The 30th International Workshop on Vertex Detectors
27–30 Sep 2021
Oxford
Europe/London time zone
12:30-13:00
(JST+8)

# Progress on SOI Pixel Sensors

**Toshinobu Miyoshi (KEK)**

**On behalf of SOIPIX collaboration**

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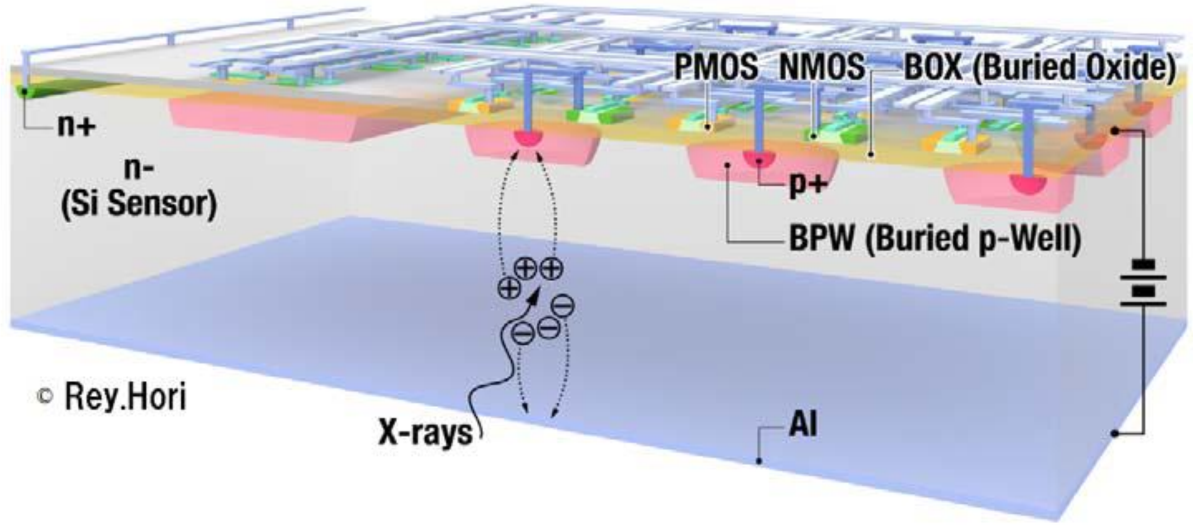
- Features of SOI sensors
- Process update
- Application
- summary

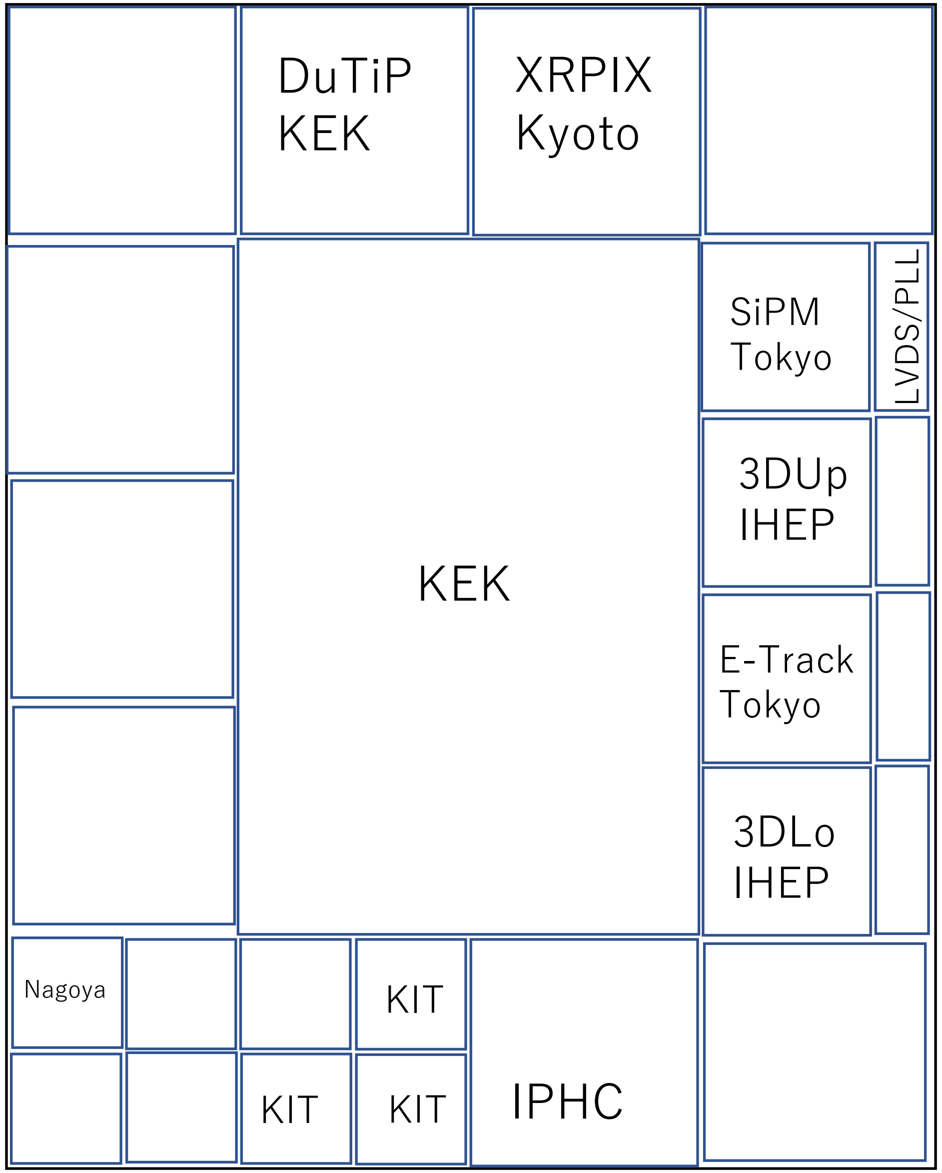
# SOI sensor




Monilithic SOI pixel detector
Commercial SOI pixel process
Lapis Semiconductor 0.2um SOI pixel process
Low material budget (after thinning)
Full depletion (sensor layer < 725um)

•No mechanical bump bonding. Fabricated with semiconductor process only
• Fully depleted (thick / thin) sensing region
with low sense node capacitance (~10 fF@17 um pixel) → high sensor gain
・SOI-CMOS; Analog and digital circuit can be closer (“active marge”)→ smaller pixel size
• Wide temperature range (1-570K)
• Low single event cross section

# Process update




2020.11 FY20 MPW (MX2254)

Blank areas are also reserved

FY2020 MPW run was done
FY2021 MPW run is planned (Tape out : 2021 Nov.)

We can choose 3.3V or 1.8V for IO cells

Pinned Depleted Diode (PDD) structure is also available

A wafer for 3D chips is required to scribe a large area around the chips

We can request thinning if required up to 70um (=sensor thickness) and a thinning less than 70 um might be ordered to a different vendor

A back side treatment (such as laser annealing etc.) can be requested

We can select an option for Al sputtering at the back side

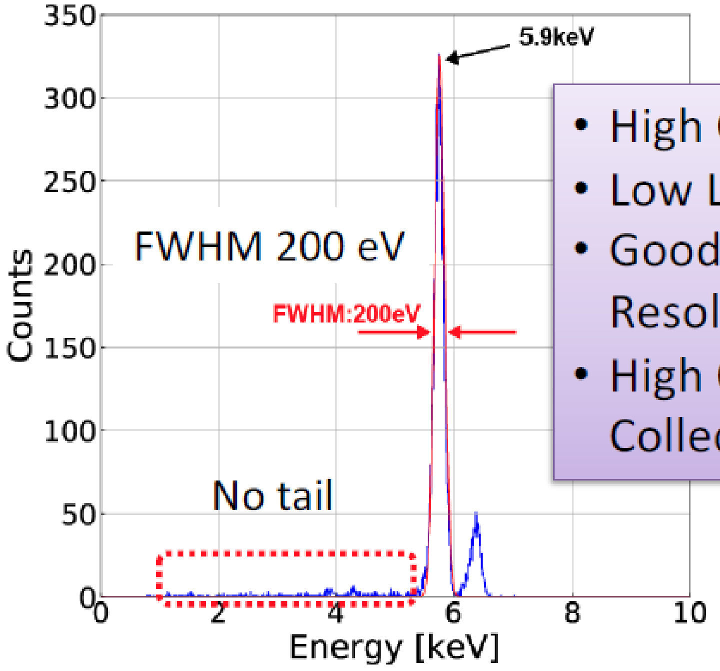
(24.6 mm x 30.8 mm)

# Pinned Depleted Diode (PDD) Structure



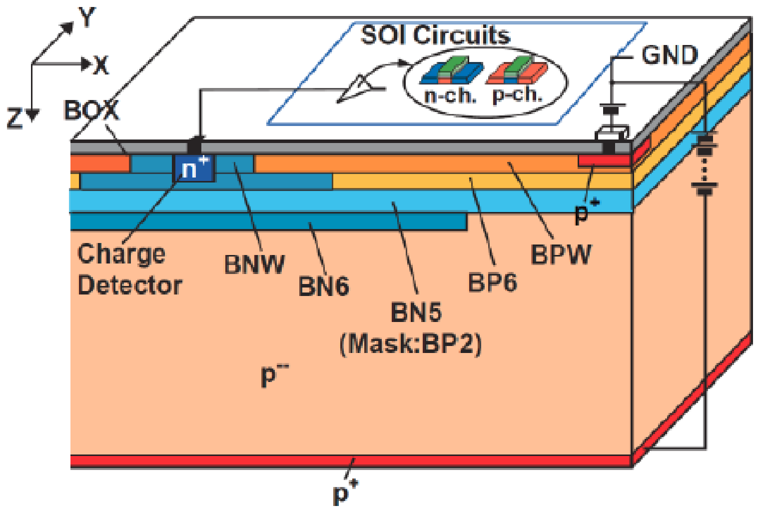
"A Low-Noise X-ray Astronomical Silicon-On-Insulator Pixel Detector Using a Pinned Depleted Diode Structure", H. Kamehama, S. Kawahito et al.,Sensors 2018, 18(1), 27

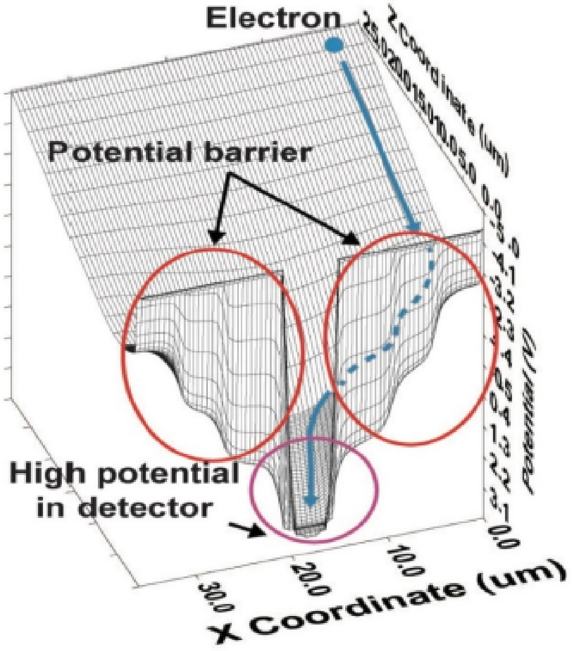
Gain = 70 μV/e-
Noise = 11.0 e-
Dark Current = 57 pA/cm2 @-35˚C




55-Fe measurement

- High Gain
- Low Leak Current
- Good Energy Resolution
- High Charge Collection Efficiency



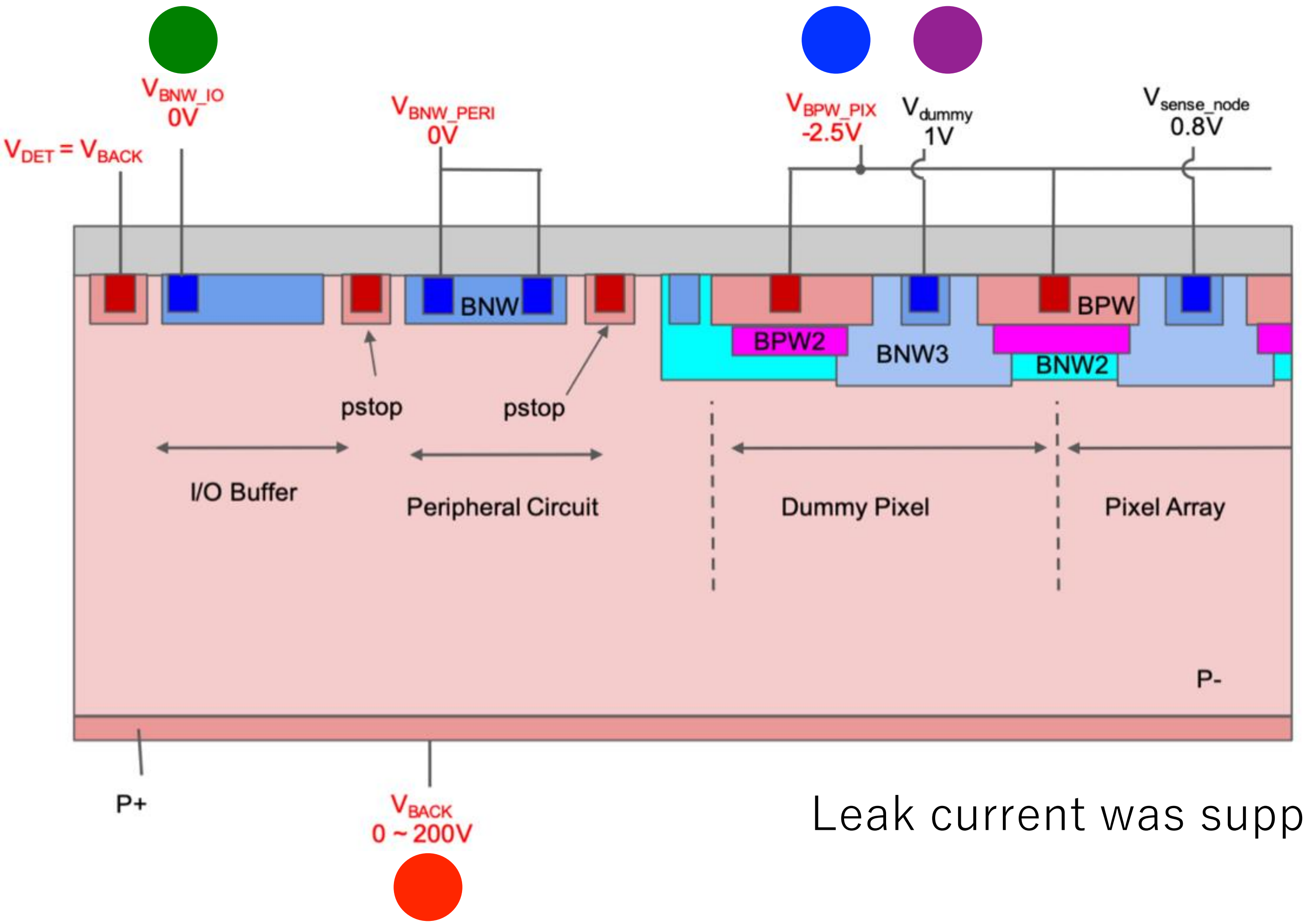



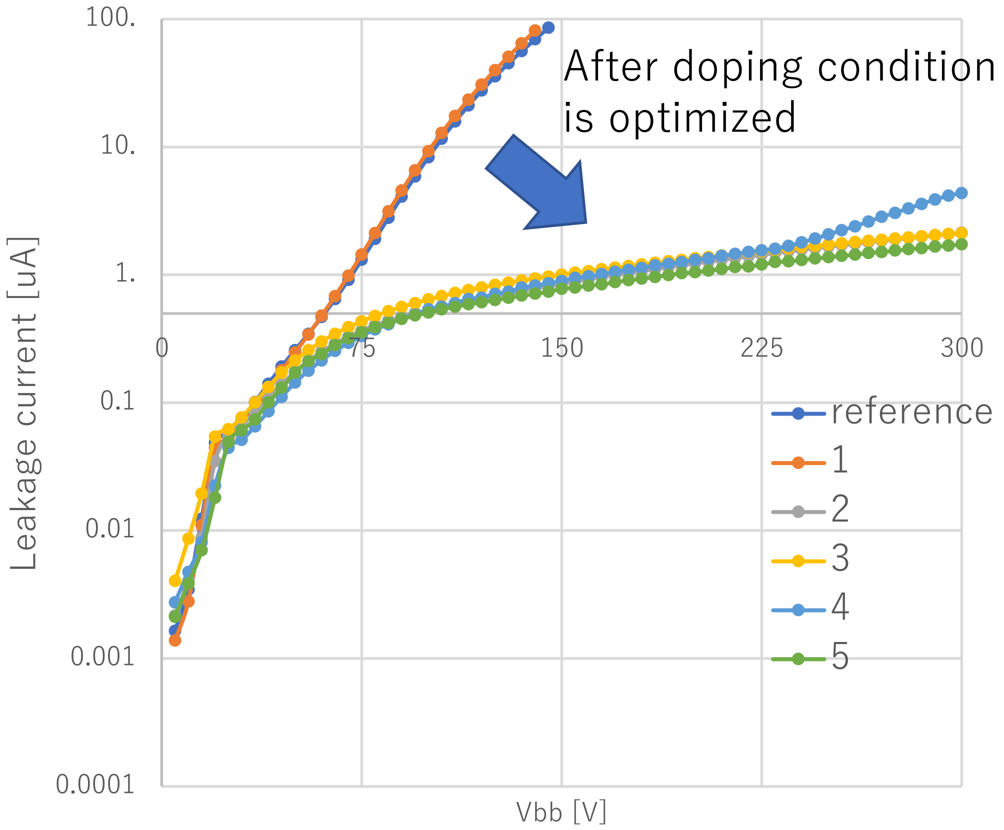

Simulation

# Optimization of PDD structure

A. Takeda, M. Yukumoto
(Univ. of Miyazaki)

Doping condition is optimized in the pixel region




Leak current was suppressed below back bias=300V

# On-going project

Application

**Use existing sensors**

**1. neutron experiment**

**2. Electron micrography**

**3. Muon beam monitor**

Fabricate new chips (FY2020-)

4 High-energy physics experiment (DuTiP)

5. X-ray astronomy (XRPIX)

6. Photon-counting CT/PET (SOI-SiPM)

7. Electron Track (ET) Compton Camera (SOI E-Track)

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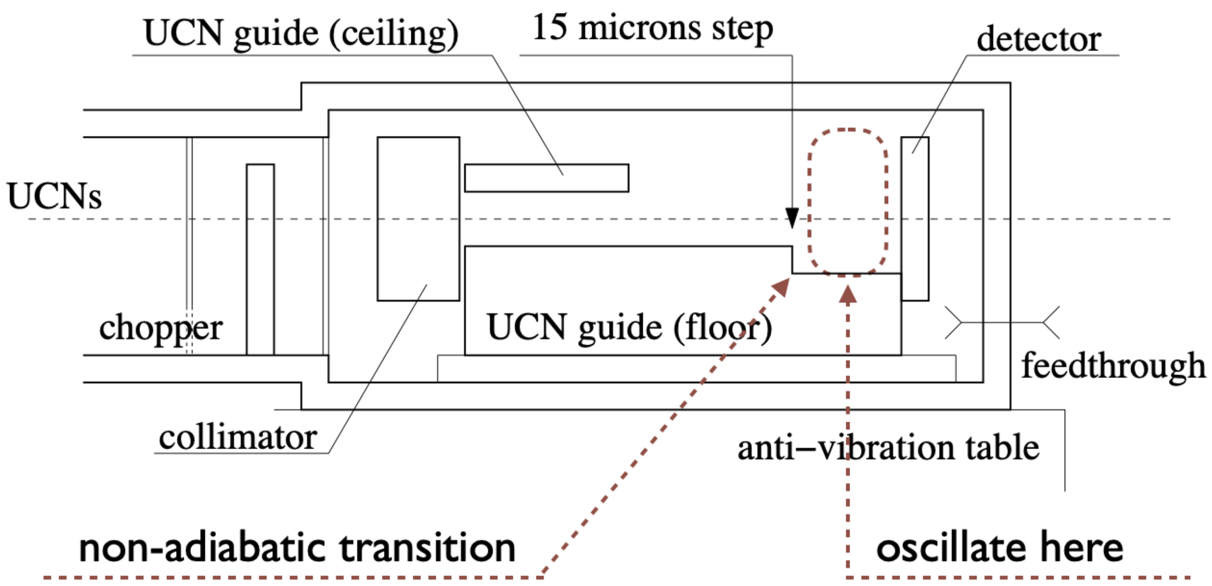
# Application for Neutron measurement

Measure gravitational/inertial mass ratio of neutron
to test the weak equivalence principle in the quantum regime




Y. Kamiya et al., Physics of fundamental Symmetries and Interactions
– PSI2016, Switzerland, Oct. 16 -20 (2016)

Time-resolving imaging detector

- Evaluate the length scale of gravitationally bound neutron states by measuring the special distribution

G. Ichikawa, S. Komamiya, Y. Kamiya et al., PRL 112, 071101 (2014)

- Evaluate the energy scale of the bound states by measuring the oscillation frequency

Requirement of pixel sensor:
Small pixel size : < a few tens of um
Frame rate < 5ms

SOIPIXs (INTPIX/XRPIX) are the promising candidates

Univ. of Tokyo

# Development of $^{10}$B-INTPIX4

Y. Kamiya, T. Miyoshi, H. Iwase et al., NIMA979, 164400 (2020)

## INTPIX4

+ 512 x 832 pixels ( 17 μm-square / 10.2 x 15.4 mm$^2$ )
+ Thickness ~ 300 μm
+ Readout speed : 280 nsec / pixel (measured)
+ Gain 13.1 μV/e$^-$

(S. Mitsui, Y. Arai, T. Miyoshi, and A. Takeda, NIMA 953, 163106 (2019) )

## Formation of 10B layer

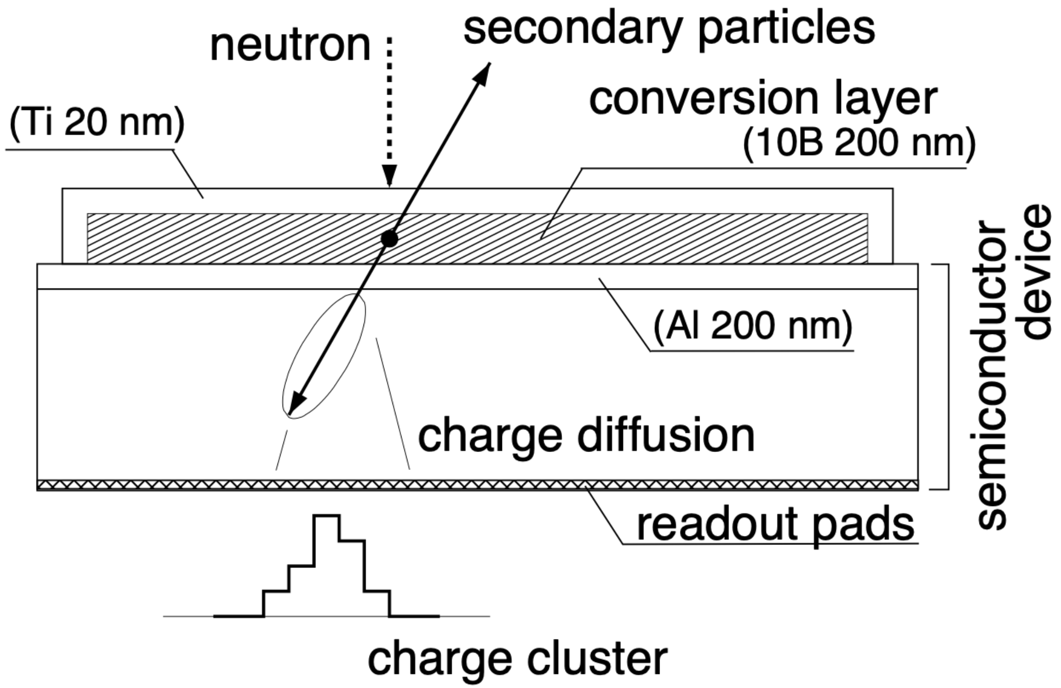
Argon RF sputtering

Nanotechnology platform @ univ. of Tokyo

Shibaura CFS-4EP

+ 400(100) W RF Power for Ti/B (pre-sputtering)
+ Sputtering rate for Ti(B): ~ 1.5(0.3)/10 [nm/sec]

sputtering machine in the clean room (class 100)



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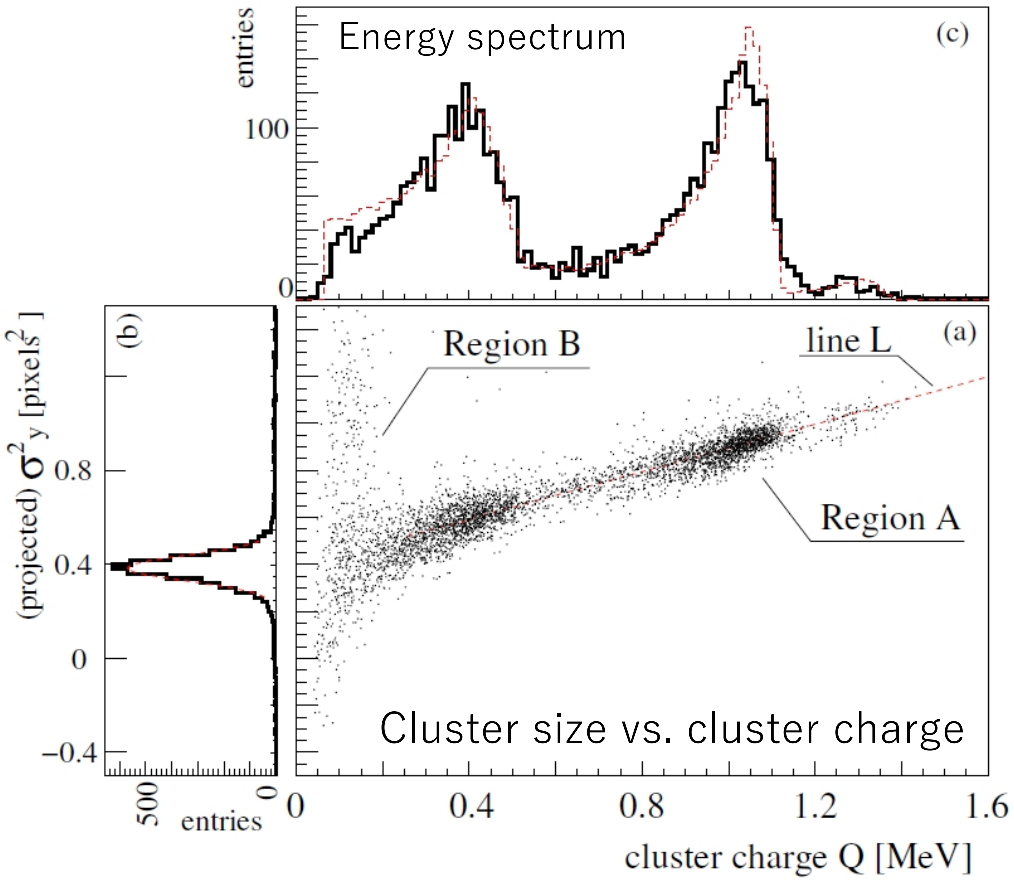
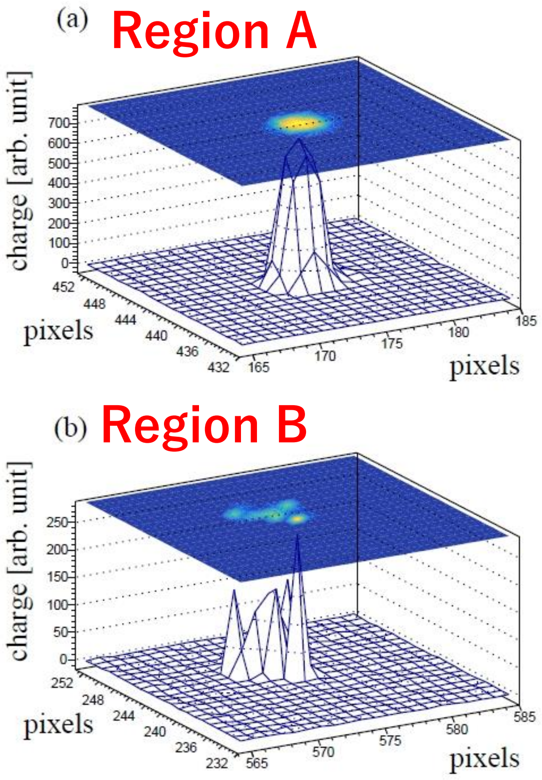
# Neutron irradiation tests

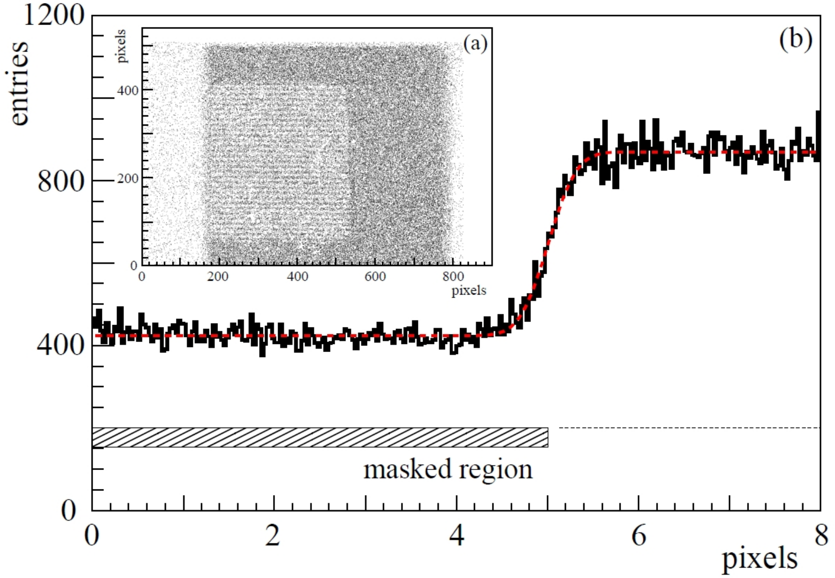
Y. Kamiya, T. Miyoshi, H. Iwase et al., NIMA979, 164400 (2020)

The Standard Thermal Neutron Irradiation Laboratory (STNL) at KEK
The E3 port at the Kyoto University reactor (KUR)
The BL10 beamline of the MLF, J-PARC center




Profile of an accumulated edge shadow




Measured at MLF in 2020
Mask pattern (Gd, 100um pitch, trench depth is 100um) are observed
Spatial resolution 4.1 +/- 0.2 um

Measurement was done at STNL in 2019
Find clusters in 7x7 pixels
Neutron events can be distinguished

FY2019- 10B-INTPIX4
FY2020- 10B-XRPIX7: Zhang Lan(Univ. of Tokyo)
FY2021- 10B-INTPIX4NA

T. Ishida
(Nagoya Univ.)

# Application to electron micrography

名古屋大学 NAGOYA UNIVERSITY

IMaSS 未来材料・システム研究所 Institute of Materials and Systems for Sustainability

Start collaboration between KEK and Nagoya Univ. in 2018
Goals:
Time-resolved transmission electron microscopy (TR-TEM) with sub-us order
Demonstration with INTPIX4 SOI sensors
Feasibility study in Low Voltage(LV) TEM

30-kV spin-polarized transmission electron microscope with GaAs-GaAsP strained superlattice photocathode

*Kuwahara et. al., APL (2012)

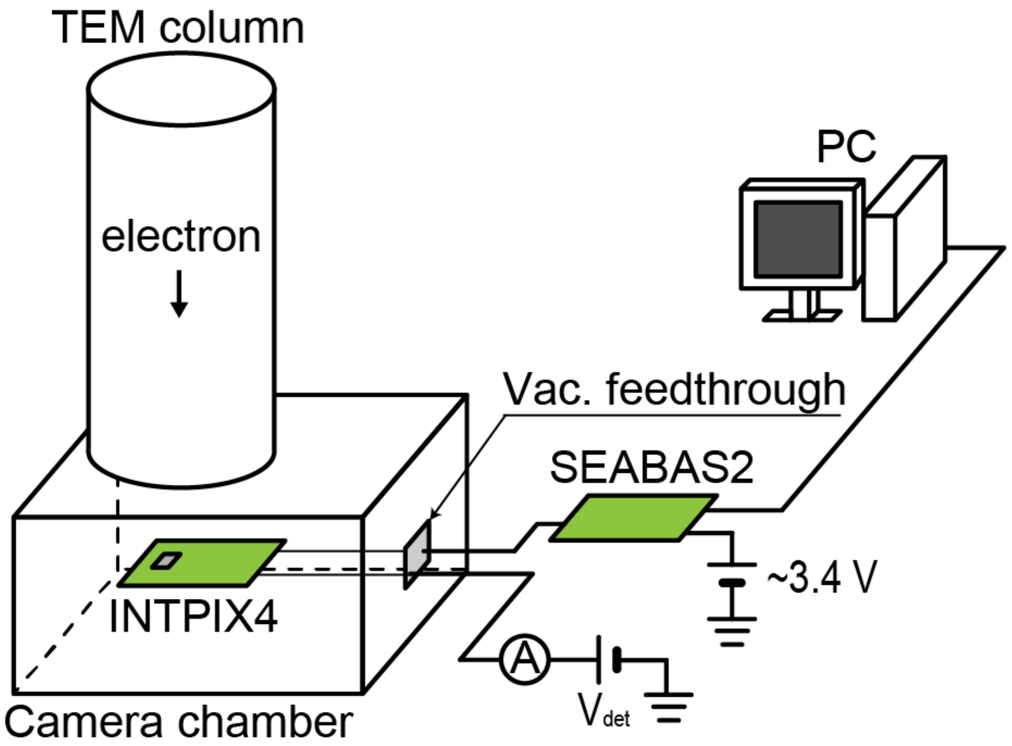
INTPIX4
Pixel size 17um x 17um, 512x832
Sensor thickness 500um
Back bias ~280V (full depletion)

**Mitsui et. al., NIM (2020)

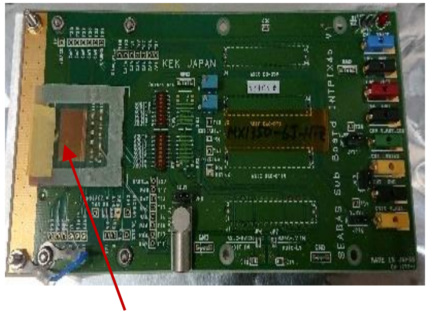
DAQ board(SEABAS2)
12-bit ADC output, frame rate 10 fps (Max. 100 fps)

***Nishimura et. al., NIM (2016)

"Performance of a silicon-on-insulator direct electron detector in a low-voltage transmission electron microscope", Takafumi Ishida, Akira Shinozaki, Makoto Kuwahara, Toshinobu Miyoshi, Koh Saitoh, Yasuo Arai, Microscopy, Volume 70, Issue 3, June 2021, Pages 321–325




Back side illumination

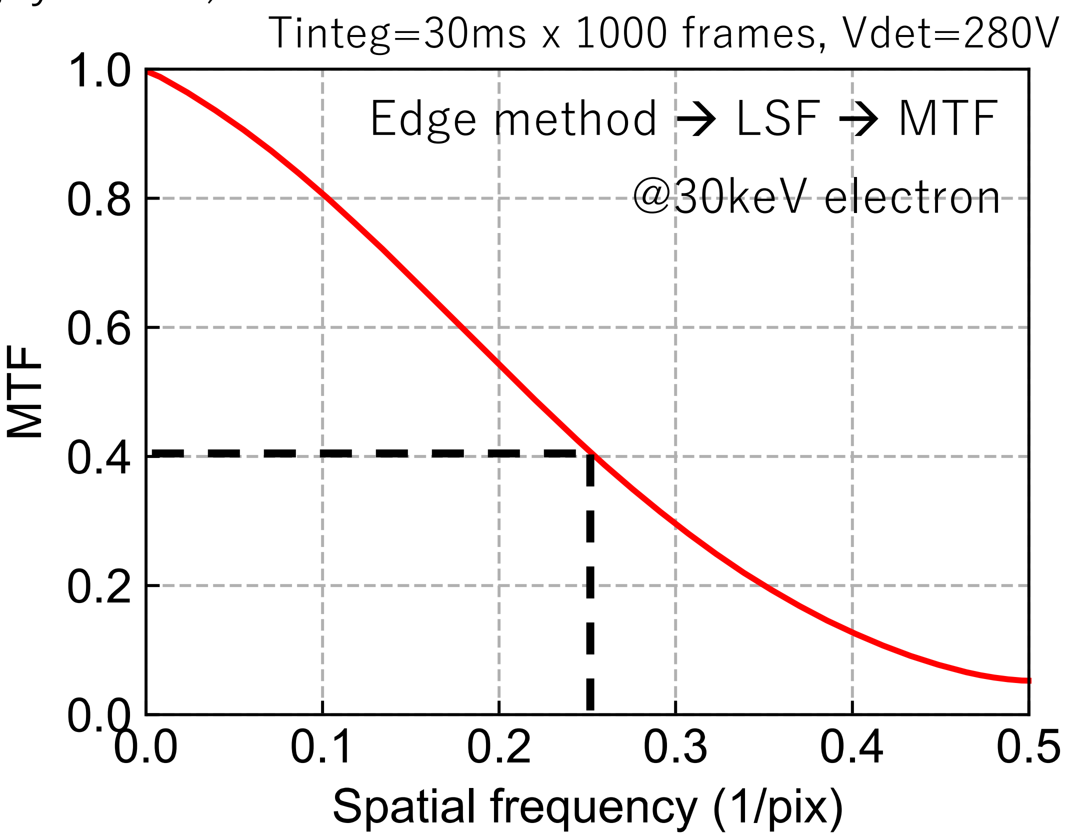


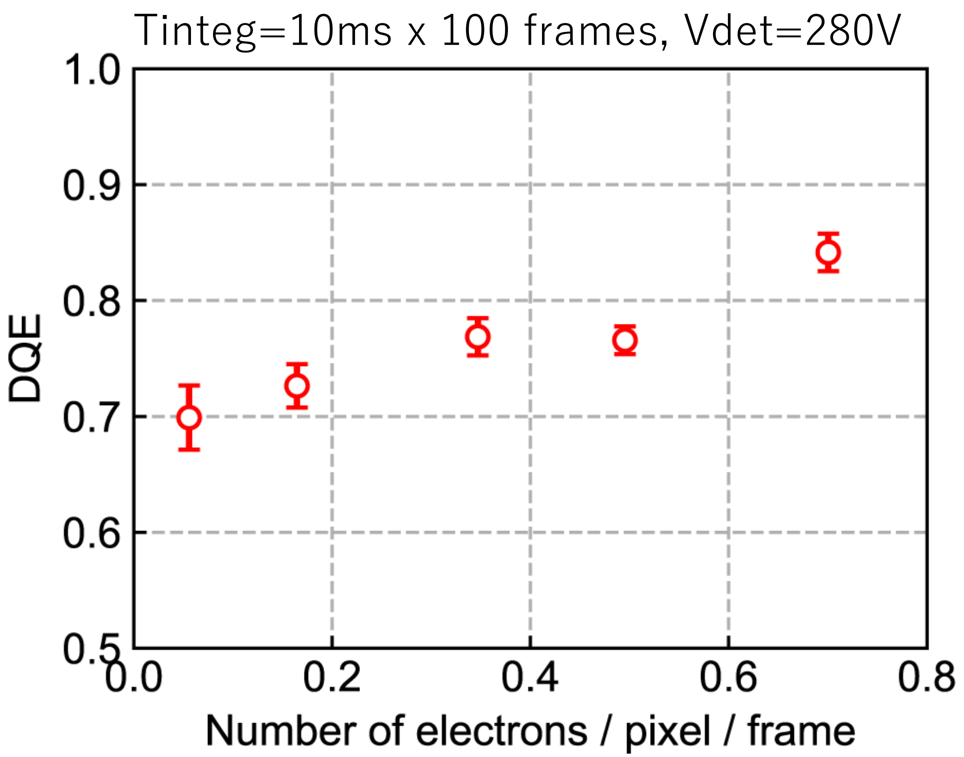
INTPIX4

SEABAS2

T. Ishida
(Nagoya Univ.)

# MTF and DQE




$$DQE = \left(\frac{SNR_{out}}{SNR_{in}}\right)^2 = \frac{\bar{I}^2/\mathrm{var}(I)}{m \cdot \bar{n}}$$

INTPIX4@30keV
→ ~0.4 (0.25 $\mathrm{pix}^{-1}$)

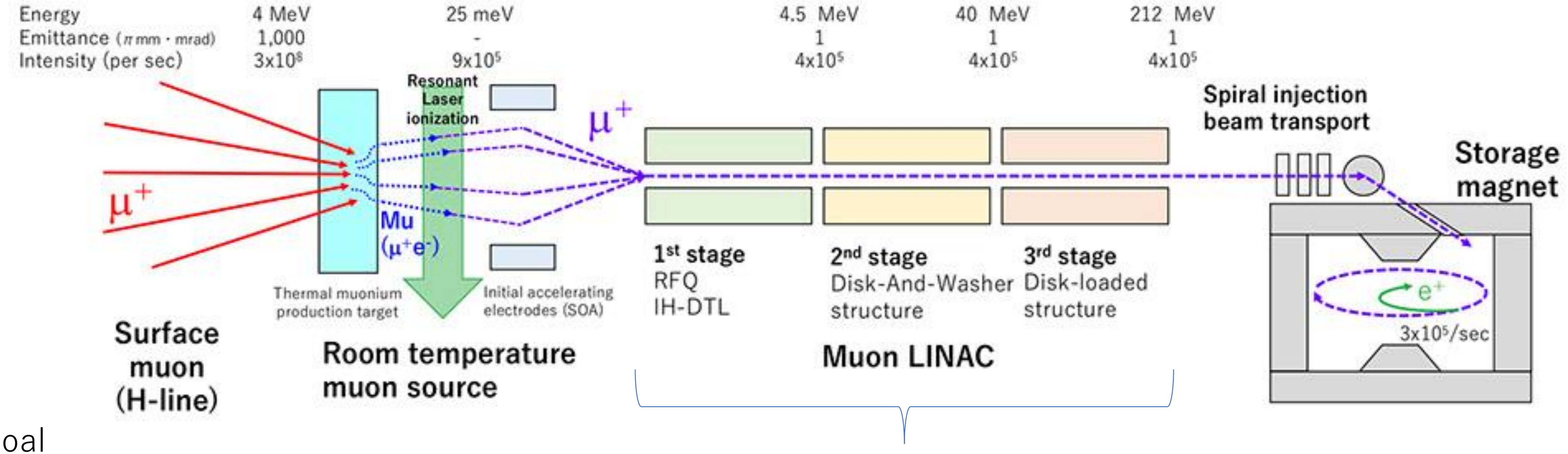
Ave. # of output counts ：$\bar{I}$
Variance：$\mathrm{var}(I)$
Ave. # of incident electron： $\bar{n}$

Mixing factor*：$m = 7.56$
*Ishizuka, Ultramicroscopy (1993)

FY2021 evaluation of SOI sensor in TR-TEM
FY2022 development of large area SOI sensor for further evaluation

# Muon g-2/EDM experiment at J-PARC

https://g-2.kek.jp/portal/




Goal
Anomalous magnetic moment 0.1 ppm
Electric dipole moment (EDM) 10^-21 e.cm

Muon beam monitor:

Initially proposed method
MPC-Phosphor-CCD combination

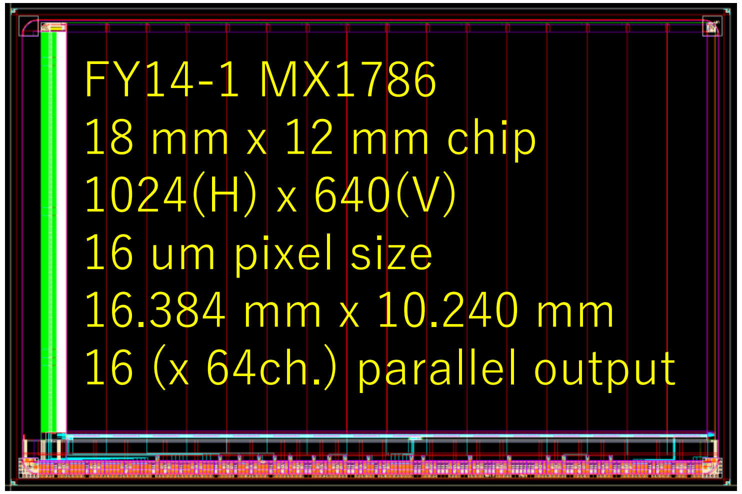
“A new approach for measuring the muon anomalous magnetic moment and electric dipole moment”, M Abe, et al., Prog. of Theo. and Exp. Phys., Volume 2019, Issue 5, May 2019, 053C02

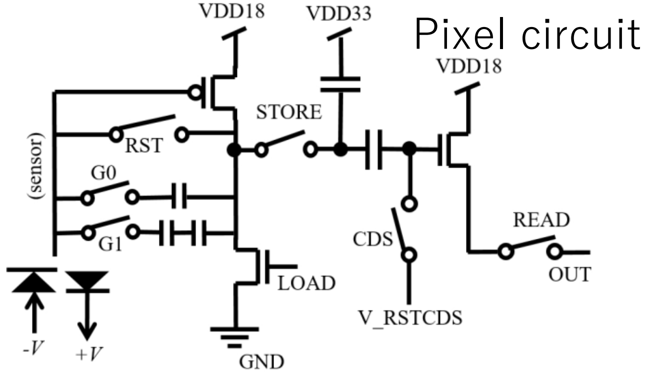
Muon LINAC: 3 stages
Beam monitor at the exit of 3 stages:
4.5 MeV, 40 MeV, 212 MeV
Different energy deposit in each energy

<u>SOI pixel sensor is proposed as a beam monitor:</u>
INTPIX8 pixel size 16 um x 16 um, 1024 x 640

T. Youssef (SOKENDAI)

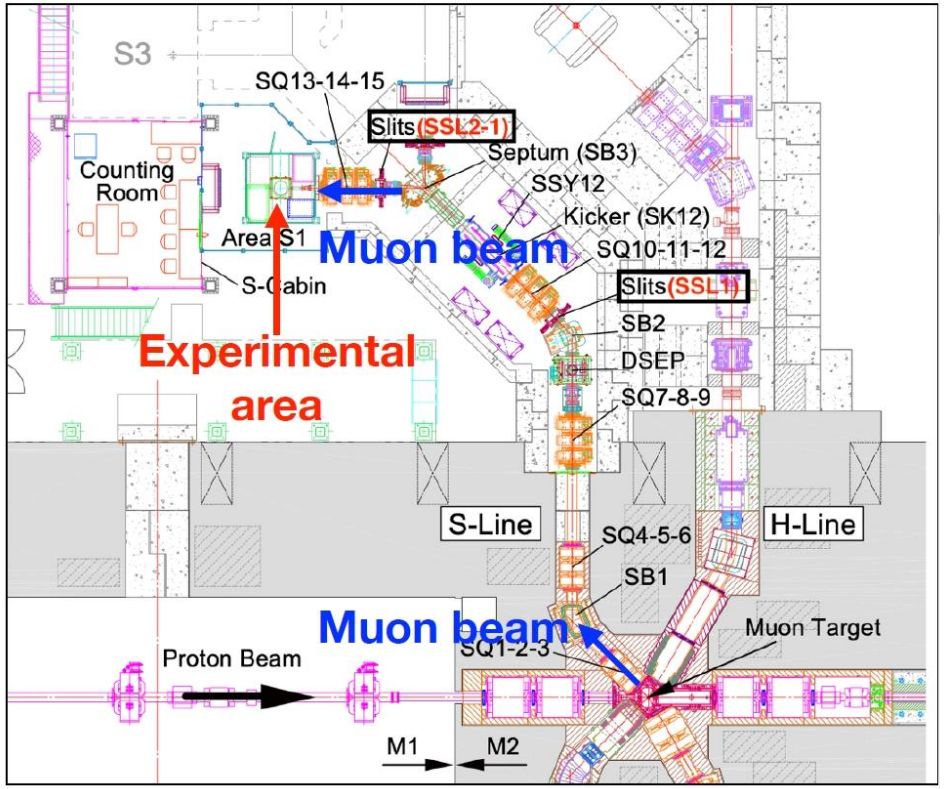
# Application to muon beam monitor




(OK) Required area 10 x 10 mm$^2$
(OK) special resolution > 0.1 mm
(OK) readout time 25 Hz
(OK) expodure time > 10 ns
(?) Dynamic range : <u>a few to 10$^4$ muons</u>

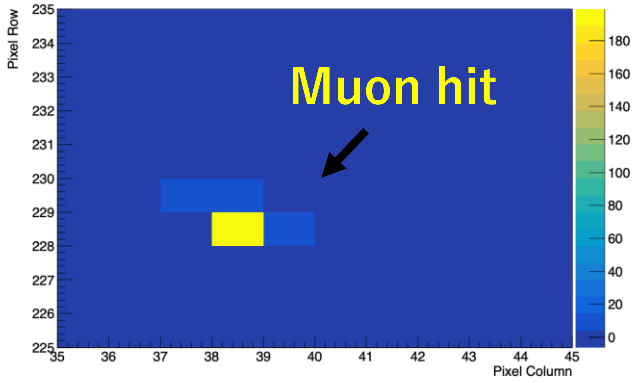
## Muon beam test at J-PARC (Mar. 2020)



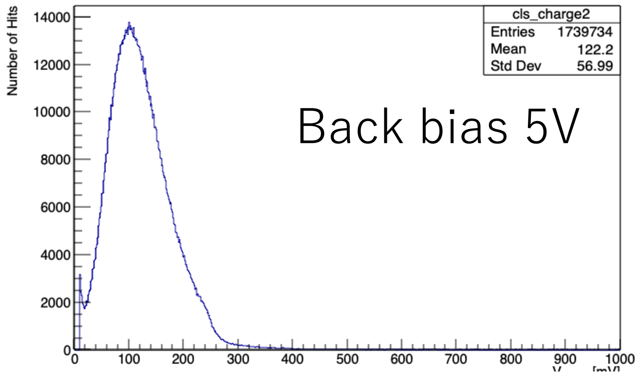

- Muon detection
- Detection in partial depletion
- Dynamic range test

Intensity 1.4x10^5Hz (<10^6Hz)
Beam energy 4 MeV (~IH-DTL)
Beam size ~2.5cm$\phi$ (>a few mm$\phi$)
Integration time 200ns

### An example of muon hit




### A muon spectrum




Voutput[mV]

Analysis is ongoing; next → Construct a vacuum chamber for the sensor to accelerator tube test

# On-going project

Application

Use existing sensors

1. neutron experiment
2. Electron micrography
3. Muon beam monitor

**Fabricate new chips (FY2020-)**

**4 High-energy physics experiment (DuTiP)**

**5. X-ray astronomy (XRPIX)**

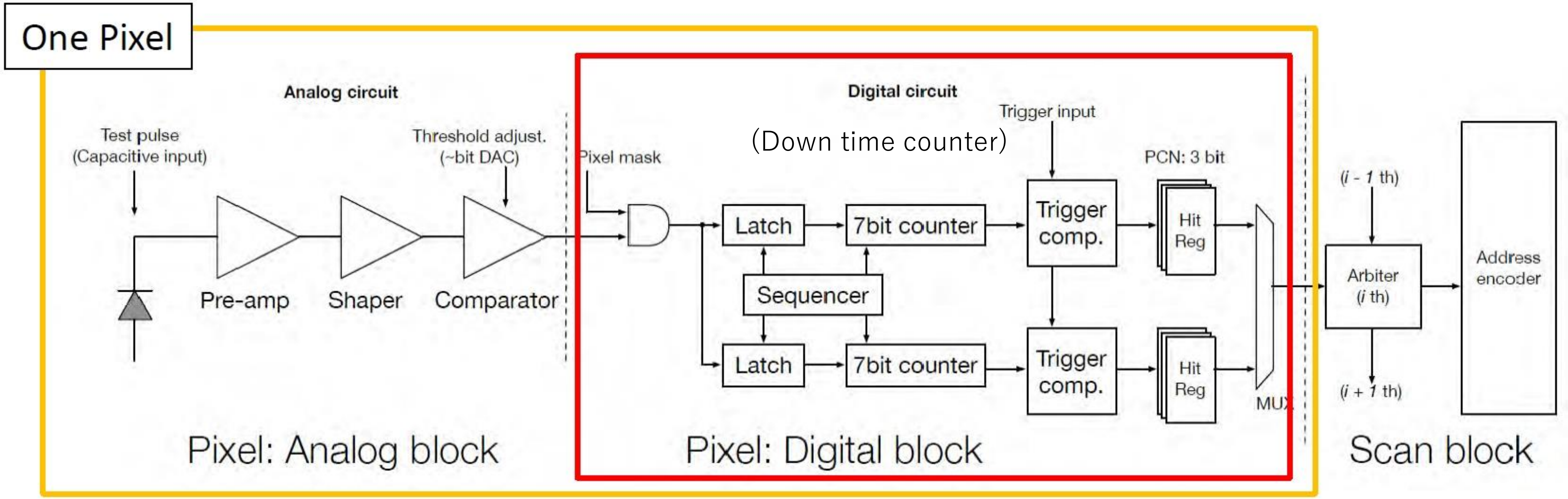
**6. Photon-counting CT/PET (SOI-SiPM)**

**7. Electron Track (ET) Compton Camera (SOI E-Track)**

# DuTiP for Belle II upgrade

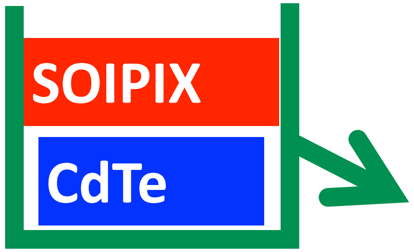
Also refer to Nakamura-san's talk (Sep. 28)

Dual Timer Pixel concept
Binary detector / 45 um x 45 um pixel size / 50um thickness / Two 7-bit timers to hold signals and wait for trigger / 15.9 MHz clock (63ns) synchronized with SuperKEKB clock
7-layer vertex detector replacing PXD+SVD
PDD structure is applied

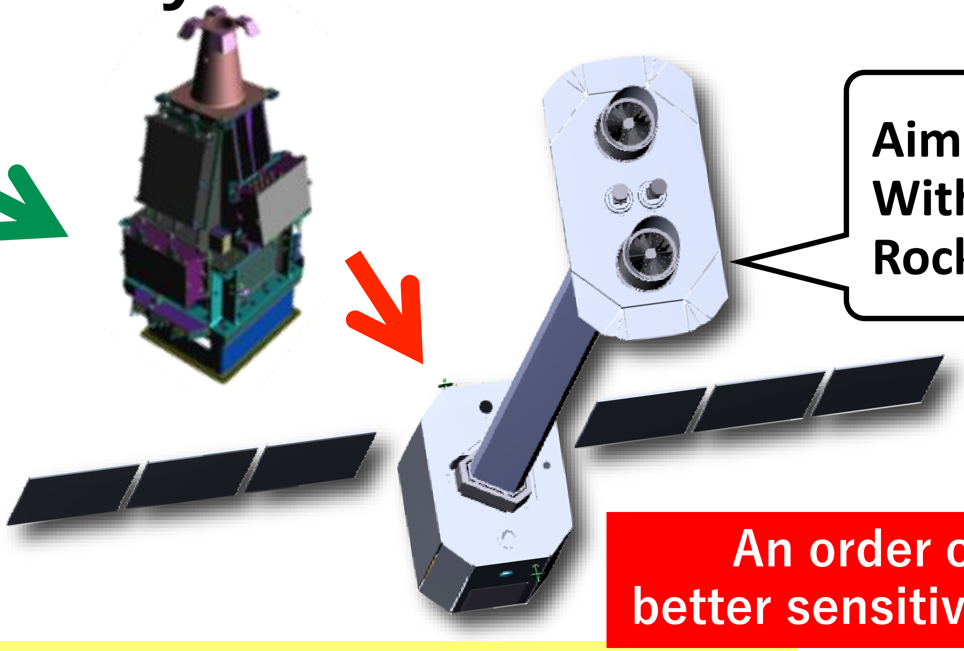



FY2020 DuTiP1 (basic component and pixel matrix) was developed and testing
FY2021 DuTiP2 (full function, row direction) will be submitted

# X-ray astronomy




## Wide-band X-ray Astronomy Satellite "FORCE"

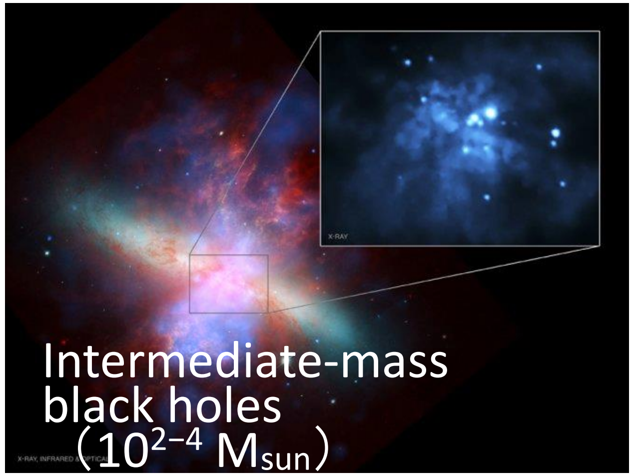


**Aiming for a launch ~2030 With a JAXA epsilon Rocket.**

**An order of magnitude better sensitivity than NuSTAR**

Goal

**To complete a census of black holes across cosmic time and mass scale**



## XRPIX collaboration

Kyoto U.
U. Of Miyazaki
Tokyo U. of Sci.
Shizuoka U.
Konan, U.
KEK

Development of XRPIX

Primary purpose:

X-ray astronomy

Other applications:

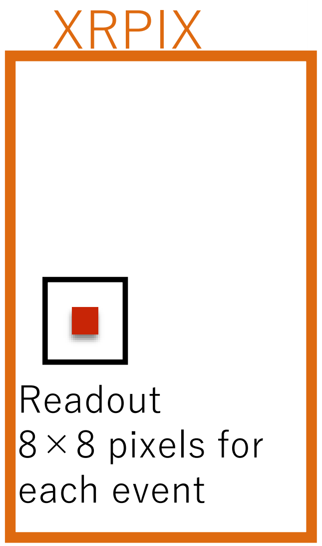
MeV-γ

Axion search

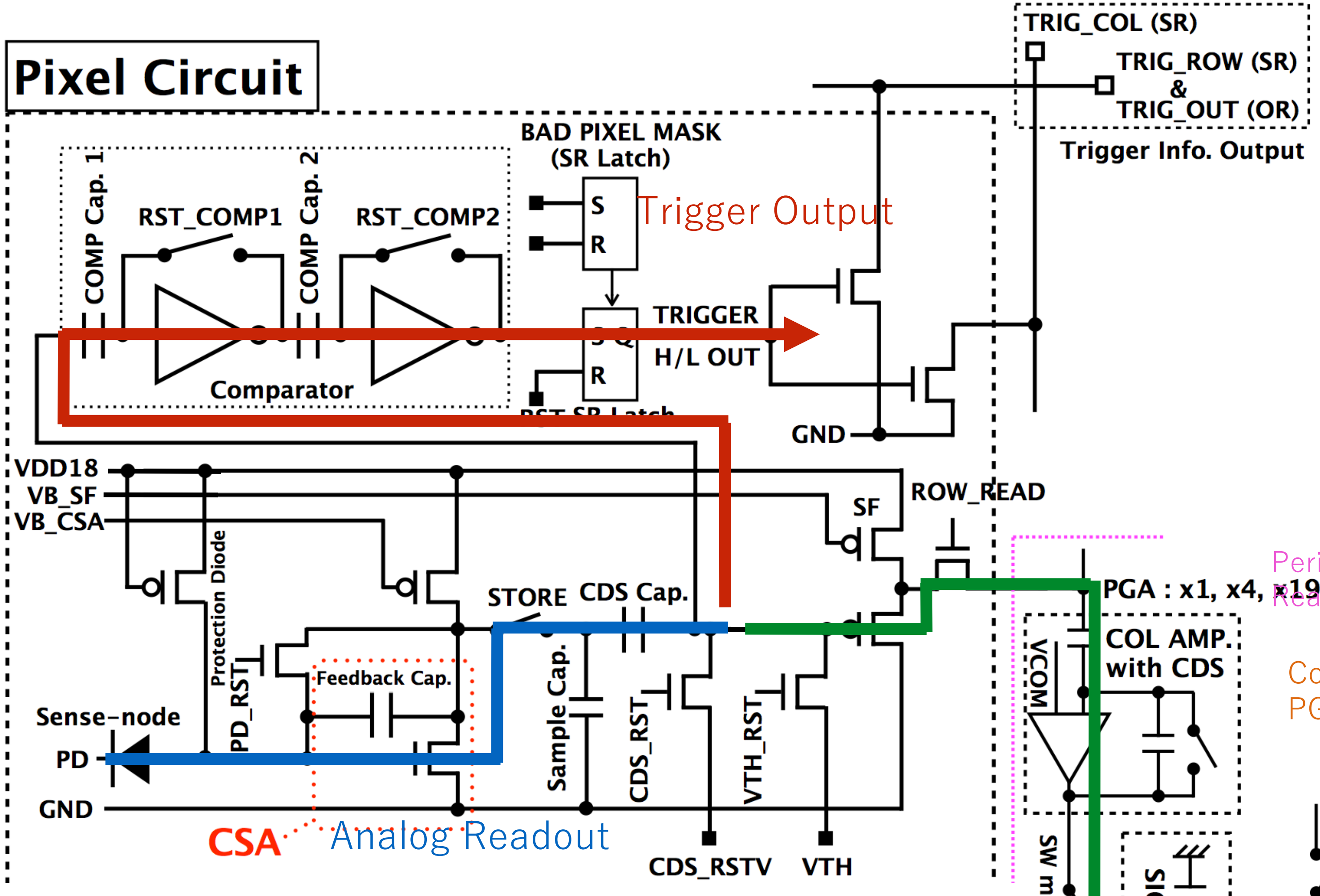
Neutron

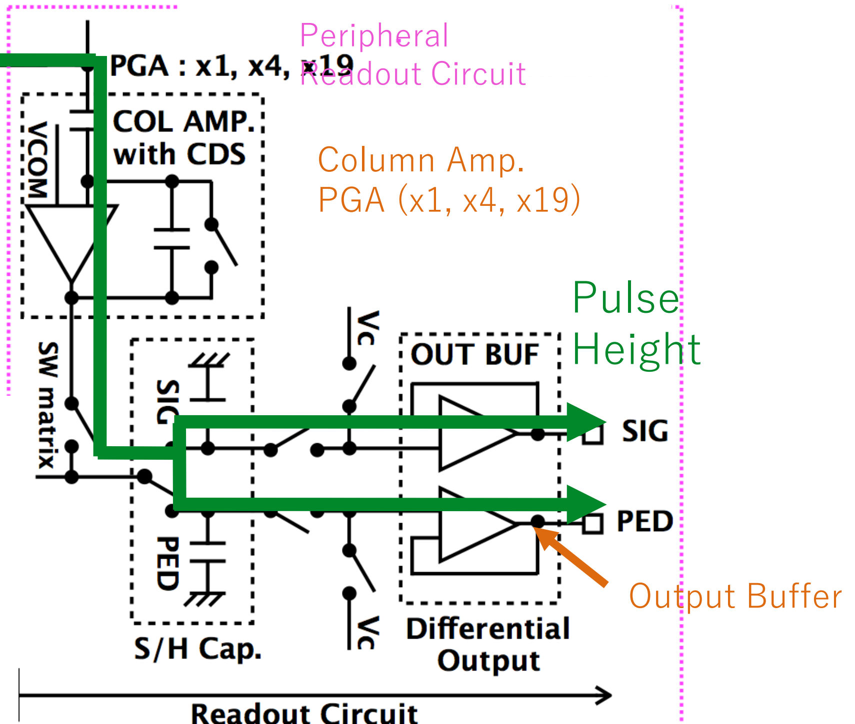
# XRPIX:Pixel and Perophereal Circuits (since ver. 5)

XRPIX collaboration

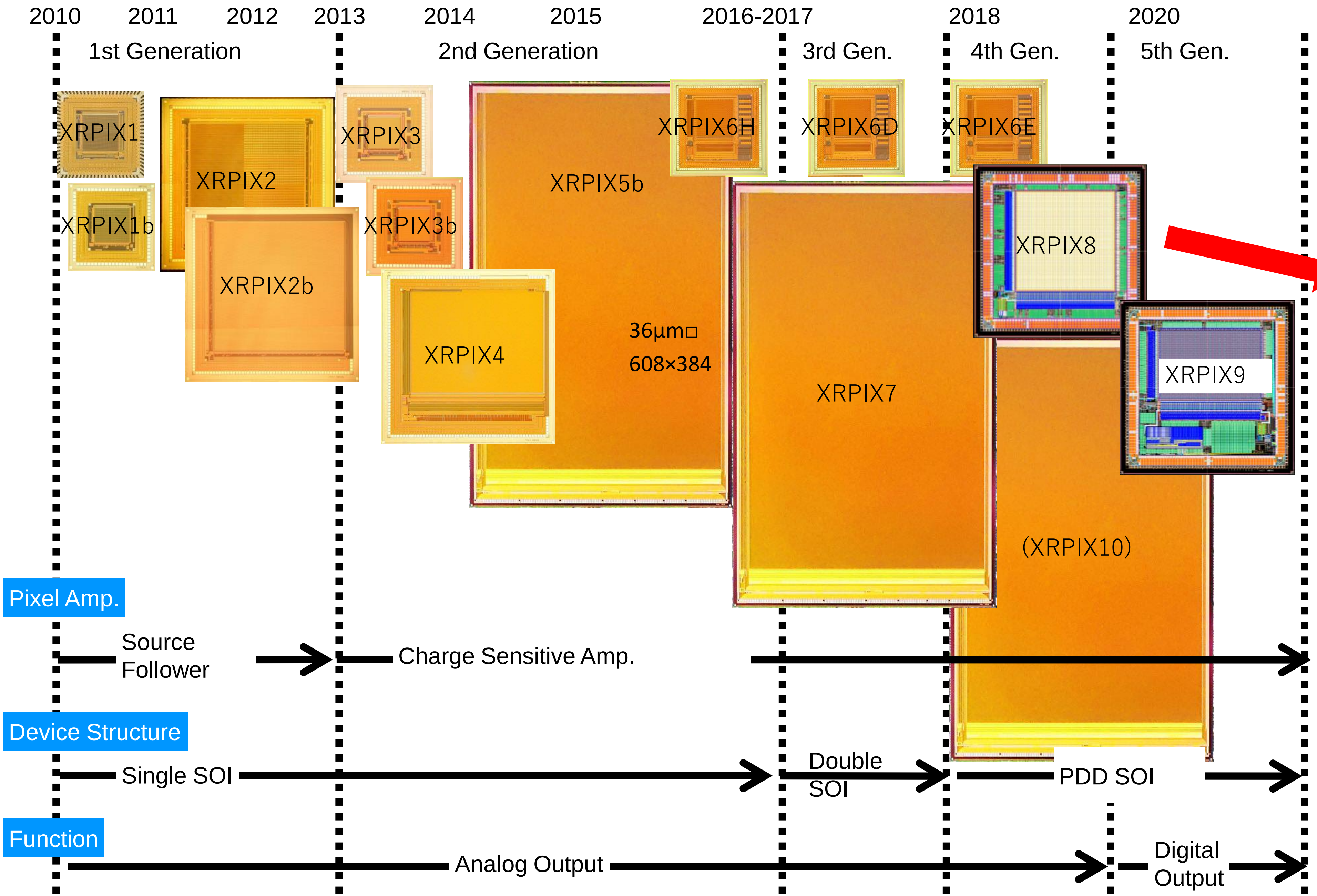



Kyoto U.
Miyazaki U.
Tokyo U. of Sci.
Shizuoka U.
Konan, U.
KEK



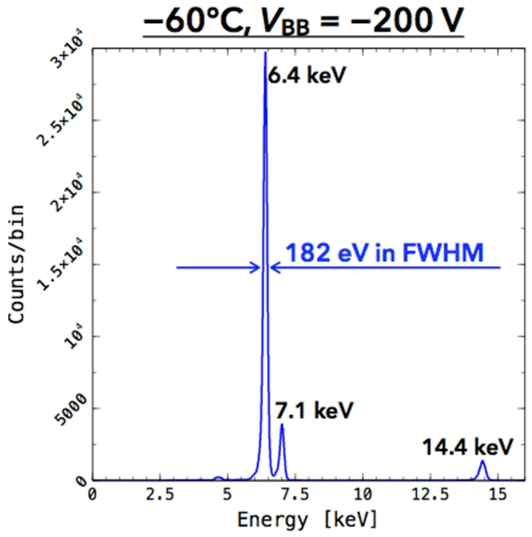
# History of the development




## XRPIX collaboration

Kyoto U.
Miyazaki U.
Tokyo U. of Sci.
Shizuoka U.
Konan, U.
KEK

**XRPIX8**
Event driven
94×94 pixels FI
with gain correction



K. Shimazoe

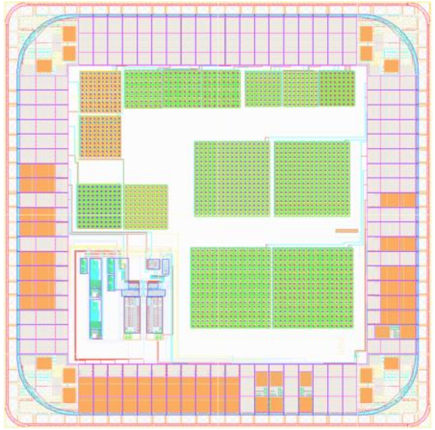
# Development of SOI SiPM

The Univ. of Tokyo, Bioengineering Department, Takahashi Laboratory

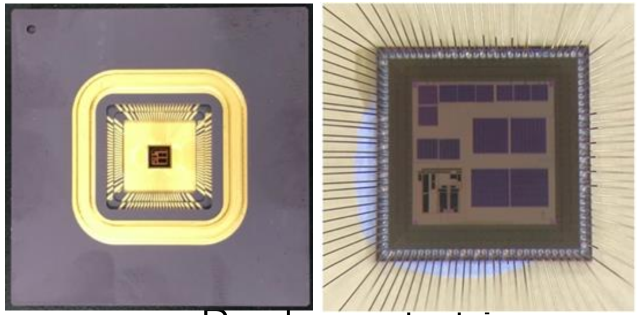
Application : photon-counting CT or PET

Version 1
- Chip size：2.9 mm x 2.9 mm
- 6 microcell

Quench R：100kΩ＆200kΩ
  - Reduce cathode and guard ring
- Cell size：28～30 μm



Chip layout



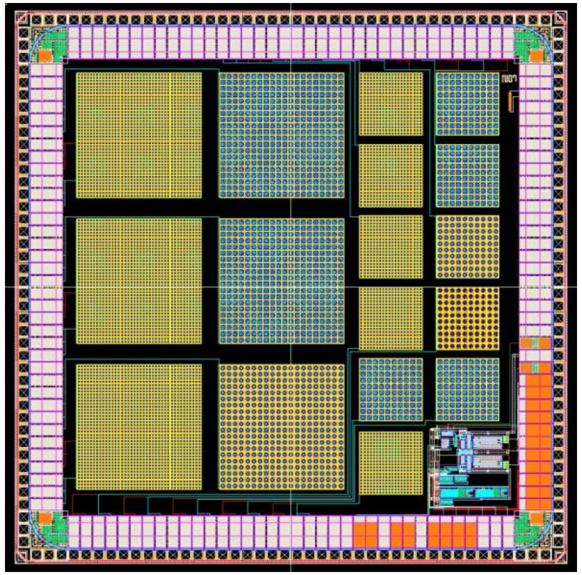
Packaged chip

Version 2 (version 1 was modified)

**Chip size**: 4.45 × 4.45 $mm^2$

**Pixel Dimension**
- 1.0 × 1.0 $mm^2$ TEGs: 6
- 0.5 × 0.5 $mm^2$ TEGs: 11

**Design Variable**
- Size of microcell
- Size of cathode
- Thickness of guard ring
- Shape of anode



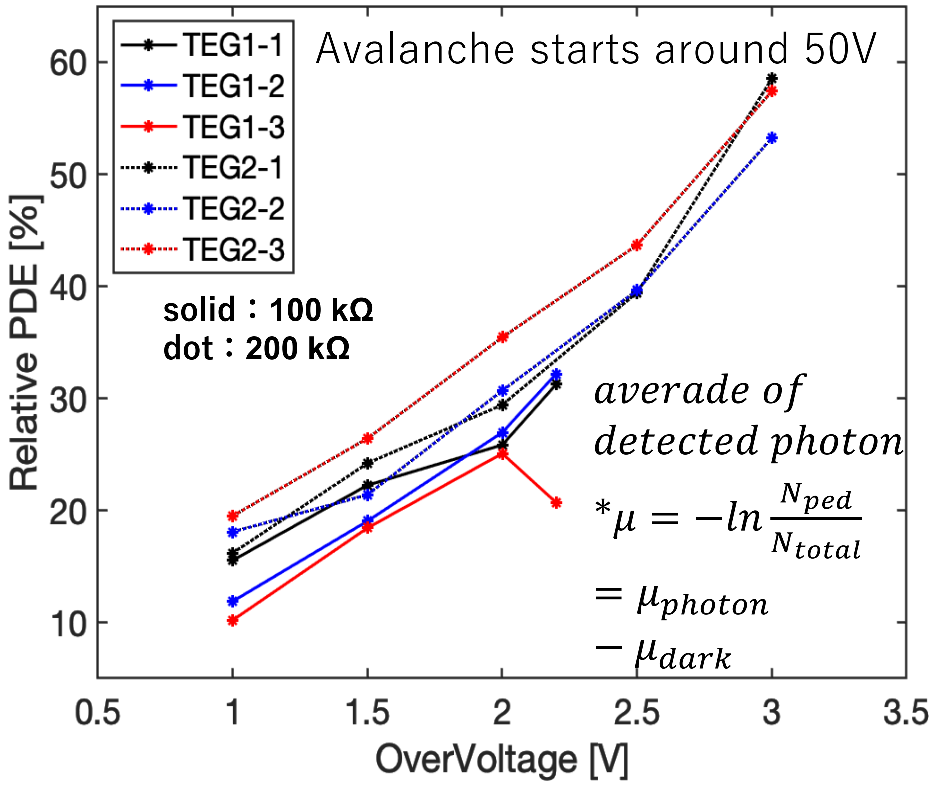
70 $\mu$m thinning for back illumination

Evaluation test is underway

K. Shimazoe

# Evaluation test in SOI-SiPM ver. 1

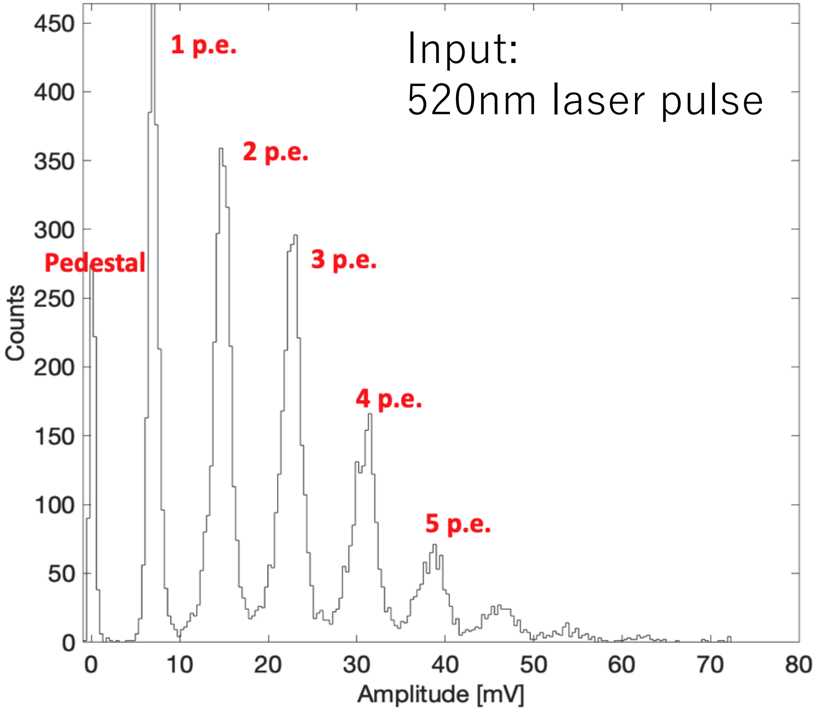
## PDE(photon detection efficiency)




| | Average detected photon [%] | ND filter | area [$mm^2$] | PDE [%] |
|---|---|---|---|---|
| **KETEK*** | 32.5 | 4.0 | 3×3 | **17 %** |
| **SOI-SiPM** | 39.6 | 1.4 | 0.24×0.24 | **8.1 %** |

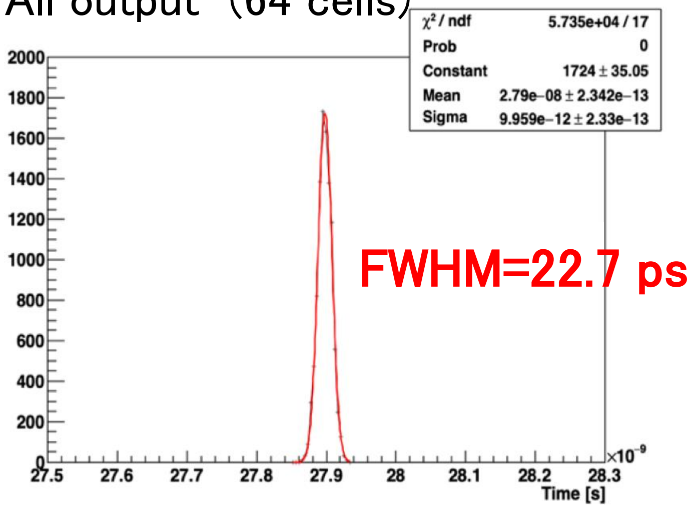
* PM3350

## Photon spectrum

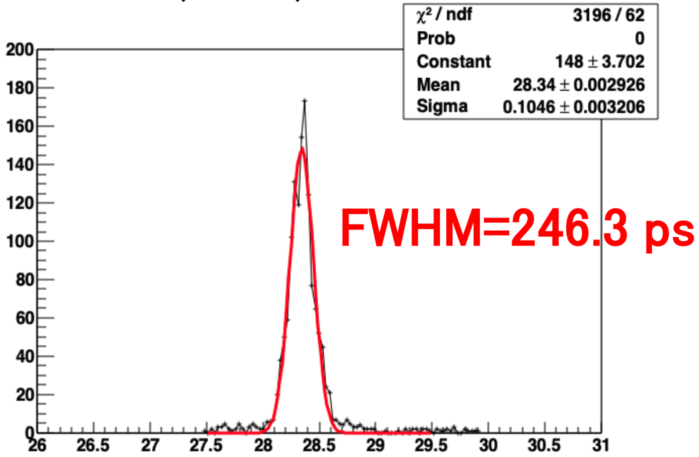



## Time resolution

All output（64 cells)




SPTR *（1 cell)

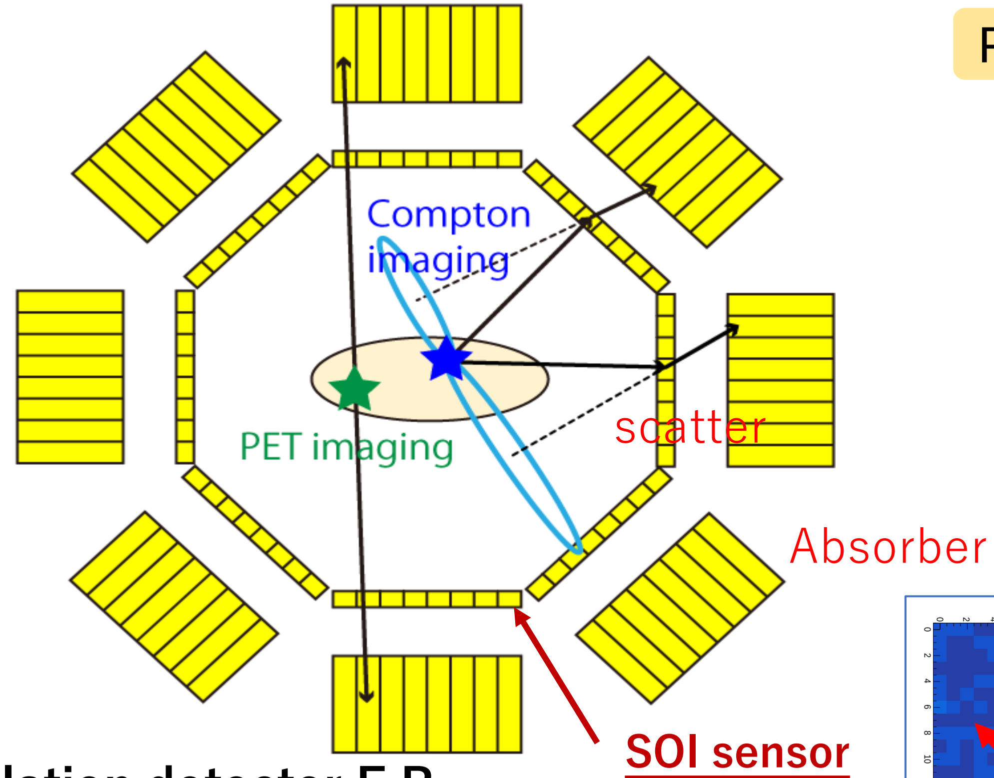


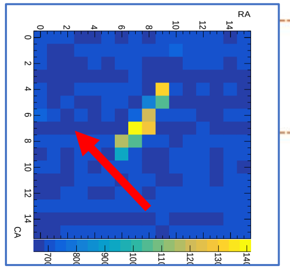

coincidence event between trigger and SiPM
Time spectrum = t_SiPM – t_trig

* Single Photon Time Resolution

# SOI based electron tracking Compton-PET scanner

## Compton-PET hybrid camera

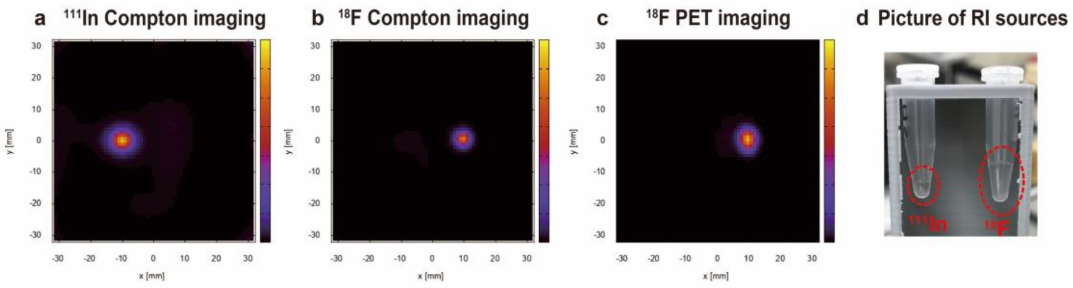


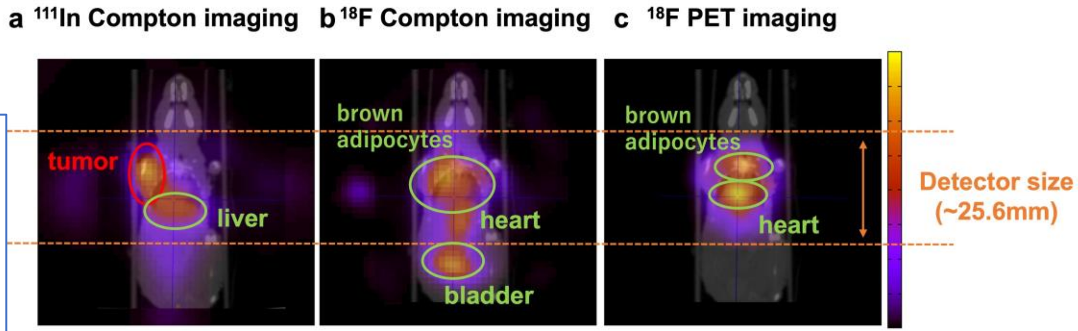
**Scintillation detector E.R.**
**energy was limited ＞150 keV in imaging**

## 511 keV and 245 keV

PET ($^{18}$F–FDG) and SPECT ($^{111}$In) Simultaneous Imaging[1]




*in vivo* Simultaneous Imaging




**SOI based “electron tracking” Compton imaging system for medical imaging (Compton-PET)**

[1] M.Uenomachi et al., ”Simultaneous in vivo imaging with PET and SPECT tracers using a Compton-PET hybrid camera”, Scientific Reports (2021)

# Electron-tracking (ET) Compton Camera

- Conventional Compton imaging **limits the quantitative imaging**. In order to fully reconstruct the Compton images, the **electron-tracking Compton imaging** method has been investigated to estimate the incident directions of gamma rays

A method for the full reconstruction of Compton images by measuring **the direction and energy** of the **recoil electrons**.

- With the **direction and energy of the recoil electrons**, we can calculate the angle of incident gamma ray photon
- Then we can obtain the direction of incident gamma-ray since the incident gamma-ray, the scattered photon and the recoil electron must be on the same plane.

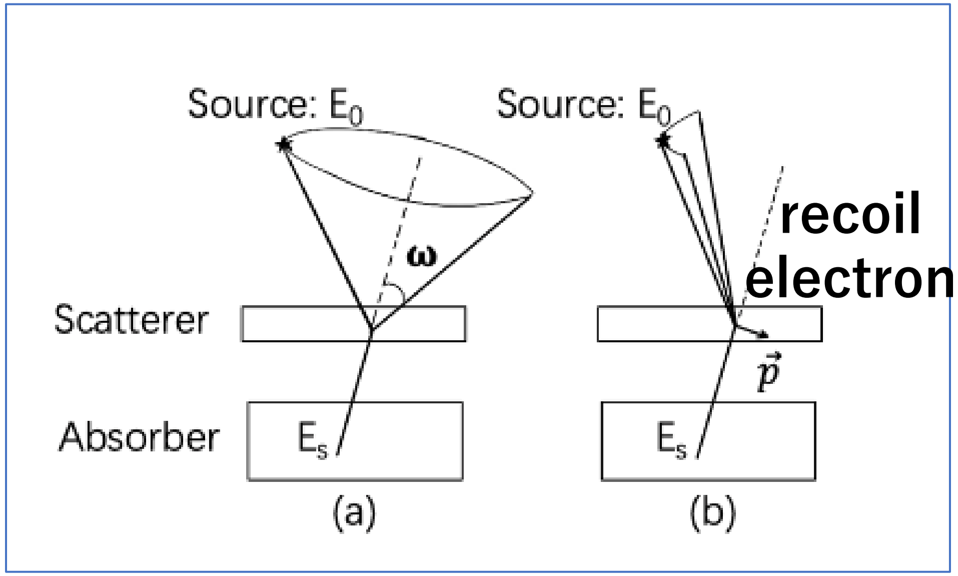



**Fig.2 Schematic of (a) Conventional Compton imaging and (b) Electron-tracking Compton imaging**

# E.T. Compton Camera(Previous study)

**Image reconstruction without Electron Tracking**

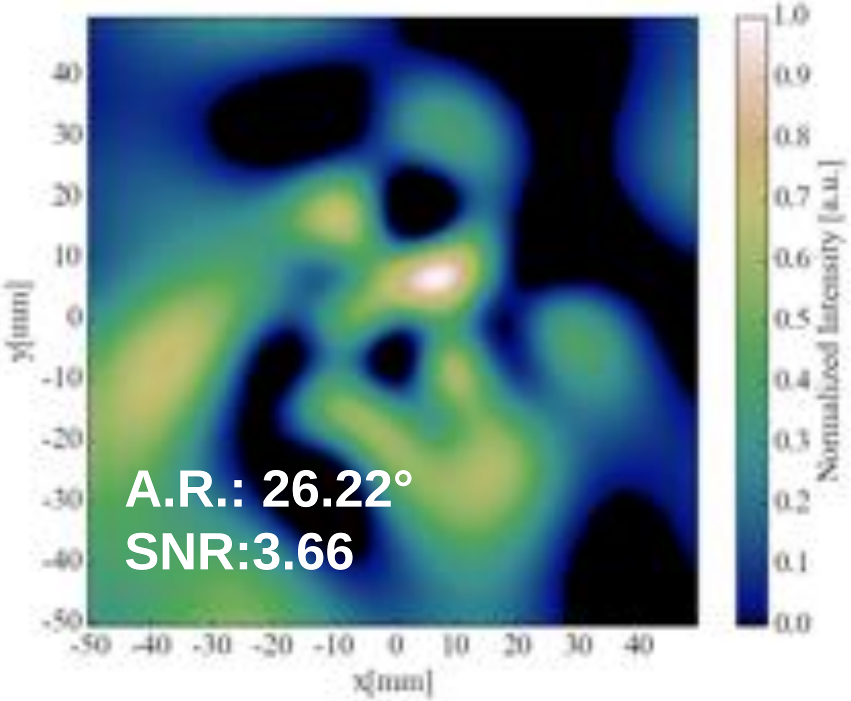
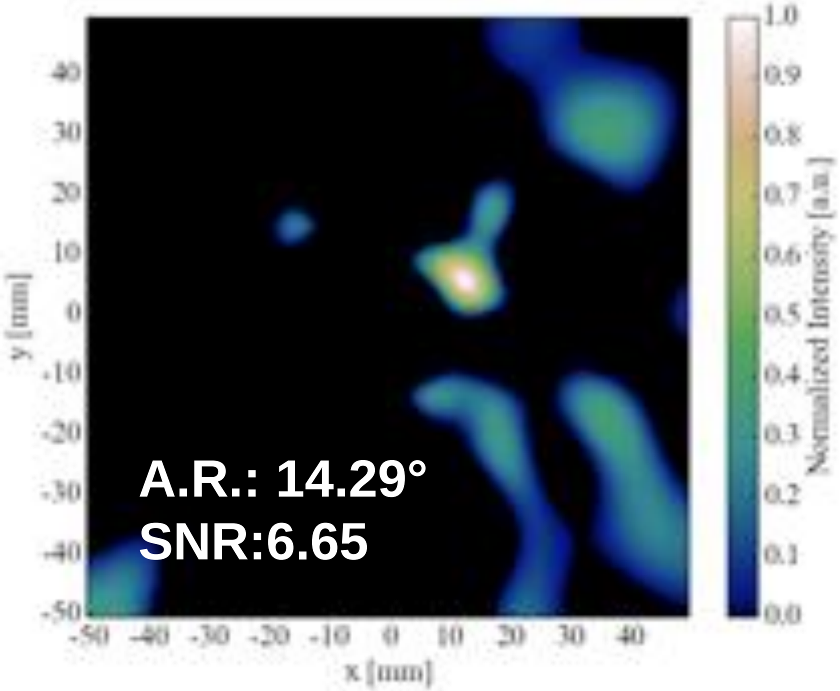
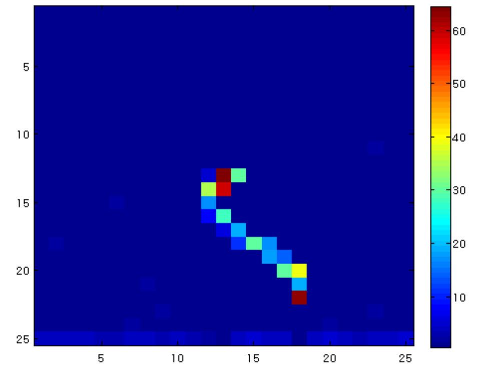
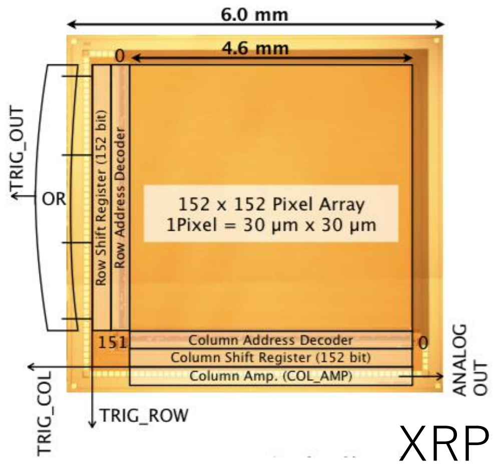



**Image reconstruction with Electron Tracking [2][3]**






XRPIX

**SOI detector area was limited around 4.5 mm, hence efficiency was low**

[2]Shimazoe, K., et a.. "Electron Pattern Recognition using trigger mode SOI pixel sensor for Advanced Compton Imaging." Journal of Instrumentation 11, no. 02 (2016): C02030.

[3]Yoshihara, Y., Shimazoe, et al, Y. (2017). Development of electron-tracking Compton imaging system with 30-μm SOI pixel sensor. Journal of Instrumentation, 12(01), C01045.

* A.R. = Angular Resolution

# Summary

We have developed SOI pixel sensors for 16 years.
MPW run was held in FY2020.
MPW run is also planned in FY2021.

New structure, PDD, can be used in recent MPW runs

Existing sensors were applied for various applications:
Neutron (INTPIX, XRPIX)
Electron micrography (INTPIX)
Muon beam monitor (INTPIX)

In recent MPW runs, sensors for several application were developed
High energy physics (DuTiP)
X-ray astronomy (XRPIX)
Photon counting CT/PET (SOI-SiPM)
ET Compton Camera (SOI-E-track)