Development of Pixelated Capacitive-Coupled LGAD (ACLGADpix) Detectors

Koji Nakamura (KEK)

on behalf of AC-LGAD Japan Collaboration

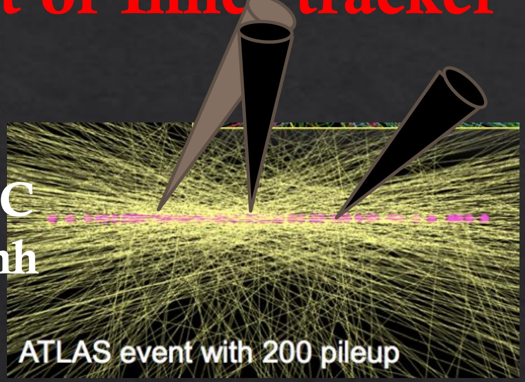
Challenge of the real 4D tracking detector

- Multiple interaction in an event at
  - HL-LHC : 140-200 collision in an event,
  - Future collider: 1500 !
- How to solve this issue?
  1. ***Improve granularity*** : Current ATLAS&CMS HL-LHC detector : 50um pitch pixel detector and hard to make smaller (data transmission limitation)…
  2. ***Timing information***: New information for tracking : Potential drastic improvement of track reconstruction →Should help if timing resolution achieved 1cm/c ~ **30ps**

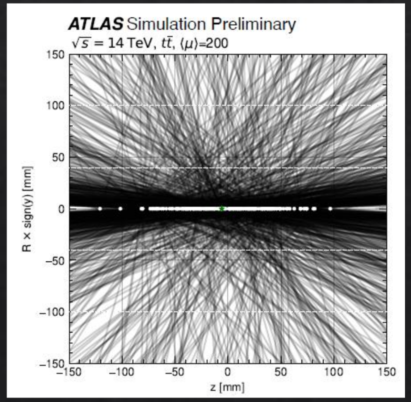
Improvement of Inner tracker

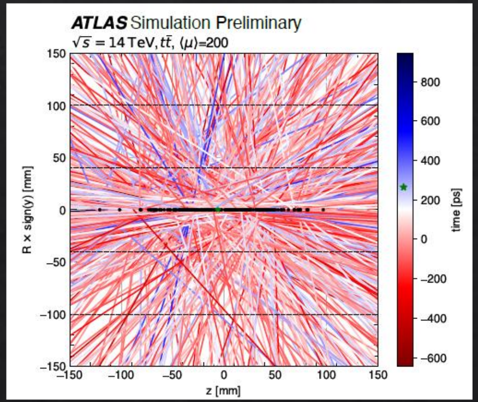
Very dense tracks

140 pileup @ HL-LHC
1500 pileup @ FCC-hh



4D tracking !





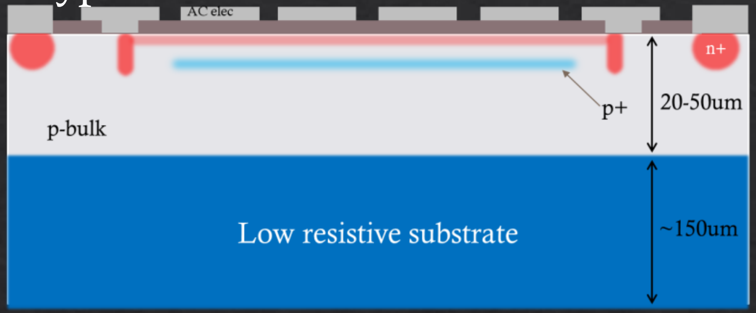
Final Goal : replace all tracking detector with timing capability

Timing silicon detector & AC-LGAD

- **We didn't have o(10)ps timing capability MIP particle detector 10 years ago.**
- World wide LGAD detector R&D started around 2015
  - **Low Gain Avalanche Diode (LGAD) detector**
  - Hamamatsu Photonics K.K. can produce LGAD detector in Japan!

AC-LGAD technology make break through improvement

Typical AC-LGAD structure



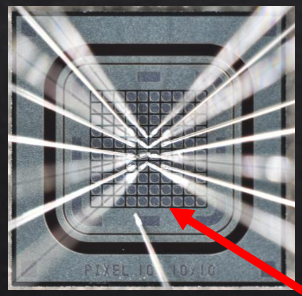
First prototype in 2015

remarkable improvement

- **Spatial resolution**
- **Timing resolution**
- **Understanding Radiation hardness**

Recent prototype (in 2022)

ACLGADpix detector



1mm

In Pad Type (500um pitch) :

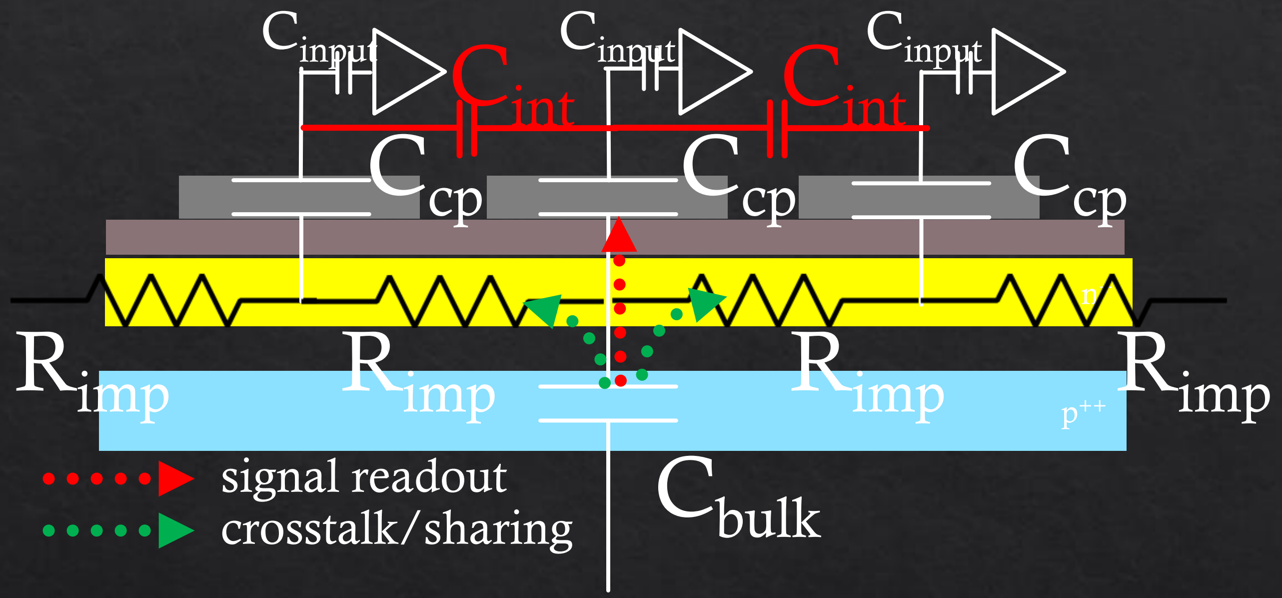
20ps timing resolution achieved

Pixel size :
100µm x 100µm
(50µm x 50µm)

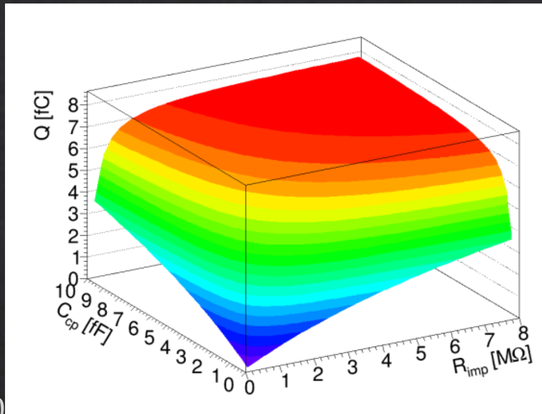
Today's presentation

AC-LGAD sensors

- **Read out principle of AC-LGAD**



◈ Charge split : Impedance ratio



Assuming Z_{Cbulk},Z_{cint}>>Z_{Ccp}…

$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$

◈ Amount of produced charge:Q_0

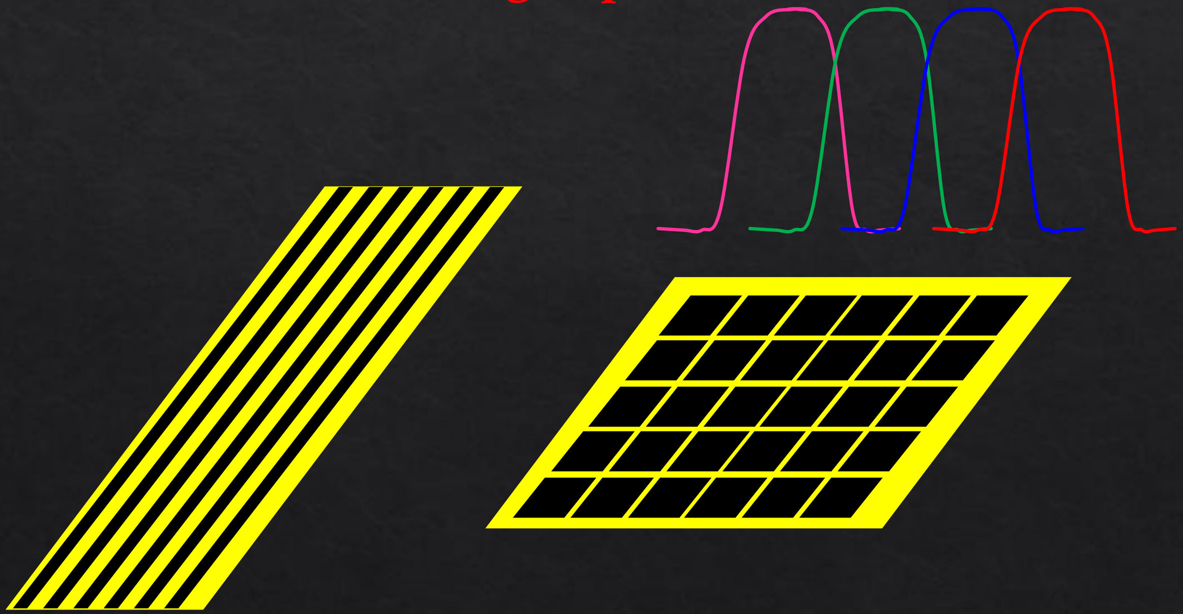
◈ Readout Charge :Q

Optimization of parameters published :
NIMA 1048(2023) 168009

- Charge sharing could be controlled by Ccp and Rimp
  – Depends on application (size of electrode or if we need charge waiting) we can select optimal parameter
- Additional cross talk is expected due to the inter electrode capacitance C_{int}
  – Amount of cross talk may also depend on input capacitance on the electronics.
  – Especially for strip detector. Challenging to make strip structure in both AC-LGAD readout and ASIC design point of view.

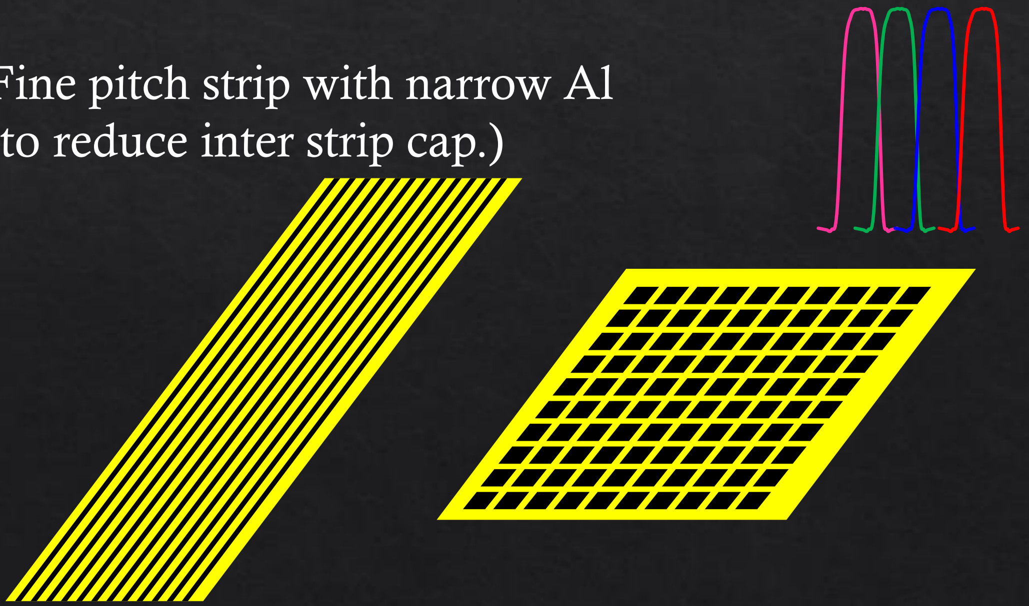
Two approaches for spatial resolution

- ***Charge sharing approach***
  - **For low occupancy colliders like lepton colliders or electron-ion collider.**
  - Reconstruct particle position using charge sharing (charge fraction to next channels)
    - Relatively low n+ implant resistivity
  - **Pros. : Smaller number of channel →Save ASIC power consumption.**
  - **Cons. : Large detector capacitance. Need high resolution ADC to get spatial resolution.**



- ***Fine pitch electrode approach***
  - **For High occupancy experiment like hadron collider.**
  - Reduce crosstalk (charge sharing)
    - High n+ implant resistivity
  - **Pros. : Smaller detector capacitance. Smaller ASIC power consumption per channel. Smaller occupancy per channel**
  - **Cons. : # of channels get huge…**

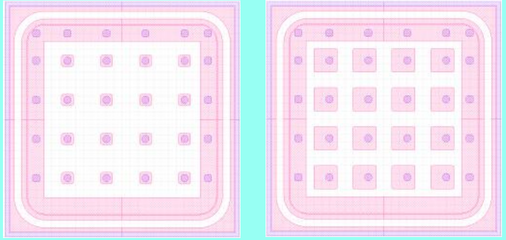
Fine pitch strip with narrow Al (to reduce inter strip cap.)



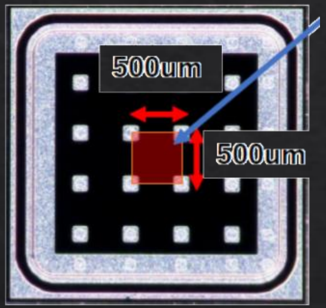
Two approaches for spatial resolution

- ***Charge sharing approach***

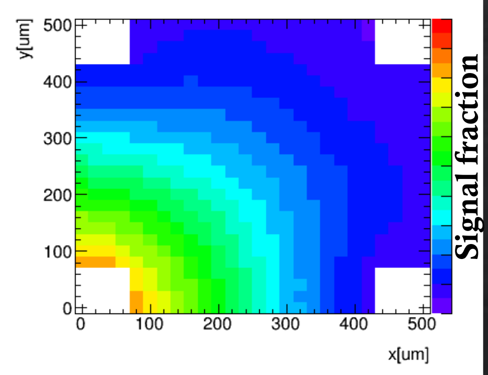
HPK EIC prototype
(500um pitch)

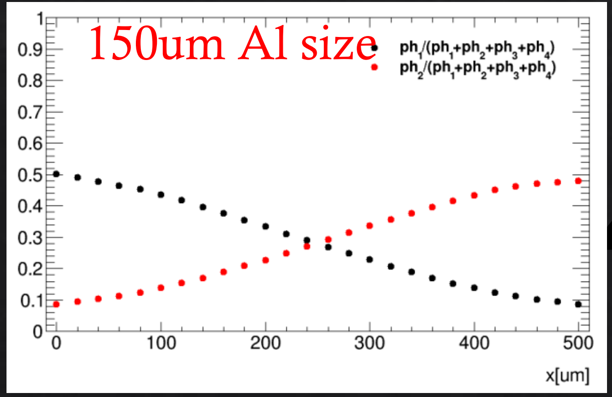


KEK-Tsukuba group with HPK produced
500um pitch pad/strip for future colliders (e.g. EIC)

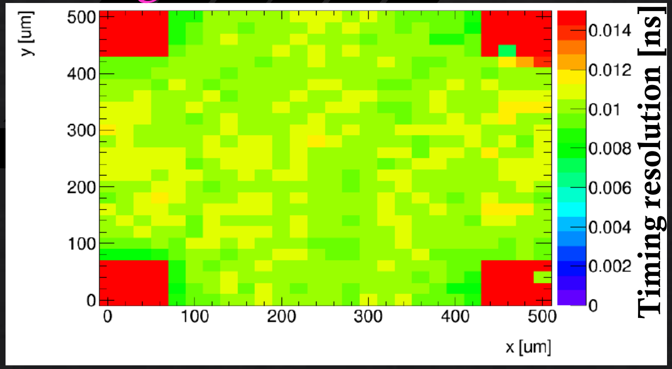


IR laser
Scan area

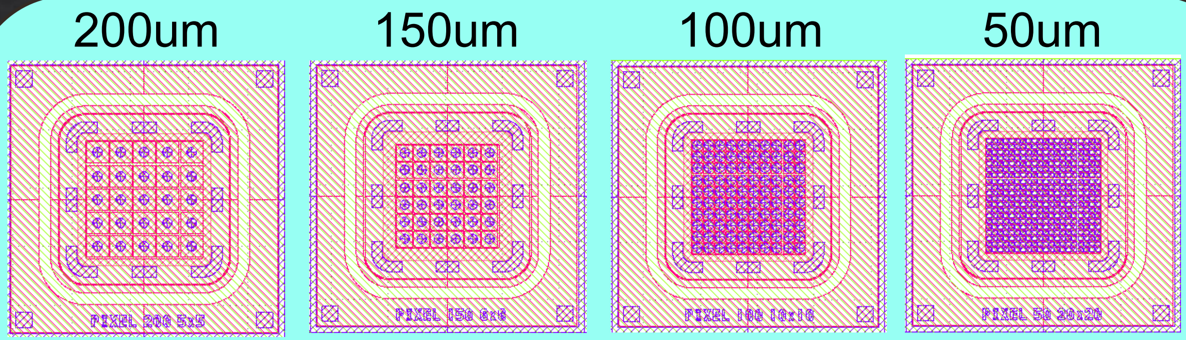




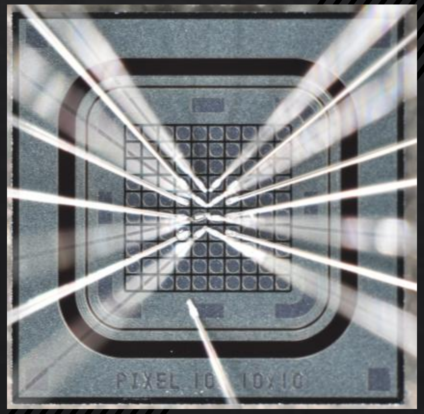
Timing resolution

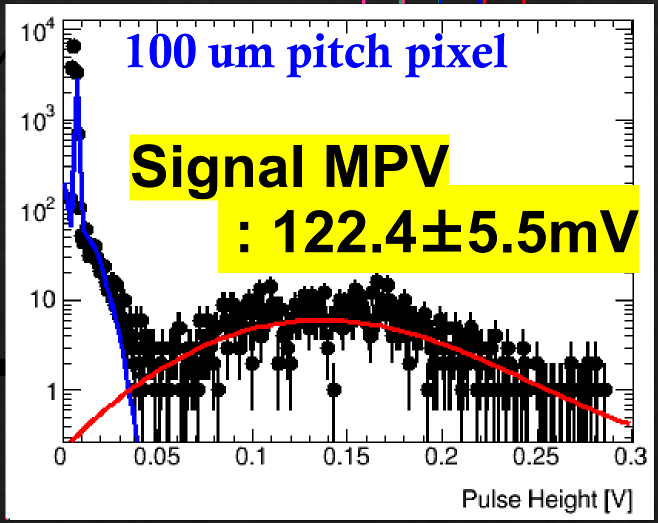


◈ ***Fine pitch electrode approach***



KEK-Tsukuba group with HPK successfully develop :
100um (50um) pitch Pixel detector
80um pitch Strip detector



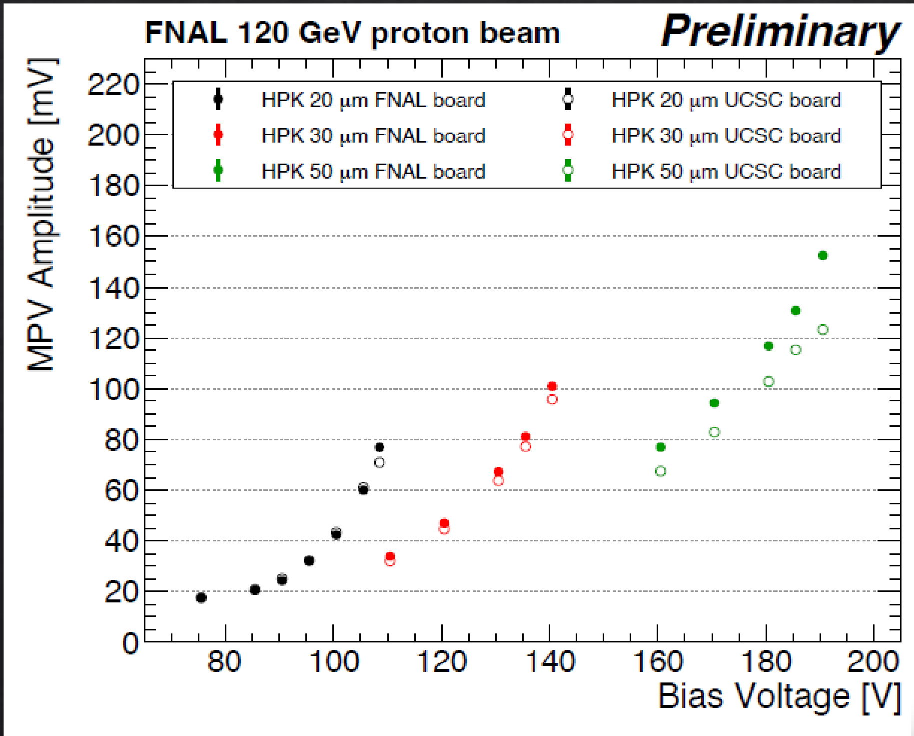


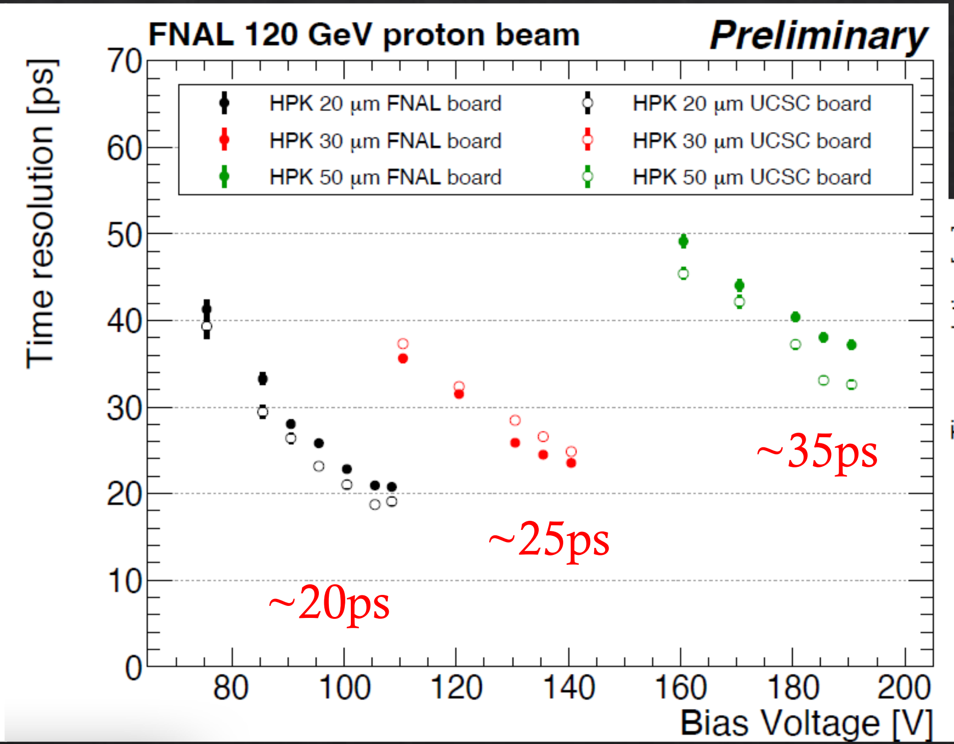
[JPS Conf. Proc. 42, 011030 (2024) VERTEX2022]

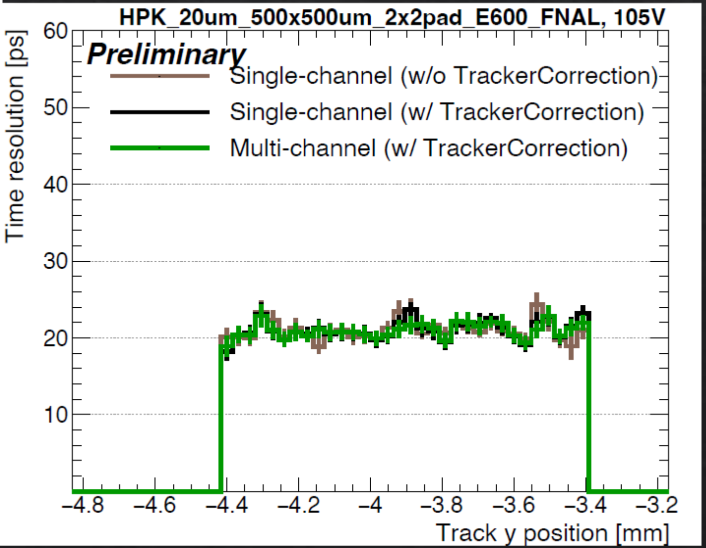
Timing resolution for 500um pitch pad sensors

- To reduce Landau noise : Fabricated 50um, 30um and 20um thick sensors
  - Signal size (amplitude) is smaller in thinner sensors.
  - **20um thick sensor has the best timing resolution : ~20ps**
  - **Uniform timing resolution at the gap region as well.**

All results are 500um pad detector



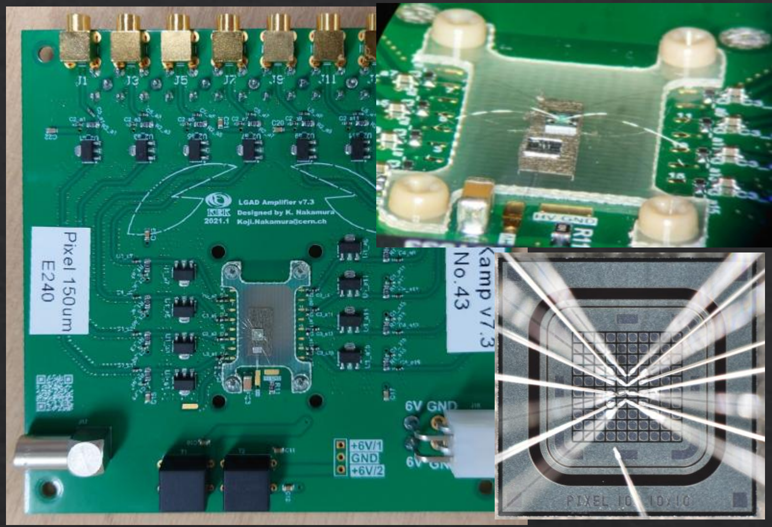




NIMA Volume 1072, March 2025, 170224

AC-LGADpix detector for 4D tracking

- Do the pixelated AC-LGAD detectors have similar timing resolution as pad sensor?
  - **Present in this talk**
- Development of proper ASIC (fast & low power)
  - Should be small detector capacitance by fine pitch pixelated electrode →Lower power consumption
  - First results in this talk using Si-Ge ASIC
- Is the detector radiation hard if detector install to hadron colliders?
  - Progressing but not covered in this talk.



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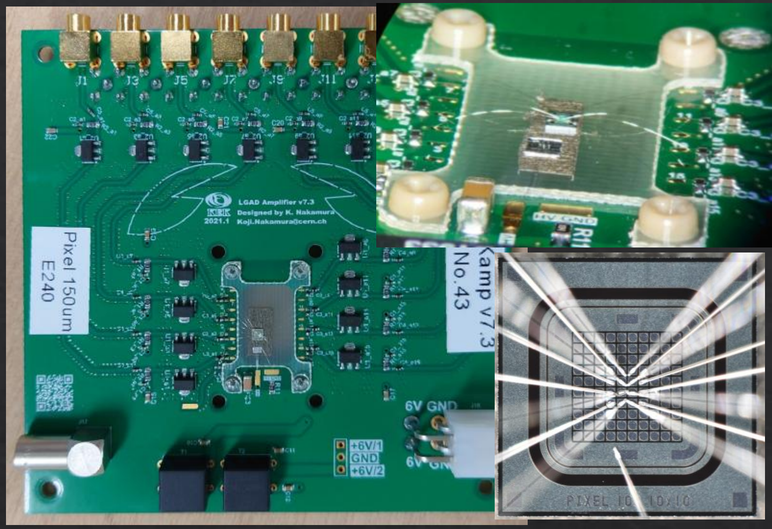

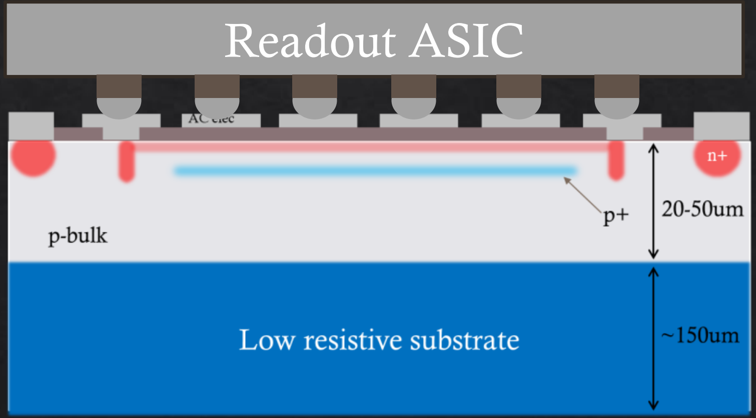

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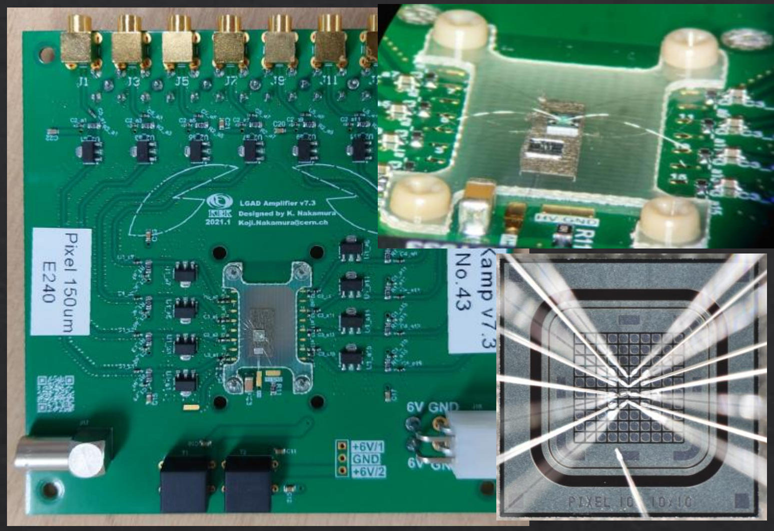
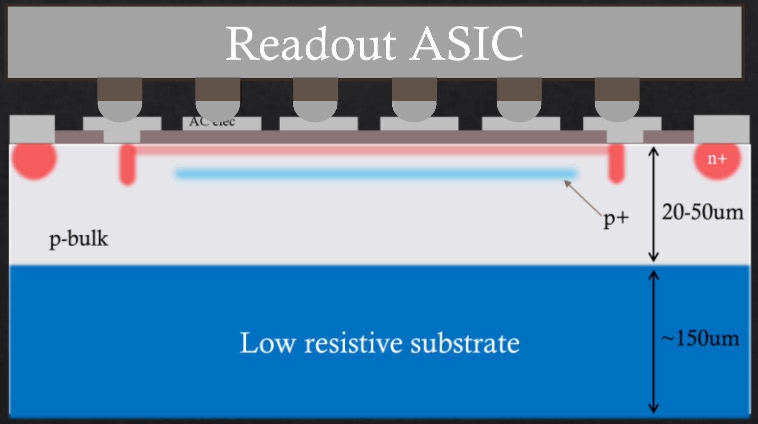
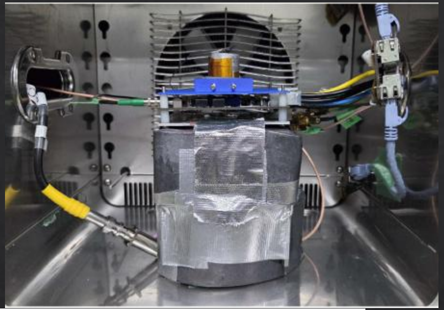
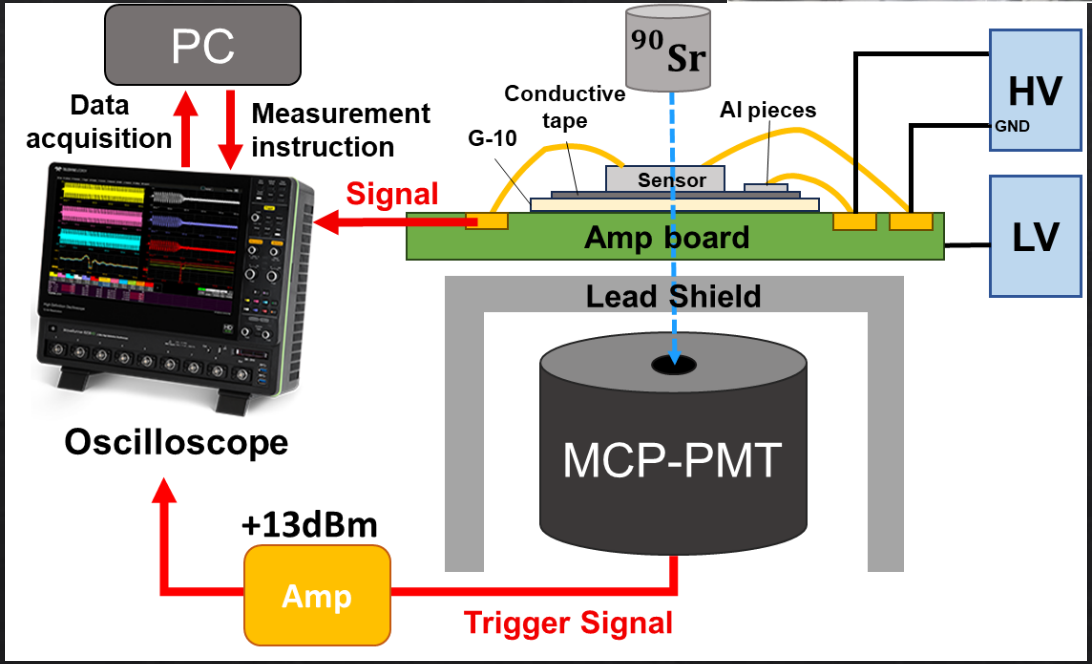




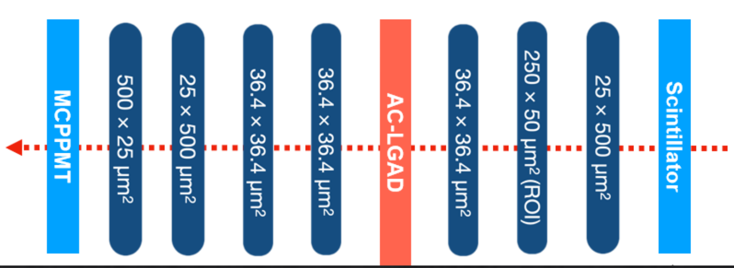
ACLGADpix Timing resolution measurement

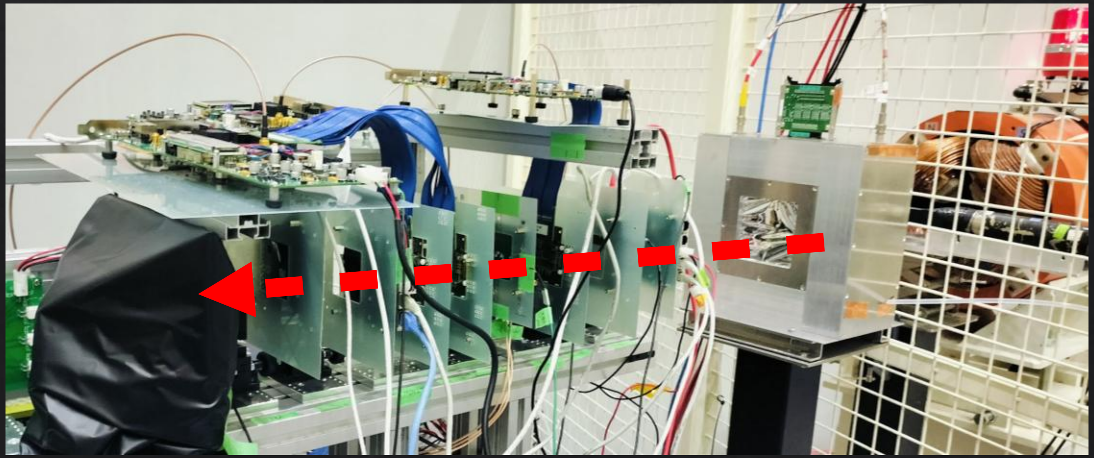
- ^{90}Sr beta-ray measurement
  - MCPPMT as timing reference (<10ps)





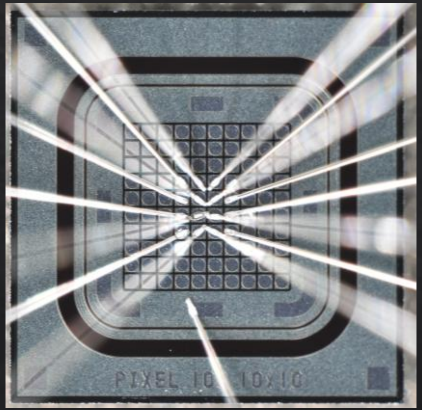
- Testbeam measurement at KEK AR
  - 3GeV electron beam
    - Non-negligible multiple scattering
  - FE-I4 + MALTA based Telescope

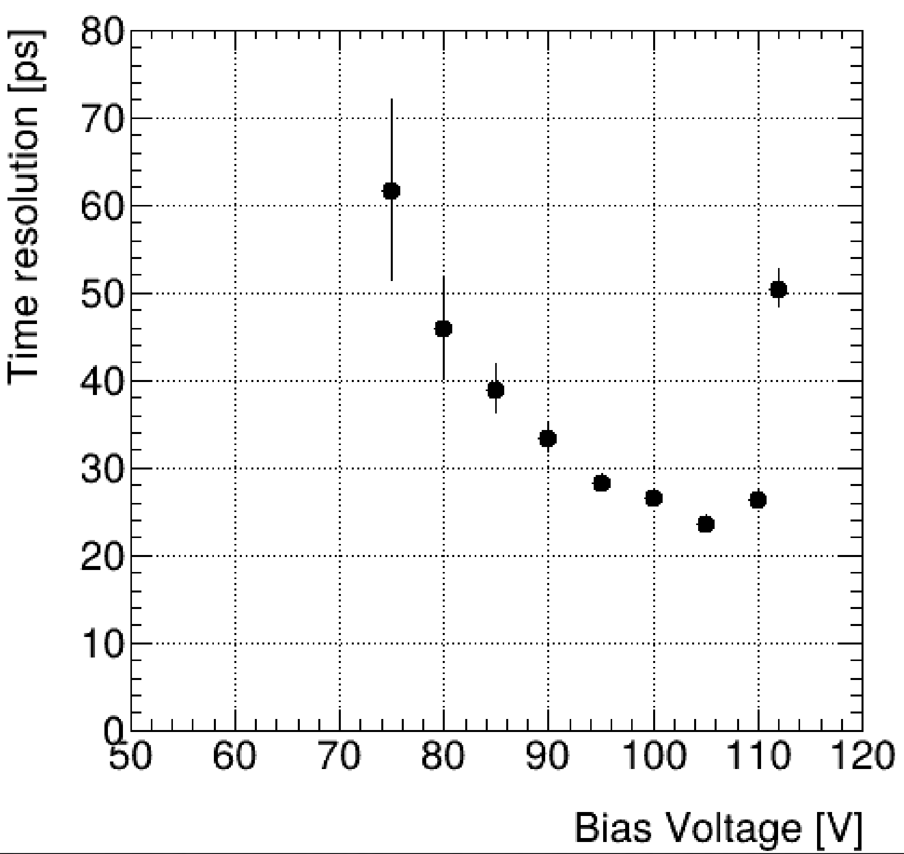


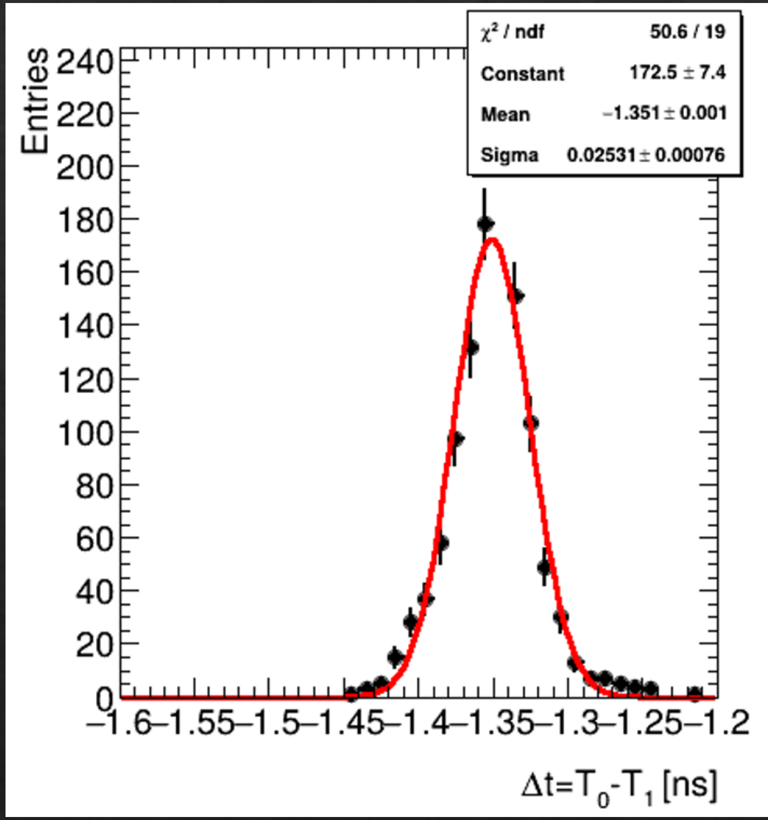


^{90}Sr beta-ray measurement

- Measurement conditions
  - 20um thick sensor
  - 100um x 100um pixel sensor
  - LGAD threshold : 40mV
  - LGAD HV = 105V





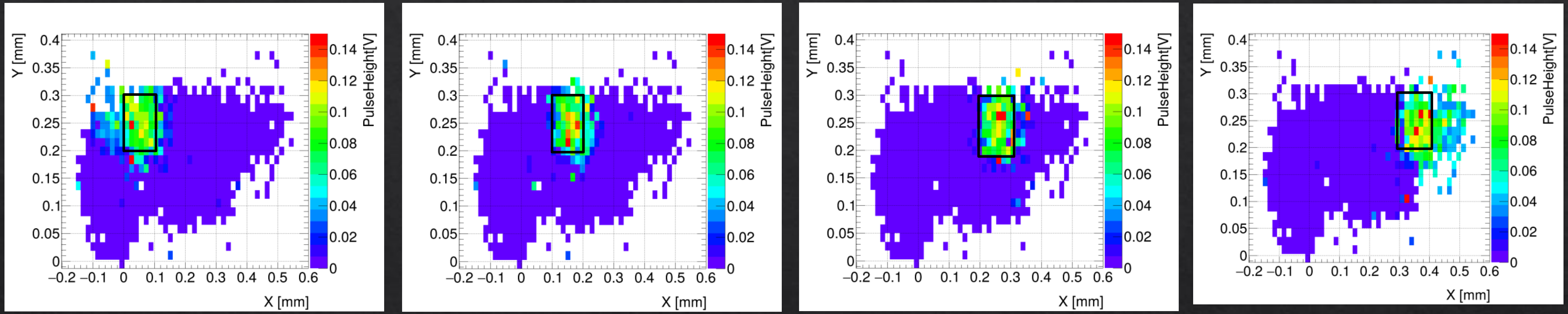


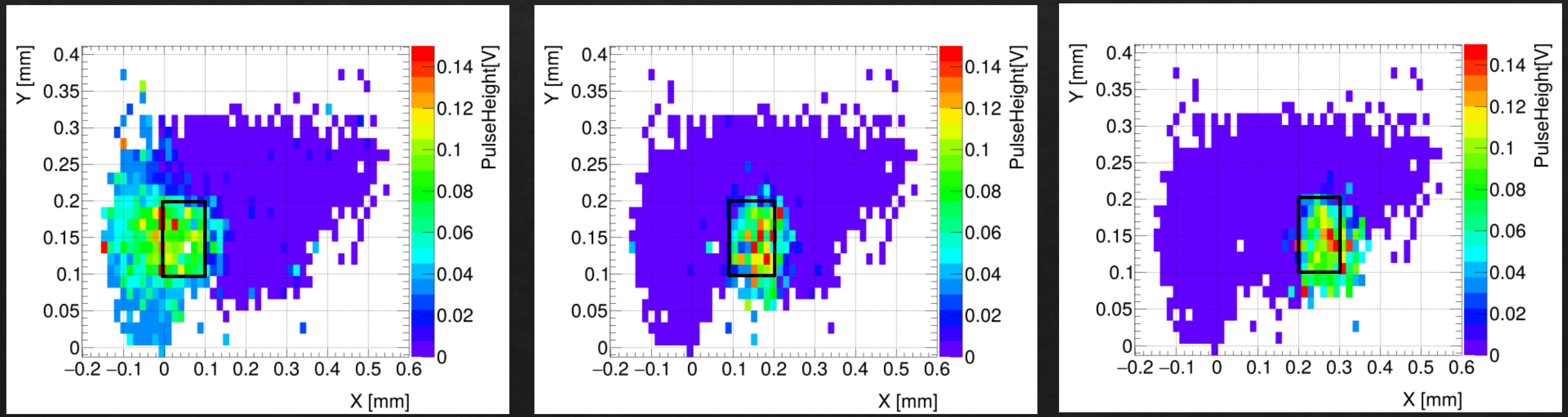
$\sigma_t = 25.3 \pm 0.1$ ps

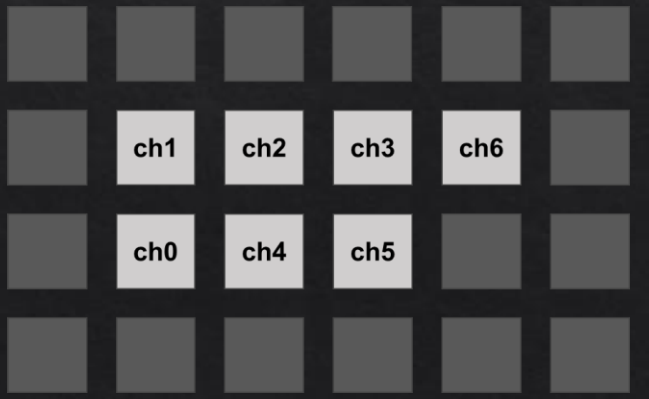
Achieved ~25ps timing resolution for 100um x 100um AC-LGAD pixel sesors

Testbeam measurement : Hit map

- Connected 7 channels (+ 1 MCPPMT channel as time reference)
  - Track hit position corresponding to the maximum pulse-height hit channels.



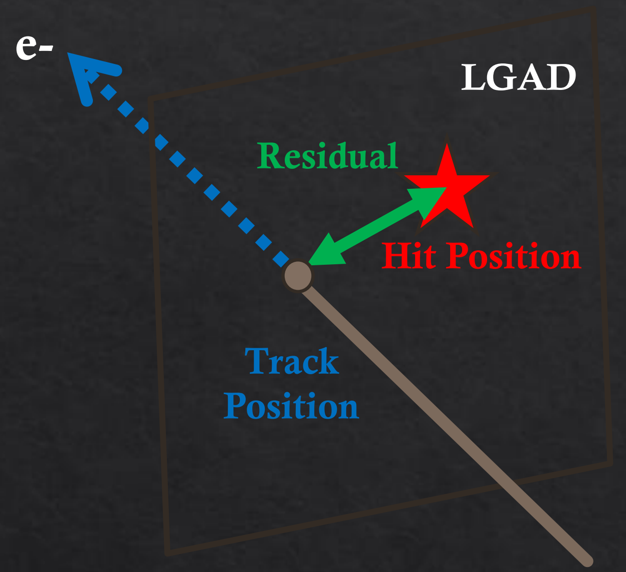




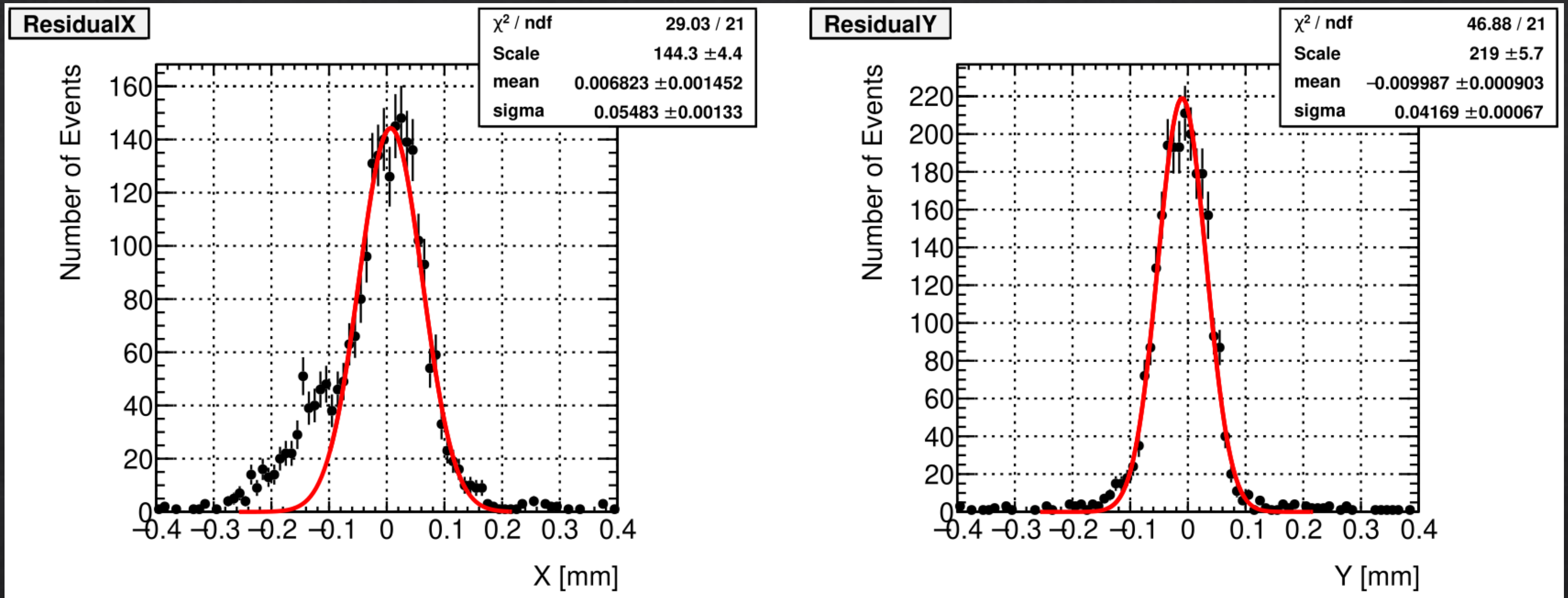
- Readout Channels

Testbeam measurement : Residual distribution

- Definition of Residual



- Residual(hit position – track position)



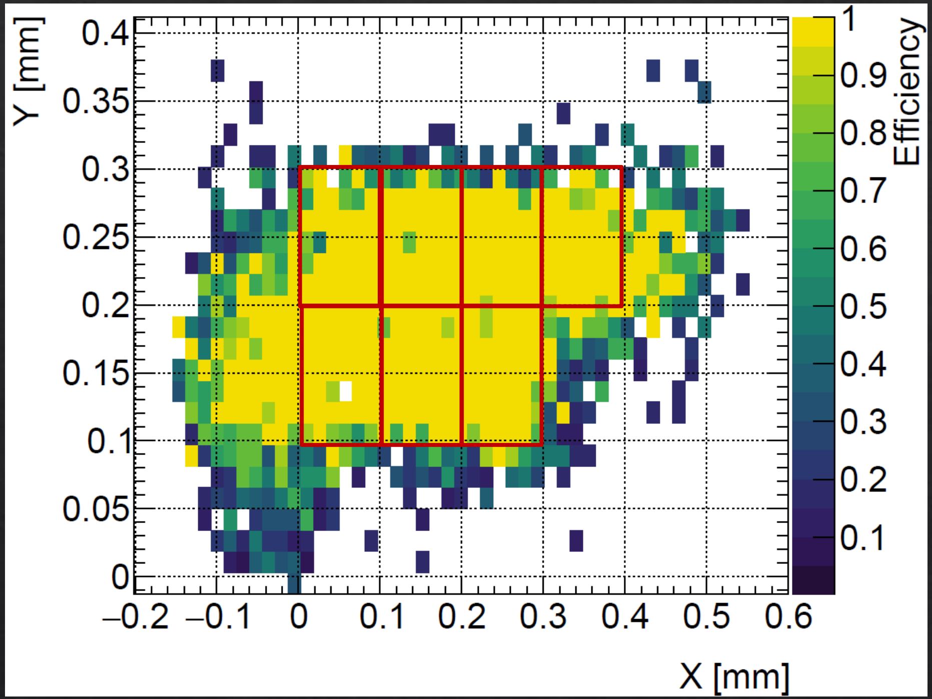
	$\sigma_{residual}$
x	54.8 um
y	41.7 um

No charge information used. (i.e. digital readout)

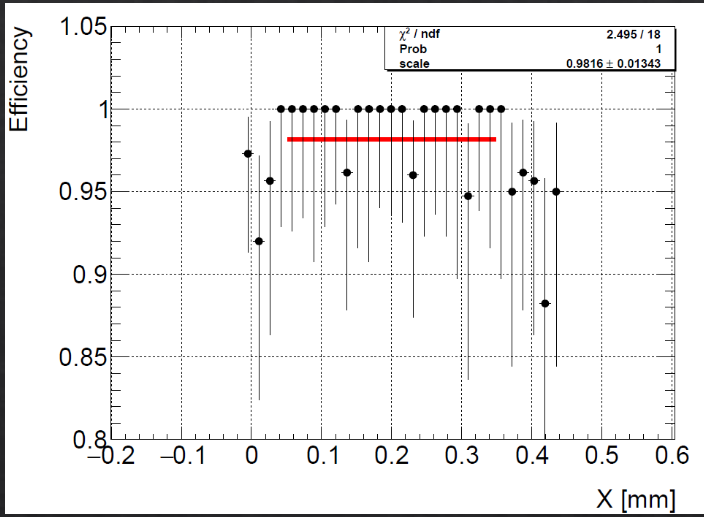
Residual distribution is dominated by Tracking and Multiple scattering effect…

Testbeam measurement : Efficiency map

■ Efficiency Map

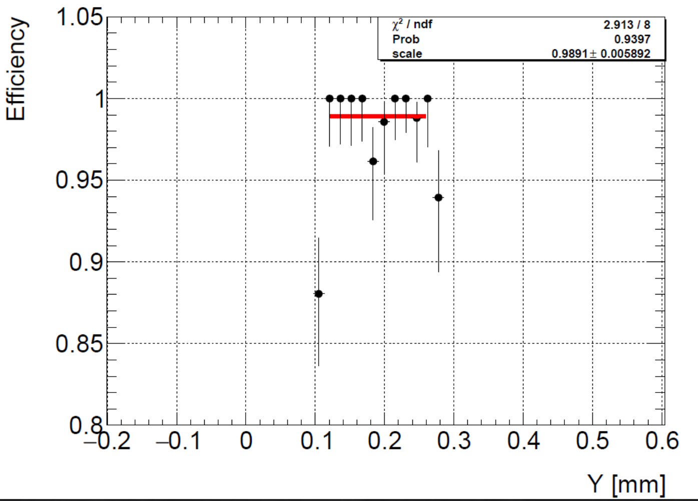


■ Projection X



Projection region
(0.2 mm <Y < 0.26 mm)

■ Projection Y



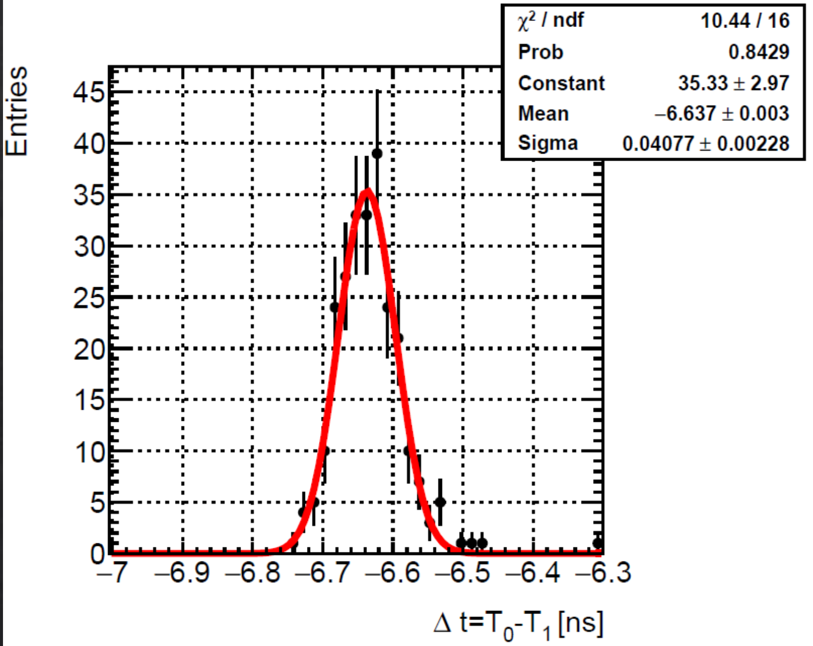
Projection region
(0.05 mm <X < 0.28 mm)

- Efficiency : 98.2±1.3% (X axis), 98.9±0.6% (Y axis)
- Overall efficiency is 99.0±0.3% (area with 3σtrk away from edge)

No significant gap efficiency drop observed. i.e. no dead region for pixel sensor!

Testbeam measurement : Time resolution & crosstalk

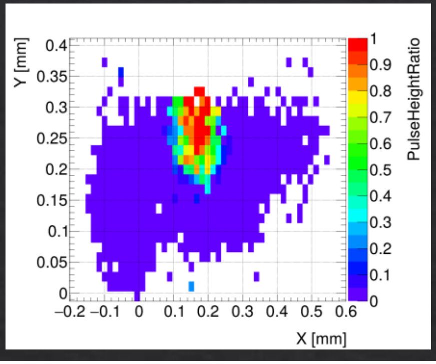
Timing resolution

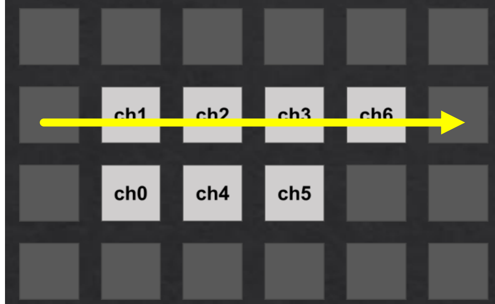


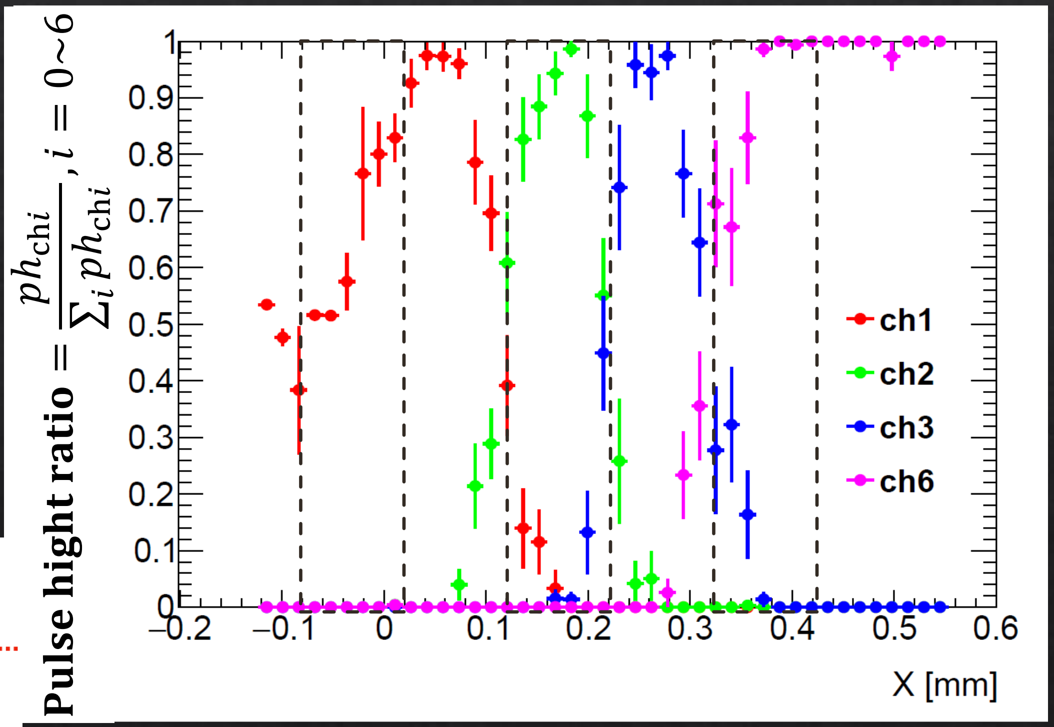
σ_t=40.7±2.2ps

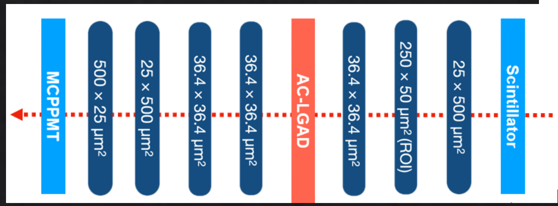
Worse timing resolution than beta-ray. Following effect are included unexpectedly…

- External amp for MCPPMT ~20ps effect
- Scattering effect ~24ps effect









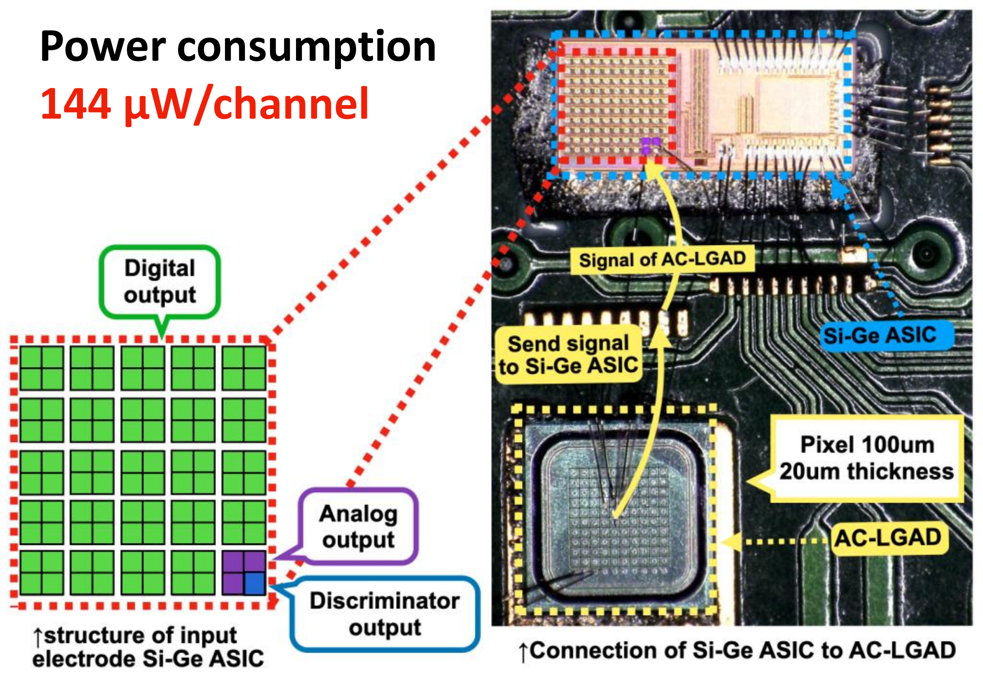
(May need to have high energy hadron testbeam) **Observed reasonably low level of cross talk**

100um ACLGADpix on Si-Ge ASIC

⟐ Features of Si-Ge ASIC

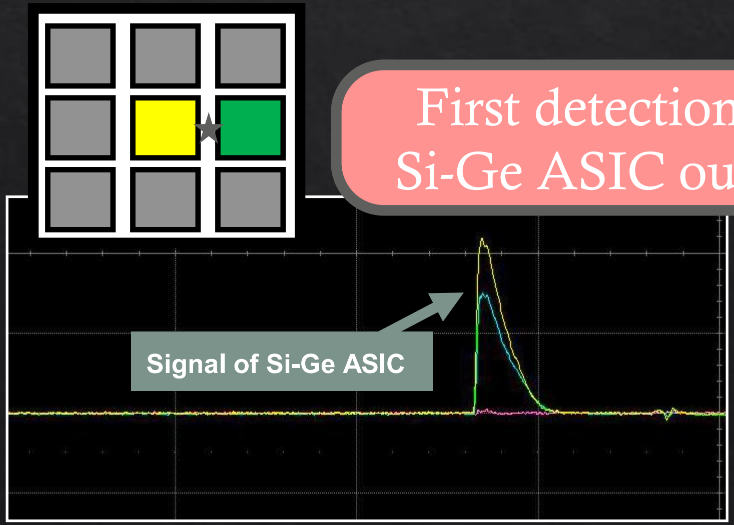
- **Si-Ge 130nm Bi-CMOS** (IHP) process.
- The preamp is made of HBT
  → Heterojunction Bipolar Transistor
- The Input electrode is a 10×10 matrix (100×100 um^2).
- There are only three pixel to output analog signals.

Developed by University of Geneva



Wire bonded

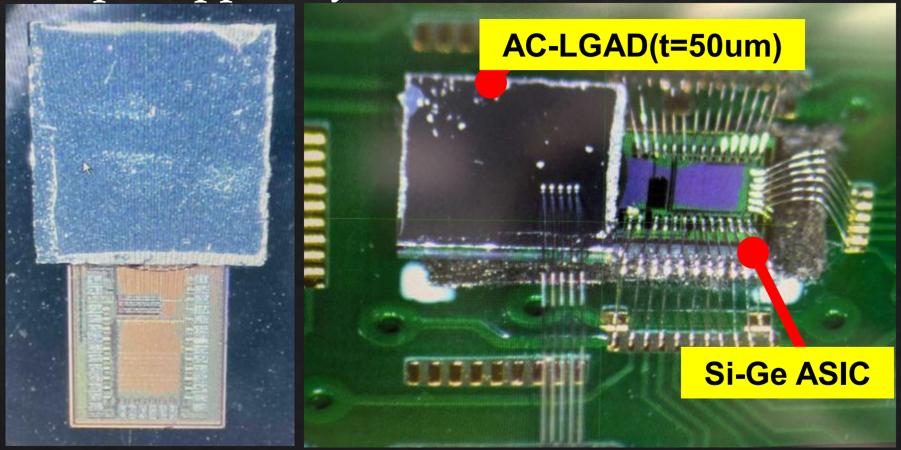
Jitter is ~5ps for MIP
I.Horikoshi VERTEX2025



First detection of Si-Ge ASIC output

↑The signal of Si-Ge ASIC

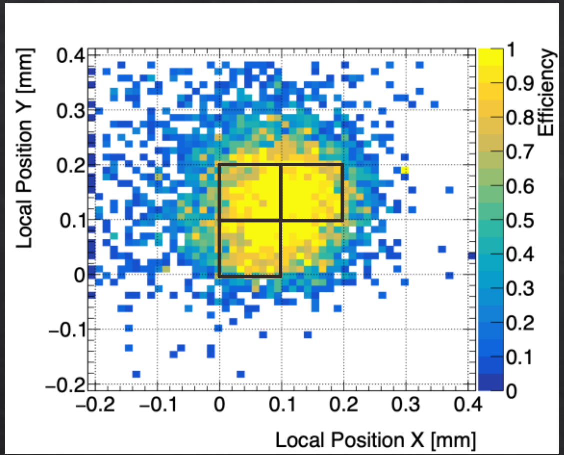
Flip-chipped by ACF

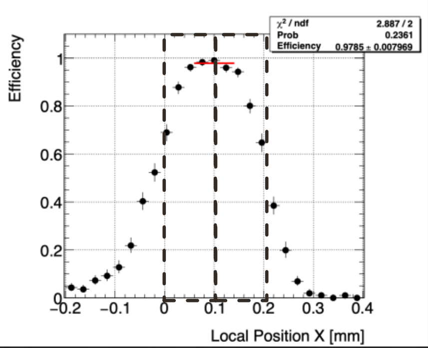


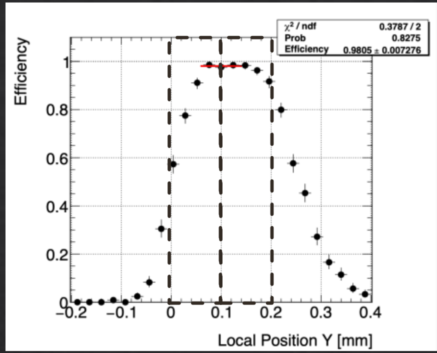
Flip-chipped sample has been tested by testbeam

100um ACLGADpix on Si-Ge ASIC (50um thick)

Efficiency







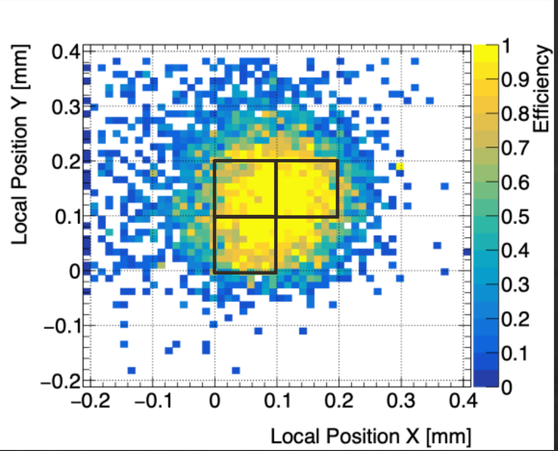
Efficiency :

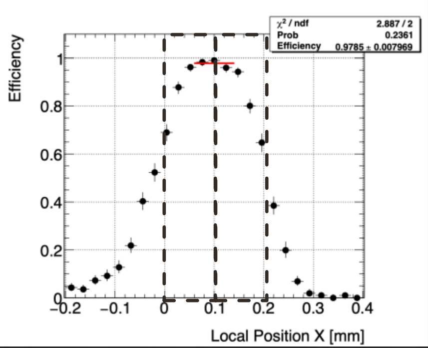
97.9±0.7% (X axis), 98.1±0.7% (Y axis)

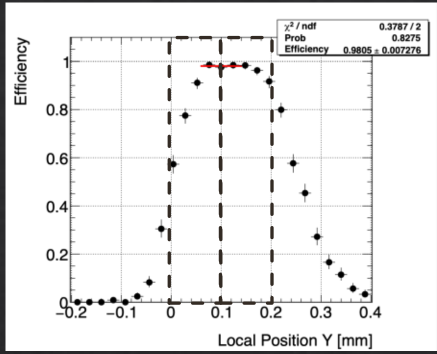
over all efficiency : 98.8±0.6%

100um ACLGADpix on Si-Ge ASIC (50um thick)

Efficiency







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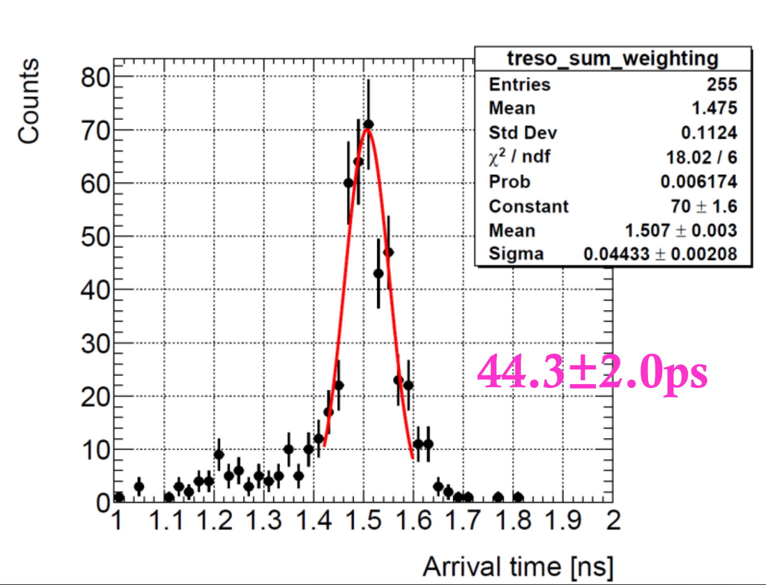
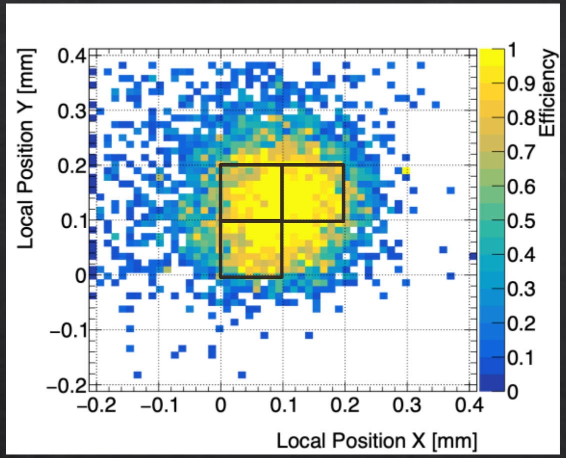
Timing resolution

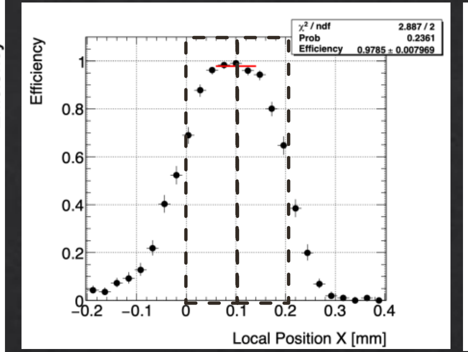


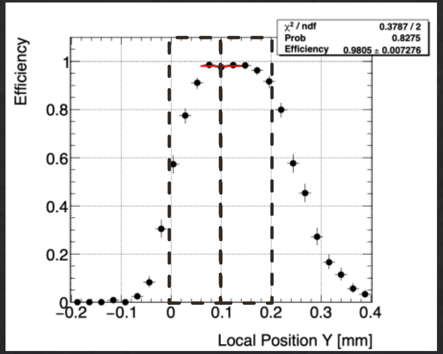
The same issue as wirebonded pixel sensors i.e. Multiple-scattering effect

100um ACLGADpix on Si-Ge ASIC (50um thick)

Efficiency

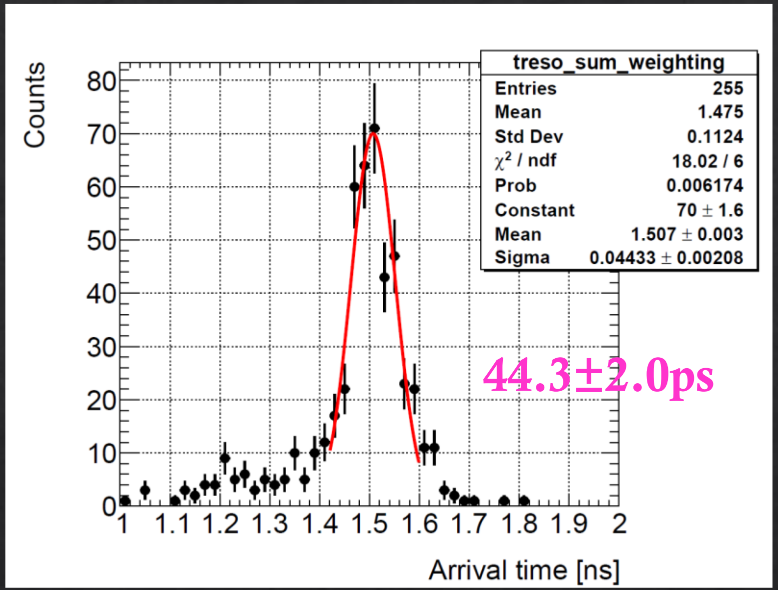






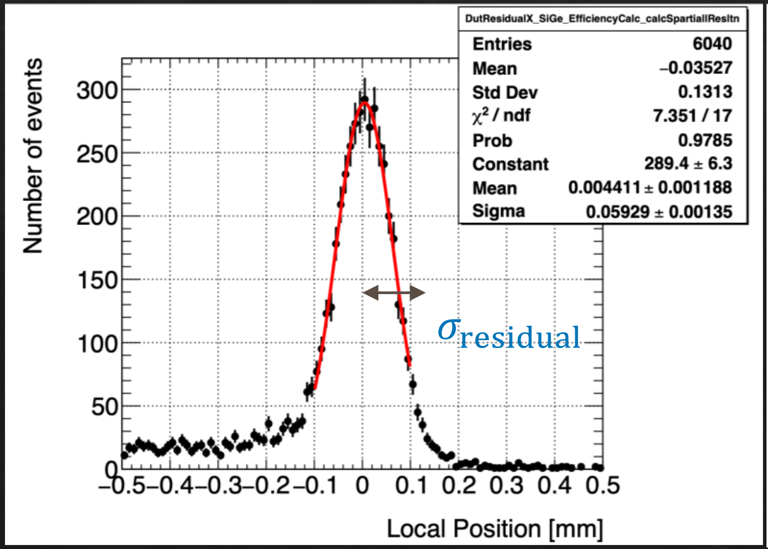
Efficiency :
97.9±0.7% (X axis), 98.1±0.7% (Y axis)
over all efficiency : 98.8±0.6%

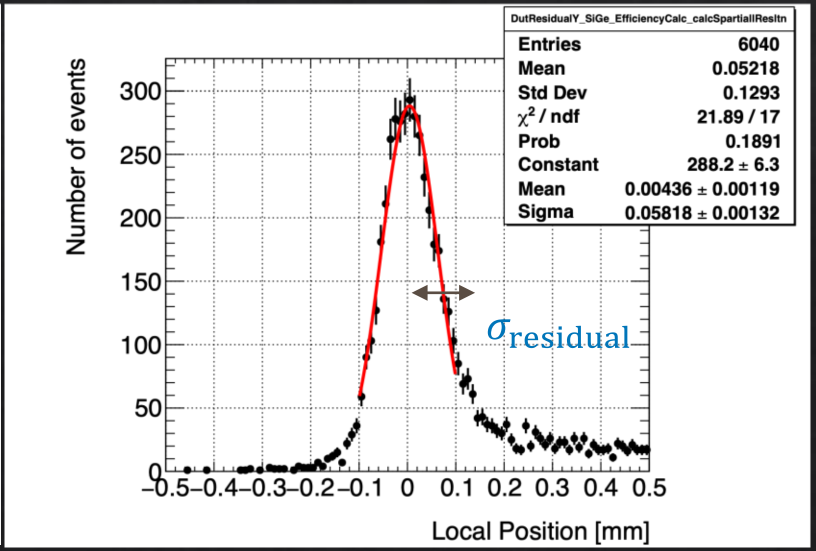
Timing resolution



The same issue as wirebonded pixel sensors i.e. Multiple-scattering effect

Residual distribution



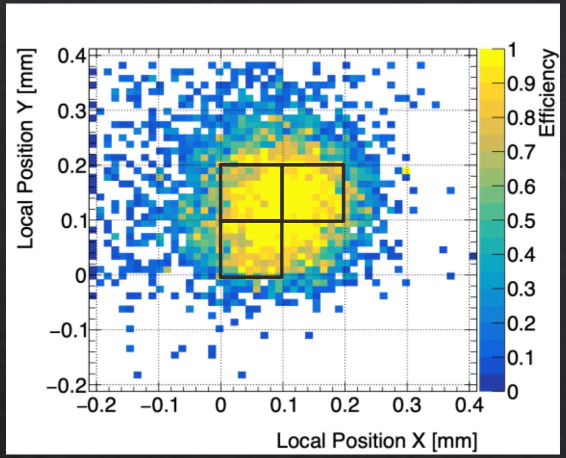


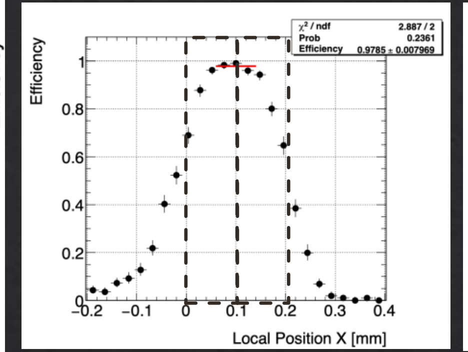
Spatial resolution

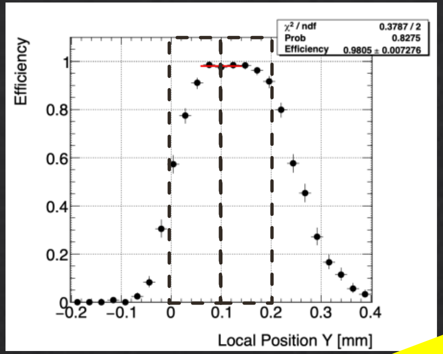
	$\sigma_{residual}$	σ_{track}	$\sigma_{detector}$
X	59.3±1.4 μm	54.3±1.4 μm	23.8±4.7 μm
Y	58.2±1.3 μm	52.6±1.2 μm	24.9±4.0 μm

100um ACLGADpix on Si-Ge ASIC (50um thick)

Efficiency





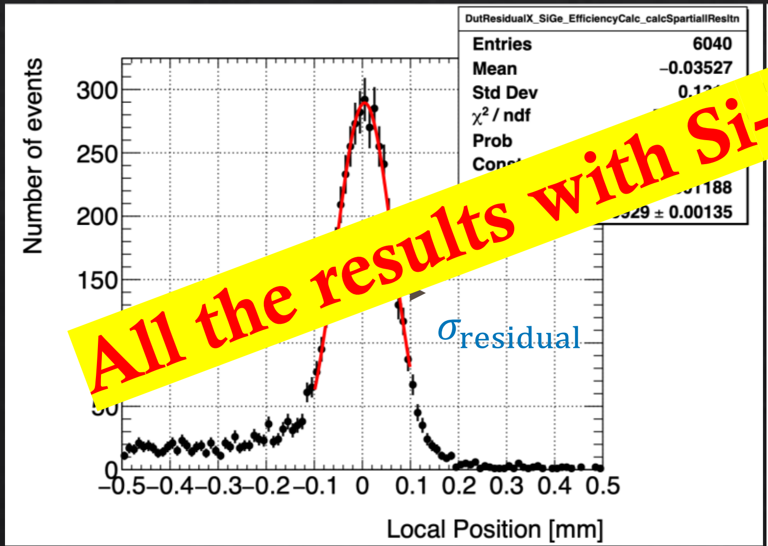


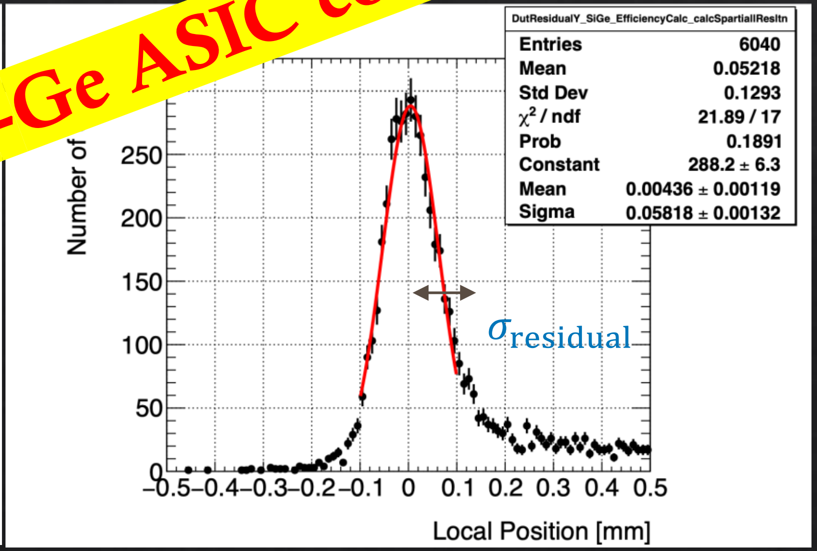
Efficiency :
97.9±0.7% (X axis), 98.1±0.[...] (Y axis)
over all efficiency : 9[...]

Timing resolution

All the results with Si-Ge ASIC consistent to the results by discrete amplifier

Residual distribution





The same issue as wirebonded pixel sensors i.e. Multiple-scattering effect

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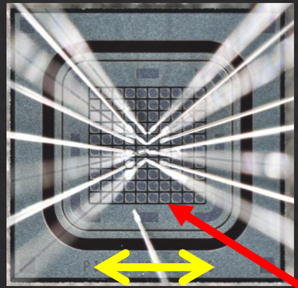
Conclusion

First prototype in 2015

remarkable improvement

Recent prototype (in 2022)
ACLGADpix detector



In Pad Type (500um pitch) :
20ps timing resolution achieved

Pixel size :
100µm x 100µm
(50µm x 50µm)

- 100um x 100um Pixelated ACLGAD showed good timing and spatial resolution :
  - Efficiency : **~99%**
  - Spatial resolution : **24.4±4.3um** → equivalent to 28.8um(=100/√12)
  - Timing resolution : beta-ray **25.3 ± 0.1 ps** , testbeam **40.7±2.2ps** (Multiple scattering effect)
  - **Reasonably low level of crosstalk** observed (cluster size should be a few pixels)

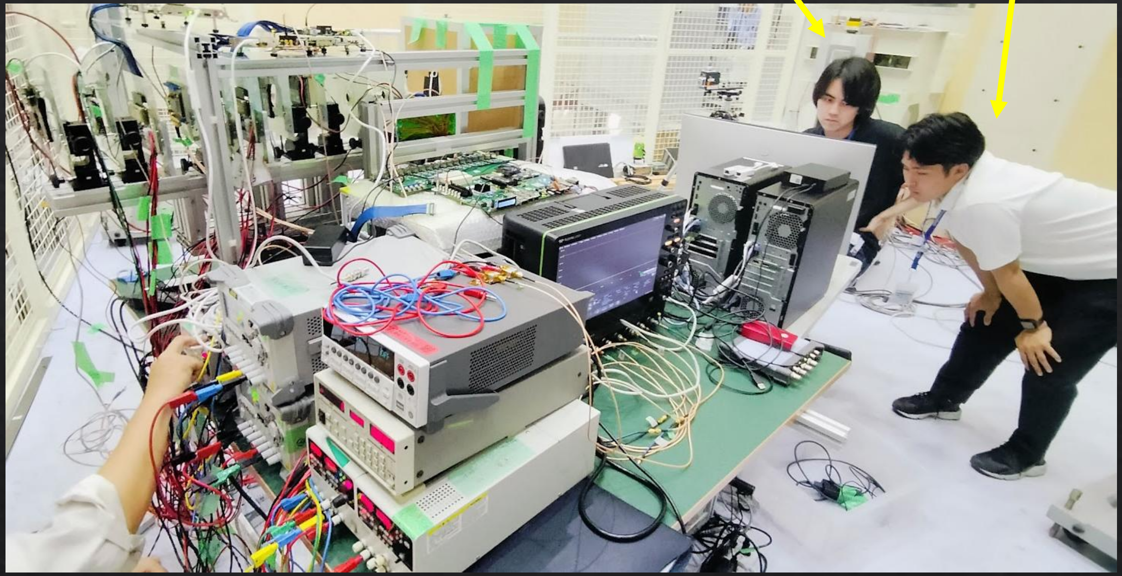
Successfully developed AC-LGAD sensors capable for both high spatial resolution and timing resolution

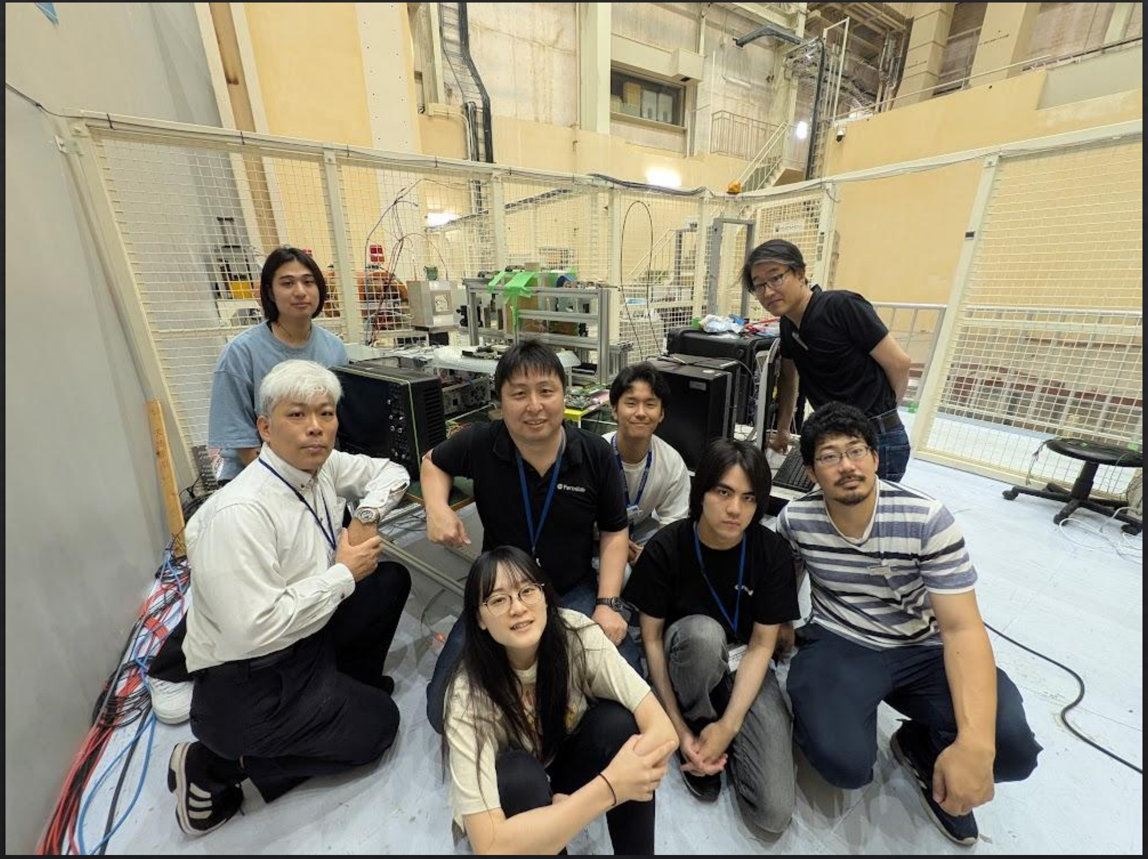
- Demonstrated Flip-chipped ACLGAD to Si-Ge ASIC (144uW/ch, analog only)
  - **Similar performance observed. → Need lower power consumption ASIC**
- Future : Radiation tolerance improvement is mandatory for hadron collider experiments.
  - New samples will be irradiated next week at RARiS, Tohoku university

Thank you!

Yua Murayama

Issei Horikoshi





backup

Break down of worth timing resolution in TB

$$\sigma_t = \sqrt{\sigma_{jitter}^2 + \sigma_{CCN}^2 + \sigma_{\text{jitter,PMT}}^2 + \sigma_{\text{tw,PMT}}^2 + \sigma_{\text{Sampling Rate}}^2 + \sigma_{scatter}^2}$$

- No ext Amp , β-ray, HV=105V, 10GS/s

$$25\text{ ps} = \sqrt{(8\text{ ps})^2 + \boldsymbol{\sigma_{CCN}^2} + (1.95\text{ ps})^2}$$

- With ext Amp、β-ray,HV=105V, 10GS/s

$$33\text{ps} = \sqrt{(8\text{ ps})^2 + \boldsymbol{\sigma_{CCN}^2} + (1.95\text{ ps})^2 + \boldsymbol{\sigma_{\text{tw},PMT}^2}}$$

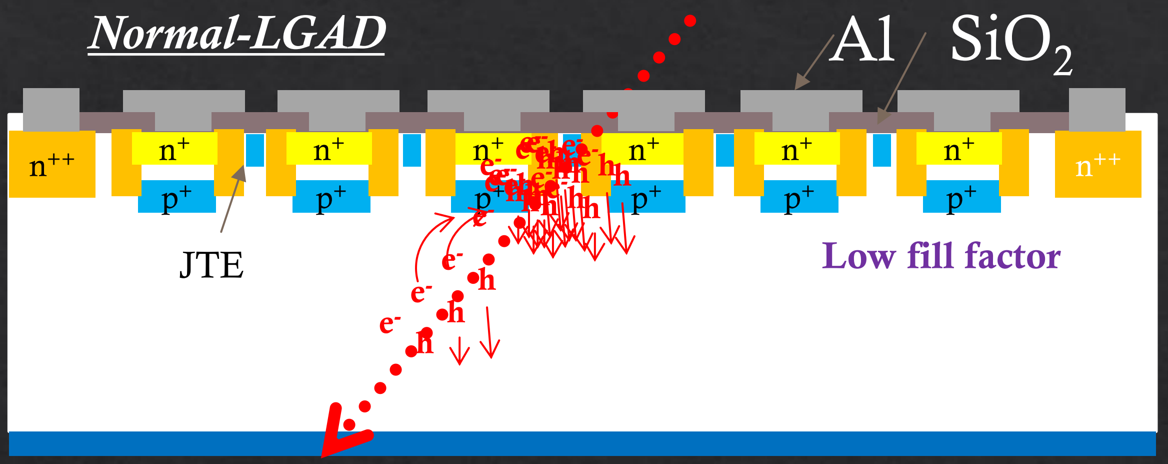
- with ext amp β-ray, HV=105V, 5GS/s

$$34\text{ps} = \sqrt{(8\text{ ps})^2 + \boldsymbol{\sigma_{CCN}^2} + (1.95\text{ ps})^2 + \boldsymbol{\sigma_{\text{tw},PMT}^2} + \boldsymbol{\sigma_{\text{5GS/s}}^2}}$$

$$\Rightarrow \quad \sigma_{CCN} = 24\text{ ps}, \quad \sigma_{\text{tw},PMT} = 20\text{ ps}, \quad \sigma_{\text{5GS/s}} = 8\text{ ps}, \quad \sigma_{scatter} = 24\text{ ps}$$

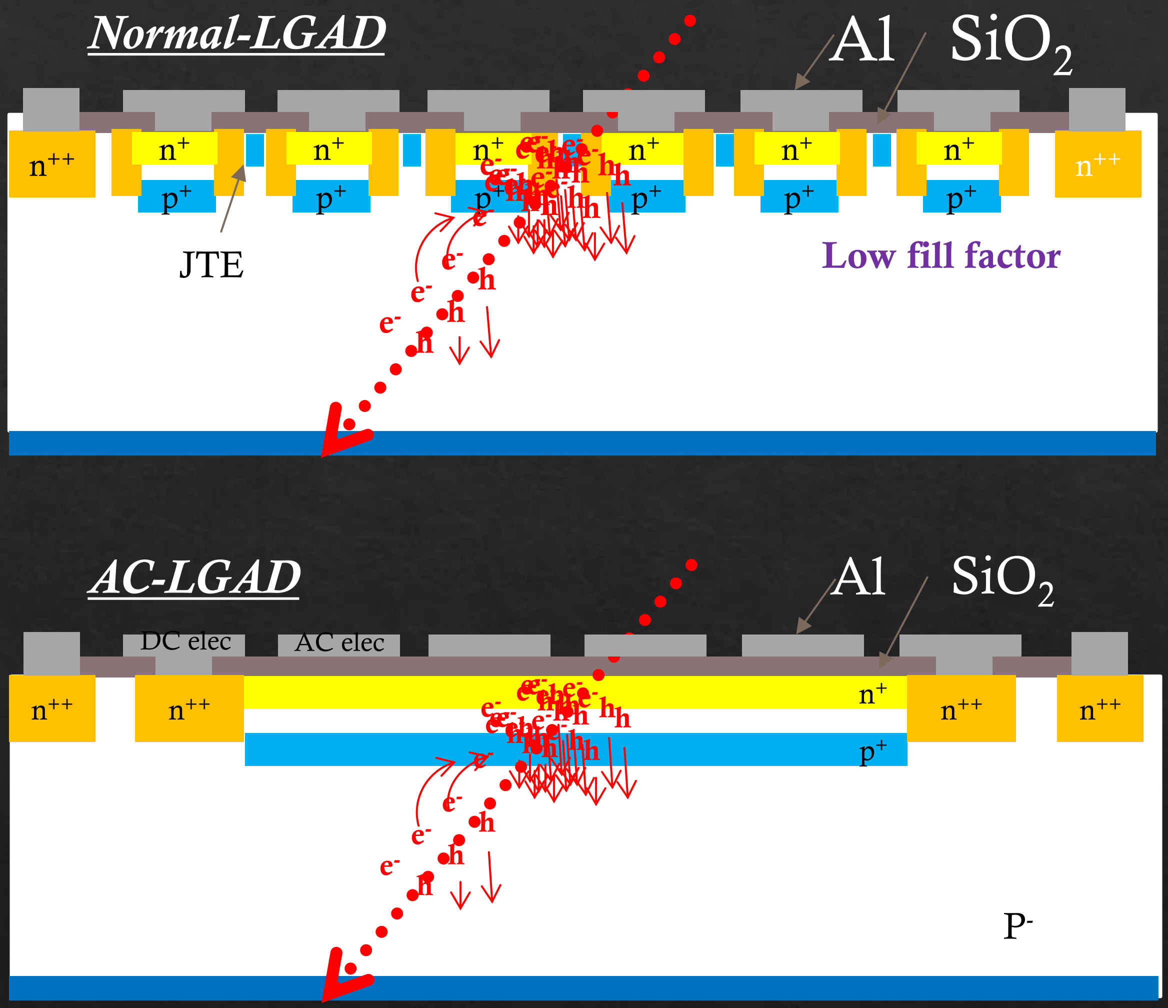
Spatial resolution of LGAD

- Segmented LGAD :
  - To have spatial resolution, strip sensors has been processed.
  - Need **Junction termination extension(**JTE) and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**



Spatial resolution of LGAD

- Segmented LGAD :
  - To have spatial resolution, strip sensors has been processed.
  - Need **Junction termination extension(**JTE) and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**
- **Uniform gain layer with AC-Coupled electrode. (AC-LGAD)**
  - **In principle, 100% fill factor.**
  - **Signal shared on neighboring electrodes.**
    - Need optimization of n+ resistivity



What is timing resolution?

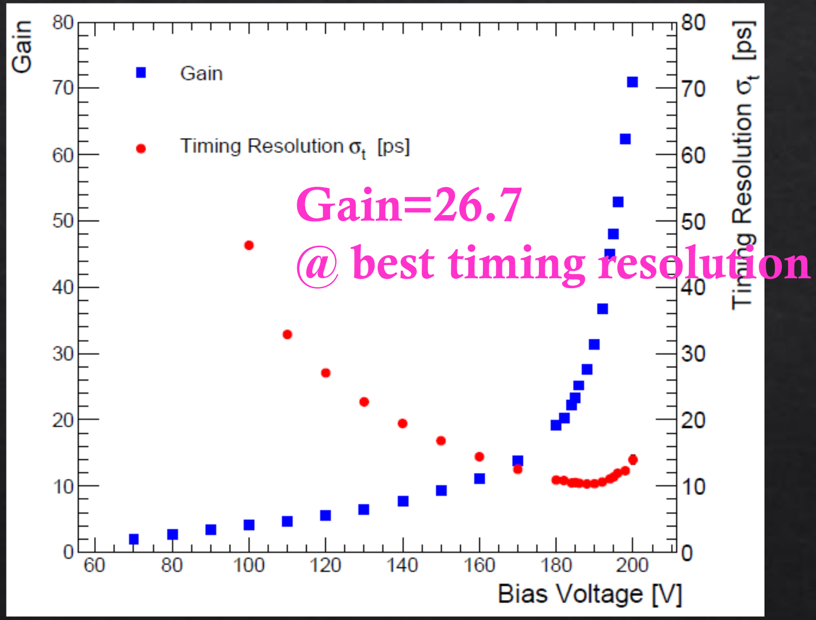
$$\sigma_{t} = \underbrace{\sigma_{\text{avalanche}} + \sigma_{\text{charge-collection}}}_{\text{Sensor related noise}} + \underbrace{\sigma_{\text{pre-amp-jitter}} + \sigma_{\text{comp-jitter}} + \sigma_{\text{timewalk}} + \sigma_{\text{tdc}}}_{\text{Readout ASIC related noise}} + \underbrace{\sigma_{\text{trigger-jitter}} + \ldots}_{\text{Other noise??}}$$

What is timing resolution?

$$\sigma_t = \sigma_{\text{avalanche}} + \sigma_{\text{charge-collection}} + \sigma_{\text{pre-amp-jitter}} + \sigma_{\text{comp-jitter}} + \sigma_{\text{timewalk}} + \sigma_{\text{tdc}} + \sigma_{\text{trigger-jitter}} + \ldots$$

Avalanche noise

Gain measurement (AC-LGAD):

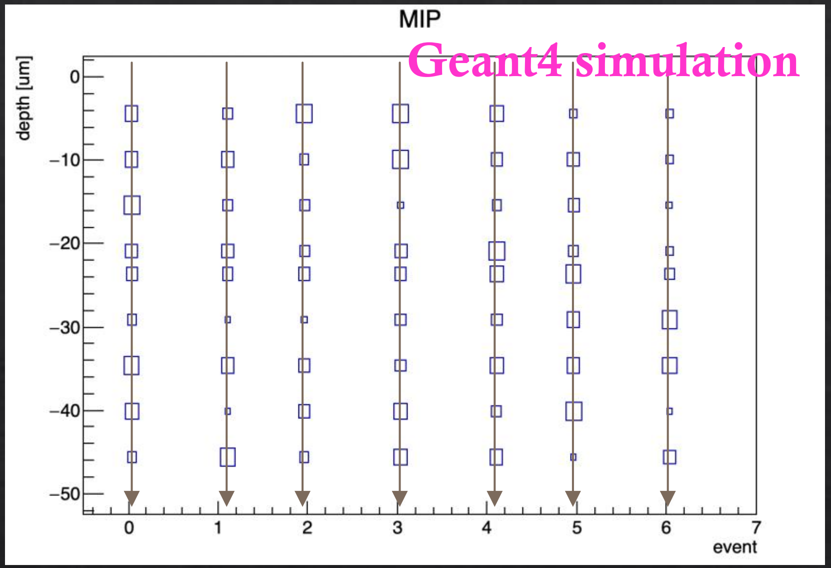


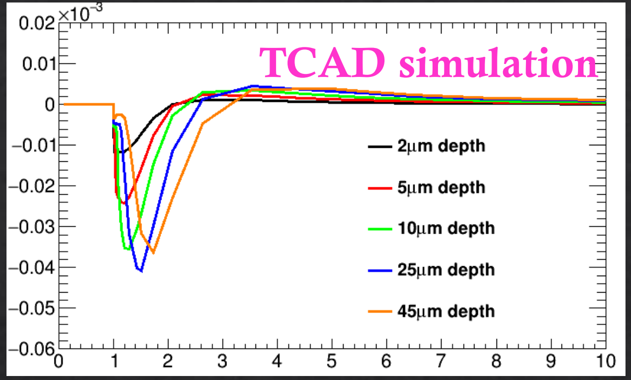
To high gain introduce avalanche noise

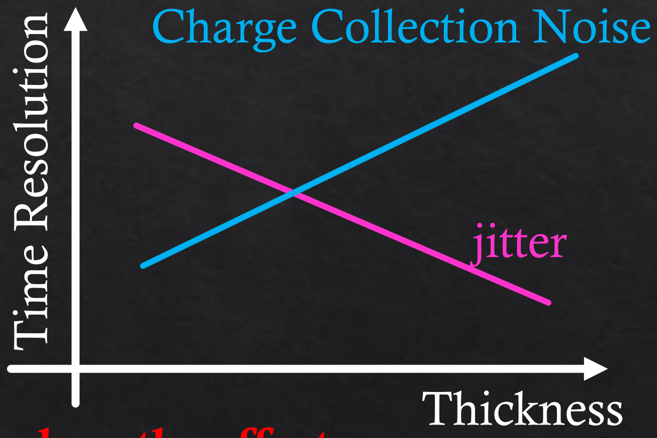
→ Ignored by operating the right voltage(190V)

Charge collection noise

Non-Uniform charge deposition







Thinner active thickness will help to reduce the effect

50um thick sensor : ~30ps CCN → 35ps in actual device achieved.

20um thick sensor : ~15ps CCN → 20ps in actual device achieved.

→10um thick sensor?

Smaller signal size (worse jitter) but better CCN.

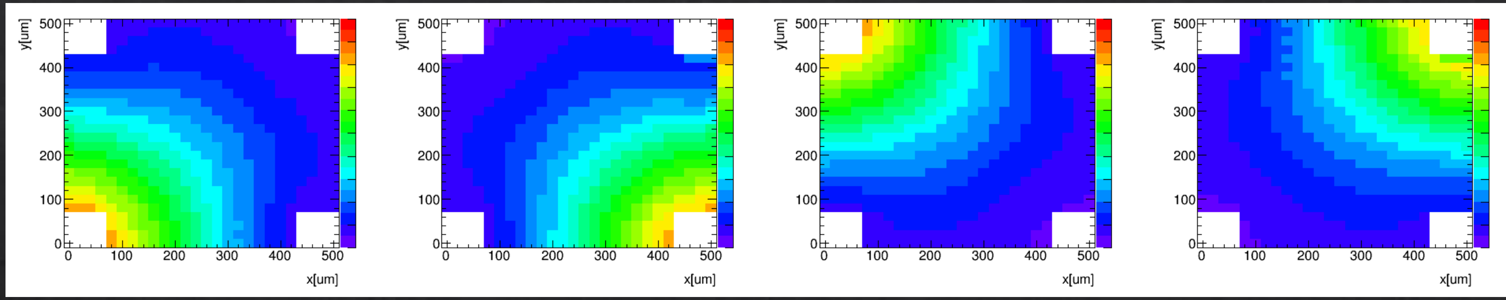
Charge sharing approach

R_{imp} [Ω/□]			
1600	E120	E240	E600
400	C120	C240	C600
C_{cp} [pF/mm^2]			

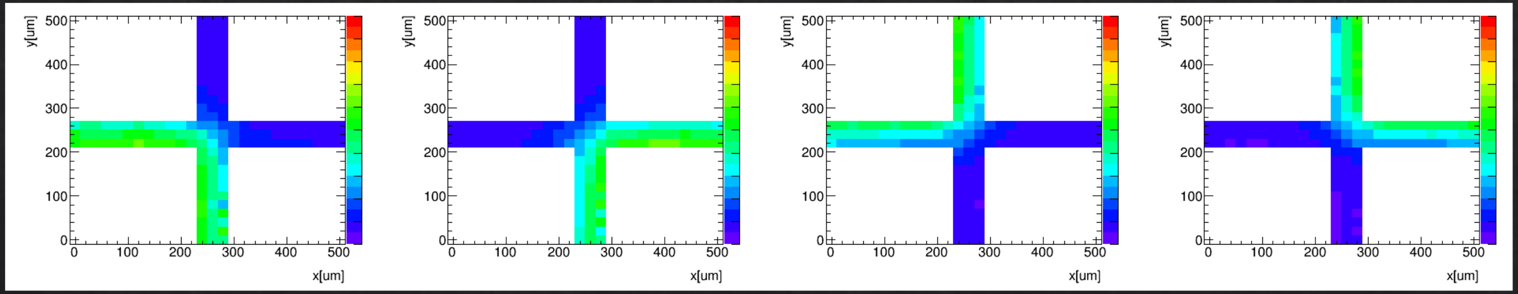
- Fabricated 500um pitch pad type sensor with various electrode size for EIC prototype.
- Scanned Laser injection position in 500um x 500um area.

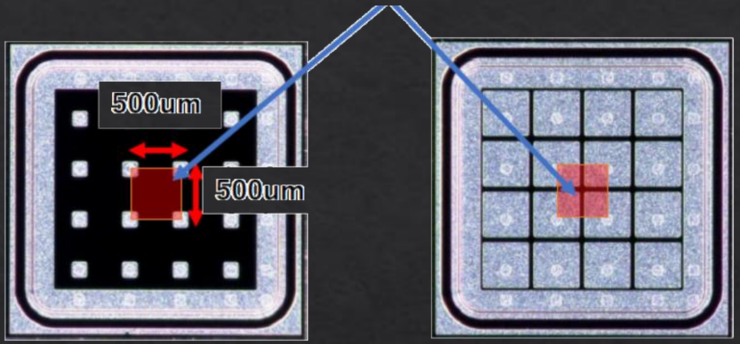
Scanned Area

150um Al size



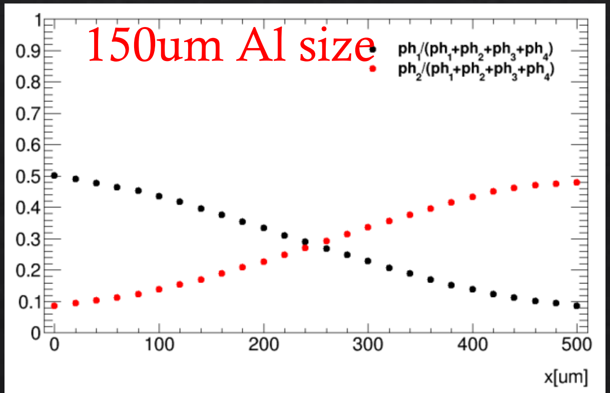
450um Al size

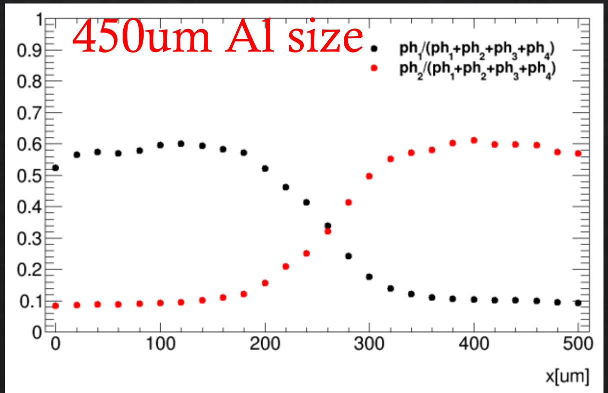




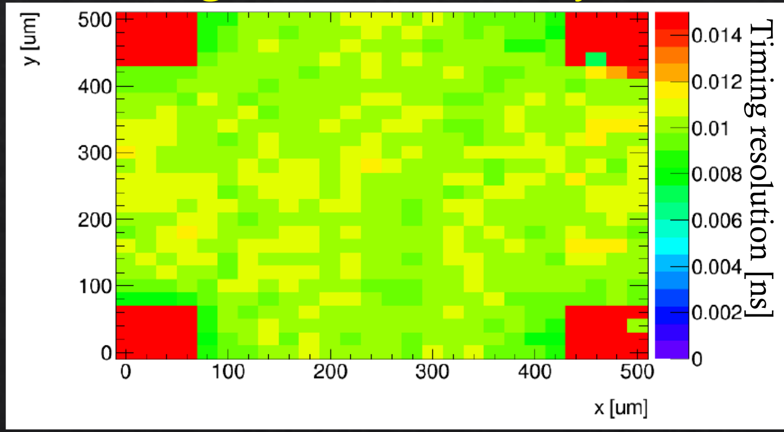
150um Al size 450um Al size

Smaller Electrode size showed quite linear behavior of charge ratio





Timing resolution is very uniform



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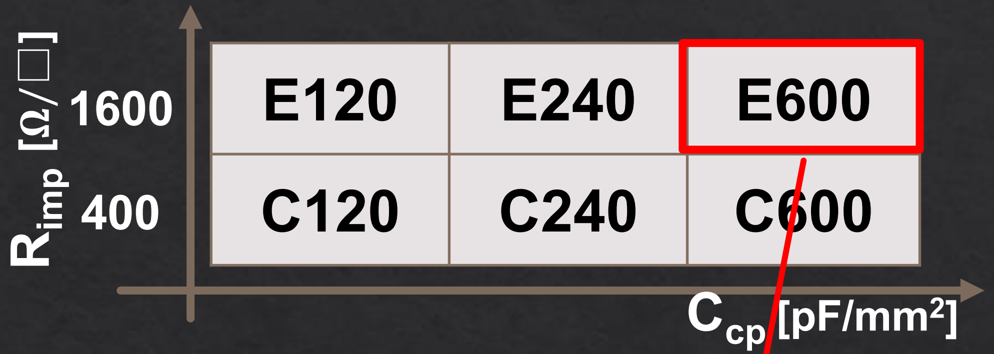
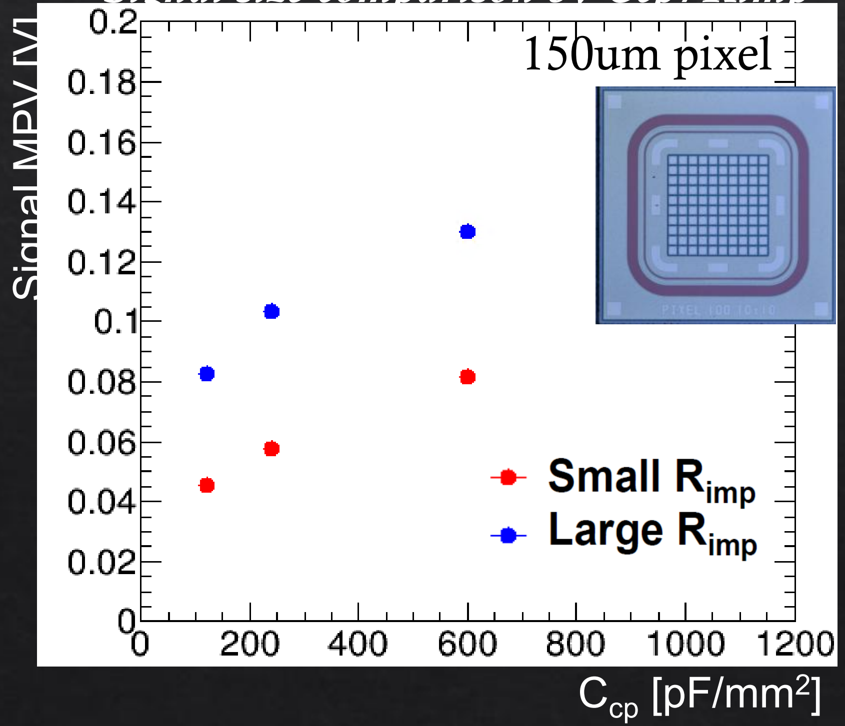
How small electrode could we achieve?

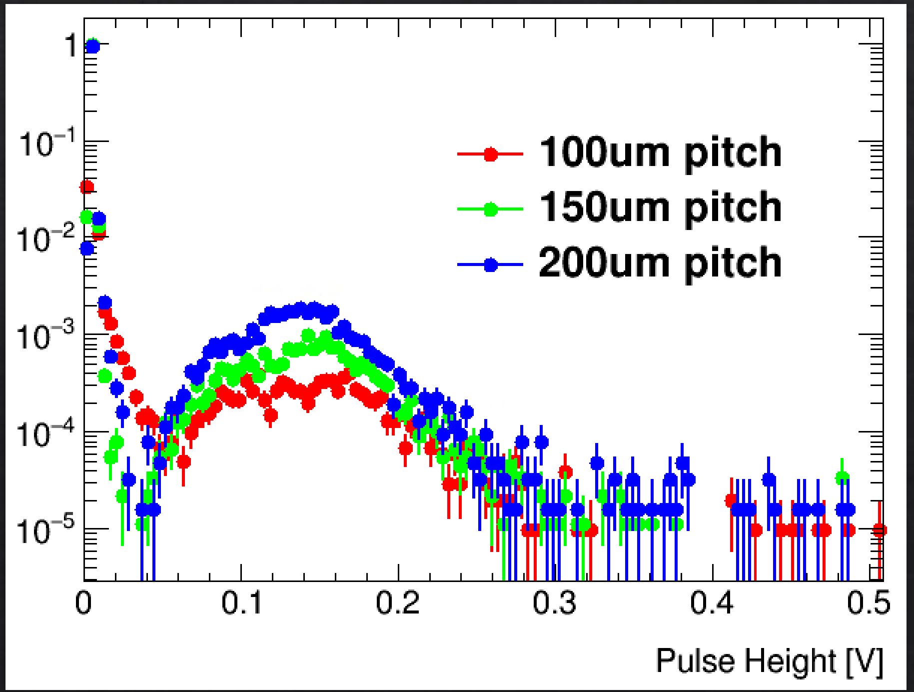
- Compared signal size of 6 types C_{cp}/R_{imp}.
  - 150um pixel sensors
  - Two n+ resistivity types and 3 Ccp types
- Compared signal size of 3 pixel size
  - 100/150/200um pitches are compared.

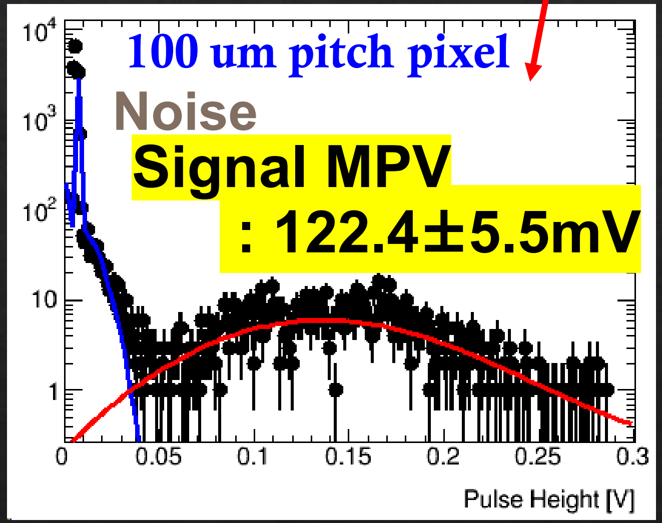


Signal size comparison by Ccp/Rimp



Pulse height comparison by pixel pitches





Successfully developed Good S/N 100um pitch pixel detector!

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AC-LGAD collaboration