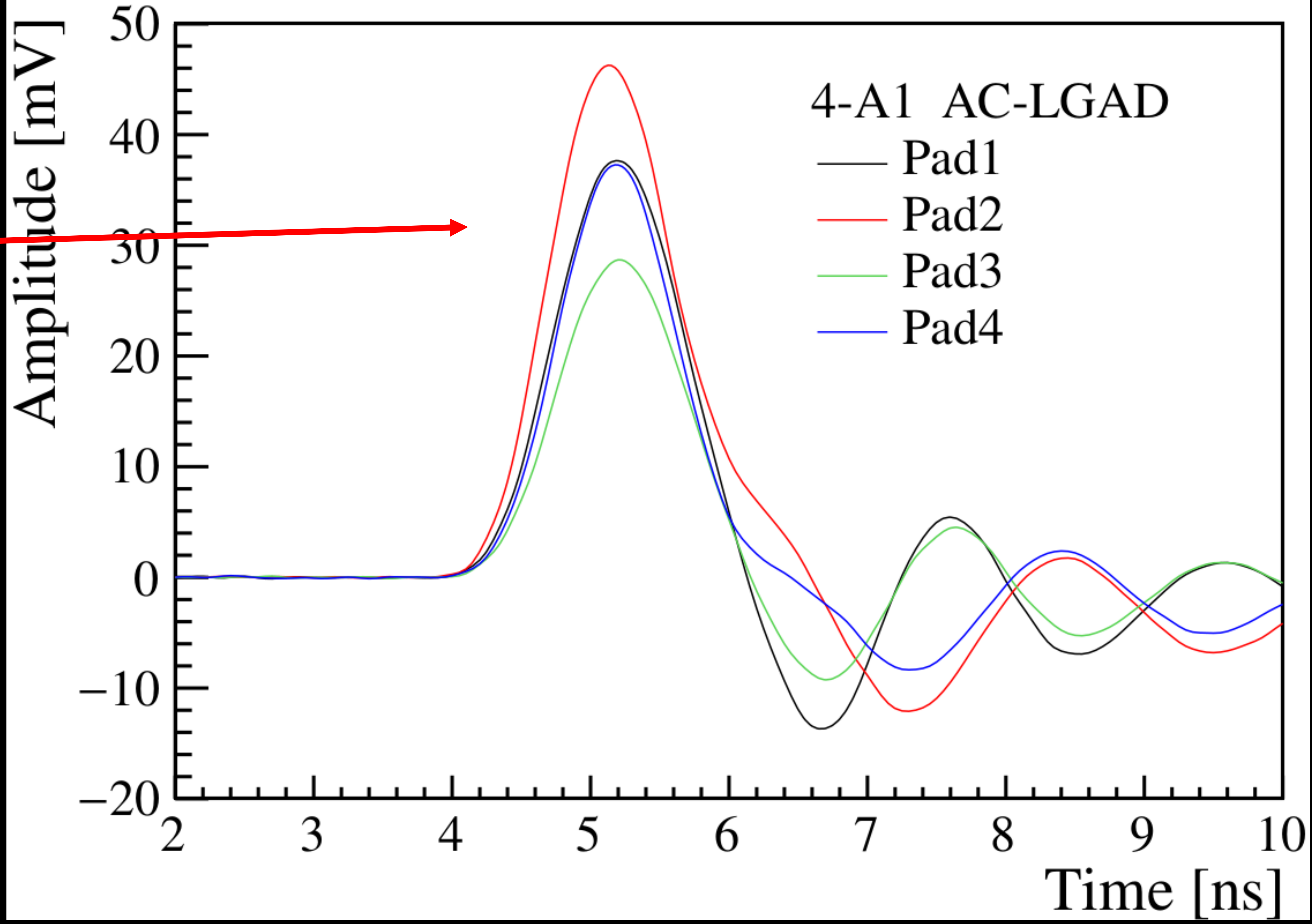
- **Pico-second laser testing for AC-LGAD**
- **4 channels readout board with fast amplifiers (~2GHz)**
- 3D X-Y-Z stage platform (precision : ~1um)
- the ballistic deficit of the signal is smaller in large AC pads

Laser shooting in the middle
4 channels has similar signal amplitude

Laser shooting in the upper right
Upper right channel has larger amplitude

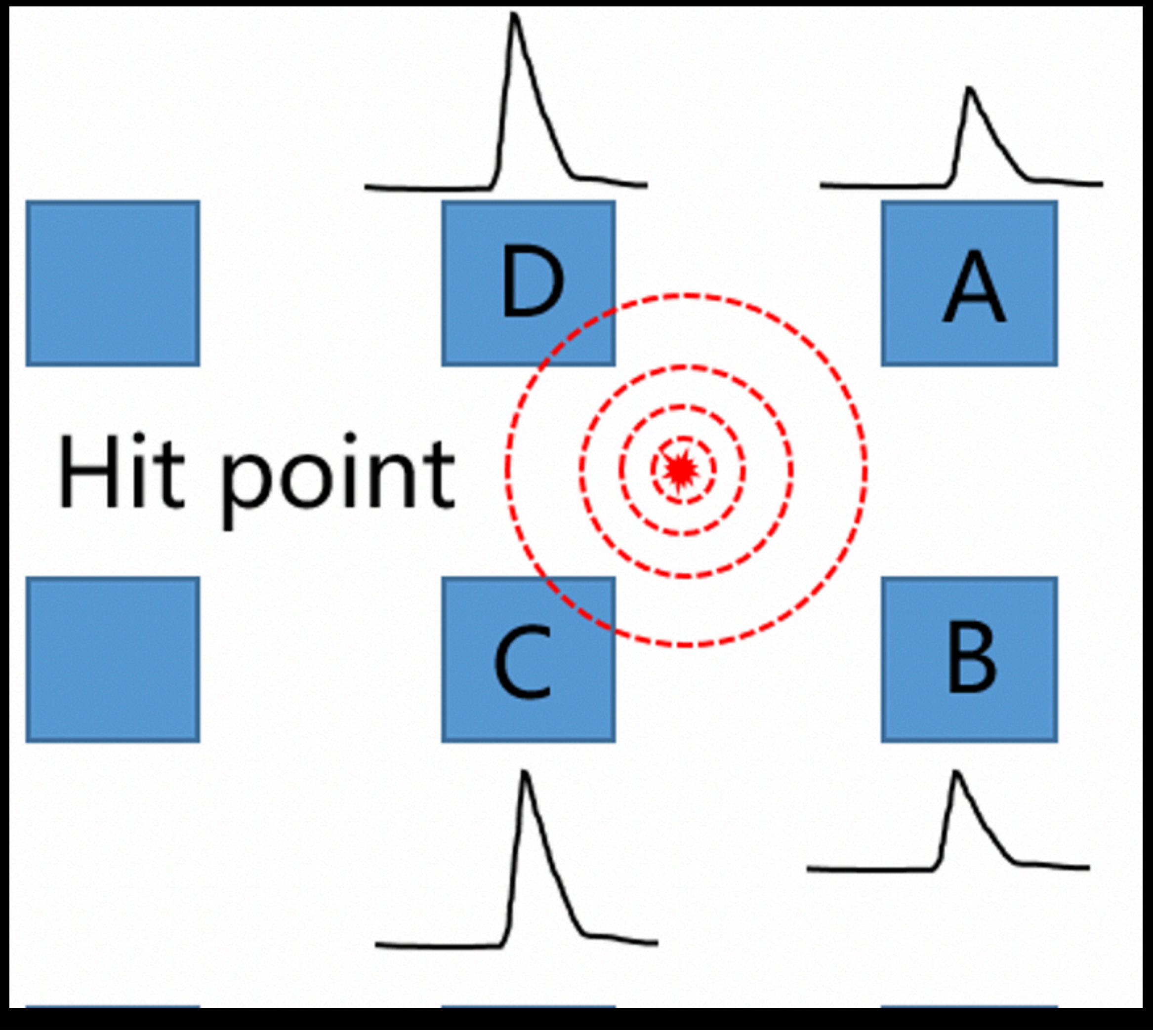






Laser testing for AC-LGAD： Readout and spatial reconstruction

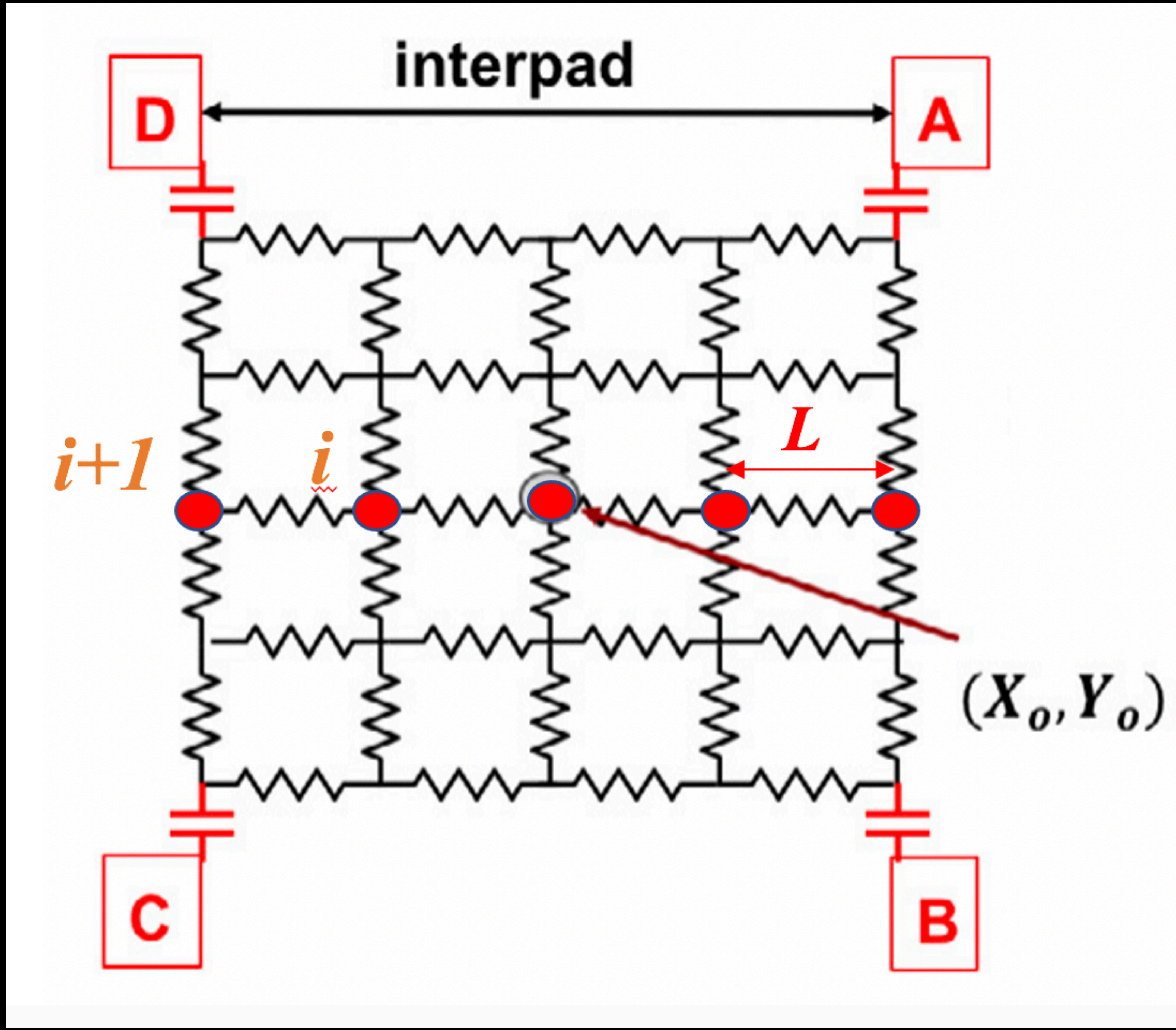
- **Position reconstruction by Discretized Positioning Circuit model (DPC)**
- **Input is 4 channels signal amplitude**



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

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

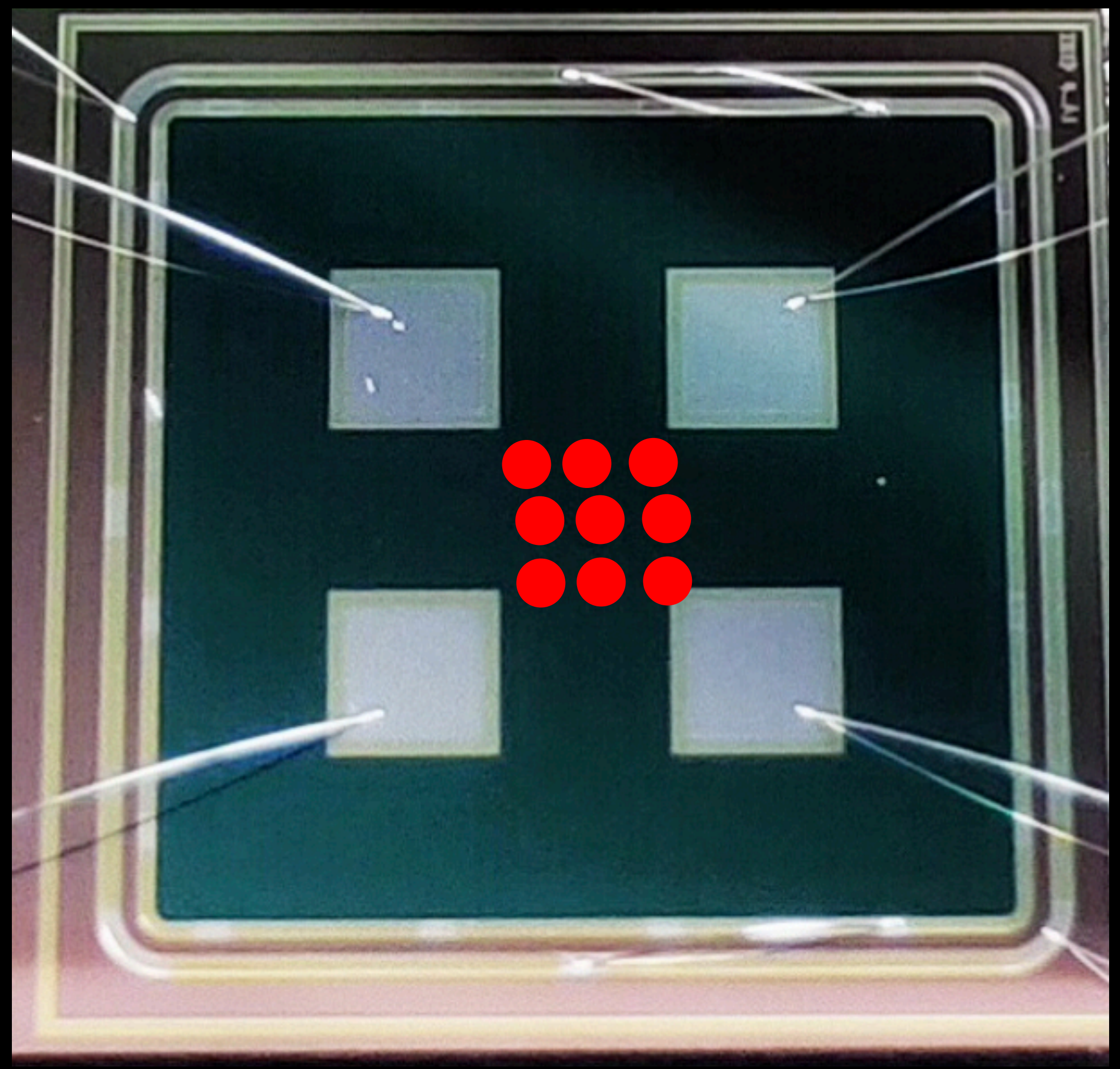
$$k_x = L\frac{\sum(m_{i+1} - m_i)}{\sum(m_{i+1} - m_i)^2} \qquad k_y = L\frac{\sum(n_{i+1} - n_i)}{\sum(n_{i+1} - n_i)^2}$$

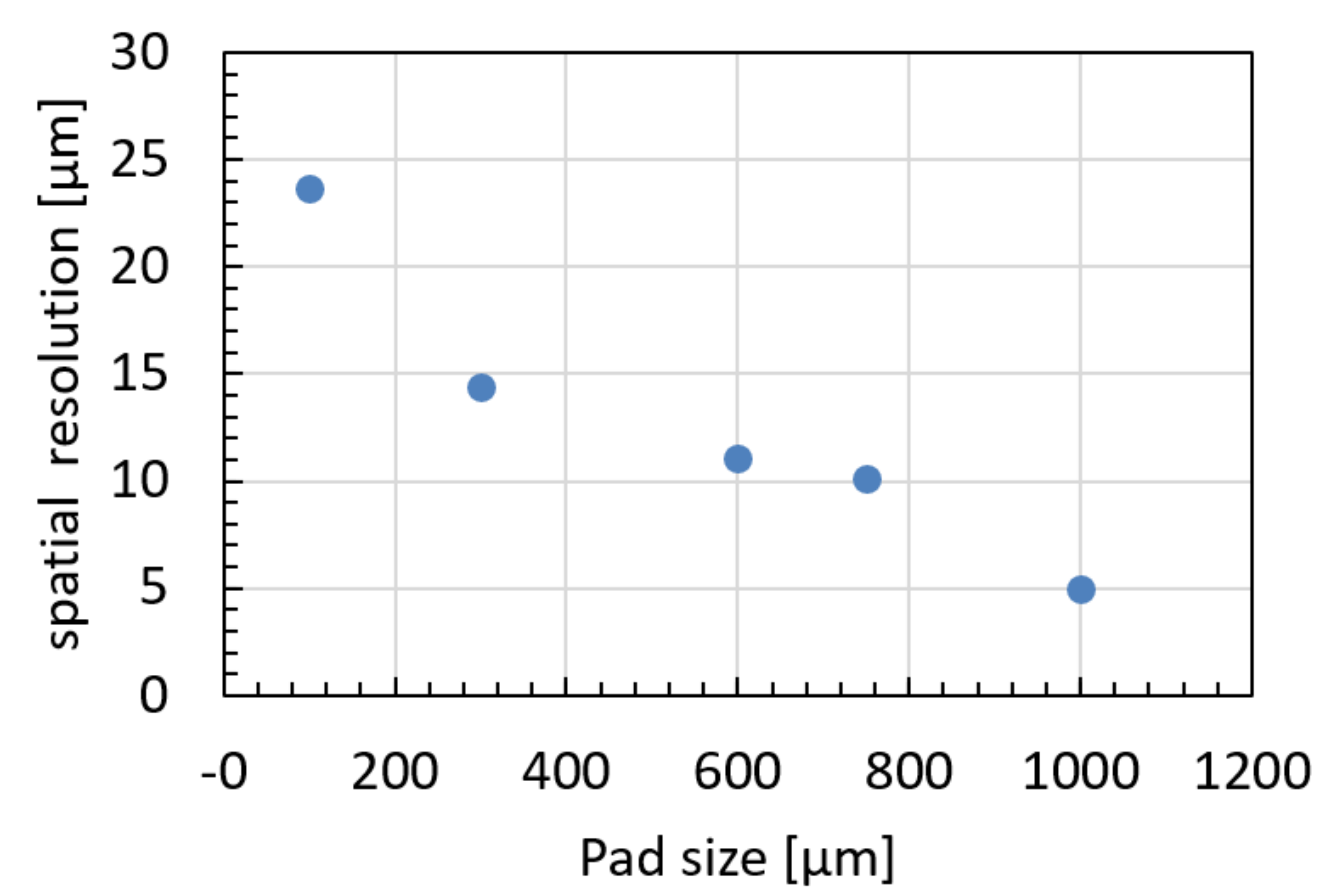


Laser testing for AC-LGAD: spatial resolution

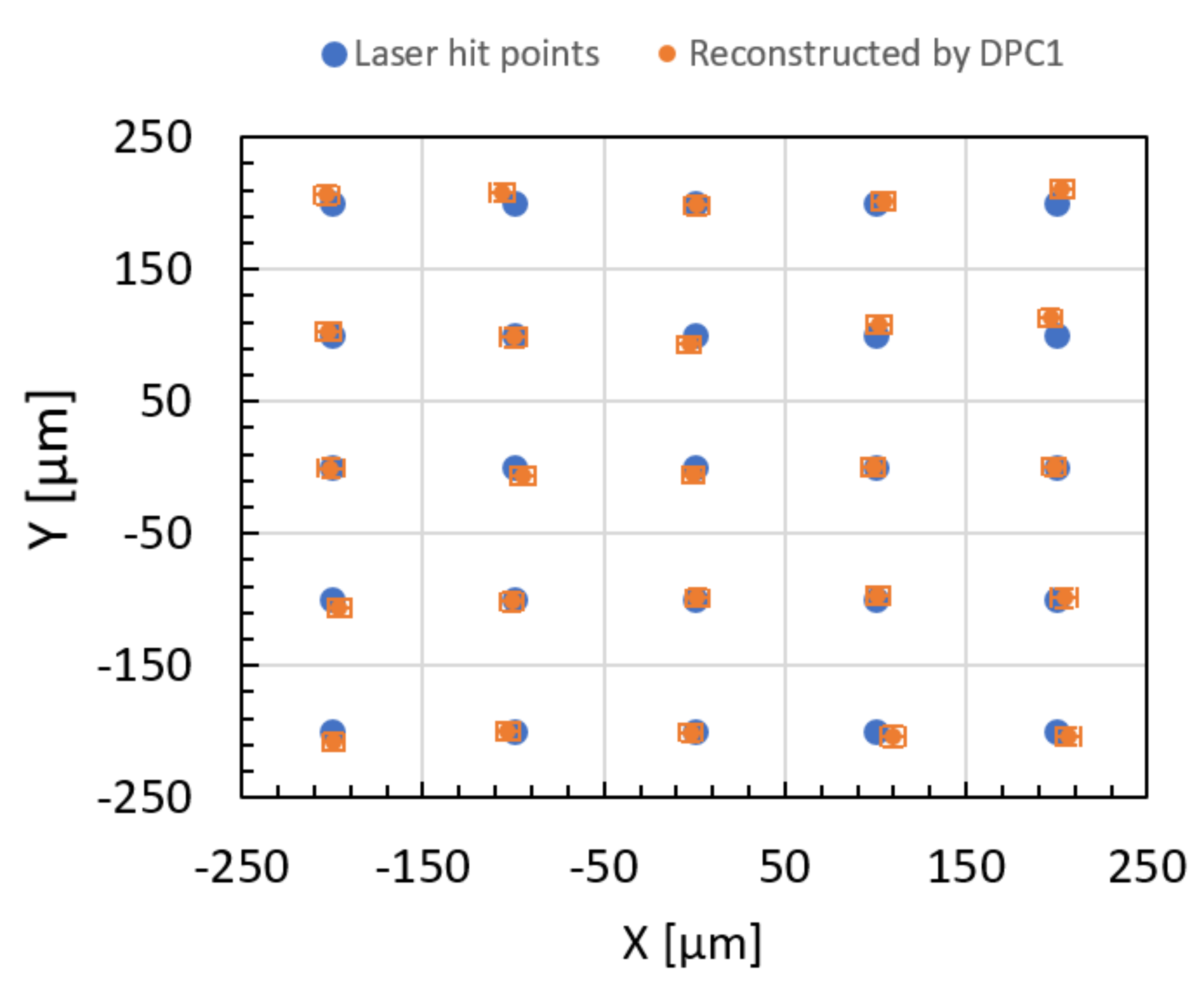
- **The larger the AC-pad, the better the position resolution.**
- the ballistic deficit of the signal is small in large AC pads
- The best resolution can reach 5μm （4-A1）

Sensors	Sensor size [μm]	AC-pad size [μm]	Picth size [μm]
4-A1	4000	1000	2000





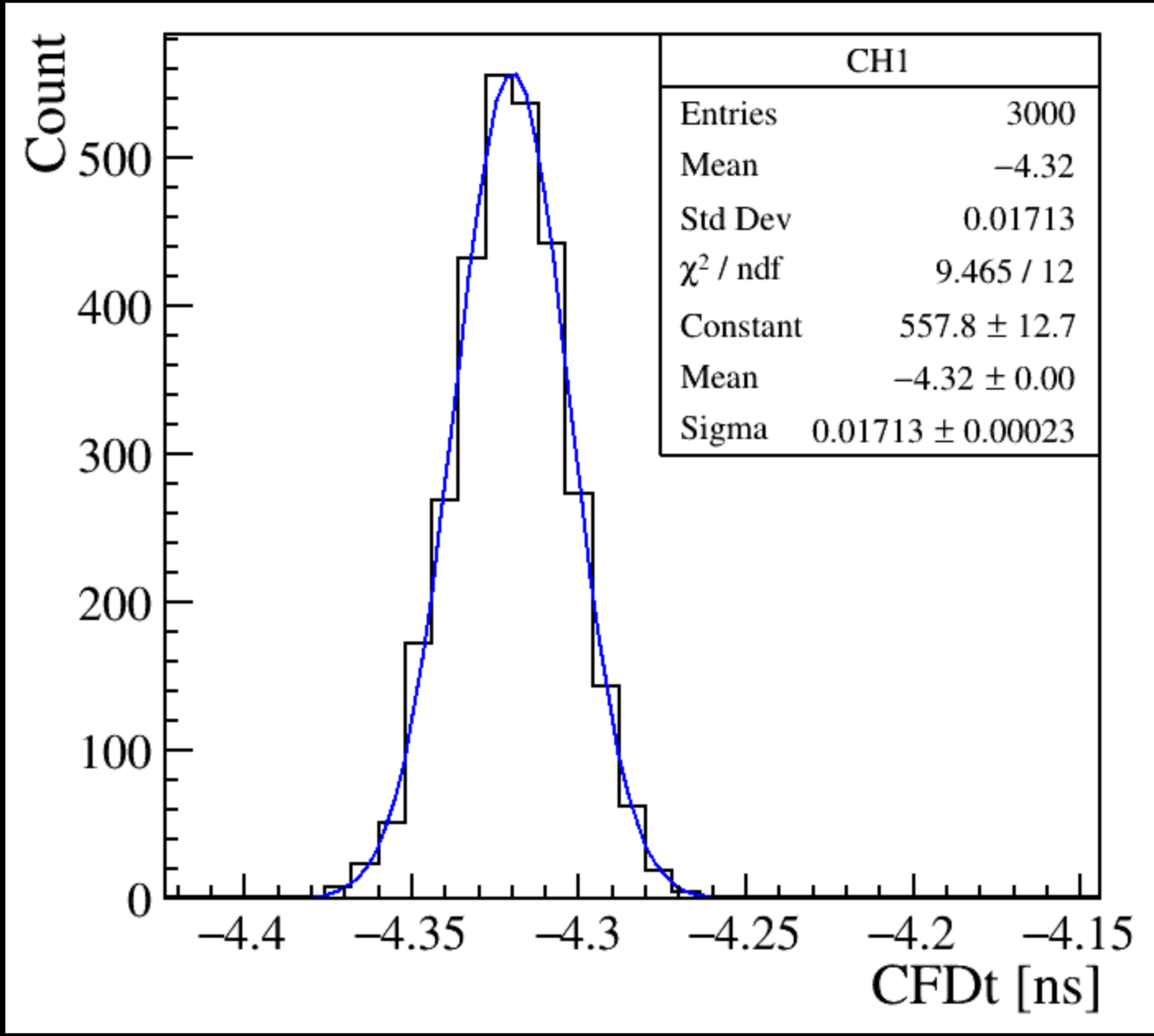
hit position vs Reconstructed position



Laser testing for AC-LGAD: timing resolution

- The timing resolution is about 15-17 ps
- Almost no difference for different size of the pads

Arrival time distribution



Sensors	Timing resolution (ps)
1-A7	15
2-A2	16
2-A1	17
2-A3	17
4-A1	17

Summary

- DC-LGAD is joint CEPC TOF+ ATLAS HGTD R & D
- First full wafer prototyping runs (IHEP-IME)
- Full-size LGAD sensors (2×2 cm) with reasonable yield

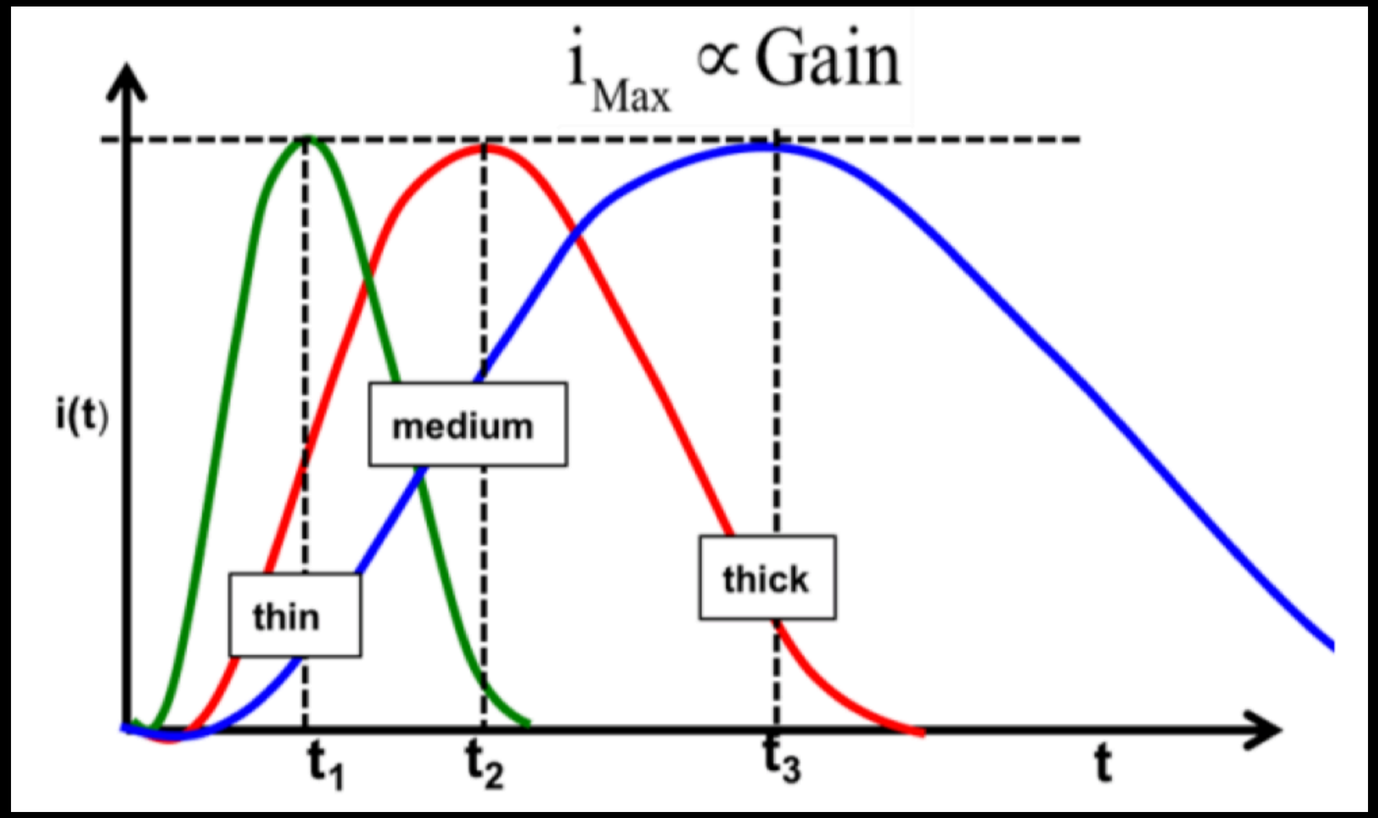
- AC-LGAD is a new 4D detector （position + time）
- First AC-LGAD prototype by IHEP is successful
- Picosecond laser test and reconstructed by DPC model
- The best spatial resolution ~5μm
- Timing resolution ~17ps （Laser test）

Low-Gain-Avalanche-detector

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

Landau Noise term:

- Signal fluctuation due to non-uniform charge deposition
- Minimized by reducing thickness of the sensor (50um)

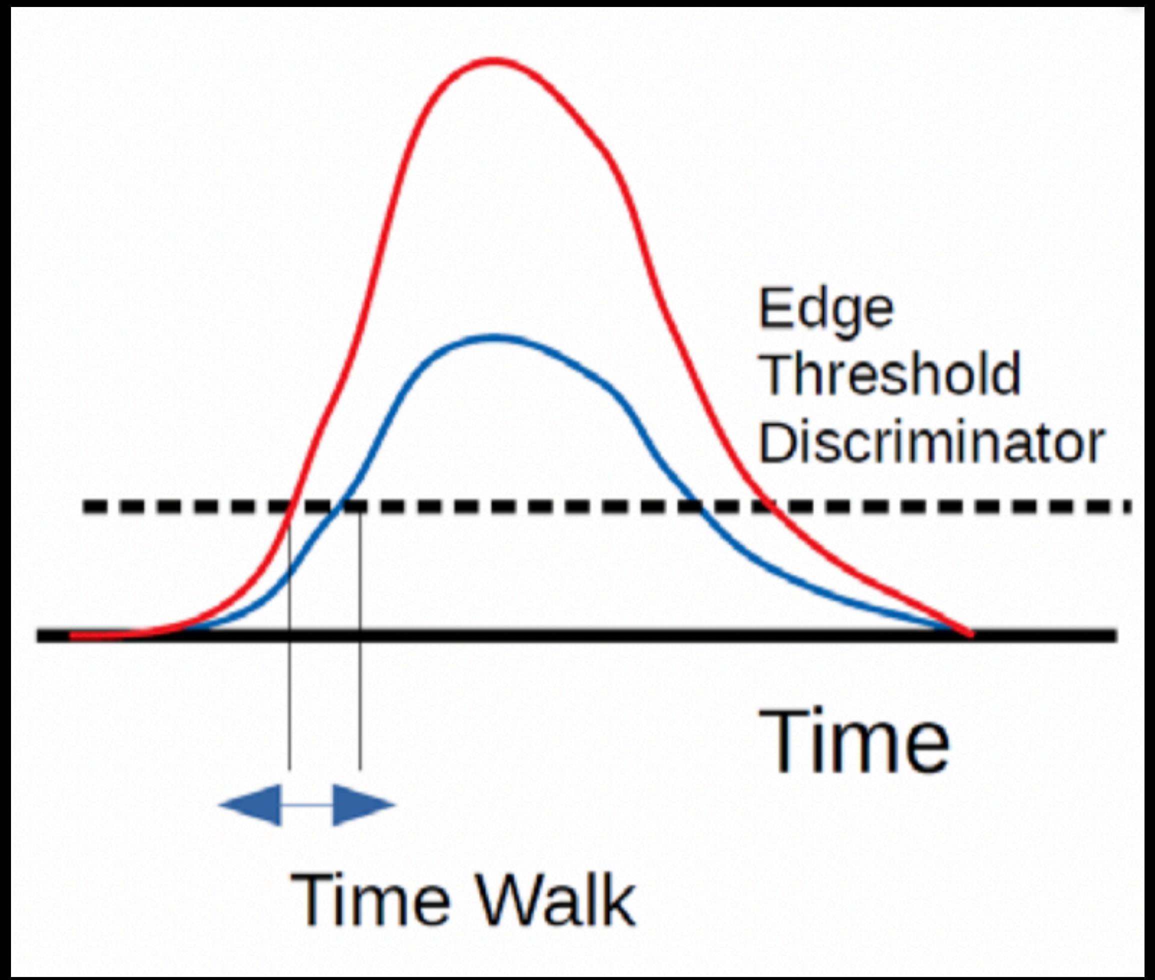


$$\sigma_{jitter}^2 = \left(\frac{t_{rise}}{S/N}\right)^2$$

Jitter

- Need gain to increase S/N
- Need thin detector to decrease t_{rise}

fixed threshold



$$\sigma_{timewalk}^2 = \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{\mathrm{RMS}}\right)^2$$

Time walk

- corrected using the amplitude estimate with the time over threshold (TOT).

[1] G. Pellegrini et al., NIM A765 (2014) 12
[2] H.-W. Sadrozinski et al., arXiv: 1704.08666
[3] F. Cenna et al, NIM A796 (2015) 149-153

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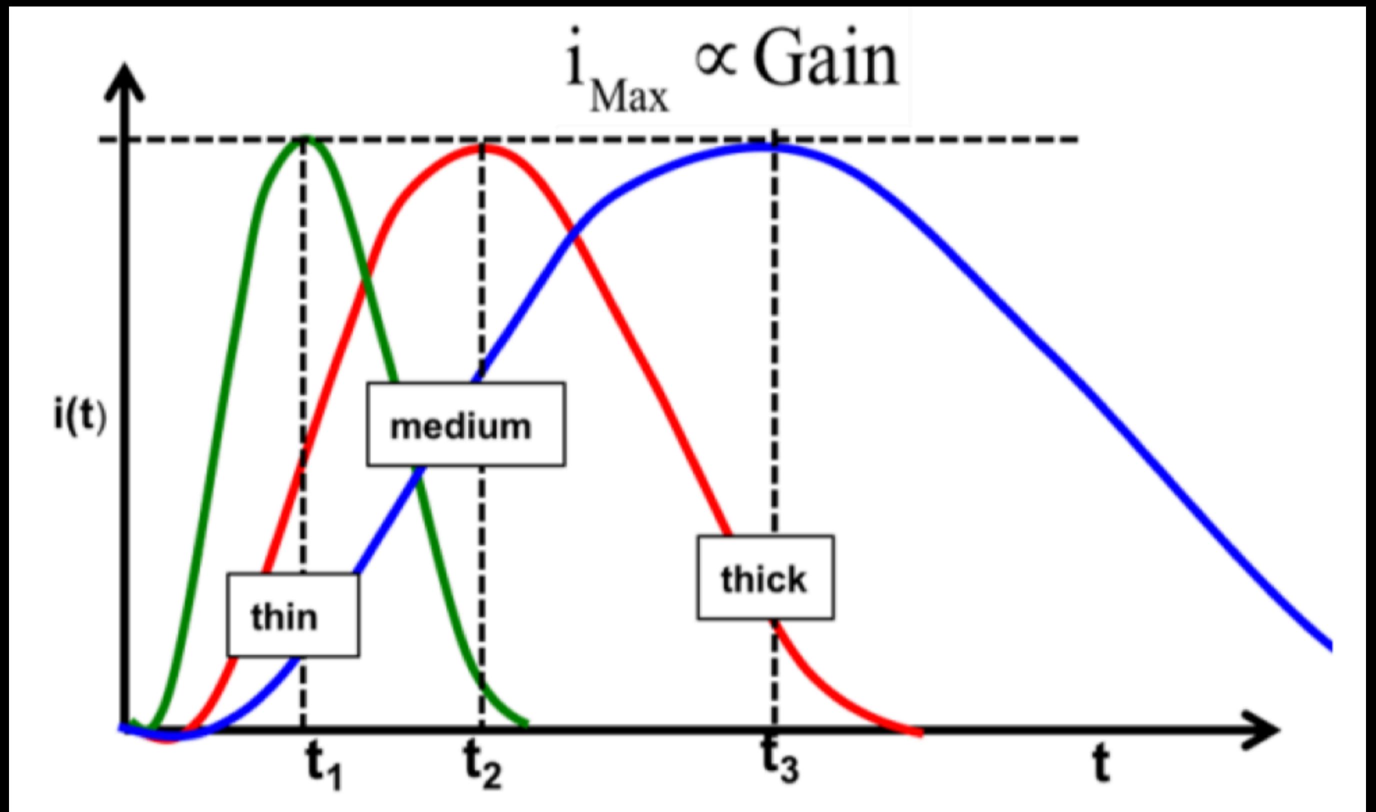

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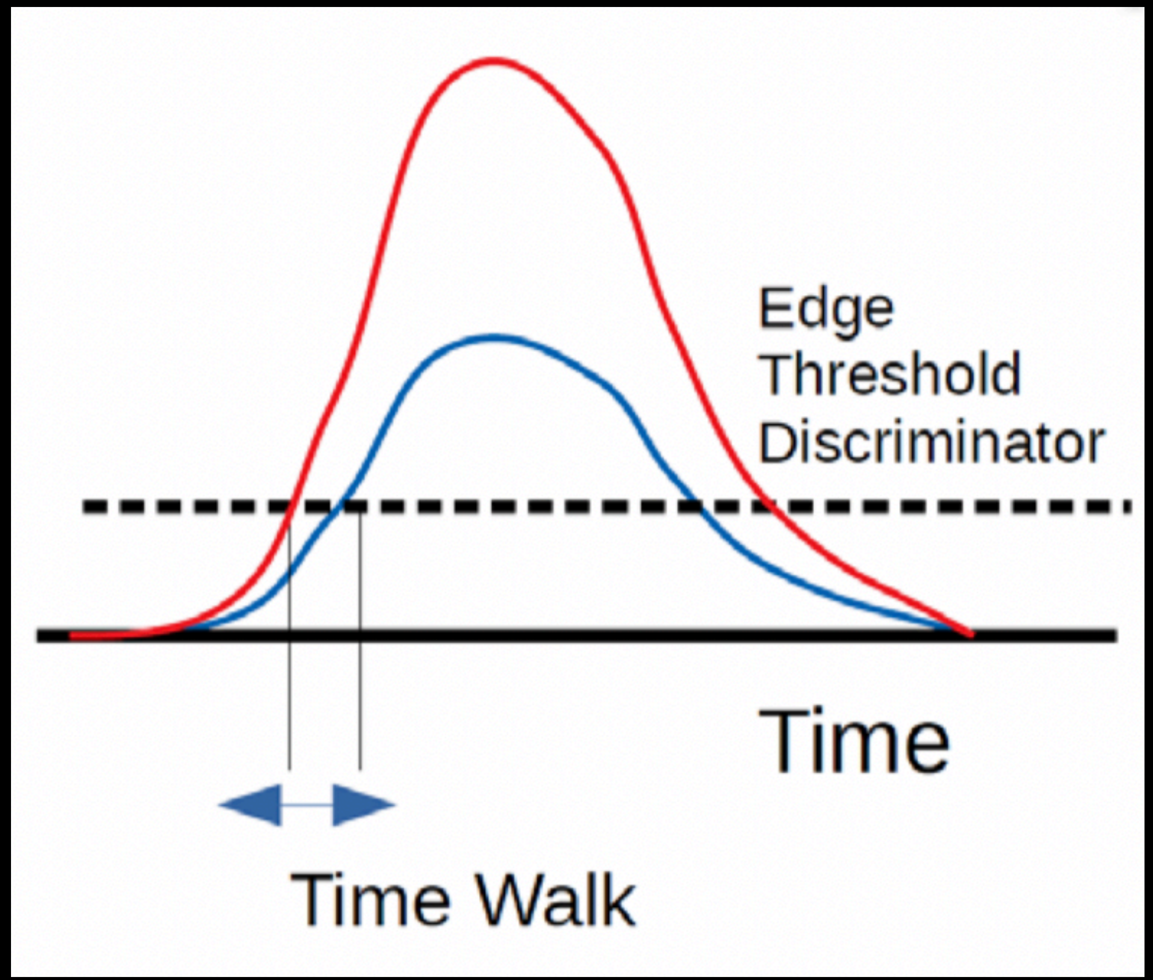

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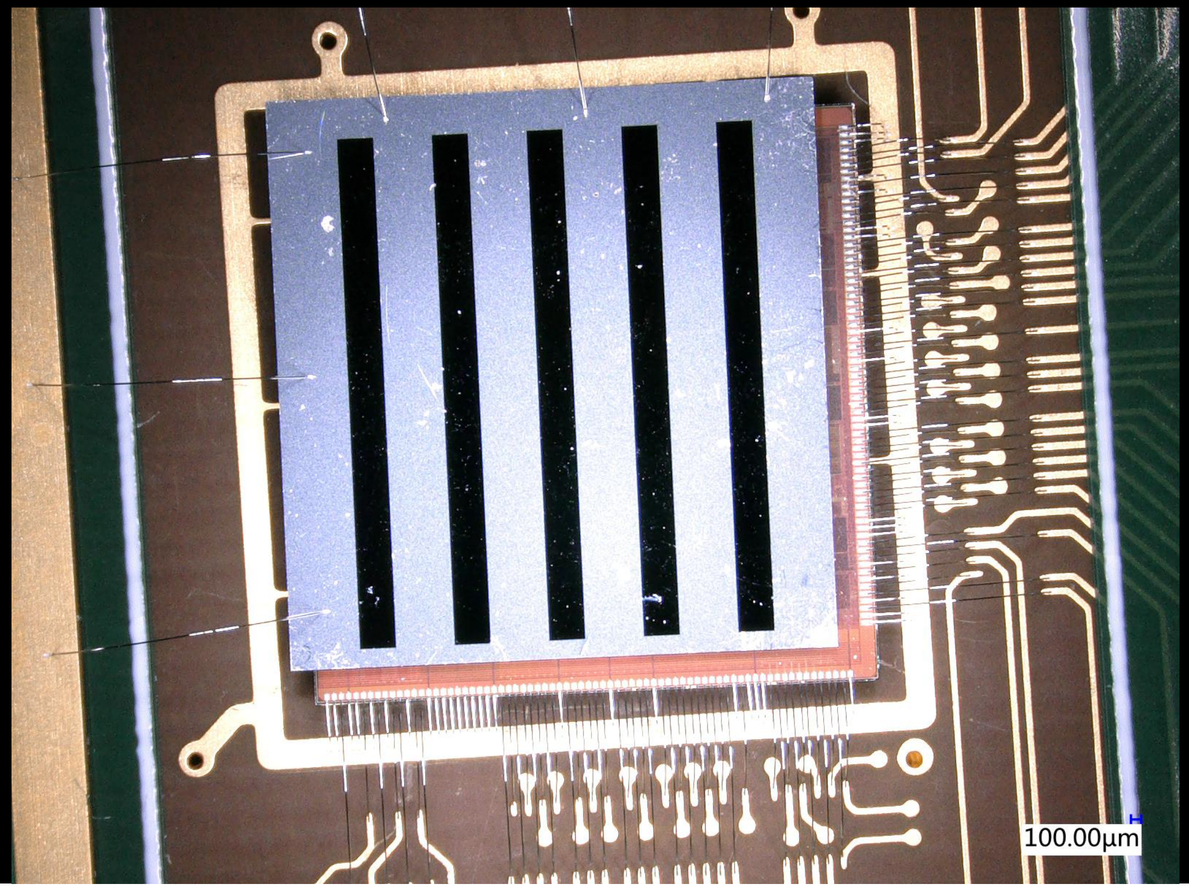
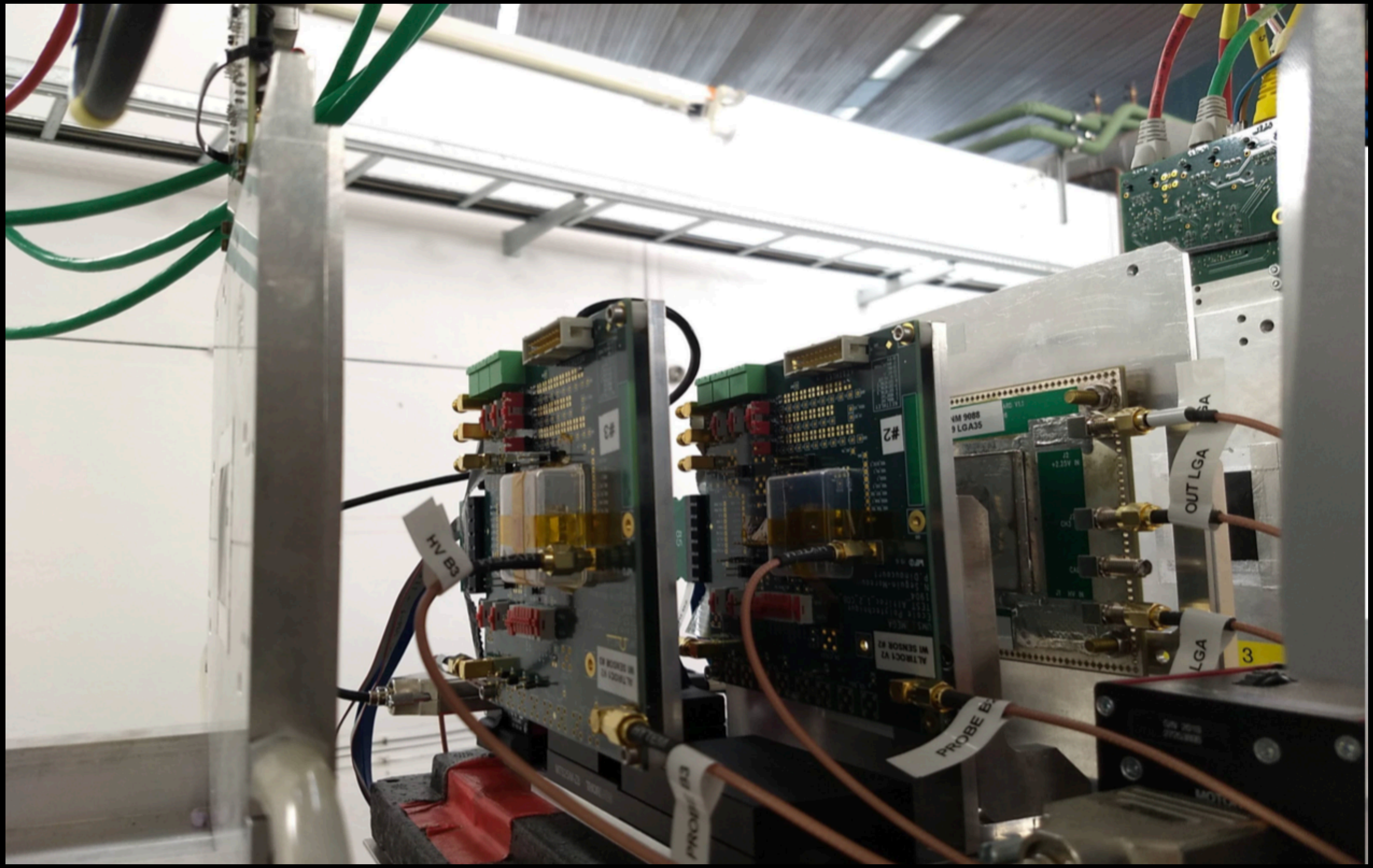
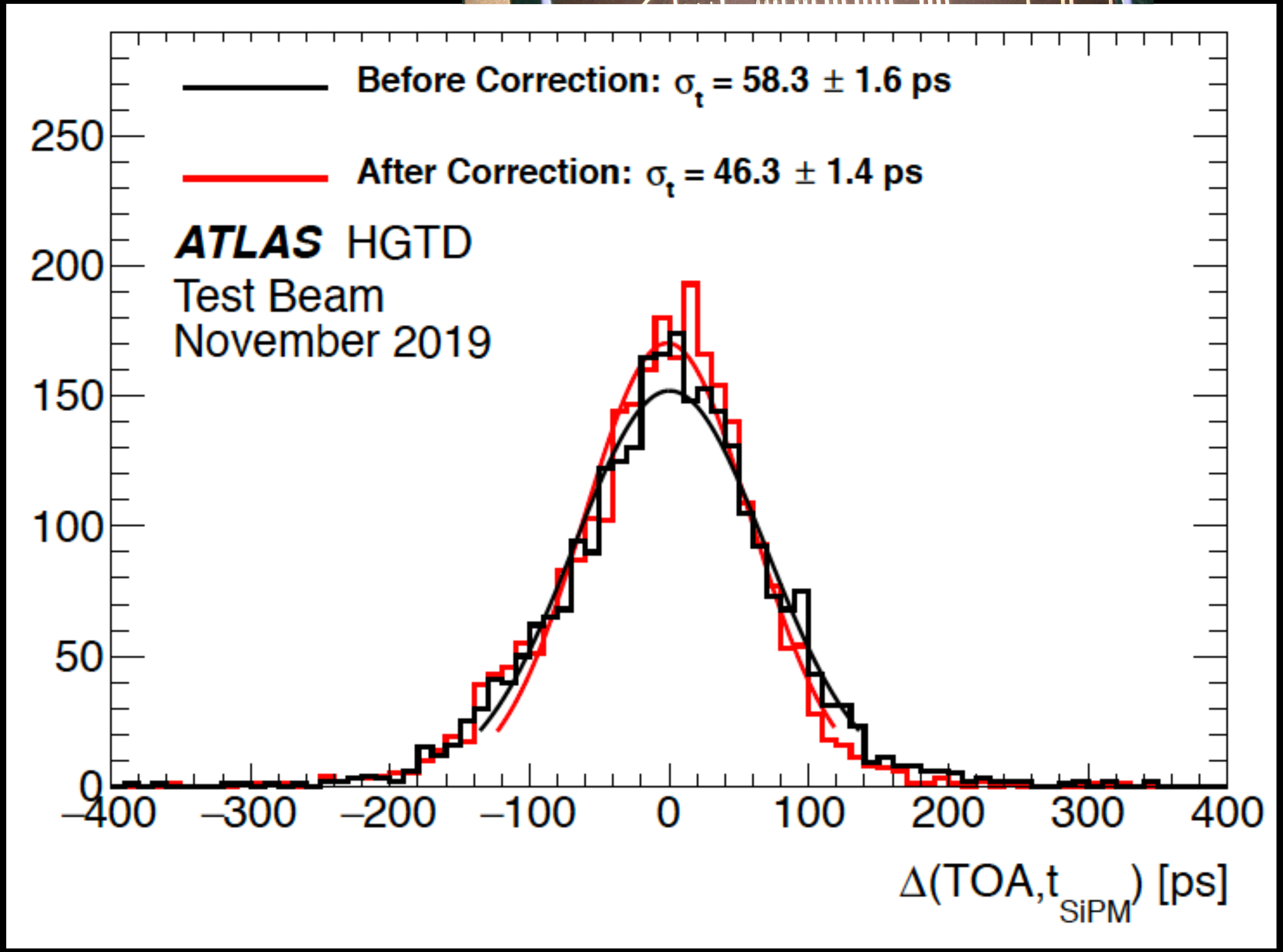
Outlook: Testbeam with ATLAS HGTD module



- **Time resolution: 45ps**
- **Position resolution: ~1mm**
- **Area : 6.5mm*6.5mm --> (2cm*4cm)**





CEPC timing detector : Concept

- **Each module size : ~5cm * 15cm**
- **Further optimization is on going**