Deployment status of CITIUS

a 17.4 kframes/s
integration-type X-ray imaging detector
with 1 Gphoton/s/pixel detection capability at 10 keV
(18 Tcps/cm^2)

Sensor development: 2015-2020

Takaki Hatsui

RIKEN SPring-8 Center

Outline

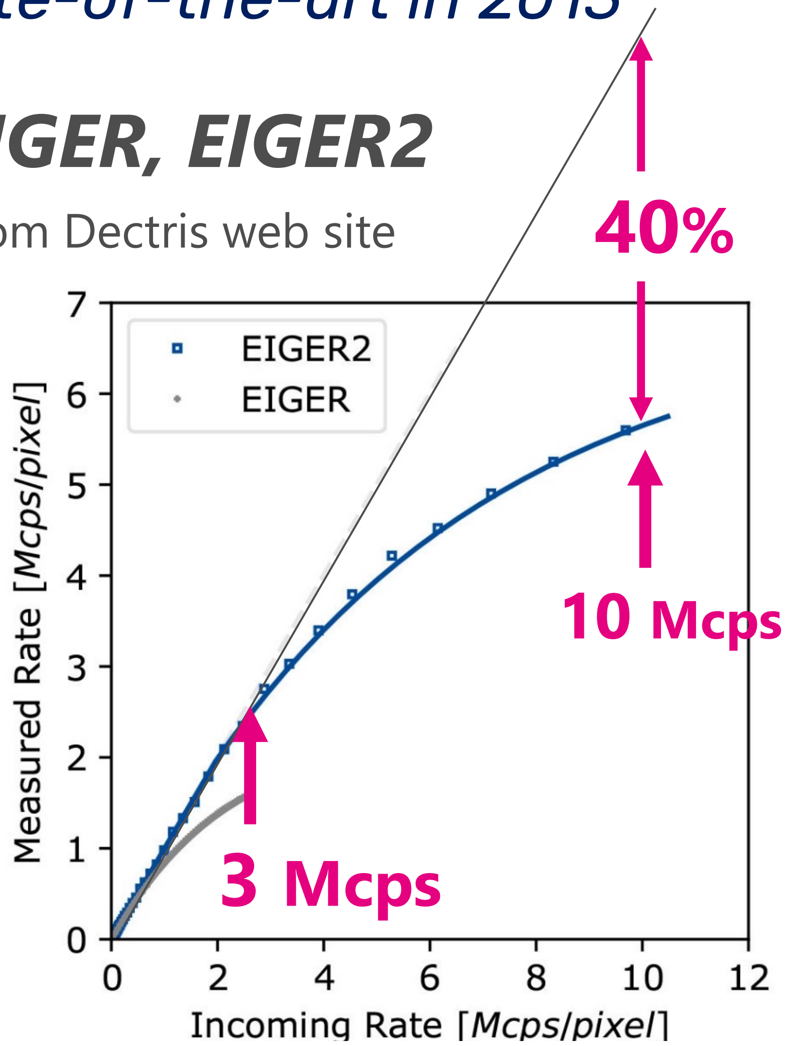
- Motivation
- The CITIUS performance
  - for XFEL applications
  - for SR applications
- Development
- Summary

Photon Counting?

State-of-the-art in 2013

EIGER, EIGER2

From Dectris web site



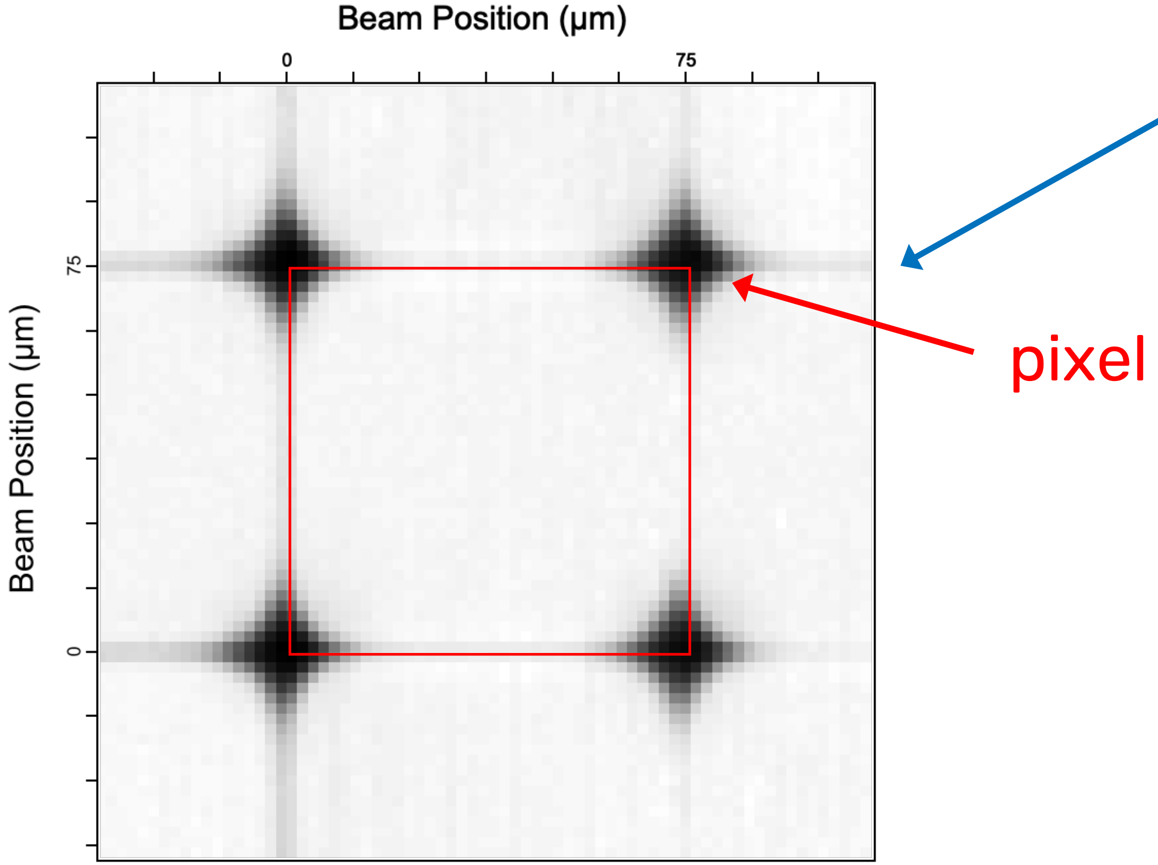
10 Mcps @ 10 kframes/s
1 frame can detect up to 1,000 photons

Count rates decrease at “several bunch modes” by x10

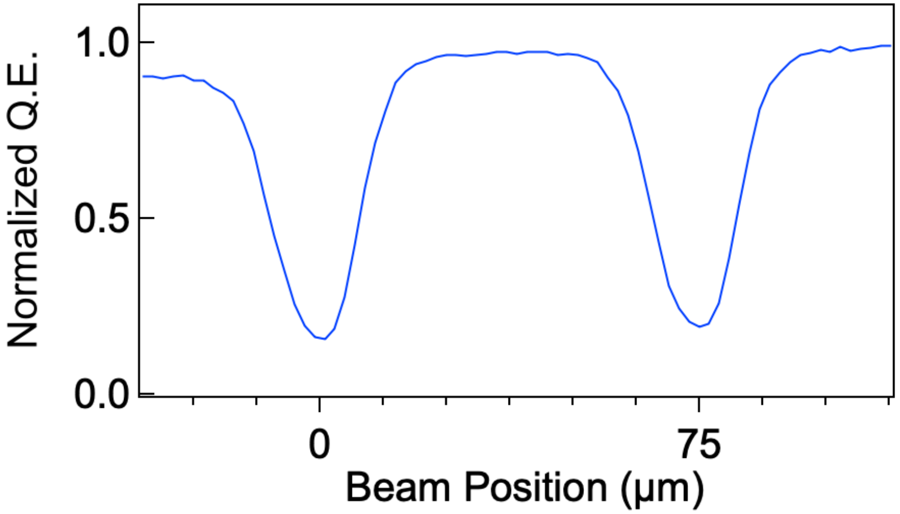
Higher count rates are needed.
→ integrating-type detector

Photon Counting?

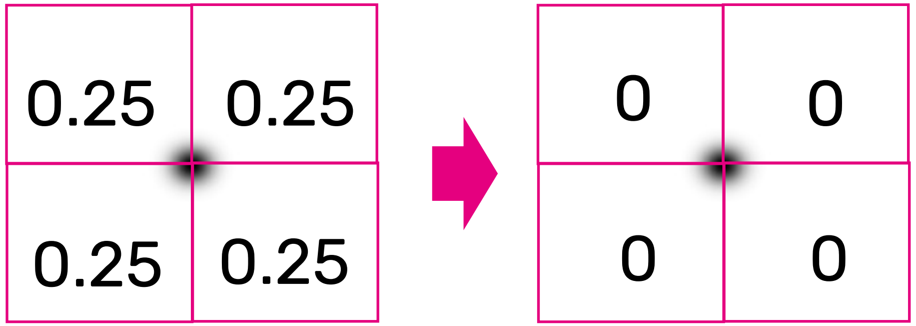
Corner Response



Q.E. map by scanning a pencil beam
Eiger, 8 keV @SPring-8 BL40XU



Threshold = 0.5 photons



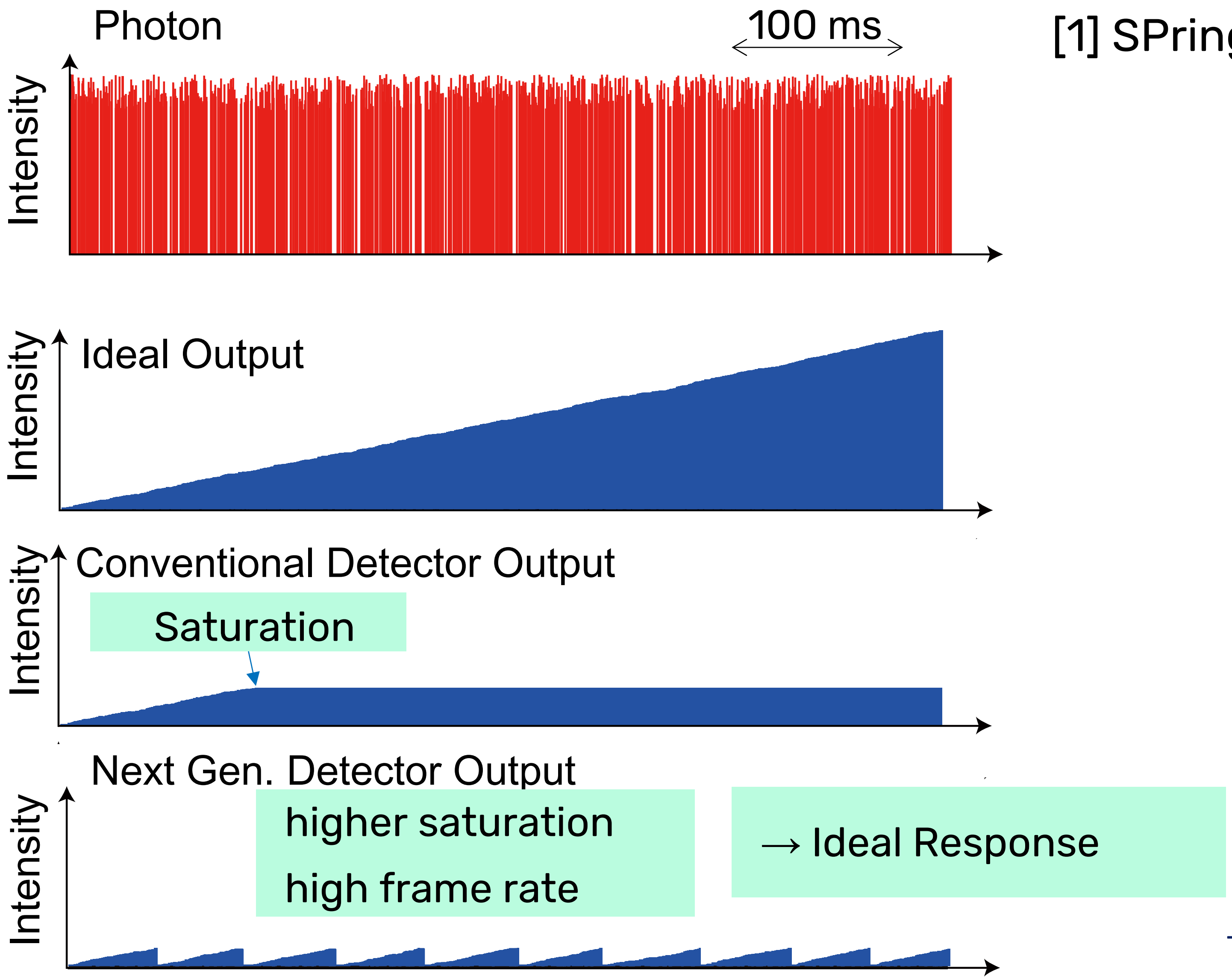
Medipix solved this by summing
at the penalty of the count rate

Uniform Sensitivity

Architecture [1]

Integrating Pixel & High Frame Rate

[1] SPring-8 II CDR (2014



CITIUS

Y. Honjo K. Ozaki, H. Nishino et.al,

Experimentally verified Performance

Parameters		Value	
Sensor	Thickness	650 μm	
	Pixel Size	72.6 μm	
	Pixel Number	0.28 Mpixel/sensor	
	Noise	0.018 phs.@8 keV (40 e-)	
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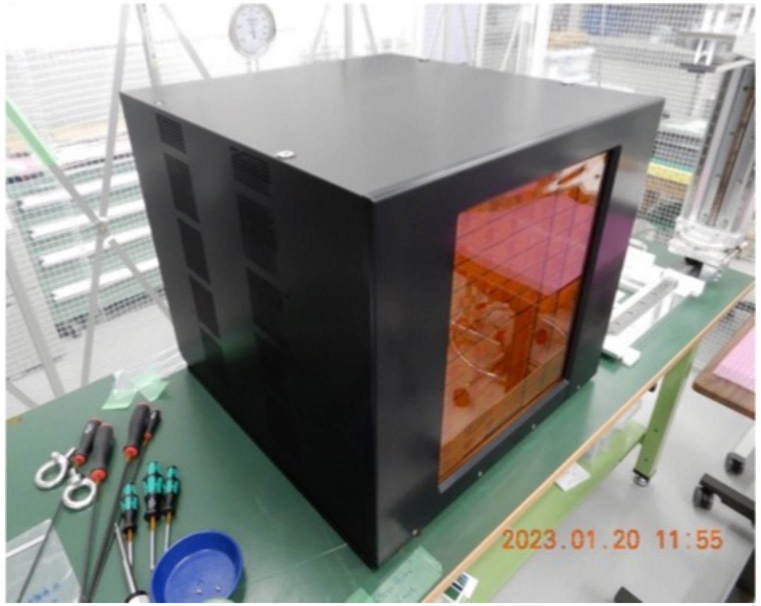
	Frame Rate	5 kHz	17.4 kHz

30 Mcps/pixel @12 keV
1 Gcps/pixel @10 keV in an extended mode

26.1 kfps for spectro-imaging
104.4 kfps for ROI spectro-imaging

System Development

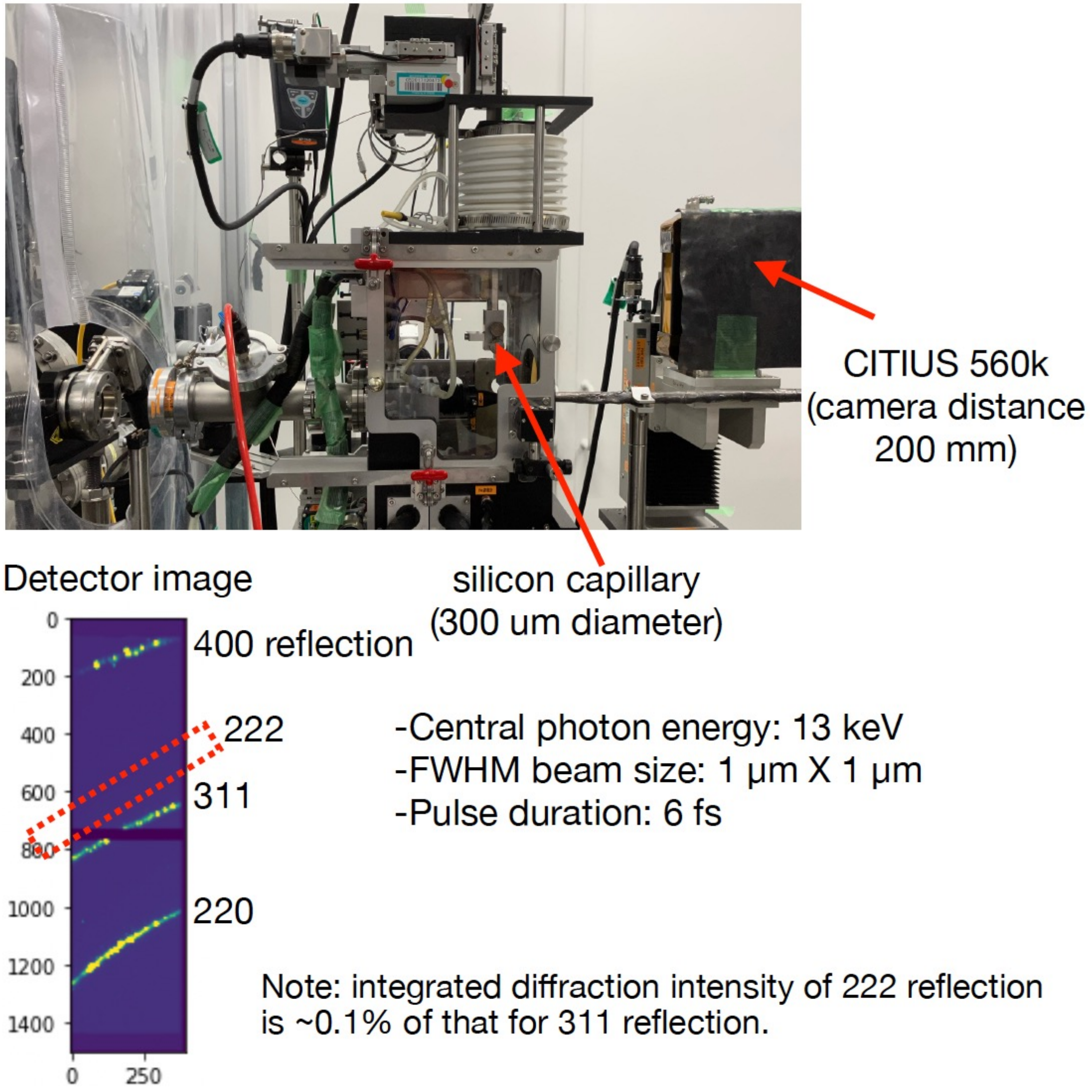
Largest System	Pixel Number	20.2 Mpixel
	Image Area	325 x 363 mm



to be installed to SACLA June 2024

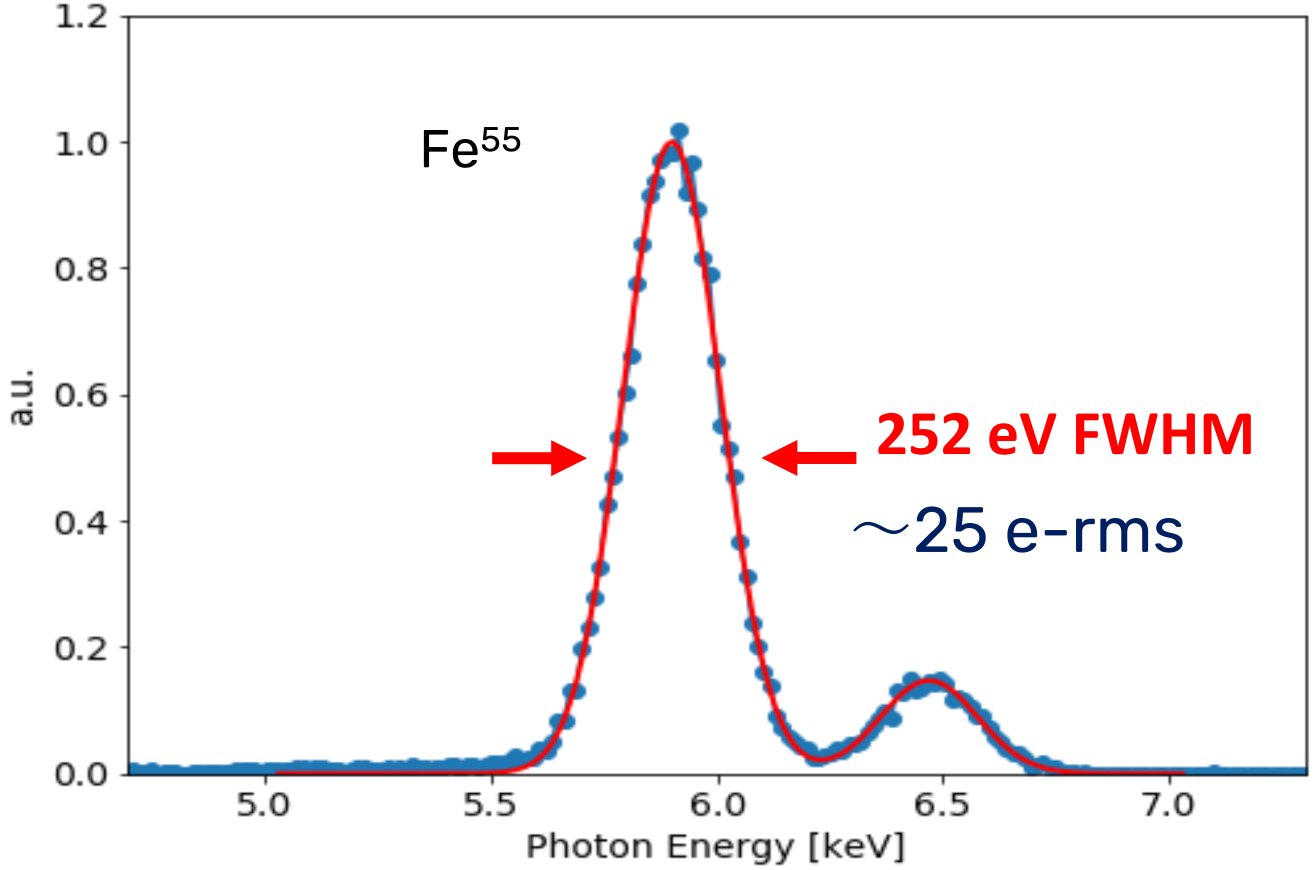
XFEL Variants

SACLA Feasibility Study



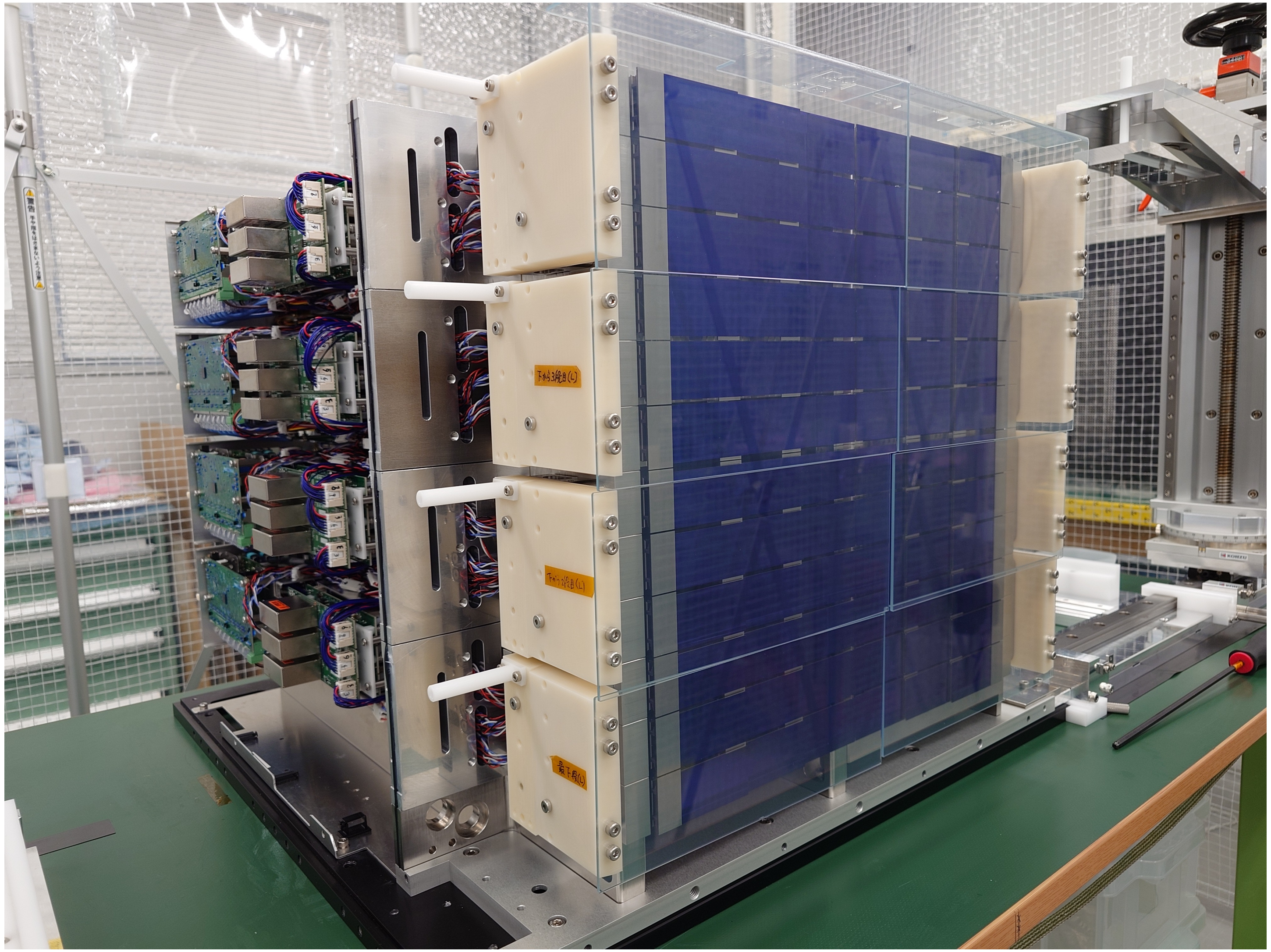
- First scientific experiment
  - Non-linear Quantum Optics
  - a test for linearity and systematic errors of CITIUS
  - successful data
  - *Ichiro Inoue et.al., to be submitted*

Low Noise Operations for SACLA



Operating at 960 frames/s
16 frames for one shot
lower noise from 40 to 25 e-rms

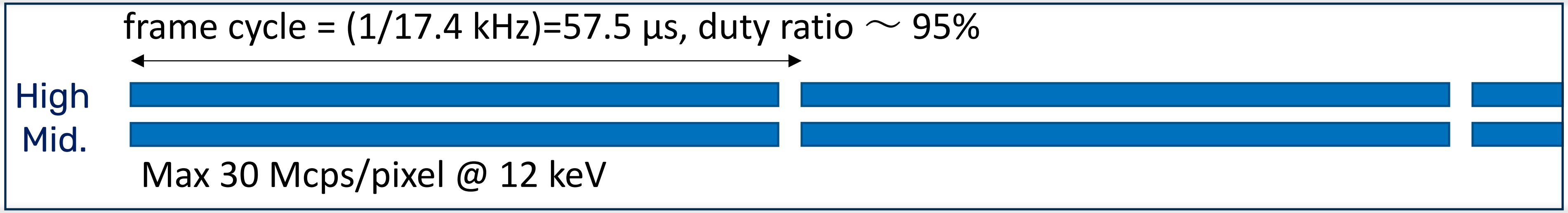
20.2M CITIUS for SACLA



to be installed June 2024

SR Variants

CITIUS for SR: Standard Mode: Bragg-CDI

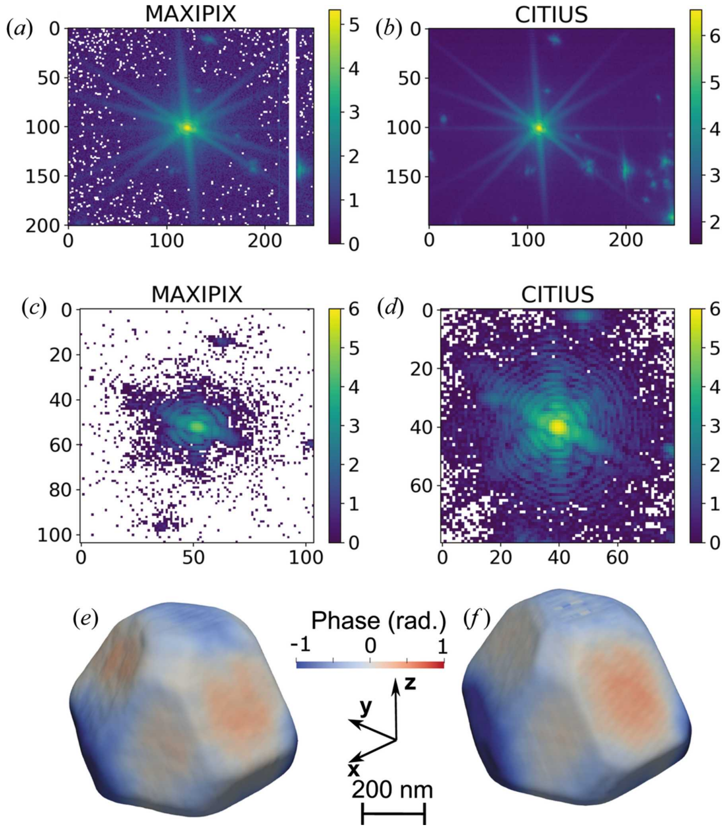


Bragg CDI at ESRF

	Count rate	Resolution	Acquisition Time
CITIUS	30 Mcps/pixel	20 ± 6 nm	23 s
MARPIX	1 Mcps/pixel	22 ± 9 nm	200 s

A detailed analysis showed CITIUS with 1 ms exposure gives similar quality of data with MARPIX with 1 s exposure.

M. Grimes et.al., J. Appl. Cryst. 56(4)
https://doi.org/10.1107/S1600576723004314



Extended mode
945 Mcps/pixel at 10 keV demonstrated

Standard mode

frame cycle = (1/17.4 kHz)
duty ratio ～ 95%

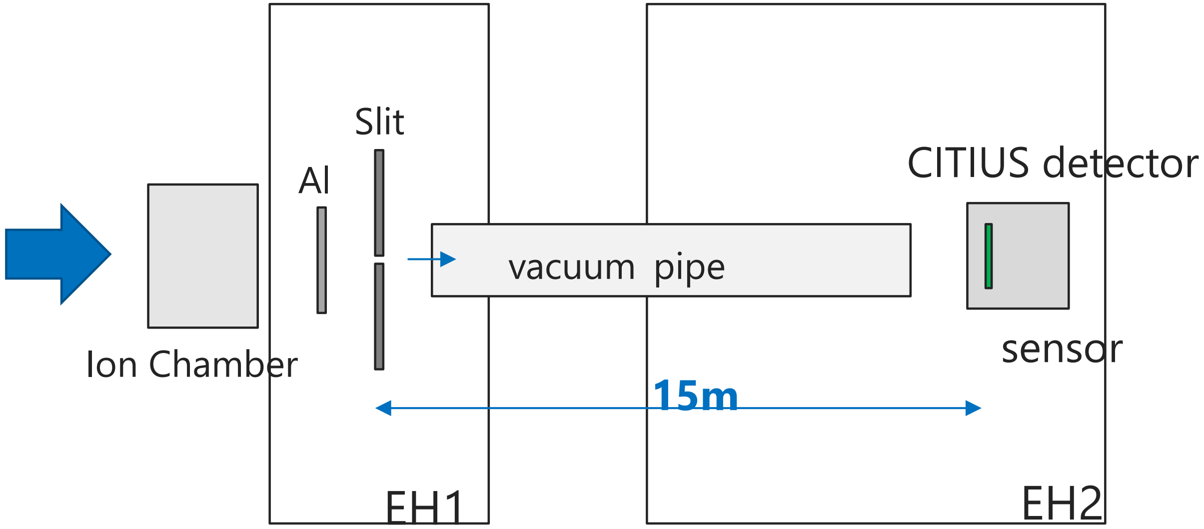
Extended mode

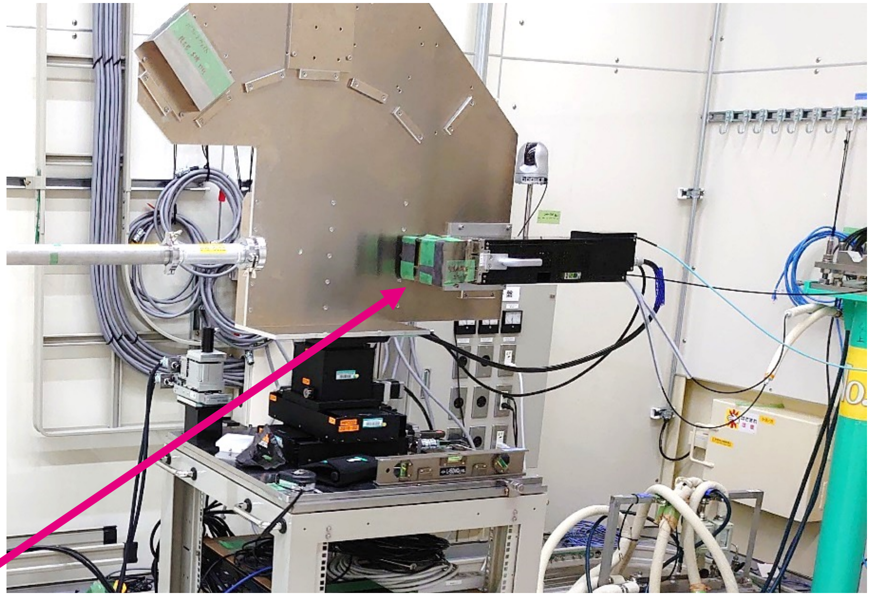
super frame = 2 * (1/17.4 kHz)
duty ratio ～ 90 %

Undulator Direct beam through a 20 μm□ slit
Experiment Setup @ BL29XU

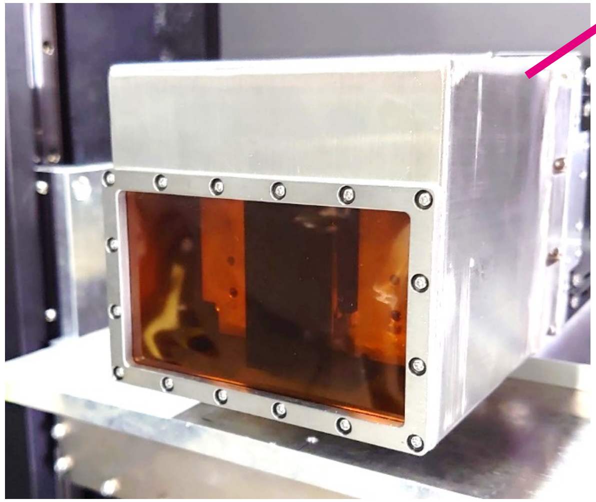
X-ray through
higher-order-cut mirrors

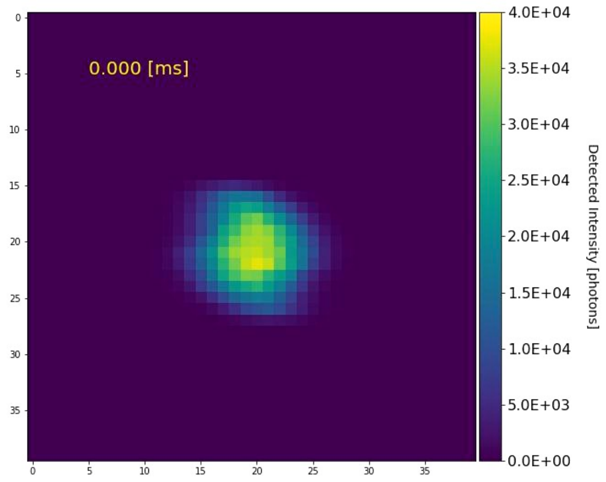
Y. Honjo, K. Ozaki, et.al.,





840k detector (3 sensors)
Prototype of 2.2M detector
This data was taken with a detector that houses only one sensor module





17.4 kfps
57.5 μs/frame
10 keV

Y. Honjo K. Ozaki, et.al,

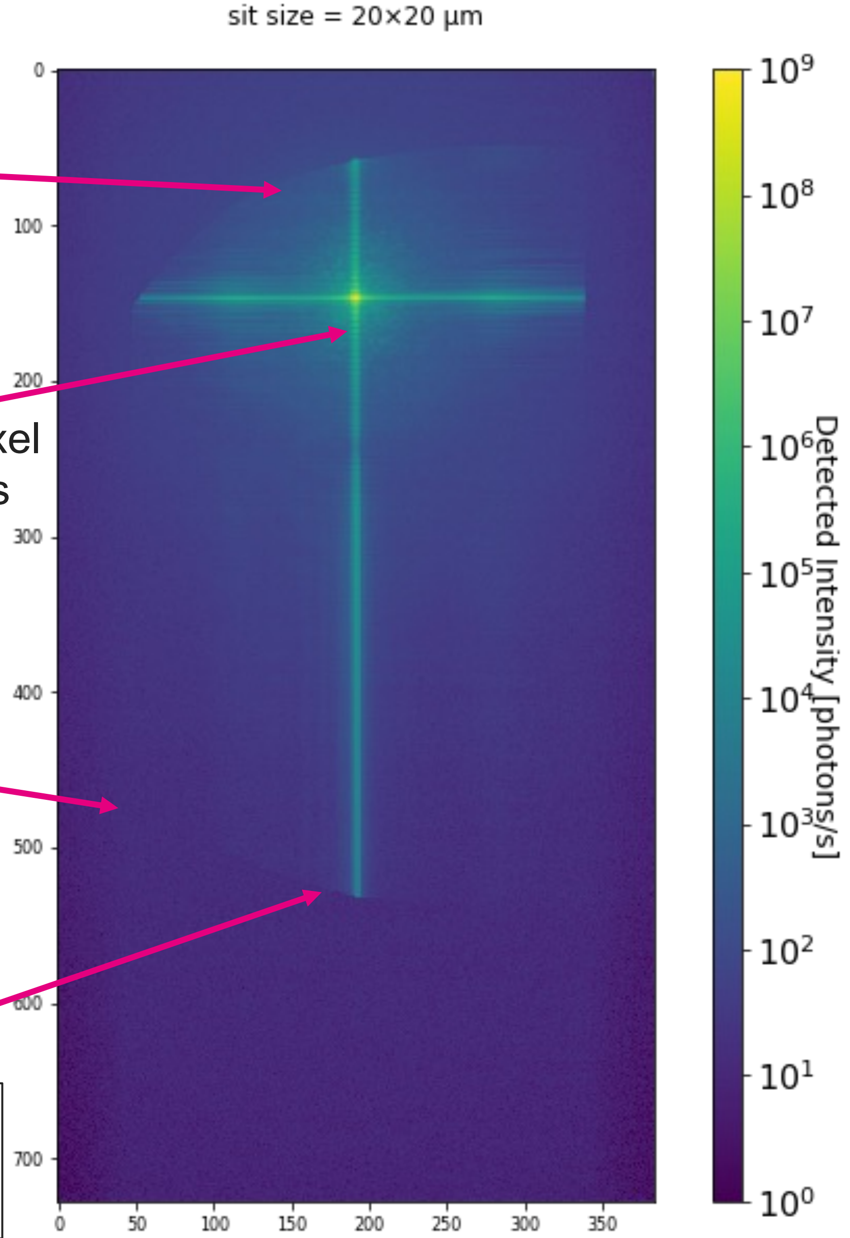
Undulator Direct beam through a 20 μm□ slit

Edge of the vacuum pipe

The most intense pixel reaches to 590 Mcps

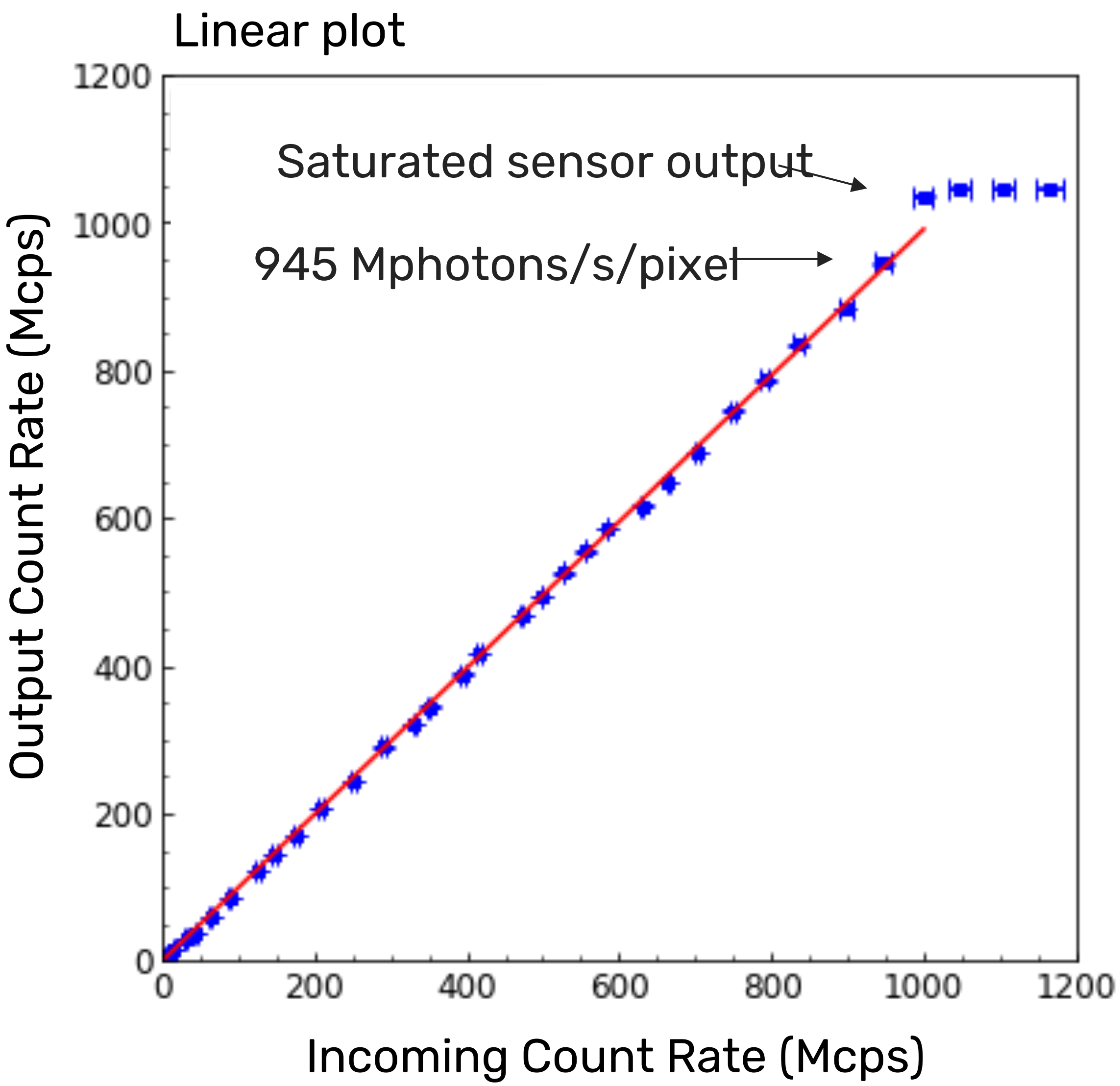
Single photon

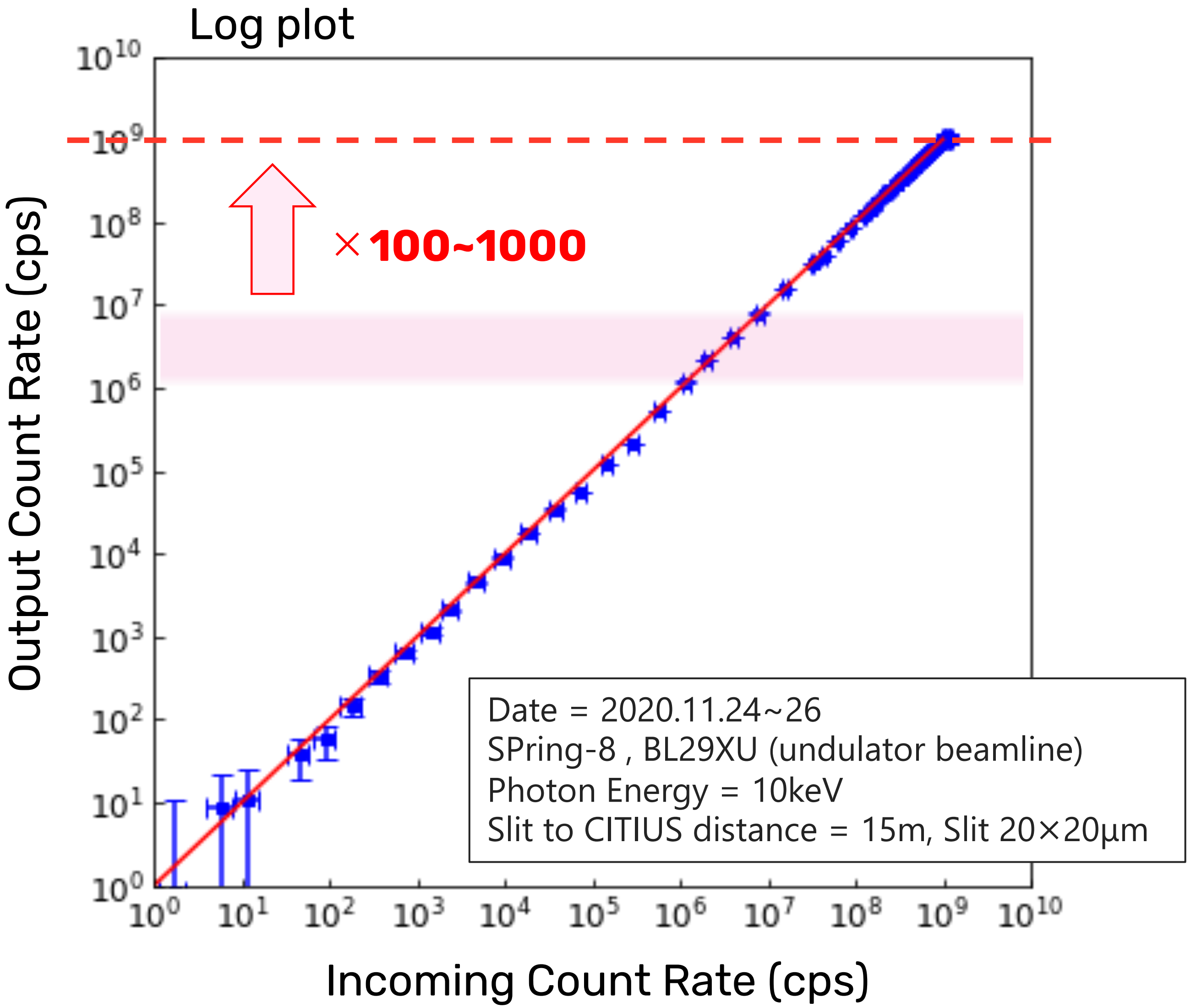
Edge of the vacuum pipe



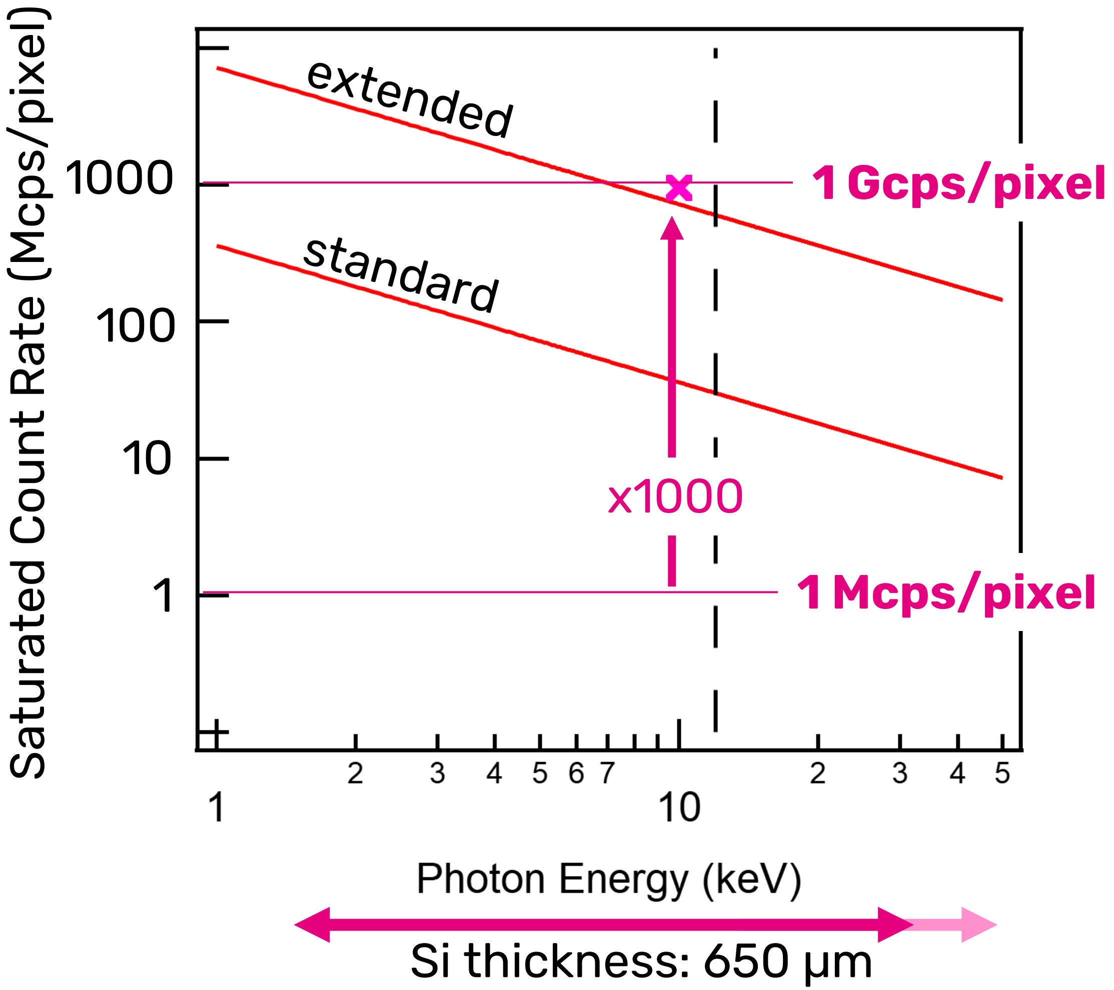
Data taken on Dec. 10th, 2020
SPring-8 BL29XU

Undulator Direct beam through a 20 μm□ slit Detection Capability





Detection Capability v.s. Photon Energy

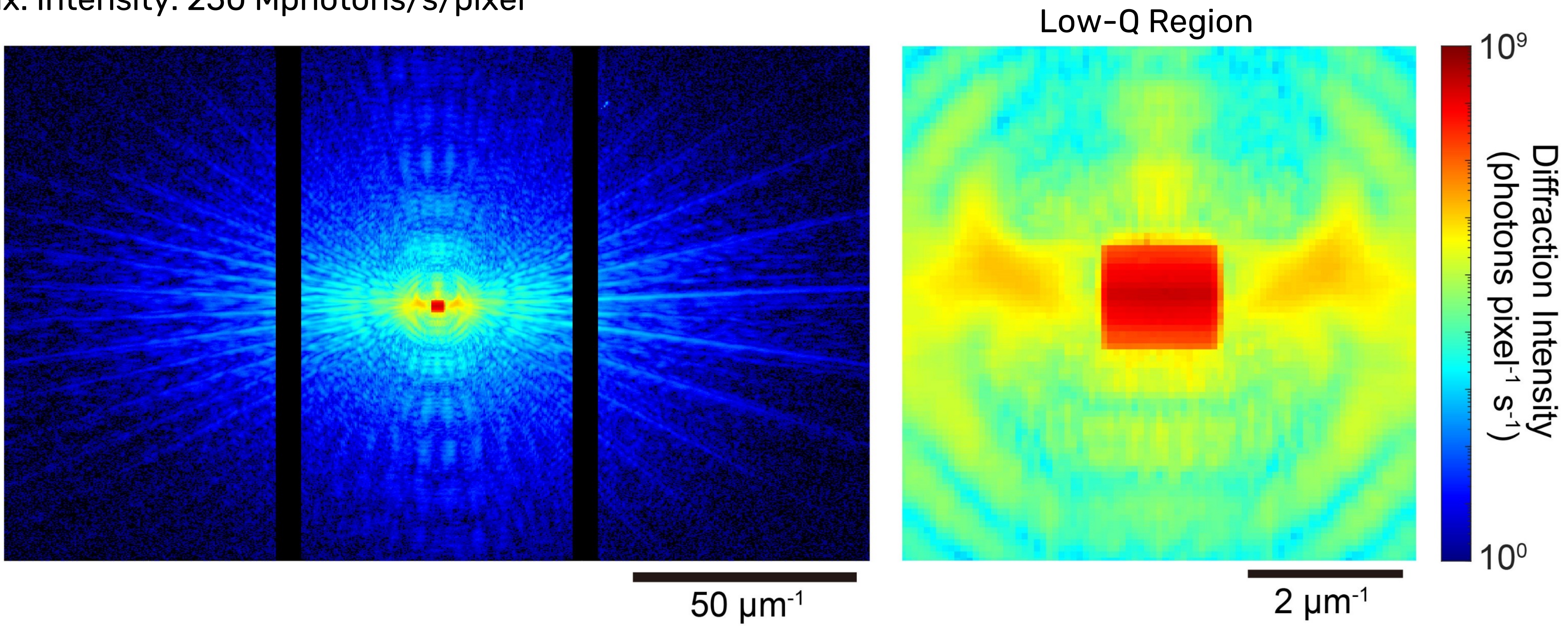


Sample: Ta Test Chart (NTT-AT) 200 nm thick (phase shift 0.41 rad@6.5keV)

Virtual Source Size: 30mm × 150mm
Exposure Time: 1 second
Max. Intensity: 250 Mphotons/s/pixel

Y. Takahashi et.al., JSR 2023

talk by Y. Takahashi



A dynamic range of 8 orders of magnitude has been demonstrated without attenuators.
The fringes around the direct beam seems to give better stability in reconstruction.

CITIUS

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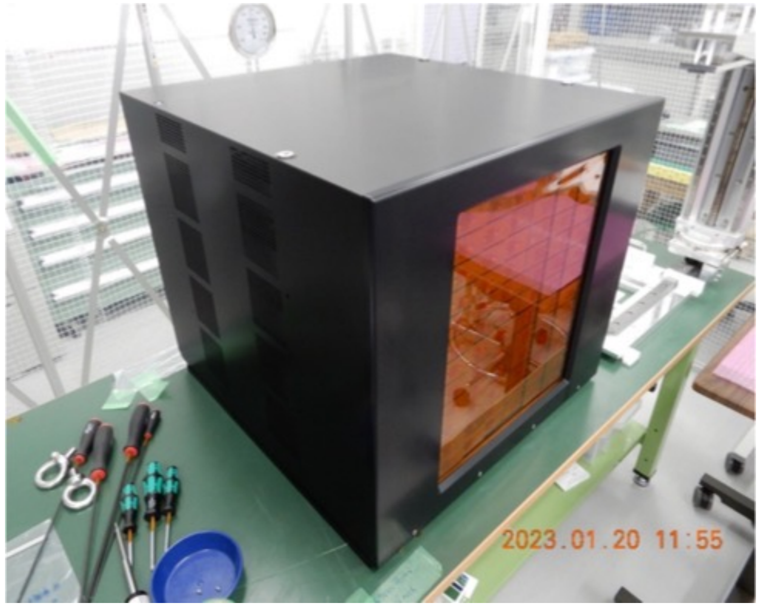


to be installed to SACLA June 2024

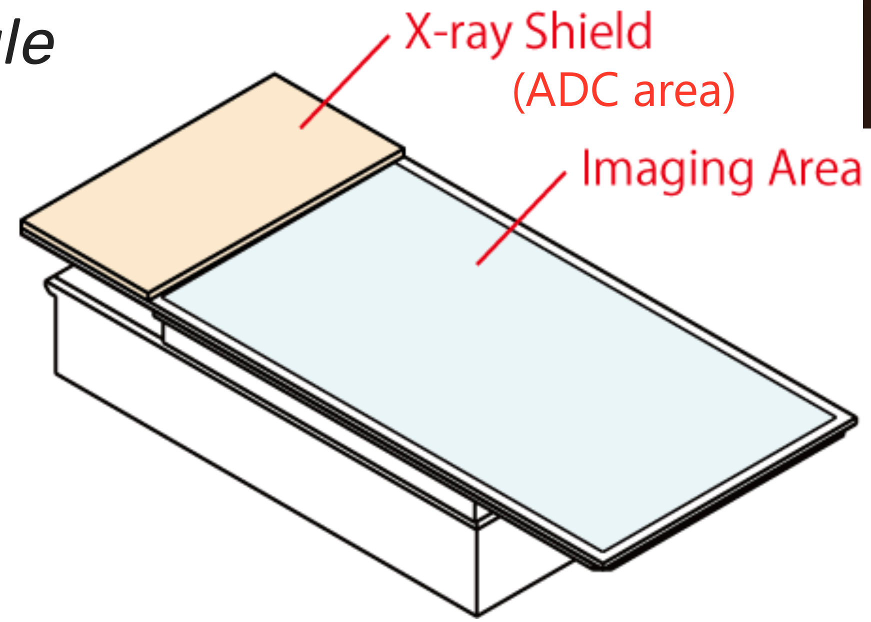
Sensor Module

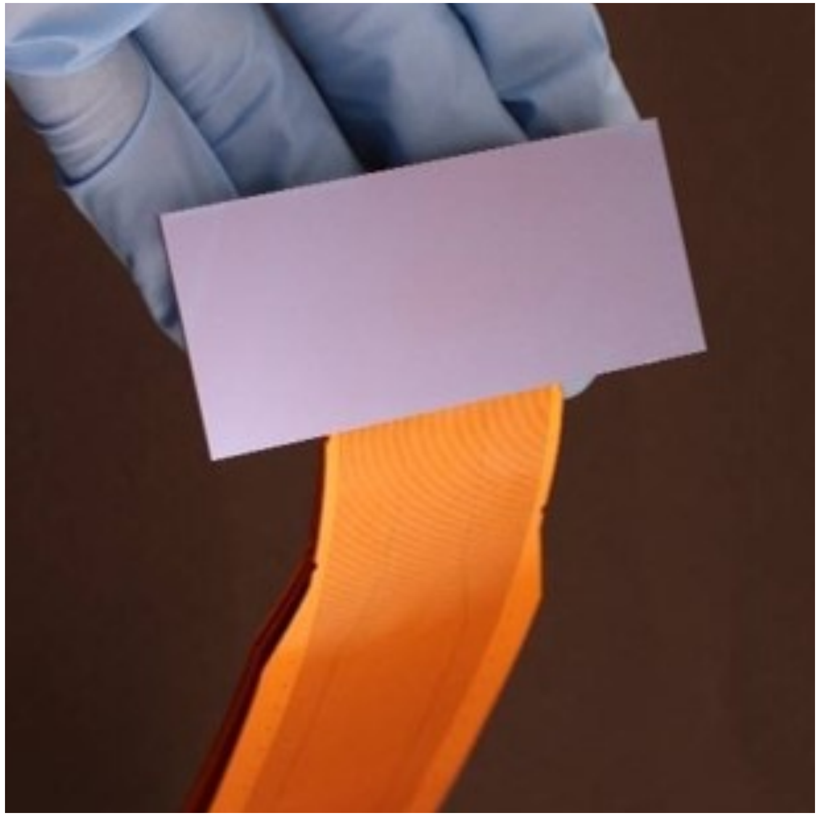
Format: about 280 kpixels
- *horizontal 384 pixels*
- *Vertical 728 pixels*

ADCs
- *one ADC for 8 pixels*

Digital computation
- *Gain selection*
- *48 Serializers @ 2.9 Gbps/lane*
- *Total 140 Gpbs/module*

Technology
- *Stitching lithography*
- *3D integration*





Stitching Lithography and 3D integration (by Sony Semiconductor Solutions)

Stitching Lithography

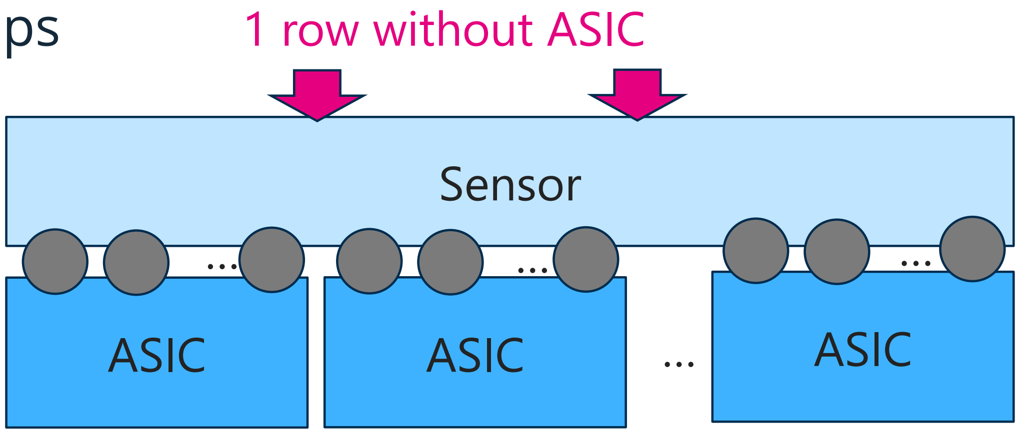
- technique to make chips larger than on lithography shot (> 30 mm)
- Widely used for camera with 35mm Full-frame Image Sensor

from https://electronics.sony.com/

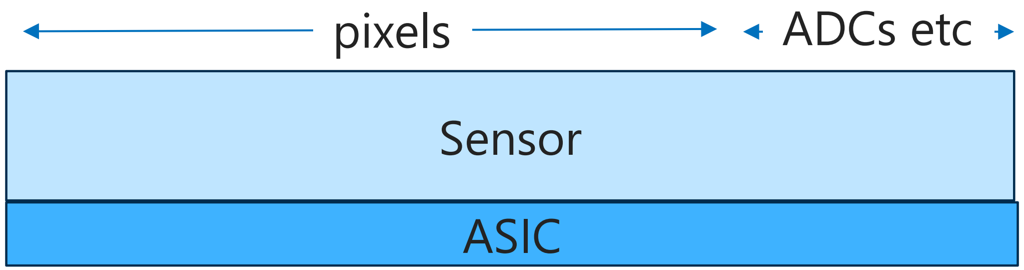
3D integration

- no bumps results in uniform response for high-energy X-rays
- no fluorescence from bumps

Classical Hybrid

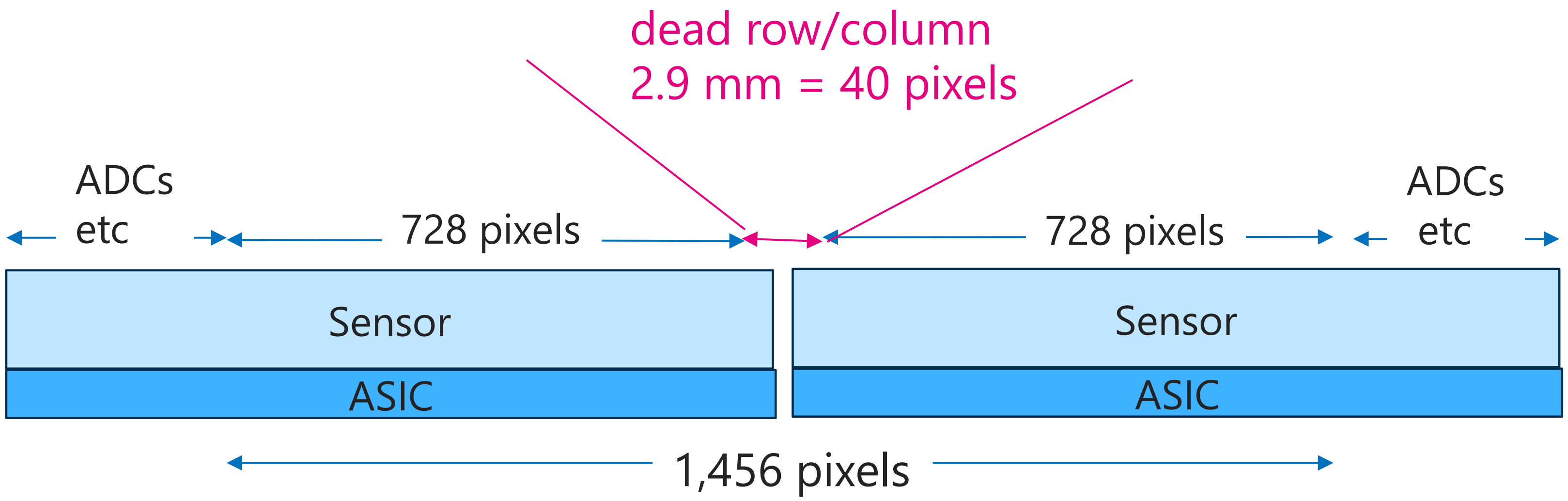


CITIUS

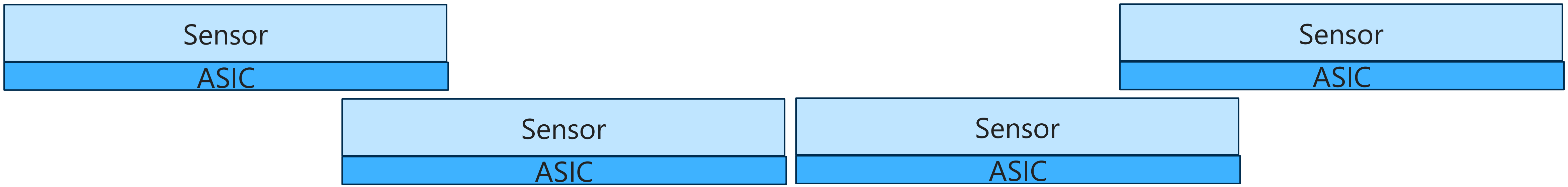


Tiling in CITIUS

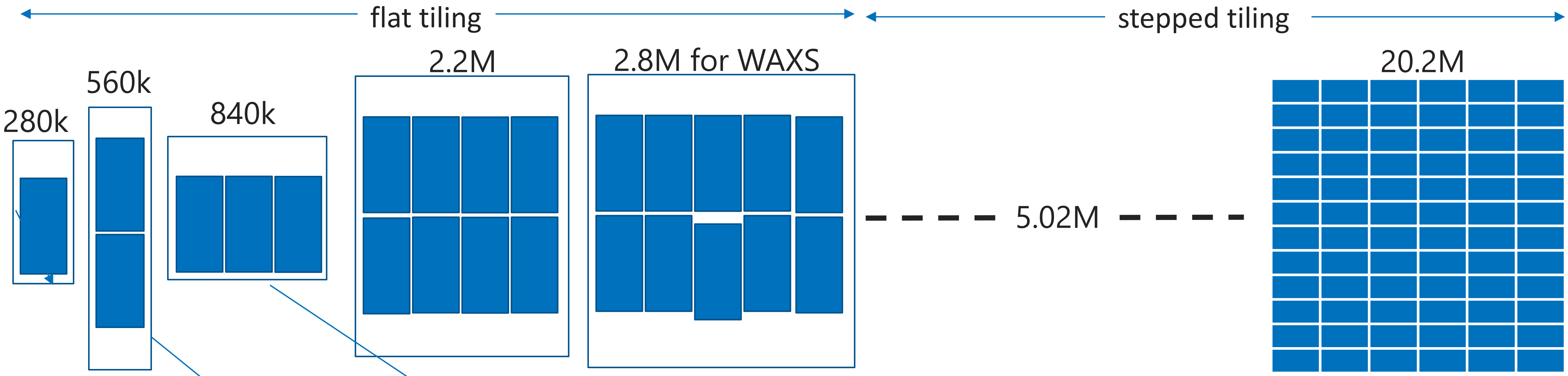
- Flat tiling



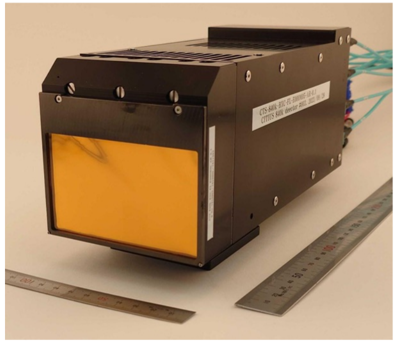
- Stepped Tiling



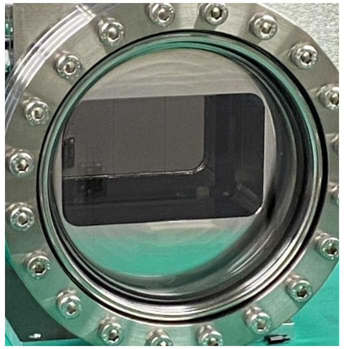
Camera Head developed or under development



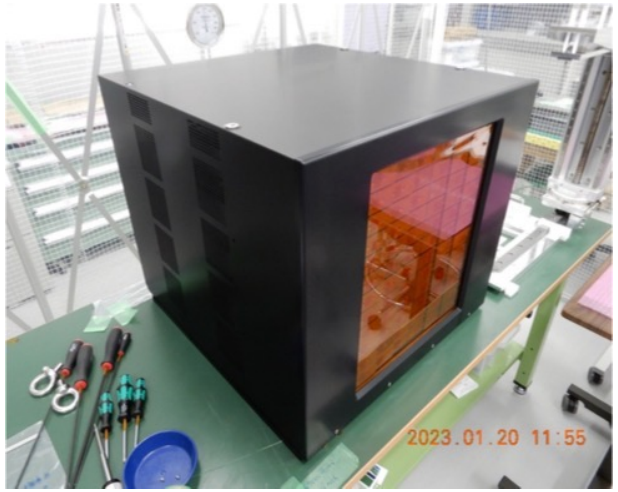
280k
$96 \times 36\ \mathrm{mm} \times 196\ \mathrm{mm}^3$



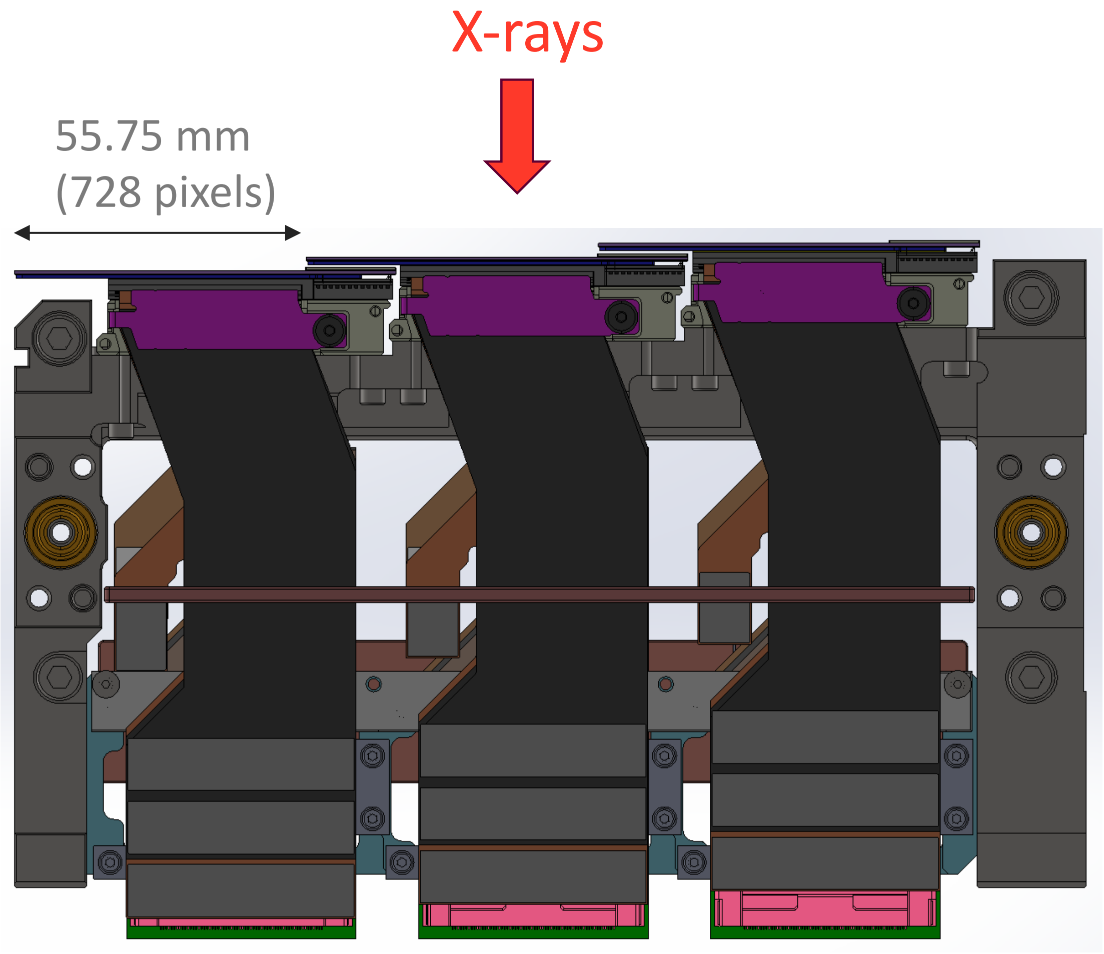
840k

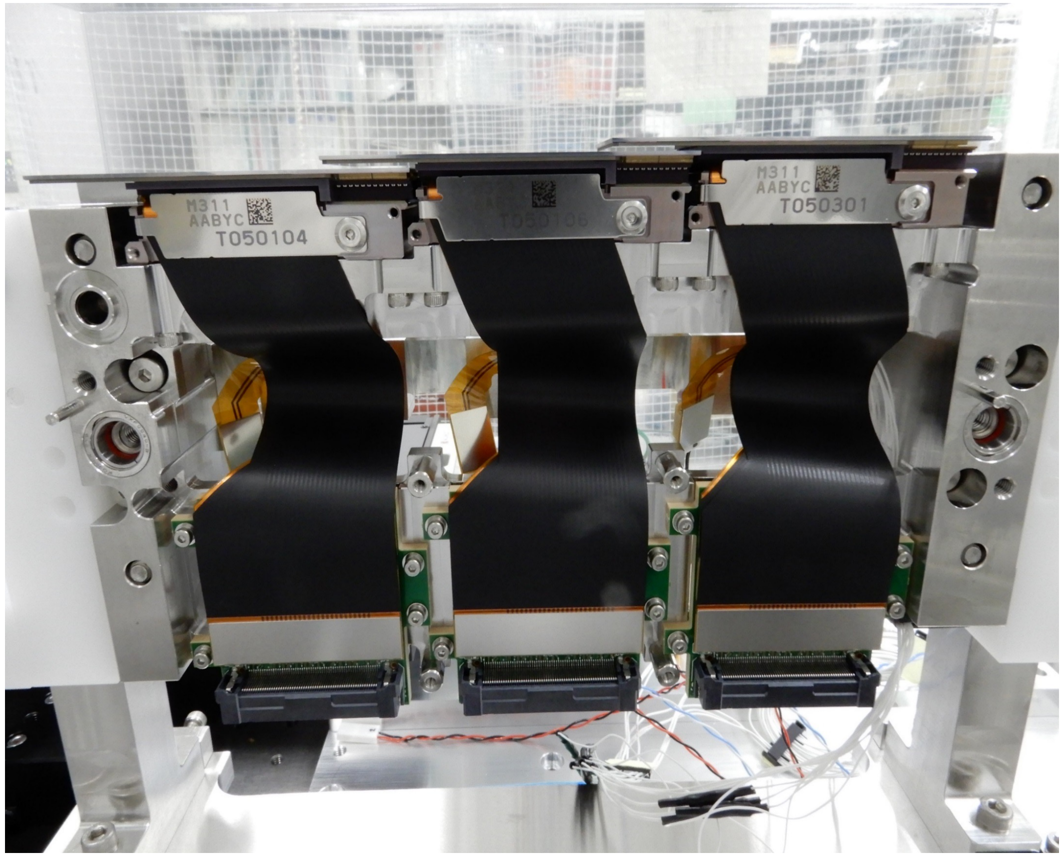


840k flange-mount camera head

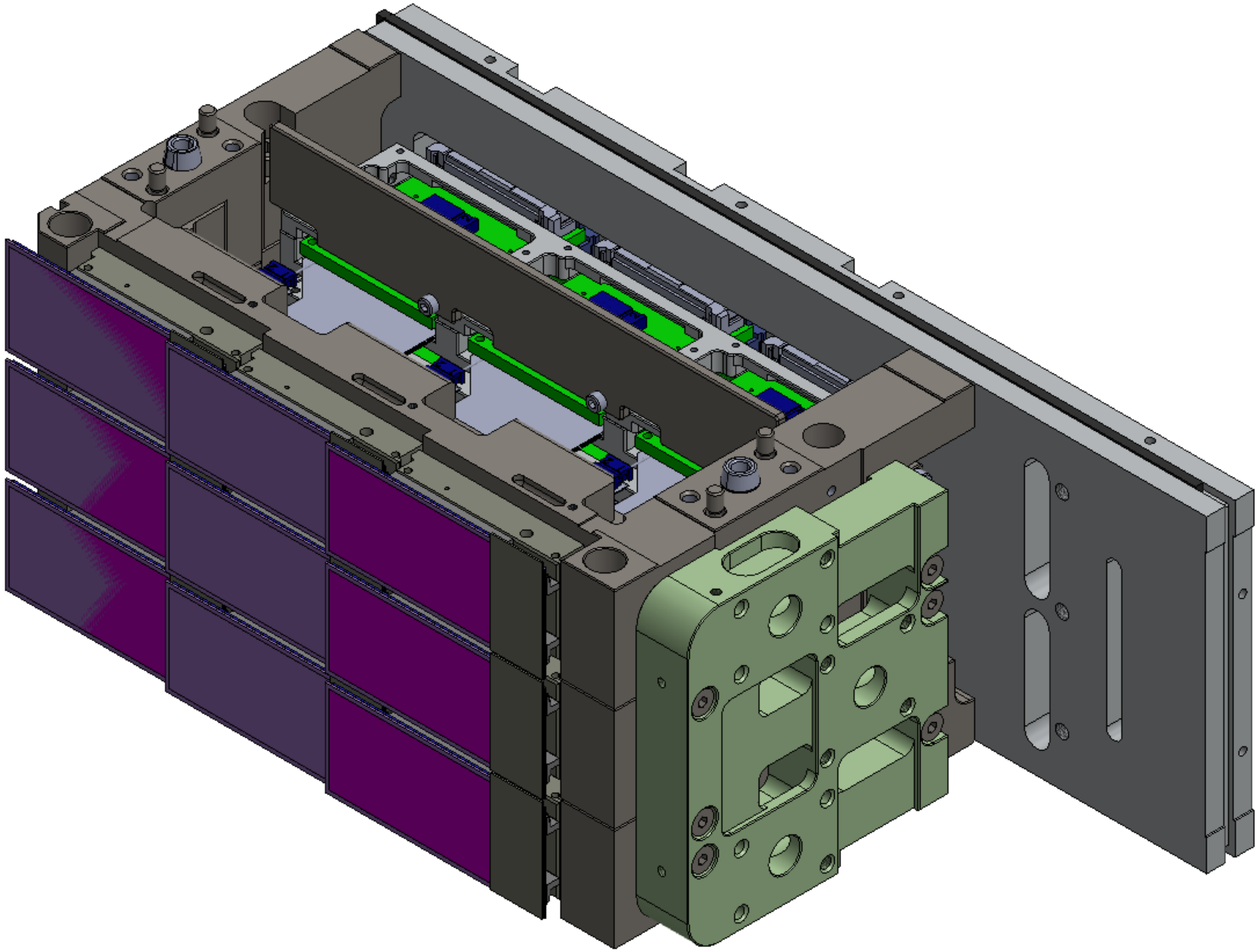


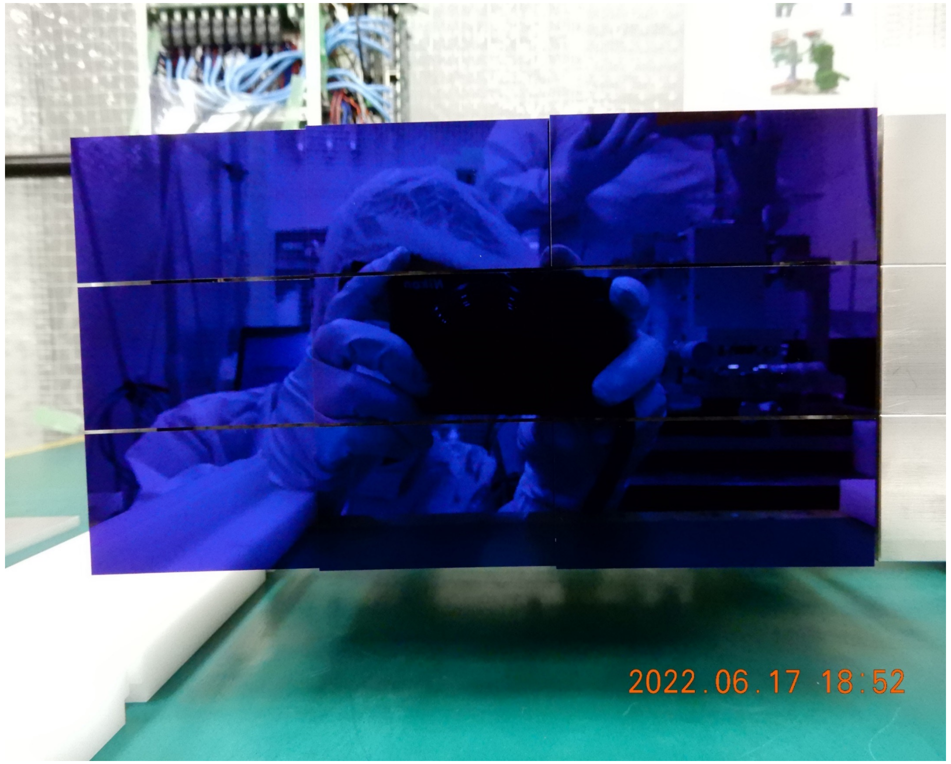
A stepped Tiling with a 728 pixel pitch





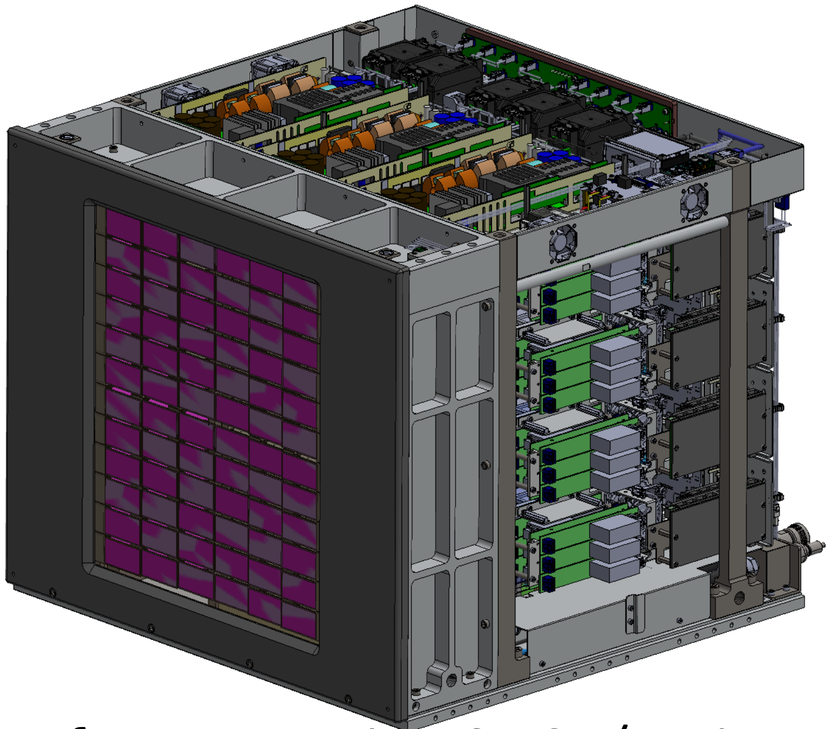
Assembly around the sensors



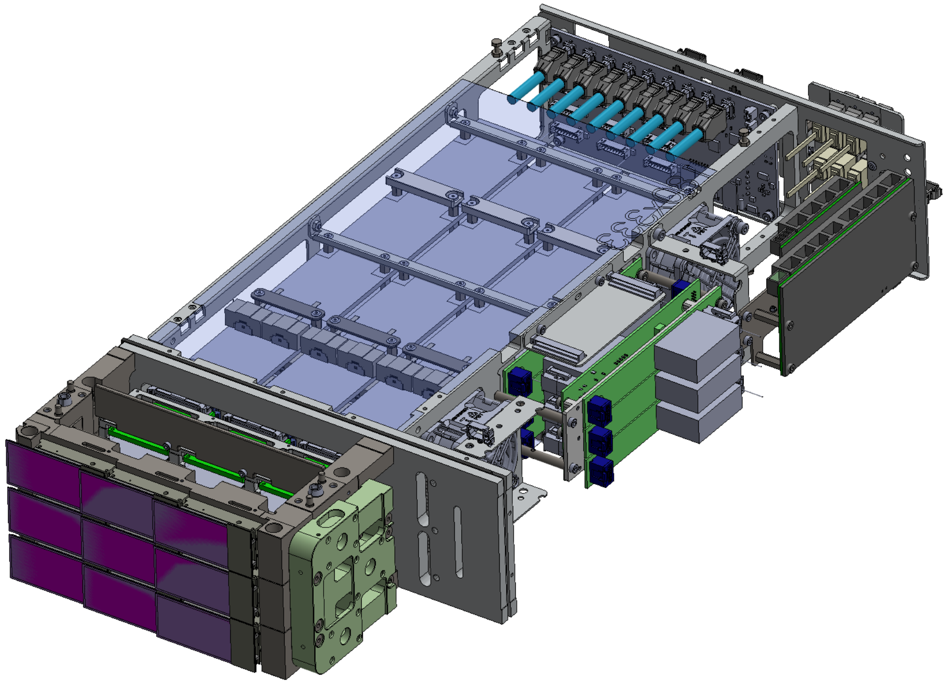


Mechanical Assembly of 20.2M CITIUS

Top roof:
voltage generators (AC 100V to 24V)
Ethernet hub for command comm.



# of components: 12,586/system



Sensor Sus-System (SSS)
2.52 Mpixels
fully functional unit
Calibration/Experiments can be done with a dedicated housing with external 24V power

CITIUS

Y. Honjo K. Ozaki, H. Nishino et.al,

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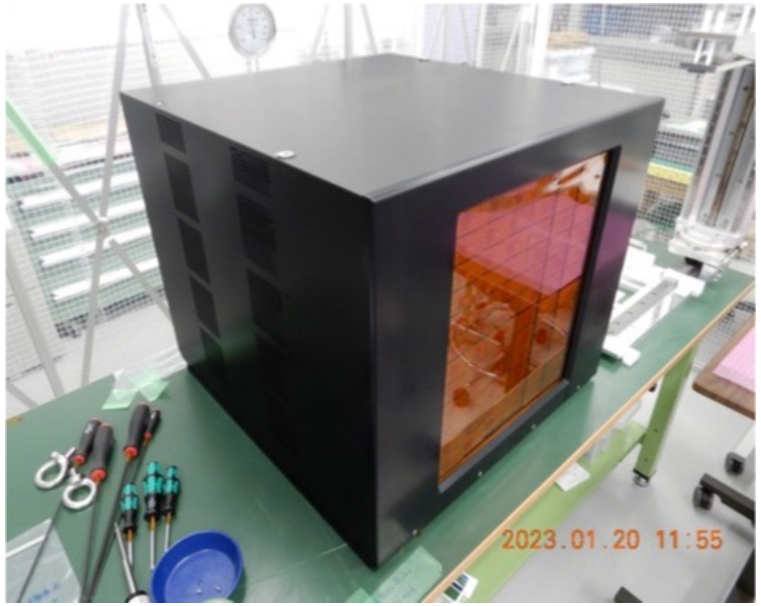


to be installed to SACLA June 2024

Quantum Efficiency

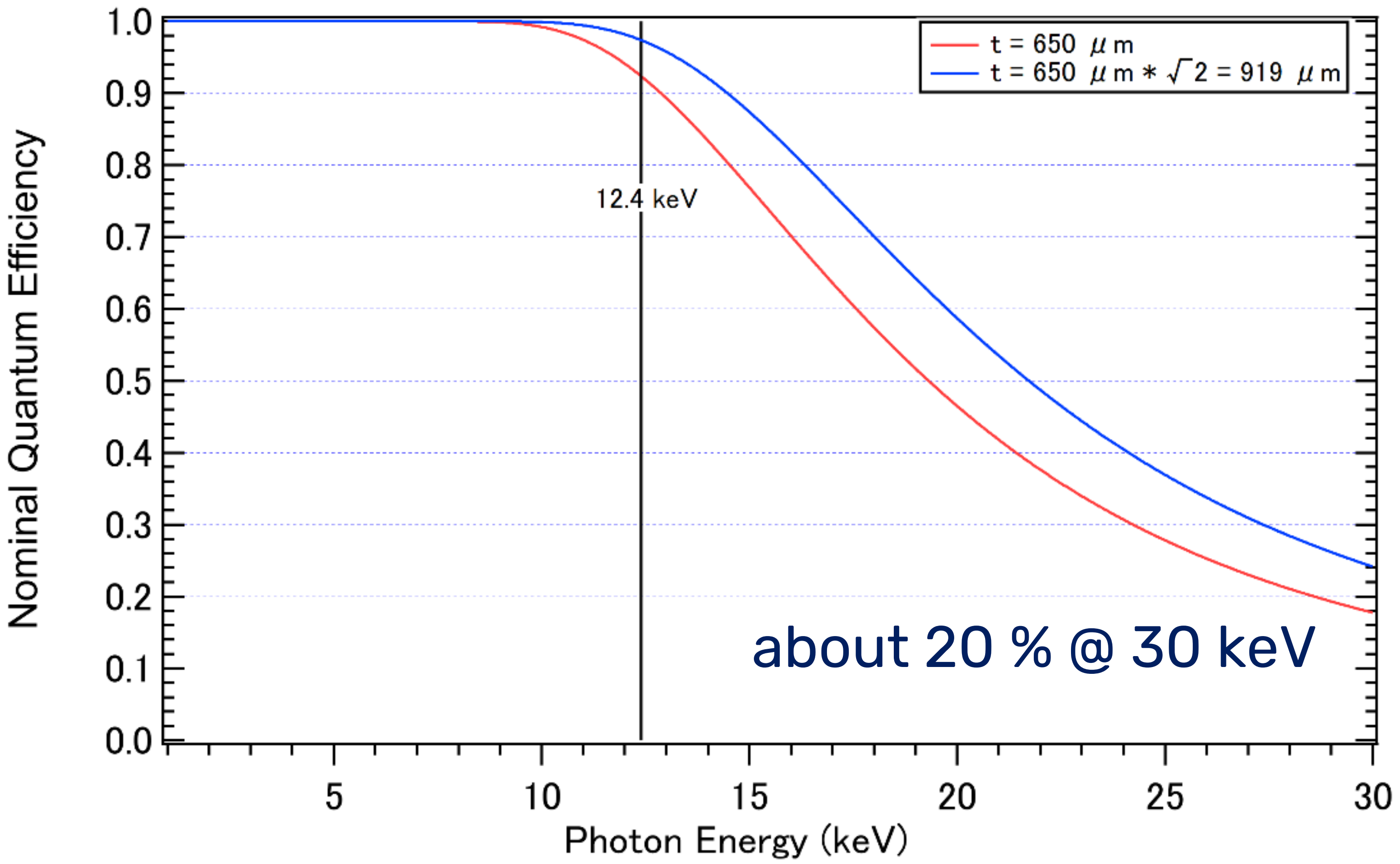
Photodiode 650 µm

Use cases up to 37 keV

3DXRD for electronics investigation

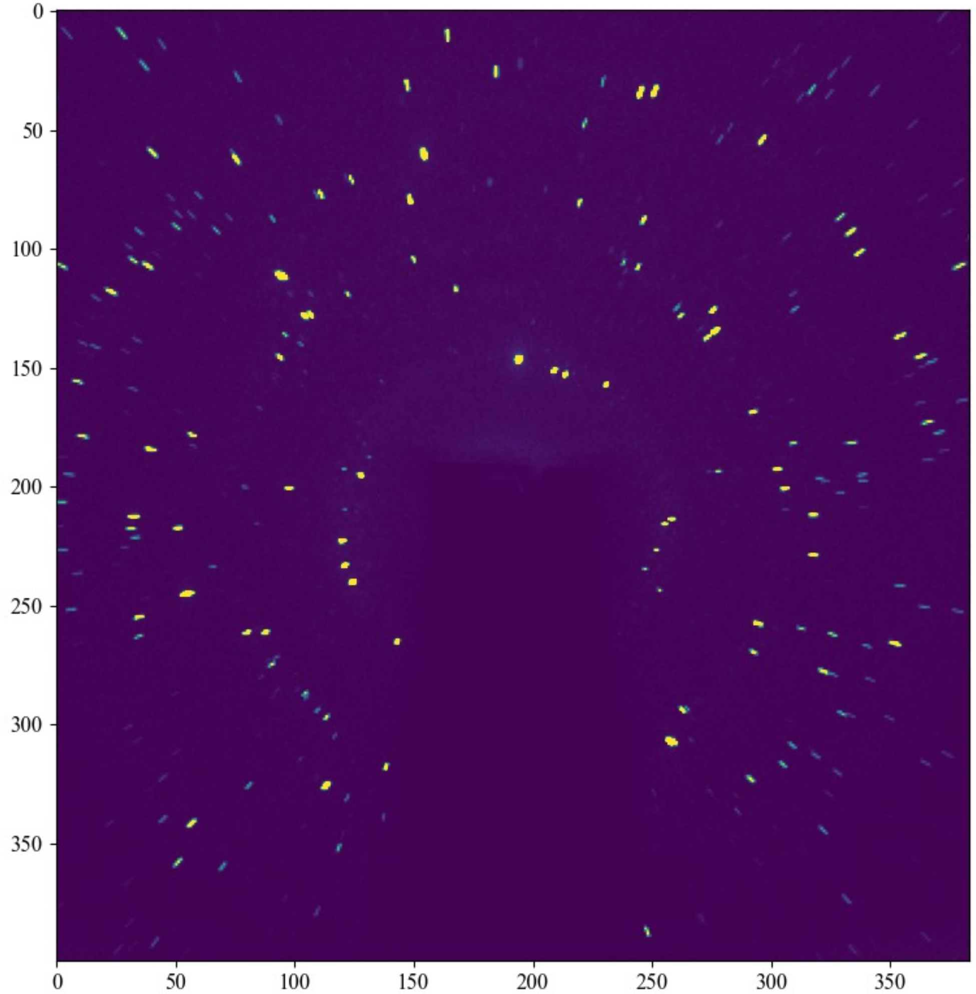
Previously with flat panels

Hayashi, et.al., Science 366, 1492-1496 (2019).

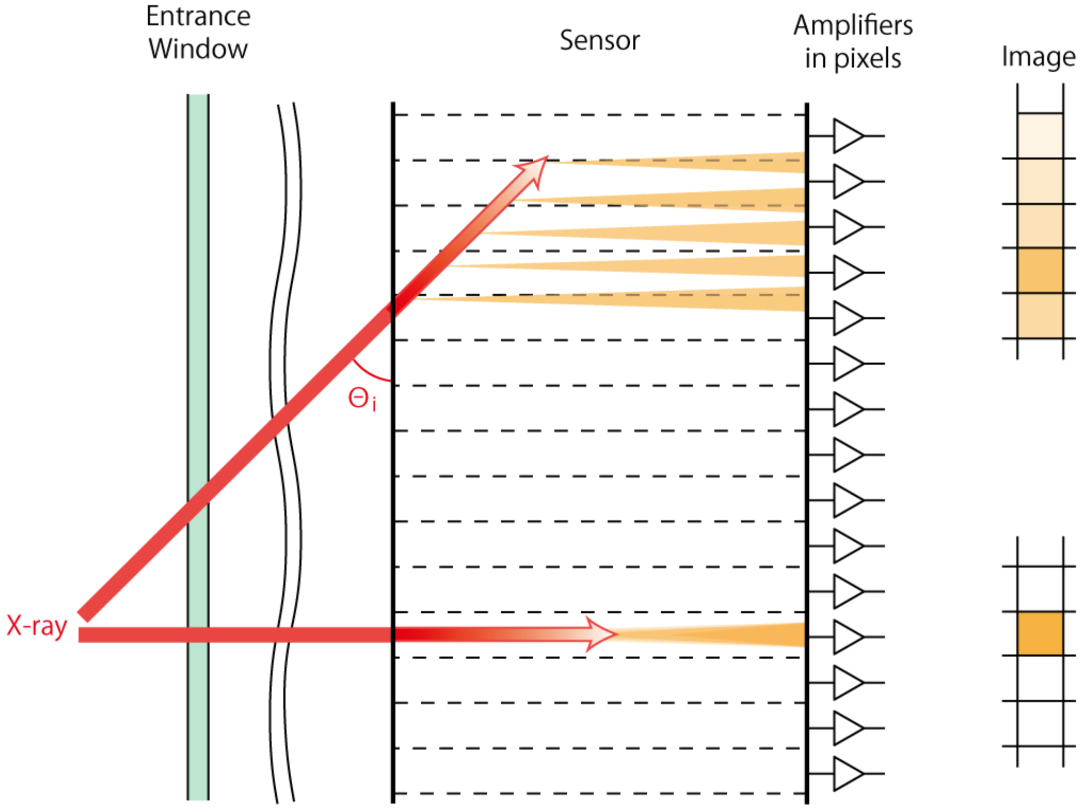


Parallax

Data at 37 keV



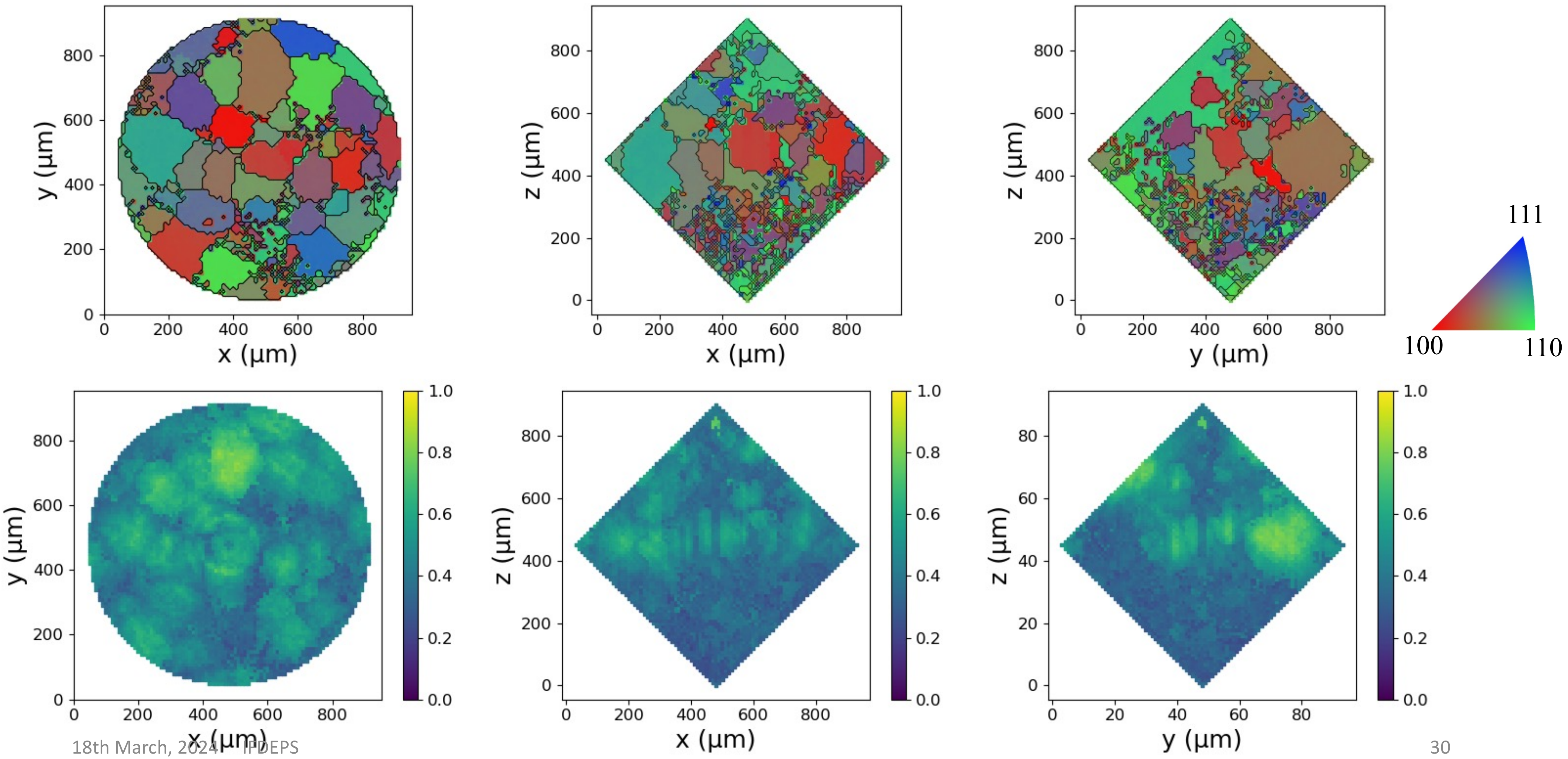
Courtesy of Jaemyung Kim & Y. Hayashi (RIKEN)



deconvolution software under development

3D XRD to visualize the metal grains

Courtesy of Jaemyung Kim & Y. Hayashi (RIKEN)



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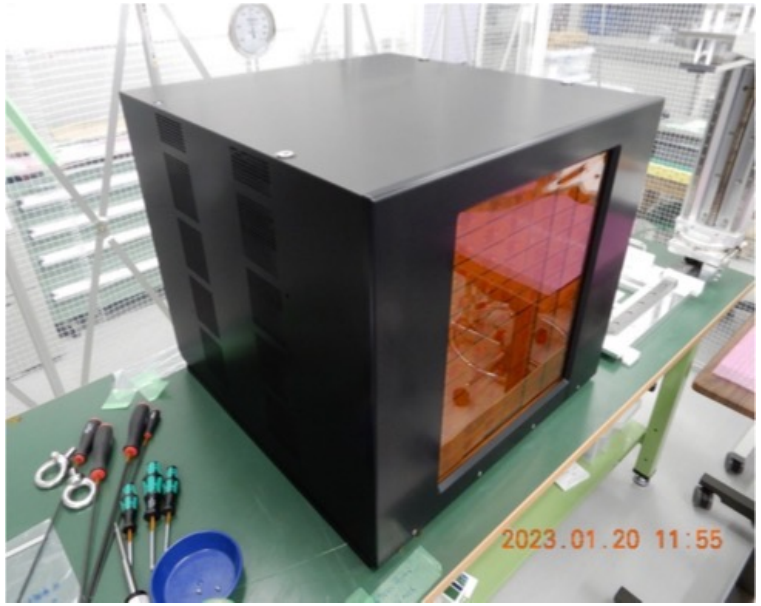
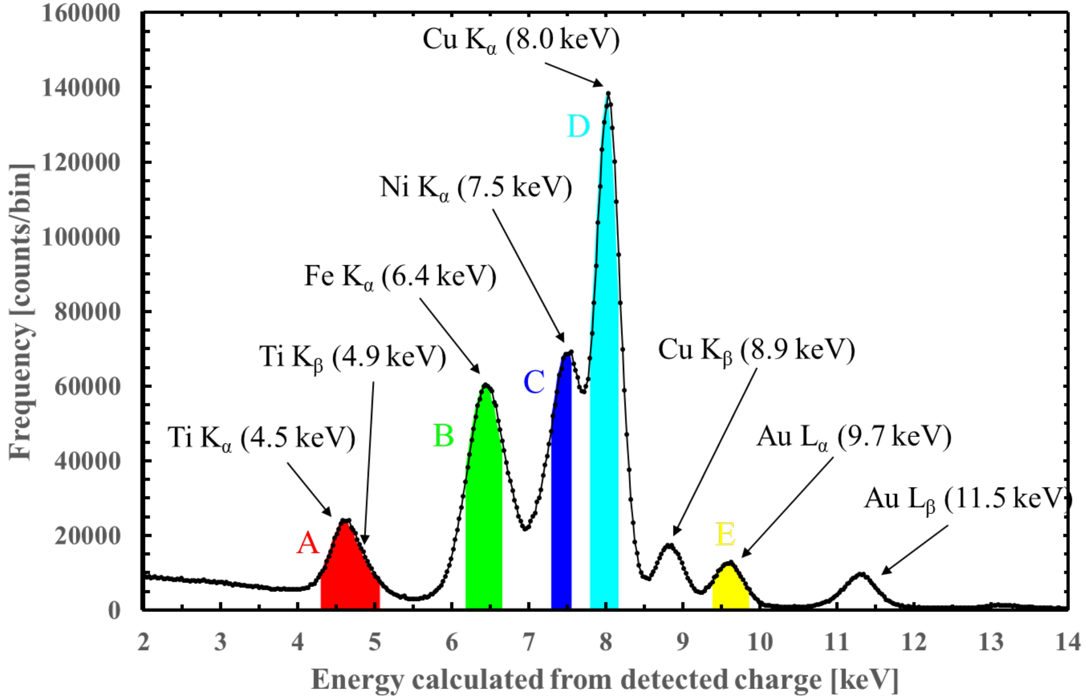


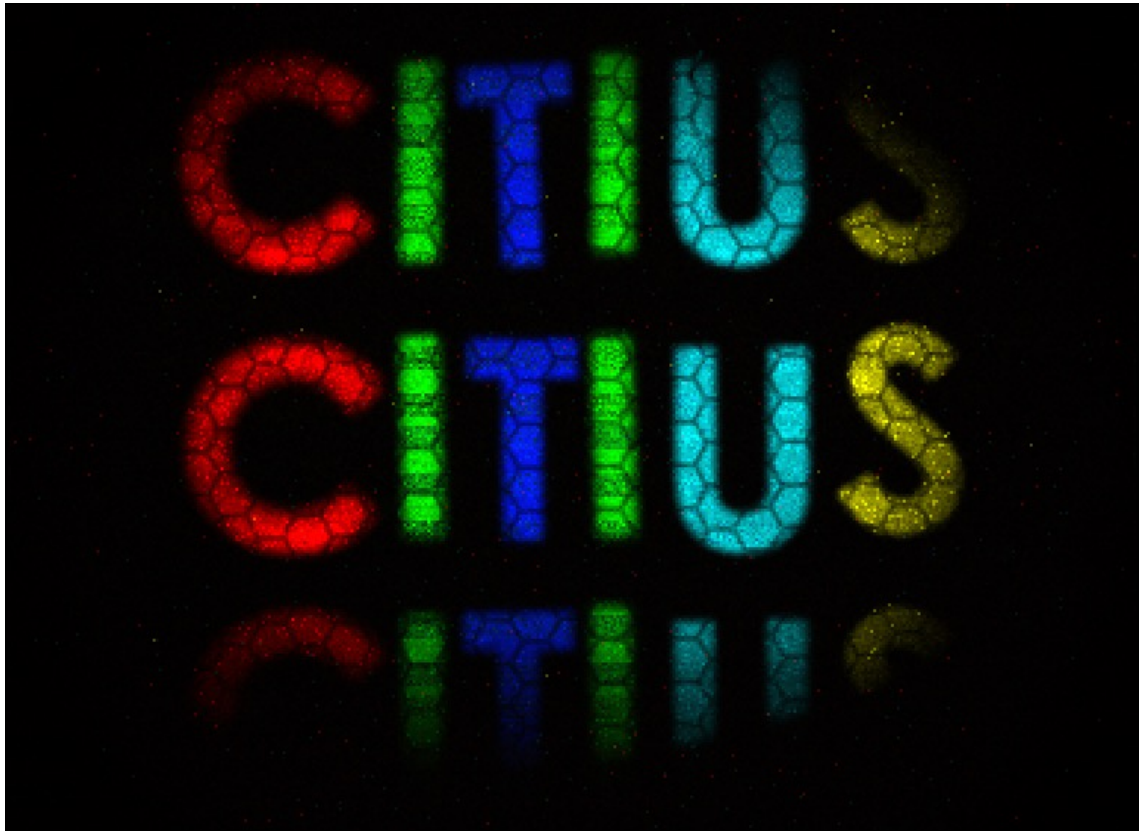
to be installed to SACLA June 2024

Sensitivity

- → *Spectro-imaging*



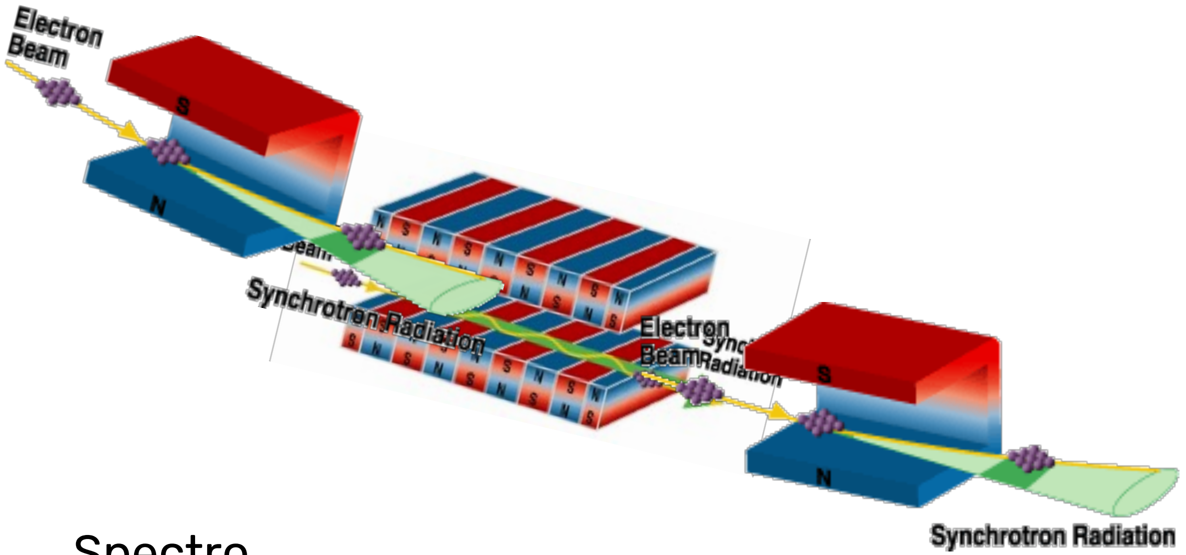
Ti. Fe. Ni. Fe Cu. Cu



K. Ozaki, Y. Honjo, et.al.,

X-ray Beam Monitor for SPring-8-II

- Accelerator feedback with electron monitors
  - not enough
- X-ray beam position monitor is required.



Spectro

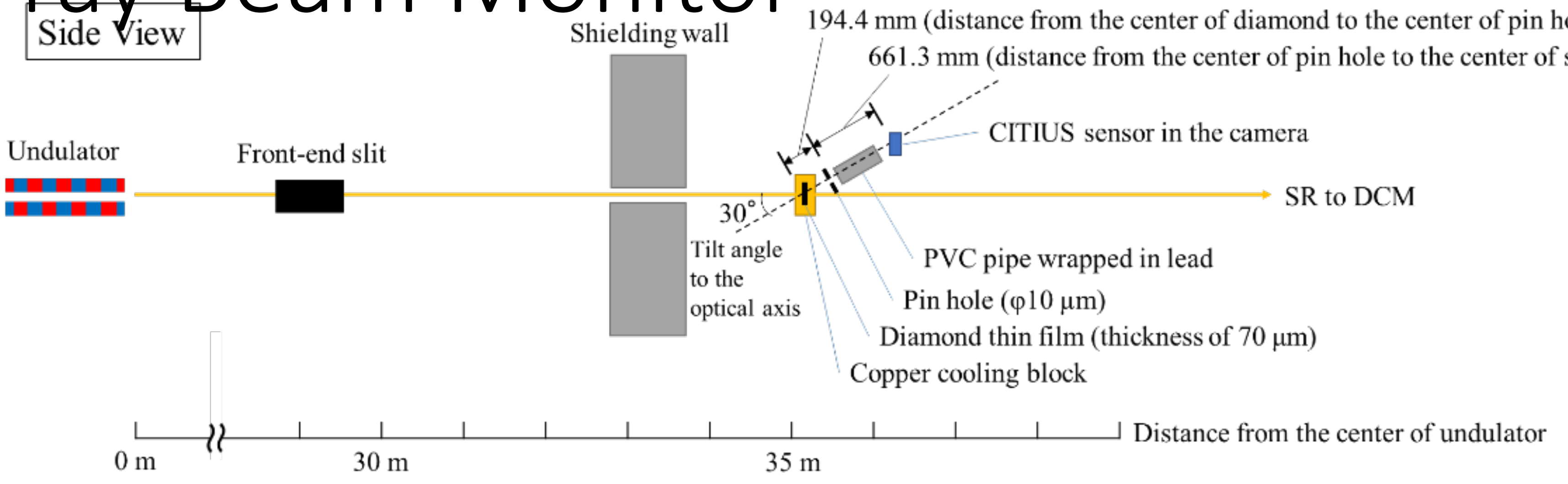
K. Ozaki, T. Kudo, S. Takahashi, M. Sano, T. Itoga, et.al.,

X-ray Intensity Image

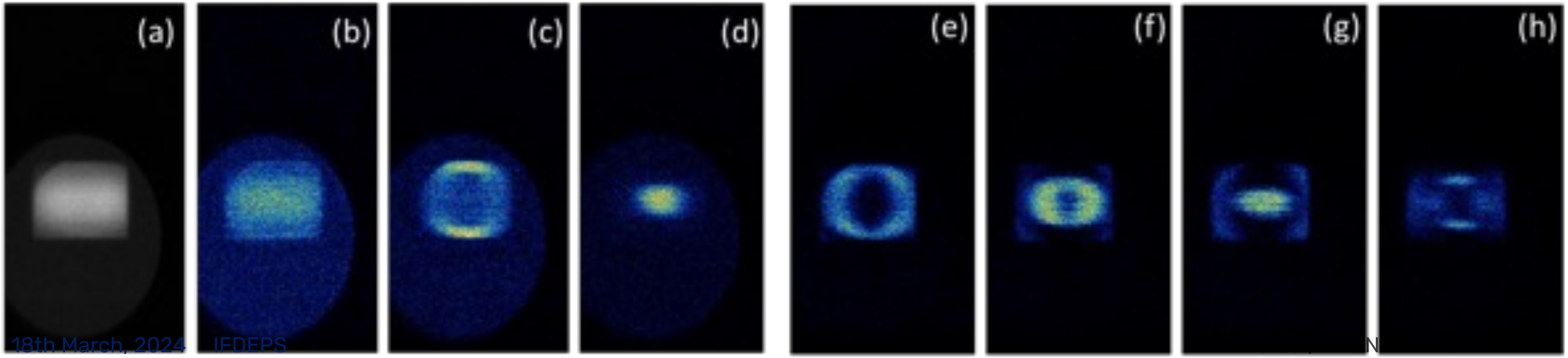
Undulator beam is hidden by the bending X-rays

X-ray Beam Monitor

T. Kudo et.al., J. Synchrotron Rad. (2022). 29, 670-676



K. Ozaki, T. Kudo, S. Takahashi, M. Sano, T. Itoga, et.al.,



1

CITIUS development

Charge **I**ntegration **T**ype **I**maging **U**nit with high-**S**peed extended-Dynamic-Range

Development of CITIUS pixels with Sony

2015-2020

Integrating type

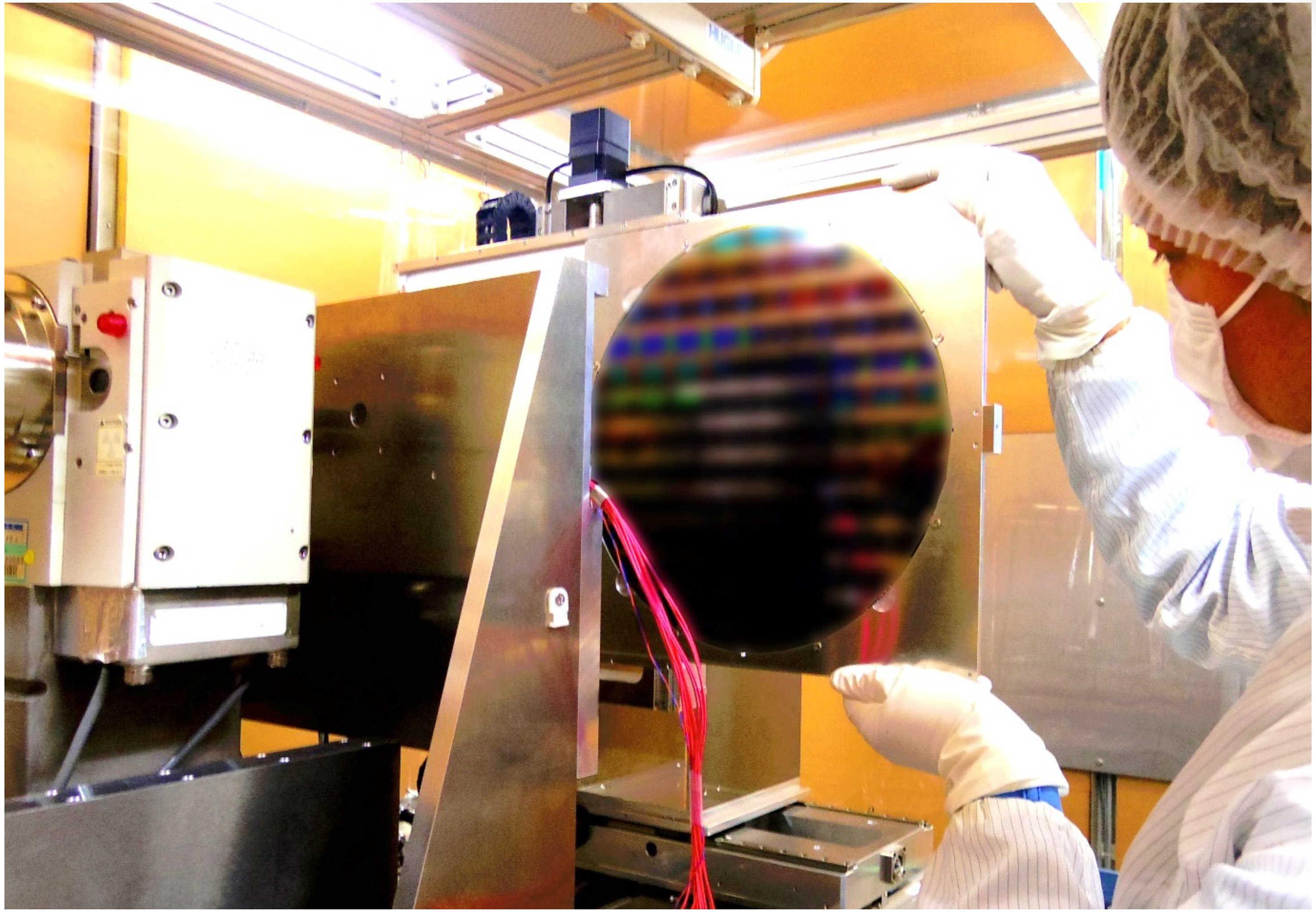
Gain selection (≠ gain switching)

High frame rate @ low power

650 µm thick silicon photodiode

Low noise

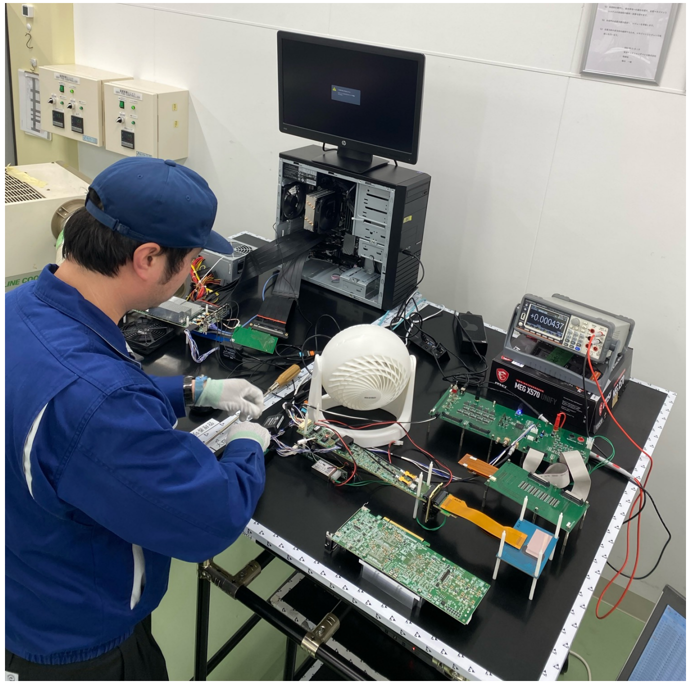
~~Radiation~~ hard



Bottleneck delivering CITIUS: 2020–2023 Global chip shortage

Sensor modules: Sony produced and delivered on time.
After the reliability review, we got approval for mass production (MP),
In total, 249 MP devices have been produced.

Proximity board, data-processing cards:
delayed by about one year, but now solved and under production at 100 units/year



Data Size

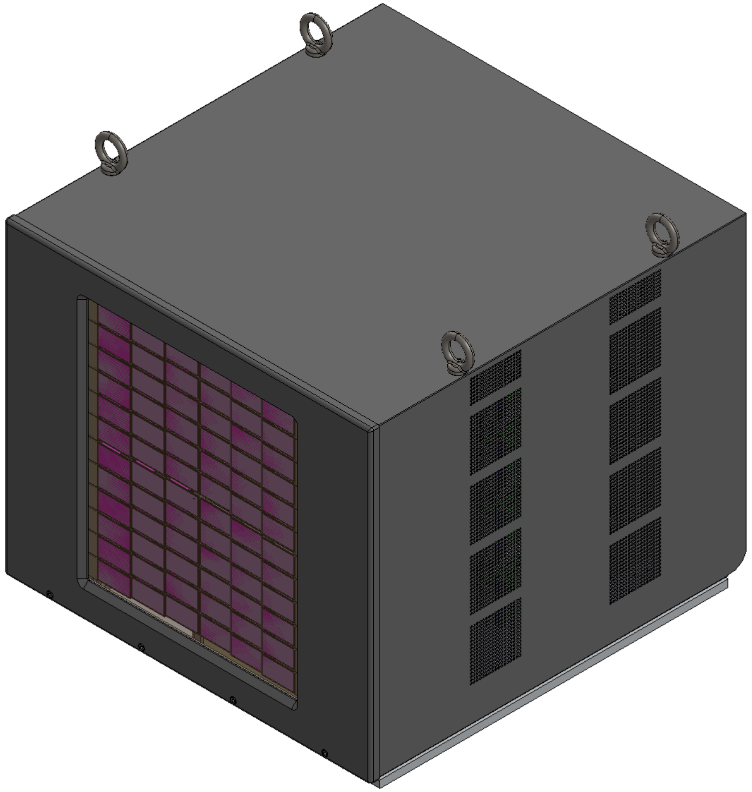
280k pixels
17.4 kframes/s
32 bits/pixel after calib.

2 min.
2.4 TB

1 day
1.7 PB

Data Size Estimation

20.2 Mpixels
17.4 kframes/s



1 hour
5 PB

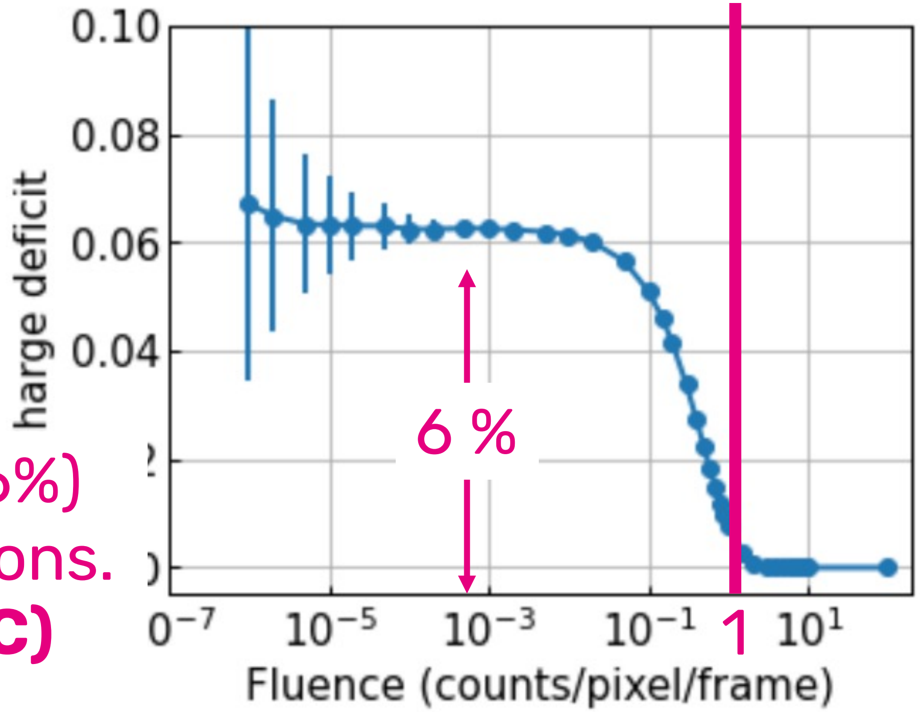
4000 hours/year
30 % data taking
6 EB/year

Charge Sharing in Integrating-pixels

Charge Deficit in a realistic detector

Simulation Parameters	Values
Point spreading function (pixel)	0.154
Detector noise σ_{det} (e^{-})	60
W (eV)	3.65
T_1 for single thresholding	$7\sigma_{det}$

Photon Energy	10 keV
T_1 for single thresholding	$7\sigma_{det}$



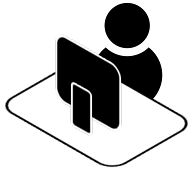
Charge Deficit of 6 % (effective QE drops by 6%) is not acceptable for high-accuracy applications.
→ **Statistically-Lossless Compression (SLC)**

Data Compression on the fly
quasi-elastic scattering

Makina Saito et.al.,
SACLA/SPring-8 Basic Development Program
M.Saito et al., submitted

CITIUS
840k/17.4 kfps

58.5 GB/s
5.1 PB/day

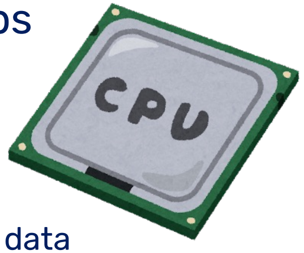


Edge Servers

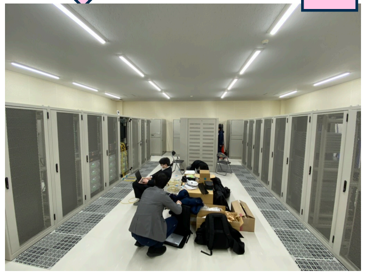
9 FPGA boards developed for CITIUS

840k/8.7 kfps

SLC[1]
Lower entropy data



310 MB/day



SPring-8 DC（5 kcore)

with RIKEN R-CCS

Dr. Sano Team
Reconfigurable High-Performance Computing

[1] T.N. Hiraki et.al.,
SLC(Statistically Lossless Compression)

Summary

Motivation, Development History

Architecture: Integrating pixels & High Frame rate

- High Count rate: *945 Mcps/pixel*
- Uniform Sensitivity: *Spectro-imaging with 252 eV FWHM*
- Faster Recording: *17.4 kframes/s*

Detector variants from 280 kpixels to 20.2 Mpixels

Data-size: 20.2 Mpixels at 17.4 kframes/s produces 6 EB/year

- SPring-8 Data Center Initiative, a hybrid of
  - FPGA-accelerated Edge computing
  - On-Site supercomputing
  - Cloud supercomputing

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RIKEN R-CCS

- S. Matsuoka, K. Sato, K. Sano, F, Shoji and their division members

Private Companies

- Sony Semiconductor Solutions
- GLORY System Create Ltd
- Nihon Gijyutu Center
- Meisei Electric Co. Ltd.
- JEPICO Corporation
- Tokyo Electron Device Limited

Thank you for your attention.

Proposal of Statistically-Lossless Compression (SLC)

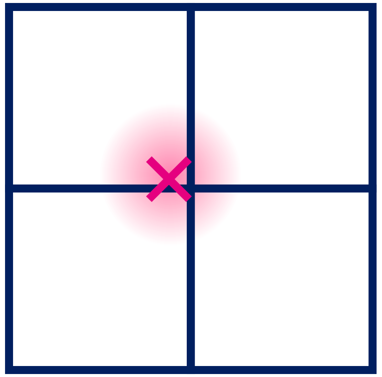
In the definition of information technology, it is a kind of *lossy* compression, which gives higher compression ratio.

SLC is defined as a type of compression that preserves or almost preserves the 1st and 2nd moments of the statistical information.

- Poisson-statistics is to be kept.

Charge Sharing in Integrating-pixels (1/4)

low dose



1 photon/4 pixels
flux density
= 0.25 photons/pix.

digitization

0.40	0.20
0.25	0.05

flux density
= 0.25 photons/pix.

"single thresholding"

$$A = \begin{cases} 0, if\ I < 0.15 \\ I, if\ I > 0.15 \end{cases}$$

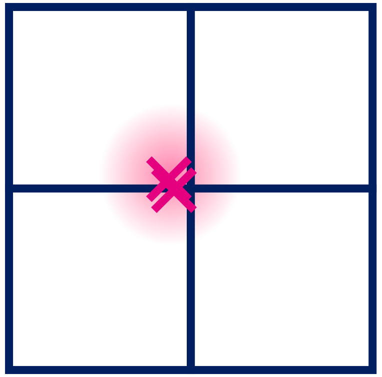
0.6	0.2
0.1	0

flux density
= 0.225 photons/pix.

Summation of the detected charge shows a "charge deficit (CD)".
CD = 0.225/0.25 = 10 %

Charge Sharing in Integrating-pixels (2/4)

hypothetical situation



2 photons/4 pixels
flux density
= 0.50 photons/pix.

digitization

0.80	0.40
0.50	0.10

flux density
= 0.50 photons/pix.

"single thresholding"

$$A = \begin{cases} 0, if\ I < 0.15 \\ I, if\ I > 0.15 \end{cases}$$

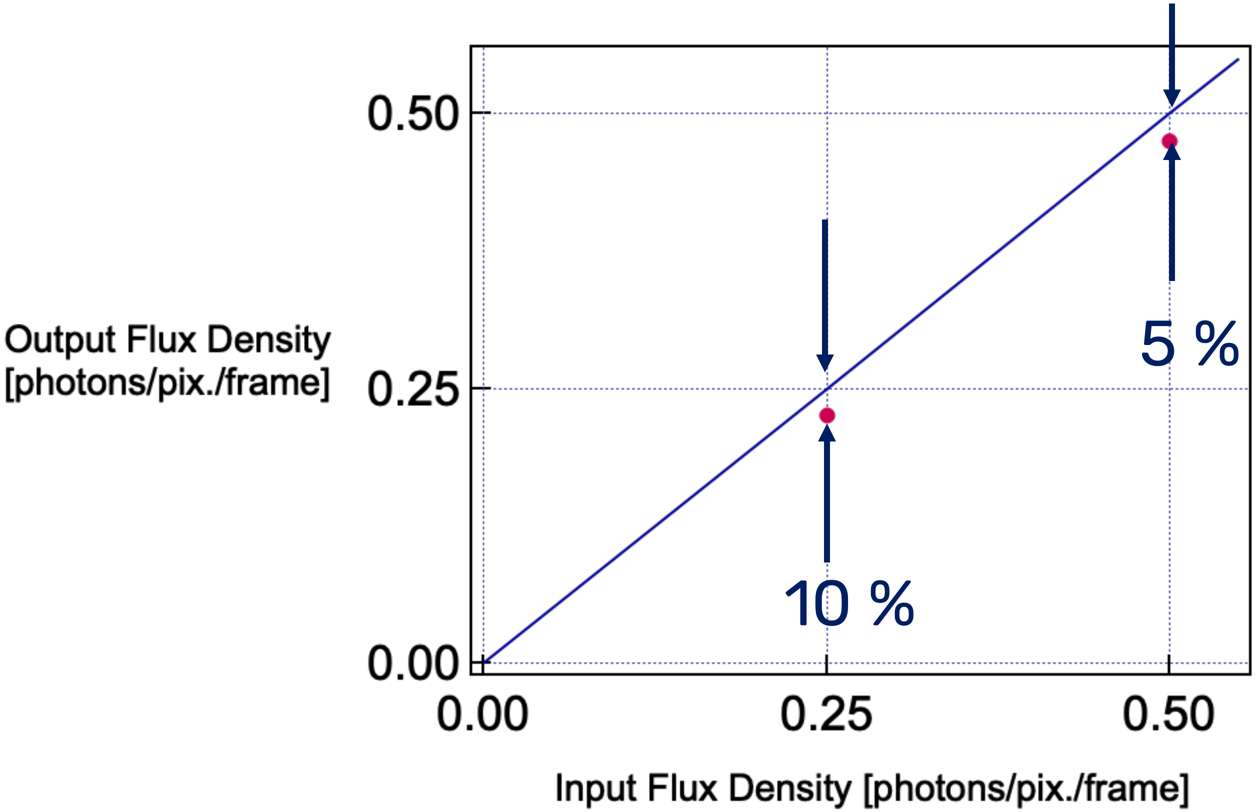
0.80	0.40
0.50	0

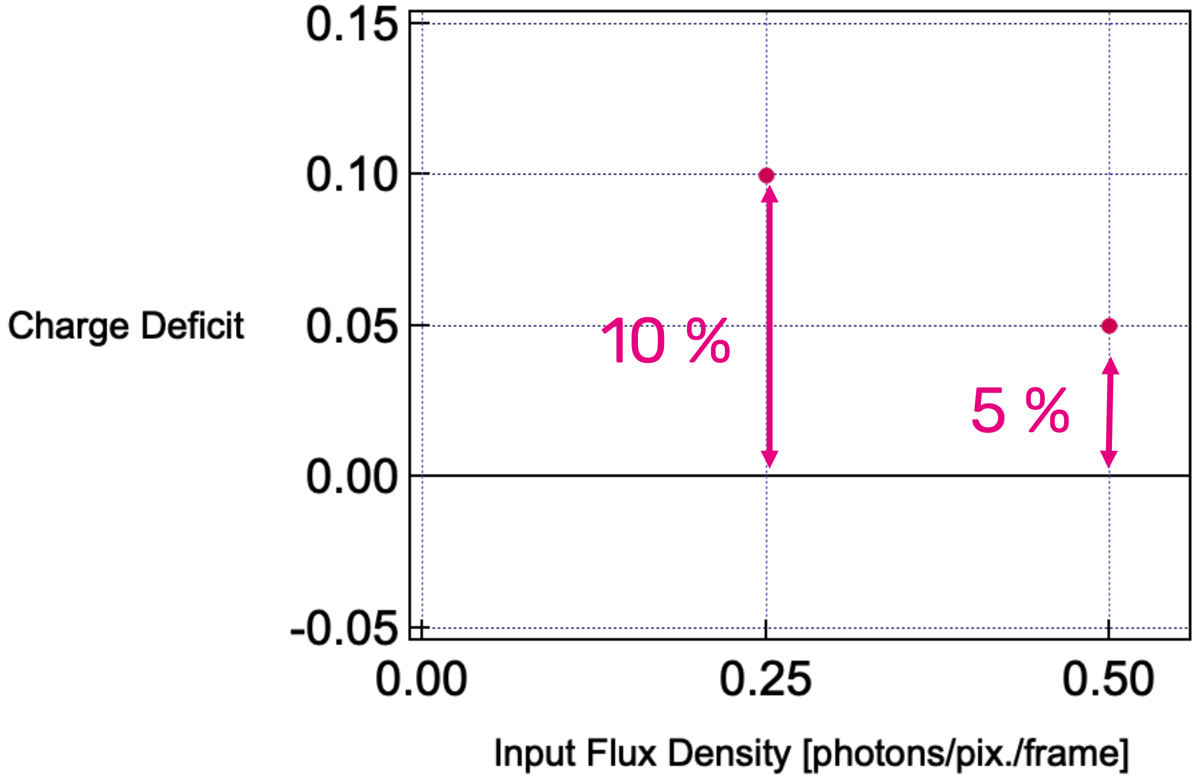
flux density
= 0.475 photons/pix.

Summation of the detected charge shows a "charge deficit (CD)".
CD = 0.475/0.50 = 5 %

Charge Sharing in Integrating-pixels (3/4)

*Charge Deficit for the **low dose** and **hypothetical situation***





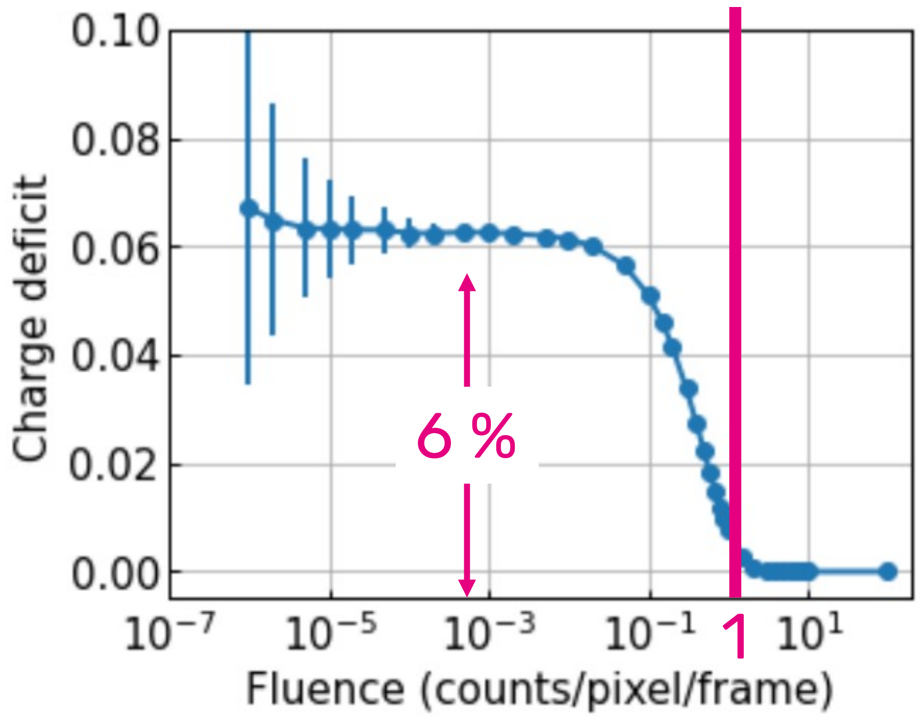
Charge sharing in combination with
"single thresholding" induces a non-linear response

Charge Sharing in Integrating-pixels (4/4)

Charge Deficit in a realistic detector

Simulation Parameters	Values
Point spreading function (pixel)	0.154
Detector noise σ_{det} (e^{-})	60
W (eV)	3.65
T_1 for single thresholding	$7\sigma_{det}$

Photon Energy	10 keV
T_1 for single thresholding	$7\sigma_{det}$



Charge Deficit of 6 %
is not acceptable
for high-accuracy applications.

2x2 sum: Overview

Process Sequence

- Look at the 2x2 pixel matrix.
- If the sum of the 2x2 matrix exceeds a threshold T1, leave them as inputs,
- otherwise, set them to 0.

Implementation

- calibration
- multiple frame buffers to calculate 2x2 sum

Advantage

- sub-pixel information is kept

Drawback

- significant complexity in memory access

(a)

Input: an image data I (2D, $(height, width) = (H, W)$), threshold T_1
Output: the processed image data I_{proc} (2D, $(height, width) = (H, W)$)
$\forall(i, j),\ I_{proc}(i, j) = 0$;
for $i = 0, \ldots, H - 2$ **do**
  for $j = 0, \ldots, W - 2$ **do**
    $q = I(i, j) + I(i + 1, j) + I(i, j + 1) + I(i + 1, j + 1)$;
    if $q \geq T_1$ **then**
      $I_{proc}(i, j) = I(i, j)$;
      $I_{proc}(i + 1, j) = I(i + 1, j)$;
      $I_{proc}(i, j + 1) = I(i, j + 1)$;
      $I_{proc}(i + 1, j + 1) = I(i + 1, j + 1)$;

(b)

Detector image $I(i,j)$

0	0.04	-0.01	-0.02	0
-0.01	0.02	-0.02	-0.02	-0.01
-0.01	0.11	0.73	0	-0.03
0.02	0	0.16	0.03	0
0.02	0	0.02	-0.01	-0.02

$T_1 = Q_{ph}/2,$
$Q_{ph} = 1$
→

Output $I_{proc}(i,j)$

0	0	0	0	0
0	0.02	-0.02	-0.02	0
0	0.11	0.73	0	0
0	0	0.16	0.03	0
0	0	0	0	0

T2C: Overview

Process Sequence

- Look at each pixel.
- If the signal < T1, set 0.
- If T2 > signal > T1, set C,
- If signal > T2, return signal.

Implementation

- calibration
- multiple frame buffers are not mandatory for T2C.

Advantage

- pixel-wise algorithm

Drawback

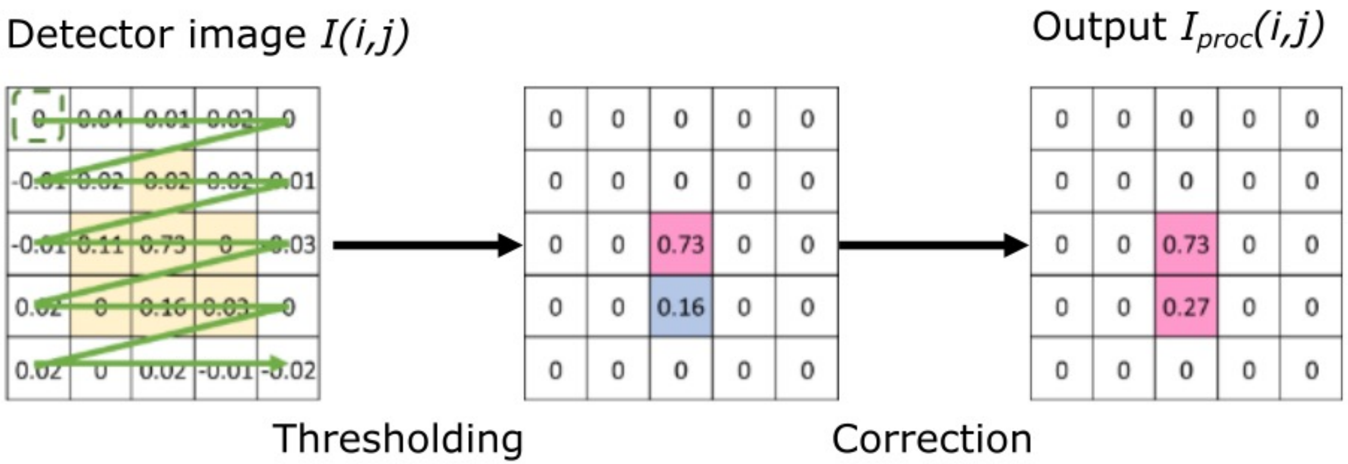
- sub-pixel information is lost

(a)

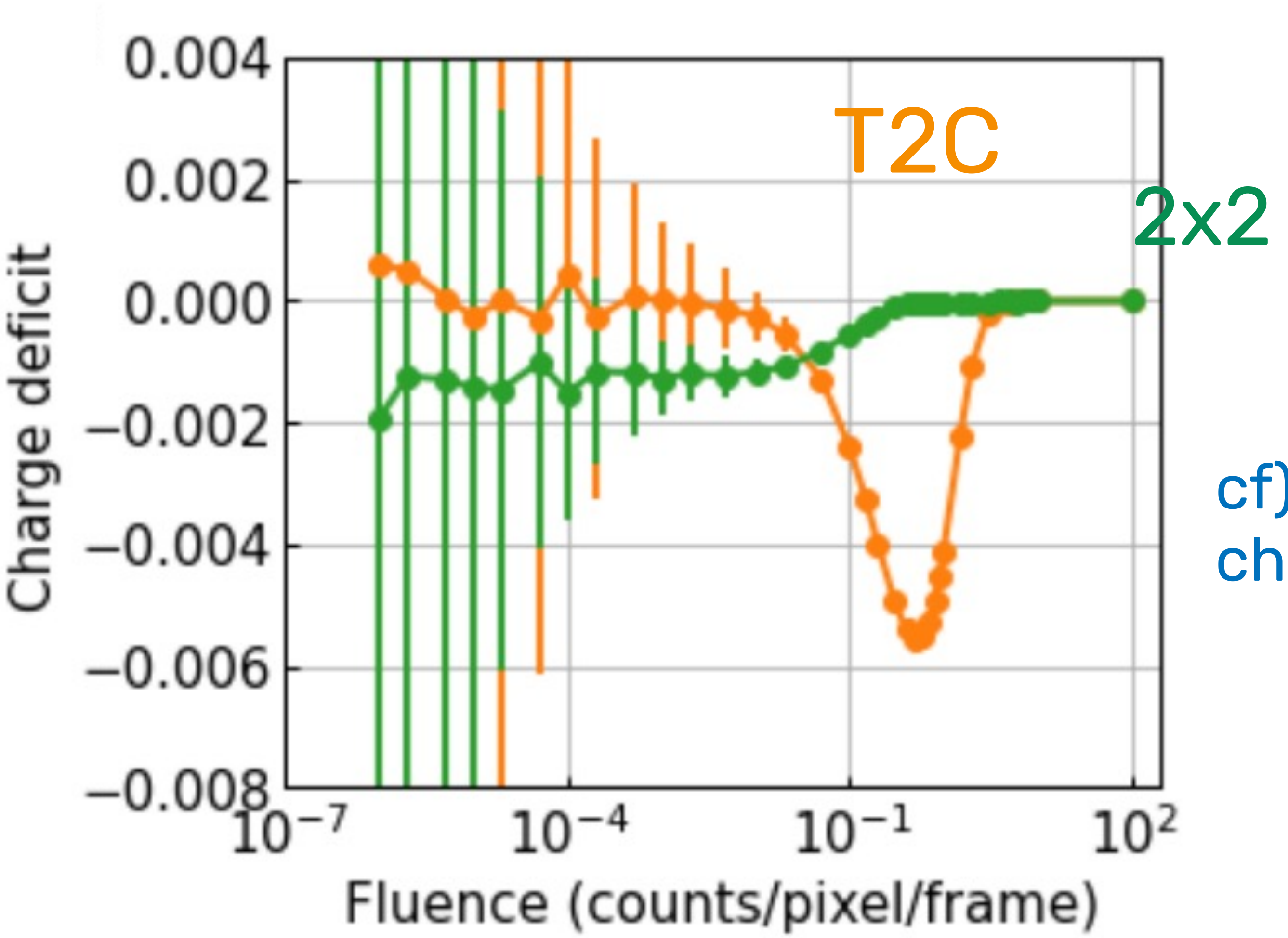
Input: an image data I (2D, $(height, width) = (H, W)$), threshold T_1, T_2, correction value C
Output: the processed image data I_{proc} (2D, $(height, width) = (H, W)$)

$\forall(i, j),\ I_{proc}(i, j) = 0;$
for $i = 0, \ldots, H-1$ **do**
  for $j = 0, \ldots, W-1$ **do**
    if $I(i, j) < T_1$ **then**
      $I_{proc}(i, j) = 0;$
    else if $I(i, j) \leq T_2$ **then**
      $I_{proc}(i, j) = C;$

(b)



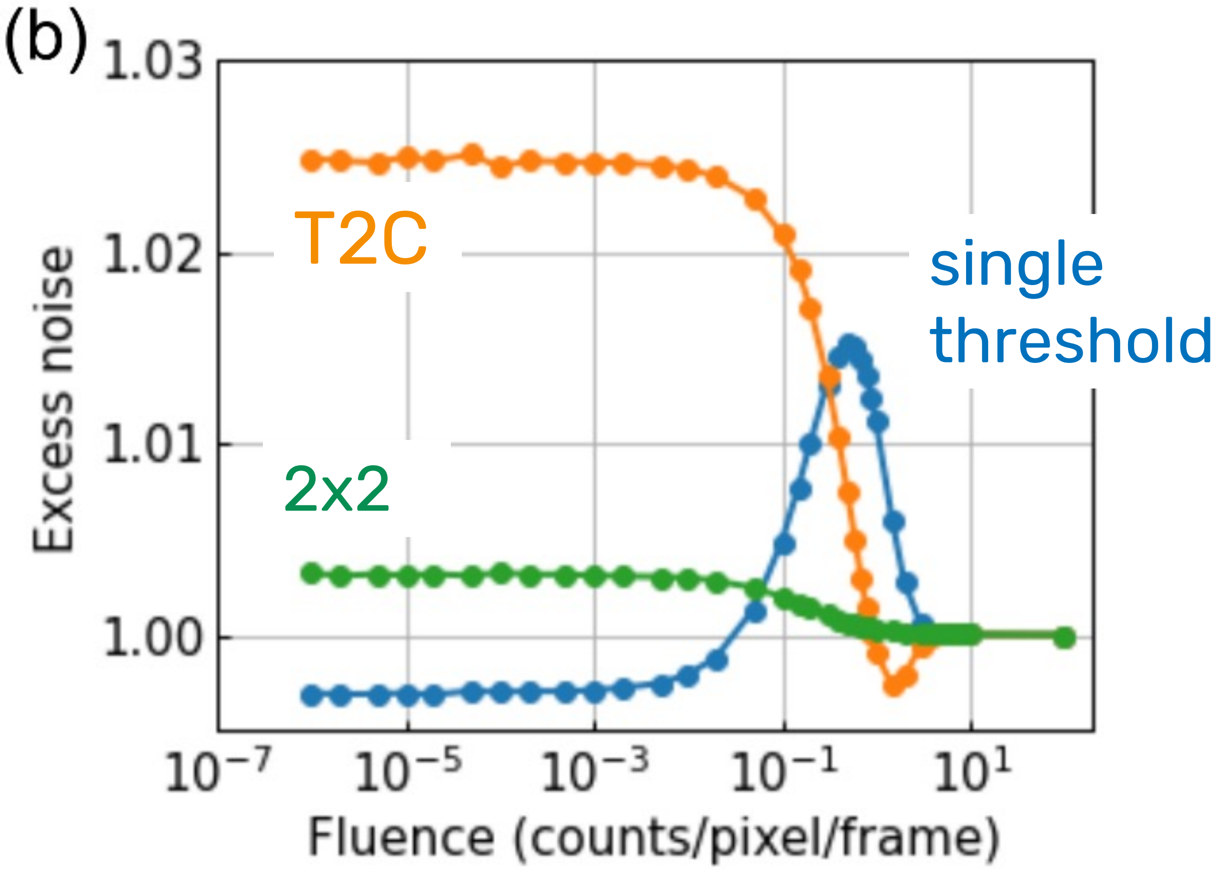
Sim. Performance: Charge Deficit



cf) for “single threshold”, charge deficit ∼ 0.06

Sim. Performance: Excess Noise

Excess noise compared to the data after digitization.



Compression Flow and Implementation

digitization → calibration → SLC pre-processing (T2C or 2x2 sum) → Lossless Compression (Zstandard)

Sensor module

FPGAs

CPUs

Compression Benchmark

for simulated coherent SAXS data at 10^-4 photons/pixel/frame equivalent to 1.7 photons/pixel/s with CITIUS standard mode

FoM \ Preprocessing	This study		Single thresholding	Detector Output
	T2C	2×2-sum		
Charge Deficit (1st moment)	0.0005 ± 0.0012	0.0013 ± 0.0006	0.06 ± 0.008	(0)
Sub-pixel information	lost	kept	kept	(kept)
Standard deviation (2nd moment)	0.9809	1.0009	0.9482	(1.0)
Algorithm Comprexity	simple	Demanding frame buffers	simple	
Compression Factor	$(3.5 \pm 0.3)\times10^3$	$(1.0 \pm 0.1)\times10^3$	$(3.3 \pm 0.2)\times10^3$	1.1
Compression Computation Speed on CPU after preprocessing on a CPU core [1] (GB/s)	0.31	0.29	0.31	0.019
Decode Rate (GB/s)	12	10	6.7	0.40

[1] Zstandard was used. Computation time for Zstandard was measured for single-core computation. Time for I/O was not included.

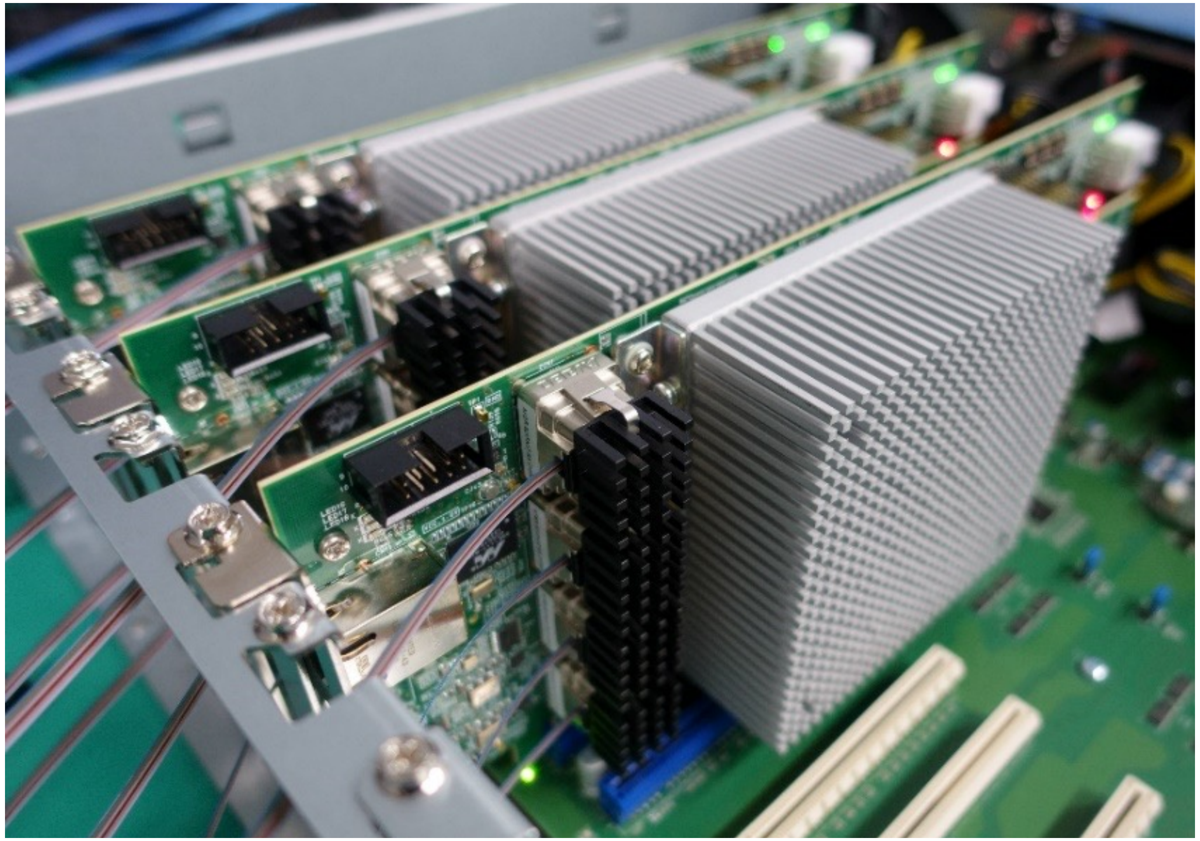
Implementation of T2C

Scientific Experiments

SPring-8 BL35XU

- Inelastic Scattering by X-ray imaging detector

Data Rate
  - 8.7 kHz, 840 kpixel
  - 2.6 PB/day
- Compression factor
  - max. x7000
  - Compressed data: 33 TB for 6 days experiments
- Scientists are no longer saving the native output of CITIUS.
- T2C processed data is now the "raw" data.



Data-Framing boards (DFBs) used in this study.
Each DFB has three Arria10 FPGAs.
On-the-fly calibration and T2C was implemented.