

Development of 5.04 Mpixel CITIUS detector for high-resolution ptychography

Charge Integration Type Imaging Unit with high-Speed extended-Dynamic-Range

This variant is in the development stage

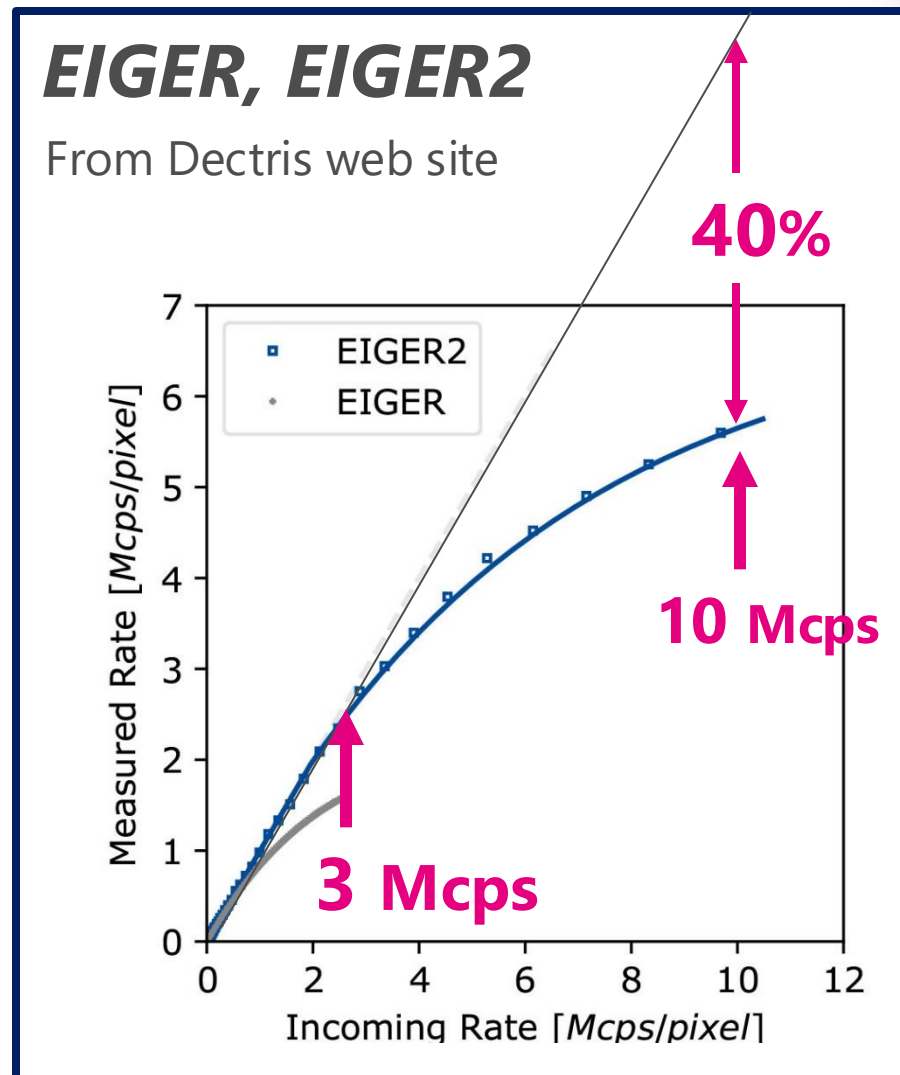
Takaki Hatsui, Kyosuke Ozaki, Yoshiaki Honjo, Haruki Nishino, Kazuo Kobayashi, Koji Motomura, Kyo Nakajima, Yasumasa Joti

RIKEN SPring-8 Center



Improve Efficiency by Advanced Detector Technology: CITIUS

Current Limits and CITIUS capability



[1] Y. Imai and T. Hatsui, J. Synchrotron Rad. 31(2) (2024) 295.

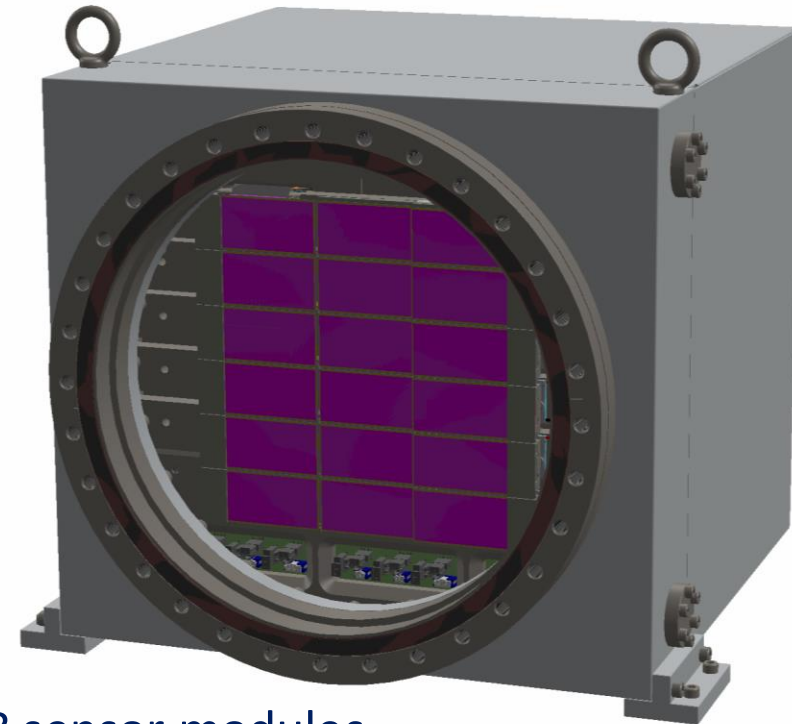
CITIUS 5.04 M

Major Specifications

Saturation Count rate	1 Gcps/pixel @ 8 keV 19 Tcps/cm ²
Sensitivity	> 90% and uniform
Sensor modules	in a vacuum
Proximity electronics	in air
Frame rate	17.4 kHz
Noise	40 e-rms (0.018 phs@8 keV)
Data bandwidth	2.8 Tbps
Data depth	32 bit floating
Pixel rate	87.7 Gpixel/s
Delivery	Dec. 2025

Camera Head (draft)

Pixel Size: 72.6 μm



18 sensor modules
(280 kpixels for each)

Photon Counting?

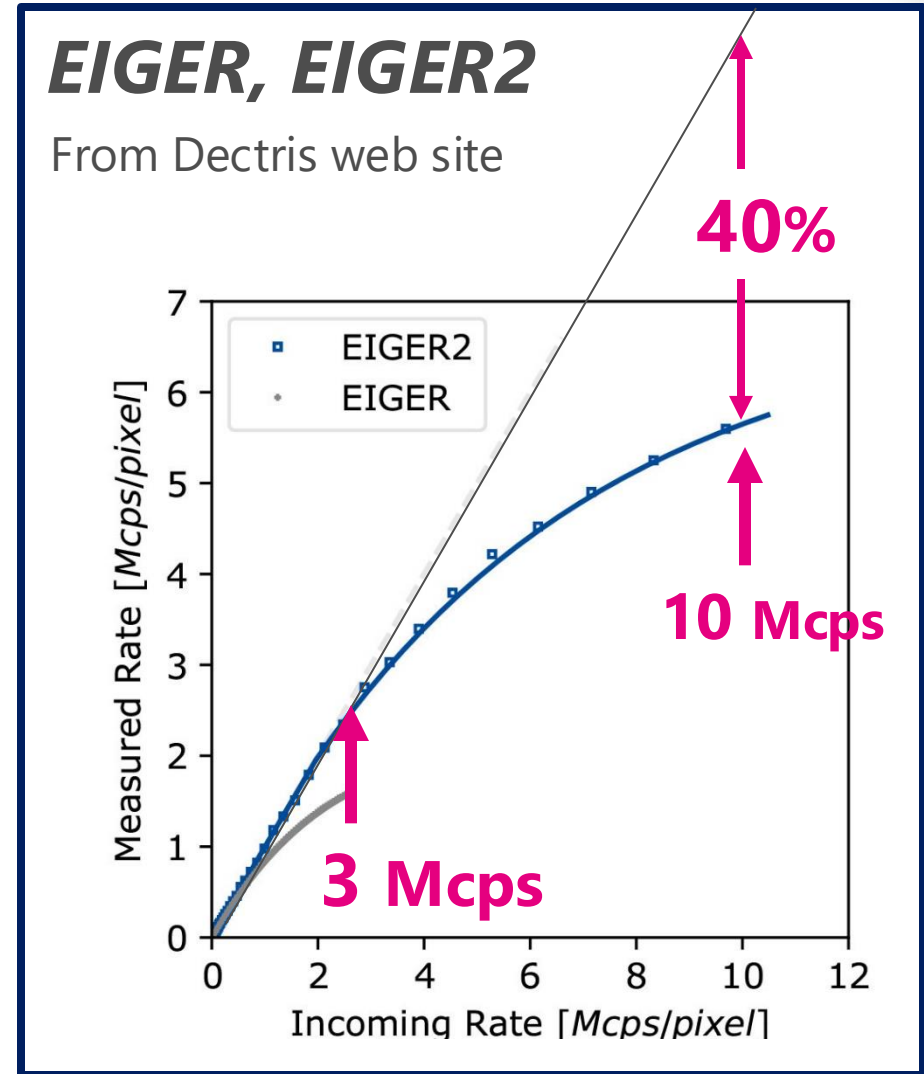
Current State-of-the-art

Existing Detectors

- PILATUS、Eiger
- Medipix-based detectors (Lambda etc.)
- HyPix series (RIGAKU)

Limited Count Rate

- 1-10 Mcps/pixel
(10^3 - 10^4 photons/pixel @ 10 kframes/s)
- reduced further by x80-390 for quasi-single bunch modes of SPring-8 [1]



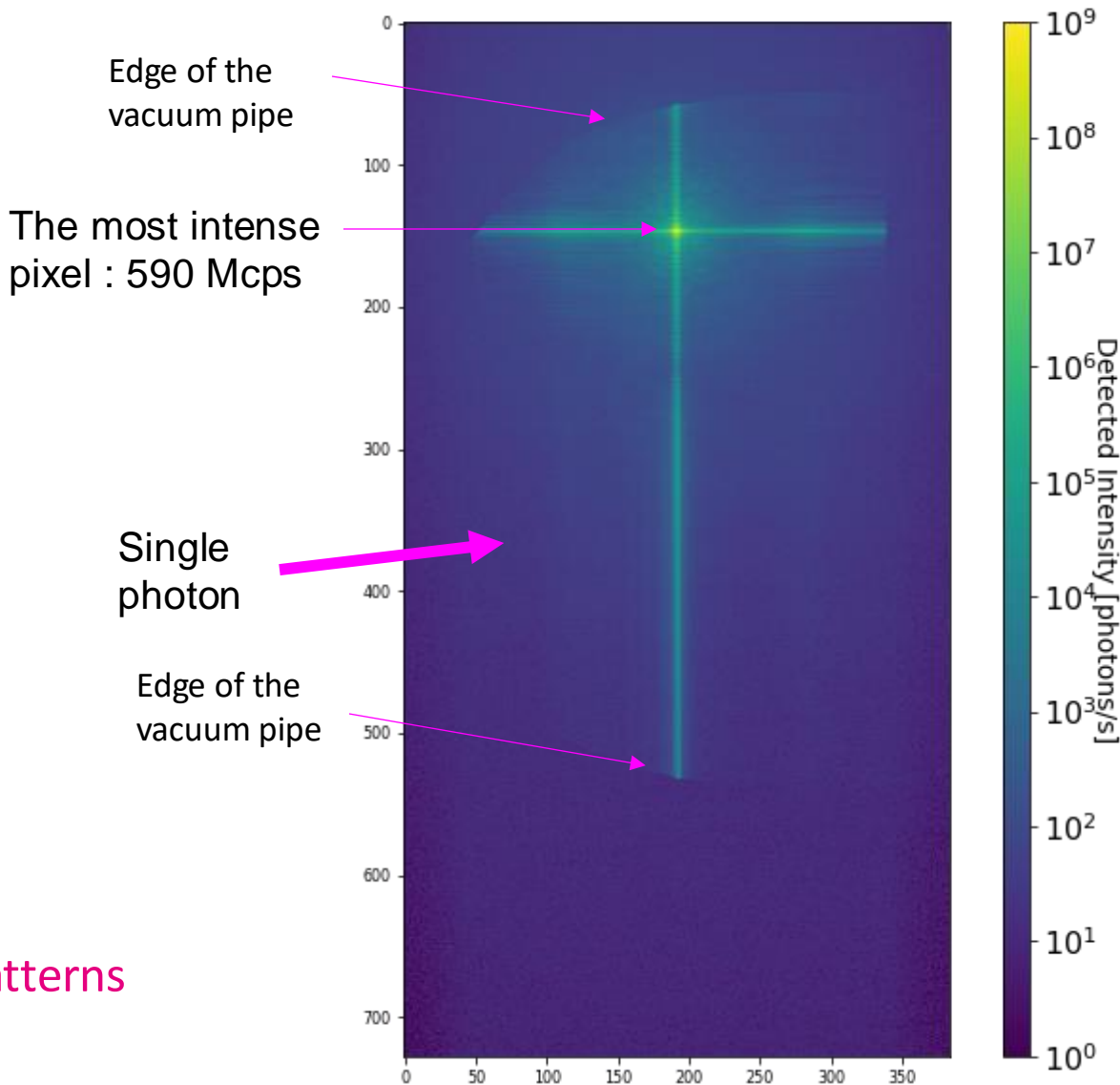
[1] Y. Imai and T. Hatsui, J. Synchrotron Rad. 31(2) (2024) 295.

Count Rate (1/2)

Photon Energy: 10keV

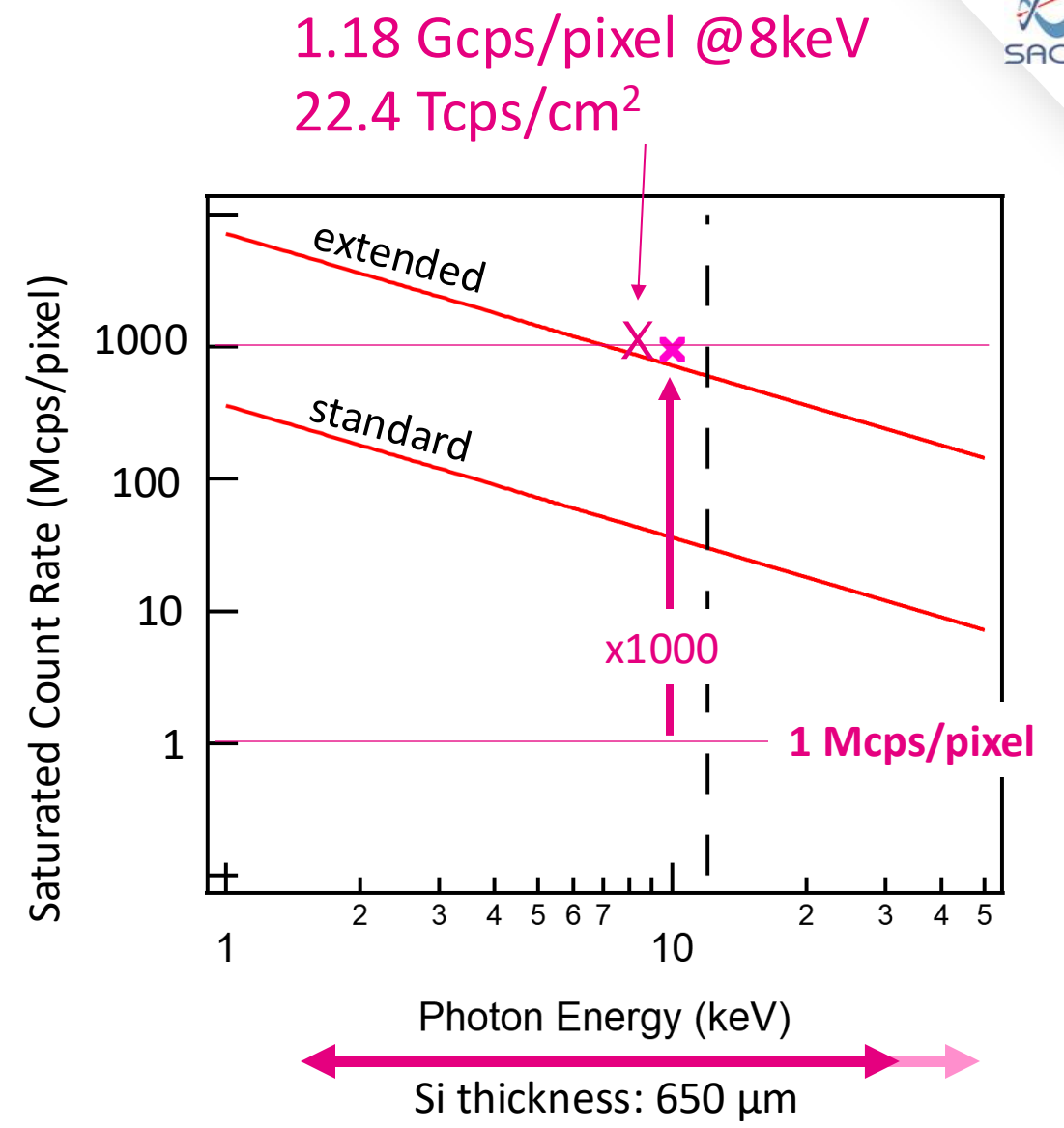
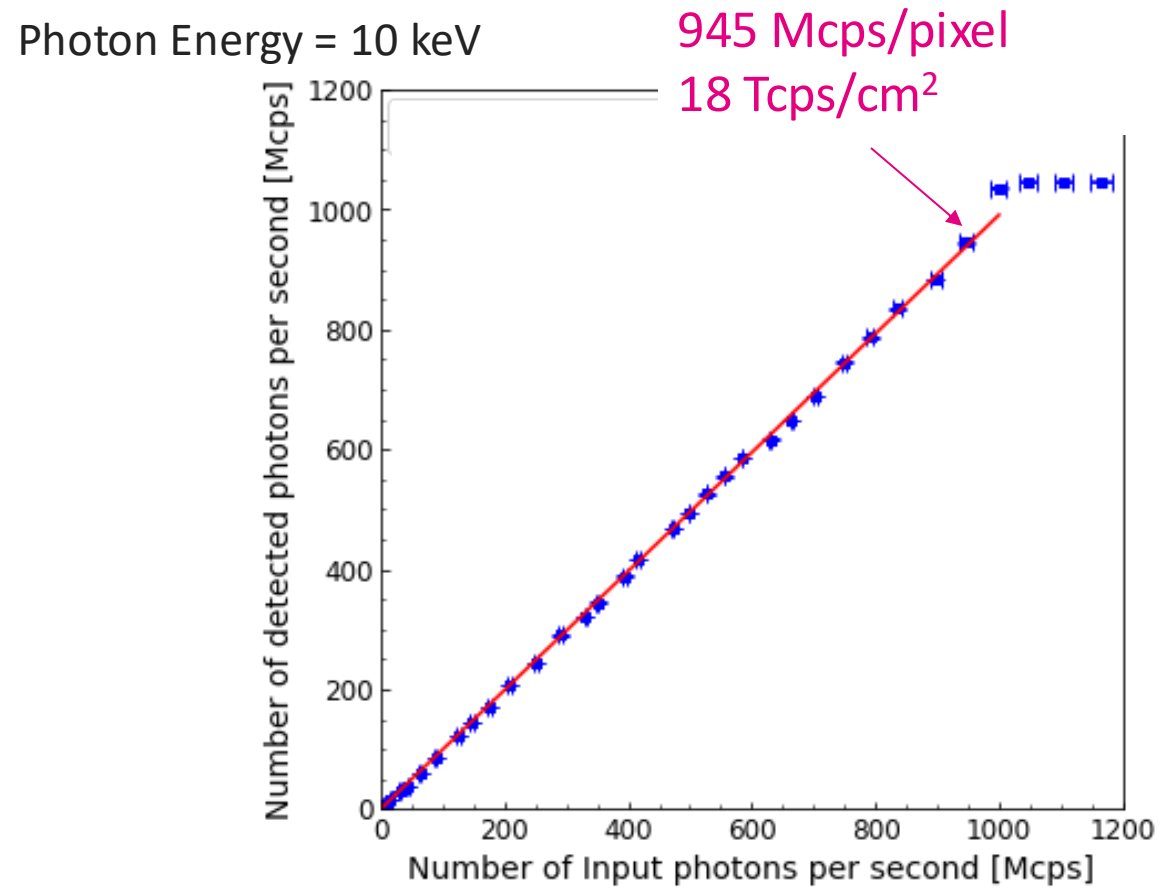
Slit to CITIUS: 15m

Slit Size: $20 \times 20 \mu\text{m}$



integrating-type pixel
count rate is independent from bunch patterns

Count Rate (2/2)

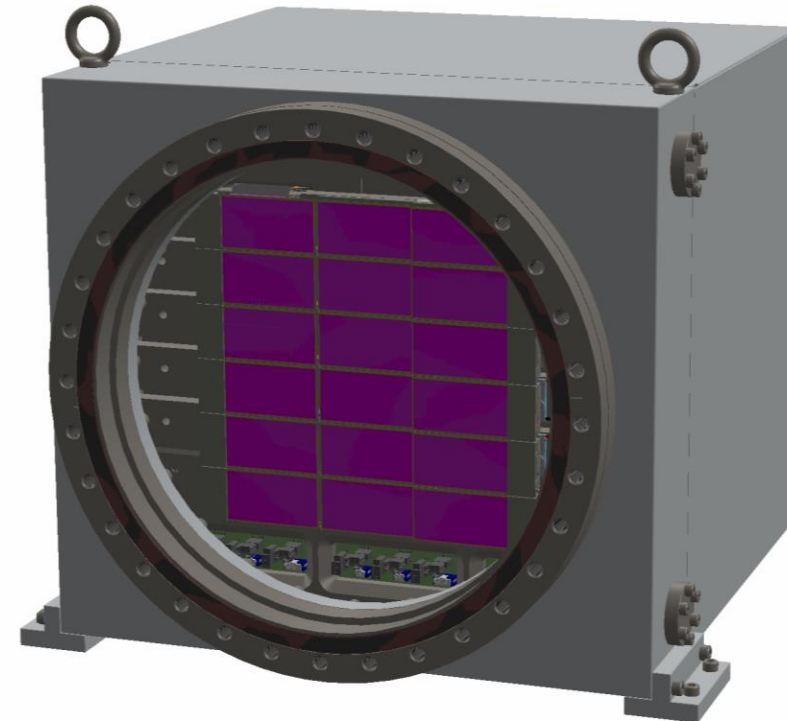


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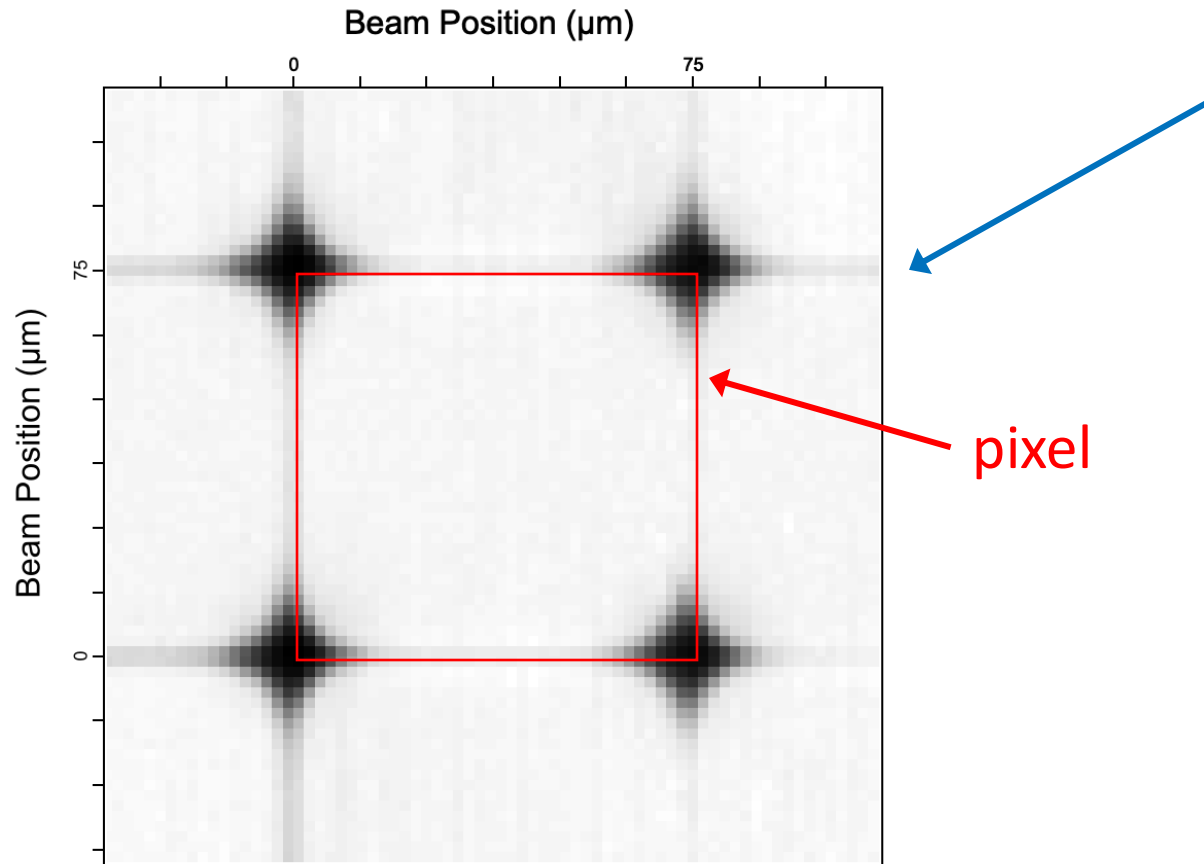
Camera Head (draft)



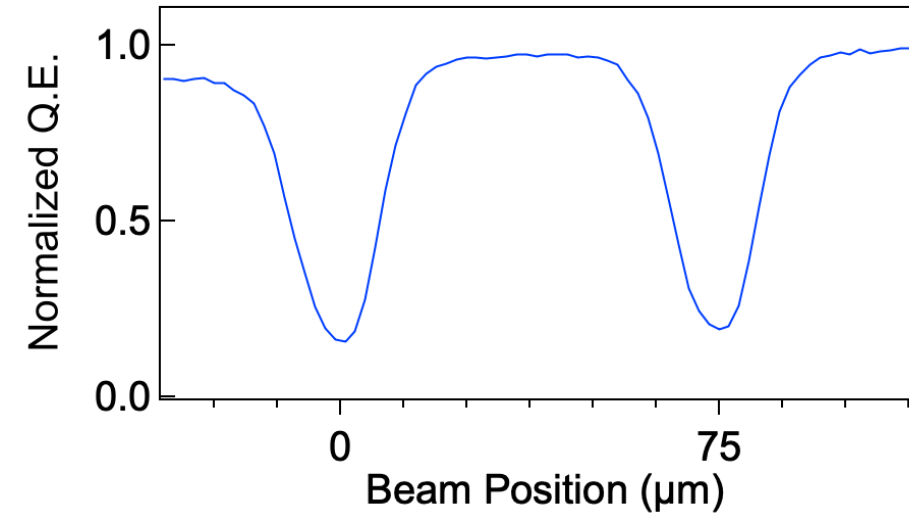
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(280 kpixels for each)

Sensitivity: Photon Counting Detector

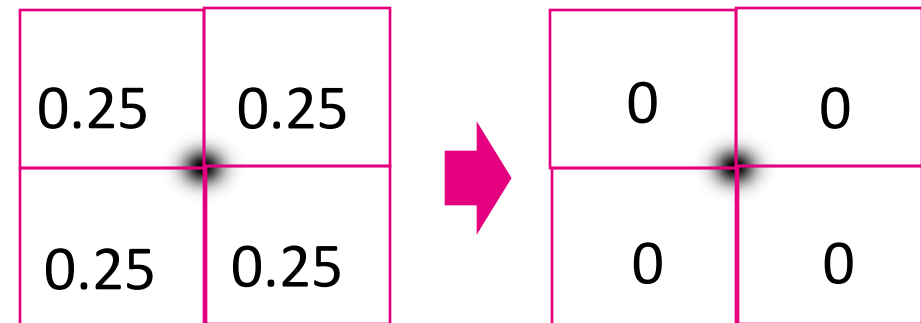
Corner Response



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

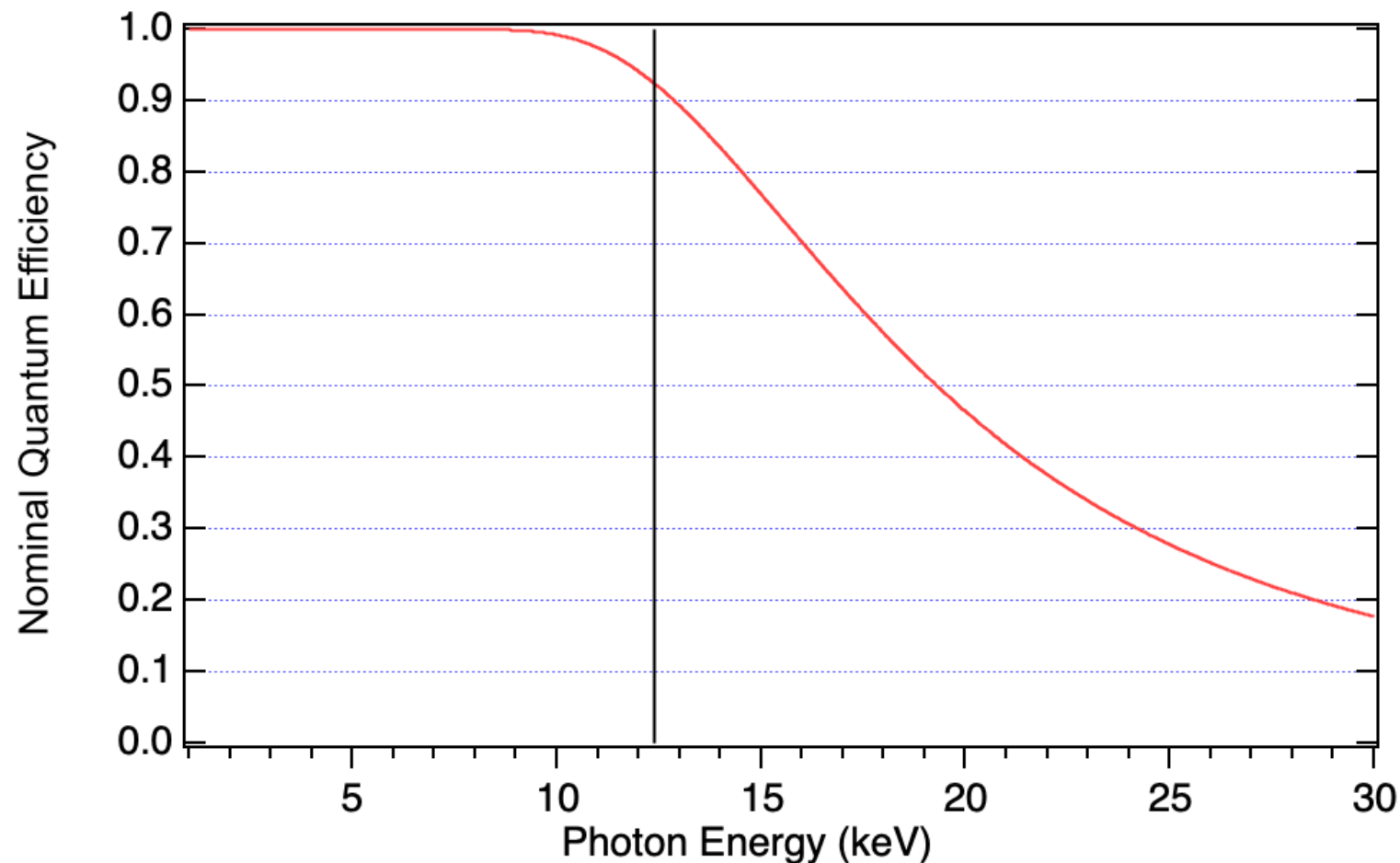
Integrating-type pixel: free from the corner sensitivity loss

Sensitivity

No aluminum filter
High QE down to 1 keV

Low energy limit
determined by the noise
for the typical case with 40 e-rms
1.5 keV with $S/N = 5$

High energy limit
650 μm thick silicon



Applications to quasi-elastic scattering

Makina Saito et.al.,
Phys. Rev. Lett. **132**, 256901 (2024)

Demands high sensitivity @ 14.4 keV

System: CITIUS 840k

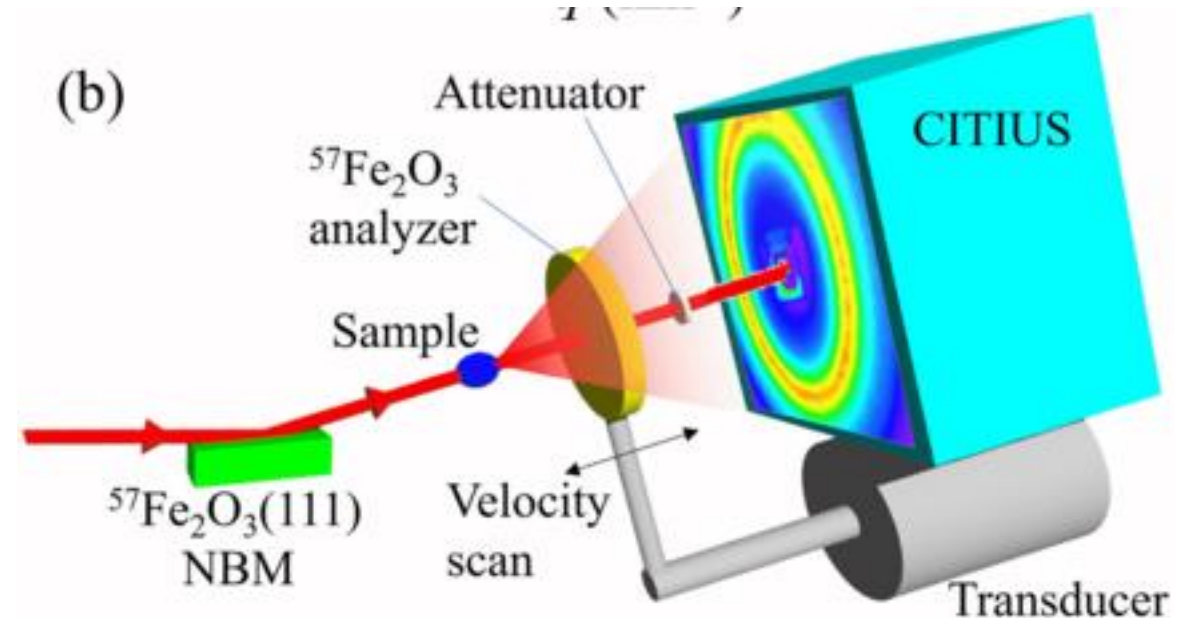
Operated at 17.4 kframes/s

5.1 PB/day (35 PB/beamtime)

Summation to 8.7 kframes

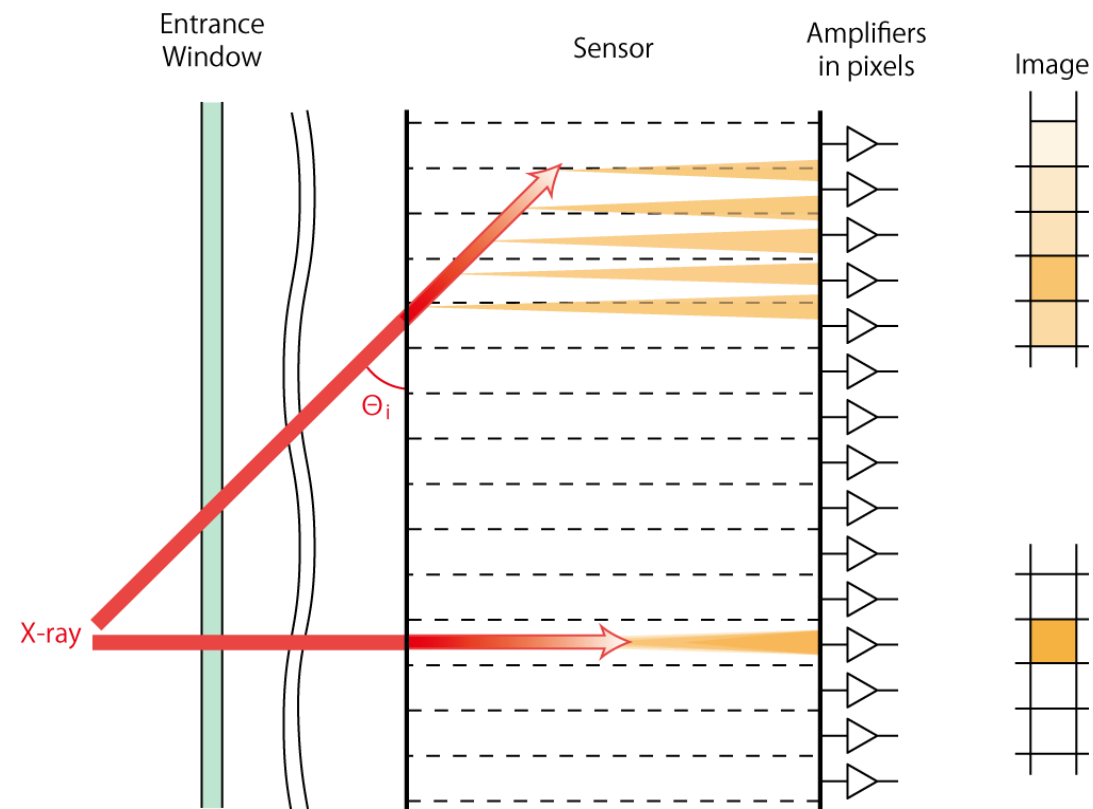
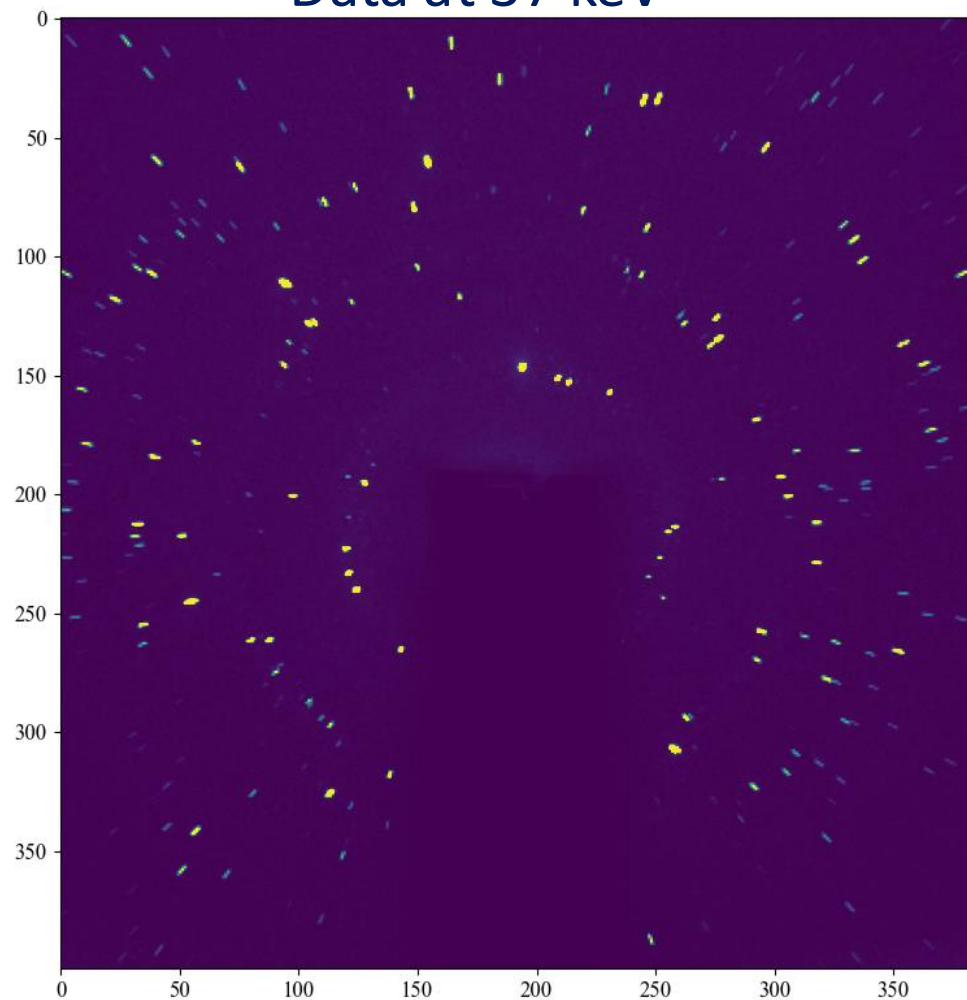
On-the-fly calibration, summation and
compression

compression ratio > 1000



Parallax

Data at 37 keV

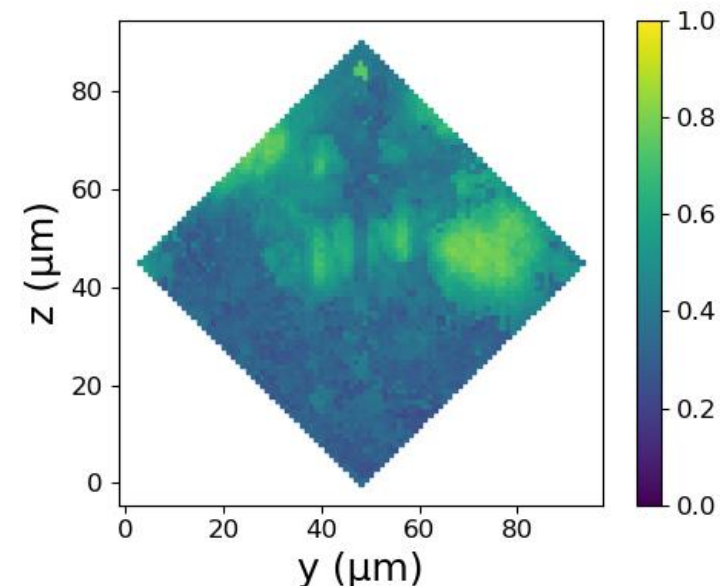
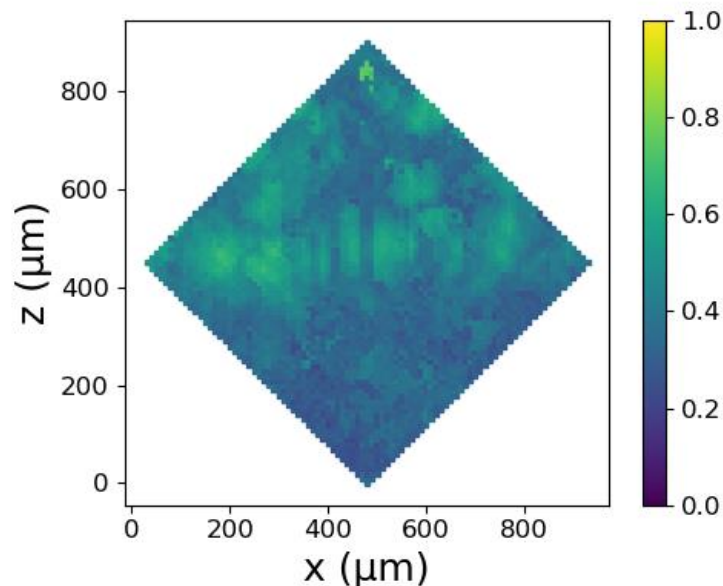
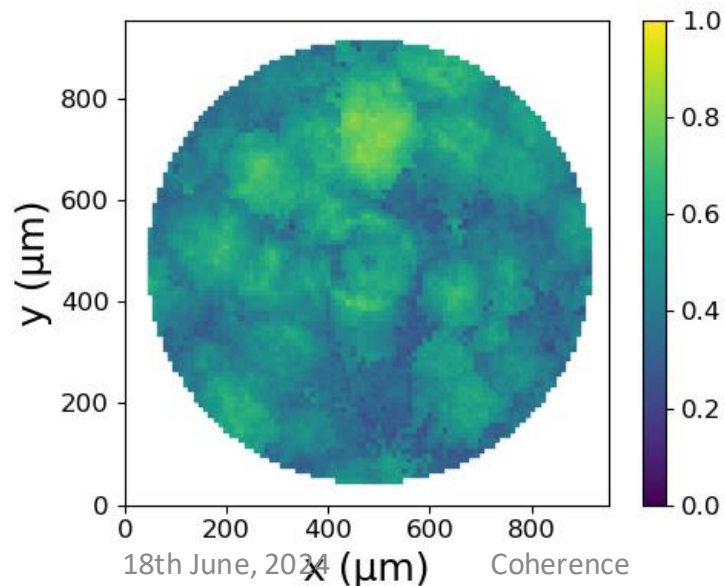
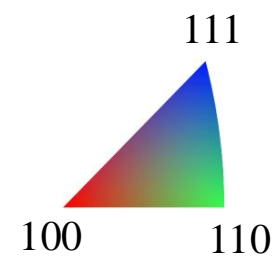
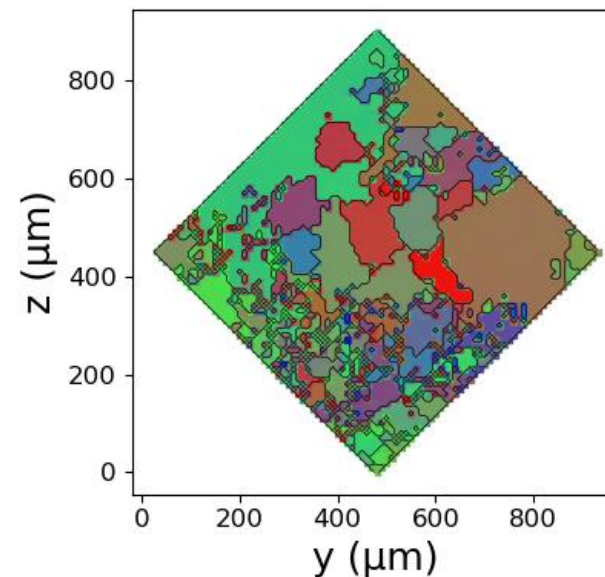
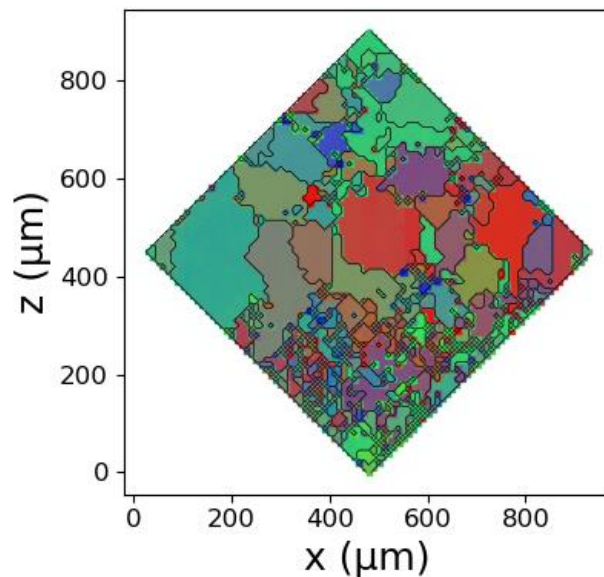
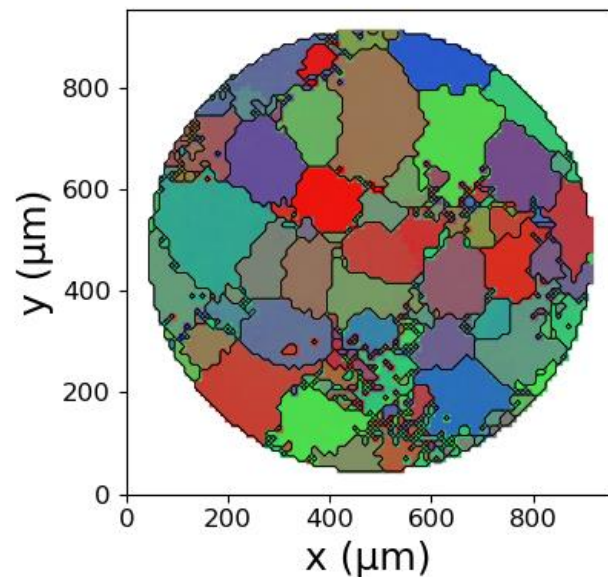


deconvolution software under development

Courtesy of Jaemyung Kim & Y. Hayashi (RIKEN)

3D XRD to visualize the metal grains

Courtesy of Jaemyung Kim & Y. Hayashi (RIKEN)

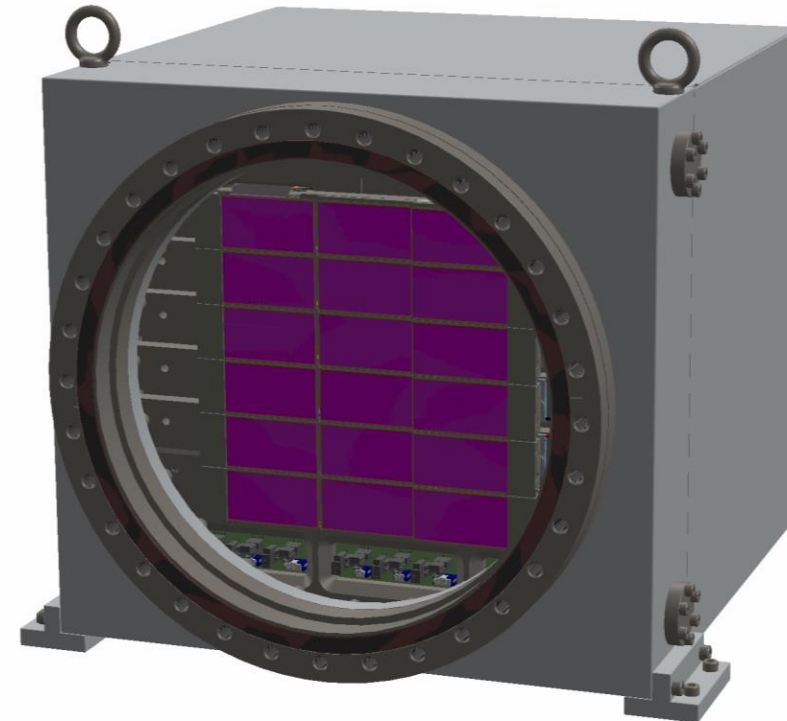


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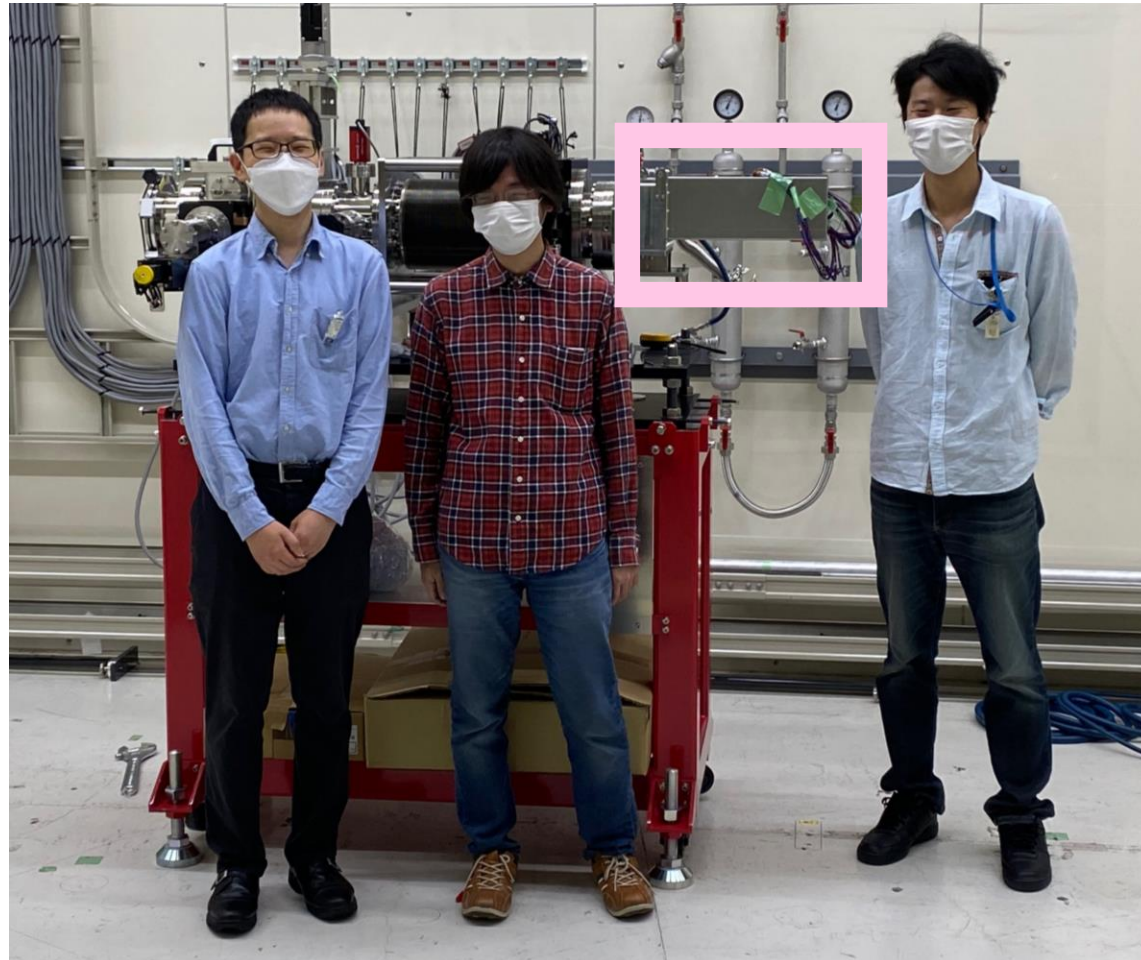
Camera Head (draft)



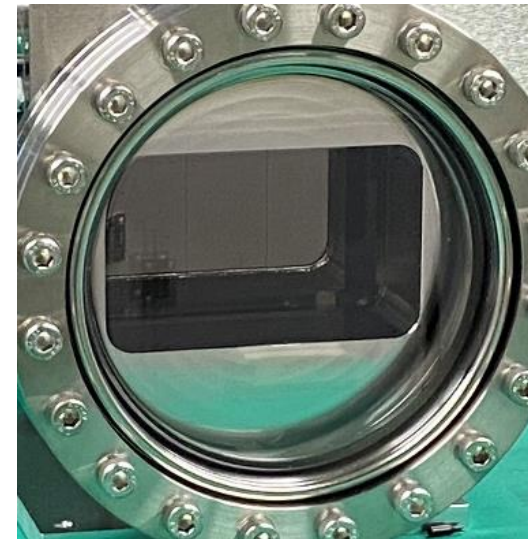
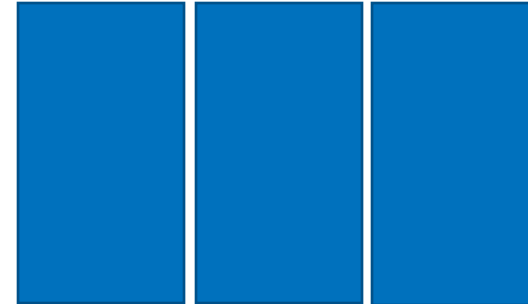
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(280 kpixels for each)

Flange-mounted in-vacuum CITIUS feasibility study for ptychography

in collab. with Y. Takahashi Group
of Tohoku Univ.



840k



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

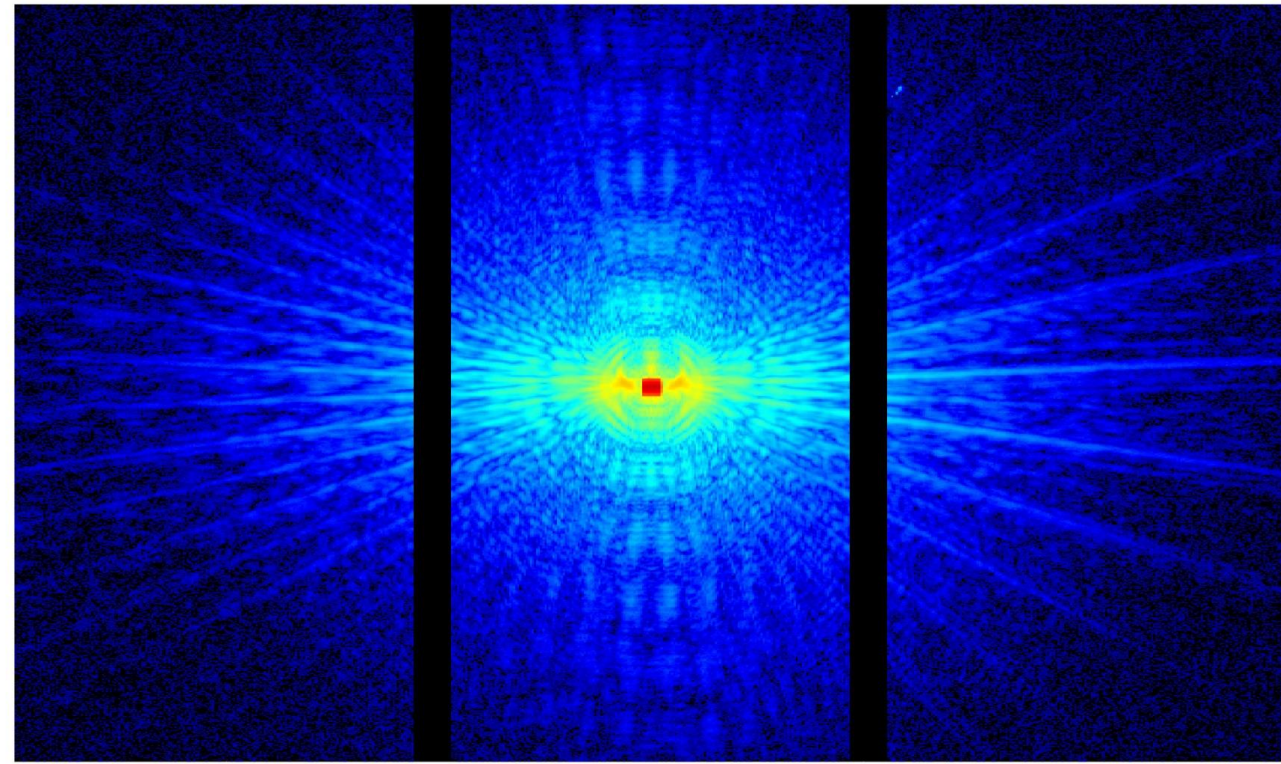
Virtual Source Size: $30 \mu\text{m} \times 150 \mu\text{m}$

Source Intensity: 2.6×10^{10} photons/s

Exposure Time: 1 second

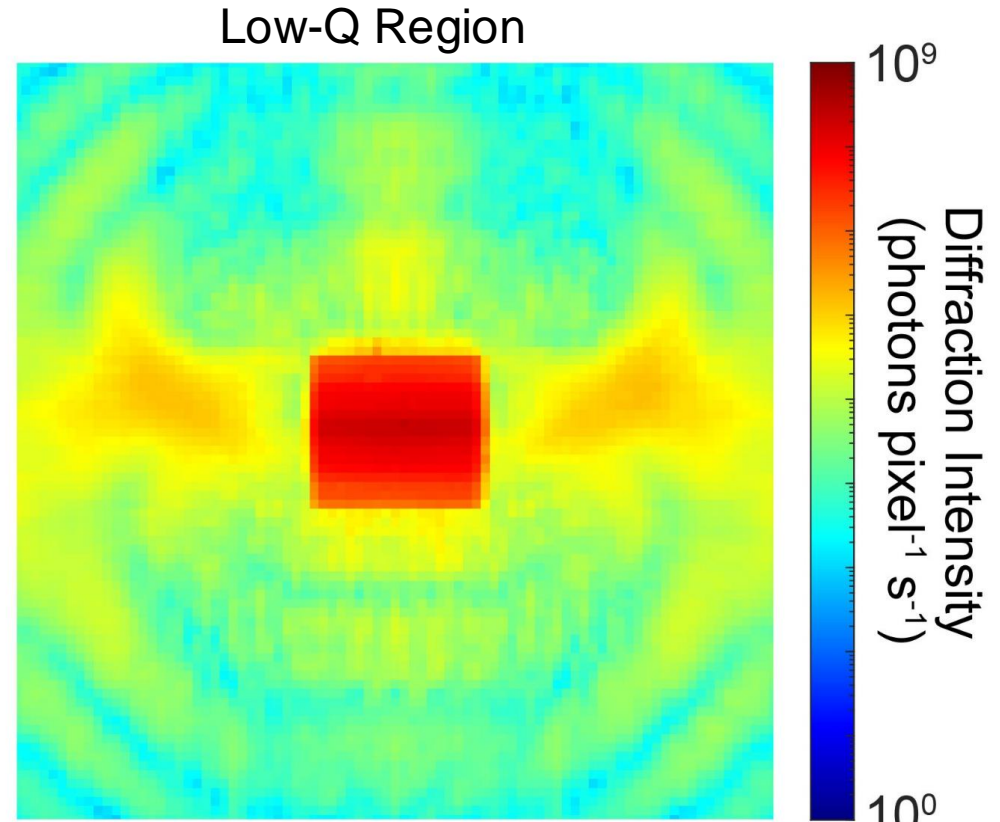
Max. Intensity: 250 Mphotons/s/pixel

Y. Takahashi et.al., J. Synchrotron Rad. Vol. 30(5) (2023) 989.



$50 \mu\text{m}^{-1}$

without attenuators



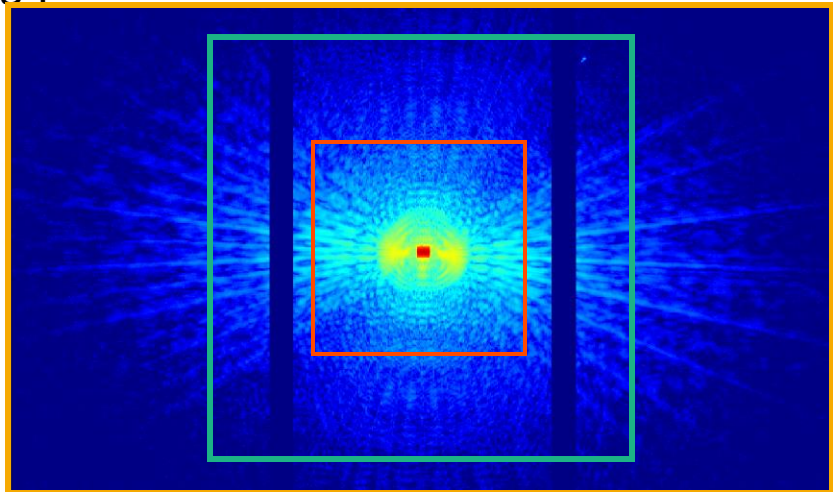
$2 \mu\text{m}^{-1}$

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

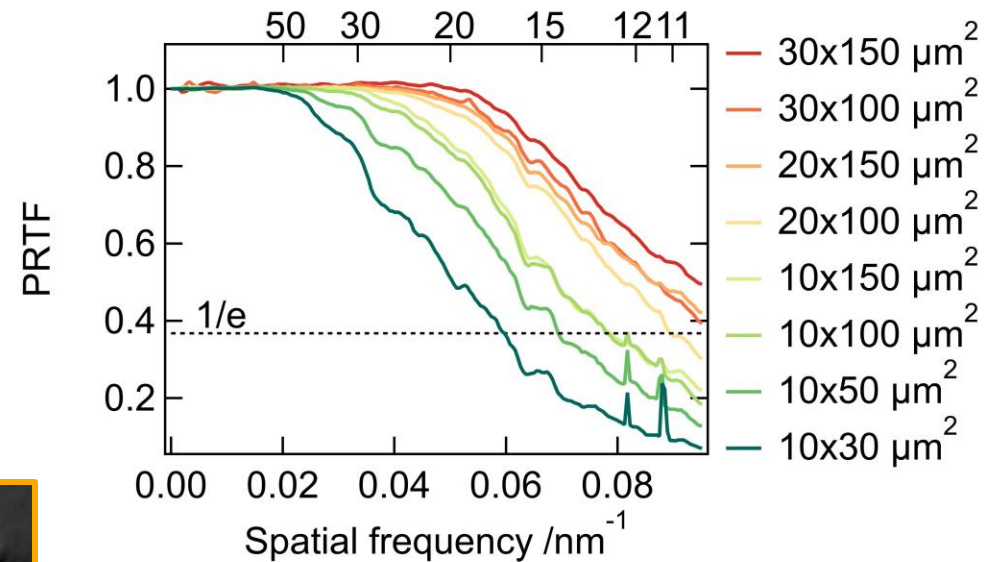
Exposure Time: 1 s/scanning point
Num. of Scanning points: 17 x 17

Y. Takahashi et.al., J. Synchrotron Rad. Vol. 30(5) (2023) 989.

Resolution Evaluation by phase retrieval transfer function



Full-period spatial resolution /nm



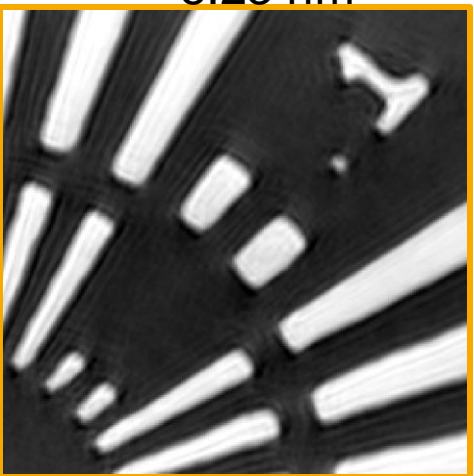
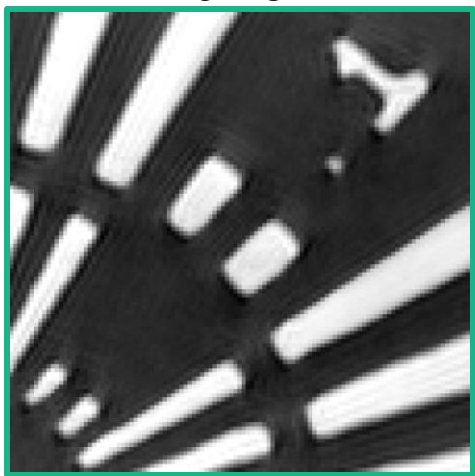
Pixel Size:

20.94 nm

10.46 nm

5.23 nm

Phase (rad)



Nov. 13rd 2023

50 nm feature Resolved

500 nm

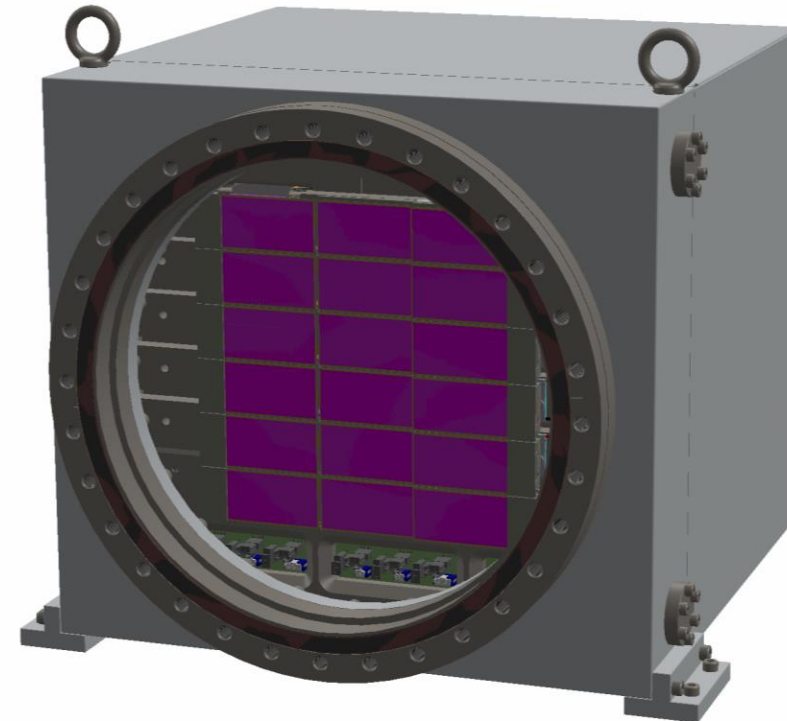
Full-period spatial resolution of about 10 nm demonstrated

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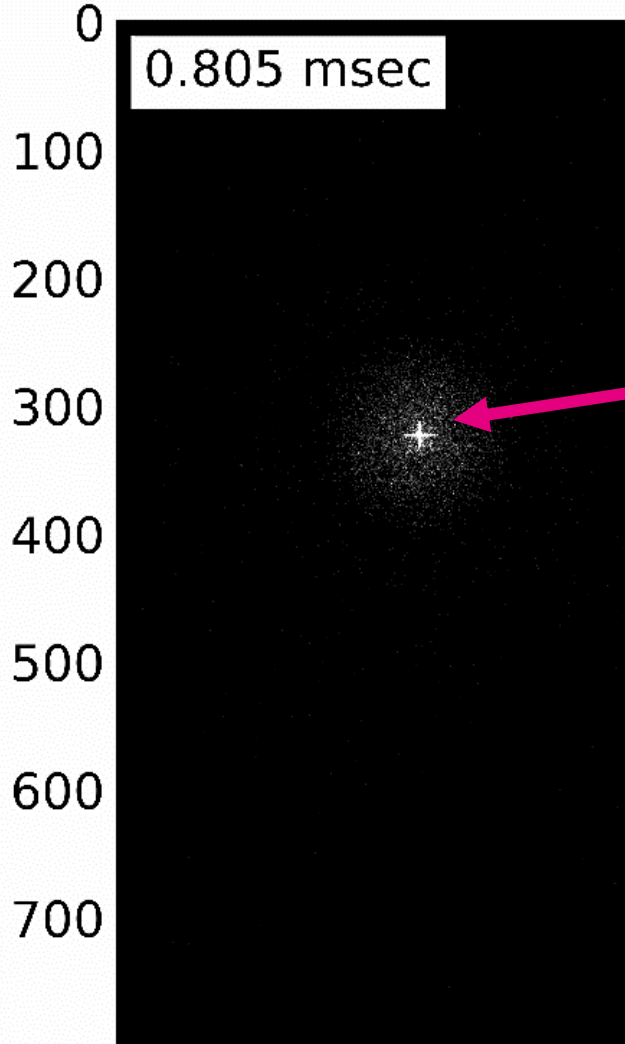
Camera Head (draft)



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BL29XU EH3 in July 2021

XPCS @ 17.4 kfps



CITIUS

Pixel Number: 280 kpixels
Frame rate: 17.4 kframes/s
Frame Cycle: 57.5 μ s
Duty ratio: 94 %

40 Mphotons/s/pixel at 8 keV.

Sample:

Silica (100 nm ϕ , 28.8 wt%)
in MEK + PEI + MeOH (66.8, 3.9, 0.5 wt%)
in 0.5mm capillary

Slit:

Size: 20 μ m \square ,
Position: 1 m upstream of the sample

Incident X-ray beam:

Photon energy: 8 keV,
Photon flux: 2E9 photons/s

Geometry:

Camera length: 3.2 m

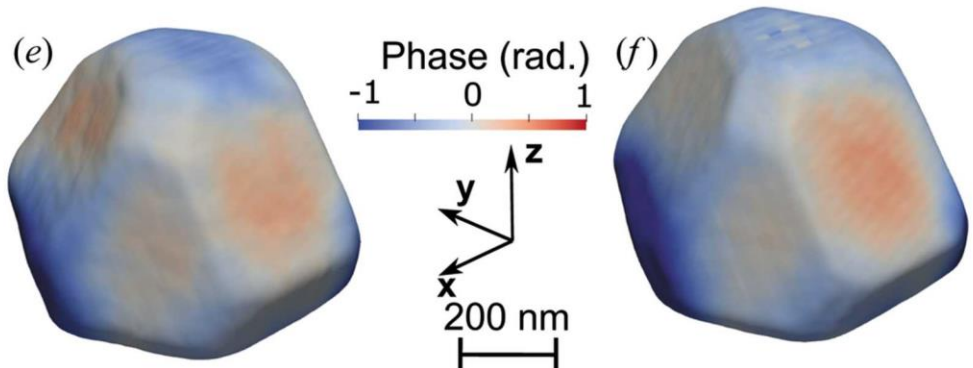
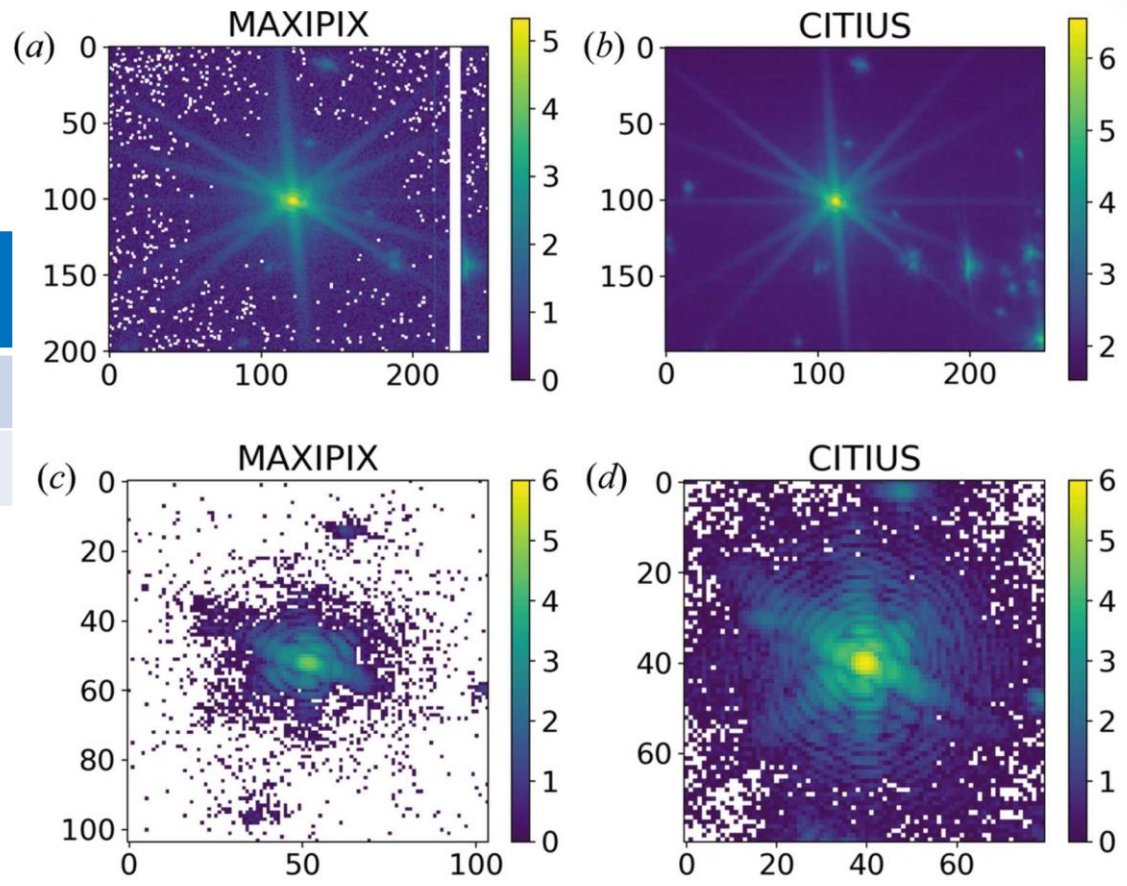
Image Processing:

Dark image subtracted

CITIUS 280k Bragg CDI at ESRF-EBS

	Count rate	Resolution	Acquisition Time
CITIUS	30 Mcps/pixel	20 ± 6 nm	23 s
MAXIPIX	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.

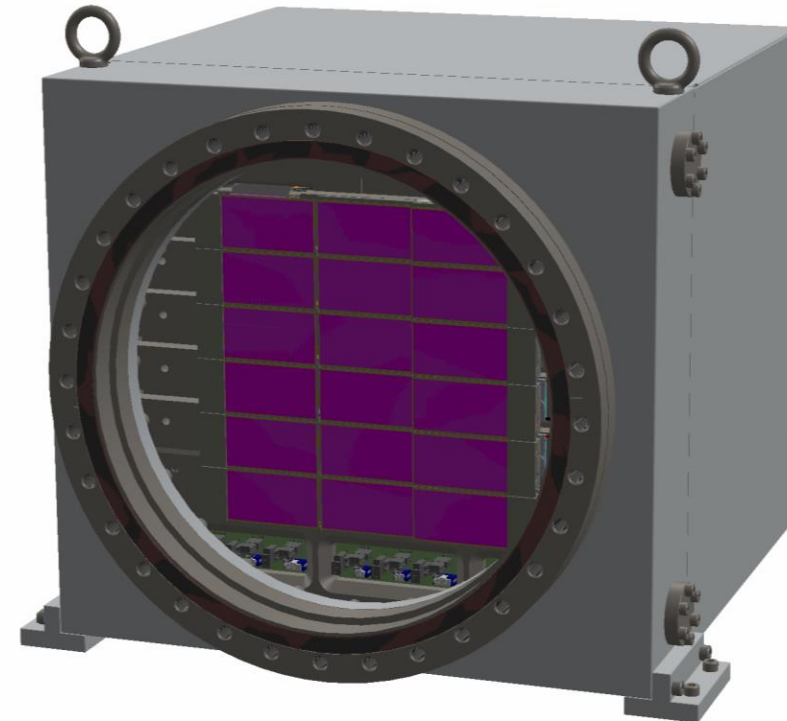


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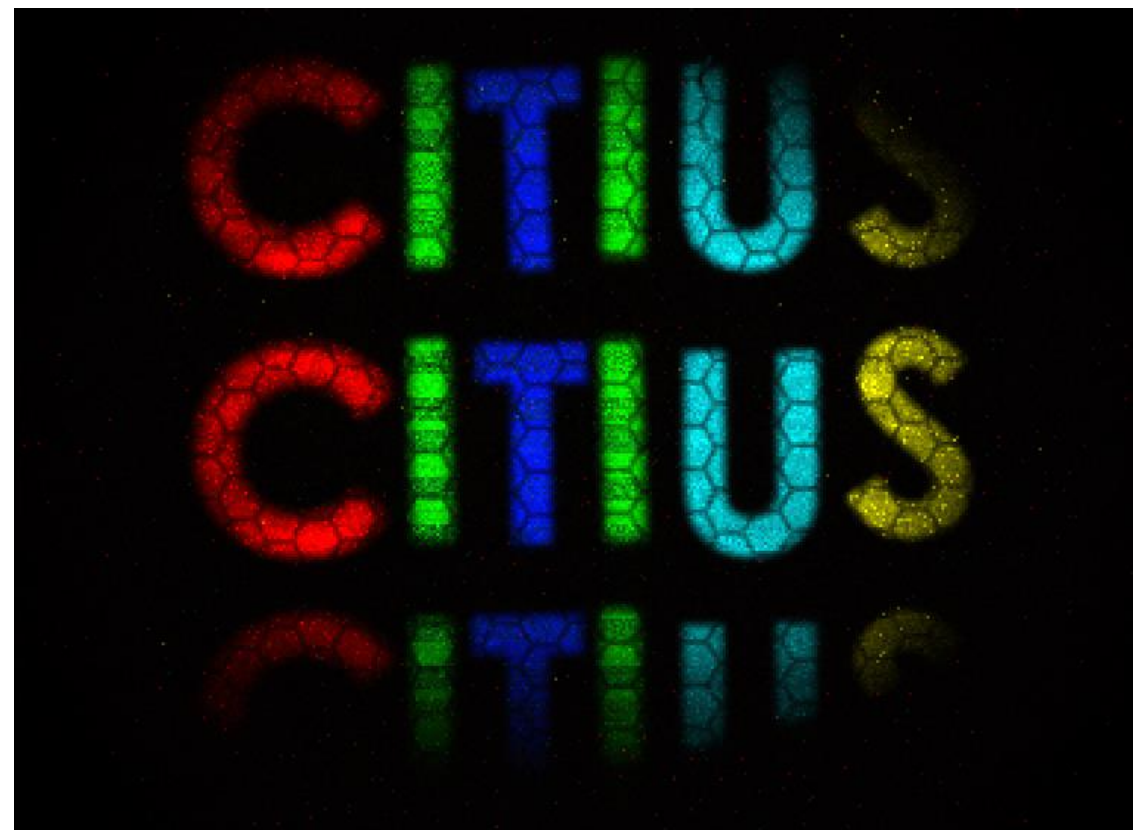
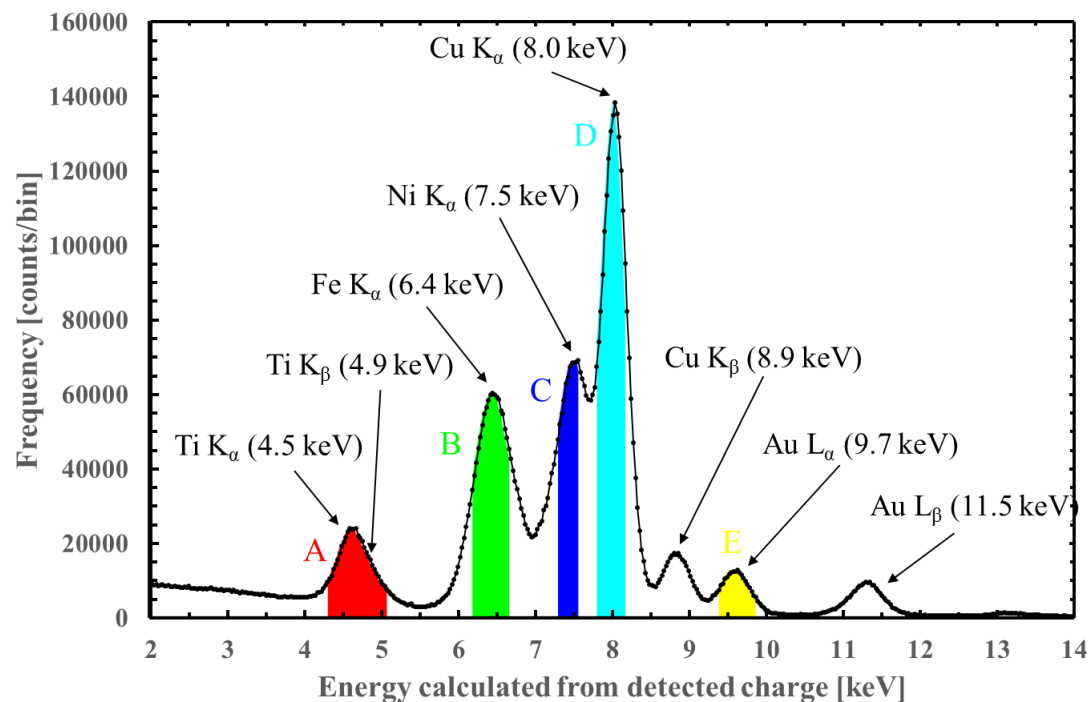


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Noise

→ Spectro-imaging

Ti. Fe. Ni. Fe. Cu.



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

X-ray Beam Monitor for SPring-8-II

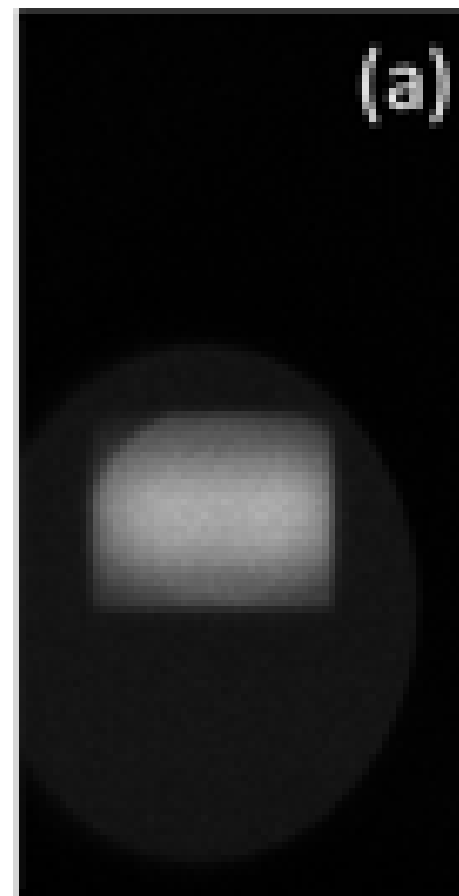
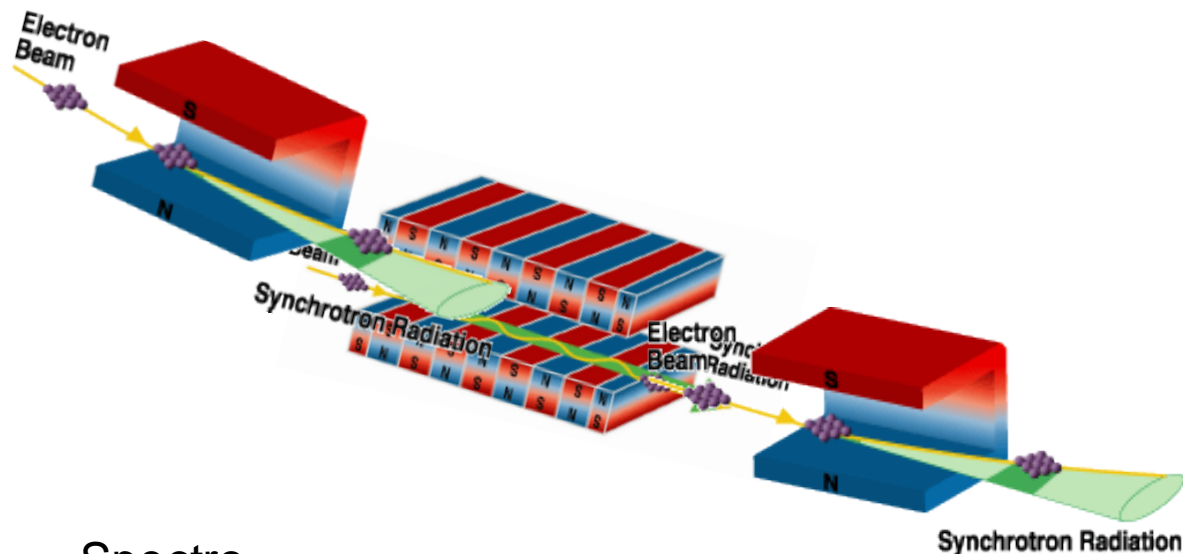
Accelerator feedback with electron monitors

- not enough

X-ray beam position monitor is required.

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

X-ray Intensity Image

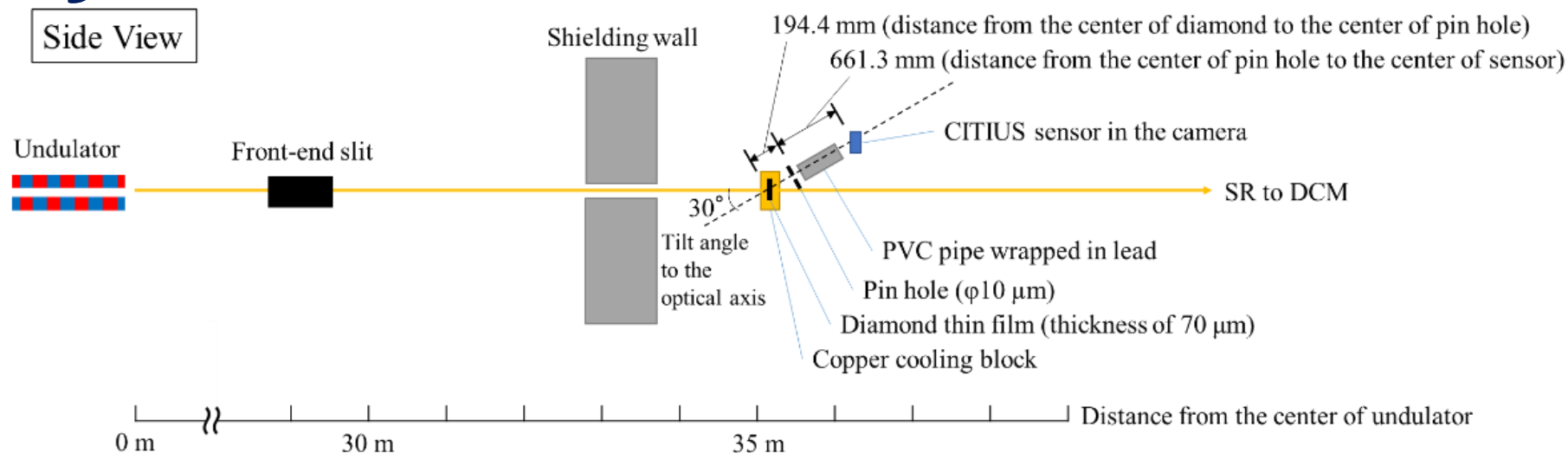


Undulator beam is hidden by the bending X-rays

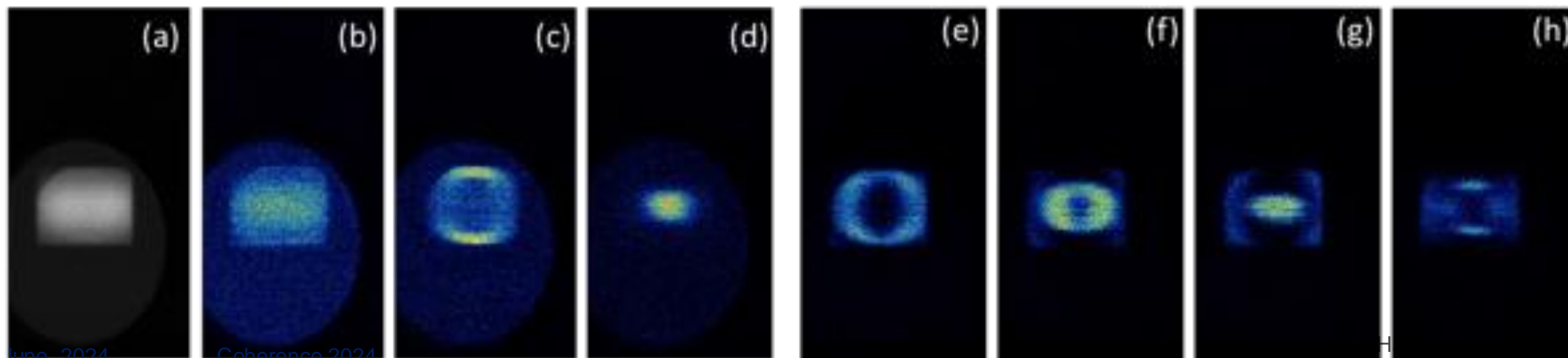
Spectro

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.,

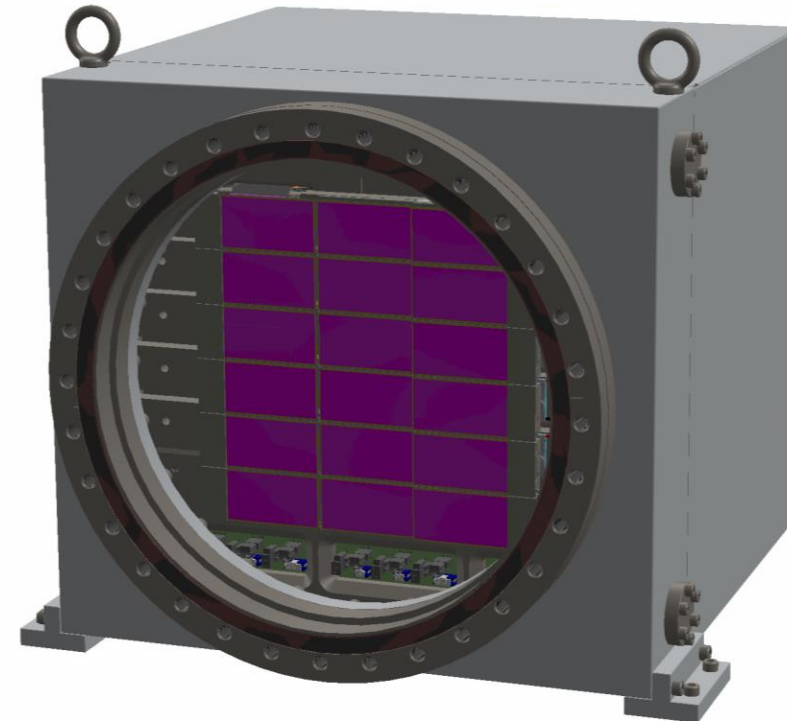


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Camera Head (draft)



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CITIUS 20.2M for SACLA

SALCA: XFEL facility with 60 Hz

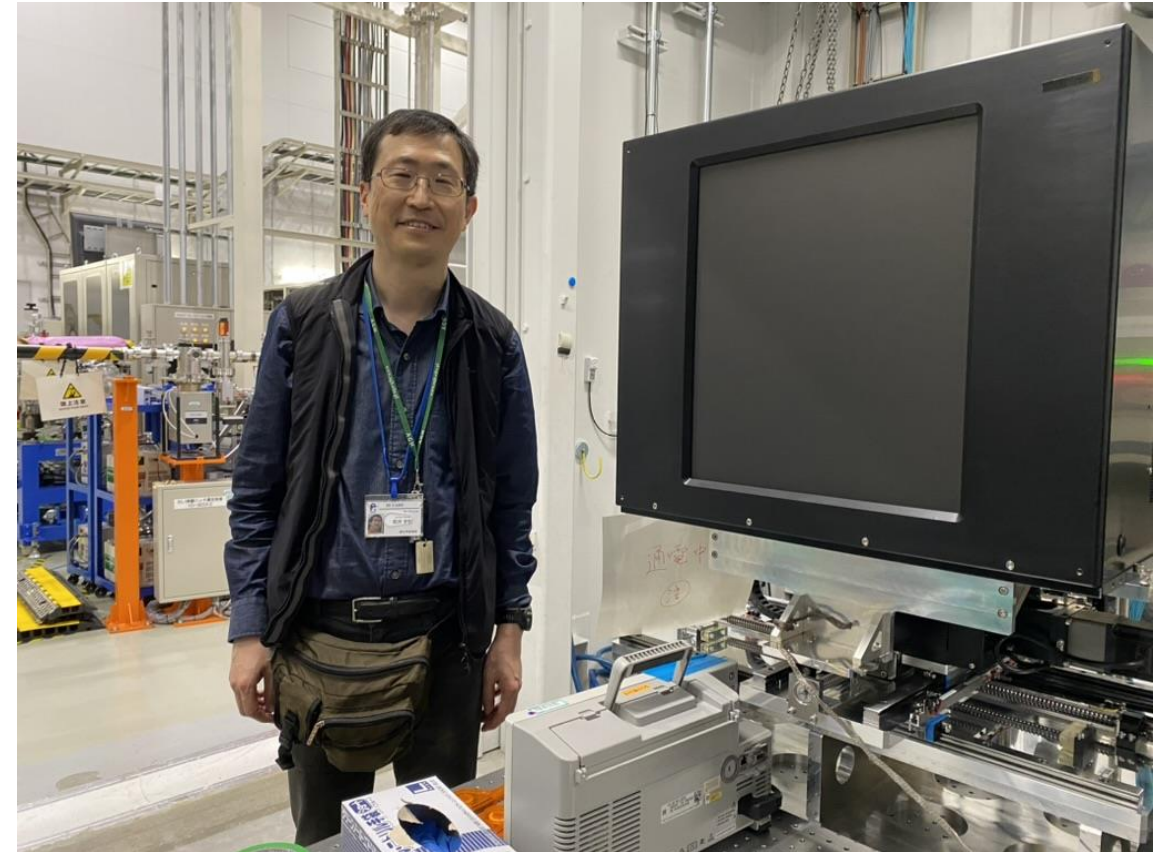
Major Specifications

Frame rate: 5 kHz

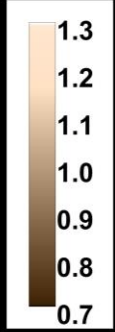
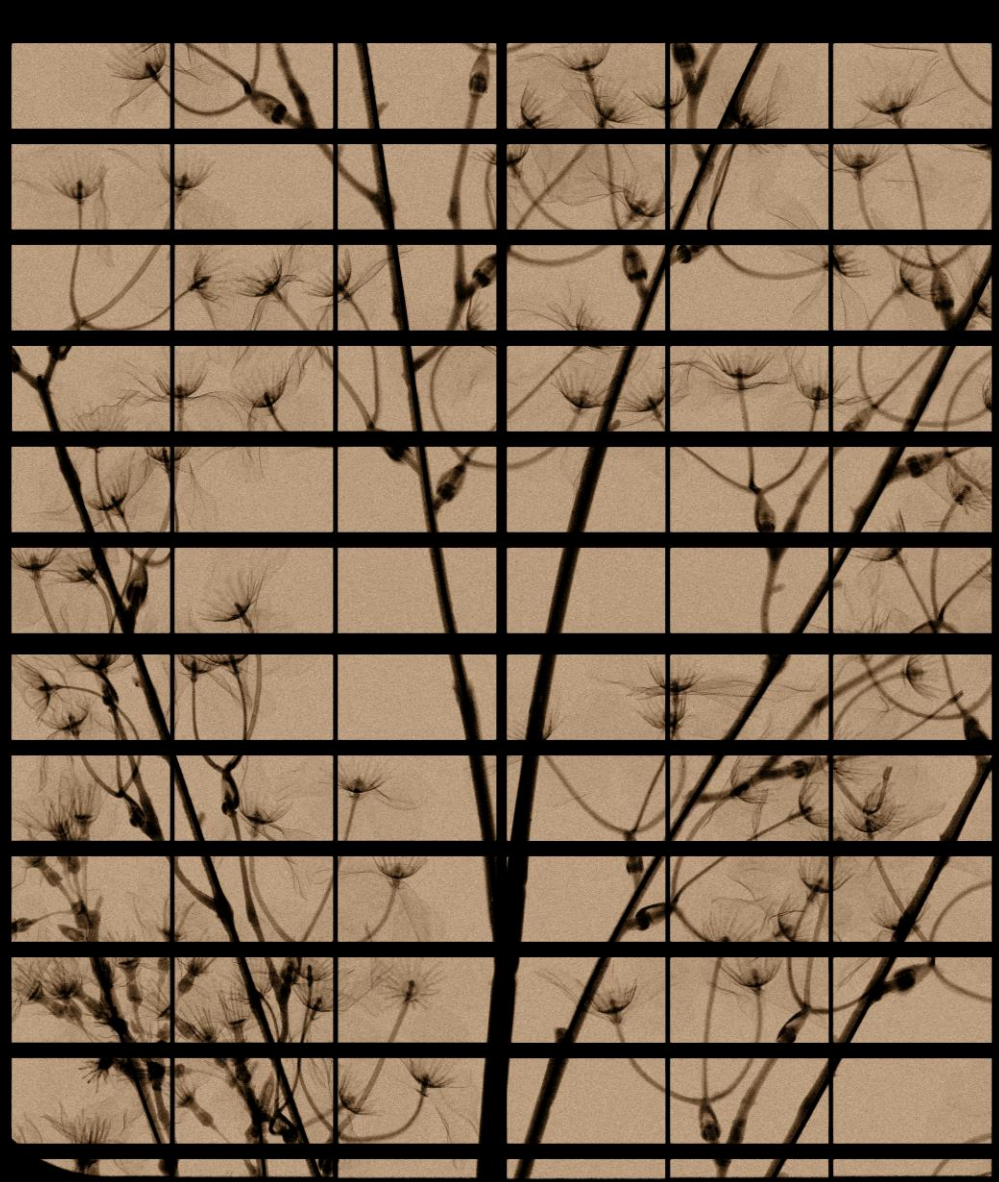
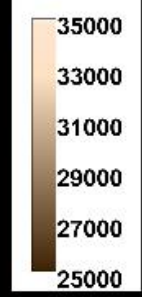
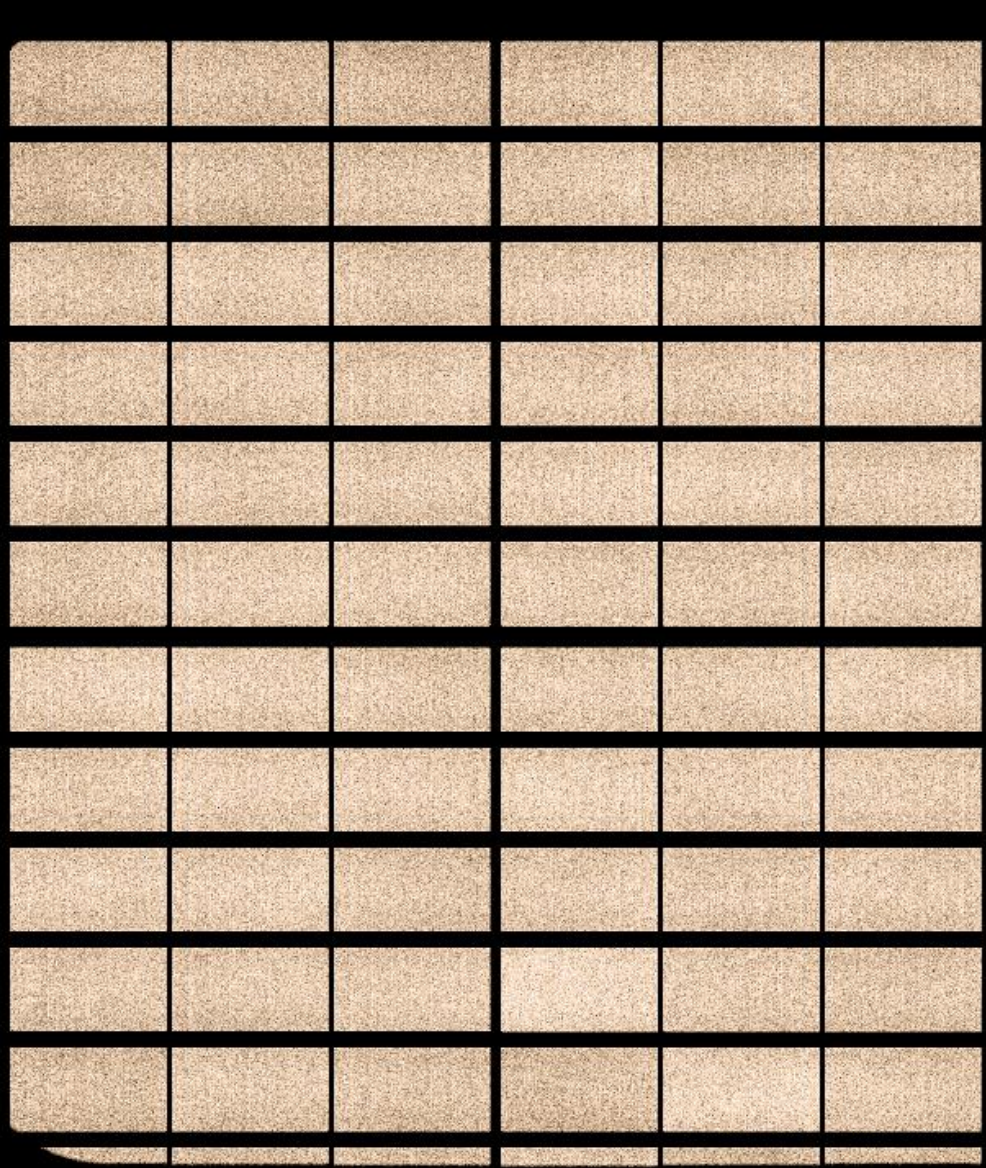
DAQ: 960 Hz in the 16-sampling mode
(1 pulse image is taken by 16 images)

DAQ bandwidth: 620 Gbps @ 32 bit/pixel

First Beam Test: July 2024



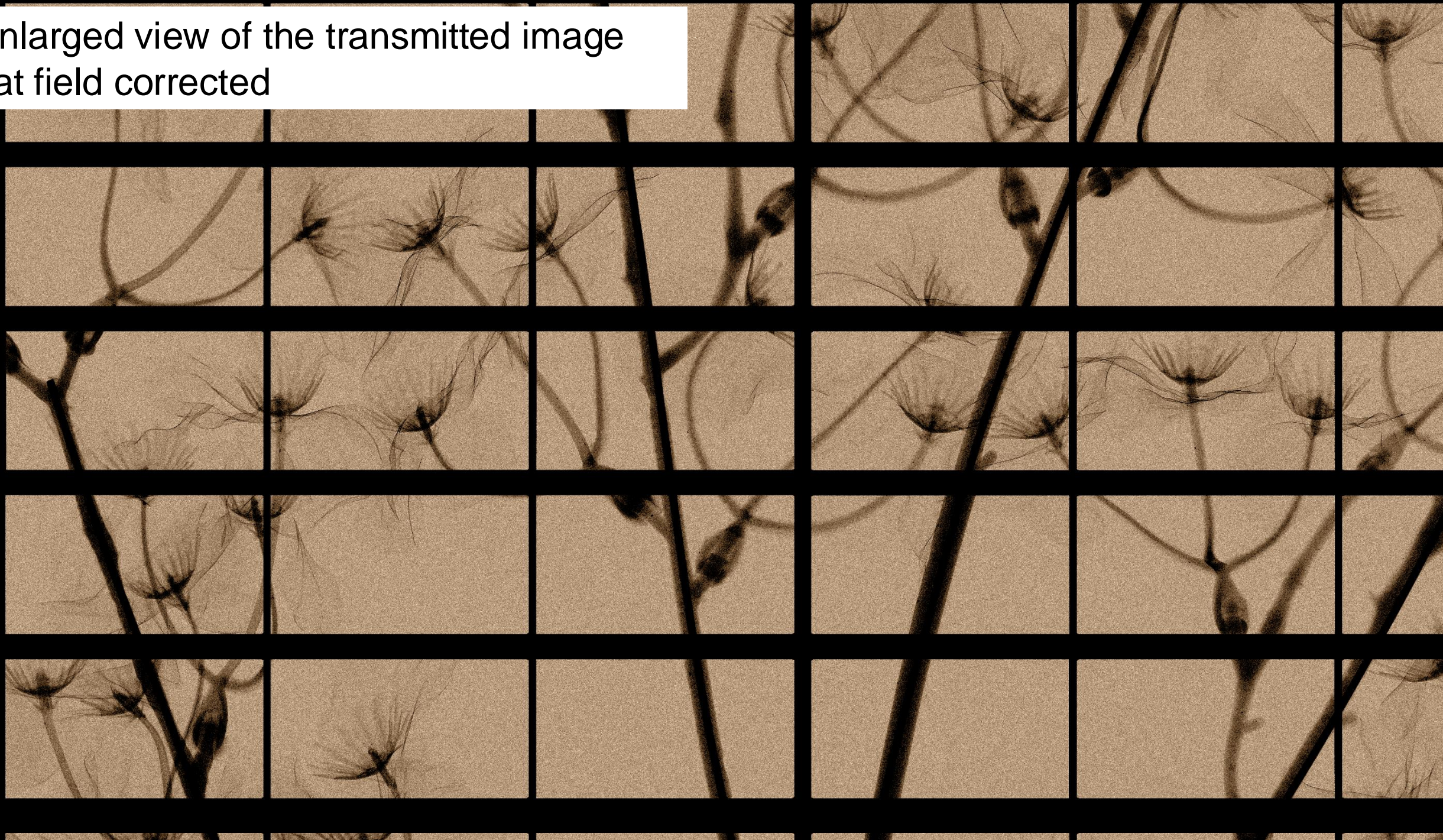
Mo 40 kV, 500 μ A, total exposure time 338 ms (6400 frames)



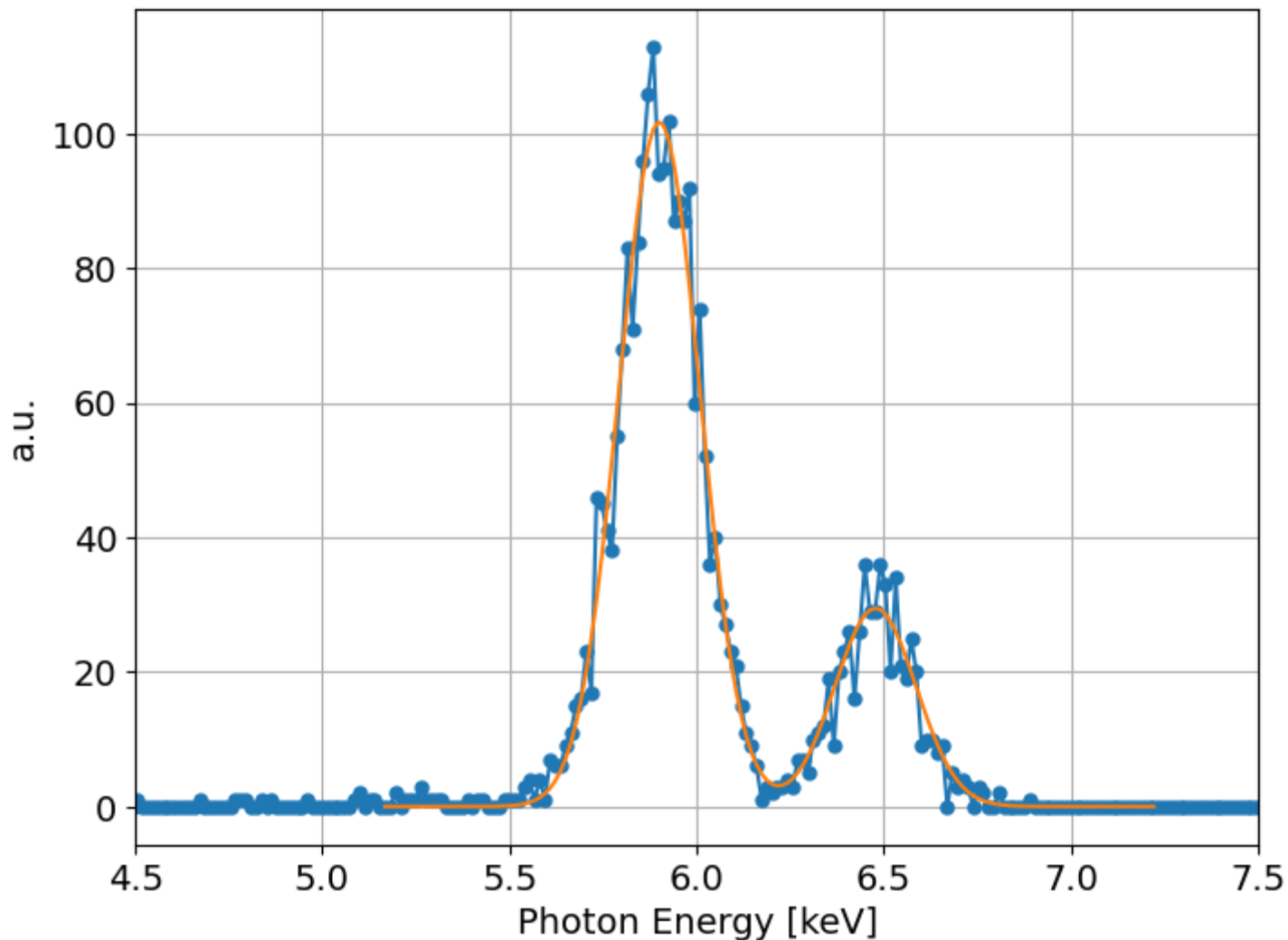
flat field image
dark subtracted

transmitted image
flat field corrected

Enlarged view of the transmitted image
flat field corrected



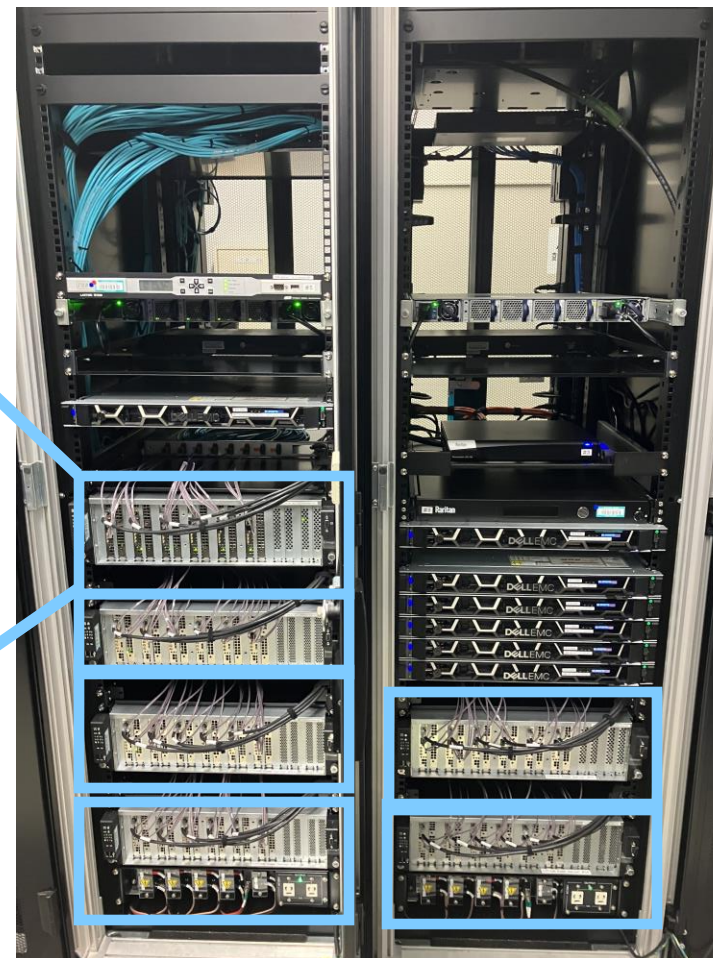
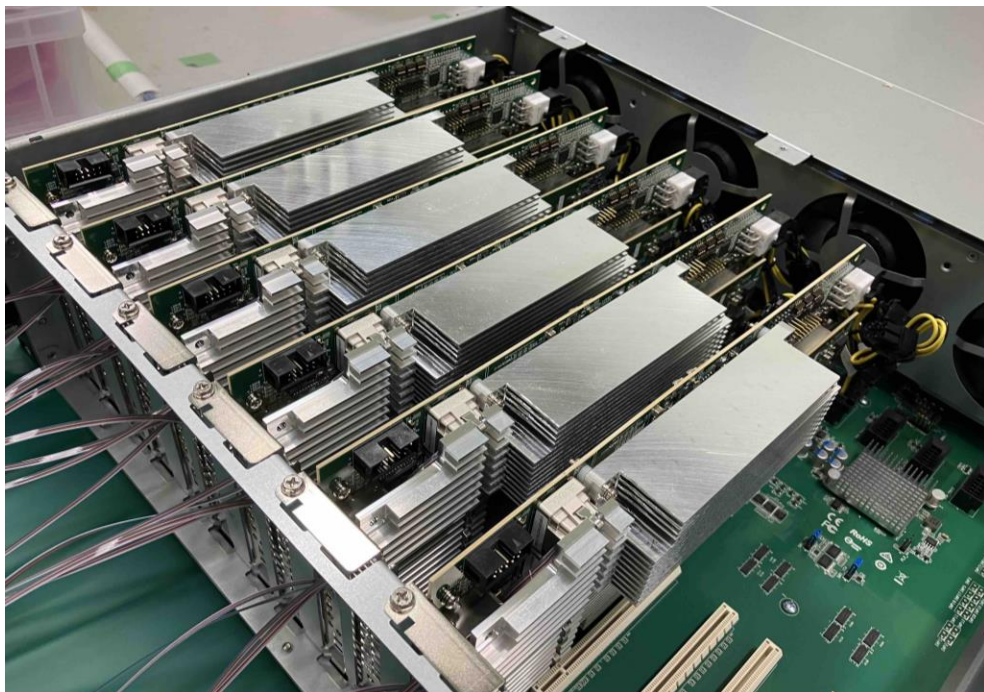
Noise and Energy Resolution



25 e-rms
~250 eV FWHM

Edge Computing for CITIUS 20.2M

FPGA-based Edge Computing



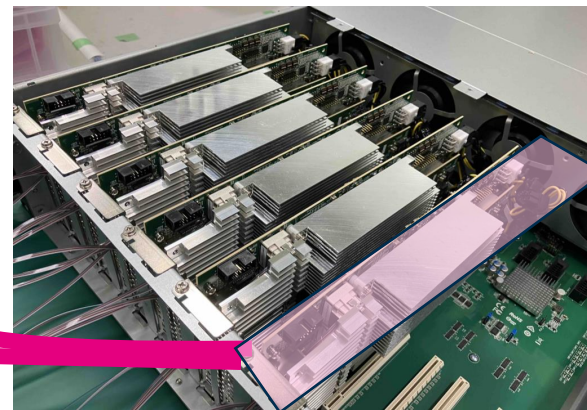
DAQ bandwidth: 620 Gbps
On-the-fly calibration and compression
developed with R-CCS Fugaku team
cf) Fugaku: a supercomputer with 488 PFLOPS

x4.5 will give 2.8 Tbps computation

Edge Server Configurations

CITIUS 20.2M
for SACLA

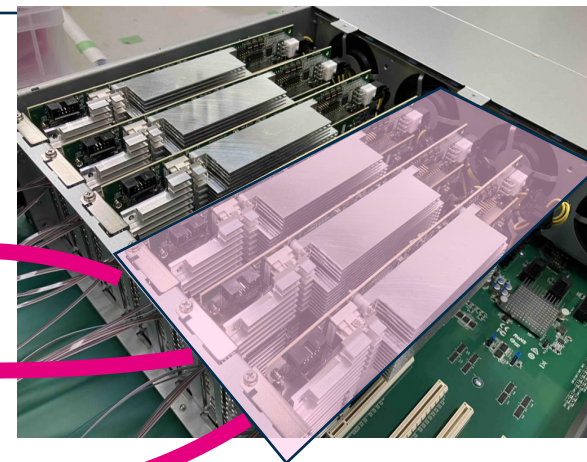
2 Sensor per 1 FPGA card



x6 computation resource

CITIUS 5.04M
for ptychography

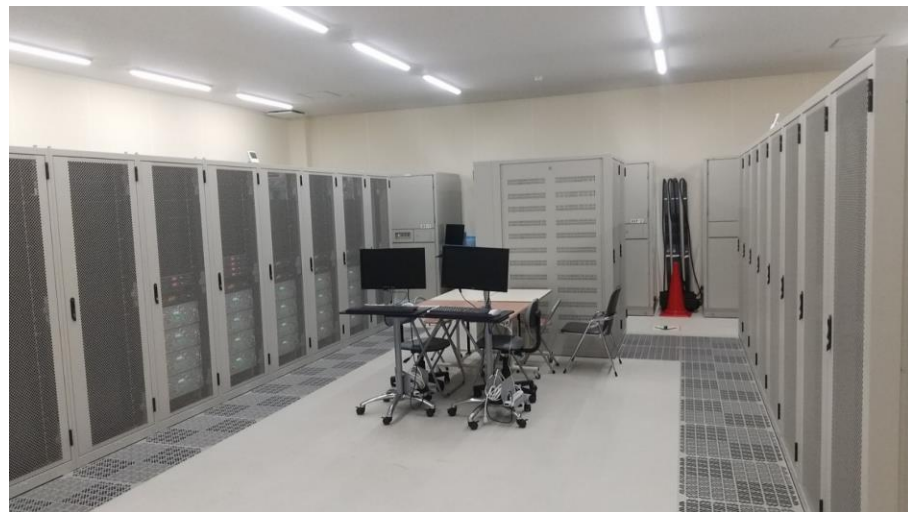
*1 Sensor per 3 FPGA cards
already validated for CITIUS 840k [1-3]*



- [1] Makina Saito et.al., Phys. Rev. Lett. **132**, 256901 (2024)
- [2] H. Nishino, Nucl. Inst. and Meth., A, Vol. 1057, (2023) article id. 168710.
- [3] Y. Takahashi, J. Synchrotron Rad. Vol. 30(5) (2023) 989.

Computation for 5.04 Mpixel CITIUS

SACLA Data Center



Theoretical peak performance: 0.360 Pflops
5k CPU cores (intel CPUs)
Nvidia A100 x16
Out-bound: 100 Gigabit network
Storage capacity: 20PB
File system: Lustre (~30GB/sec)

x2000

Fugaku



Theoretical peak performance: 488 Pflops
Arm-based CPUs
Total memory capacity: 4.85 PiB
Interconnect: Tofu Interconnect D (28 Gbps x 2 lane x 10 port)

Collaboration with Argonne National Lab

Summary

CITIUS 5.04M for ptychography is under development

- major specifications

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Delivery	Dec. 2025

demonstrated

620 Gbps demonstrated for CITIUS 20.2M
x4.5 needed
x6 resource increase by configuration change

Acknowledgment

RIKEN and JASRI Team

- T. Kudo, T. Sugimoto, M. Yamaga, T. Kameshima, Y. Inagaki, K. Fujiwara, T. Nakagawa, Y. Oyaki, M. Kimoto, M. Nakamachi, M. Yabashi, T. Ishikawa

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.

SPARE SLIDES

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

