

The CITIUS detector

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

1 Gcps/pixel with 72.6 μ m pixels (18 Tcps/cm²)

Conceptual Design: 2013-2014

Development

Sensor: 2015-2020

Data-Processing FPGA card: 2015-2023

System: 2020-

This talk: Performance and associated applications.



Takaki Hatsui
RIKEN SPring-8 Center



CITIUS: Demonstrated Sensor Performance

Pixel Size	72.6 μm square
Frame rate	17.4 kHz
Saturation Count rate	945 Mcps/pixel @ 10 keV 18 Tcps/cm ²
Sensor	Silicon (650 μm thick)
Vacuum	compliant
Intra-module gap	None
Tiling	4 side
Noise	<40 e-rms 0.018 phs rms @8 keV

Sensor



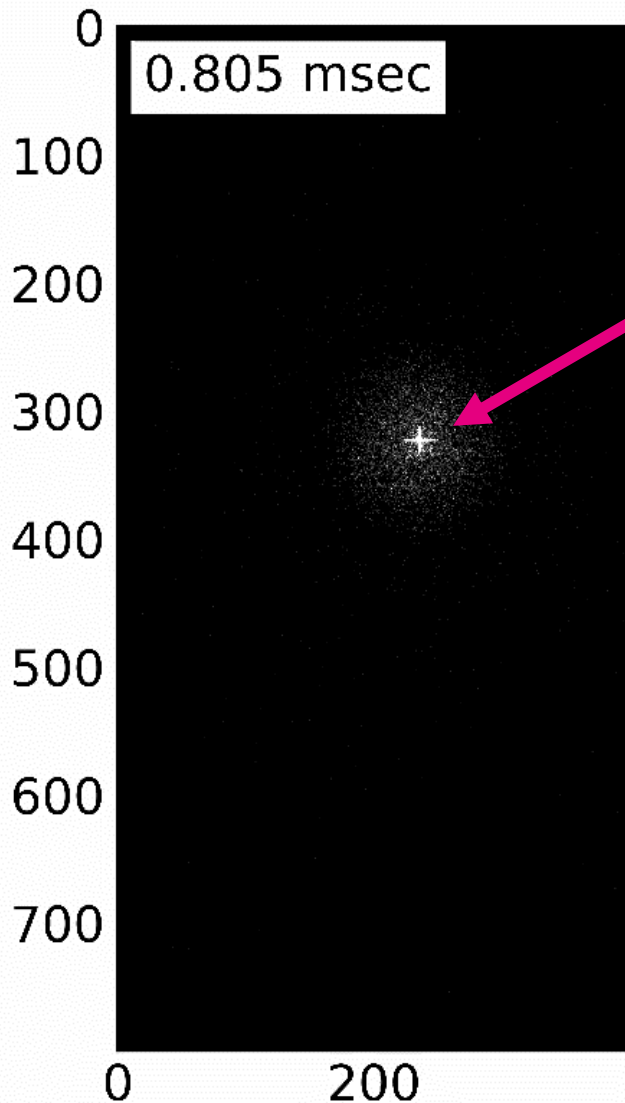
On-chip ADCs (one ADC/8 pixels)
Digital Output

- 140 Gbps/sensor (physical)
- 156 Gbps/sensor (information)
- bit depth 32 bit (information)
- 1.7 PB/day

XPCS @ 17.4 kfps

BL29XU EH3 in July 2021

Y. Honjo, K. Ozaki, H. Nishino
T. Hoshino (Tohoku Univ.)



40 Mcps/pixel at 8 keV.

Frame Rate: 117.5 kHz with 35 kpixels @1/8 ROI
Double Burst Mode: 10 MHz

CITIUS

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

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

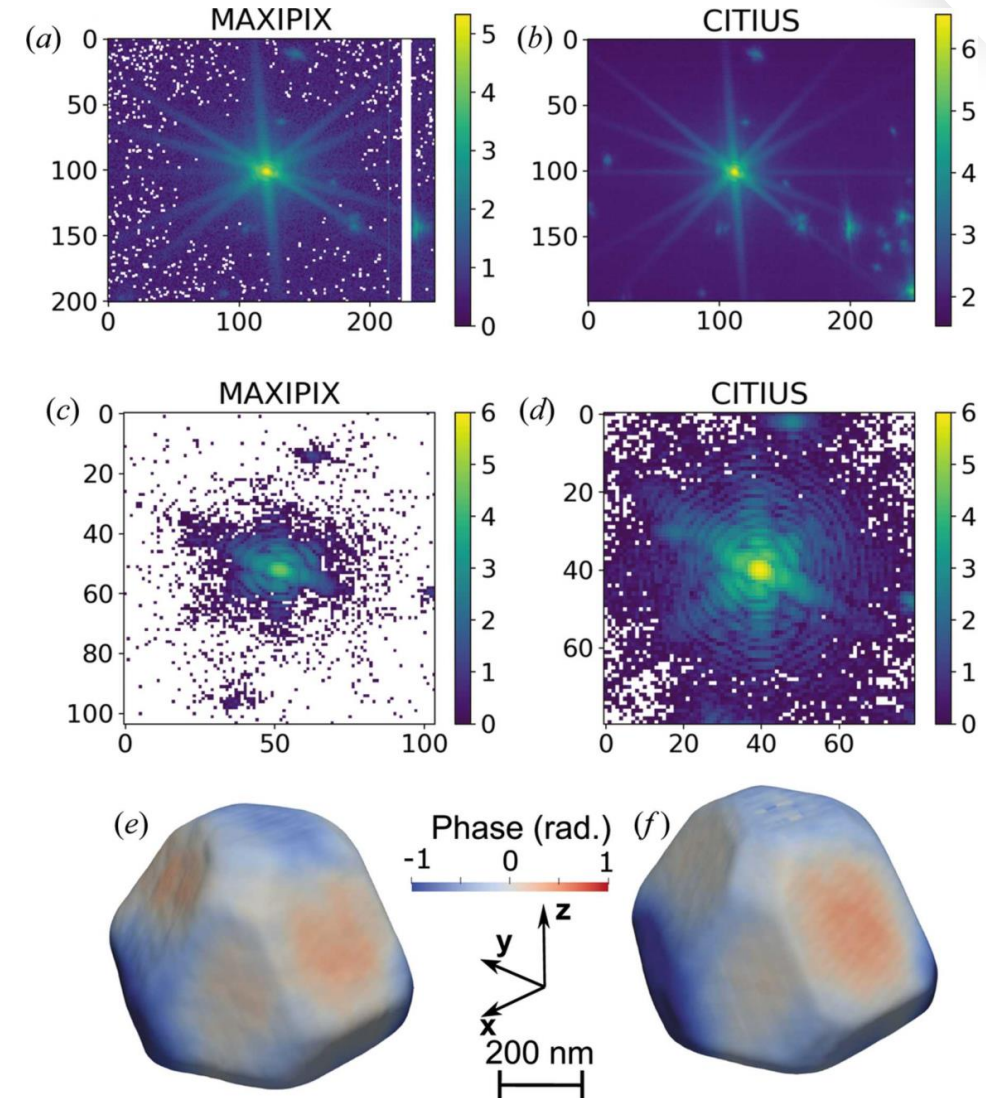
Image Processing:

Dark image subtracted

Bragg CDI at ESRF-EBS

	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 data quality to MARPIX with 1 s exposure.



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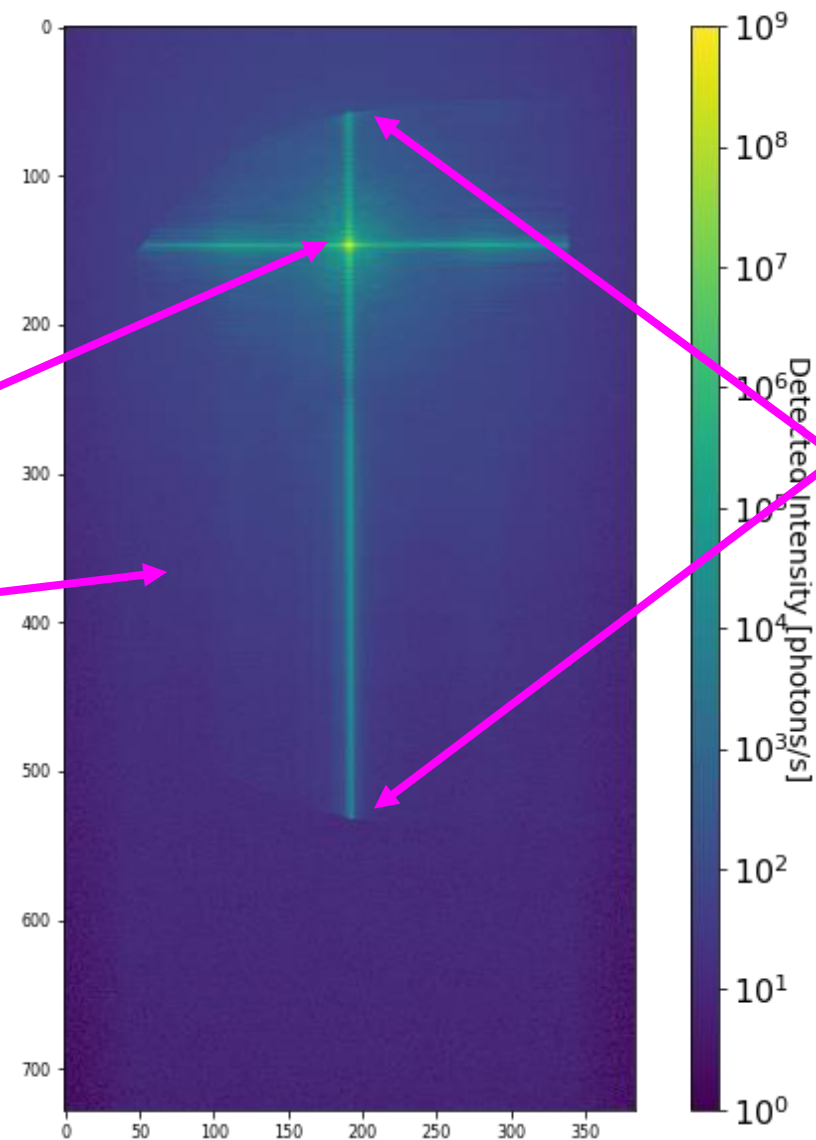
Count Rate (1/2)

Photon Energy: 10keV
Slit to CITIUS: 15m
Slit Size: $20 \times 20 \mu\text{m}$

The most intense pixel : 590
Mcps

Single
photon

Edge of the
vacuum pipe



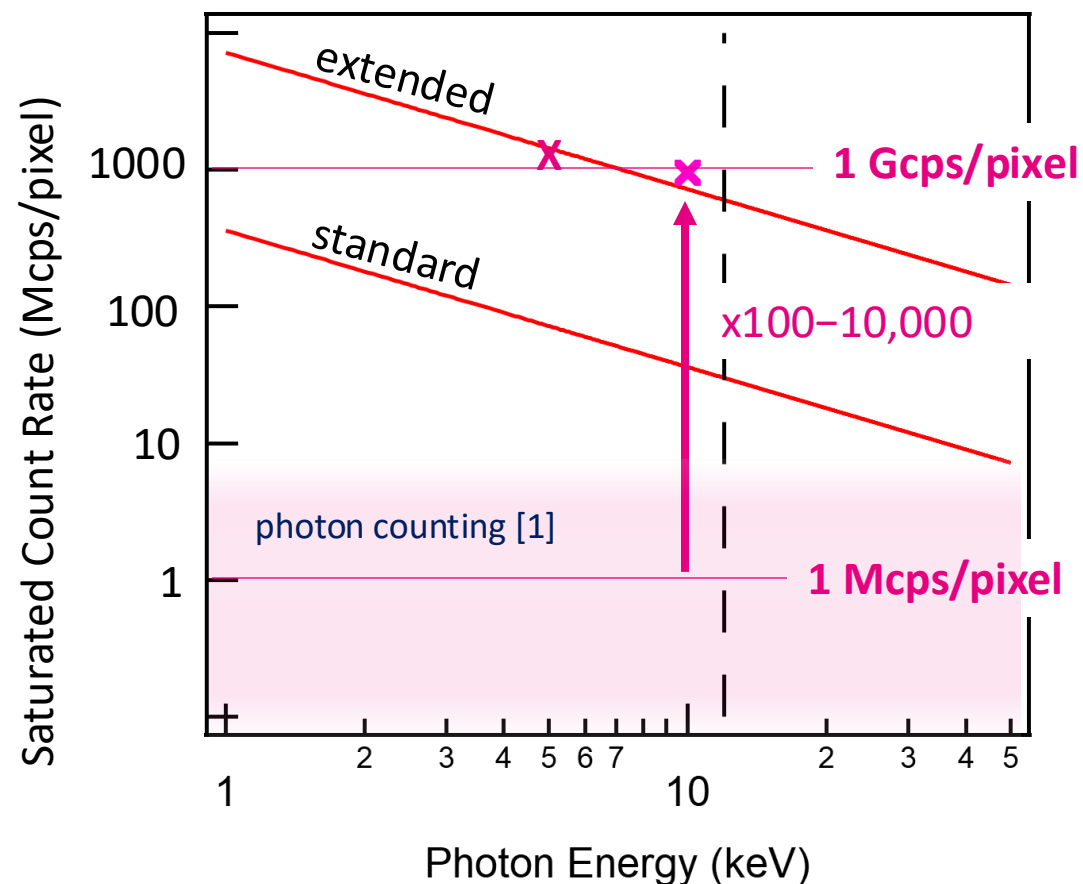
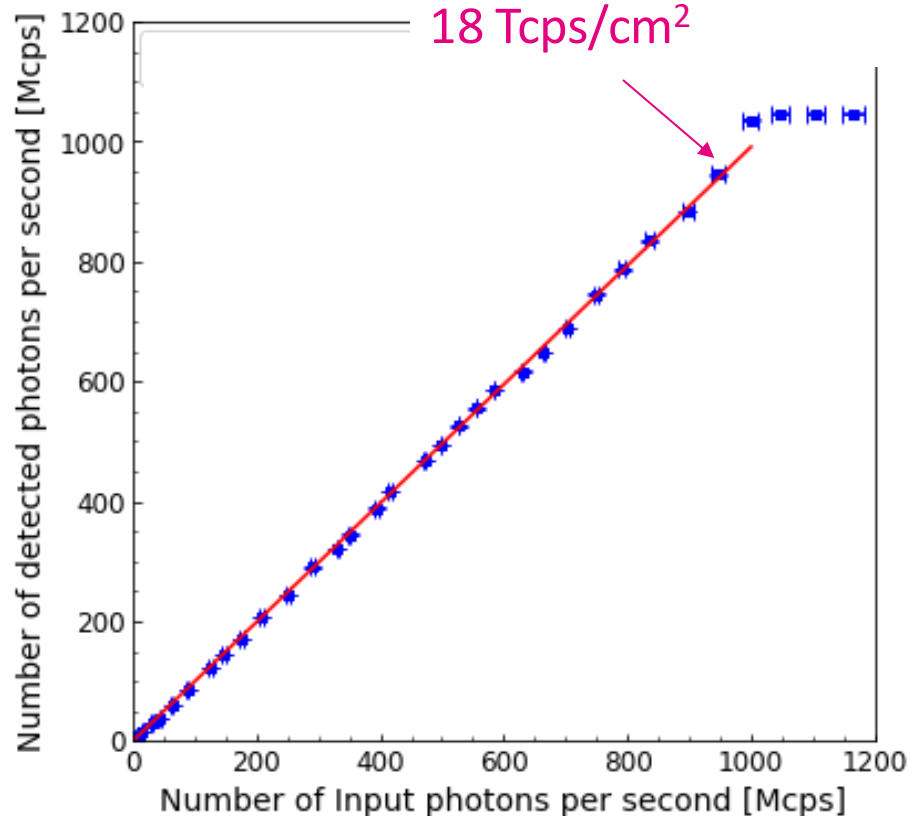
Count Rate (2/2)

Experimental Data

- 945 Mcps/pixel @ 10 keV
- 1.23 Gcps/pixel @ 5 keV

Photon Energy = 10 keV

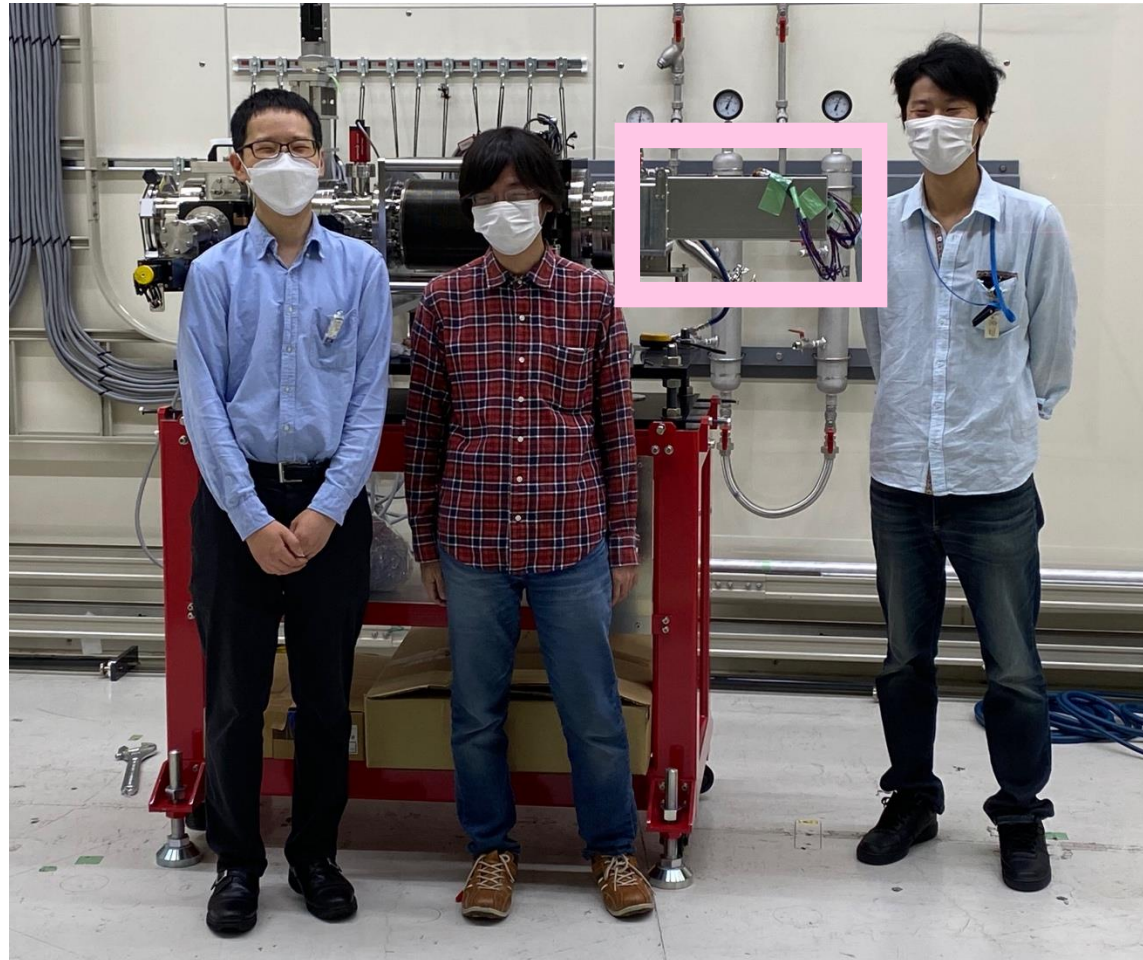
945 Mcps/pixel
18 Tcps/cm²



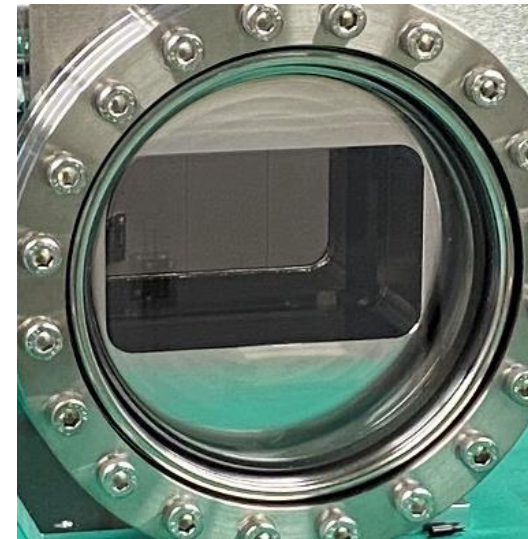
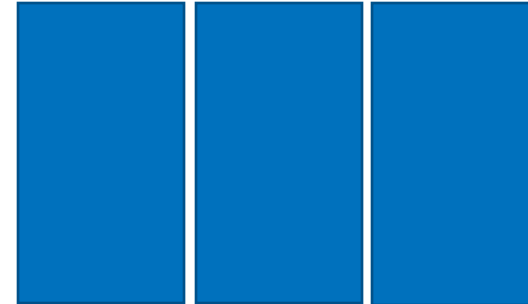
[1] Y. Imai and T. Hatsui, J. Synchrotron Rad. 31(2) (2024) 295.

Flange-mounted in-vacuum CITIUS feasibility study for ptychography

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



840k



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

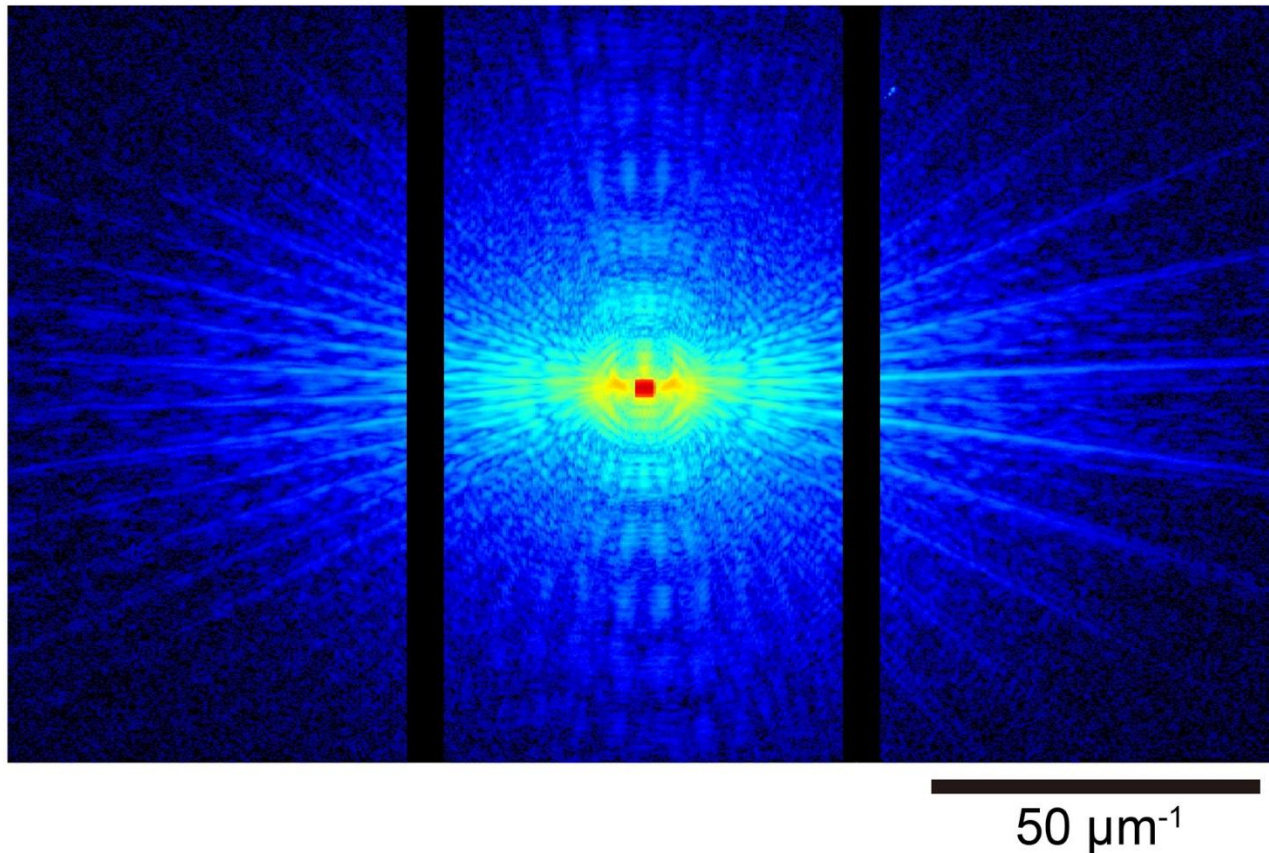
Virtual Source Size: $30 \mu\text{m} \times 150 \mu\text{m}$

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

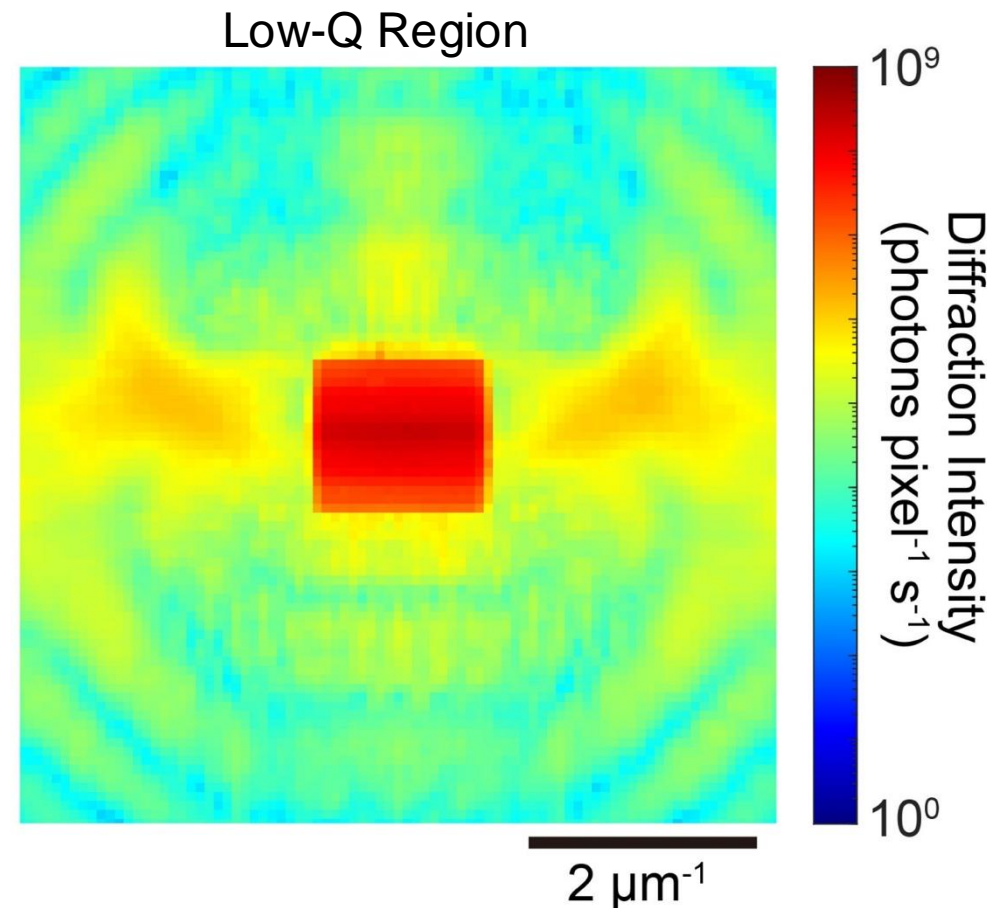
Source Intensity: 2.6×10^{10} photons/s

Exposure Time: 1 second

Max. Intensity at detector: 250 Mcps/pixel



without attenuators



Low-Q region imaged without attenuators
Higher Resolution & Phase sensitivity

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Sensor

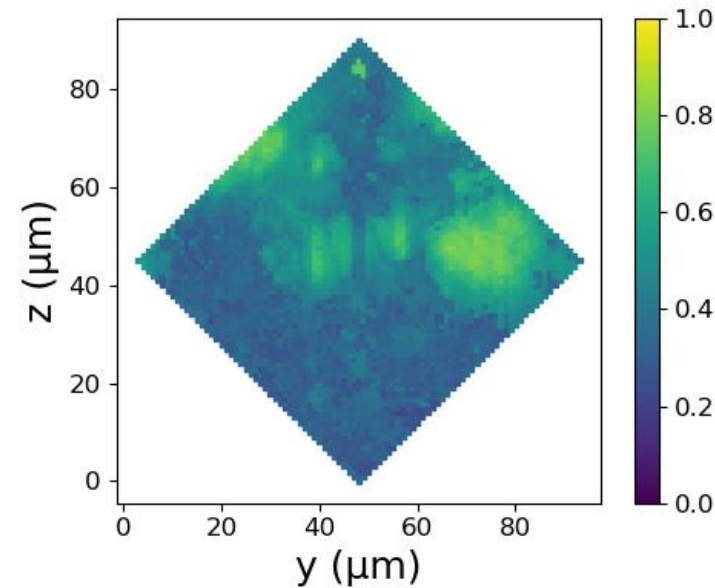
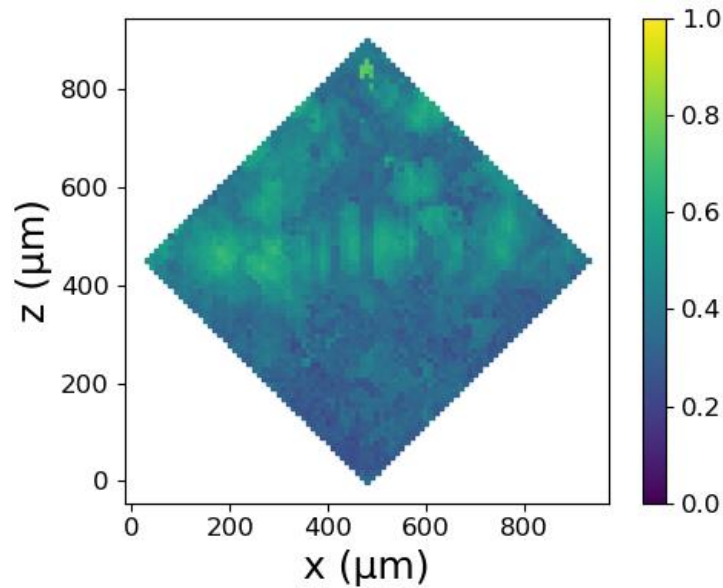
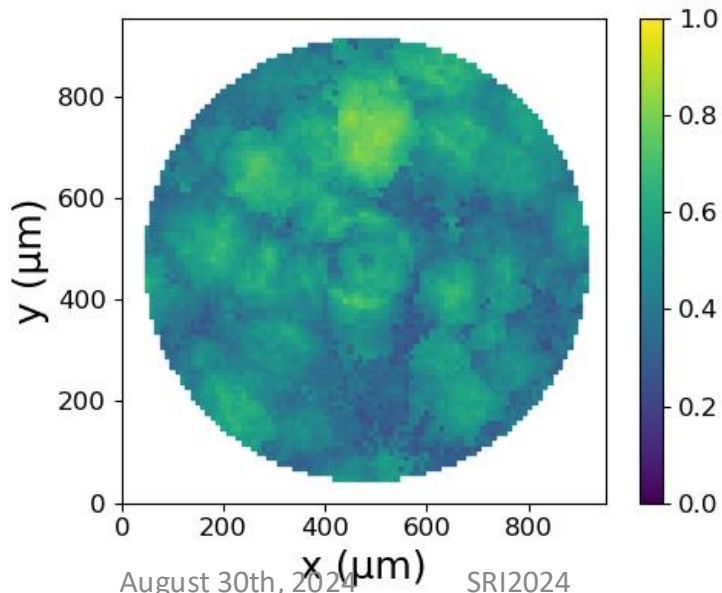
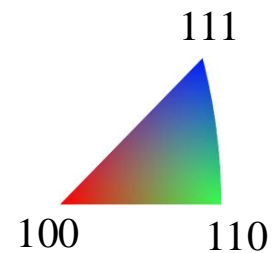
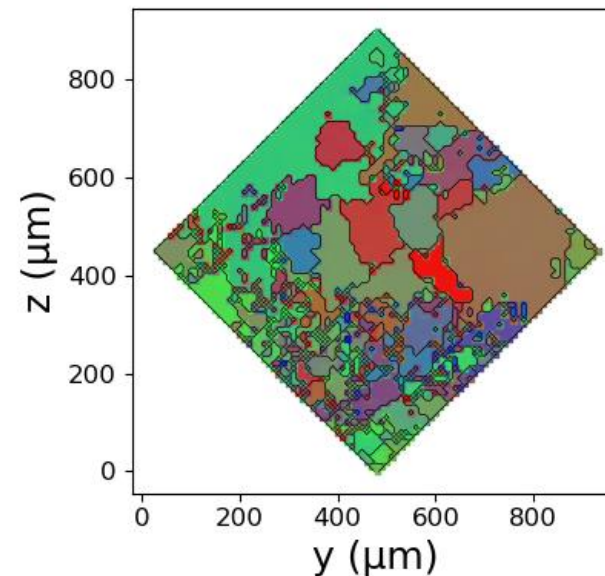
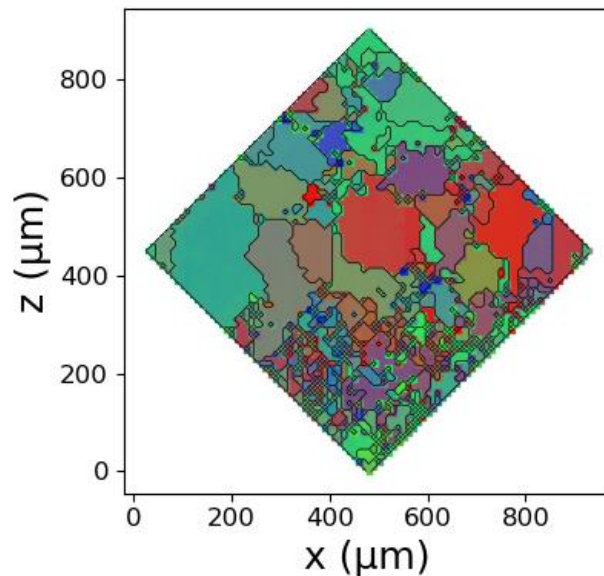
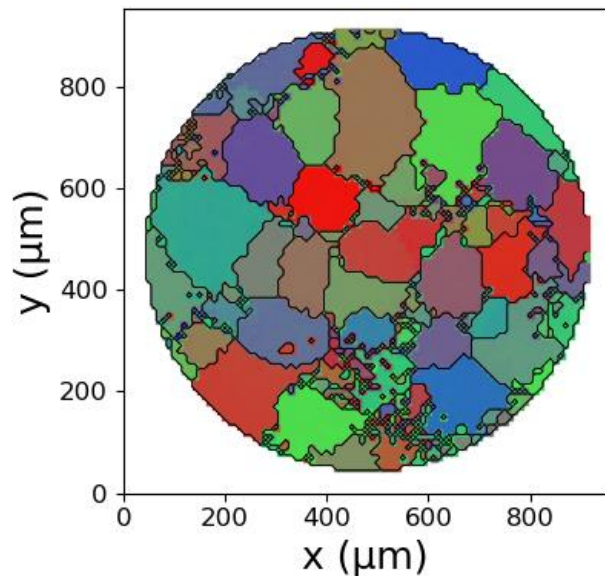


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3D XRD to visualize the metal grains

CITIUS at 37 keV



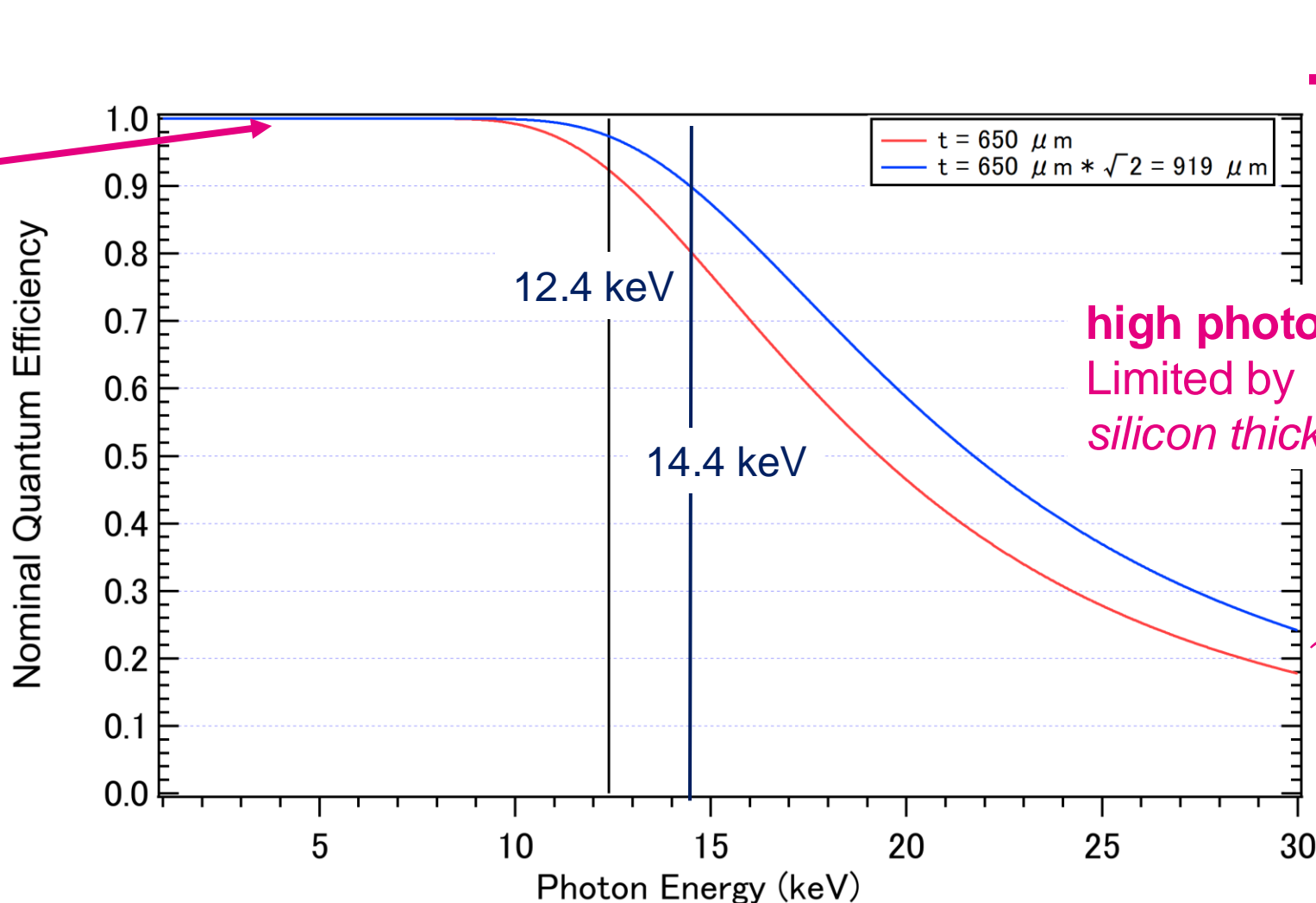
Sensitivity

No QE drop
No Al layer

Low photon energy
limited by noise
standard mode

- S/N > 7 @ 1 keV
- multi-sampling
- S/N > 7 @ 460 eV

to be confirmed



high photon energy
Limited by
silicon thickness of $650\mu\text{m}$

~20 % @ 30 keV

40 keV

Quasi-elastic scattering @ 14.4 keV

Demands

- high sensitivity @ 14.4 keV
 - 650 μm thick silicon
 - no corner QE loss
- high speed

CITIUS specifications

- 840k, 17.4 kframes/s
- 468 Gbps (58.5 GB/s, 5.1 PB/day)

On-the-fly edge compression

Data Quality Confirmation

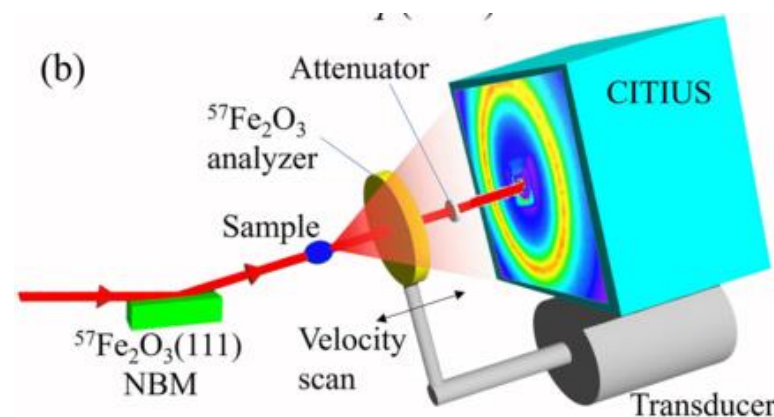
- SPRING-8 Data Center (360 TFLOPS)

Results

- 35 PB/beamtime
- compression ratio > 1000

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

Talk at Micro Symposium 12/3, Friday afternoon



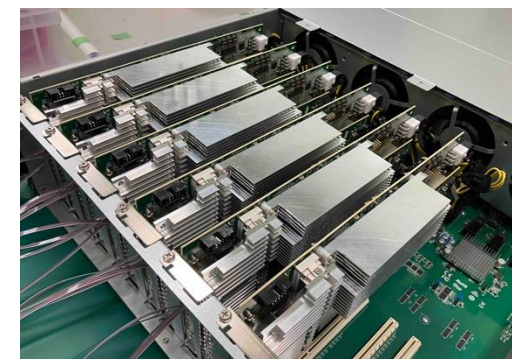
FPGA-accelerated edge computing

FPGA

- Summation of 2 frames to one
- calibration
- entropy reduction

CPU

- SZIP compression

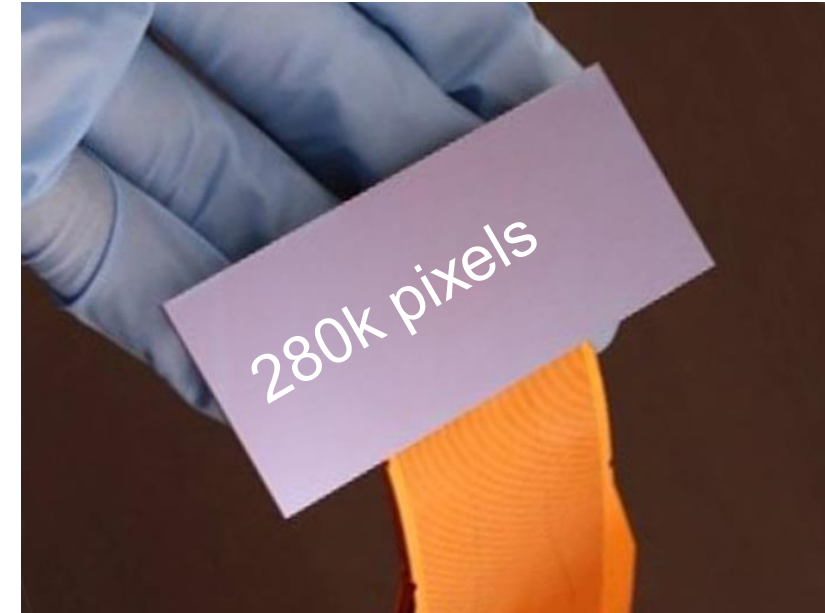


H. Nishino, et.al., Nucl. Instrum. Methods Phys. Res. A. **1057**, 168710 (2023).

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CITIUS 20.2M for SACLA

SALCA: XFEL facility with 60 Hz

Major Specifications

Max. Frame rate: 5 kHz

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

DAQ bandwidth:

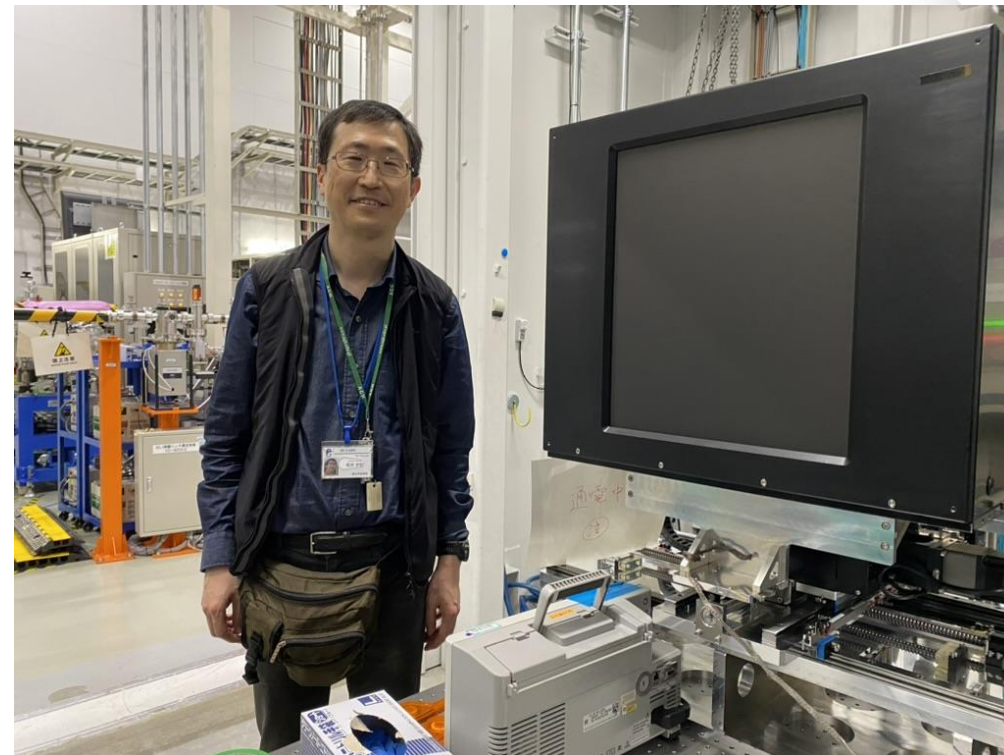
620 Gbps @ 32 bit/pixel

107 GB/s

9 PB/day, when operated continuously

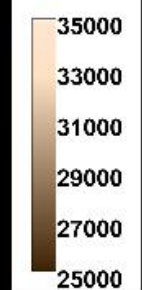
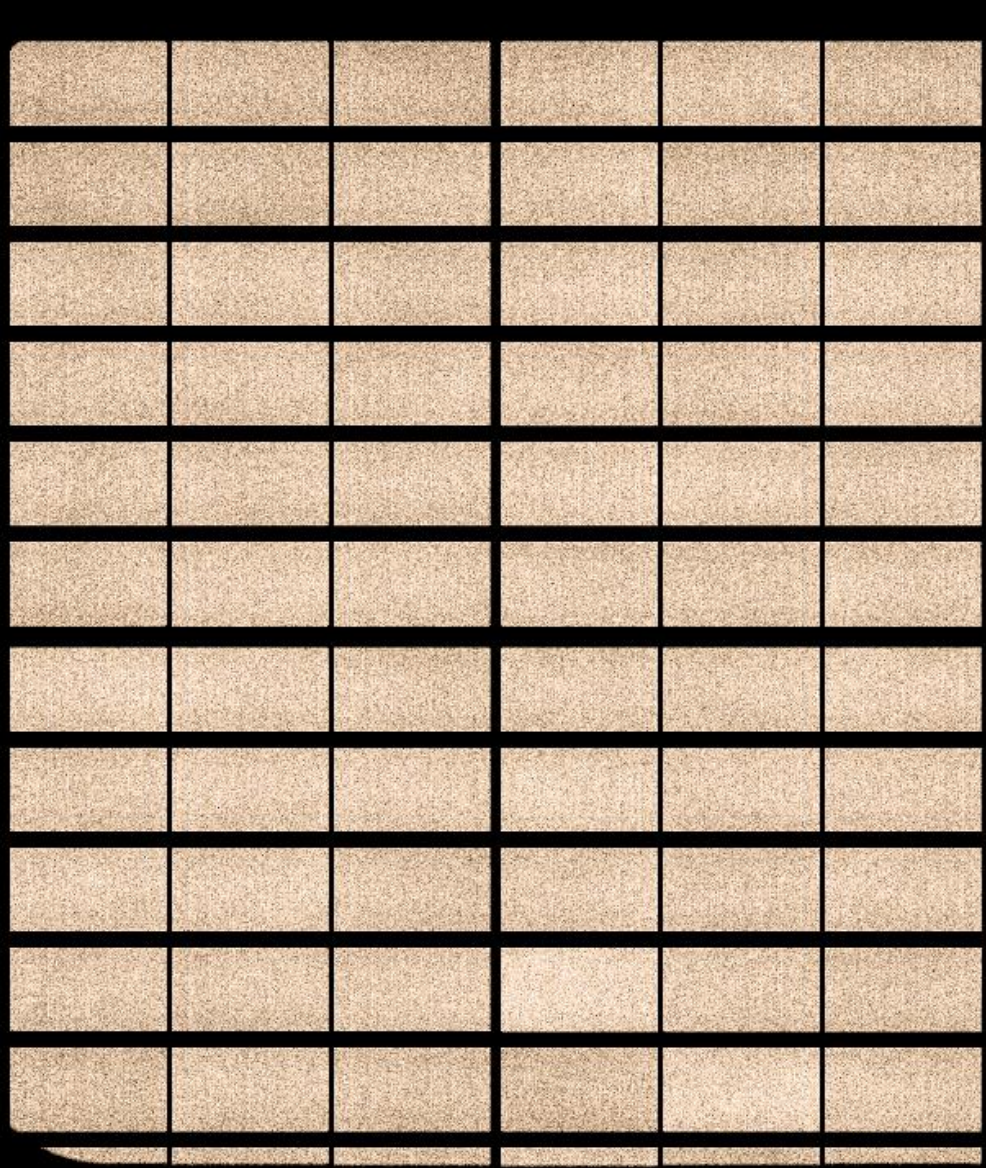
First Beam Test:

July 2024

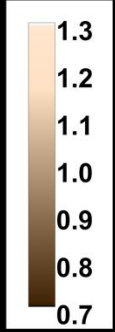
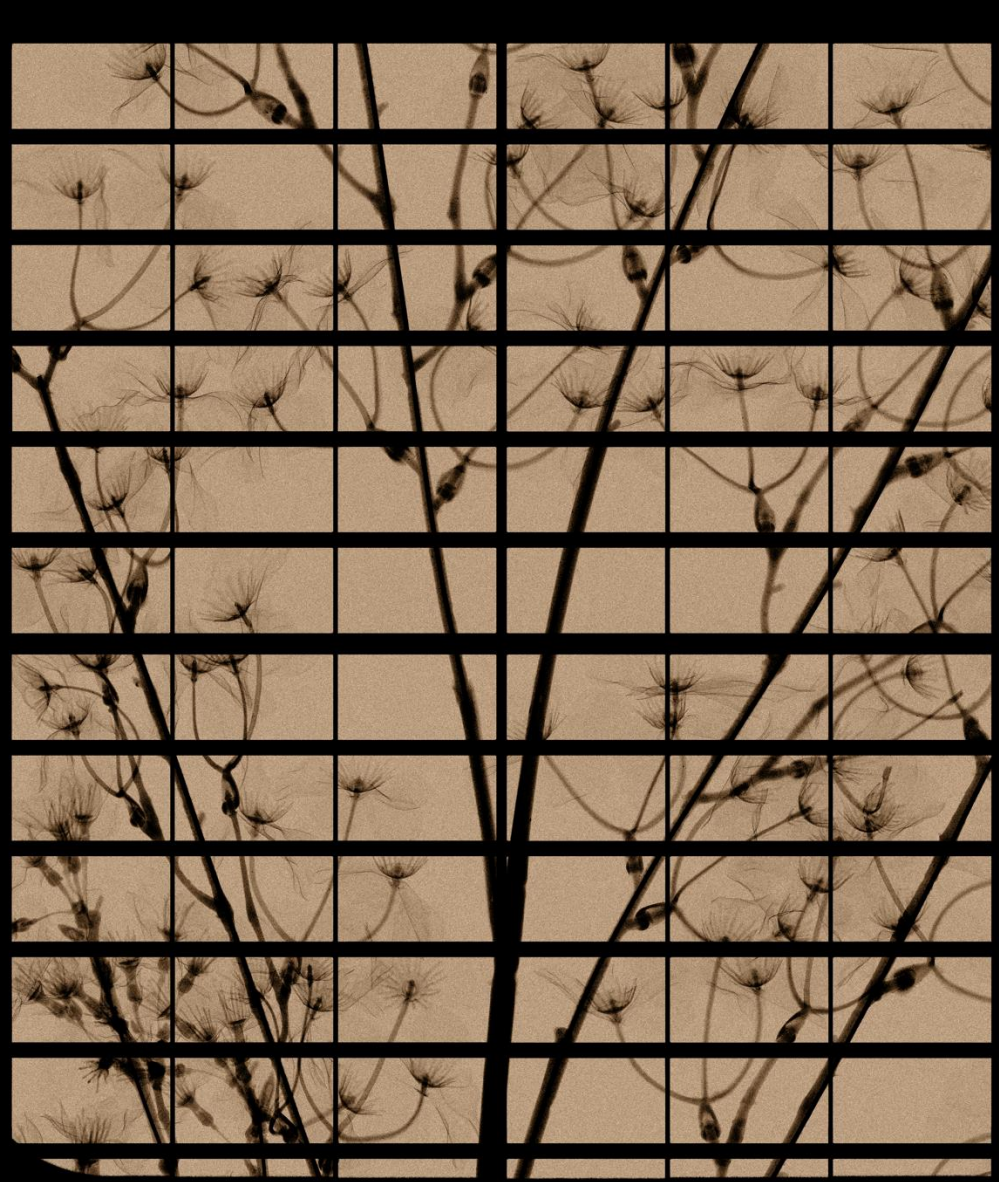


of components: 12,586/system
Engineering intensive project
The outcome of a large collaboration.

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

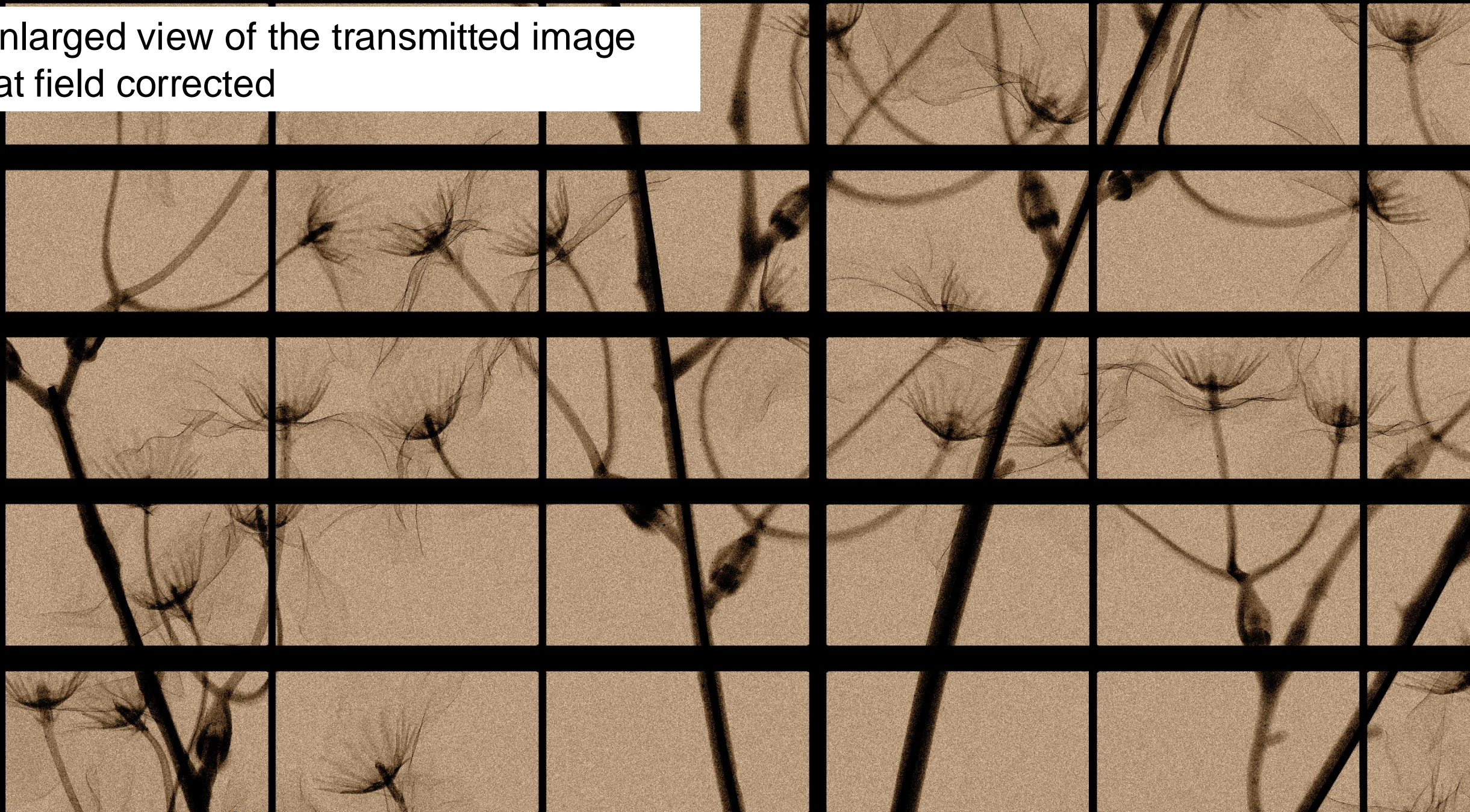


flat field image
dark subtracted

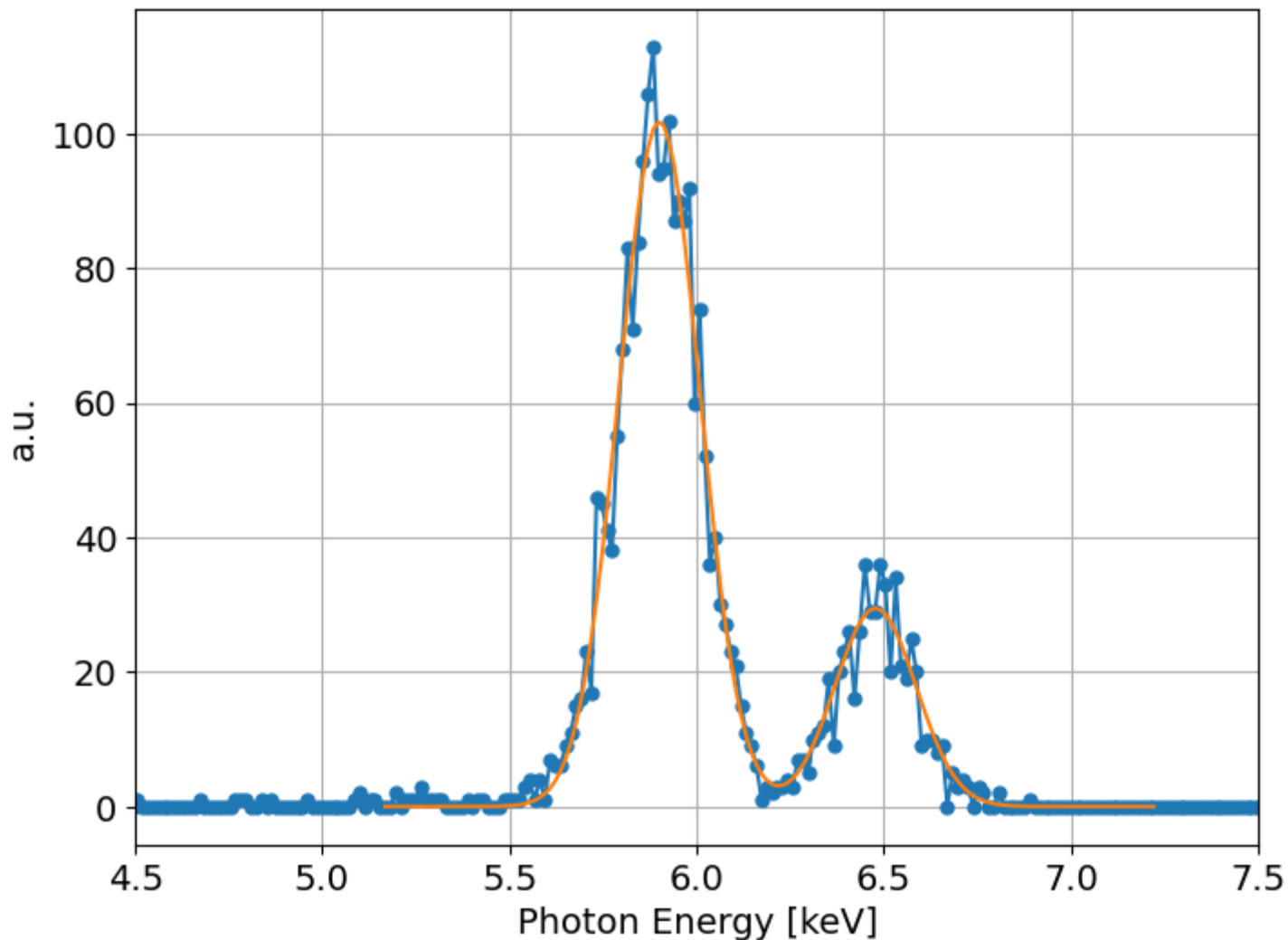


transmitted image
flat field corrected

Enlarged view of the transmitted image
flat field corrected



Noise and Energy Resolution



Noise 25 e-rms
 ~ 250 eV FWHM

Peak Signal 28 Me-
 (17,000 phs @ 6 keV)

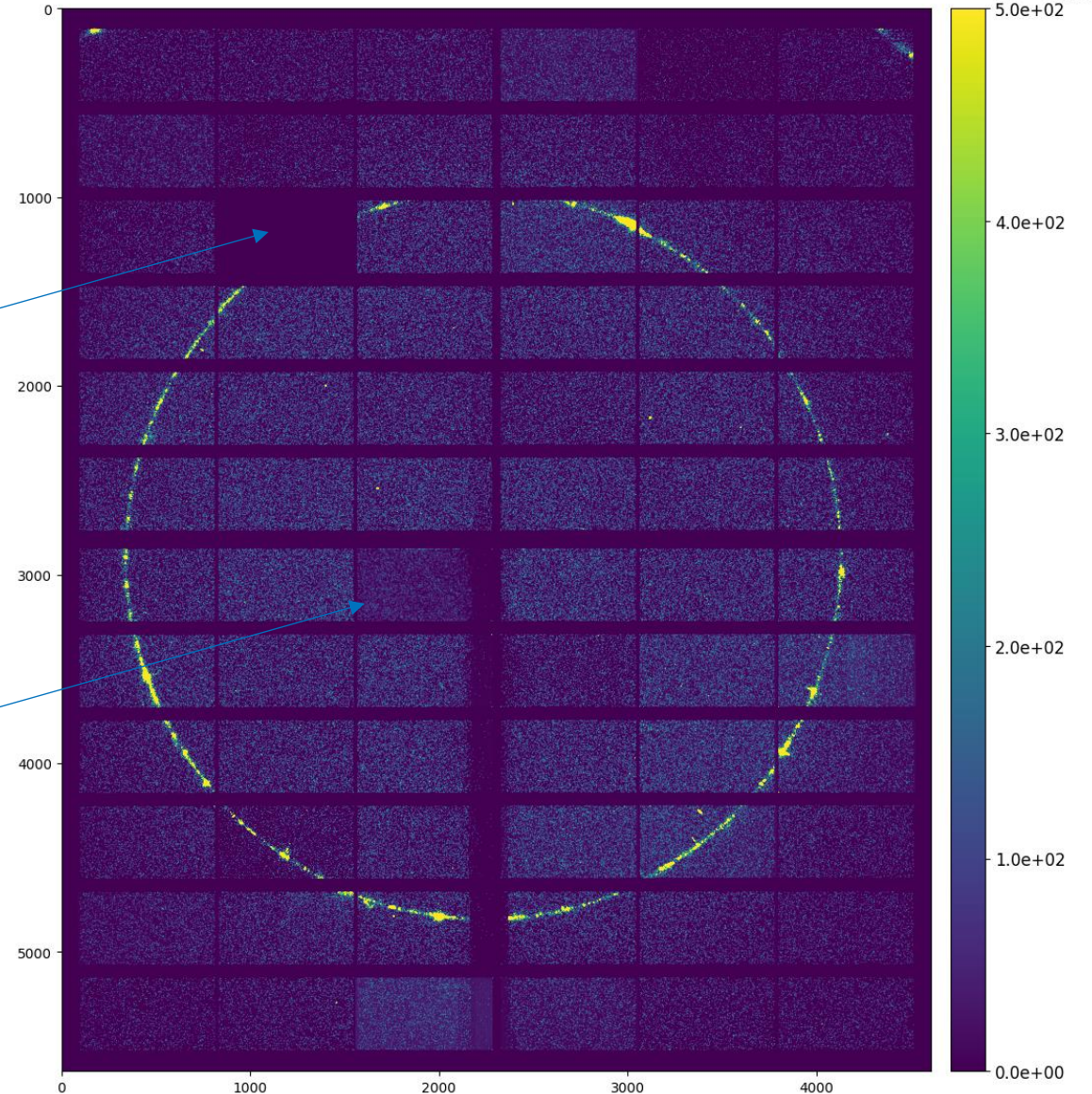
SFX at SACLA with CITIUS 20.2M

First light

failure during commissioning

one sensor damaged
by direct beam during experiments

Successful structure determination demonstrated.
The first science experiments were carried out!



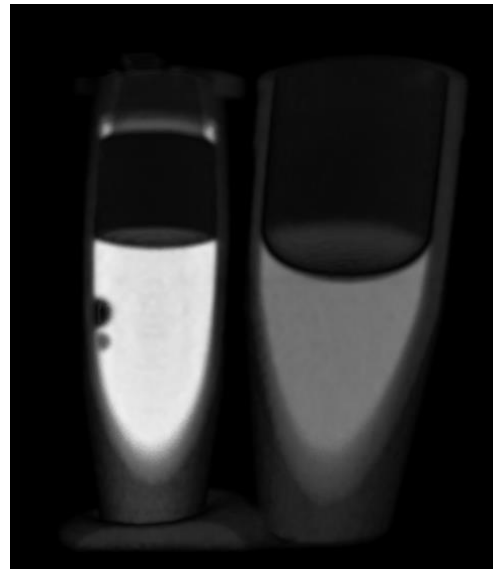
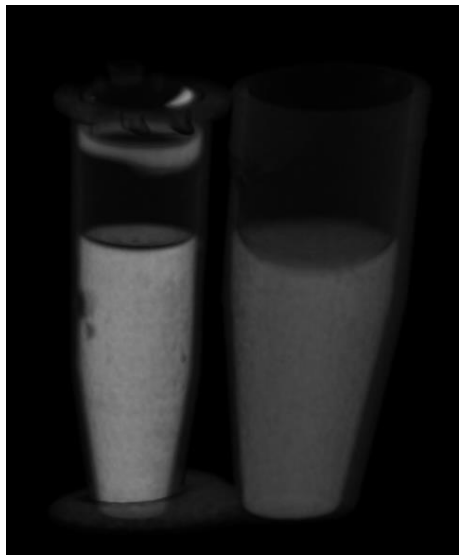
Laboratory based Spectral CT

V. Di Trapani^{1,2*}, F. De Marco^{1,2}, F. Arfelli^{1,3}, Y. Honjo⁵, K. Ozaki⁵, H. Nishino^{5,6}, Y. Joti^{5,6}, T. Hatsui⁵, F. Orsini⁵, P. Thibault^{1,2}, R. H. Menk^{2,3,4}

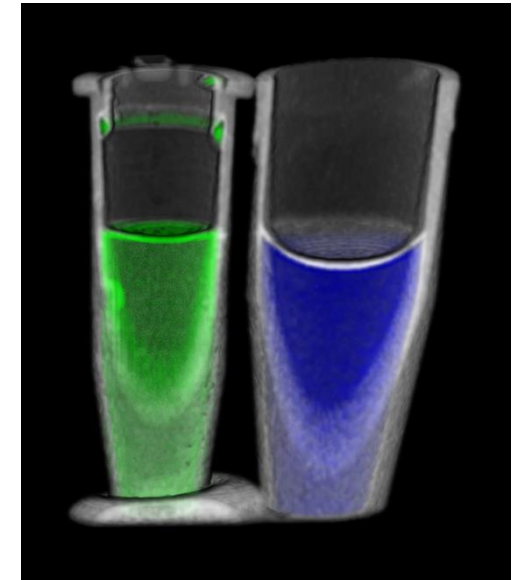
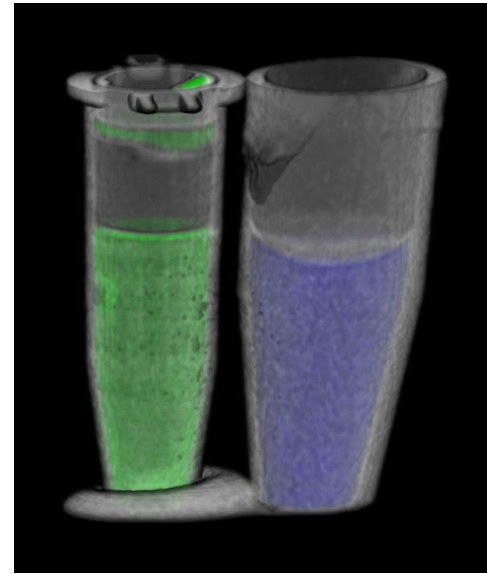
1) University of Trieste, 2) Elettra Sincrotrone 3) INFN Trieste, 4) Mid Sweden Univ., 5) RIKEN 6) JASRI

presented at iWoRiD 2024

Conventional CT



Spectral decomposed CT (blue Ag, green KBr Gray polyethylene)



Analyzed Spectral Resolution in this experiments.

- 540 eV FWHM @ 5.9 keV, 670 eV FWHM @ 27.3 keV

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Noise	<40 e-rms 0.018 phs rms @8 keV

117.5 kHz @1/8 ROI, double Burst Mode at 10 MHz
XPCS *single-crystal structure analysis*

1.23 Gcps/pixel @ 5 keV
Bragg CDI, ptychography SWAXS
3D XRD (37 keV), Quasi-elastic scattering (14.4 keV)
tender X-ray ptychography

20.2Mpixel for XFEL SFX
Serial MX at SR

250-700 eV FWHM (25-40 e-rms)

Spectral decomposed CT

Quick XAFS for battery studies

X-ray BPM for SPRING-8-II storage ring

Summary

Performance and Applications

- frame rate (> 17.4 kHz) **XPCS**, *single-crystal structure analysis*
- high-intensity (up to 1 Gcps/pixel) **Bragg CDI**, *ptychography*, **SWAXS**
- high sensitivity **3D XRD (37 keV)**, **Quasi-elastic scattering (14.4 keV)**
- Tiling **20.2Mpixel for XFEL SFX**
- Low noise \Rightarrow Spectro-imaging
 - 250-700 eV FWHM (25-40 e-rms)
 - 180 Mevents/sensor (12.2 Mevents/cm²)
 - **Spectral decomposed CT**, *Fluorescence-Yield Quick XAFS for battery studies*, *X-ray beam monitor for SPring-8-II storage ring*

Acknowledgment

RIKEN and JASRI Team

- Kyosuke Ozaki, Yoshiaki Honjo, Haruki Nishino, Kazuo Kobayashi, Koji Motomura, Kyo Nakajima, Yasumasa Joti, 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.