Precision beam tracker for the KEK AR-TB based on SOI sensor technology

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Introduction

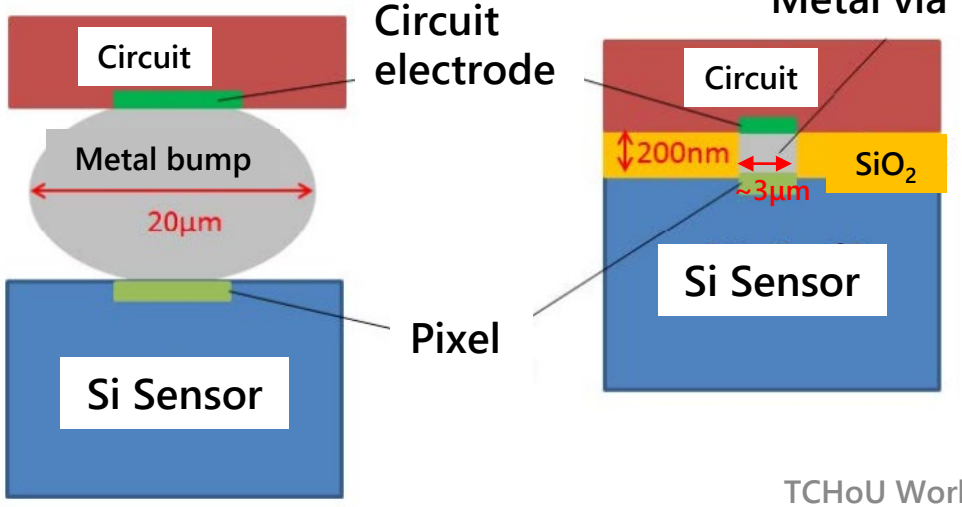
SOI Pixel Detector

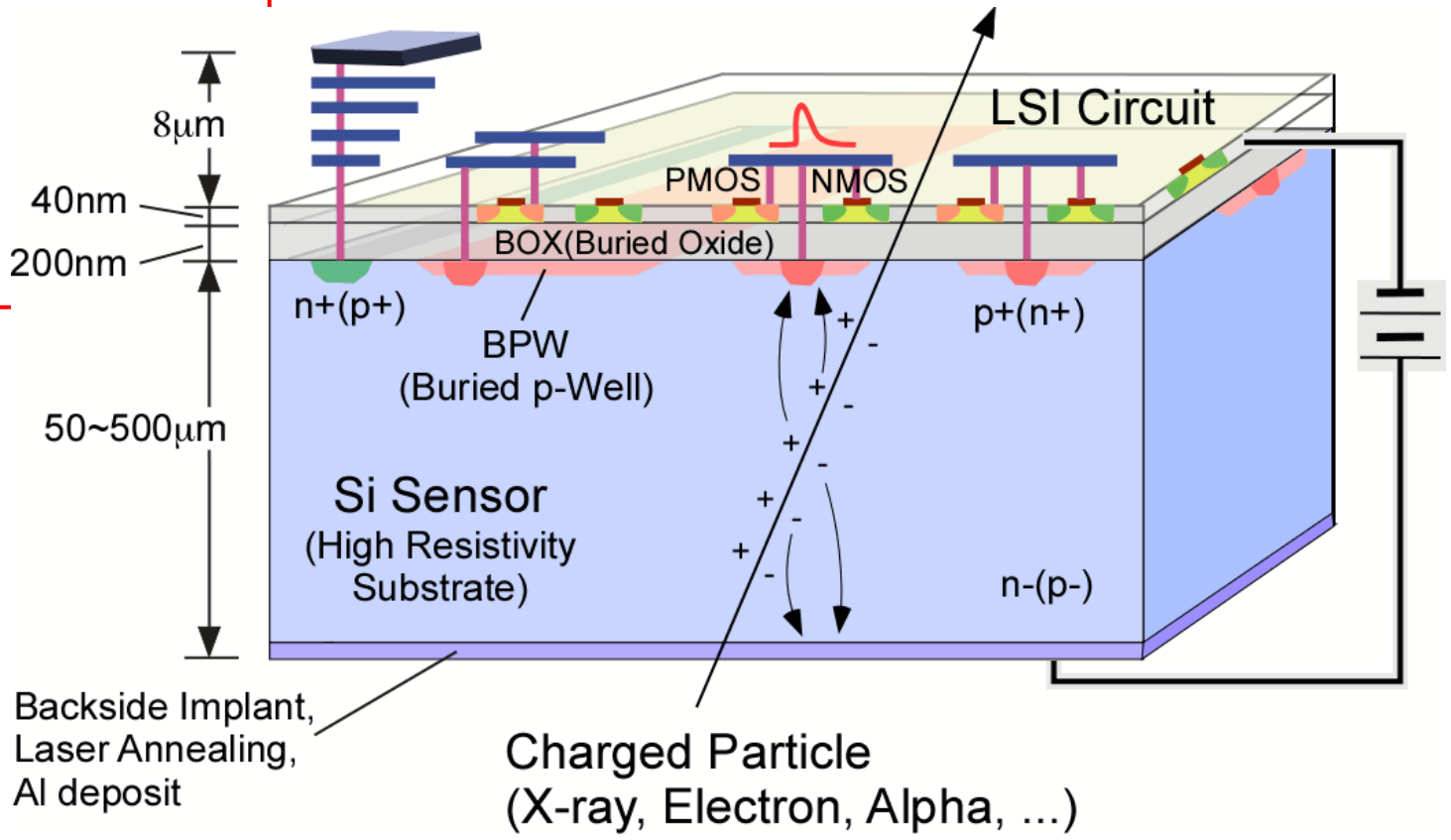
Semiconductor detector with readout circuit integrated (monolithic sensor)

Transistors are formed on buried SiO_2 oxide layer using SOI (Silicon On Insulator) technology

- SOI-CMOS
  Isolate individual transistors in oxide insulator

- Monolithic type
  → Pixel size can be miniaturized
  sensor material can be minimized





Motivation —KEK AR-TB & Telescope—

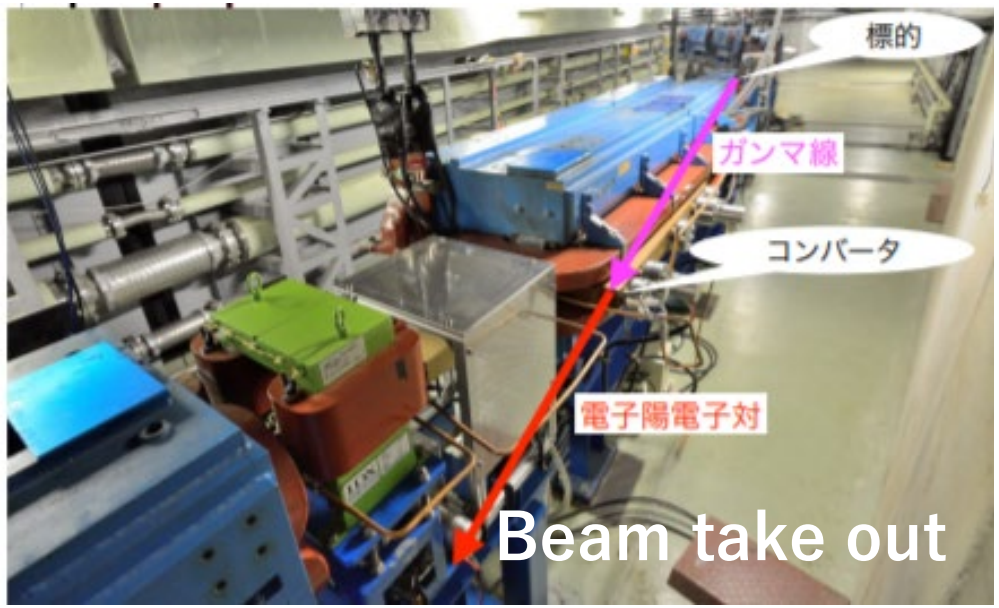
Necessity of GeV order test beamline for development of particle detectors in Japan

➡ KEK AR-TB (Electron beamline) delivered 1st beam on March 4.

1kHz(ax at 2-3GeV), 400Hz (5GeV)

Need a telescope with high position resolution

➡ **Telescope system with SOI pixel detectors is capable of low multiple scattering and fine intrinsic resolution**



Development goals and steps

Ultimate goal

◆ High-precision telescope system for various DUTs

short term goal (in 2022)

◆ Evaluation of SOI Pixel Detector "DuTiP"(test chip for Belle 2 upgrade) in AR-Test Beamline

➡ requires Position resolution of ~10 μm

◆Steps

This Study

- Detector synchronization test
- Oct 2021 820MeV/c e^+ beam test @ELPH
- GEANT4 Simulation
- Improvement (thinning? frame rate) for AR-test beamline
- 2022 Dutip Evaluation

“INTPIX4NA” sensor

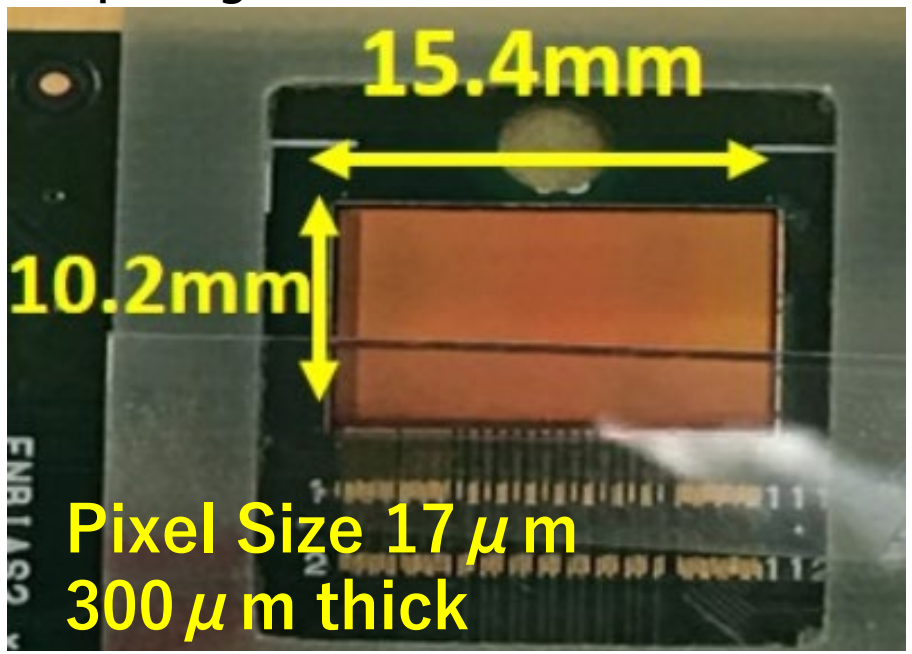
◆Fine pixel size ($17\mu m \times 17\mu m$)

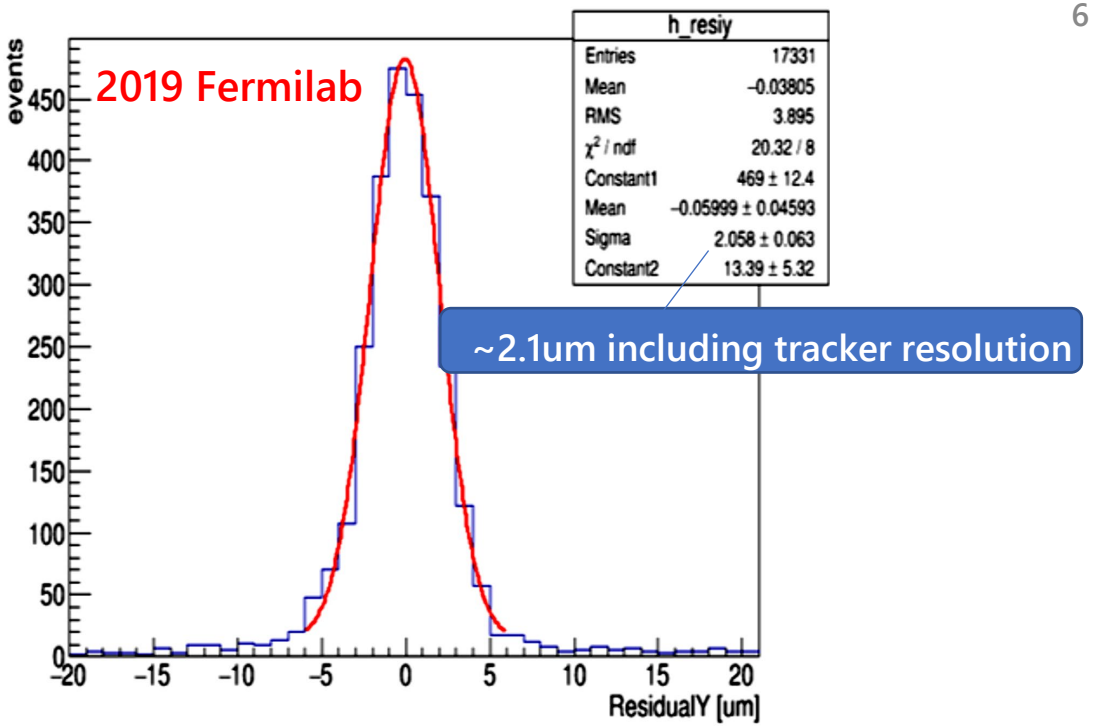
◆Large sensitive area ($14mm \times 9mm$)

◆Parallel 13-blocks analog outputs

➡ digitized off-chip with ADCs on dedicated DAQ board SEABAS2

Chip image





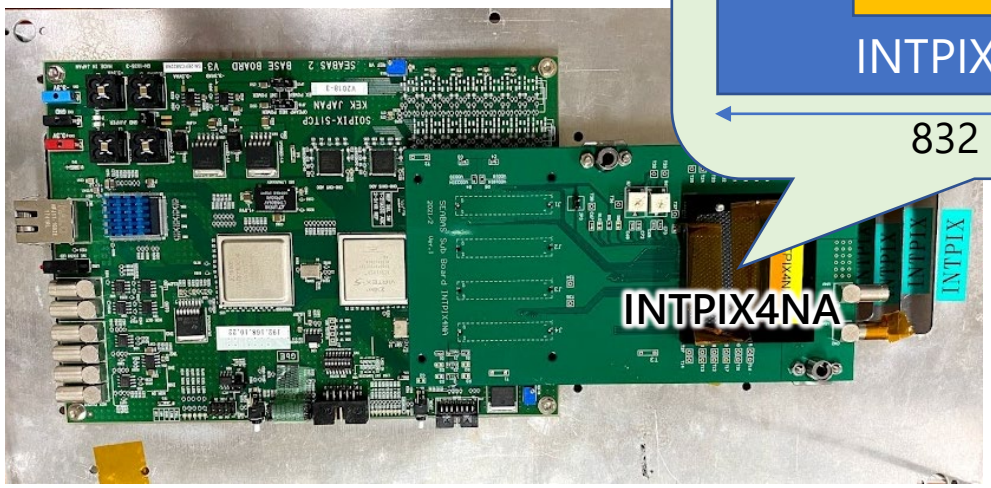
◆2019 INTPIX4 (500μm thick) @120GeV proton

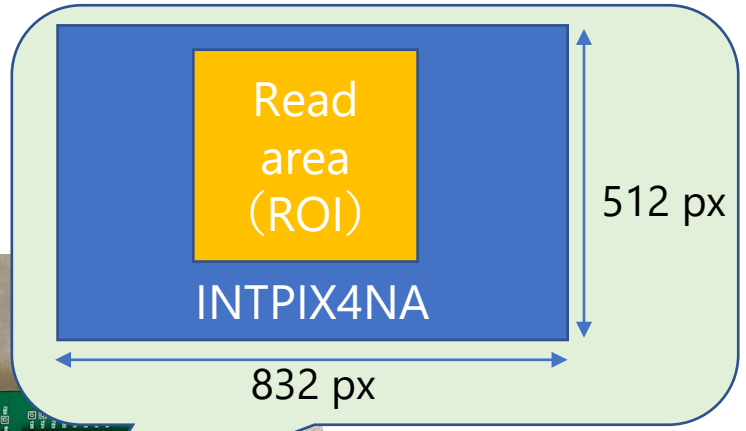
◆Intrinsic position resolution of ~1.5μm

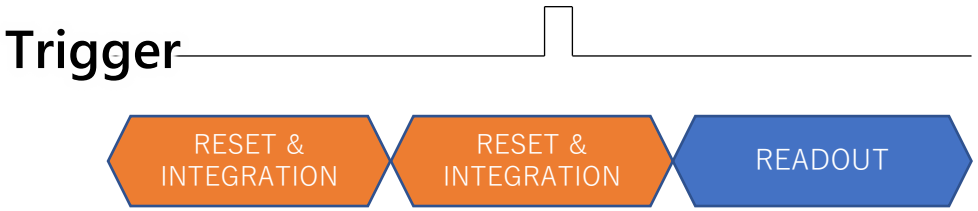
センサー	残差分布幅 [μm]	Tracking Factor	位置分解能 [μm]
INTPIX1	2.14±0.08	1.58	1.35±0.05
INTPIX2	1.75±0.04	1.29	1.34±0.03
INTPIX3	2.03±0.07	1.30	1.56±0.05
INTPIX4	2.55±0.14	1.55	1.65±0.09

INTPIX4 Position resolution (500μm thick)

Readout system

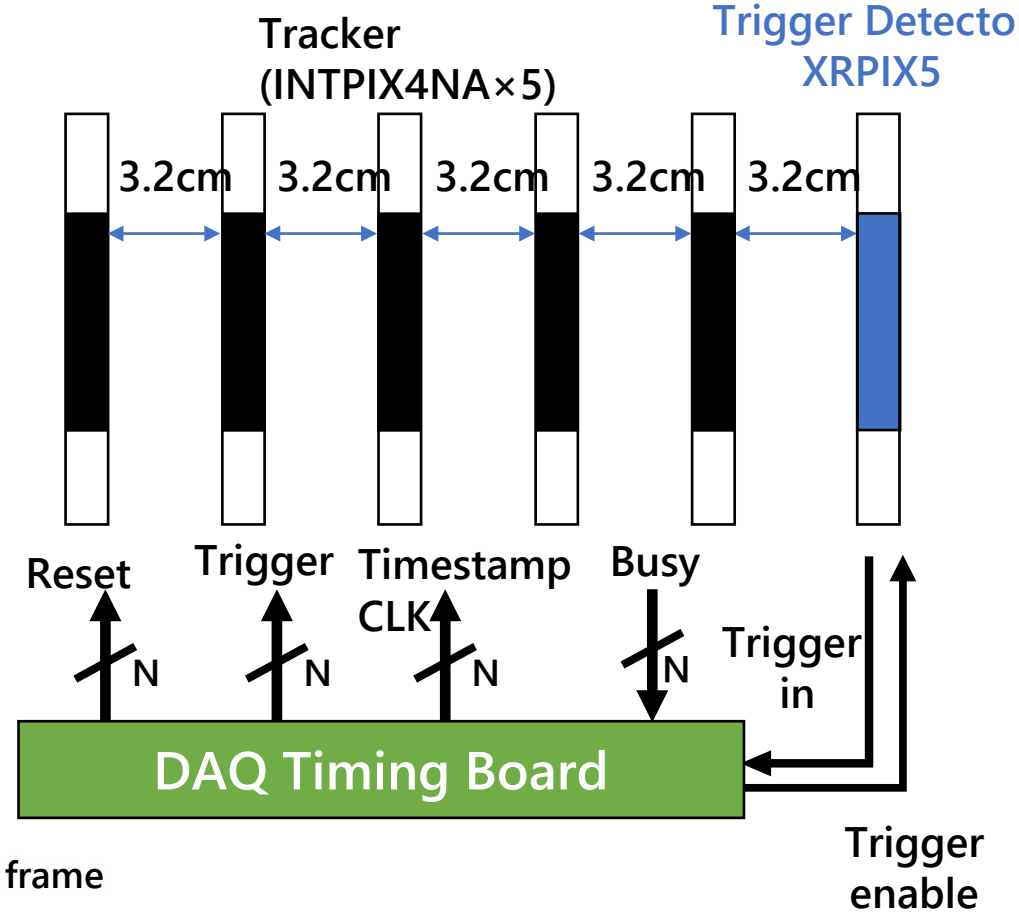






Repeat Integration & Reset

Readout after Trigger signal

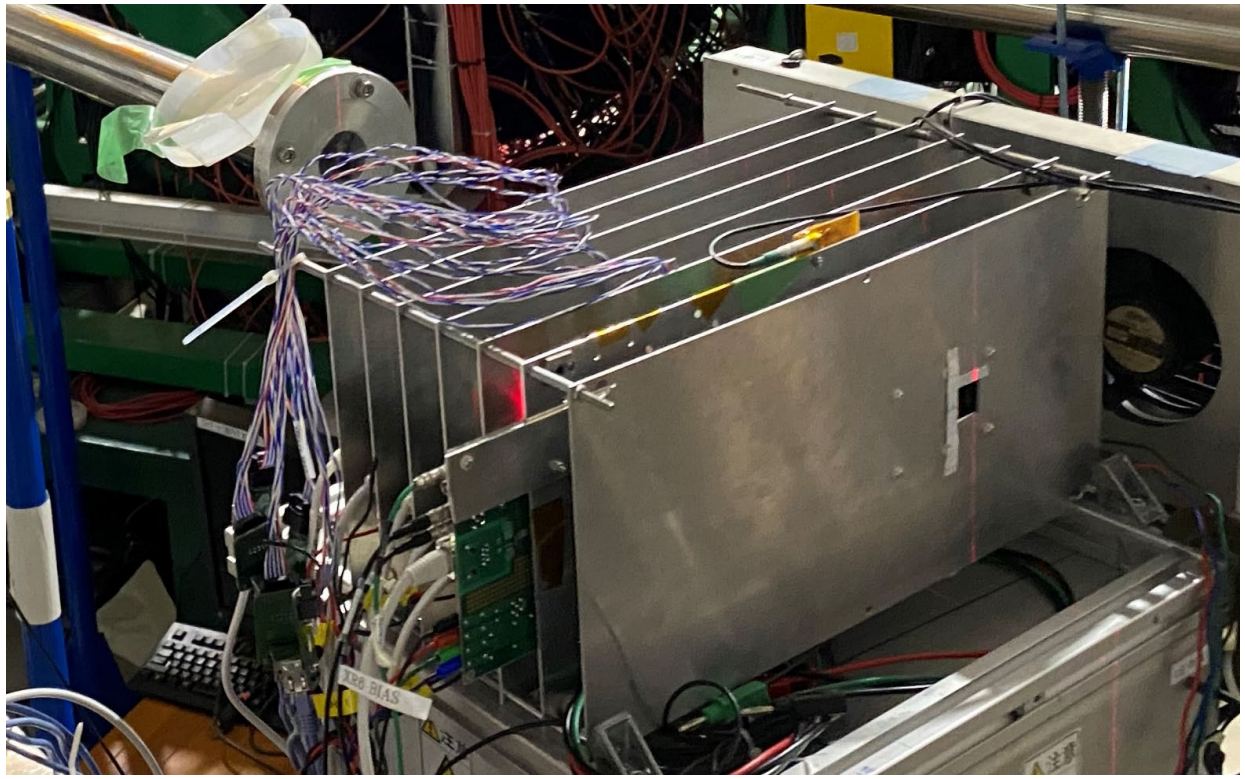


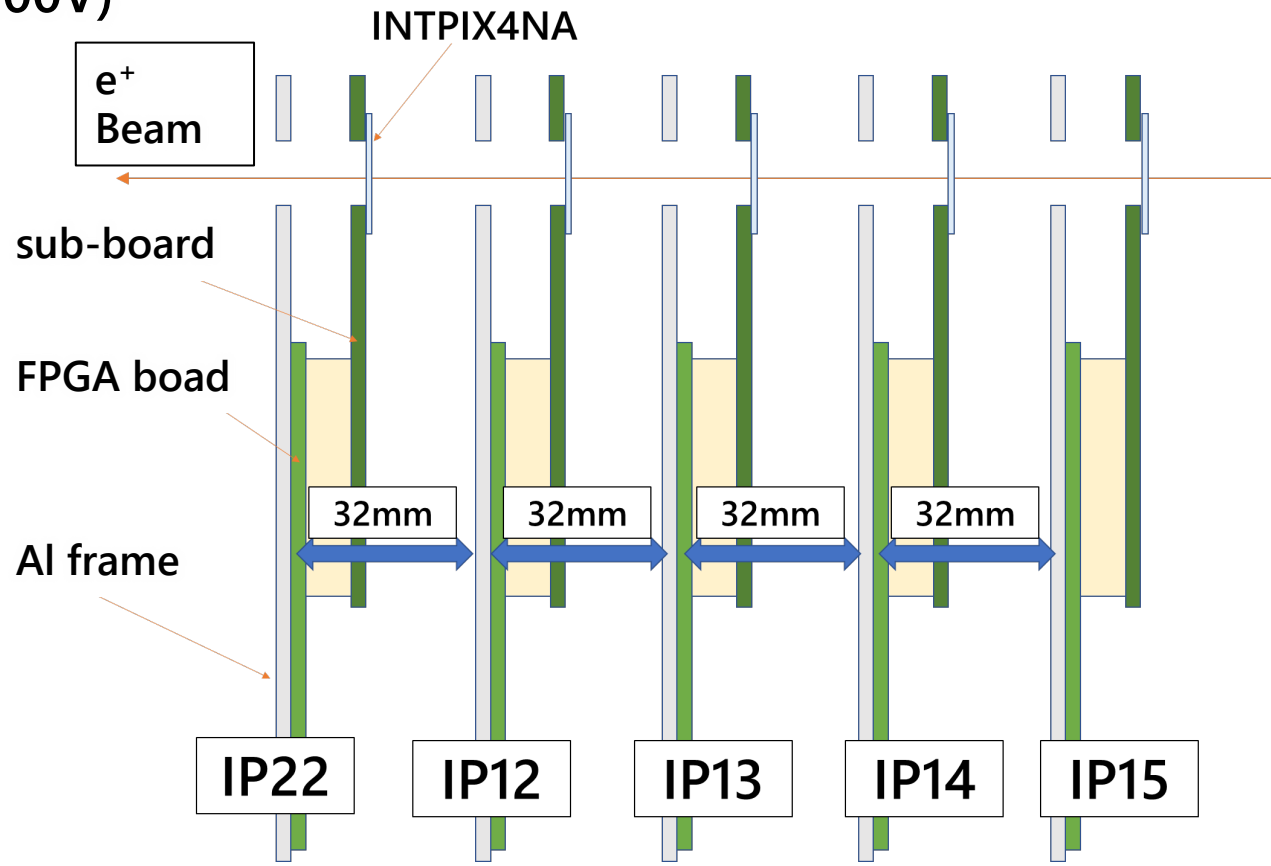
- SEABAS2(FPGA based) board + sub-board
- Region of Interest (ROI) can be set
- Chip repeats Integration & Reset until trigger is set
- Distribute control signals from the Timing board
  - ✓ Reset 5 INTPIX4NA sensors simultaneously
  - ✓ XRPIX issues Trigger on recording beam hit
  - ✓ Trigger starts readout in each sensor (BUSY is Set)
  - ✓ Guarantee synchronization by adding time information (time stamp) to each frame
  - ✓ Not accept triggers while BUSY is set in any of 5 sensors

820MeV/c Electron Beam Performance Evaluation

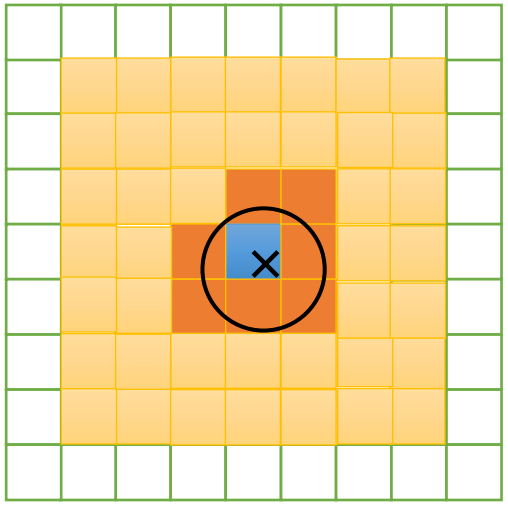
ELPH 820MeV/c positron beam test

- Clustering・S/N evaluation
- Position resolution evaluation in various DUT-tracker plane configuration
  - ✓ Nominal beam momentum 820MeV/c (momentum scan 200-820MeV/c)
  - ✓ Nominal bias voltage 20V (HV scan 1V ~ 100V)



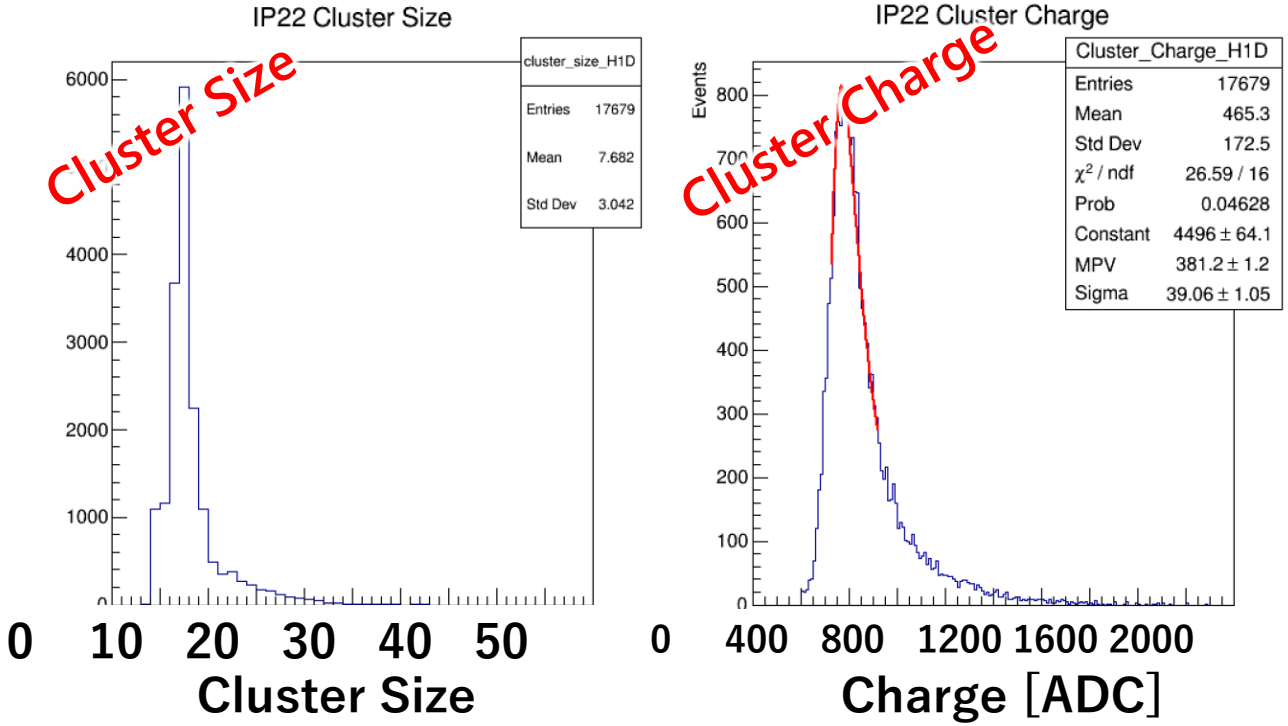


Clustering ・S/N evaluation



clustering

- Cluster seed
- Cluster range
- Extracted pixels
- Hit position
  Charge share



- Signal charge is shared by neighbor pixels
- the cluster spreads over 6-7 px in average

➡Position resolution improved by a charge centroid method

- Evaluate the S/N ratio from the cluster charge

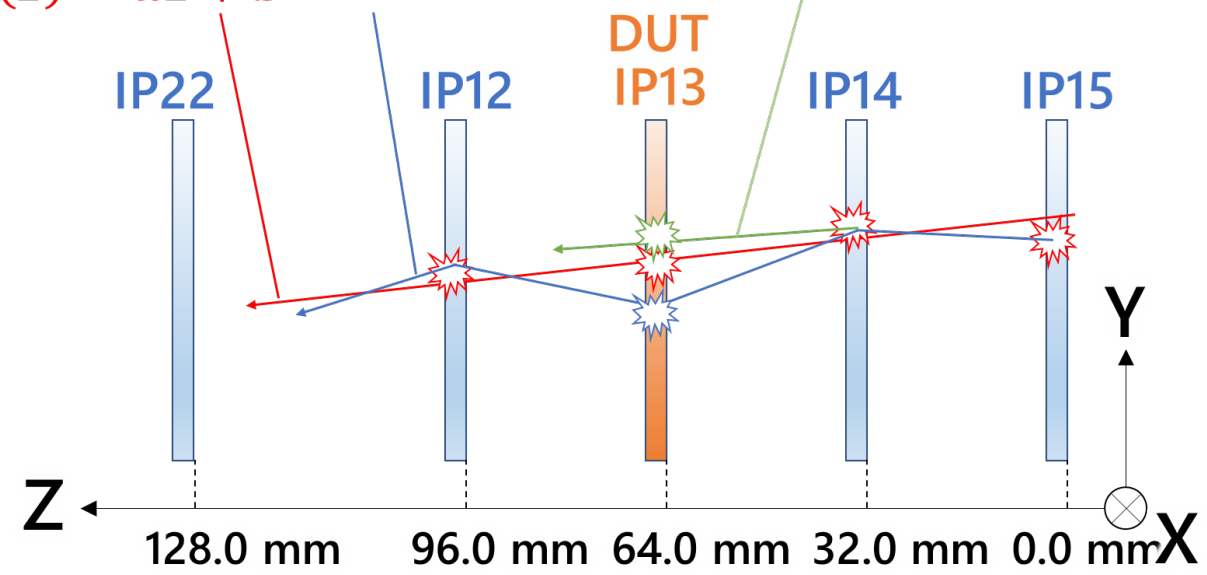
IP	noise	signal	S/N
IP22	1.6	381	237
IP12	1.8	339	188
IP13	1.8	354	188
IP14	1.7	275	156
IP15	1.6	382	242

Track reconstruction
820 MeV/c positron beam

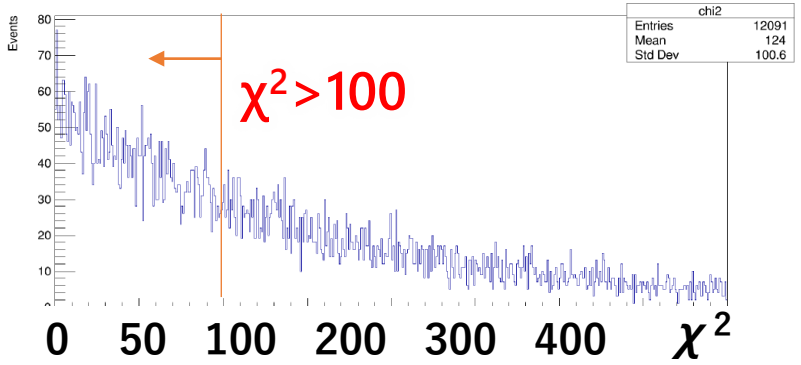
① linear track approximation

$f(z) = az + b$ Real track

②Use slope "a" & neighbor's hit position



- Track reconstruction with INTPIX4NA itself as DUT
- Highly scattered tracks are degrading 2-2 track resolution



Tracking Method

DUT → #3-2-1

Number of upstream side tracker

Number of downstream side tracker

① Linear approximation

DUT	Tracking Method	σx [um]
13	1-1	12.15±0.10
13	1-1	14.48±0.12
13	2-1	14.42±0.12
13	2-2	20.28±0.16

②Use slope "a" & neighbor's hit positon

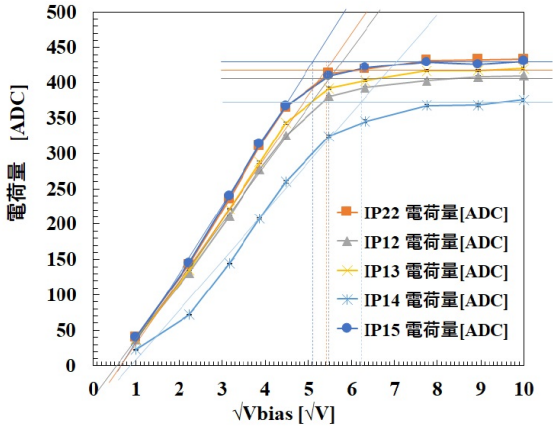
DUT	Tracking Method	σx [um]
13	1-1	12.15±0.10
13	1-1	12.18±0.10
13	2-1	11.80±0.10
13	2-2	14.57±0.12

③ χ^2cut

DUT	Tracking Method	σx [um]
13	1-1	12.15±0.10
13	1-1	10.29±0.12
13	2-1	10.25±0.12
13	2-2	12.22±0.12

HV scan

- Apply 1-100V to all sensors
- Evaluate the full-depletion voltage



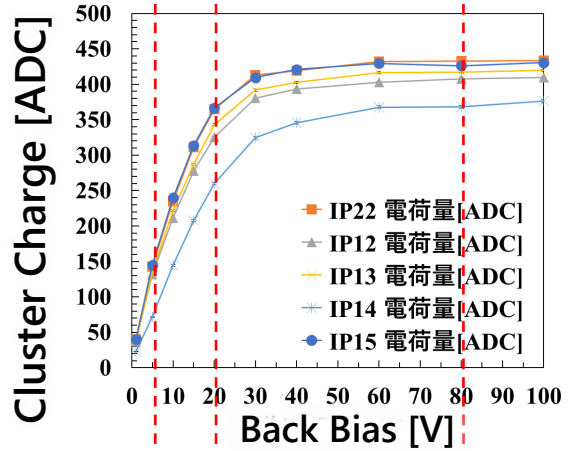
IP	Full-deptetion voltage [V]
IP22	26.01
IP12	30.25
IP13	29.16
IP14	38.44
IP15	26.01

- Cluster size is maximum at 20V
  - ✓ Increase of the depletion thickness in V<20V, spread suppressed by stronger electric field in V>20V
- Even if the cluster charge drops to 1/3, the resolution doesn't degrade.

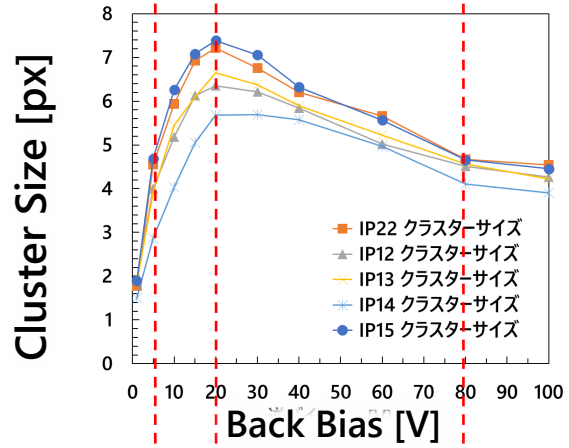
depletion thickness ~130μm@5V, ~250μm@20V

➡low scattering & fine resolution are possible by thinning

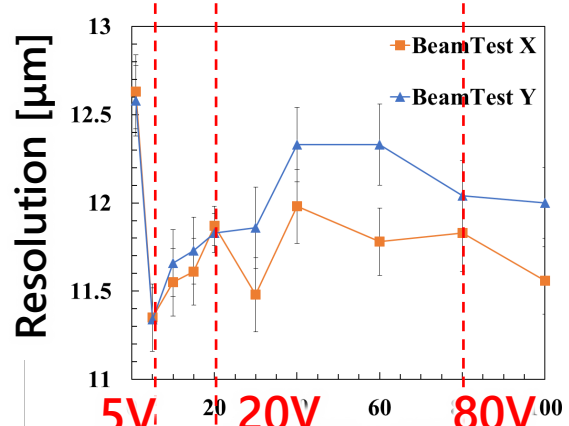
Cluster Charge



Cluster Size



2-1 tracking resolution

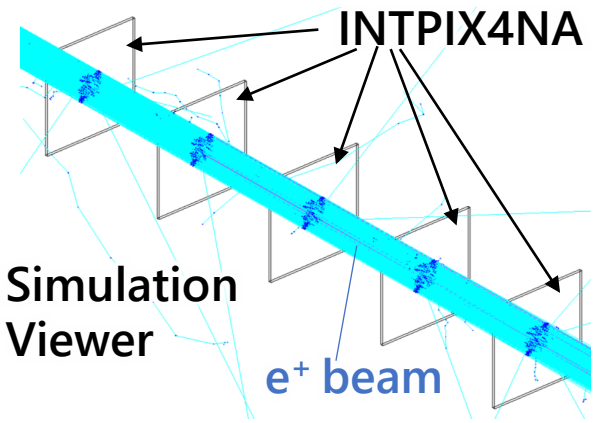


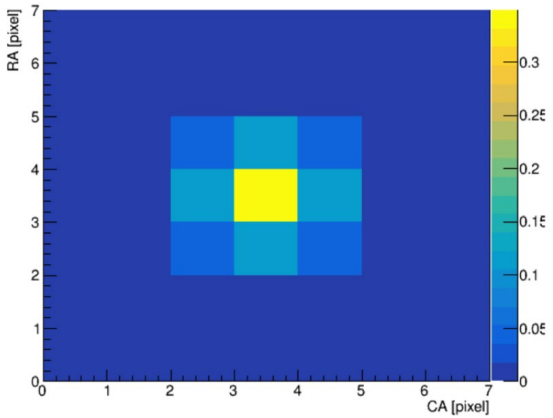
5V (128μm) 20V (249μm) 80V (300μm)

GEANT4 Simulation

Geant4 Simulation

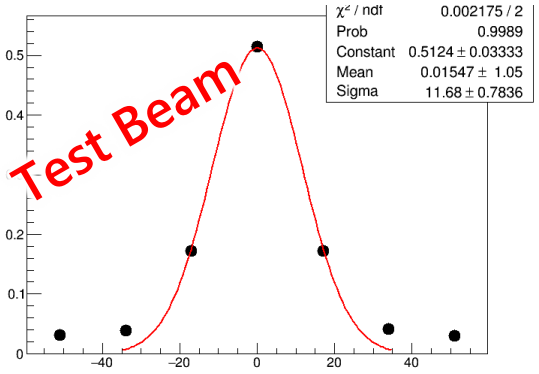
- Charge spread is added about the charge deposition by a two-dimensional Gaussian with standard deviation σ_{sim}

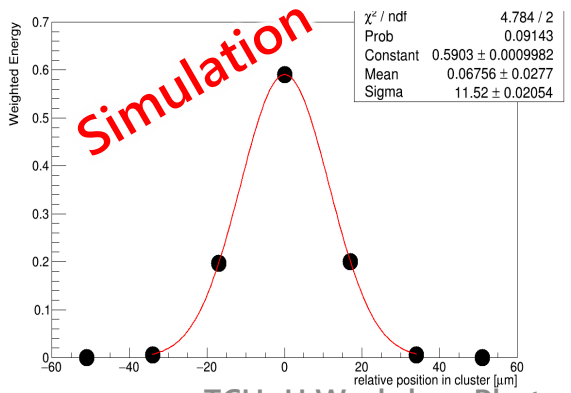


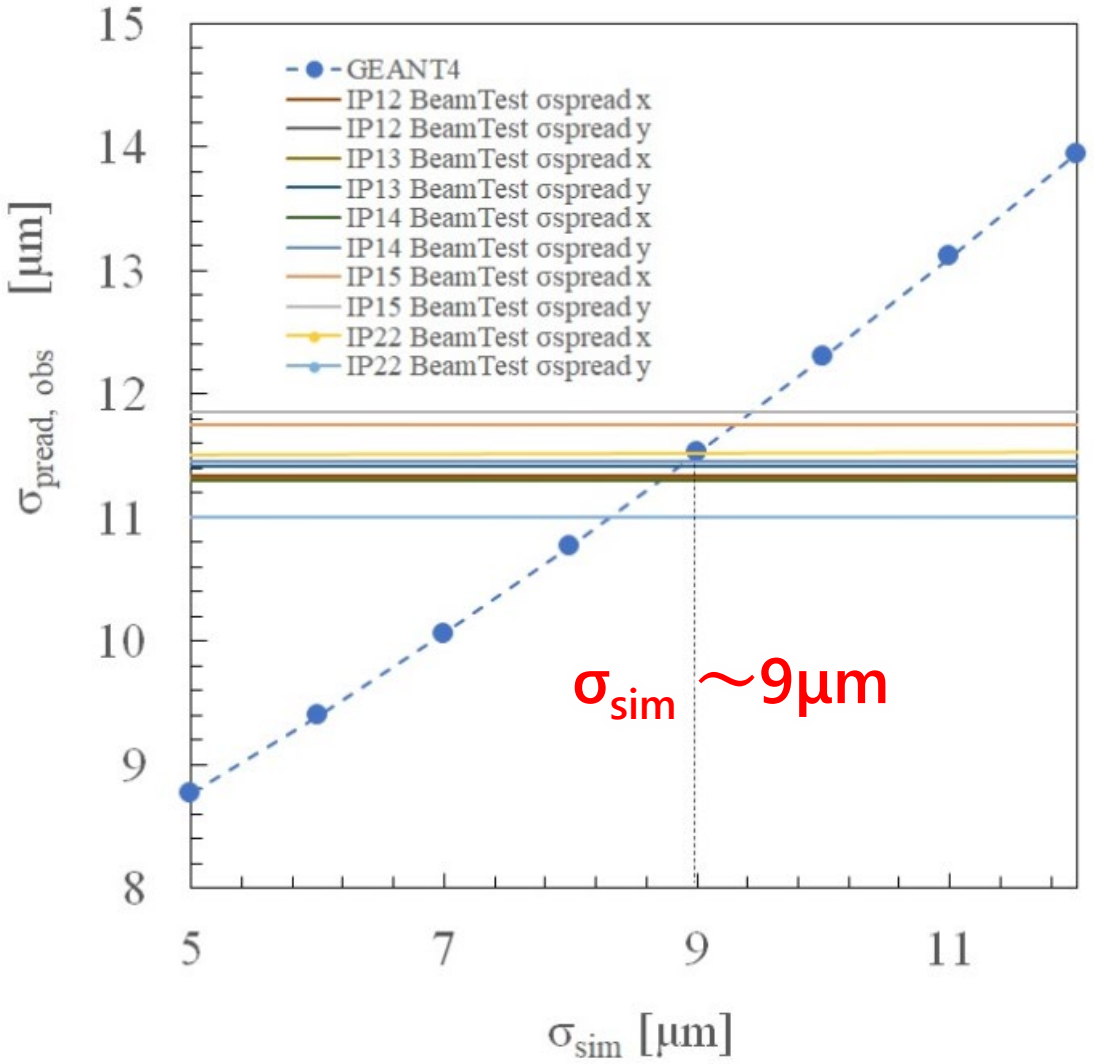


- spread among pixels is evaluated by fitting a Gauss to 1-D projections as σ_{spread}

➡set σ_{sim}=9μm from comparison with beam test





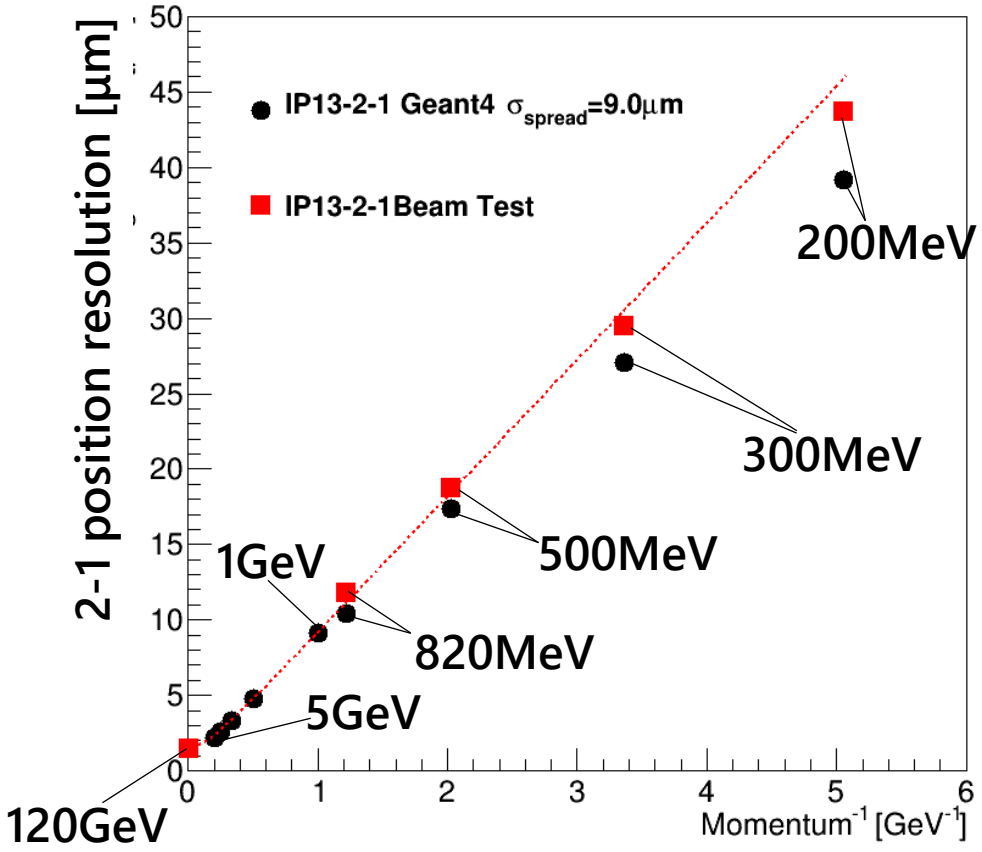


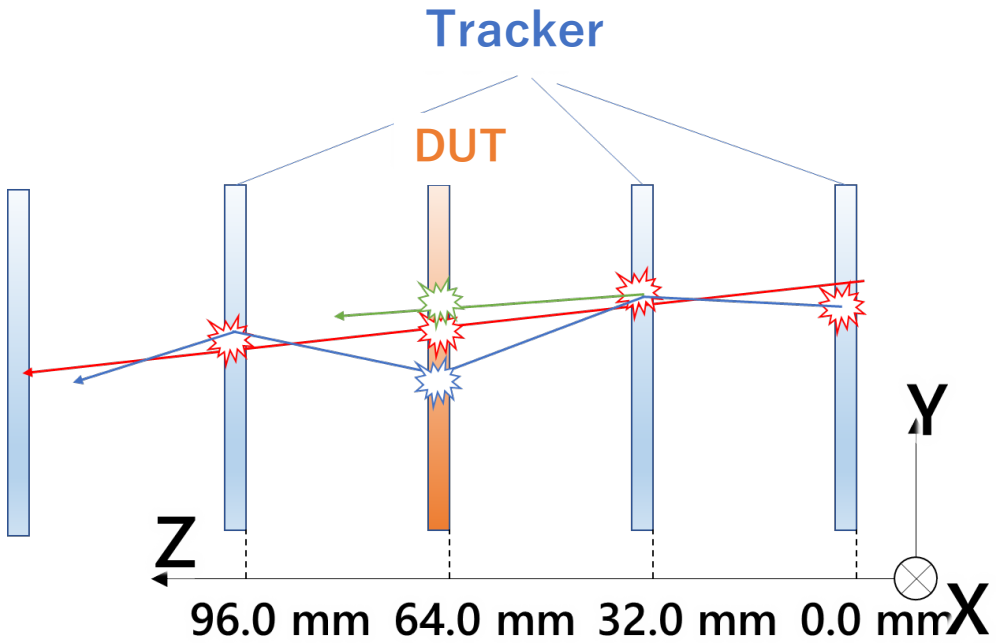
Geant4 Simulation Resolution@1~5GeV

- Calculate the position by the charged centroid method

➡ Track reconstruction with 2-1

Simulate with 200 - 820MeV, 1 - 5GeV/c





- 2-1 resolution results of beam test (200 - 820MeV/c, 120GeV/c) are

$$\sigma_{obs} \sim \sqrt{\underbrace{\sigma_{trk}^2}_{\text{Tracking resolution}} + \underbrace{\frac{\sigma_{sct}^2}{P^2}}_{\text{Scattering effect}}}$$

- Estimate the resolution @5GeV/c

2.209μm ± 0.02 μm
Geant4

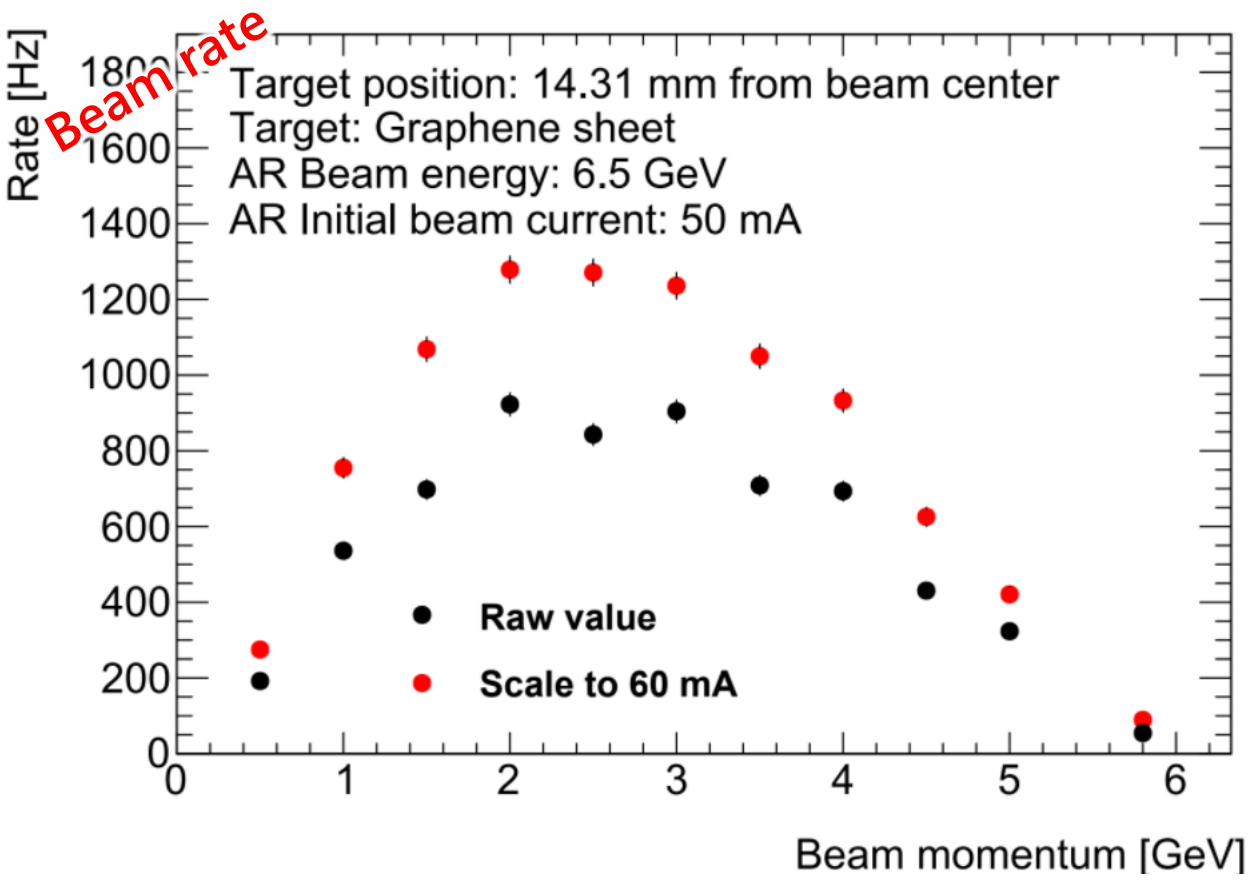
2.68 ± 0.14 μm
prediction from beam-test fit

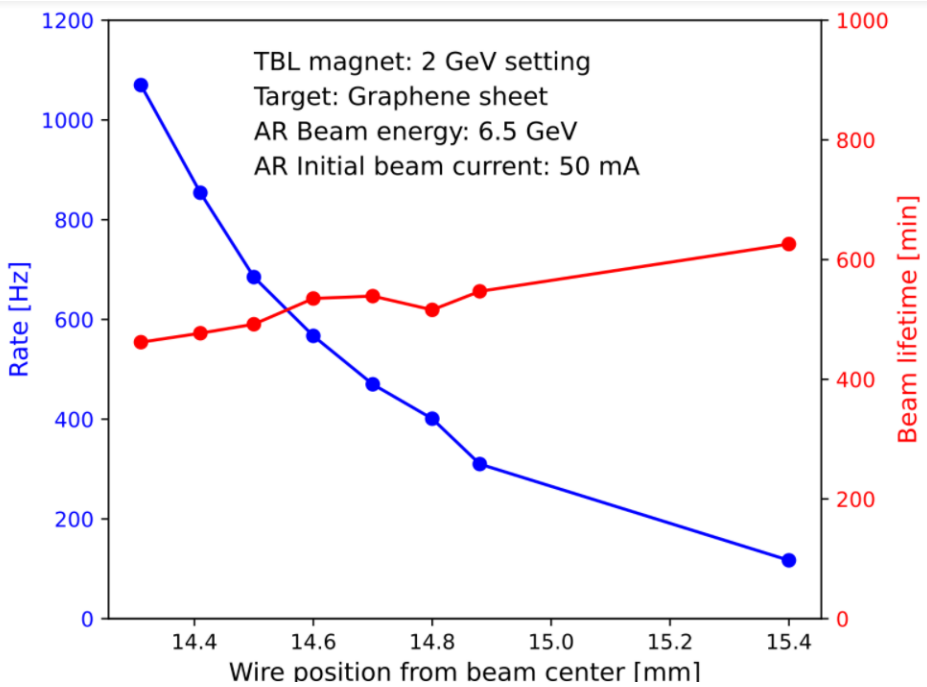
Summary

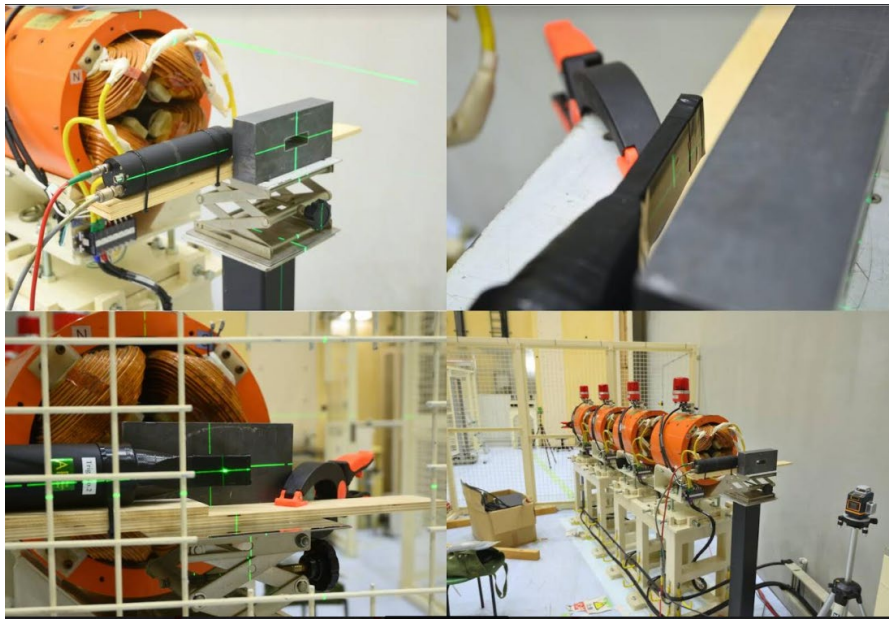
- Constructed a high-precision, low-multiple-scattering telescope for KEK AR-TB using SOI pixel detectors
- Performance verification by beam test at ELPH
  - ✓ Position resolution evaluation （Momentum scan、HV scan）
  - ✓ resolution~12μm for 820 MeV/c positrons
- Performance prediction by Geant4 Simulation and ELPH/Fermilab data
  - ✓ Position resolution prediction 2.2~2.7μm @5GeV
  - ✓ We will improve the system for AR-TB

Back up

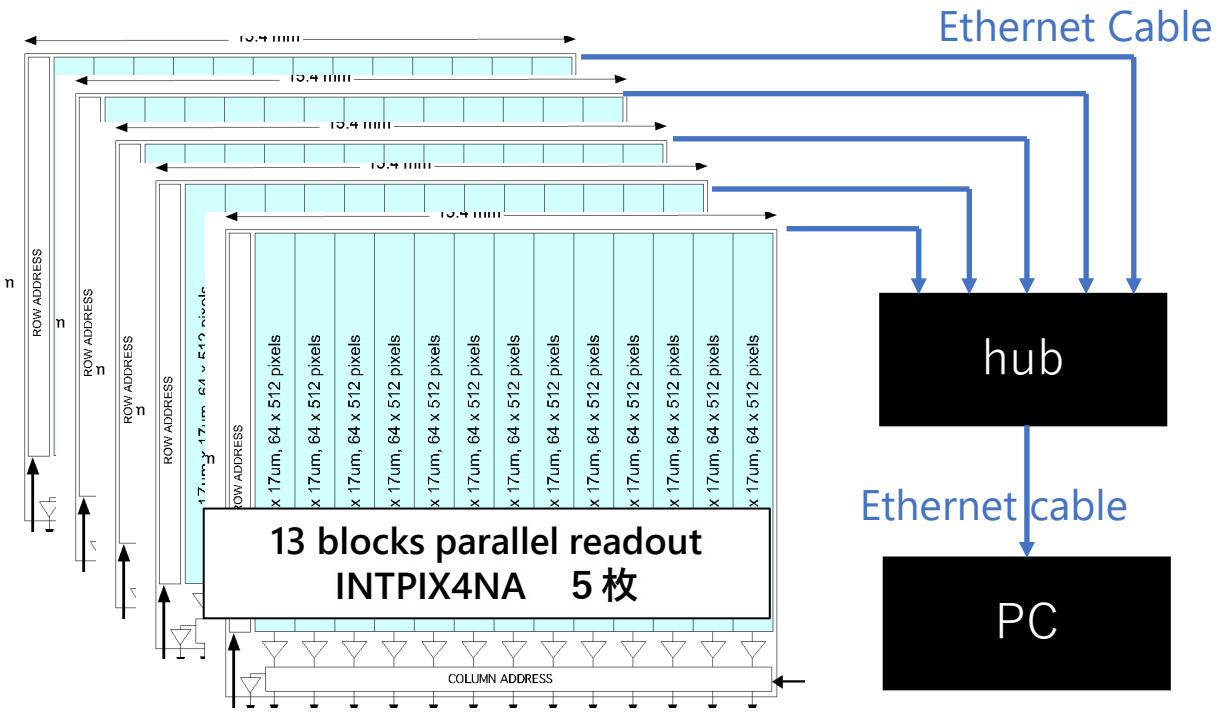
AR-TB Beam information

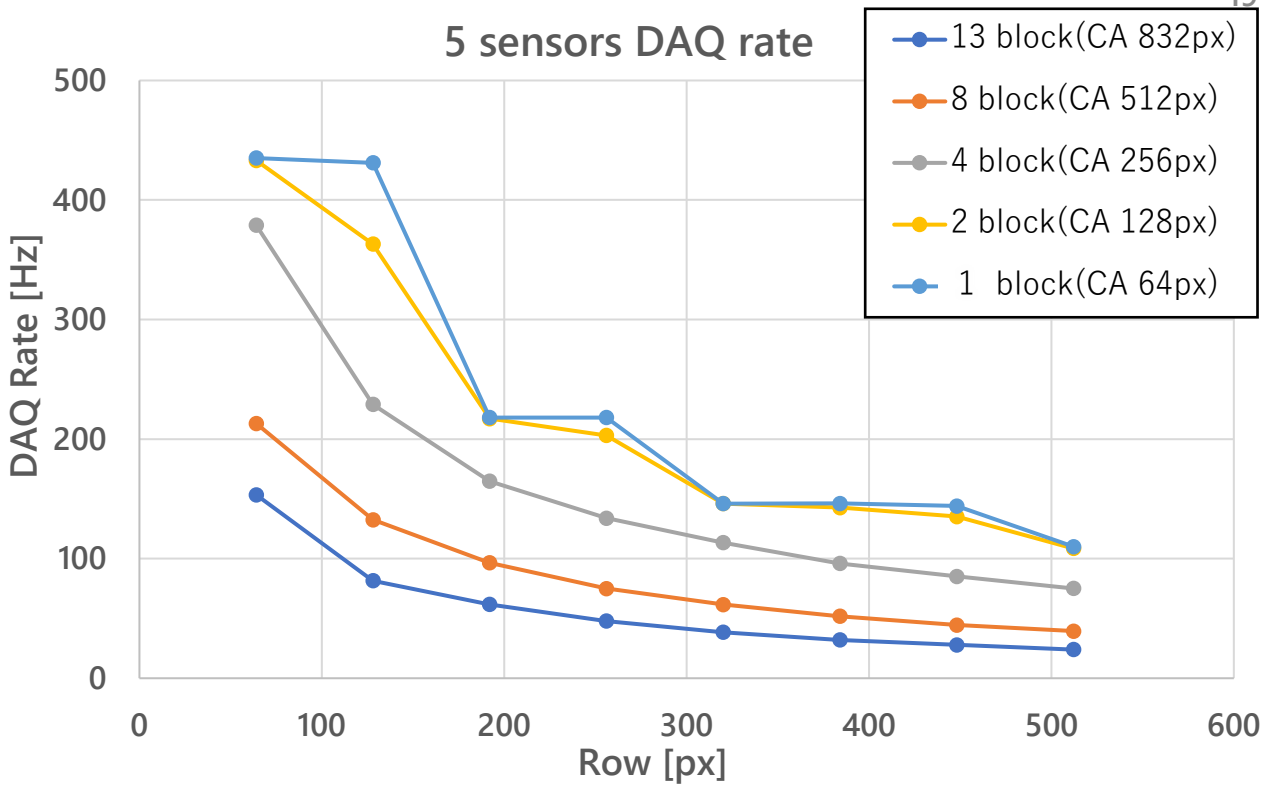


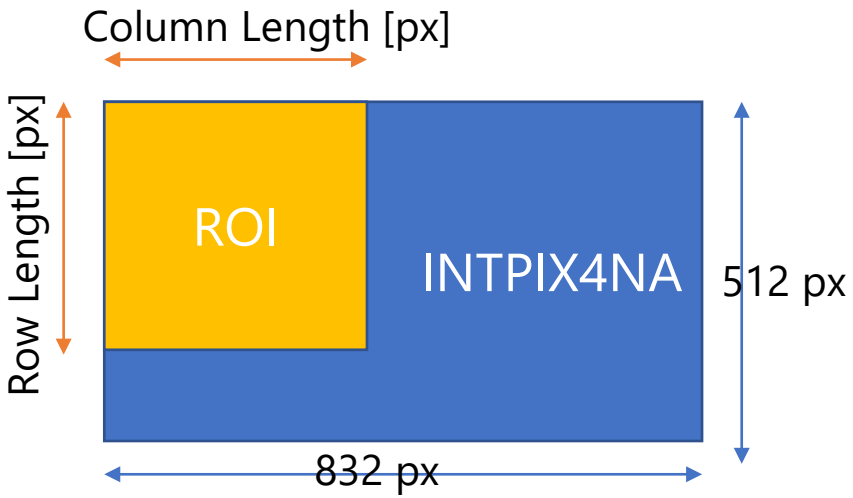




5 sensors sync. —DAQ rate—

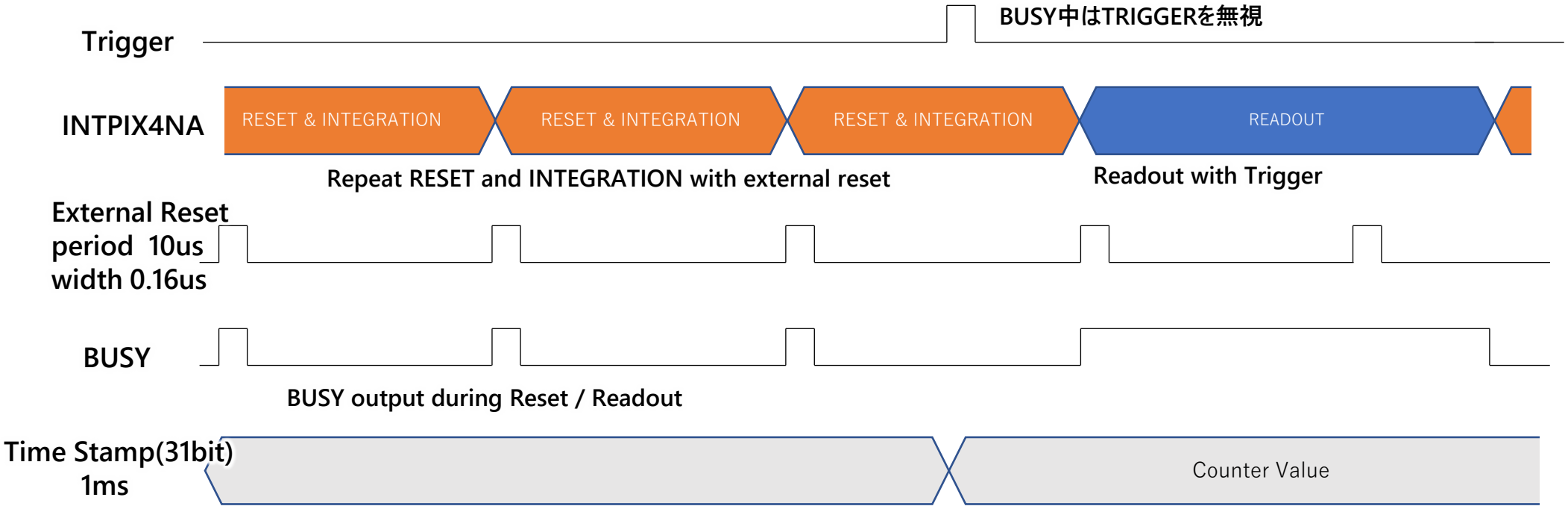


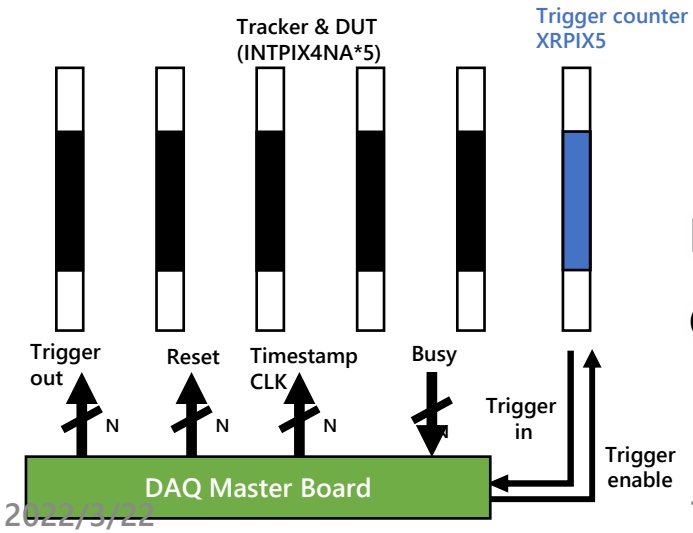




- **Readout area can be selected by ROI**
  - 512px * 512px(40Hz) ~ 64px*64px(400Hz)
- **KEK AR-TB predicts 200-300Hz events for the chip size**
  - Reduction of readout bits and development of zero suppression

5 sensors sync. — time chart / synchronization —





Hold the count when the trigger rises and add it to the data

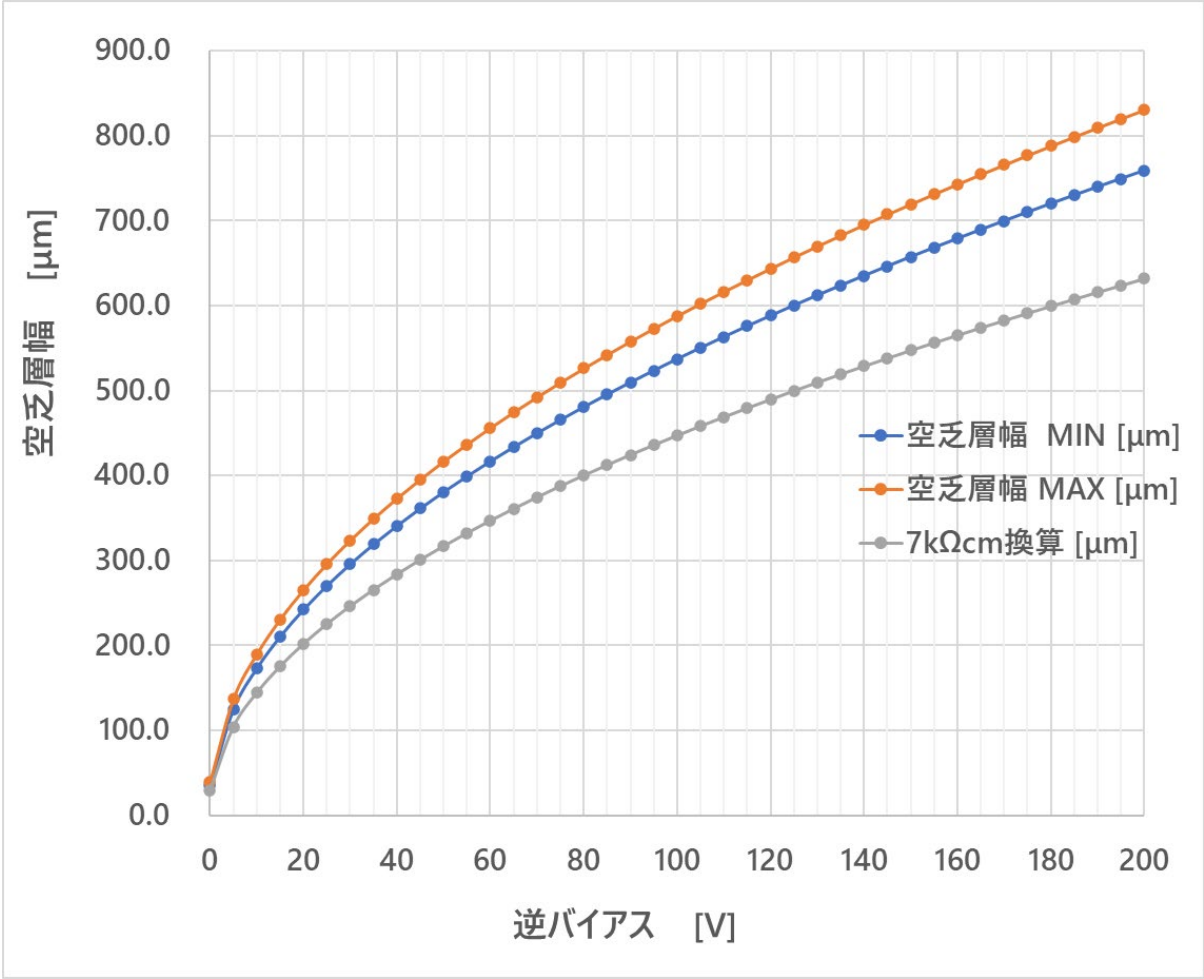
Data: ADC value (× number of read pixels) + Time Stamp

Confirm the time stamps of 5 sensors are synchronized with >99%.

Depletion layer thickness of INTPIX4NA

- Depletion layer thickness of INTPIX4NA calculated for resistivity (10.1 ~ 12.1kΩcm)

(7kΩcm is the estimated resistivity value of INTPIX4 from 2019 beam test)



逆バイアス [V]	空乏層幅 MIN [μm]	空乏層幅 MAX [μm]	7kΩcm換算 [μm]
0	35.4	38.7	29.4
5	125.0	136.8	104.0
10	173.2	189.5	144.2
15	210.6	230.5	175.3
20	242.3	265.2	201.7
25	270.3	295.9	225.1
30	295.7	323.7	246.2
35	319.1	349.2	265.6
40	340.9	373.1	283.8
45	361.3	395.5	300.8
50	380.7	416.7	316.9
55	399.1	436.8	332.3
60	416.7	456.1	346.9
65	433.6	474.6	361.0
70	449.9	492.4	374.5
75	465.6	509.6	387.6
80	480.7	526.2	400.2
85	495.5	542.3	412.5
90	509.7	557.9	424.4
95	523.6	573.2	435.9
100	537.2	588.0	447.2
105	550.4	602.4	458.2
110	563.3	616.6	469.0
115	575.9	630.4	479.4
120	588.3	643.9	489.7
125	600.3	657.1	499.8
130	612.2	670.1	509.6
135	623.8	682.8	519.3
140	635.2	695.3	528.8
145	646.4	707.5	538.2
150	657.4	719.6	547.3
155	668.3	731.5	556.4
160	678.9	743.1	565.2
165	689.4	754.6	574.0
170	699.8	765.9	582.6
175	710.0	777.1	591.1
180	720.0	788.1	599.4
185	729.9	798.9	607.7
190	739.7	809.6	615.8
195	749.4	820.2	623.8
200	758.9	830.6	631.8

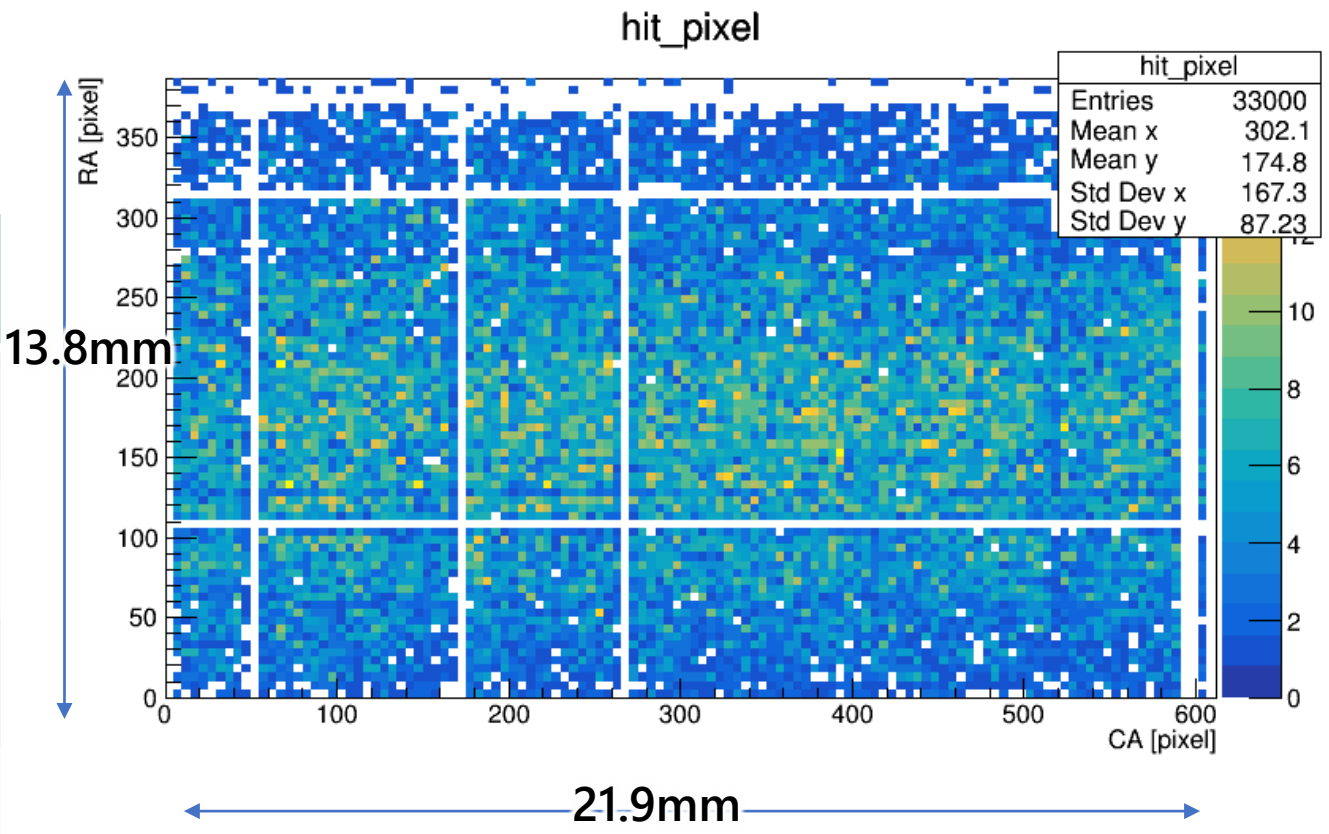
ELPHビームテスト　e⁺ビームセッティング、プロファイル

- Beam target: W (tungsten) 20μm

- Beam energy:

Current of electromagnet	momentum	Quadrupole magnet
100.0 A	197.79 MeV/c	QF=2T/m, QD=4T/m
150.0 A	297.30 MeV/c	QF=3T/m, QD=6T/m
250.0 A	492.5 MeV/c	QF=4T/m, QD=10T/m
475.0 A	822.37 MeV/c	QF=9T/m, QD=20T/m

Beam profile confirmed with XRPIX5



INTPIX4 circuit / logic