Development of AC-LGAD detector with finer pitch electrodes for high energy physics experiments

Sayuka Kita[1], Ikumi Goya[1], Tomoka Imamura[1], Koji Nakamura[2], Kazuhiko Hara[1]

University of Tsukuba[1], KEK[2]

Development of AC-LGAD detector with finer pitch electrodes for high energy physics experiments

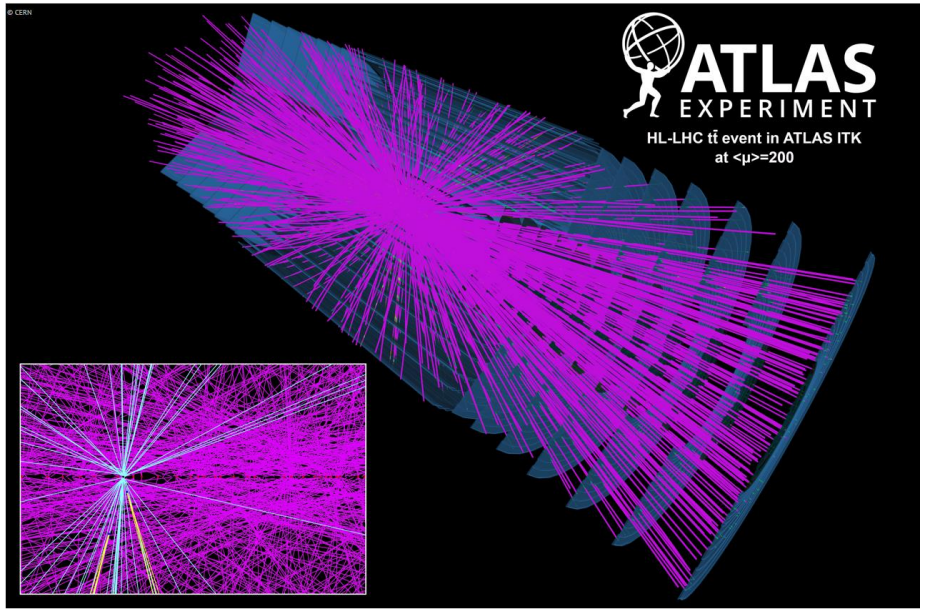
Sayuka Kita[1], Ikumi Goya[1], Tomoka Imamura[1], Koji Nakamura[2], Kazuhiko Hara[1]

University of Tsukuba[1], KEK[2]

Detector for high energy physics experiments

High energy hadron collider
→ Higher particle density environment

e.g. expected pile up events for HL-LHC



Tracking becomes difficult due to pile up.
→ **Timing information** may help

Requirement for inner tracker in future hadron collider

Timing resolution ~30ps + **Spatial resolution** ~O(10)um + **Radiation tolerance** ~$3\times10^{15} n_{eq}/cm^2$

One of strong candidates

LGAD sensor

It is difficult to get spatial resolution with standard LGAD design.

We are developing AC-LGAD to solve this problem

AC-LGAD detector

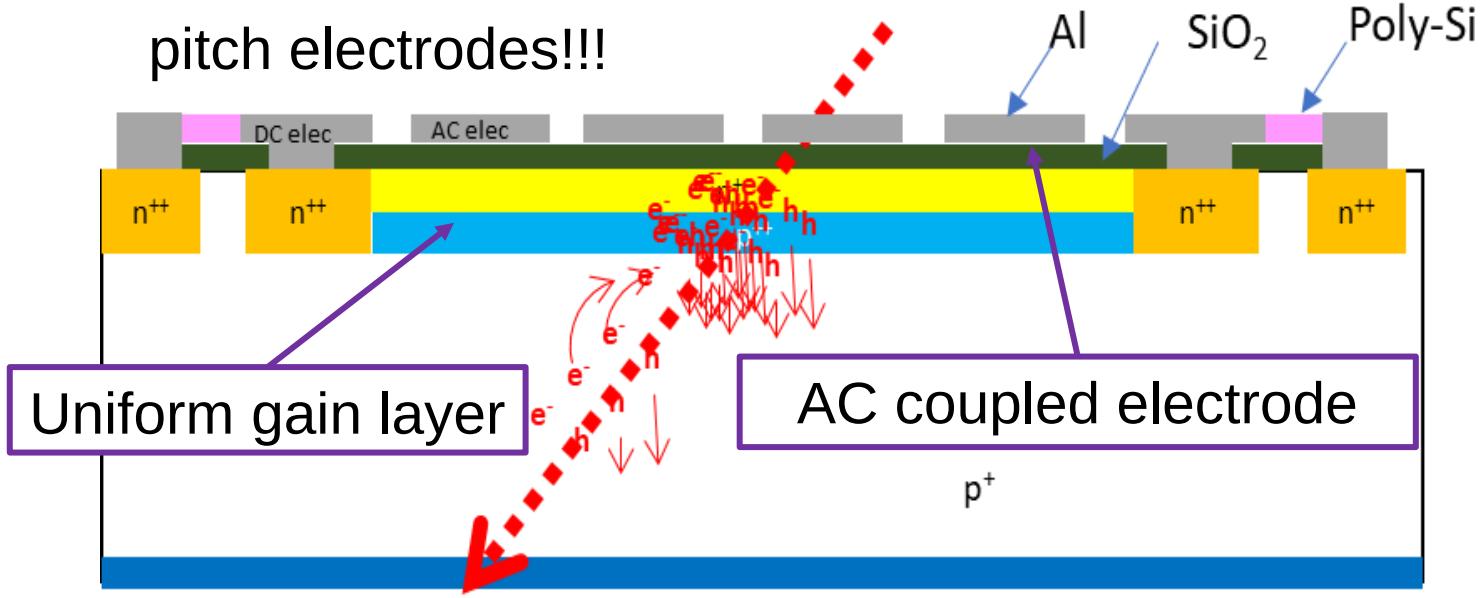
DC-LGAD (standard LGAD)

Individual gain layer for each electrode

finer pitch : non-negligible inactive area exists

AC-LGAD

100% of fill factor with finer pitch electrodes!!!



Potential issues of AC-LGAD

Crosstalk in n^+ layer

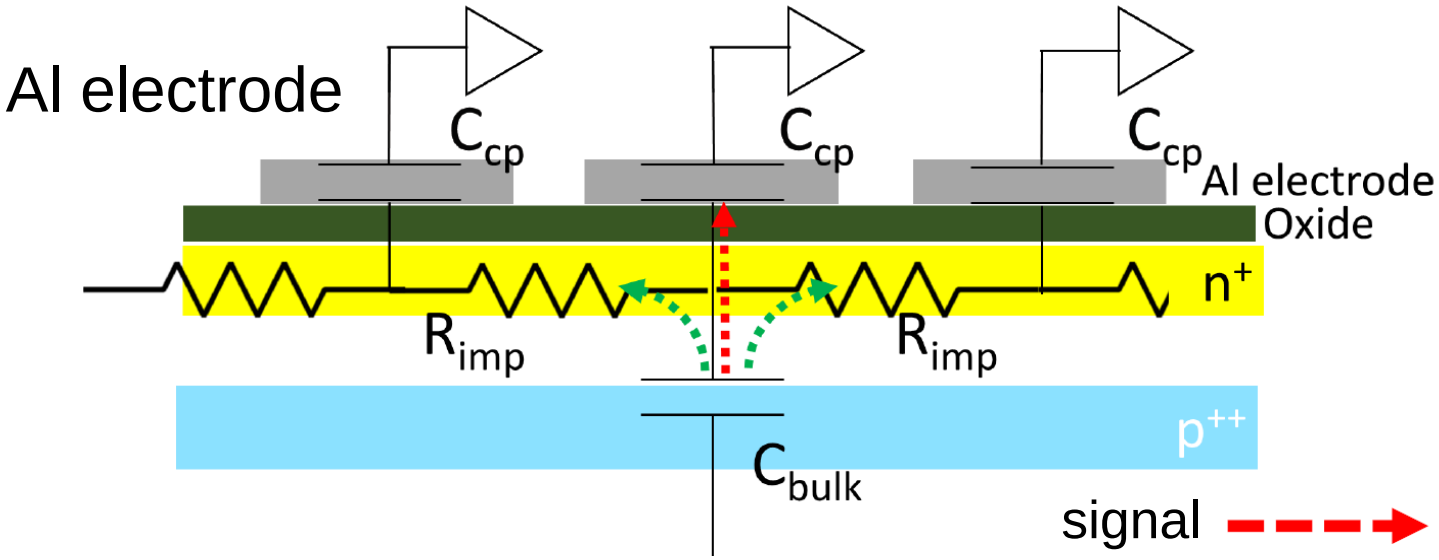
: critical in case of high occupancy environment

Smaller signal due to AC-coupling

: bad signal-to-noise ratio

Signal readout model

What is the signal readout mechanism of AC-LGAD ?



Two important parameters

R_{imp} → **larger is better**
: n^+ doping concentration

C_{cp} → **larger is better**
: Electrode size
smaller electrode → **smaller C_{cp}**
: Oxide thickness
thinner oxide → **larger C_{cp}**

Signal size
: impedance ratio of R_{imp} and C_{cp}

readout charge ← $Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$ ← generated charge

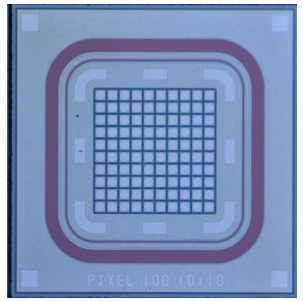
To keep larger signal and smaller crosstalk in finer pitch electrodes, larger n^+ resistivity and thinner oxide

Prototype samples

To cover whole inner tracker with AC-LGAD sensors…

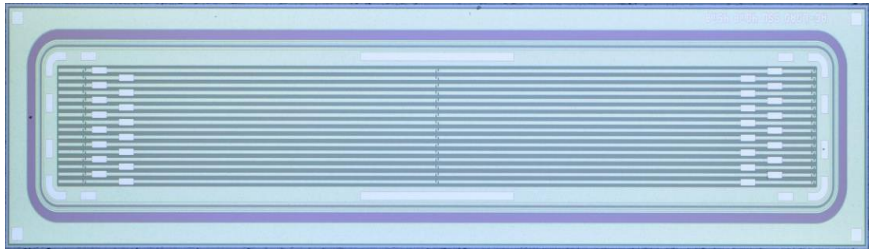
We prototyped following sensors in collaboration with HPK.

Electrode shape



Pixel

50, 100, 150, 200 um pitch
(electrode size
:40, 90, 140, 190um □)



Strip

pitch : 80um
length : ~1cm
width : 40, 45um

Parameter variation

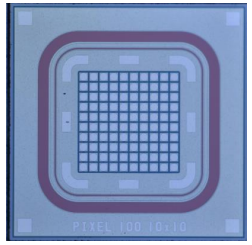
R_{imp} [Ω/□] \ C_{cp} [pF/mm²]	120	240	600
400	✓	✓	✓
1600	✓	✓	✓

6types

Pixel signal height (R_{imp} and C_{cp} dependence)

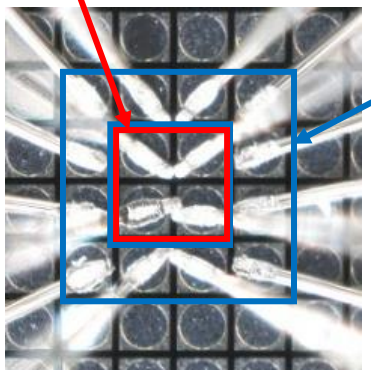
Samples

- 150um pitch pixel
- 6 parameter samples
  - ✓ 2 types of R_{imp} (n^+ resistivity)
  - ✓ 3 types of C_{cp} (oxide thickness)



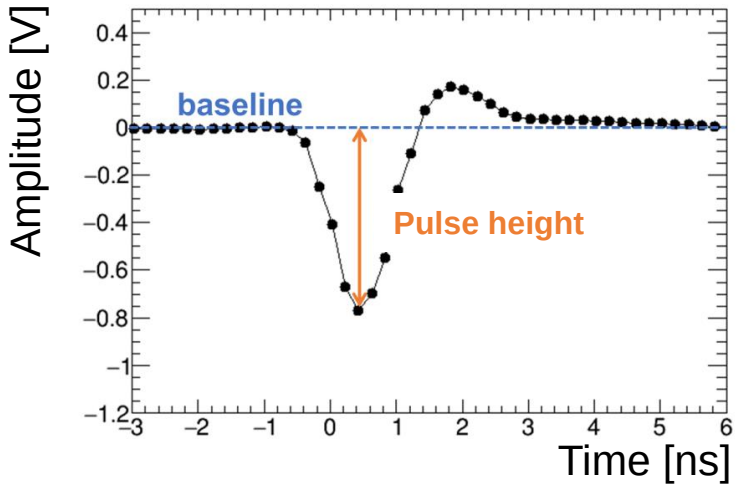
Readout channels

2x2 : analysis

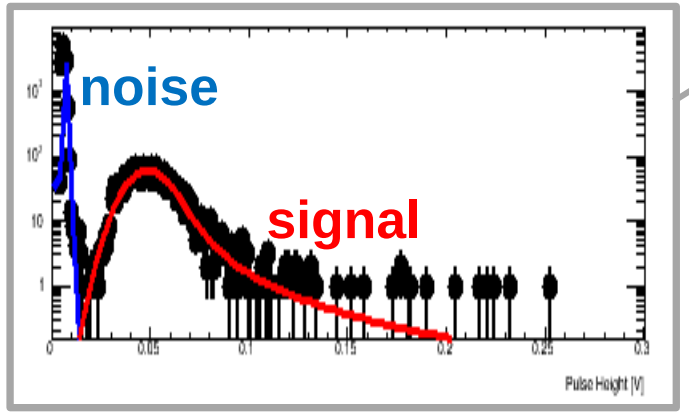


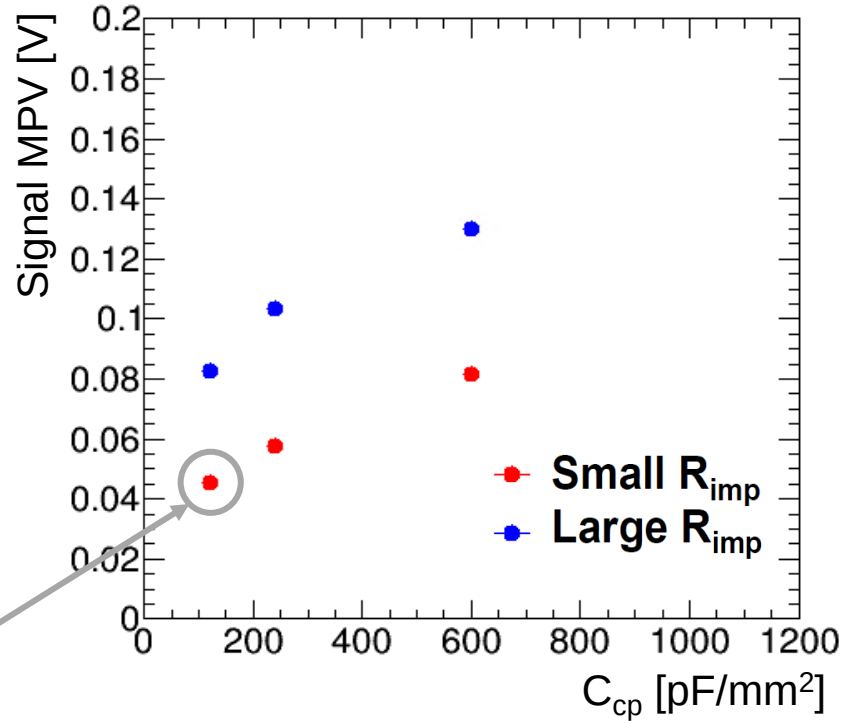
surrounded 12pixels ↑ remove crosstalk effect

Pulse shape



Pulse height distribution



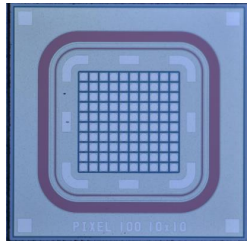


Larger R_{imp} and C_{cp} make signal larger

Pixel signal height (R_{imp} and C_{cp} dependence)

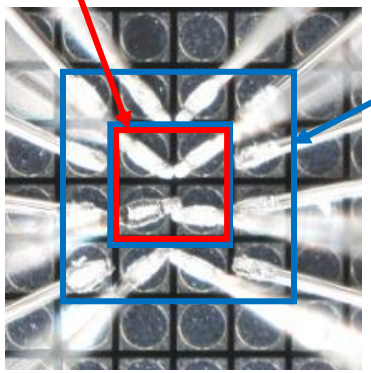
Samples

- 150um pitch pixel
- 6 parameter samples
  - ✓ 2 types of R_{imp} (n^+ resistivity)
  - ✓ 3 types of C_{cp} (oxide thickness)



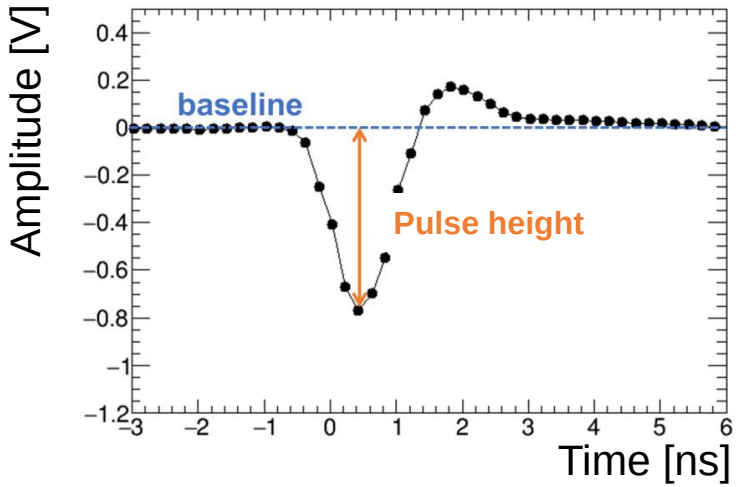
Readout channels

2x2 : analysis

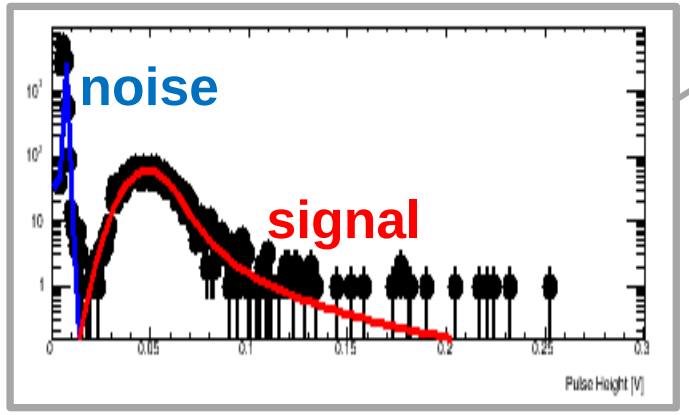


surrounded 12pixels ↑ remove crosstalk effect

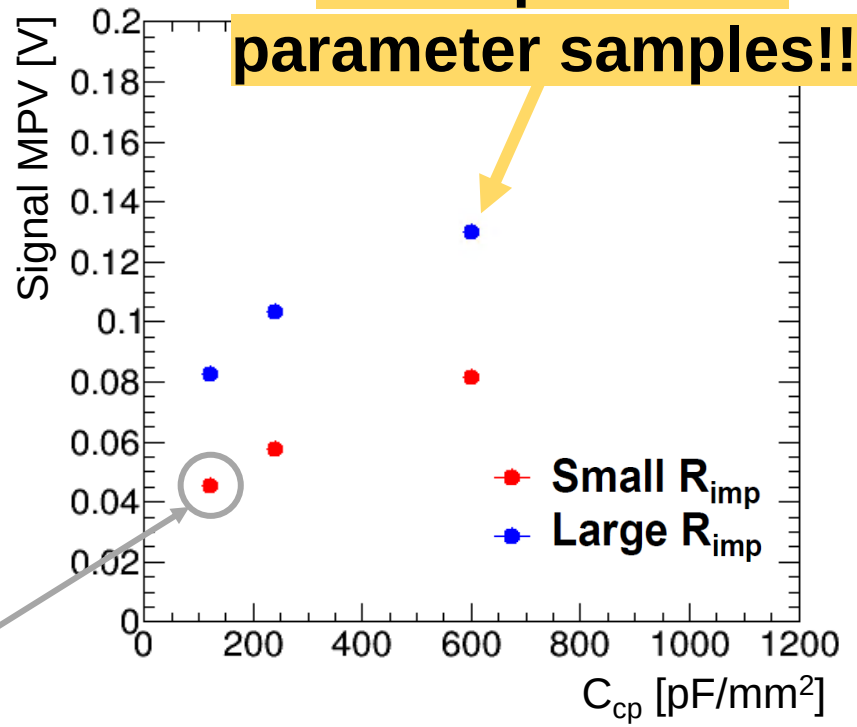
Pulse shape



Pulse height distribution



Best optimized parameter samples!!



Larger R_{imp} and C_{cp} make signal larger

Comparison of pixel pitches

Test samples with different pitches (max R_{imp} and max C_{cp})

Clear signal observed

200um pitch

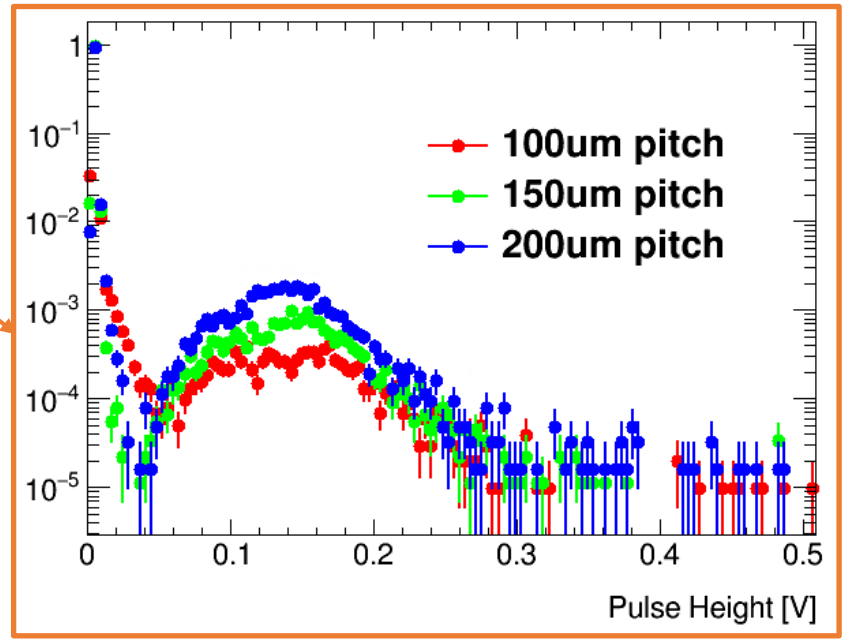
100um pitch

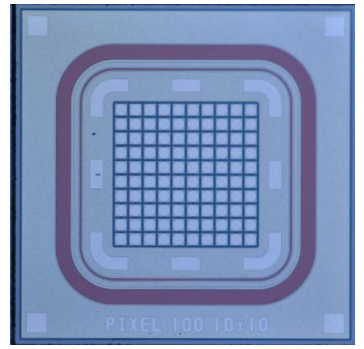
150um pitch

Poor SN ratio

50um pitch

Small C_{cp}?
Poor wirebond quality?

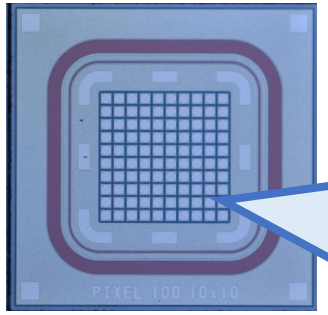




Good SN separation!

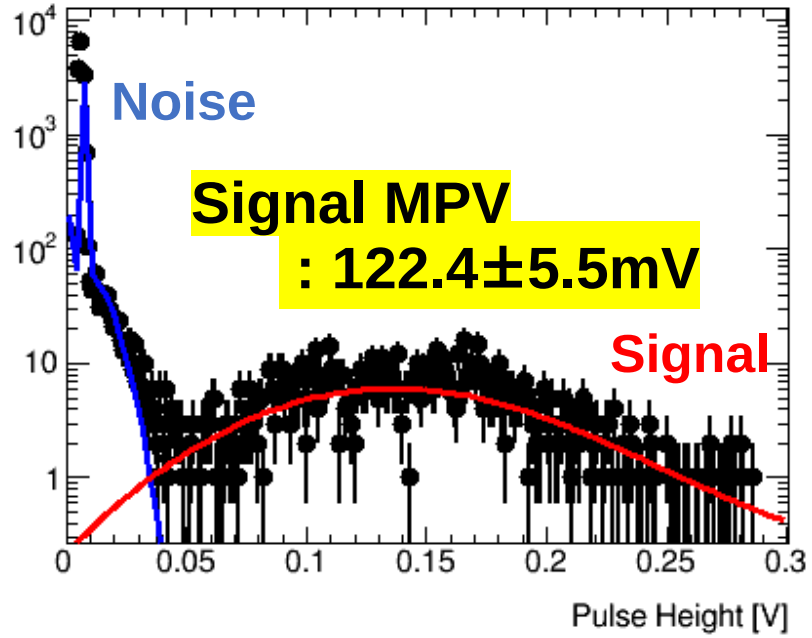
100um pitch pixel sensor is successfully working!

Performance of 100um pitch Pixel sensor

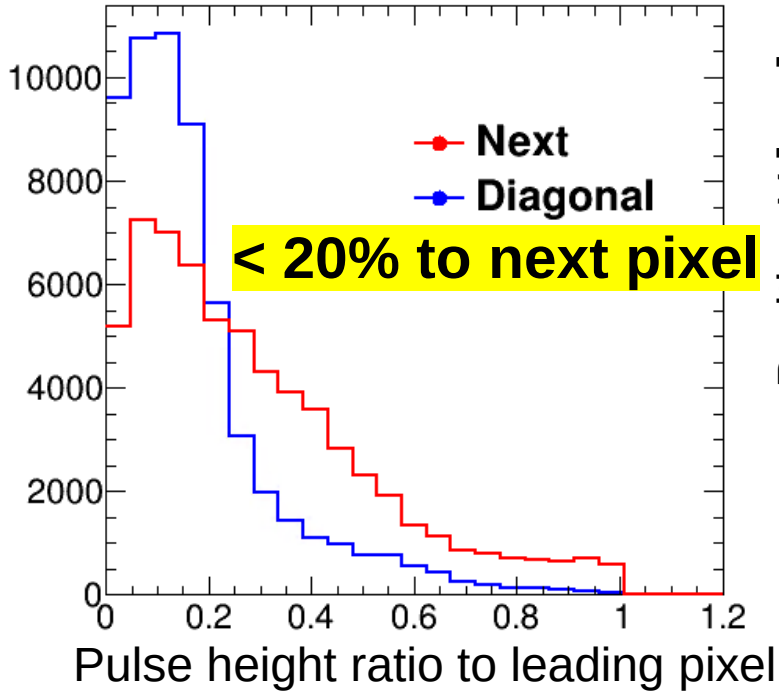


Can 100um pitch pixel sensor perform as an inner tracker?

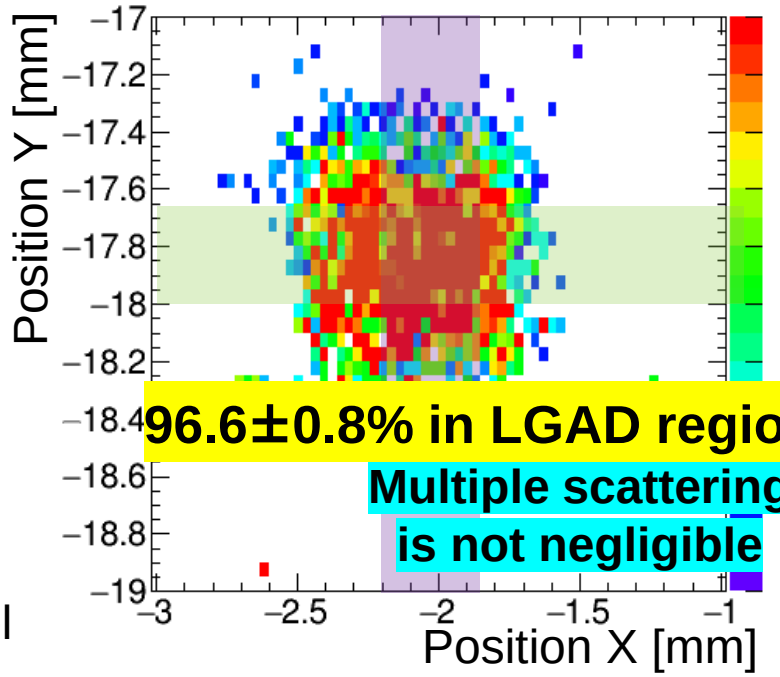
Signal size distribution



Crosstalk size



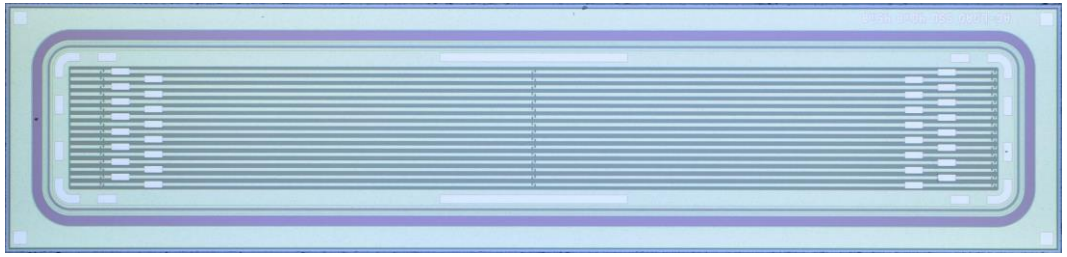
Efficiency map
(800MeV electron testbeam)



100um pitch pixel sensor has good performance
→ Next step : larger sensor (e.g. 2x2cm)
with readout electronics (ASIC)

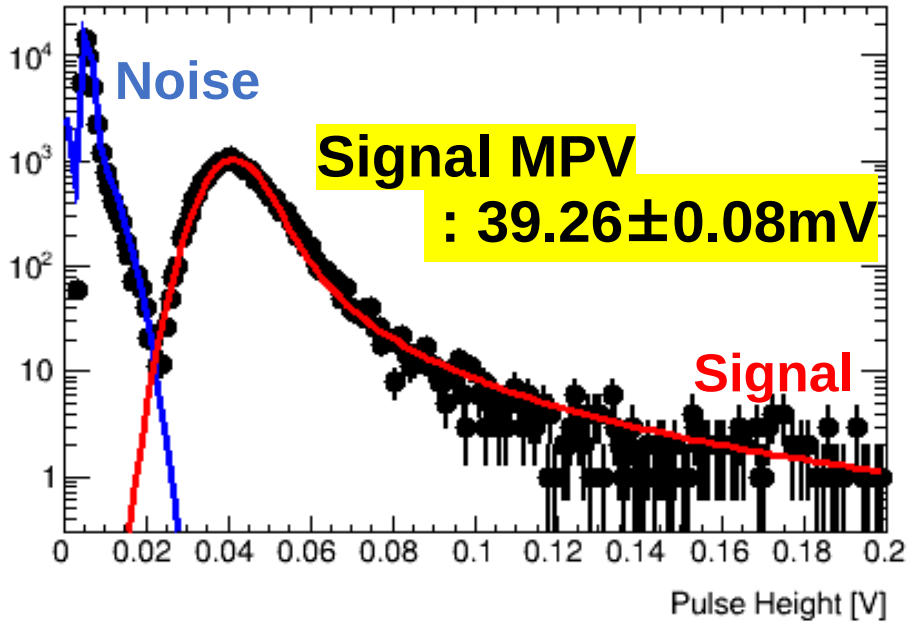
Strip sensor performance

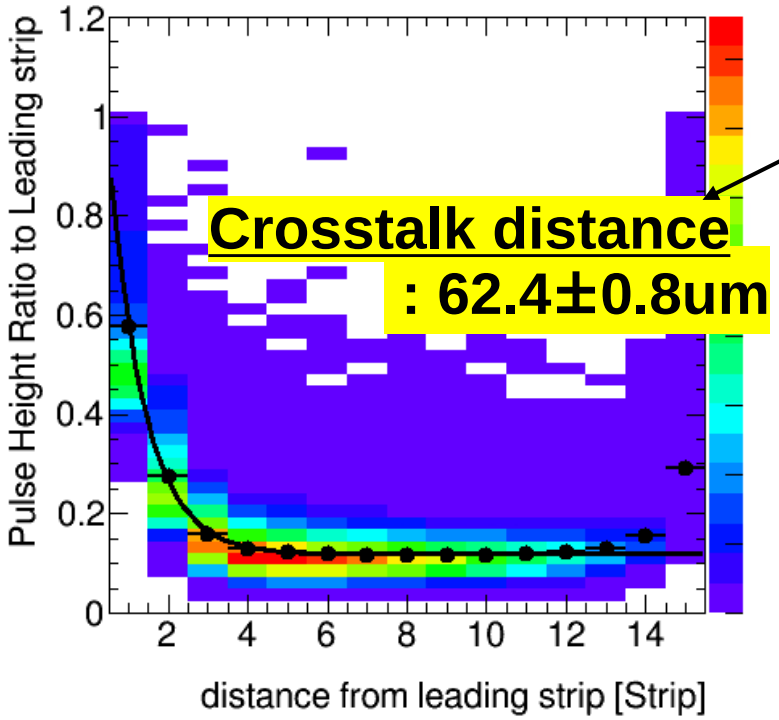
Strip sensor is necessary : pixel cannot cover full volume of inner tracker…



Max R_{imp} and max C_{cp} strip sample
- ✓ readout : 16strips
- ✓ electrode length x width : 9880 x 45um

Pulse height distribution





distance constant of fitted exponential

80um pitch strip sensor has good performance

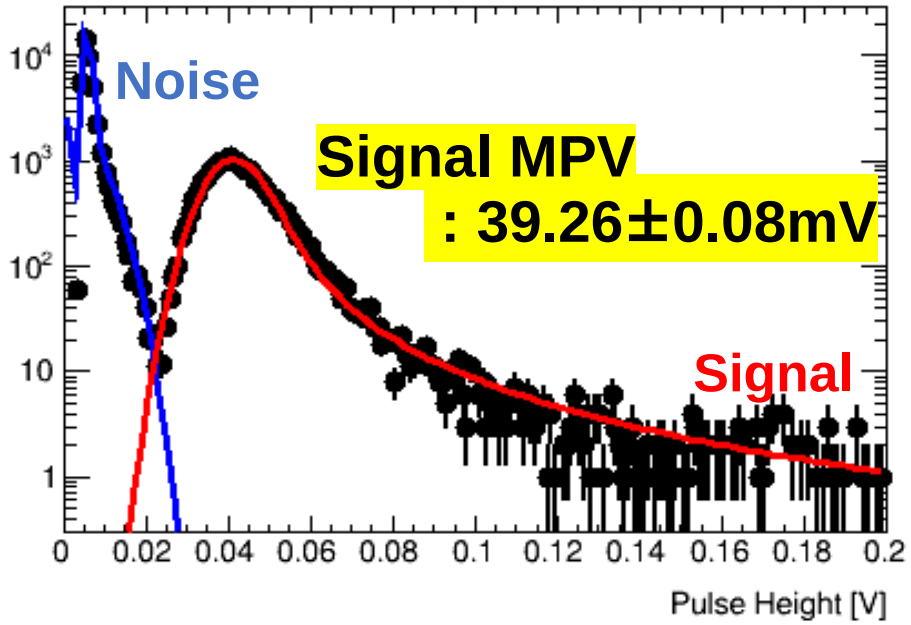
Strip sensor performance

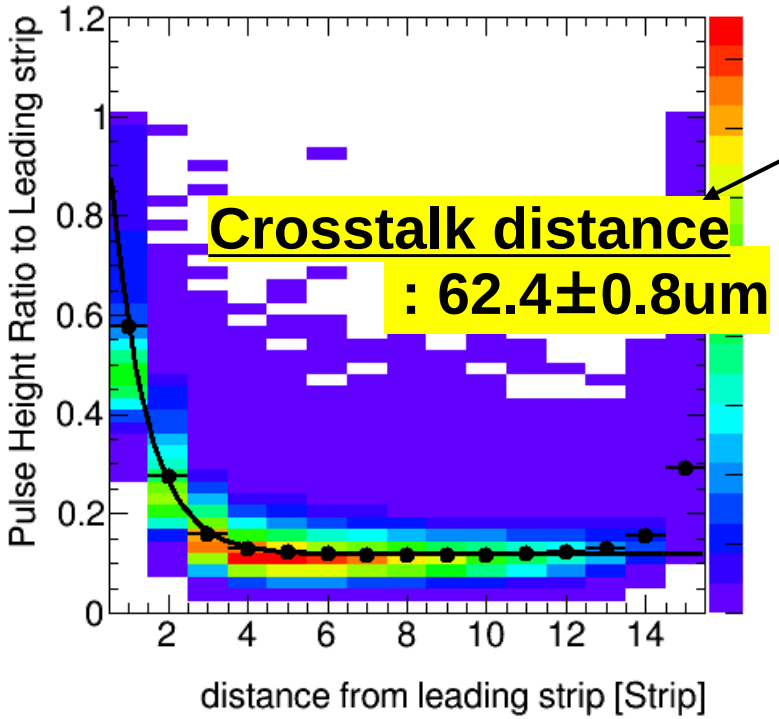
But

…ixel cannot cover full volume of inner tracker…

Max R_{imp} and max C_{cp} strip sample
- ✓ readout : 16strips
- ✓ electrode length x width : 9880 x 45um

Pulse height distribution



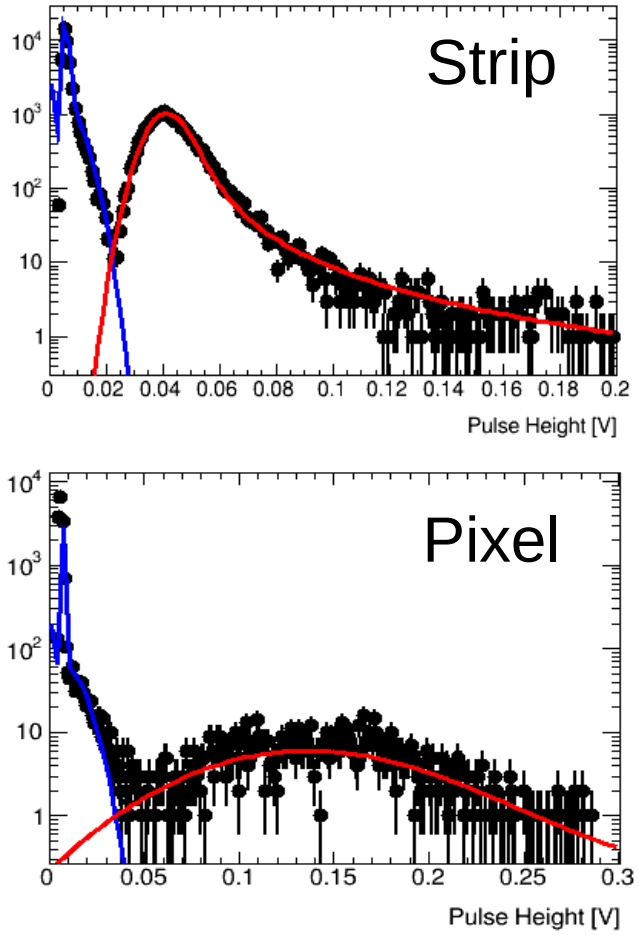


distance constant of fitted exponential

80um pitch strip sensor has good performance

Signal height of strip and pixel

Comparison of pulse height distribution between strip and pixel …

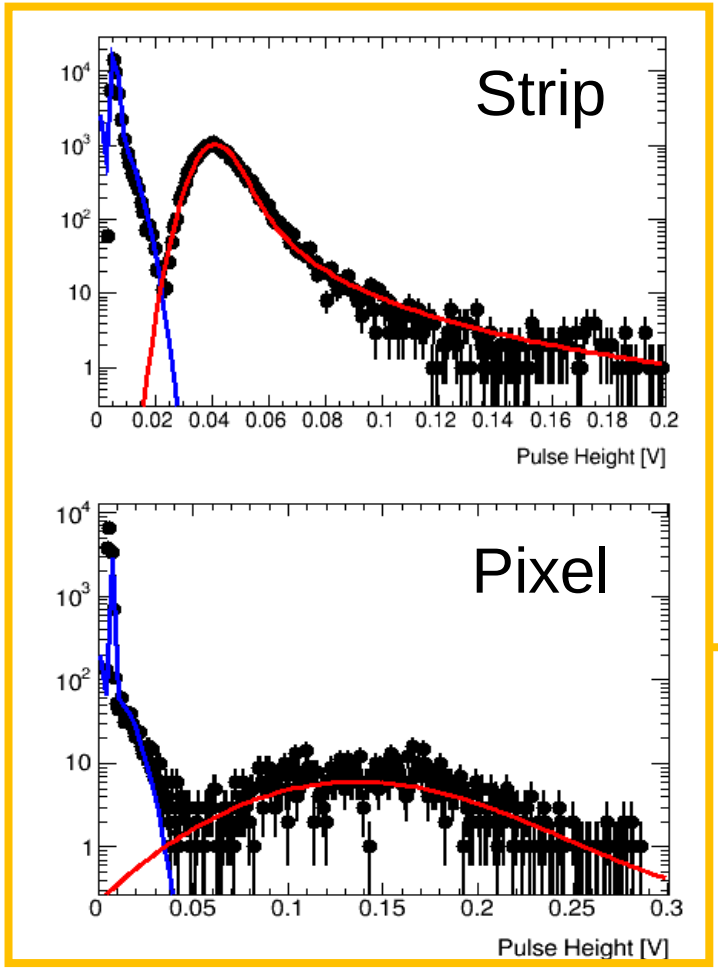


	Strip	Pixel
Area of electrode	9880x45 um^2	100x100 um^2
C_{cp} size of electrode	large	small
Signal height (**expected** from C_{cp})	large	small
Signal height (**actual result**)	39.26 ± 0.08mV small	122.4 ± 5.5mV large

Why signal height is Strip < Pixel
despite electrode area is Strip > Pixel?

Signal height of strip and pixel

Comparison of pulse height distribution between strip and pixel …



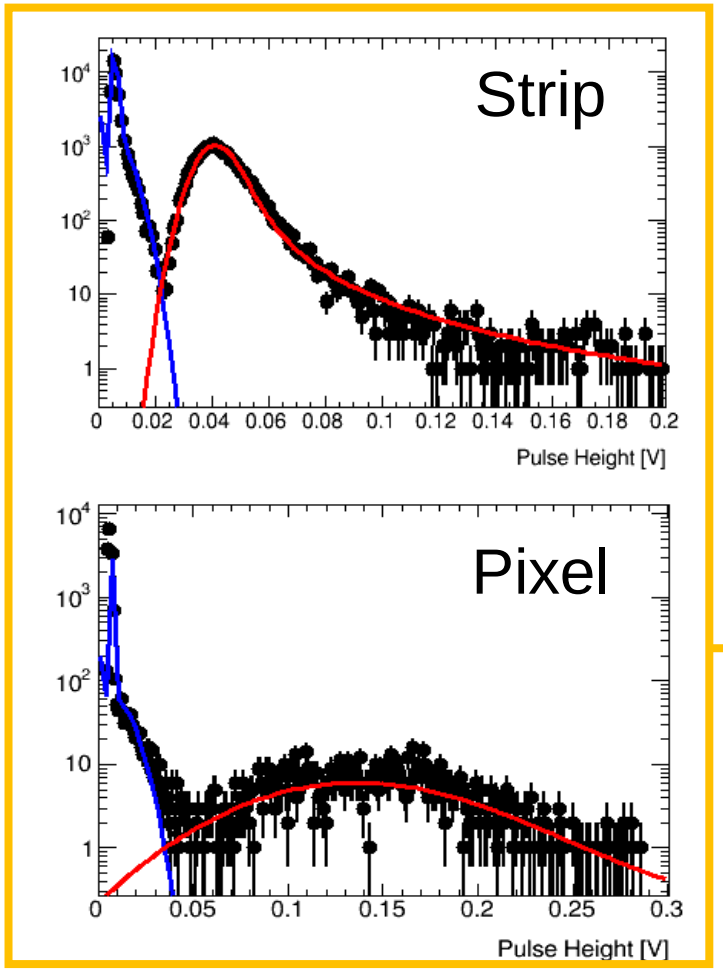
	Strip	Pixel
Area of electrode	9880x45 um^2	100x100 um^2
C_{cp} size of electrode	large	small
Signal height (**expected** from C_{cp})	large	small
Signal height (**actual result**)	39.26 ± 0.08mV small	122.4 ± 5.5mV large

Why signal height is Strip < Pixel
despite electrode area is Strip > Pixel?

Signal height of strip and pixel

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

Comparison of pulse height distribution between strip and pixel .



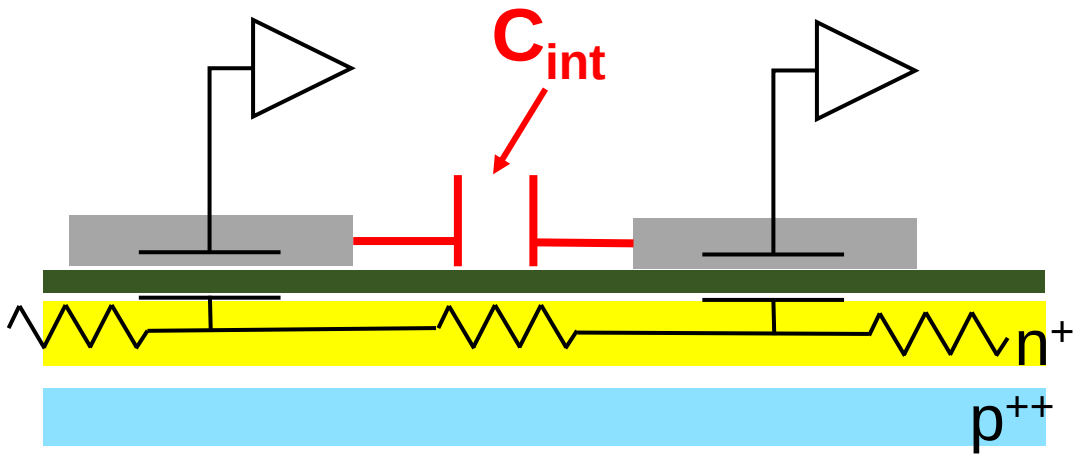
	Strip	Pixel
Area of electrode	9880x45 um^2	100x100 um^2
C_{cp} size of electrode	large	small
Signal height (**expected** from C_{cp})	large	small
Signal height (**actual result**)	39.26 ± 0.08mV small	122.4 ± 5.5mV large

Why signal height is Strip < Pixel
despite electrode area is Strip > Pixel?

Inter electrode capacitance

Result of small strip signal size comes from inter electrode capacitance effect

Inter electrode capacitance

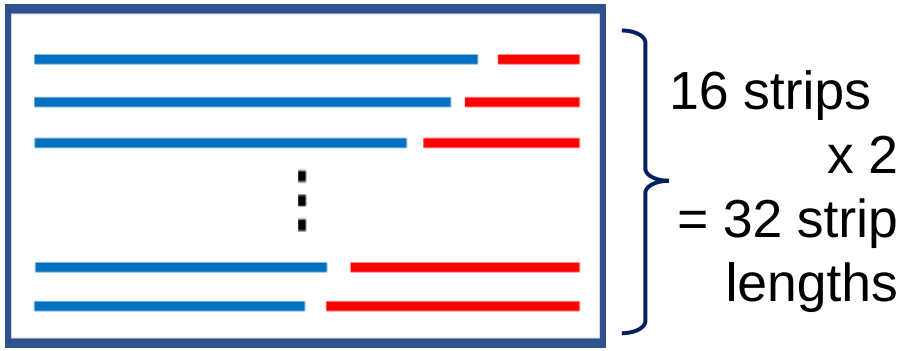


- ✓ equivalent circuit : capacitance between electrodes
- ✓ C_{int} induces charge flow to next electrode
  - → Introduce additional crosstalk by this capacitance
- ✓ Strip sensor has larger C_{int}

To check C_{int} effect…

The sample has 32 variations of strip length by cutline

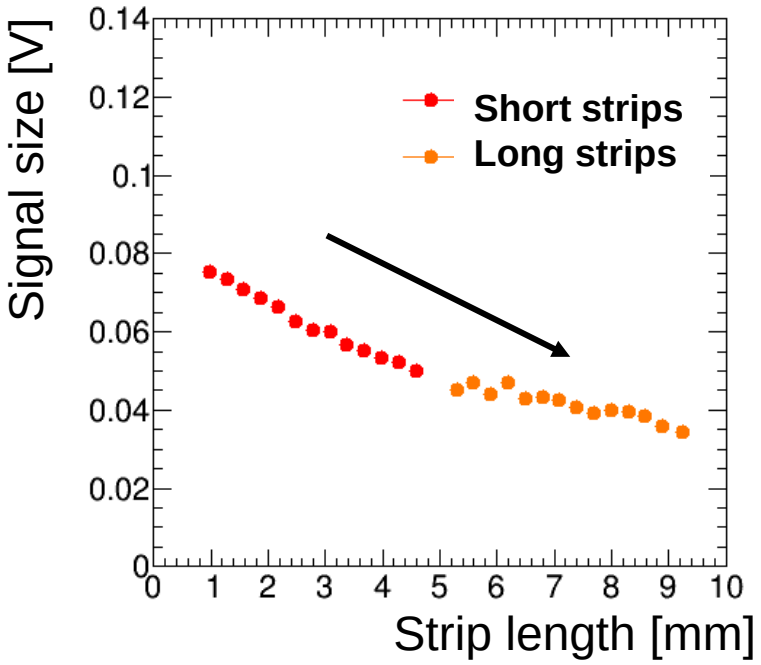
Pattern diagram

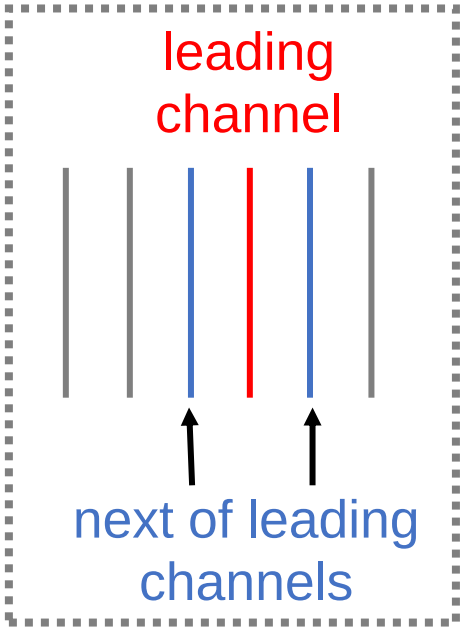


Compare signal from different lengths of strip

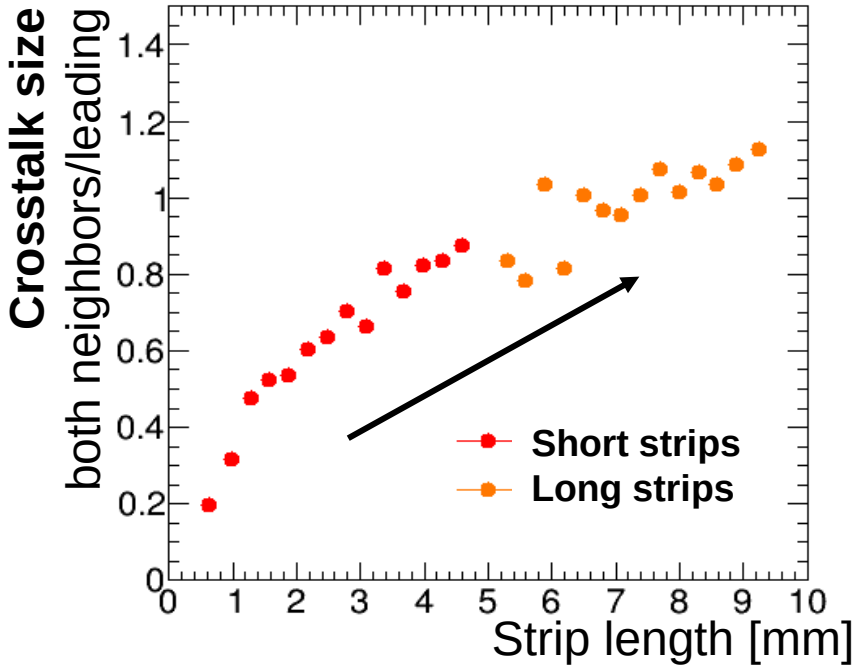
Measurement of strips with cutline

Signal size





Crosstalk size

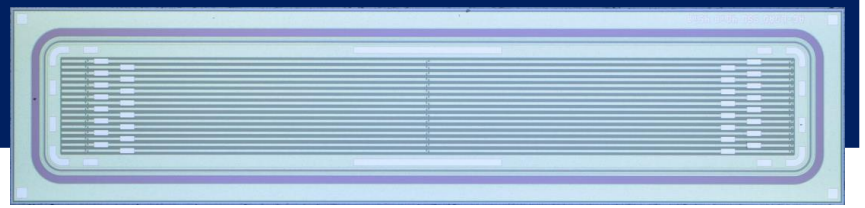


Strip sensor has large C_{int} : Smaller signal and larger crosstalk

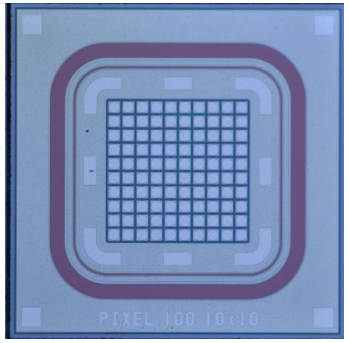
→ Sensors with longer strip length to cover large tracker area might be difficult…

(e.g. 80um pitch and length much longer than 10mm isn't realistic in current design)

Conclusion



For inner tracker in hadron collider,
finer pitch AC-LGAD sensors are prototyped with HPK.



Parameter optimization was performed.

Best type sensor (larger R_{imp} and C_{cp}) : Larger signal height and smaller crosstalk !

successfully developed !!

Pixel (100um pitch) → **larger area prototype** with **ASIC**

Strip (80um pitch) C_{int} makes strip signal smaller
→ **Test longer strip sensor** to check if the crosstalk effect is saturated

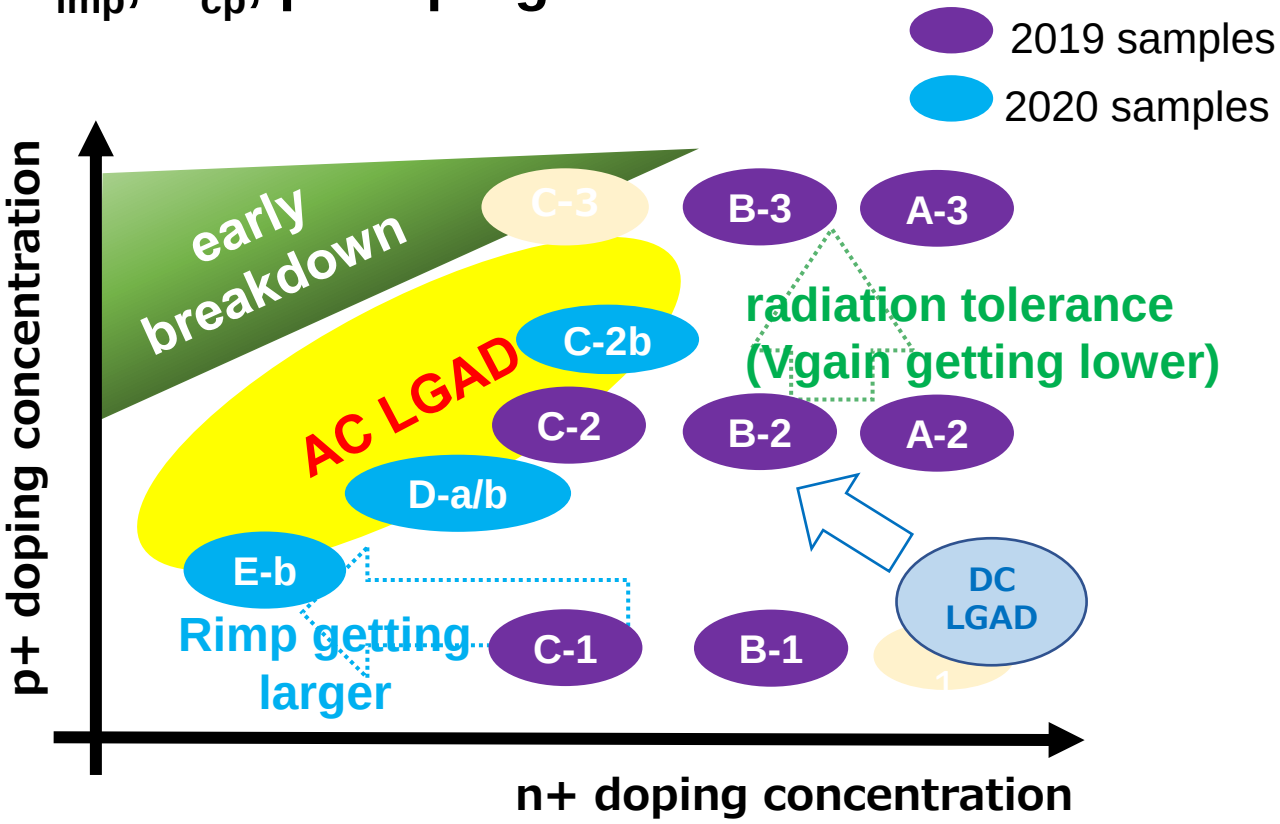
Todo
- Timing resolution
- radiation tolerance

backup

Samples

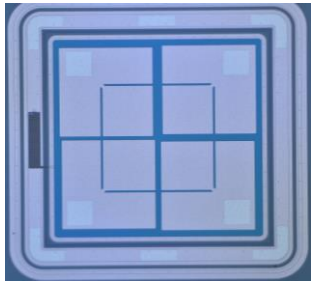
2019-2020

R_{imp}, C_{cp}, p^+ doping concentration

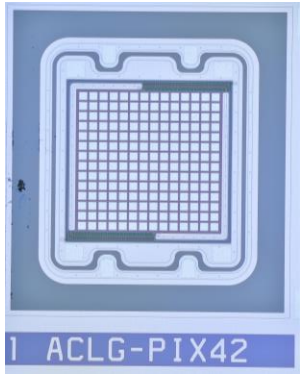


Electrode shape

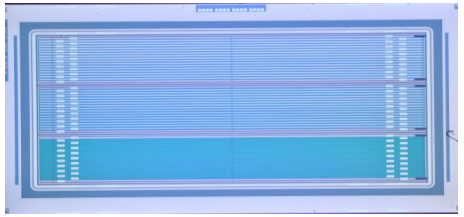
Pad (4ch)
500um x 500um



Pixel
50um pitch
42um x 42um

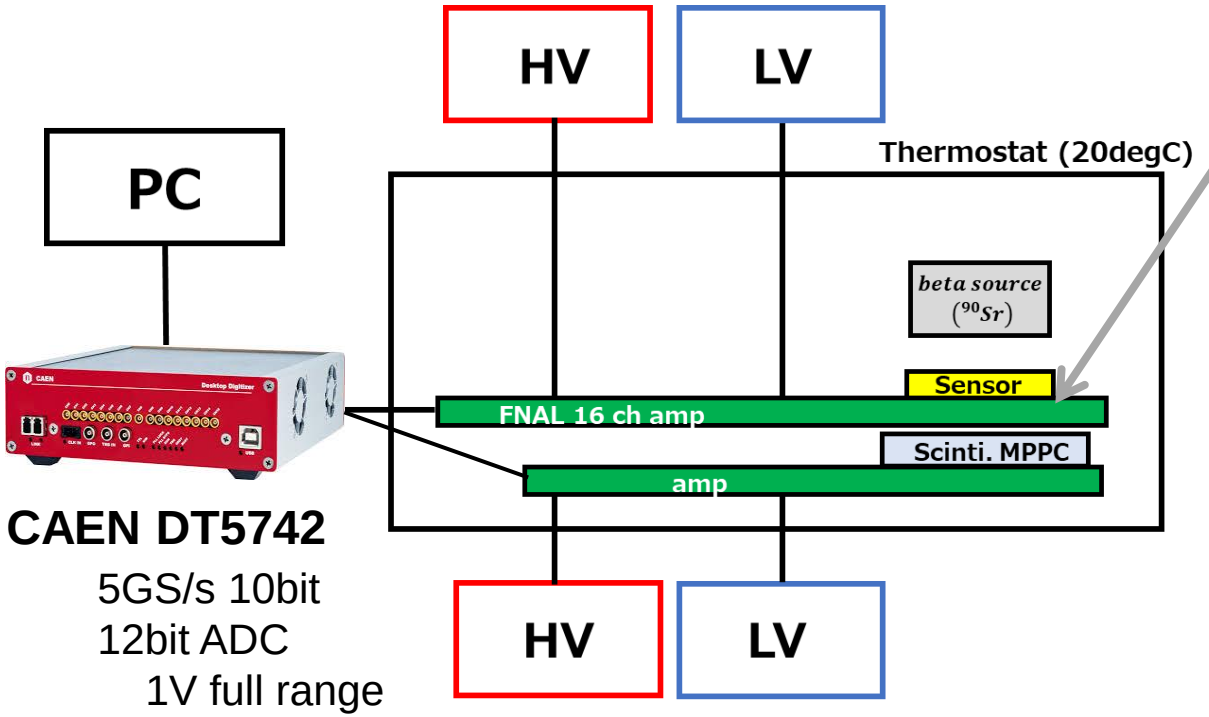


Strip (16chx3)
80um pitch
9880um
x 30, 35, 40, 45um



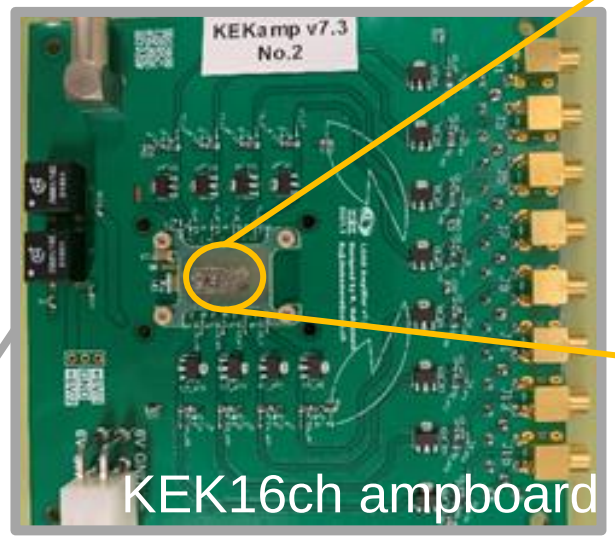
Signal size measurement

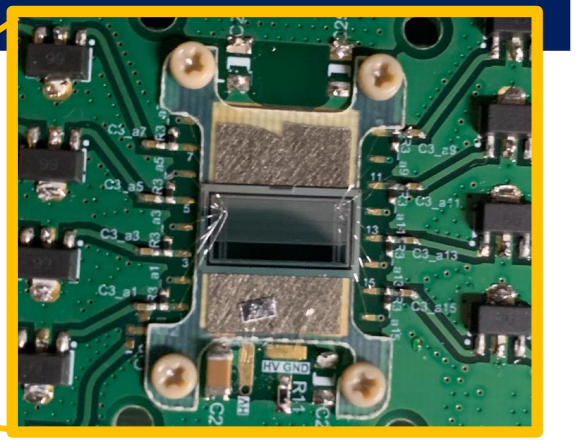
Beta-ray measurement setup



CAEN DT5742

5GS/s 10bit
12bit ADC
1V full range

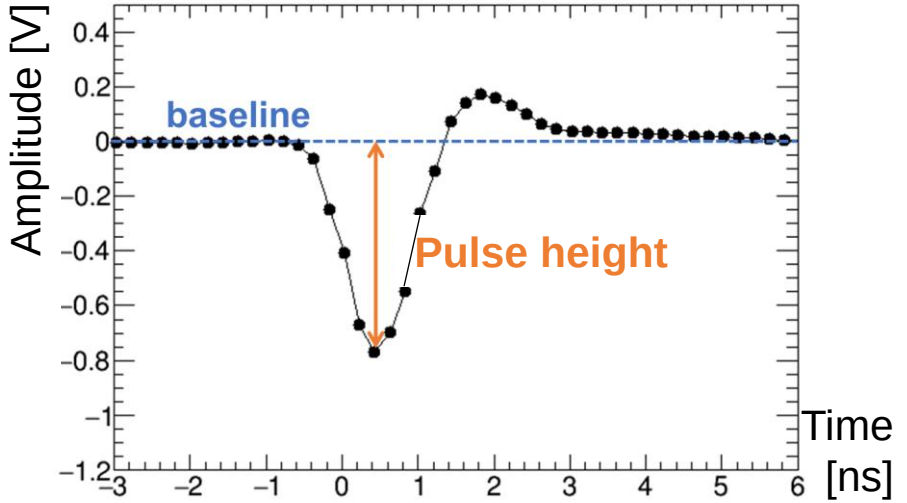




Sensor is on conductive tape
→ supply HV behind

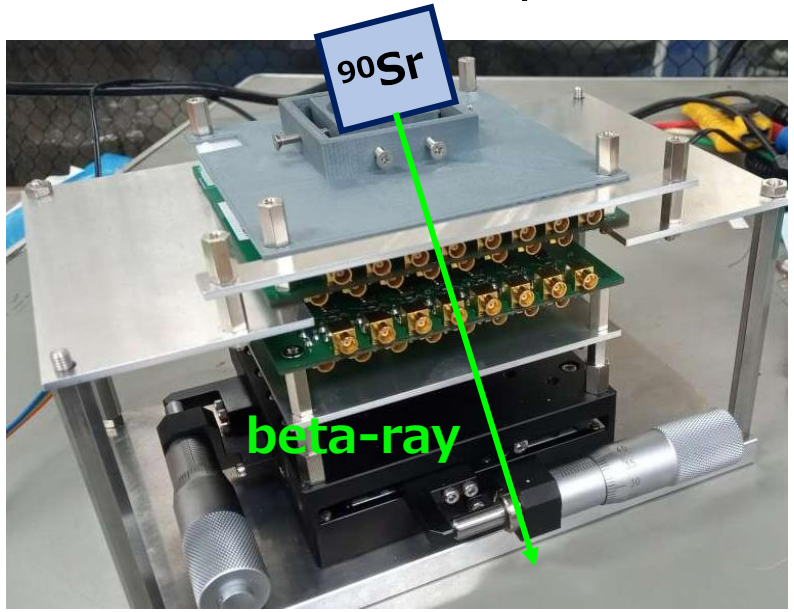
- ✓ Sensor is in thermostat keeping 20degC.
- ✓ Trigger is scinti. with MPPC

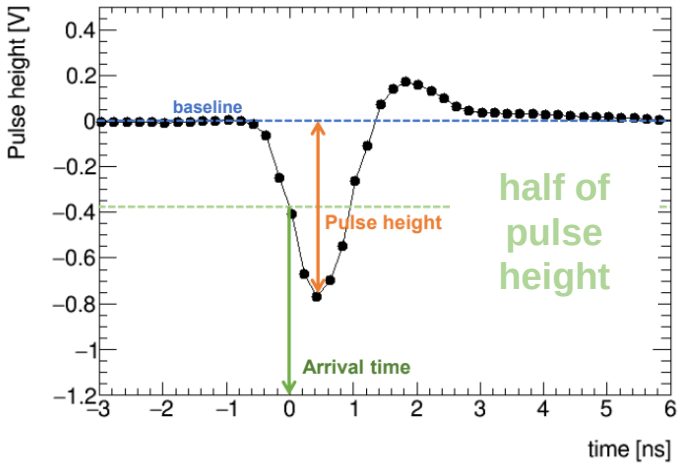
Pulse shape



Timing resolution

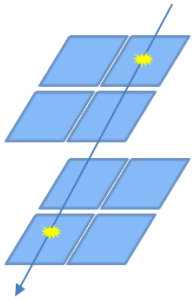
1Pad sensor on ampboard stacked





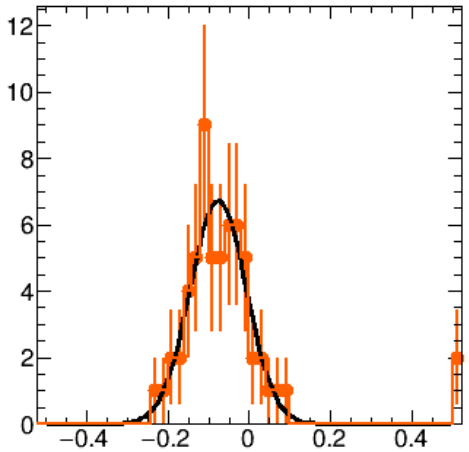
fitted arrival time difference by gaussian

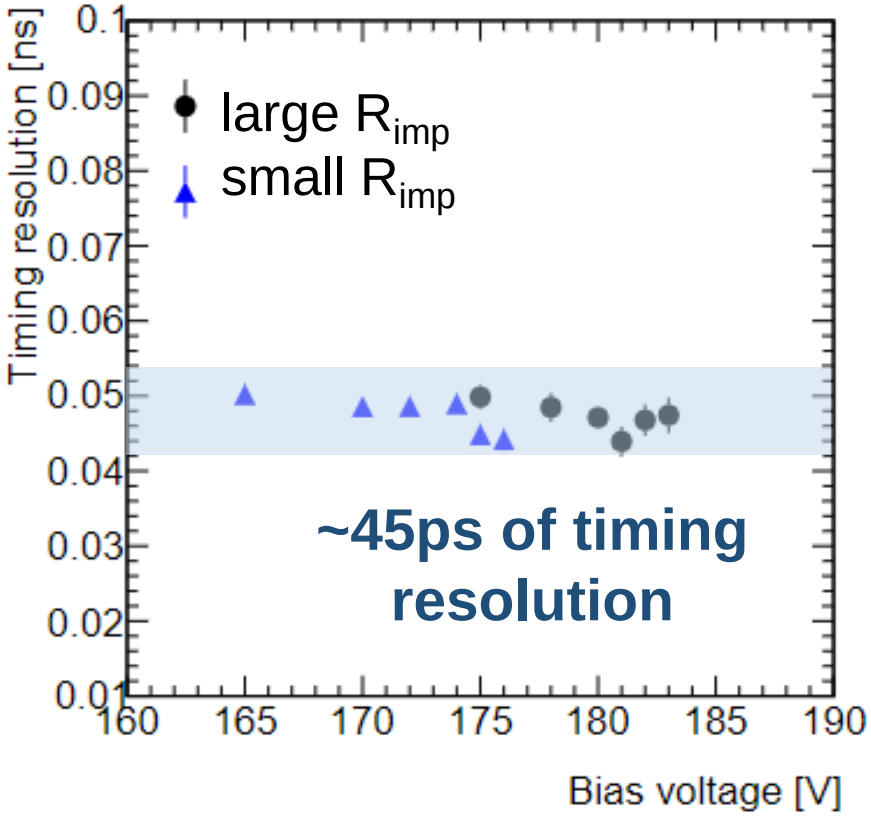
→ calculated timing resolution



Timing resolution

$$\sigma_t = \sigma(T_1 - T_2)/\sqrt{2}$$





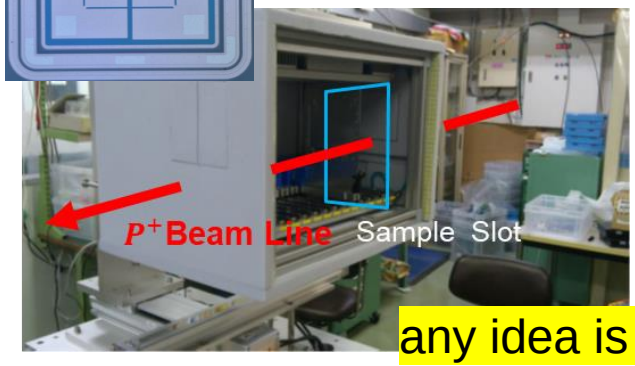
- ~45ps of timing resolution
- Why is not 30ps?

→ need to investigate

Radiation tolerance

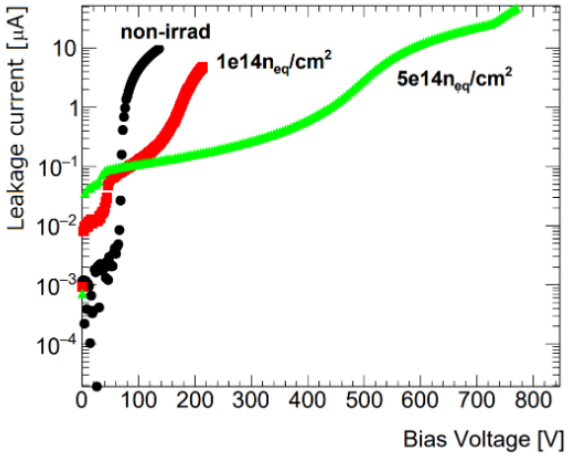
70MeV Proton beam @ CYRIC (Tohoku University)

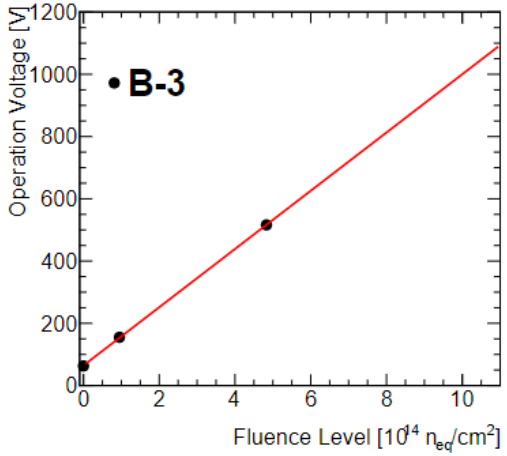
Pad B-3



- V_{bd} is getting larger with irradiated level
- > 700V cannot supply because of sensor design

any idea is needed for accepter removal



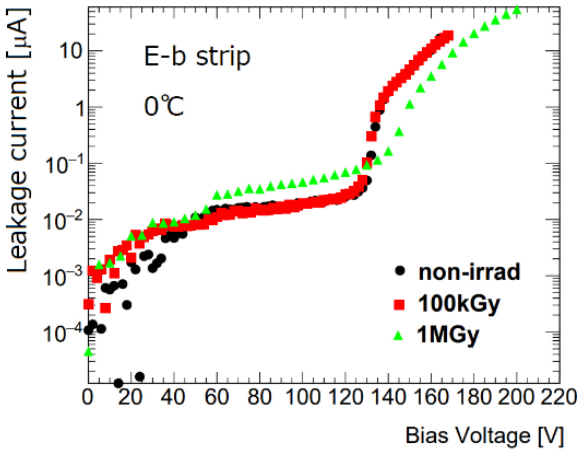


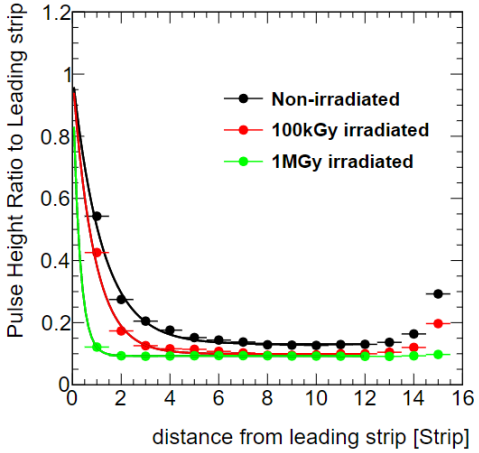
^{60}Co gamma irradiation @ Takasaki gamma facility

Strip E-b

- Vbd is not change large
- xtalk is supressed

gamma makes sensor performance good





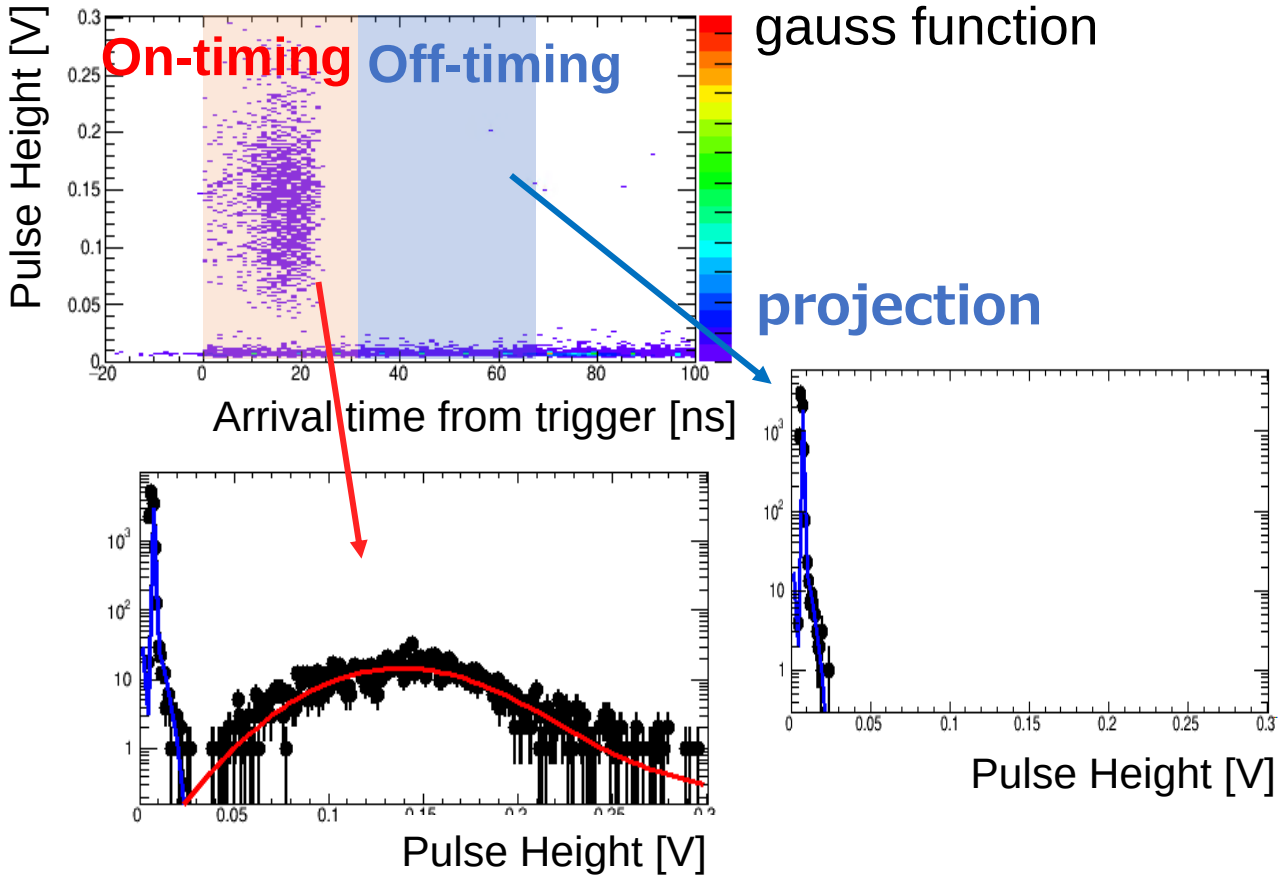
Pulse height analysis

R_{imp} [Ω/□] \ C_{cp} [pF/mm²]	120	240	600
400	✓	✓	✓
1600	✓	✓	✓

Pulse height distribution

fit off-timing by asymmetric gauss

→ fit on-timing by landau convoluted gauss function

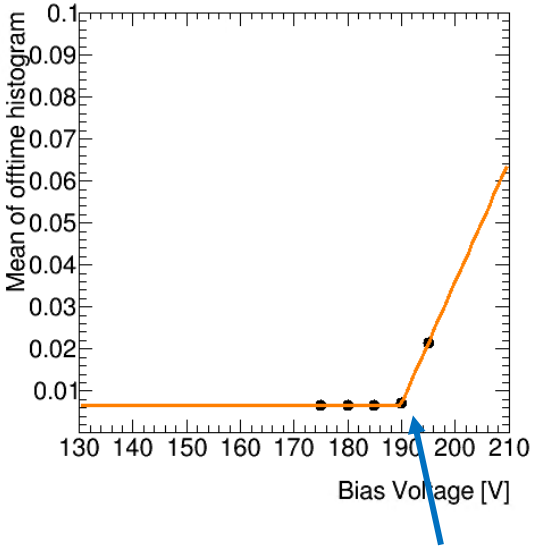


Operation voltage

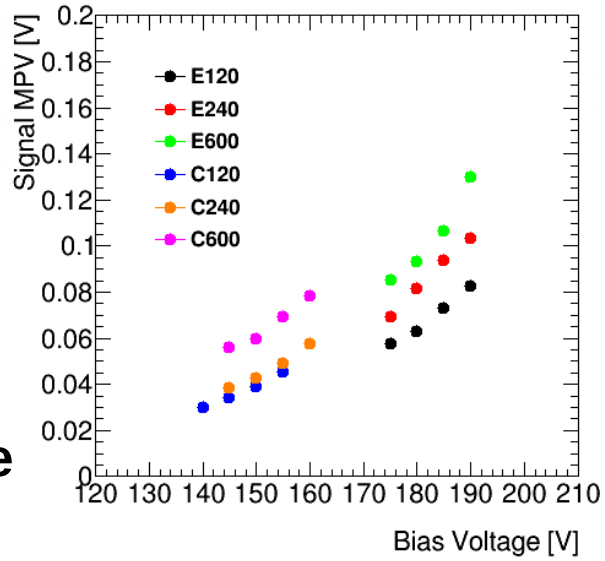
do voltage scan

→ cross point which two fitted linear function in mean of off-time histogram is operation voltage

e.g. pixel 150um E240

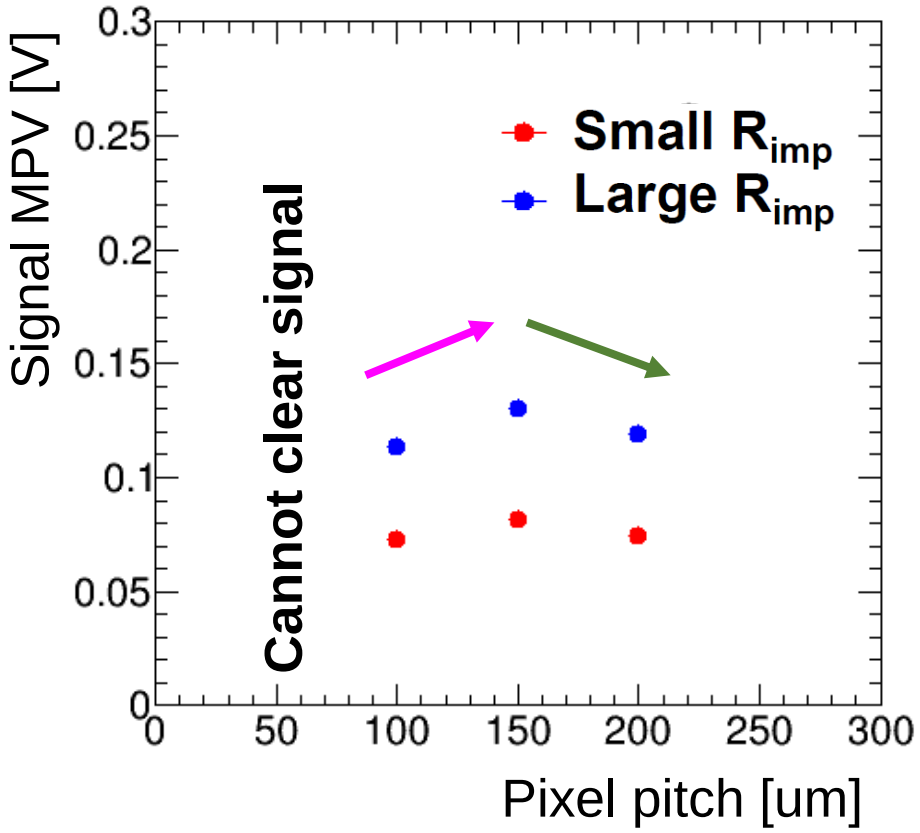


e.g. pixel 150um Vscan



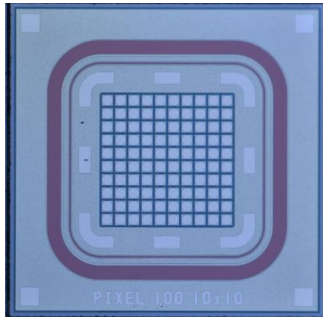
Pixel signal size (pitch dependence)

Signal size



Measured samples

- C_{cp} : 1type (largest one)
- R_{imp} : 2type
- Electrode pitch
  : 50, 100, 150, 200um pitch

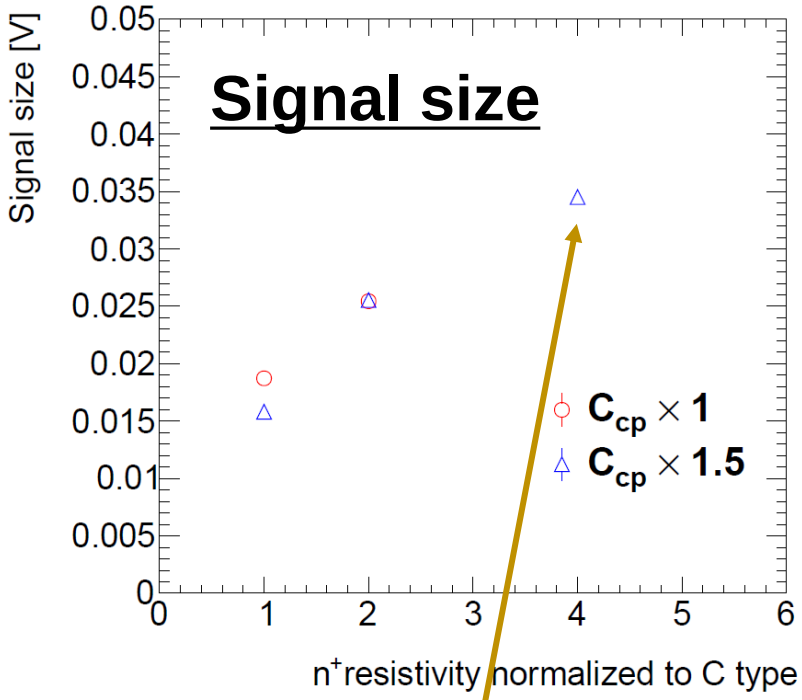


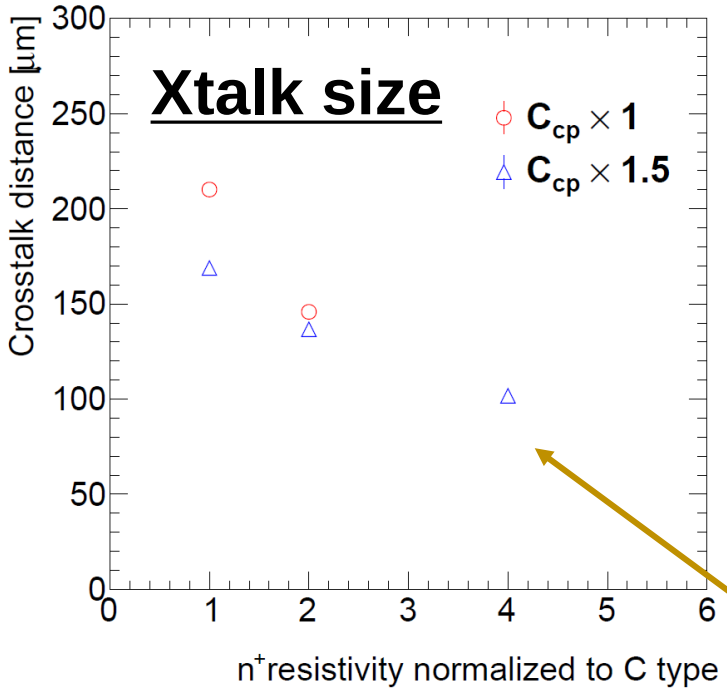
✓ **Signal size is not changed significantly**

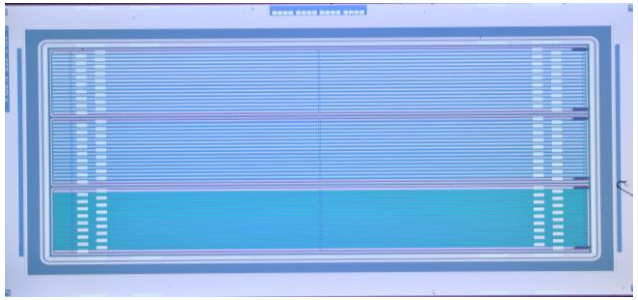
➢ **Signal increase area** : 100~150um
due to C_{cp} by electrode size ?

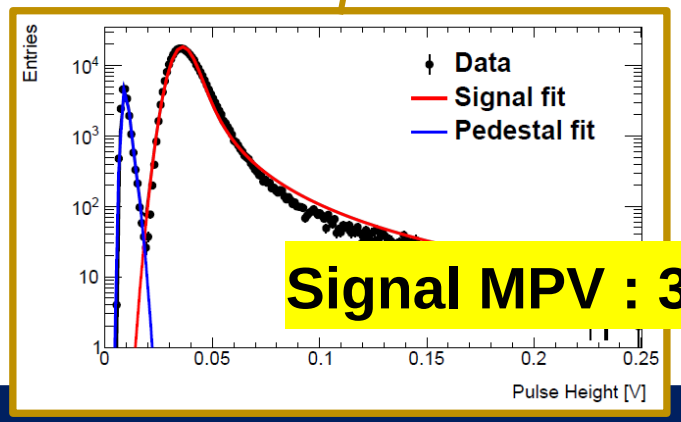
➢ **Signal decrease area** : 150~200um
due to inter pixel capacitance effect ?

Strip R_{imp} and C_{cp} dependence

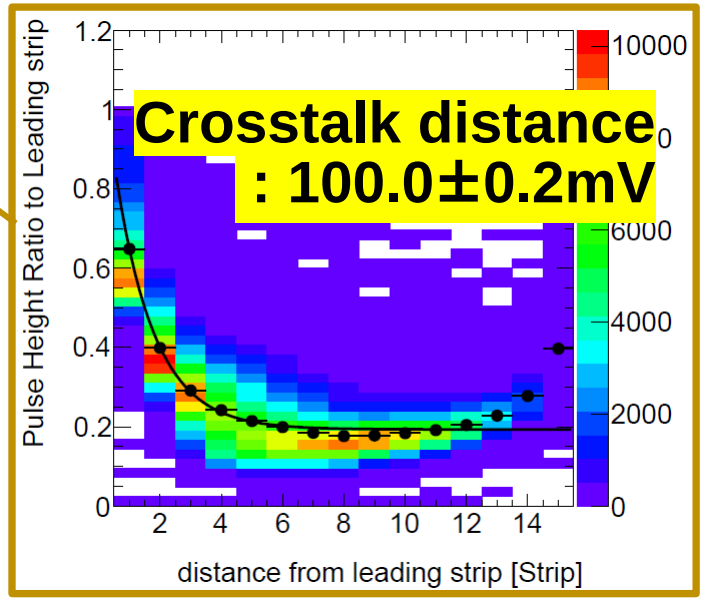






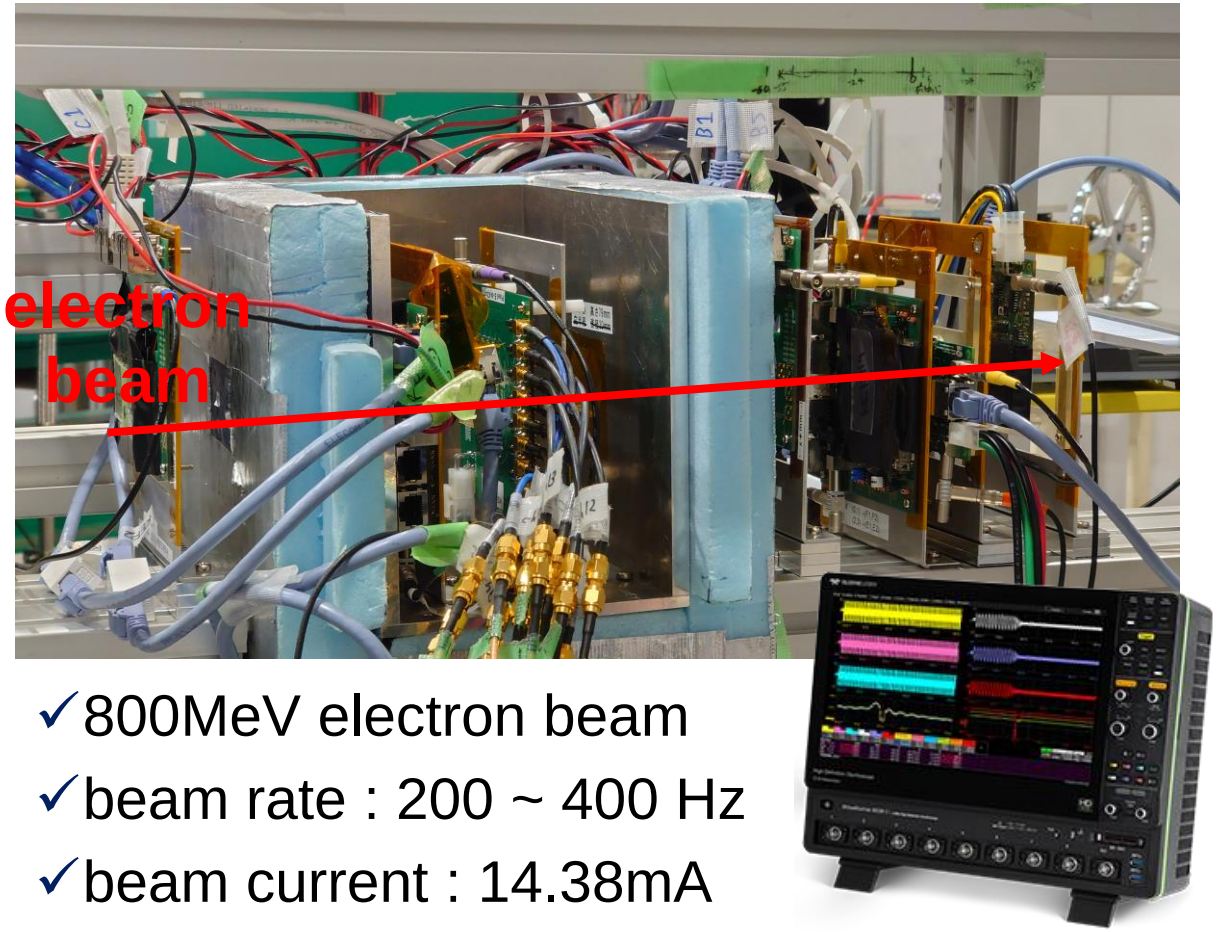


Larger R_{imp} and C_{cp} makes signal larger and crosstalk smaller



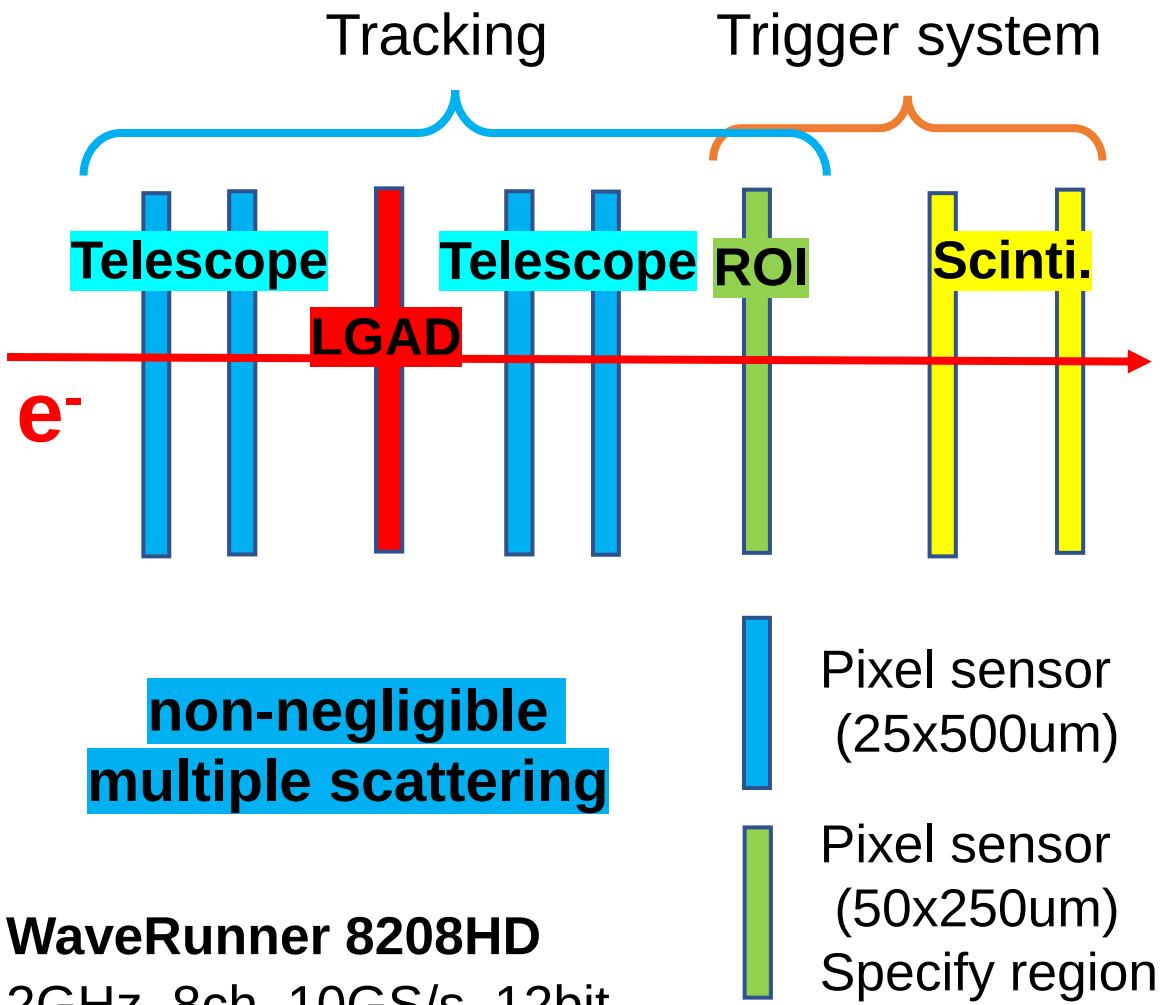
Testbeam at ELPH (Tohoku University)

Setup

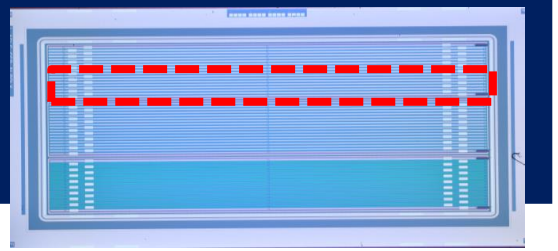


- ✓800MeV electron beam
- ✓beam rate : 200 ~ 400 Hz
- ✓beam current : 14.38mA

WaveRunner 8208HD
2GHz, 8ch, 10GS/s, 12bit

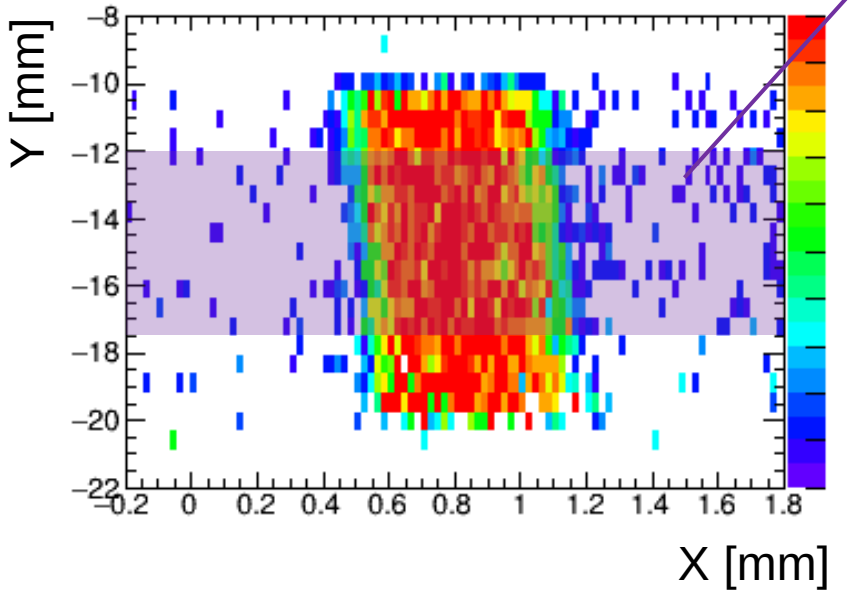


Strip efficiency (testbeam)

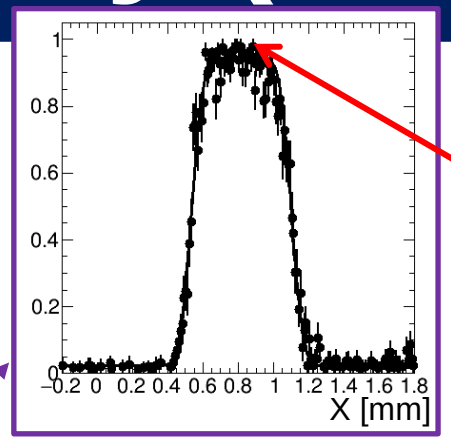


- ✓Sensor : Strip E-b
- ✓Bias voltage : 170V
- ✓channel : 9~15ch

Efficiency map

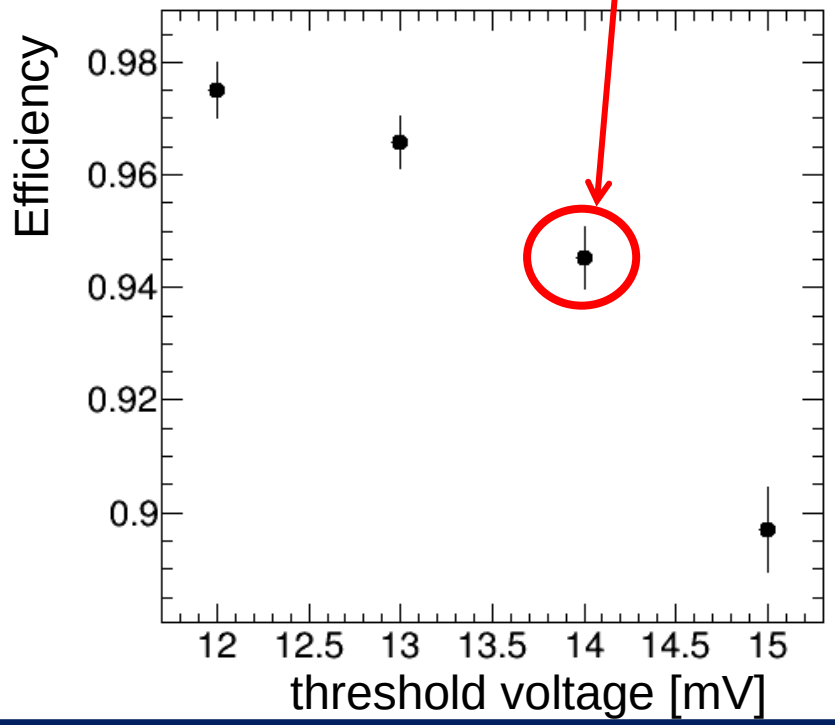


projection



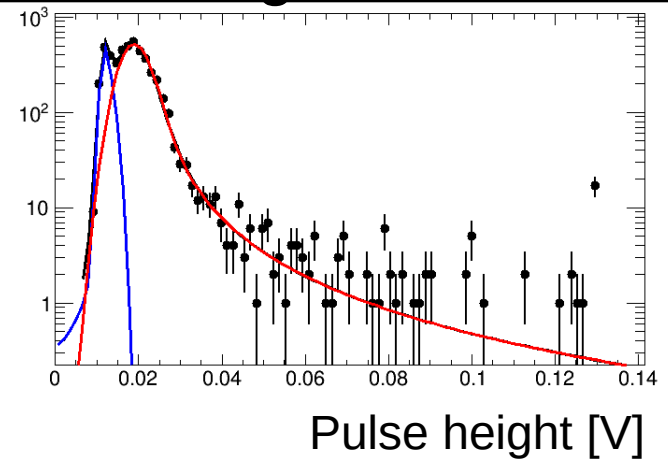
fit top region of projection plot

94.5 ± 0.6 %



Efficiency of strip is >95%!!!

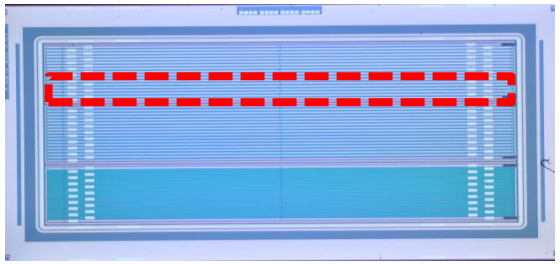
Pulse height distribution



consistent to efficiency calculated from pulse height distribution

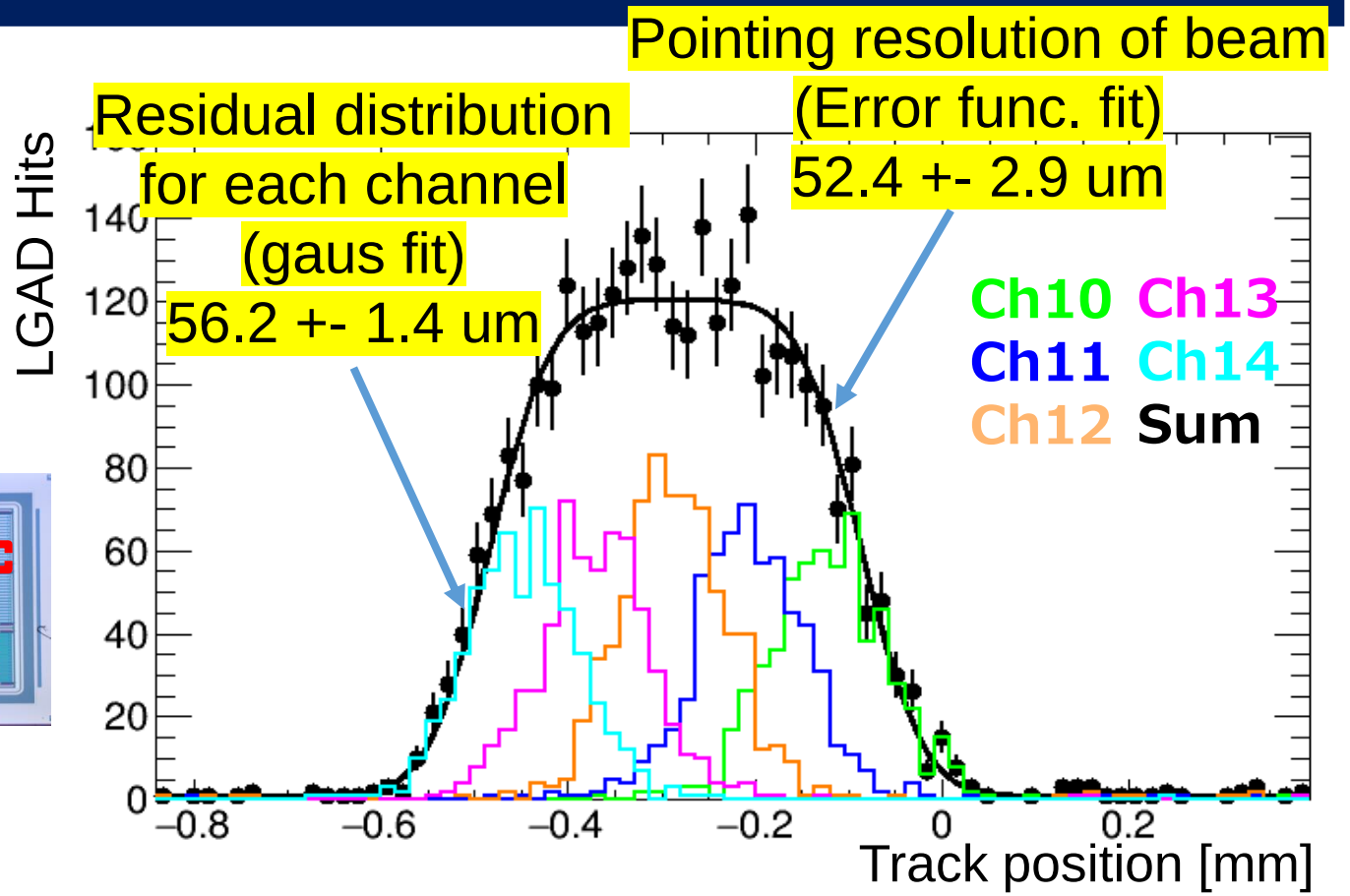
Strip spatial resolution (testbeam)

- ✓Sensor : Strip E-b
- ✓Bias voltage : 170V
- ✓channel : 10~14ch
- ✓Number of events : ~600,000



Event selection

- ✓Good tracks
  - : have hits for all tel and ROI
  - : χ^2/NDF : < 18 (x,y)
- ✓LGAD hit : > 14mV (95%efficiency)

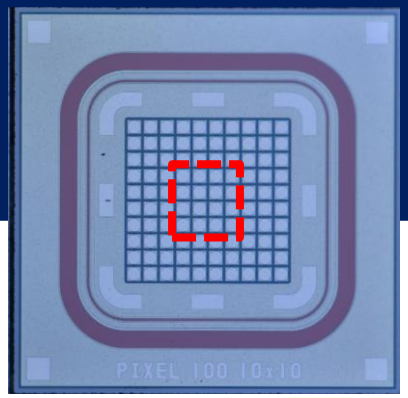


Spatial resolution of strip : 20.3±3.2um

assuming spatial resolution of 80um pitch strip (binary readout) : 80/sqrt(12) = 23um

consistent !!

Pixel efficiency (testbeam)

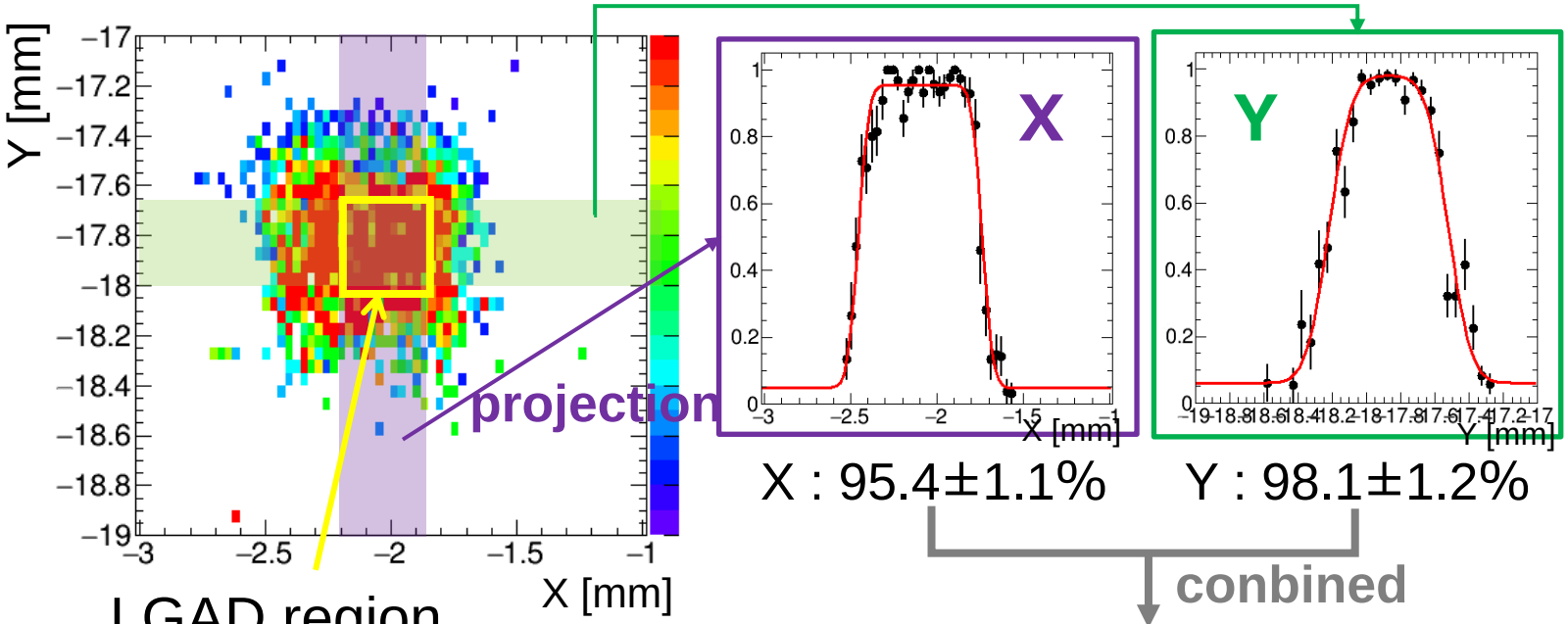


- ✓PixelE600 (100um pitch)
- ✓Bias voltage : 190V
- ✓channel : 1~16ch

Event selection

- ✓Good tracks
  - : have hits for all tel and ROI
  - : χ^2/NDF : < 20 (x,y)
- ✓LGAD hit : Threshold at noise rate 10^{-4}

Efficiency map



LGAD region (200umx200um)

X : 95.4±1.1%

Y : 98.1±1.2%

conbined

96.6±0.8%

Pointing resolution of beam

X : 62.3±17.4um

Y : 136.8±20.8um

multiple scattering…

Y pointing resolution of beam is worse than X

→ Efficiency X is poor