CITIUS: a 17400 frames/s x-ray imaging detector

Takaki Hatsui *on behalf of CITIUS collaboration*

RIKEN SPring-8 Center

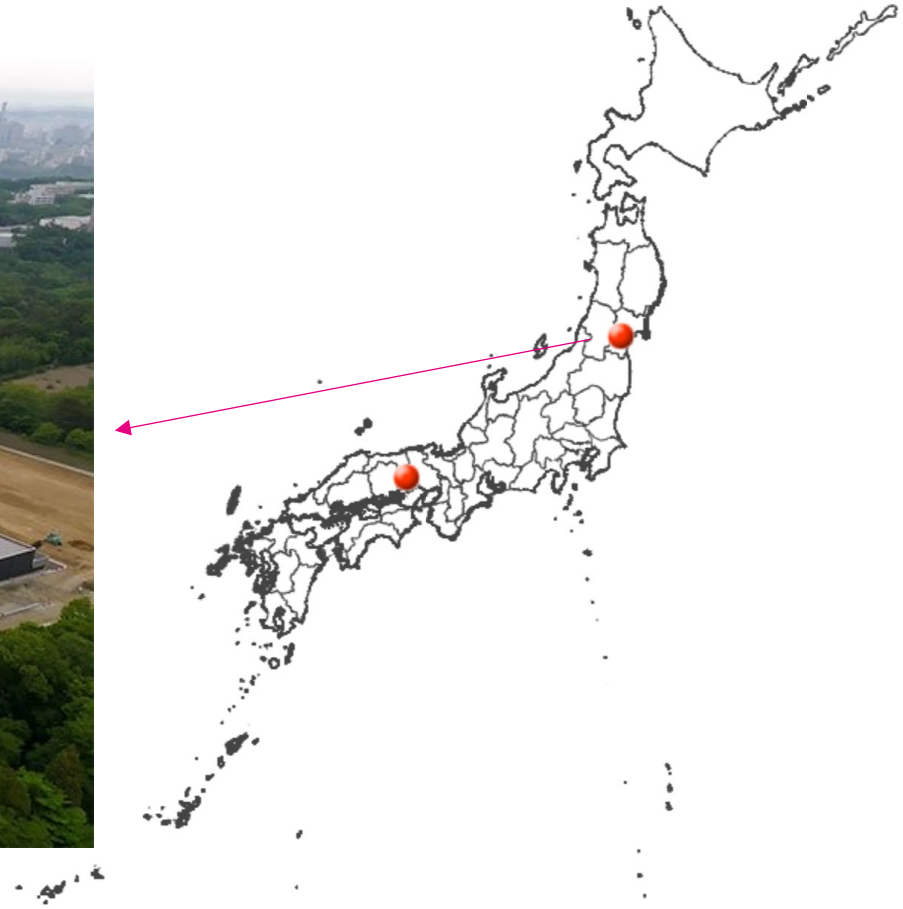
Dec.13th, 2022 PIXEL 2022

Outline

1. Our motivation for the development and performance objectives
2. Project History
3. Demonstrated Performance
4. Summary

New SR facility

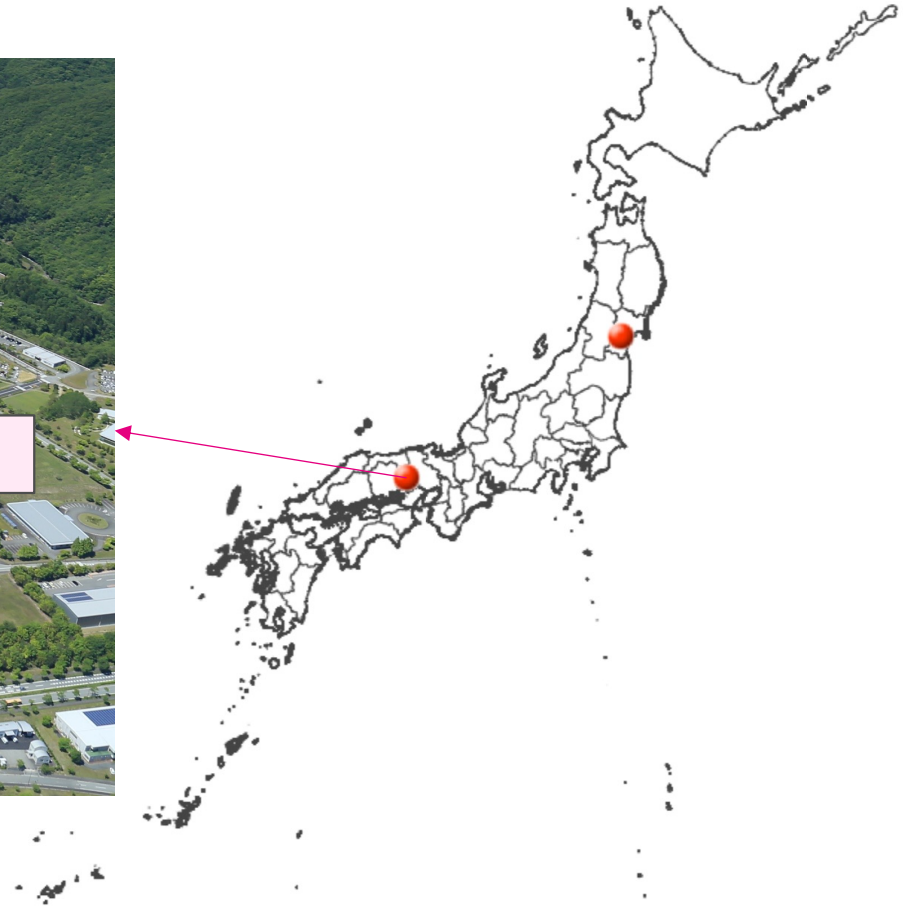
NanoTerasu (2023-)
3 GeV, 349 m



8 GeV SR・XFEL

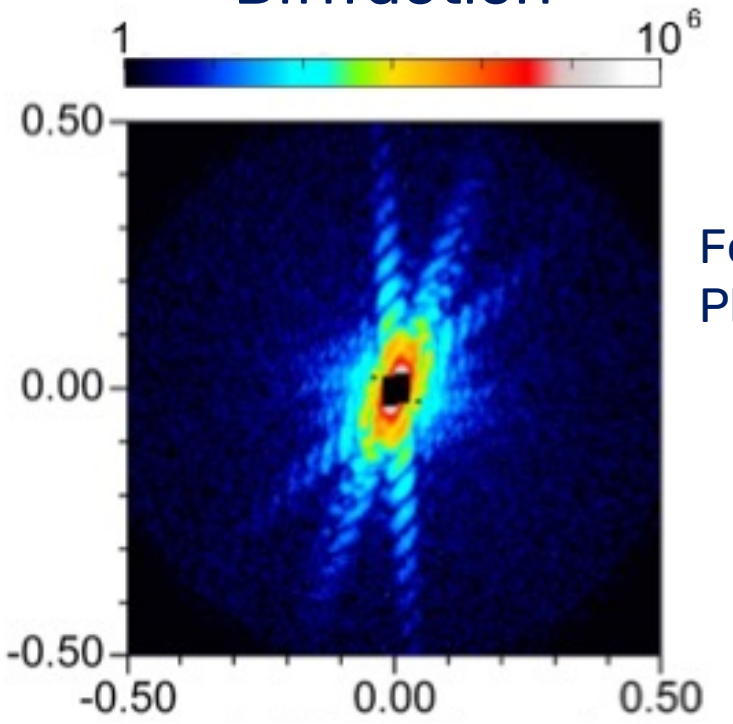
XFEL, SACLA (Since 2012-)
8 GeV 700 m long

SR, SPring-8 (Since 1997-)
8 GeV circumference 1.5 km



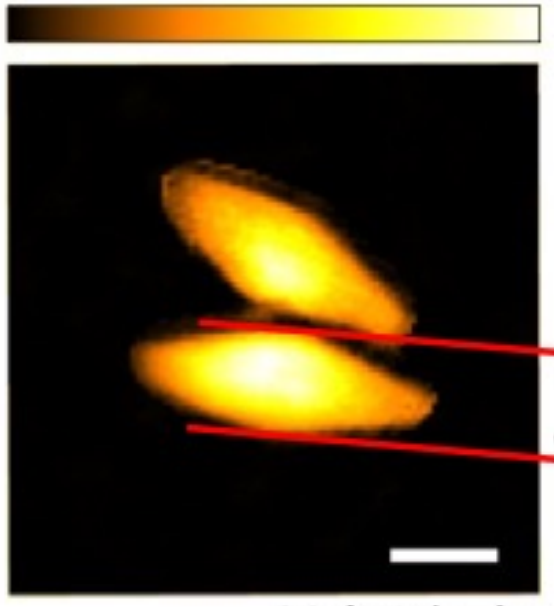
A Scientific Case

Coherent
Diffraction



Spatial Frequency (nm^{-1})

Fourier Transform
Phase retrieval



Resolution: 2 nm

80 Gold atoms

20 nm

H. Yumoto, Nature Communications volume 13, Article number: 5300 (2022)

Scientific Needs: Summary

Higher Count Rate

- beyond 1-10 Mcps/pixel

Faster Recording

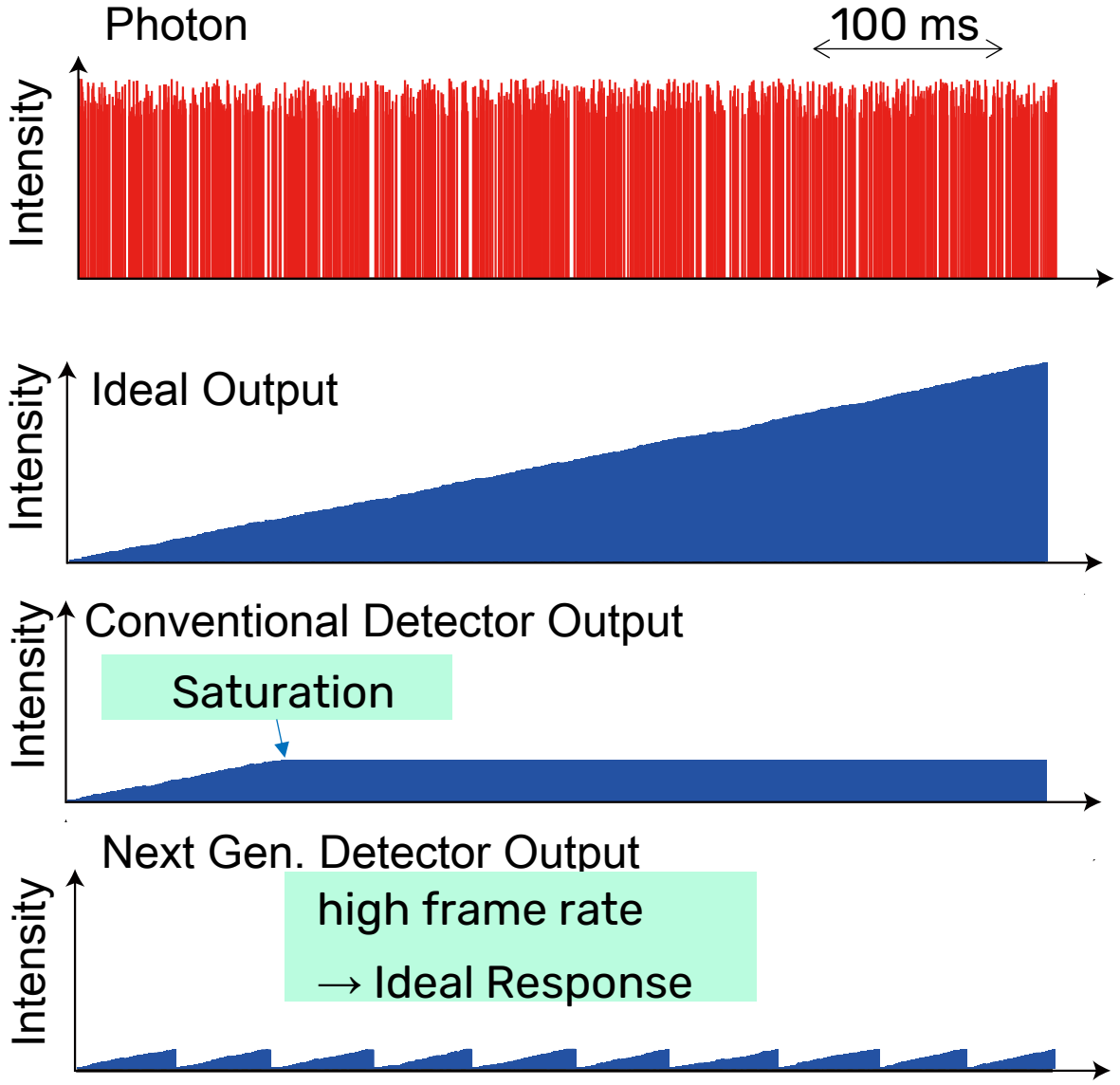
- with good S/N for each frame

Architecture [1]
Integrating Pixel & High Frame Rate

[1] SPring-8 II CDR (2014)

Architecture [1]

Integrating Pixel & High Frame Rate



[1] SPring-8 II CDR (2014

2

CITIUS: Project History

Research to Development

SACLA User
Beamtime started

Mar. 2011

Investigation
Started

Nobukazu Teranishi has joined this project from Panasonic
Inventor of pinned photodiode, expert in CMOS sensors
Technical investigation accelerated

Apr. 2013

Nov. 2014

Conceptual Design and target performance reported in SPring-8-II CDR

Sony and RIKEN agreed on the development

2015

Technology Choice (1/2)

Fully exploit the CMOS image sensor process/circuitries

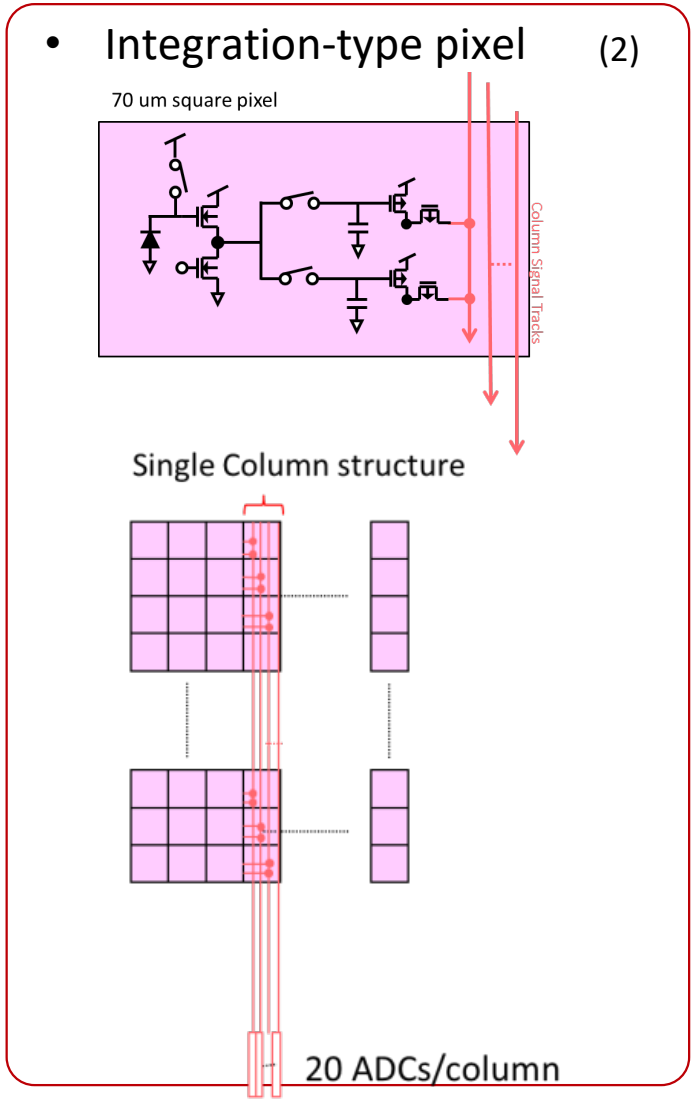
Chip level

On-chip ADC

- benchmark on performance/power dissipation
  - for all the available technologies at the time of 2014

Vertical Signal Lines

- Massively parallel



1) SPring-8 II CDR with updated values
2)T. Hatsui, presented at iWorid (June. 2014)

Technology Choice (2/2)

Fully exploit the CMOS image sensor process/circuitries

Pixel

Sensor material

- focus on silicon

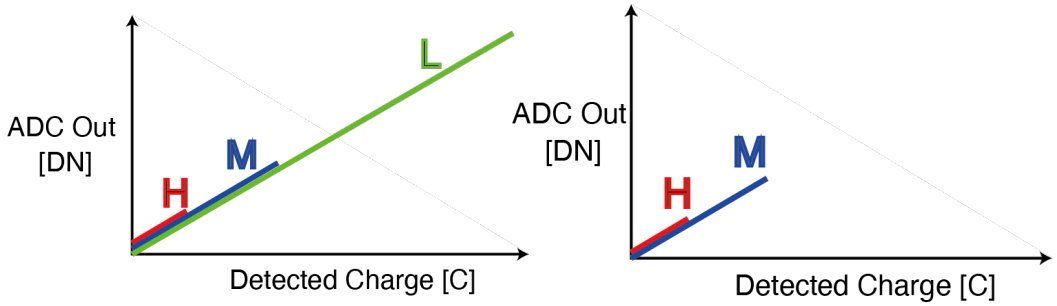
Radiation Hard pixel

- photon energies mainly >8 keV
- X-rays penetrate through silicon sensors
- TID hardness > 1 MGy

Multi-gain Pixel Circuitry without switching

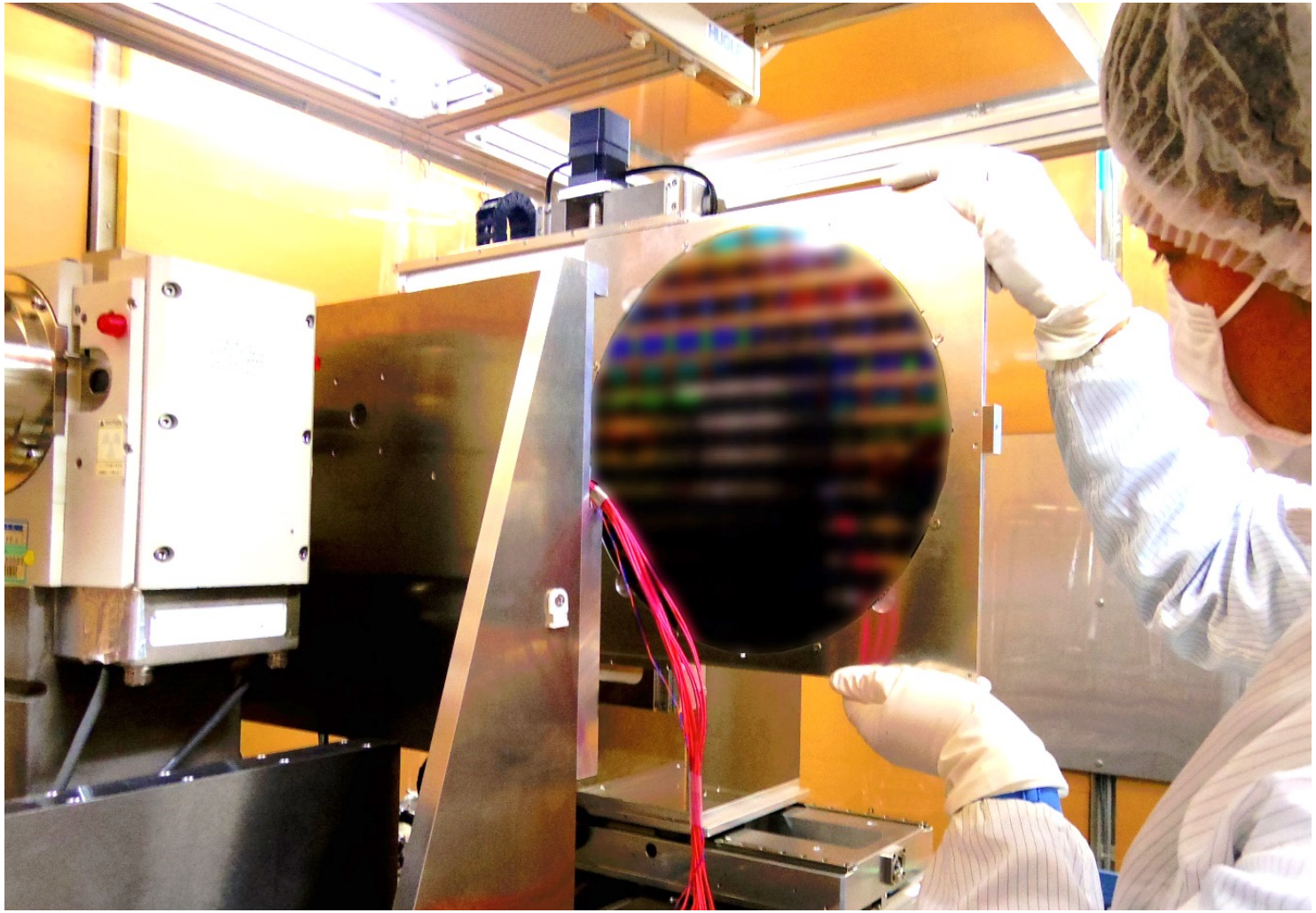
- robust calibration by FPGAs
- 3T-type circuits without charge amplifiers
  - similar to LOFIC invented by Prof. Sugawa
  - x2 or x3 digitization needed
- Low input capacitance with SF
  - Low power consumption

wo Switching point



Radiation Hard Pixels

T. Kudo, et.al., IEEE Trans. on Nuclear Science, 2014 pp. 1444.



Wafers on a dedicated semi-automatic probe station were irradiated by X-rays.

> 10,000 transistors were evaluated.

Development

Project Schedule finalized
First X-ray Image capture
scheduled on June 2020

Mar. 2016

Sep. 2020

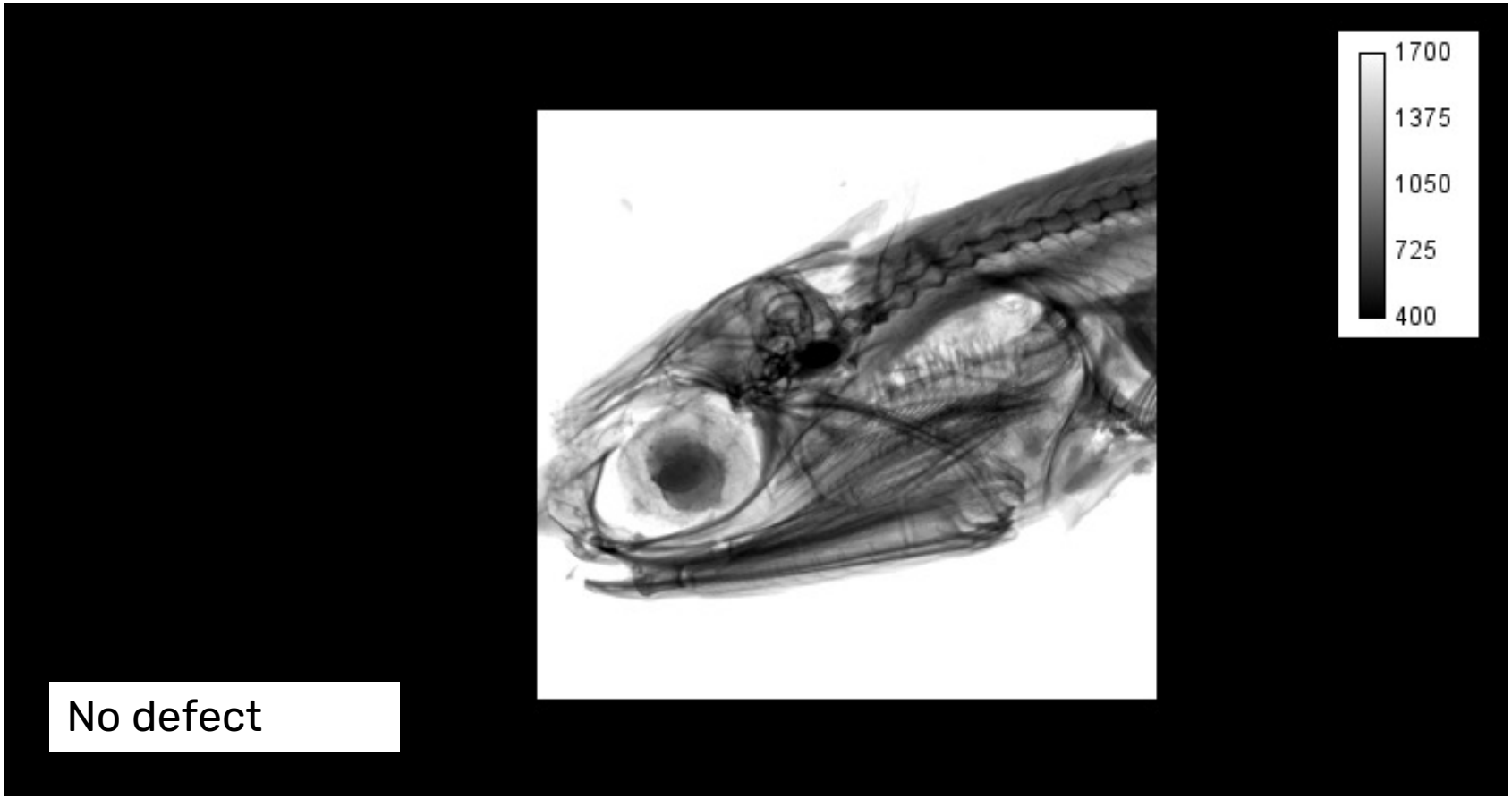
First Optical Image
System evaluation
started

First X-ray Image capture
Delayed by 3.5 months

Oct. 2nd, 2020

First Image of a dried fish at 17.4 kfps
1 k frames were accumulated

Rotating X-ray Generator: Target Element of Mo, 30 kV 65 mA
Total exposure time: 55 ms



Integration

Mar. 2016
Project Schedule finalized
First X-ray Image capture scheduled on June 2020

Sep. 2020
First Optical Image System evaluation started

Oct. 2nd, 2020
First X-ray Image capture Delayed by 3.5 months

Oct. 2021
First Science Experiment (XPCS)

Jul. 2022
First Science Experiment at Public Beamline

Jul. 2022
Feasibility Study at ESRF

Dec. 2022
First experiment at SACLA

2023
Integration to
- SWAXS
- Single Crystal Structure Analysis

2023
20.2 M detector to be integrated to SACLA

CITIUS detector

Architecture [1-3]

Integrating Pixel & High Frame Rate

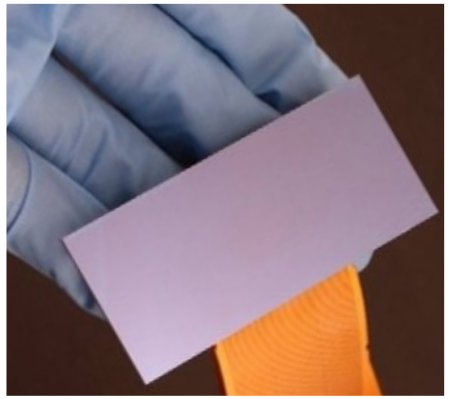
Feature

High Dynamic Range	Ultralow Systematic Error	Spectro-Imaging	High Spatial Resolution	Single Photon Sensitivity

[1] SPring-8 II CDR (2014) with updated values.
[2] T. Hatsui, presented at iWorid (June. 2014).
[3] T. Hatsui, AOSFRR (Nov. 2015)

Experimentally Verified Performance

Parameters		Value	
Sensor	Thickness	Si 650 µm	
	Pixel Size	72.6 µm	
	Pixel Number	0.28 Mpixel/sensor	
	Noise	0.027 phs.@8 keV (60 e^-)	
		SR variant	XFEL variant
	Peak Signal	1,800 phs. @ 12 keV (6 Me-)	17,000 phs.@ 6 keV (28 Me-)
	Frame Rate	17.4 kfps	5 kHz
	Sat. Count Rate @12 keV	30 or 600 Mcps	-
	Pixel Readout Rate	4.87 Gpixels/s	1.4 Gpixels/s



CITIUS Project

Nov. 2014. SPring-8-II Conceptual Design Report

38 Mcps/pixel with 70 μm□ pixel	20.88 kfps max 1840 photons/frame

2022 CITIUS: demonstrated performance

945 Mcps/pixel with 72.6 μm□ pixel	**17.4 kfps** max 1840 photons/frame

SPring-8 revolving frequency: 208.8 kHz

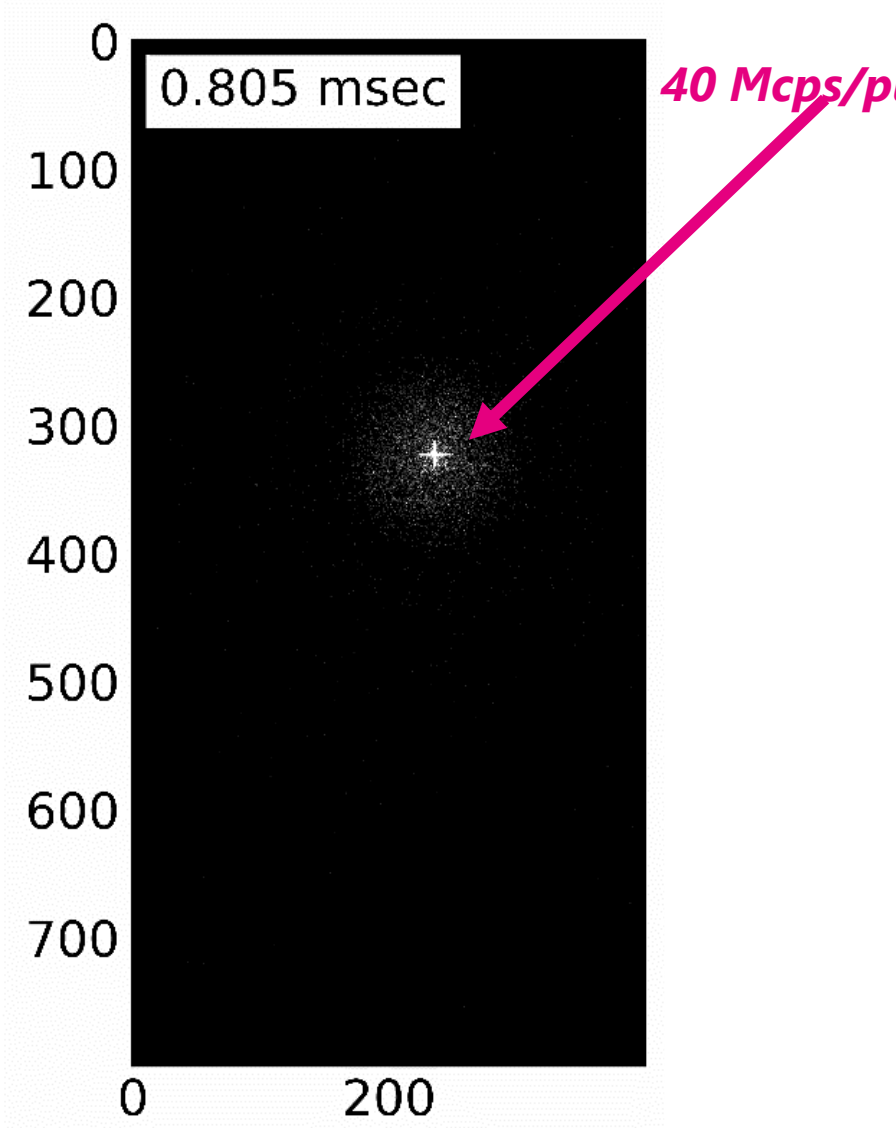
3

Demonstrated Performance

Primary Performance

BL29XU EH3 in July 2021
XPCS @ 17.4 kfps

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



CITIUS
- Pixel Number: 280 kpixels
- Frame rate: 17.4 kframes/s
- Frame Cycle: 57.5 μs

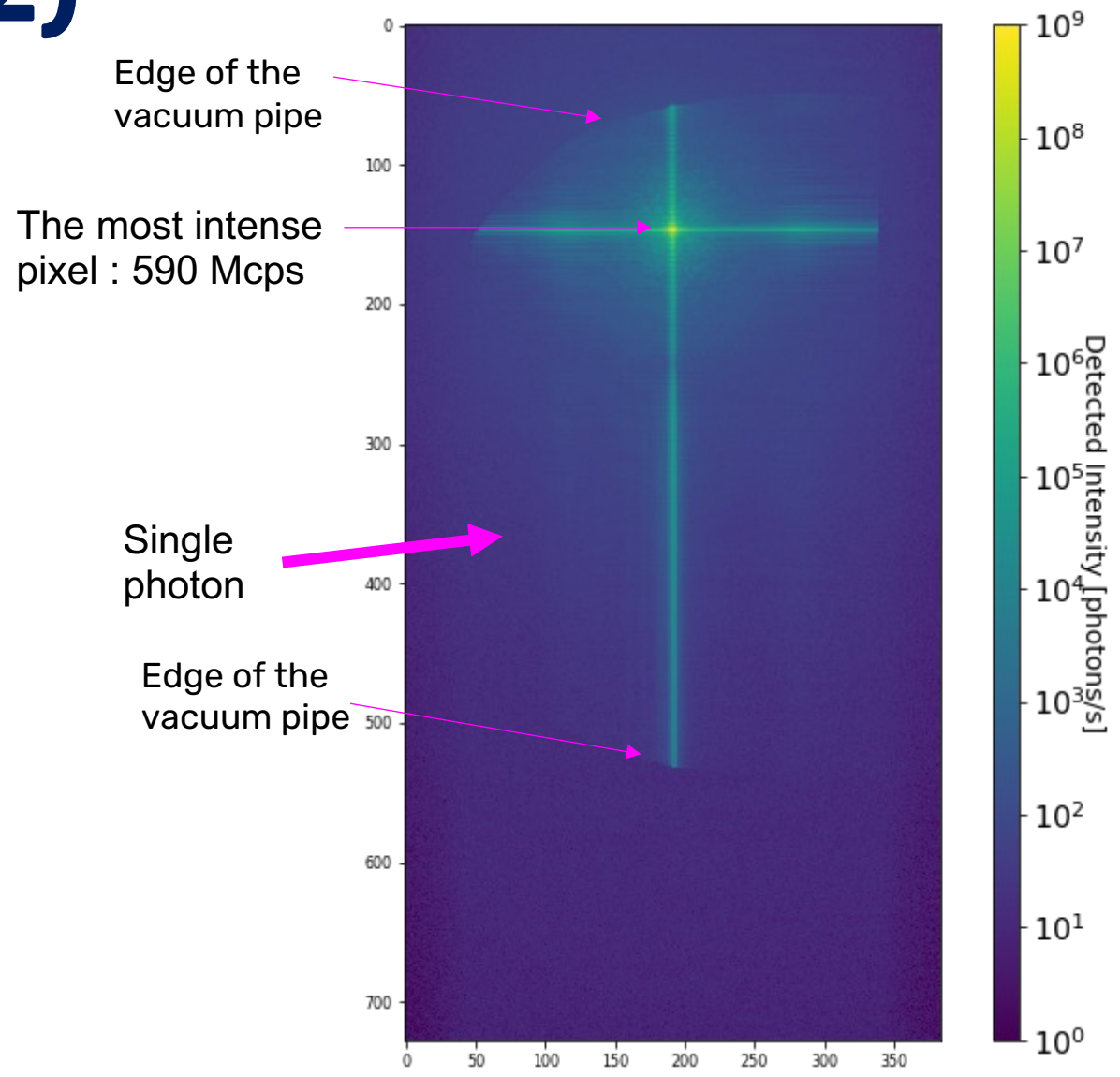
Sample:
- Silica (100 nmφ, 28.8 wt%)
  - in MEK + PEI + MeOH (66.8, 3.9, 0.5 wt%)
  - in 0.5mm capillary

Count Rate (1/2)

Photon Energy: 10keV

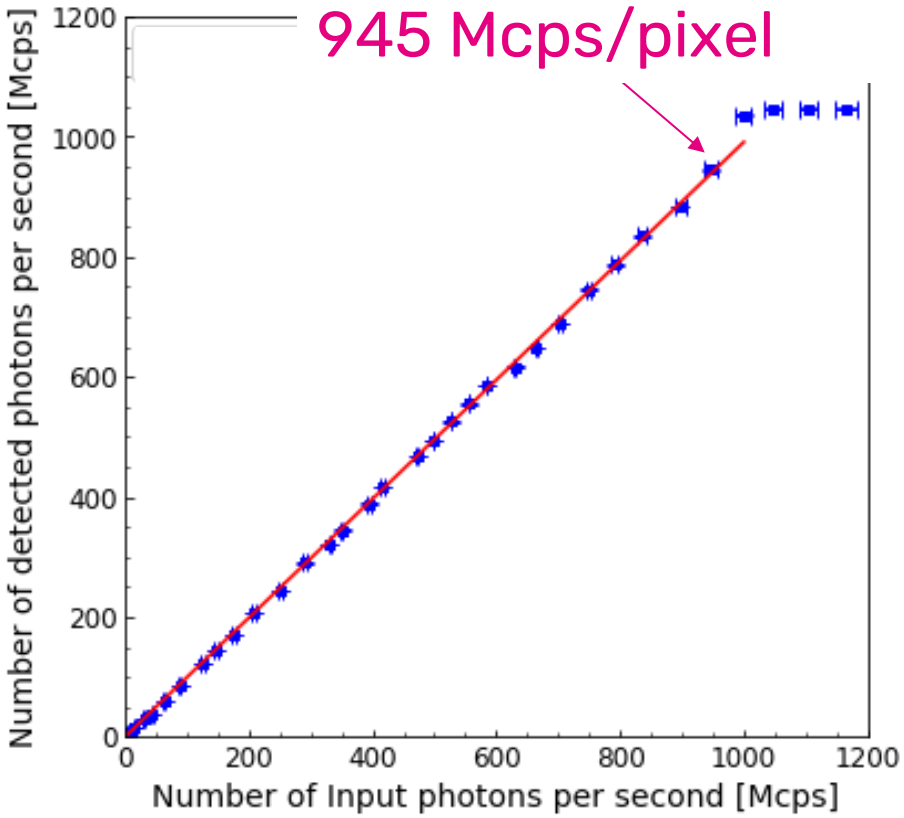
Slit to CITIUS: 15m

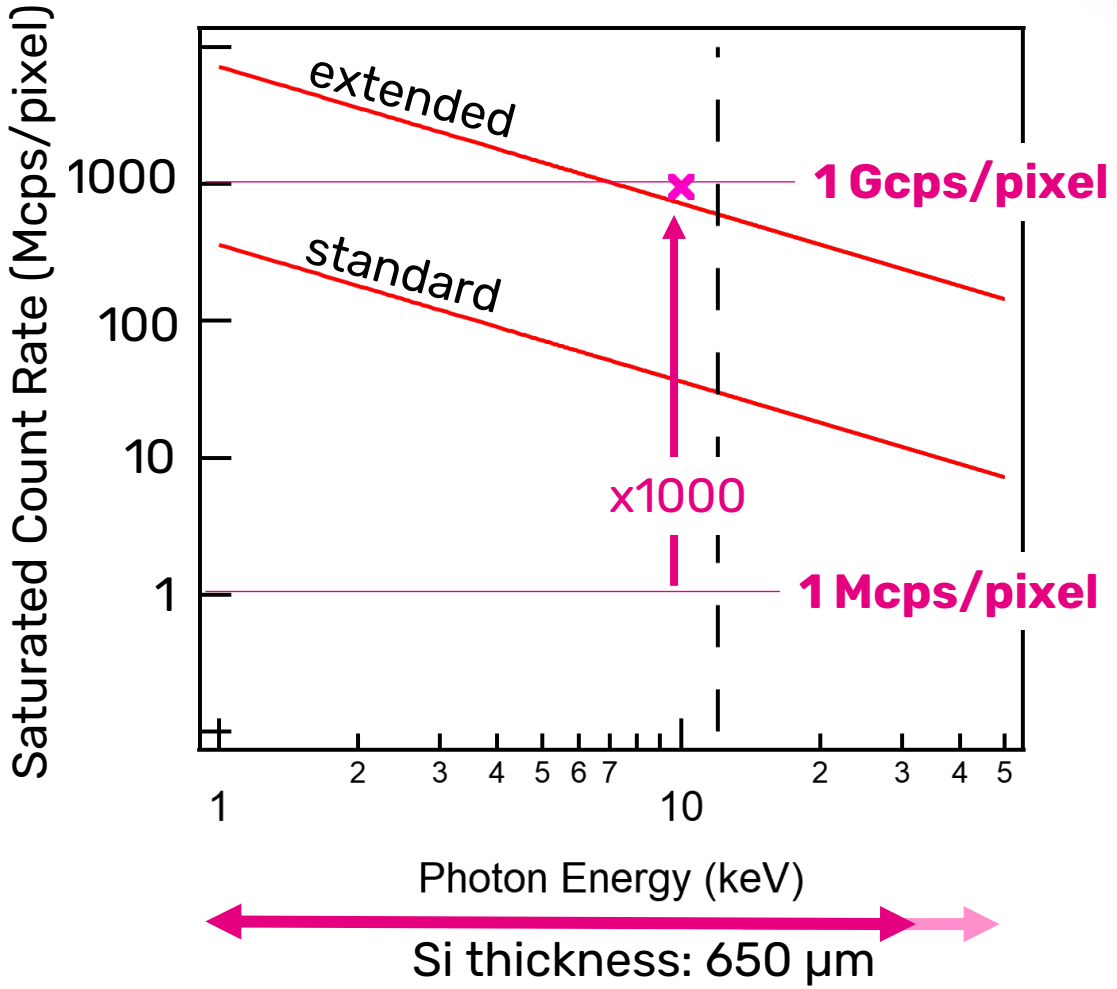
Slit Size: 20 × 20μm



Count Rate (2/2)

Photon Energy = 10 keV

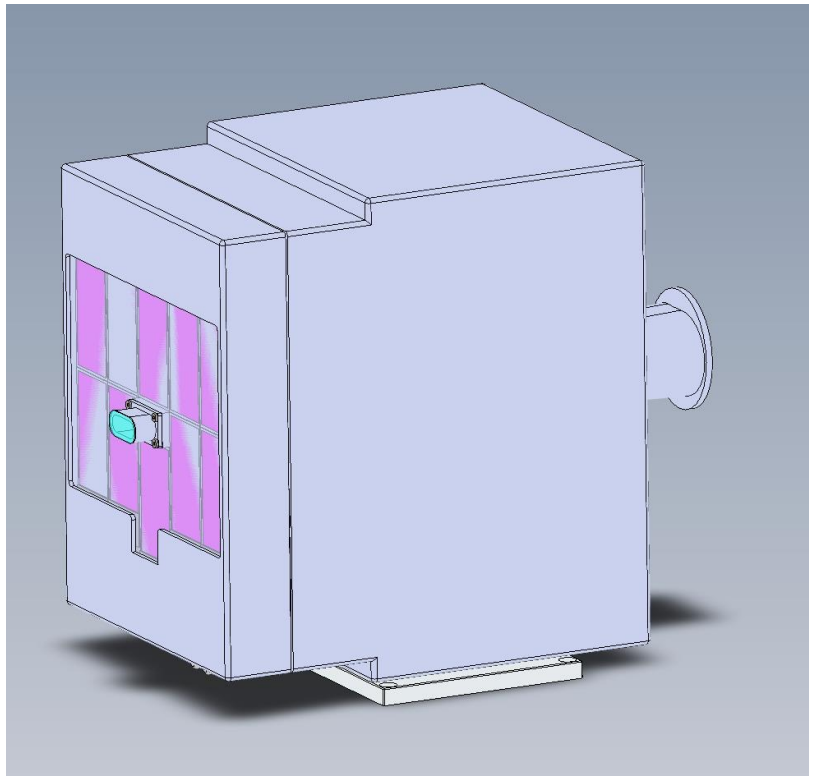




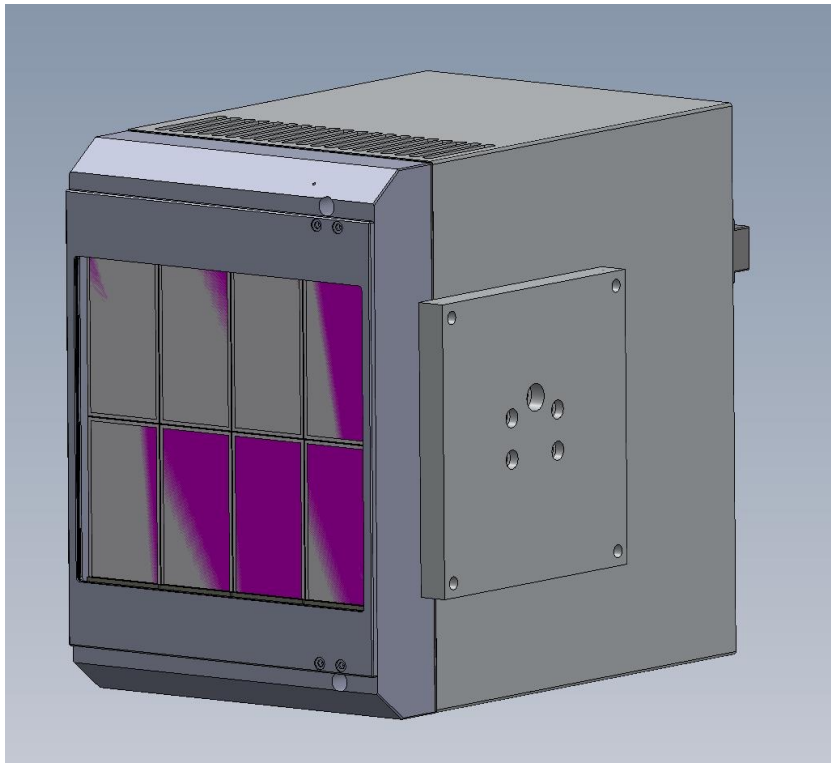
Tandem CITIUS for SPring-8 new SWAXS beamline

in collabo. with H. Sekiguchi et.al.,

Upstream WAXS detector
2.8 Mpixels



Downstream SAXS detector
2.2 Mpixels

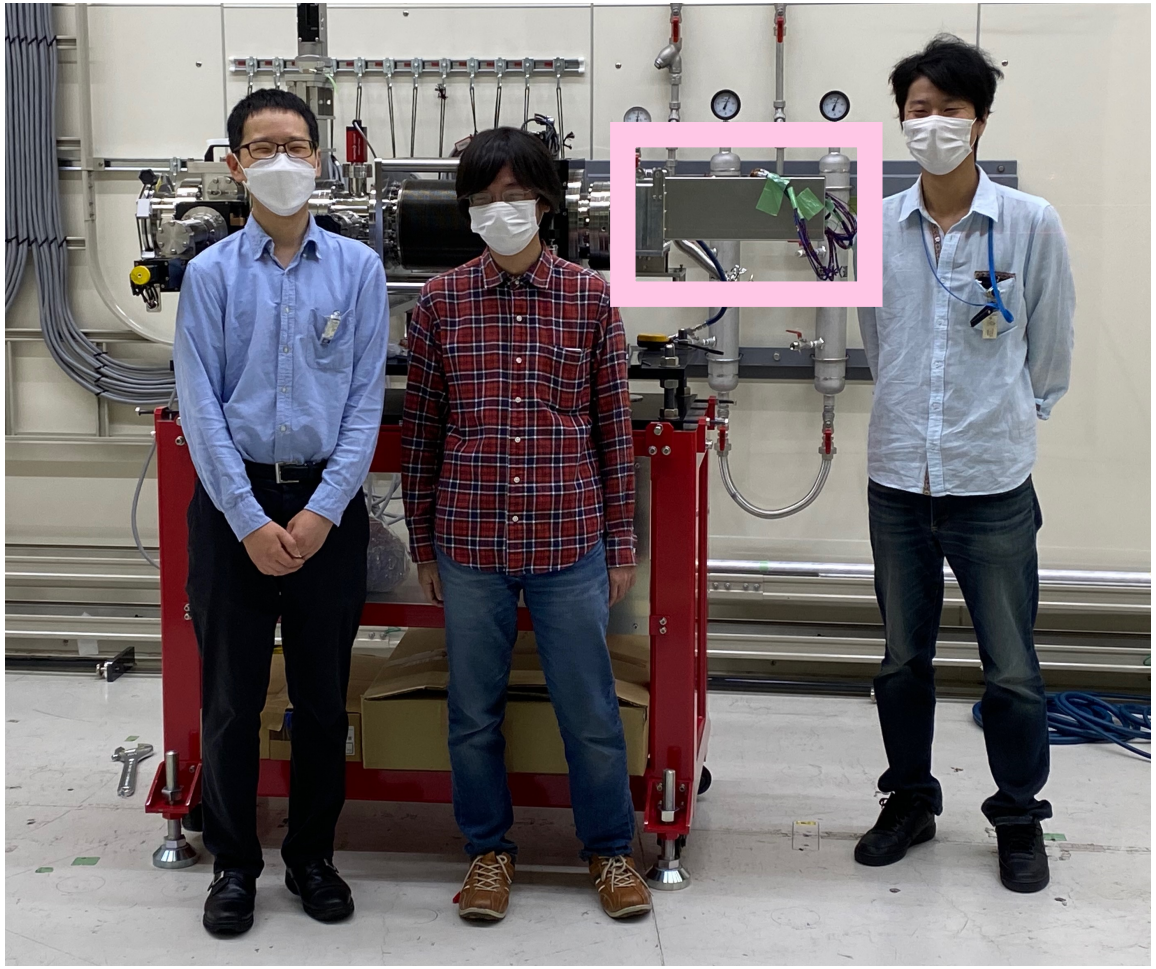


to be integrated in 2023

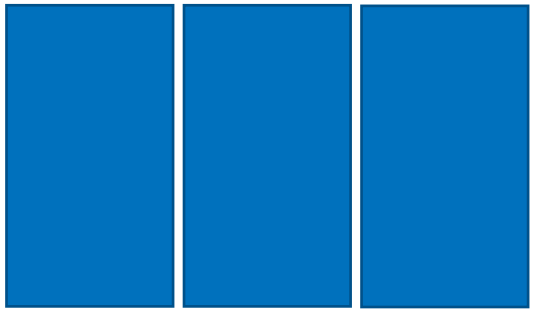
Feasibility Study of CITIUS for ptychography

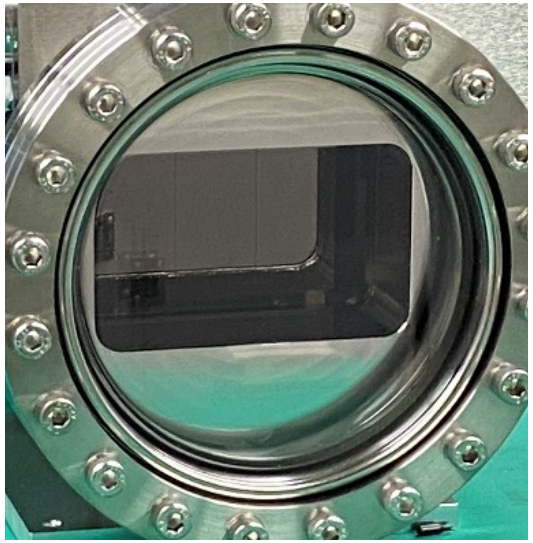
K. Ozaki, Y. Honjo, T.N. Hiraki et.al.,
Y. Takahashi Group (Tohoku Univ.)

Nov. 2022 Feasibility study
Dec . 2022 first science experiments



840k





CITIUS detector for synchrotron radiation

Architecture [1-3]

Integrating Pixel & High Frame Rate

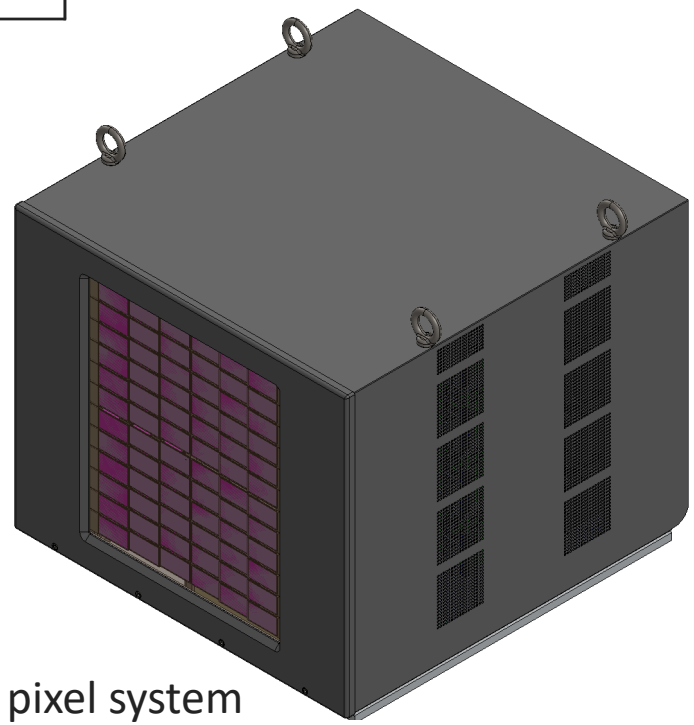
[1] SPring-8 II CDR (2014) with updated values.
[2] T. Hatsui, presented at iWorid (June. 2014).
[3] T. Hatsui, AOSFRR (Nov. 2015)

Feature

High Dynamic Range	Ultralow Systematic Error	Spectro-Imaging	High Spatial Resolution	Single Photon Sensitivity

Detector Performance

Parameters		Value
Sensor	Thickness	Si 650 μm
	Pixel Size	72.6 μm
	Pixel Number	0.28 Mpixel/sensor
	Noise	0.027 phs.@8 keV (60 e^-)
	Peak Signal	1,800 phs. @ 12 keV
	Frame Rate	17.4 kfps
	Sat. Count Rate @12 keV	30 or 600 Mcps
Largest System	Pixel Number	20.2 Mpixel
	Image Area	325 x 363 mm

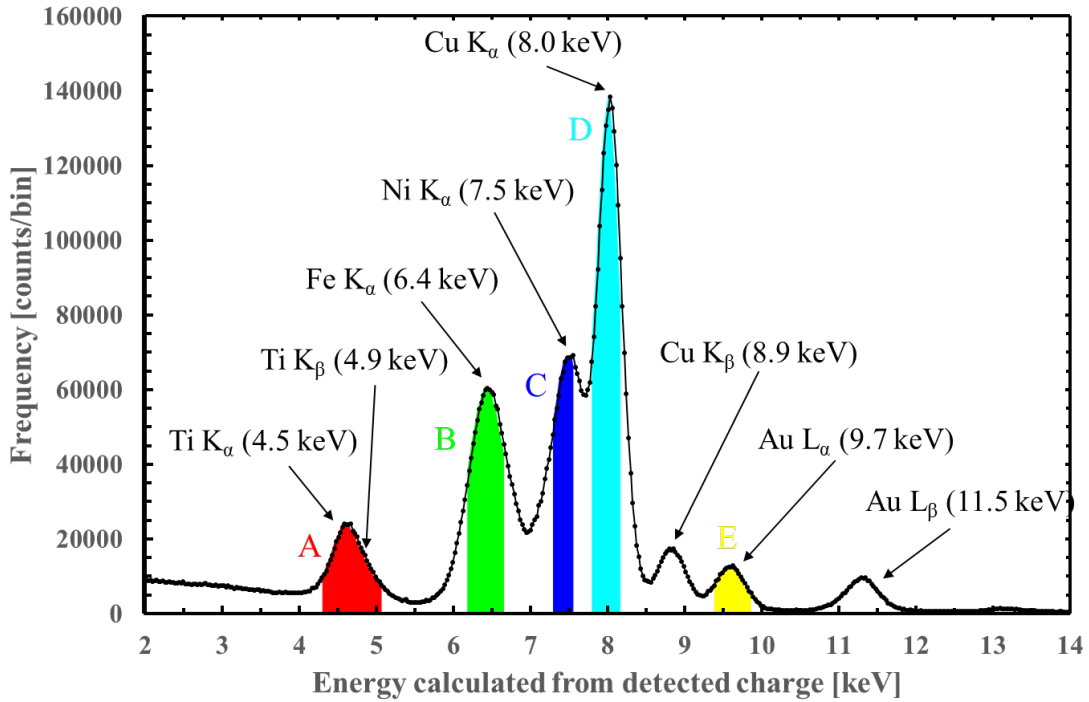


20.2M pixel system

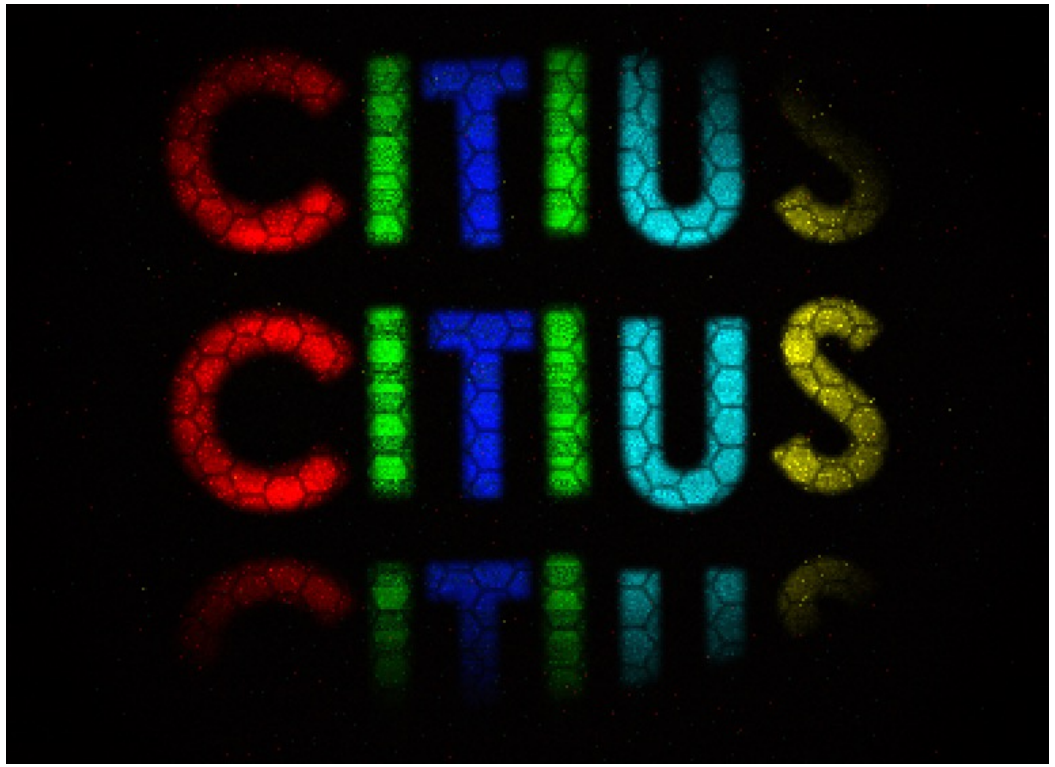
K. Ozaki, Y. Honjo, et.al.,

Spectro-Imaging

with Laboratory X-ray sources



Ti. Fe. Ni. Fe Cu. Au



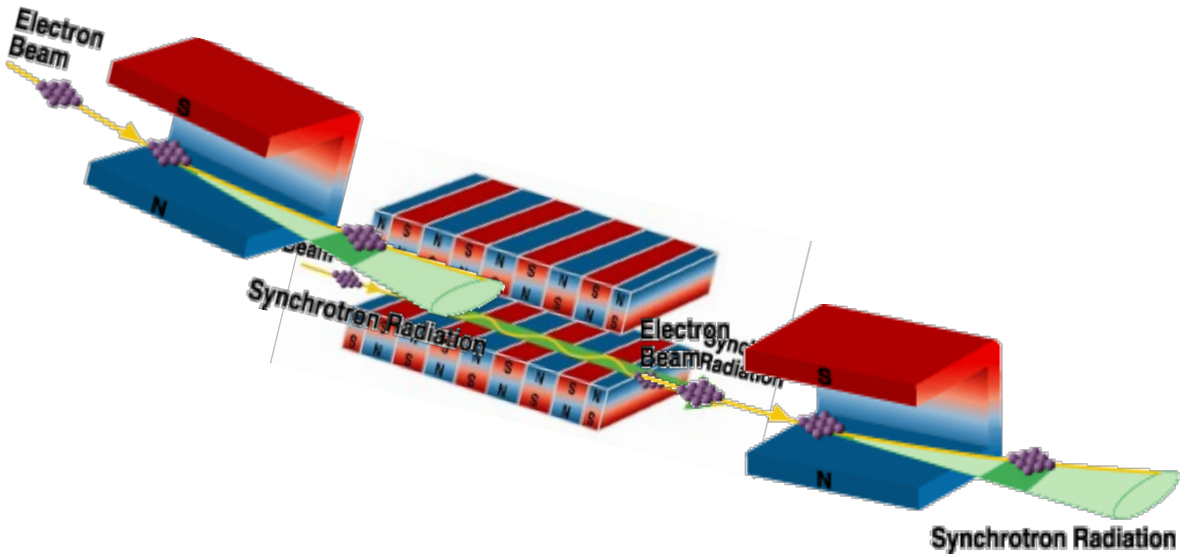
projected by capillary optics
Characters made of Ti, Fe, Ni, and Au elements

X-ray Beam Monitor for SPring-8-II

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

Accelerator feedback with electron monitors

- not enough

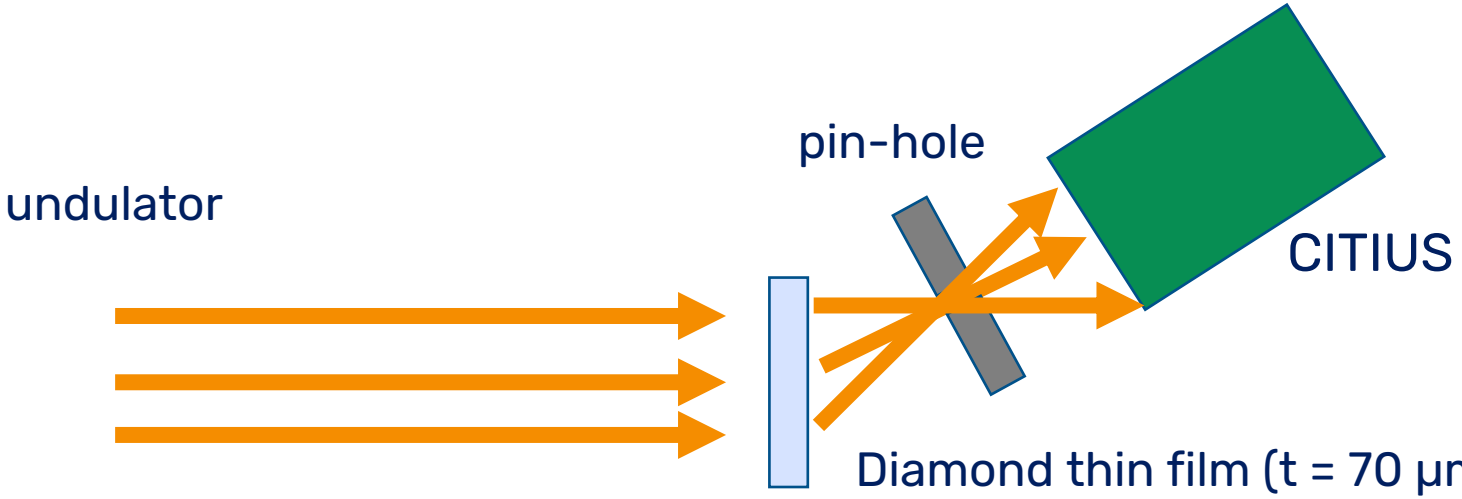


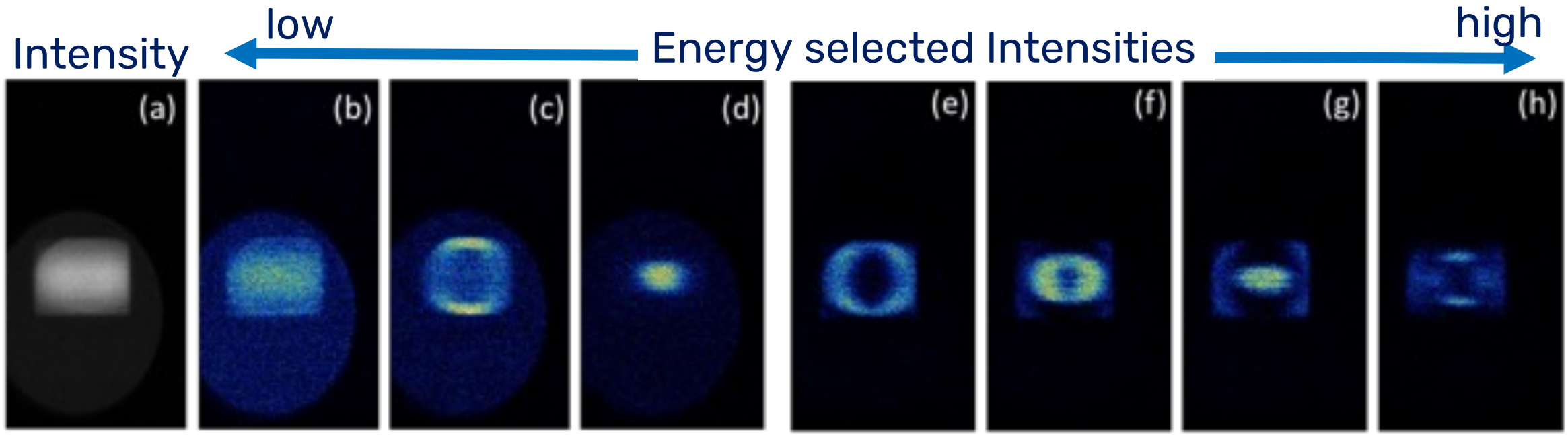
X-ray Intensity Image

Undulator beam is hidden by the bending X-rays

X-ray Beam Monitor for SPring-8-II

T. Kudo et.al., J. Synchrotron Rad. (2022). 29, 670-676
K. Ozaki, T. Kudo, S. Takahashi, M. Sano, T. Itoga, et.al.,

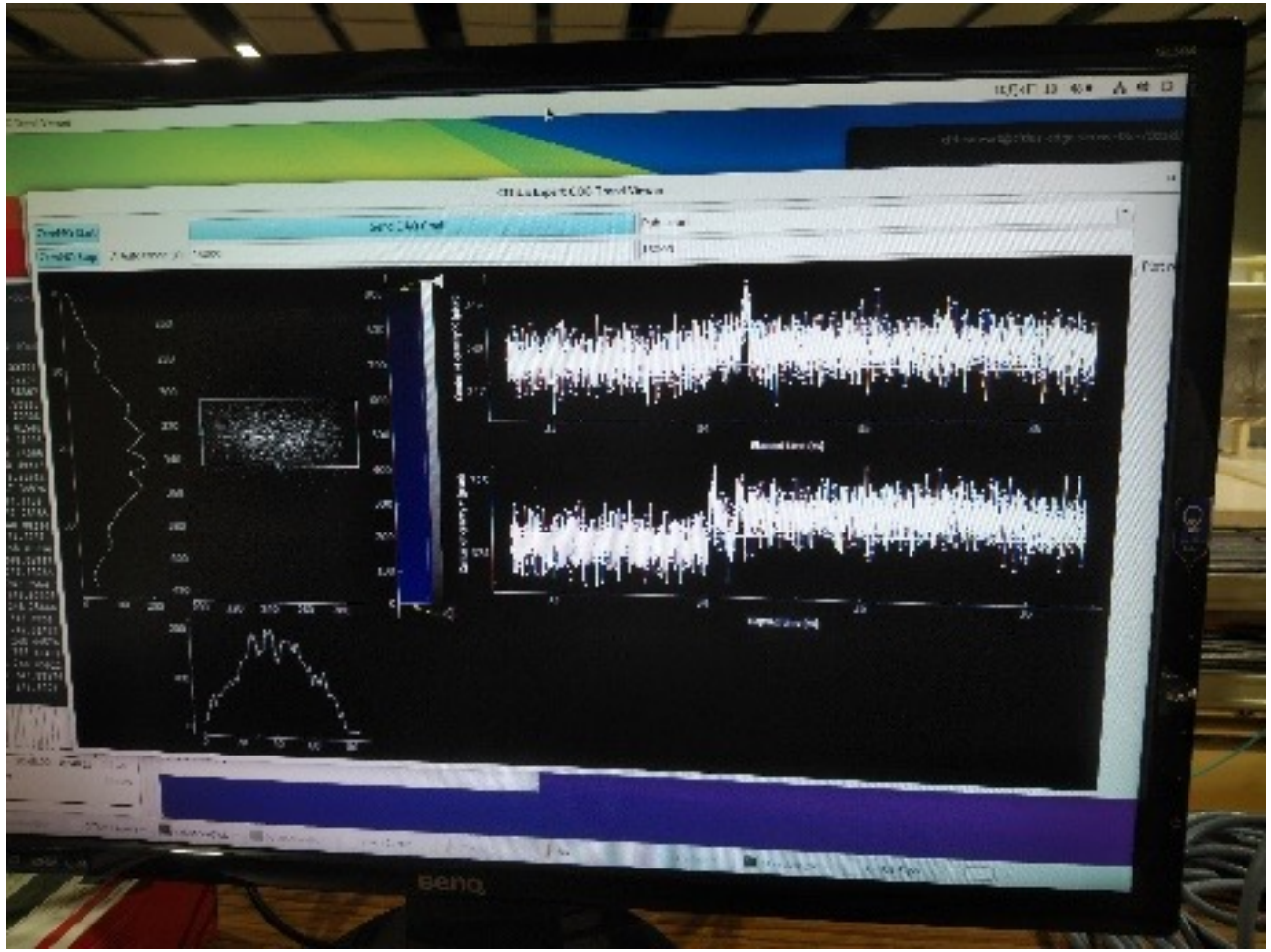




Beam Position Trends

sub-second feedback by using this monitor to the accelerator system is feasible

note: every second, we get 17.4 kframes.

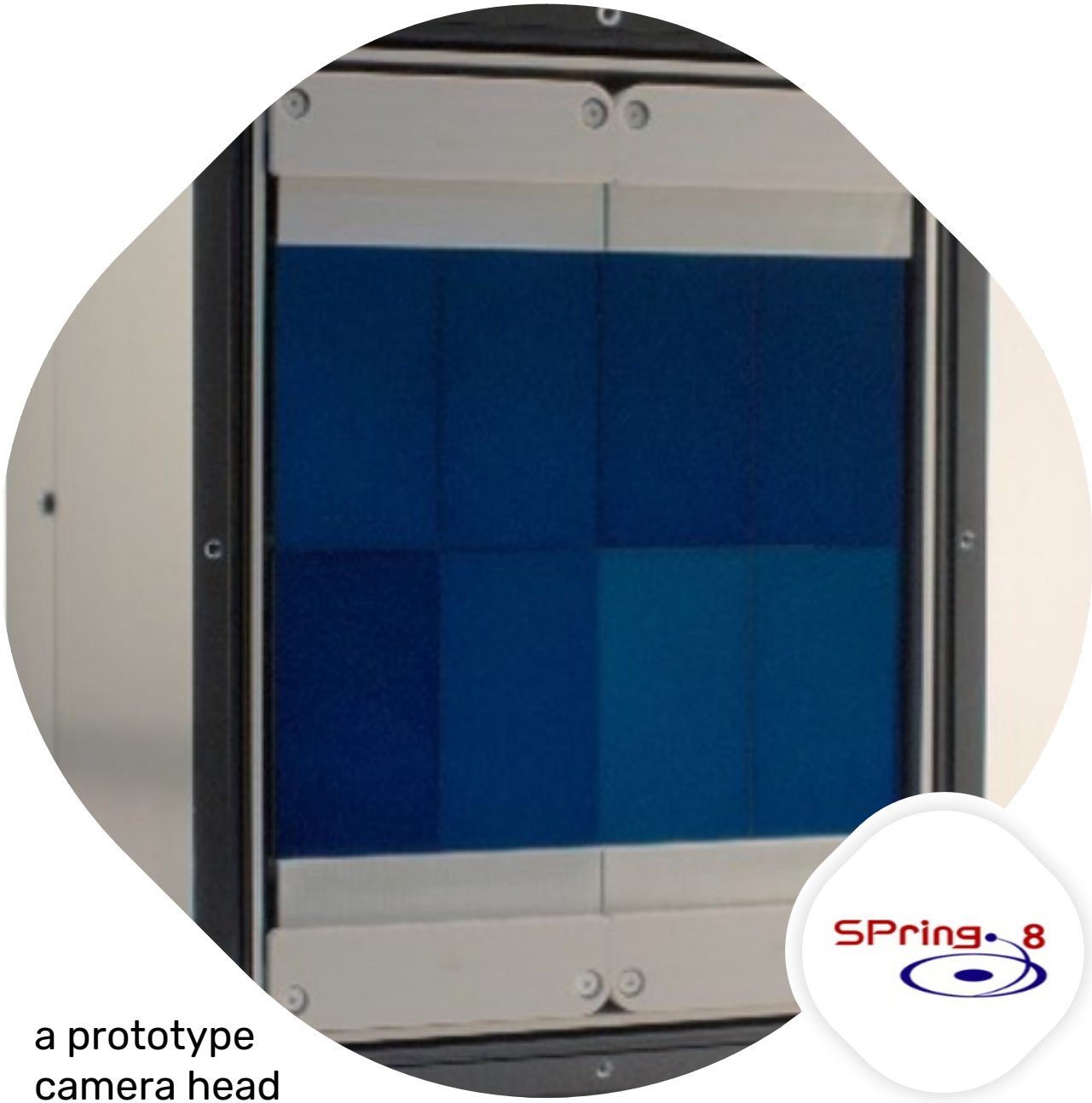


X-ray Fluorescence Yield Detector for XAFS

Upgrade of SDD and/or Photon Counting Detector

Spectro-Imaging Mode

- Max. 3.2 Gcps/system @ 2.2 Mpixels
- 8 sensors
- weight < 10 kg
- 280 k x 8 module may be another option



a prototype camera head

CITIUS detector

Architecture [1-3]

Integrating Pixel & High Frame Rate

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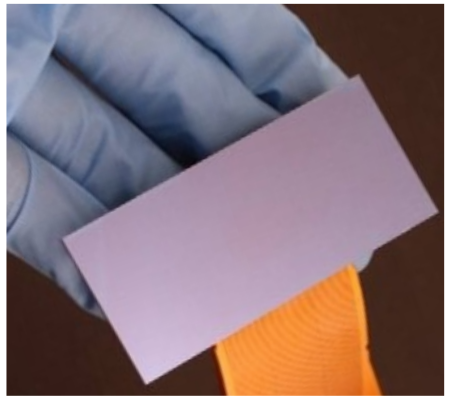
	Peak Signal	1,800 phs. @ 12 keV (6 Me-)	17,000 phs.@ 6 keV (28 Me-)
	Frame Rate	17.4 kfps	5 kHz
	Sat. Count Rate @12 keV	30 or 600 Mcps	-
	Pixel Readout Rate	4.87 Gpixels/s	1.4 Gpixels/s



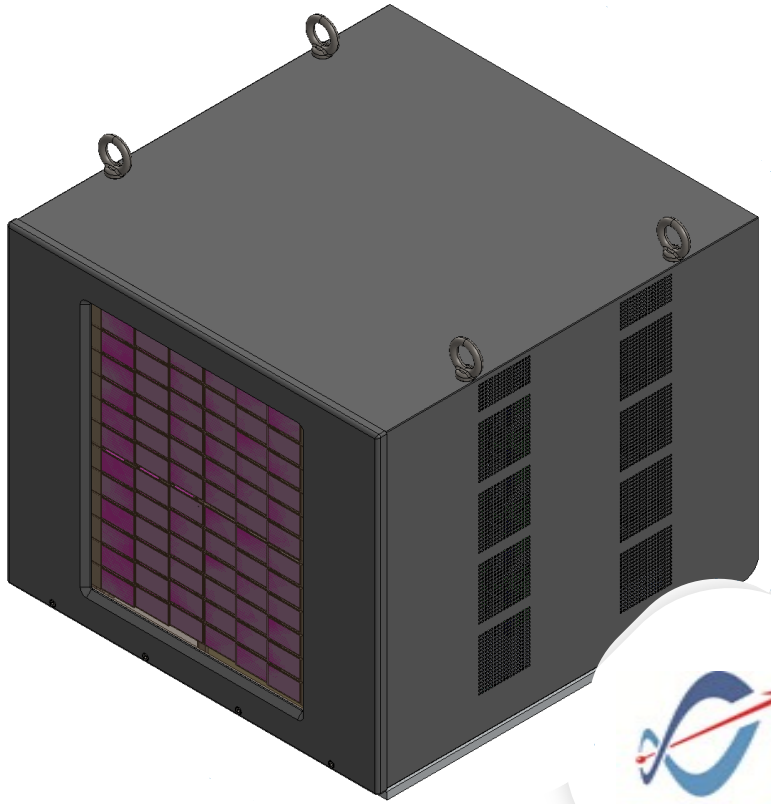
20.2M Large Area Detector

To be integrated to SACLA in 2023

- 20.2 Mpixel @ 60 frames/s
  - 72 sensors

Development for SPring-8 MX beamline under discussion

- 20.2 Mpixel @ 17.4 kfps



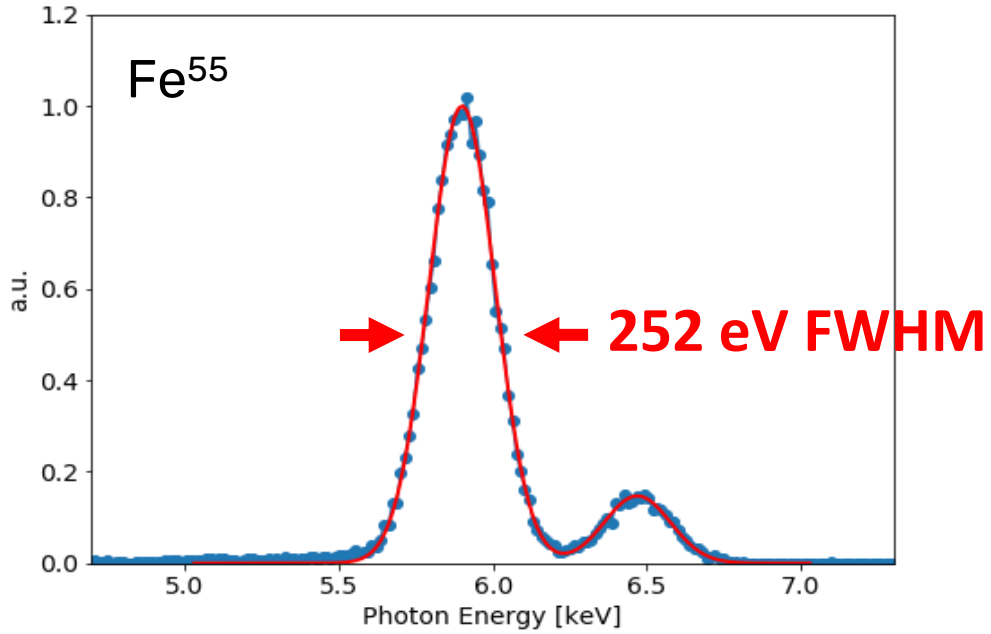
20.2 M: Sensor Sub System

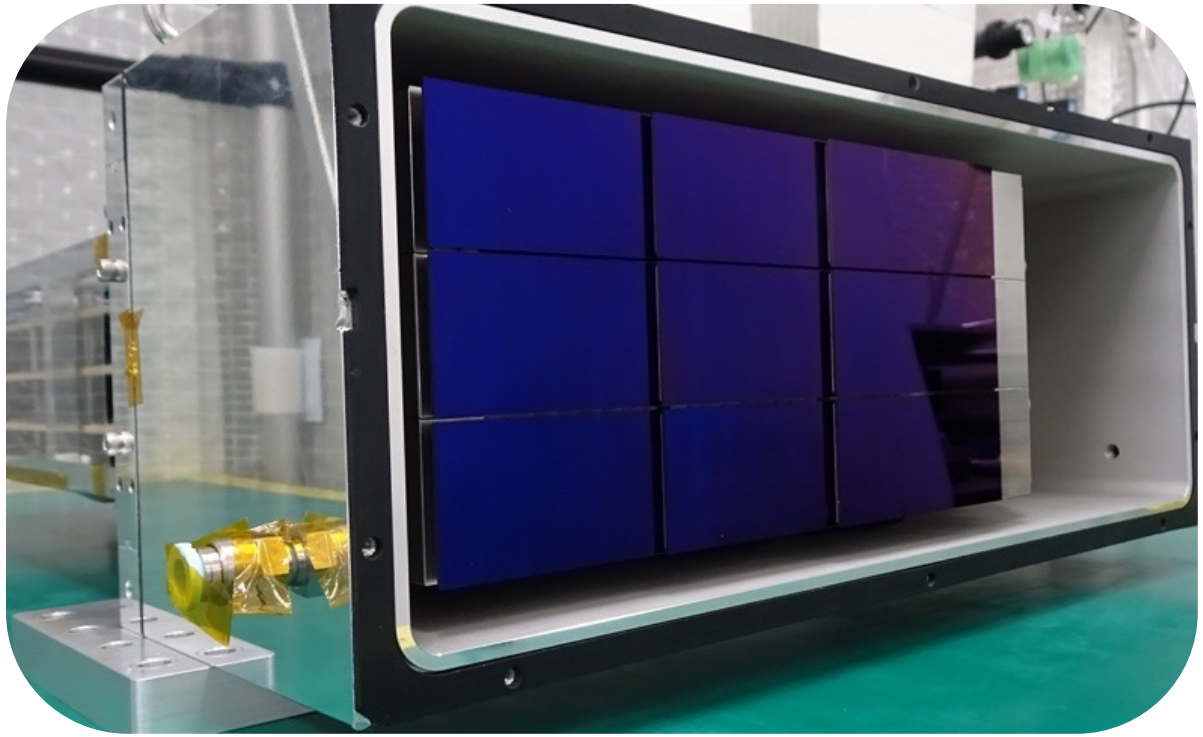
Each Sensor Sub System can be tested and calibrated.

2.52 Mpixels

Spare Units in case of damage

Optimized for SACLA operation





Summary

Motivation, Development History

Architecture: Integrating pixels & High Frame rate

- High Count rate: *945 Mcps/pixel (18 Tcps/cm^2)*
- Faster Recording: *17.4 kframes/s for full frame readout of 280k pixels*
- *Spectro-imaging:* *242 eV FWHM @ 5.9 keV*

Detector variants from 280 kpixels to 20.2 Mpixels

Issues not covered in this talk: Data

- 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

Acknowledgment

RIKEN and JASRI Team

- K. Ozaki, Y. Honjo, H. Nishino, K. Kobayashi, K. Nakajima, T. Hiraki, Y. 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

SPARE SLIDES

4

Now, CITIUS detectors are ramping up.

Any obstacle foreseen?

Data Size Estimation (1/2)

280k pixels
17.4 kframes/s

about 1 kg

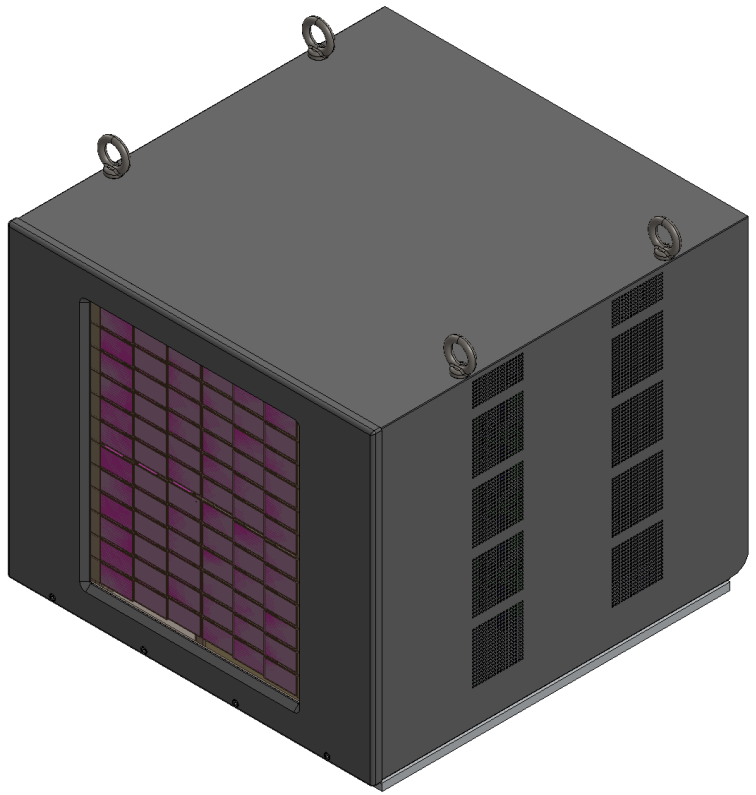
2 min.
2.4 TB

1 day
1.7 PB

552 k$/year
at AWS S3 storage
in Japan

Data Size Estimation (2/2)

20.2 Mpixels
17.4 kframes/s



1 hour
5 PB

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

8.7 km tall
500 racks & 2.2 MW
Conclusion: saving raw data is not economically feasible

FPGA-based Data Processing on-the-fly

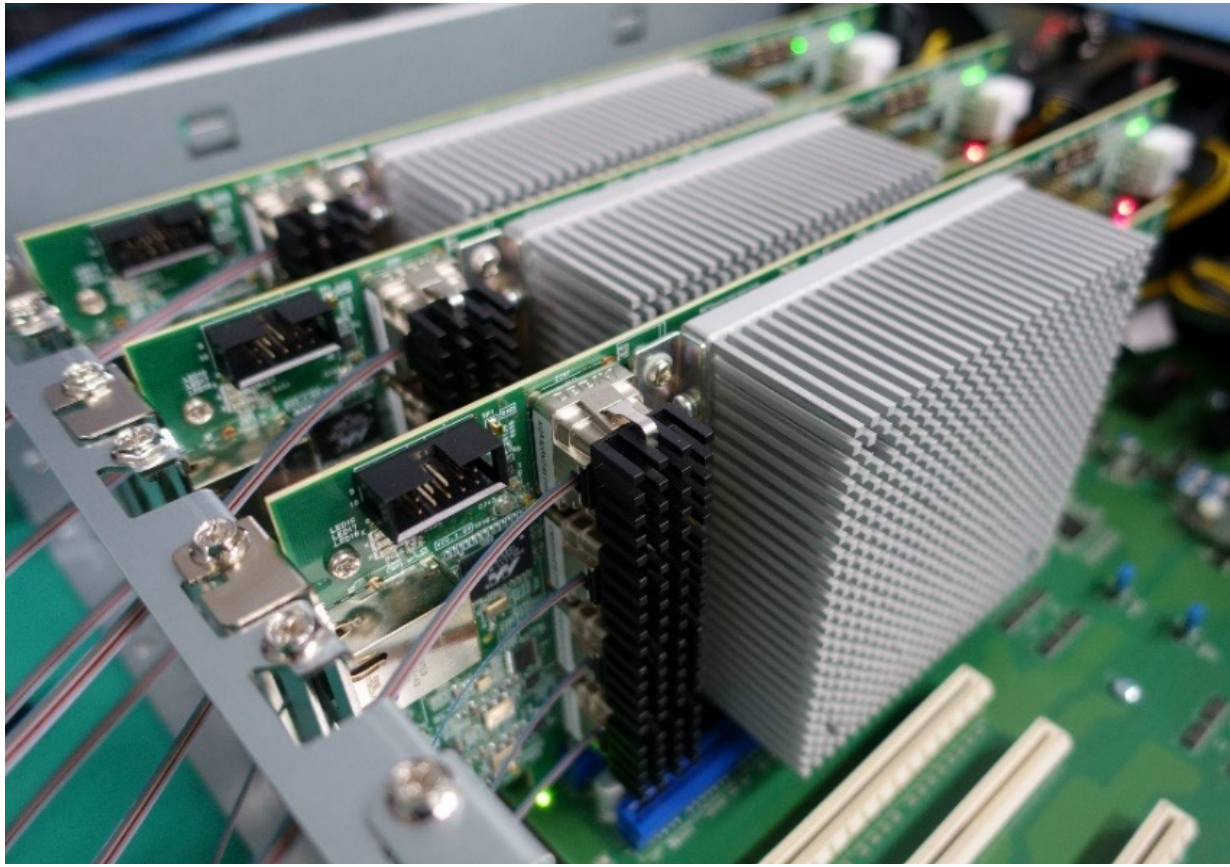
K. Ozaki, H. Nishino, et.al.,

Data-Framing Board

- support 130 Gbps data/board

Functions

- Calibration
- Preprocessing for compression
  - compression ratio of >1000 was obtained for some experiments.
- Selection of the meaningful frames
- Accumulation
- Photon-Energy Window



SPring-8 Data Center Initiative

Y. Joti, T. N. Hiraki et.al.,

Edge Computing	On-Site	Off-site
FPGA acceleration	Supercomputer under construction	Fugaku (7.6 Mcore, 540 Pflops)
	10 PB storage	HPCI supercomputers
	5 kcore CPUs	Public Cloud (Amazon etc.)