4th March 2025

SACLA Users Meeting 2025

X-ray imaging detector DIFRAS for SACLA experiments

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Collaborators

- SPring-8/SACLA
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- Konoshima chemical
- SIGMAKOKI
- GLORY Technical Solutions
- Nitto Computor Service
- JTEC Corporation
- NIKON
- PLIOPS
- TORAY

Contents

- DIFRAS： High-resolution X-ray imaging detector
- DIFRAS-widefield: DIFRAS + Large-format image sensor
- DIFRAS Edge: 100 Gbps DAQ system
- Summary

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- DIFRAS： High-resolution X-ray imaging detector
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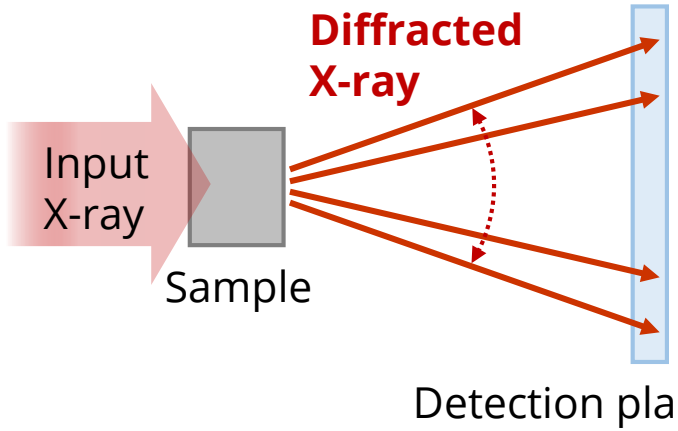
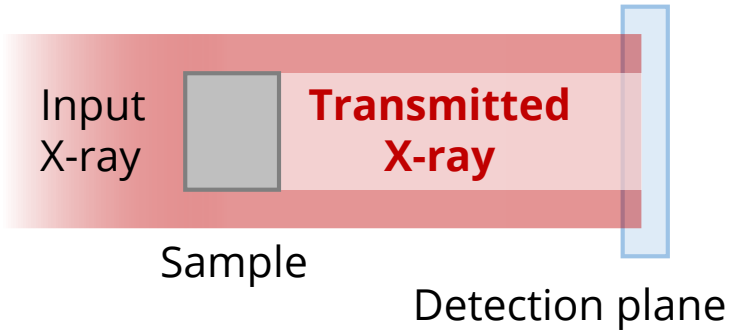
SPring-8/SACLA X-ray imaging detector

- Diffractive X-ray
  - Relatively large pixel (~ several 10 μm)
  - Large FOV to detect wide angled signal (> 100 mm)



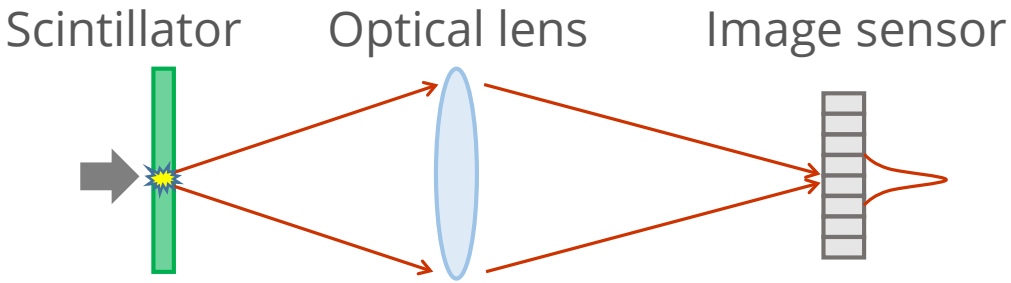
- Transmission X-ray
  - High resolution (μm ~ sub-μm)
  - FOV wider than X-ray beam size (~mm)



▶ **Development using different detection technology**

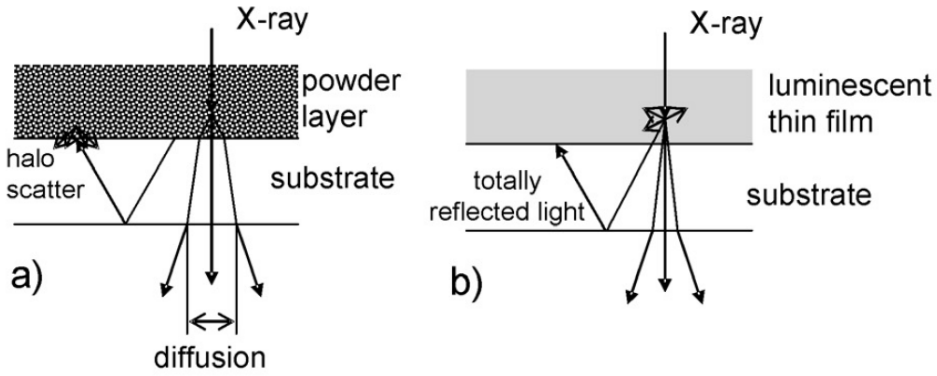
Lens-coupled X-ray imaging detector

Detector components



- X-ray to visible-light conversion in the scintillator
- Projection to image sensor through optical lenses

Resolution deterioration



H. Graafsma and T. Martin, in Advanced tomographic methods in materials research and engineering 277 (2008)

- Optical defects in the scintillator
- Transparency degradation induced by X-ray damage

▶ **Optical defects and damage layers cause photo-diffusion**

Photodiffusion-free transparent scintillator (DIFRAS)

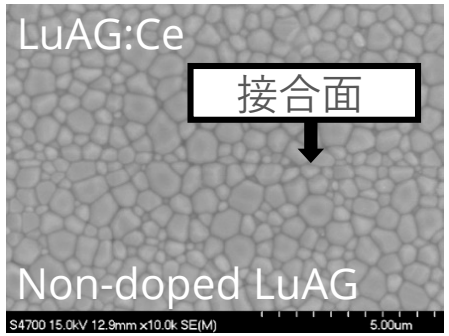
T. Kameshima et al., Optics Letters 44, 1403 (2019)

Development of thin LuAG:Ce film

(a)

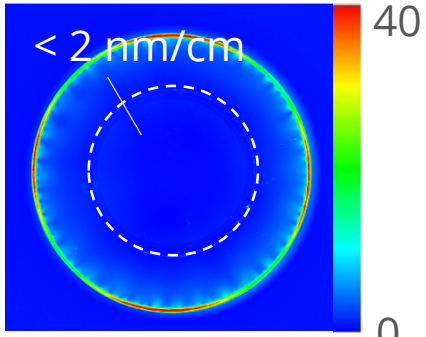
5 μm-thick LuAG:Ce

(b)



SEM image of bonding area

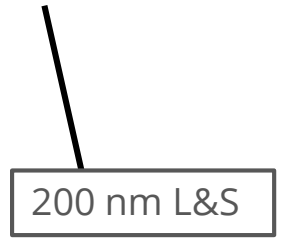
(c)



Distortion map

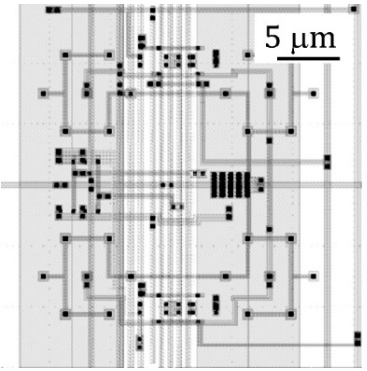
Resolution evaluation

(d)



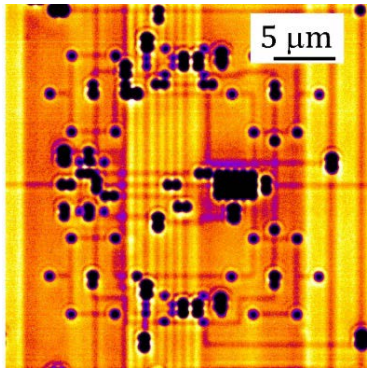
X-ray transmission image of test chart

(e)



200 nm process VLSI circuit drawing

(f)



X-ray transmission image of VLSI

- Identical host material
- Fully-densified polycrystalline
- sub-nm grain boundary

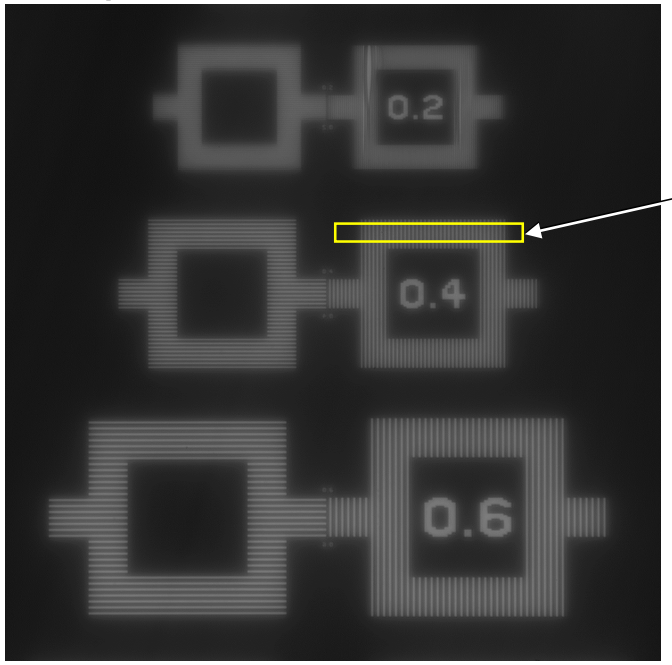
- < 200 nm L&S cutoff resolution
- Uniform spatial resolution across the entire field of view

▶ Quasi-diffraction-limited resolution & Damage-free operation

Matching scintillator thickness and lens depth of field

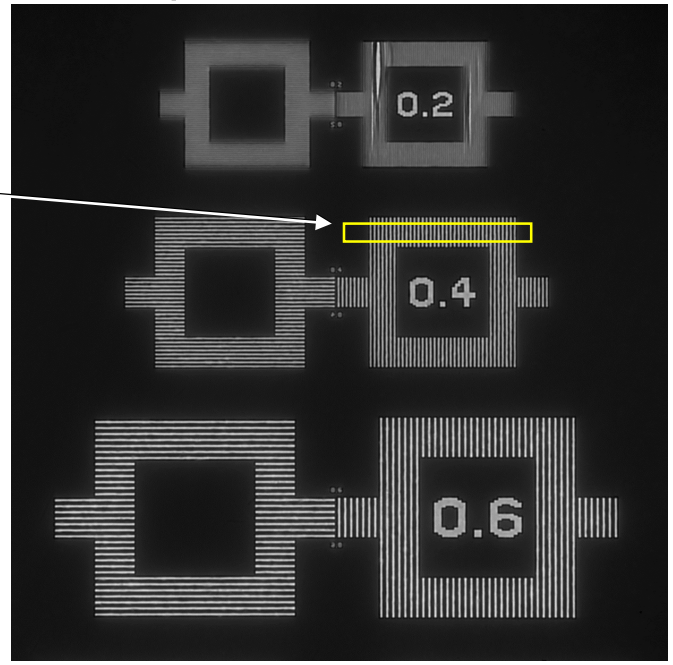
Courtesy of Dr. M. Kanaoka, Mr. S. Iguchi (JTEC Corporation)

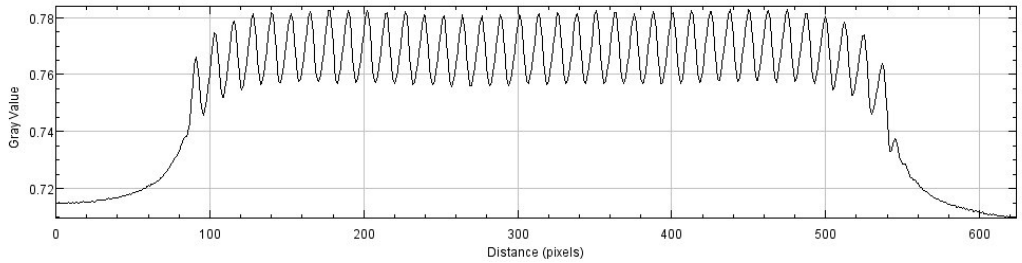
5 μm-thick LuAG:Ce

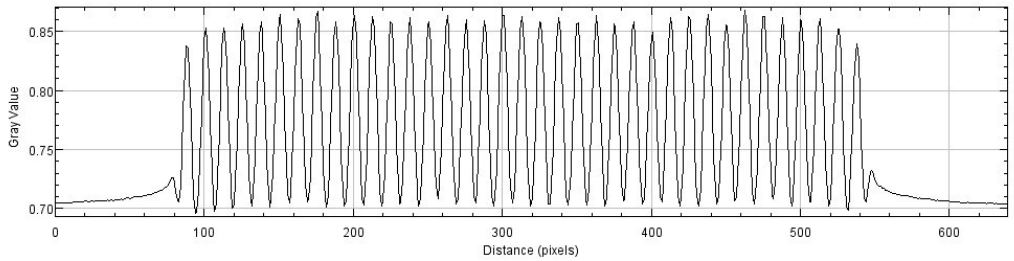


Profile area

1.4 μm-thick LuAG:Ce





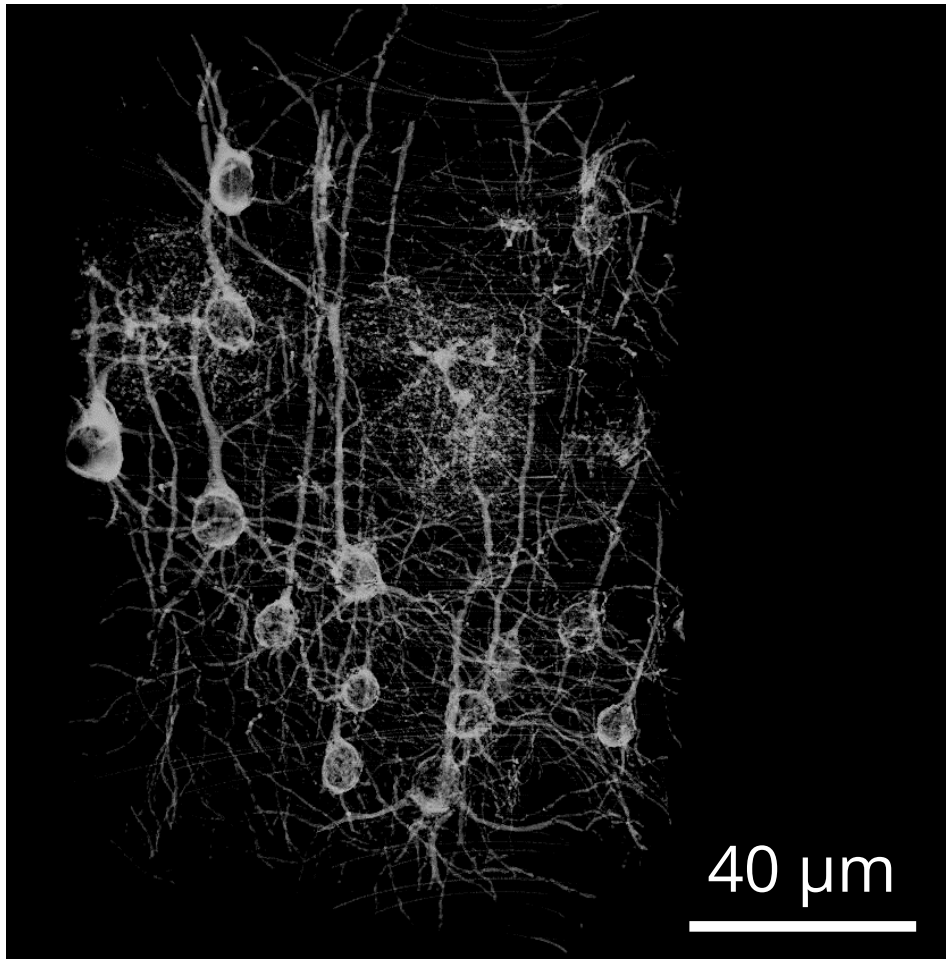


▶ **Close to 100 % visibility at 400 nm L&S**

1.4 μm-thick DIFRAS application

Courtesy of Dr. H. Takano, Dr. Y. Kohmura (RIKEN RSC), Dr. M. Murayama, Dr. M. Odagawa (RIKEN CBS)
Prof. R. Mizutani (Tokai univ.), Prof. Y. Takayama (Tohoku univ.)

Sample:	Golgi staining brain sample
Light source:	SPring-8 BL29XUL EH3, 8 keV
Effective pixel size:	137 nm
Effective FOV:	730 μm (H) x 631 μm (V)



DIFRAS

Capillary

▶ **Proximate capillary imaging at Fresnel zone**

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Large-format image sensor + Large image-circle optics

T. Kameshima and T. Hatsui, J. Phys.: Conf. Ser. 2380 012094 (2022)

I. Implementation of the largest format COTS image sensor

II. Construction of microscopic optics with an large image circle

III. Fabrication of thin-film scintillator with active area matched to FOV

SONY large-format image sensor

- 130 ~ 250 MPixels
- Diagonal 57 ~ 67 mm
- 14 ~ 16 bit depth

Nikon Rayfact series

- Large image circle Φ60 ~ Φ82
- High NA
- Low distortion
- Homogeneous relative illumination

▶ Matching design of image sensor diagonal and image circle

DIFRAS widefield configuration list

T. Kameshima and T. Hatsui, J. Phys.: Conf. Ser. 2380 012094 (2022)

		Lens A1	Lens A2z	Lens A2	Lens A3	Lens A4	Lens A5
Lens category		Development	COTS	COTS	COTS	COTS	COTS
NA		0.85	0.35	0.35	0.27	0.159	0.083
Magnification		20x	10x	7x	5.2x	3.5x	1.0x
Image circle		Φ67	Φ82	Φ64	Φ64	Φ67	Φ67
Resolution (L&S)	**[μm]**	~0.2	0.45	0.45	0.6	1.0	4
FOV	**[mm²]**	2.6 x 1.9	5.3 x 4.0	7.6 x 5.7	10.3 x 7.7	15.2 x 11.4	53.3x 40.0
Photon energy	**[keV]**	≤ 10	20~50	20~50	20~50	50 ~ 200	100 ~ 200
Status		Pending	**Completed**	**Completed**	**Completed**	**Completed**	**Completed**

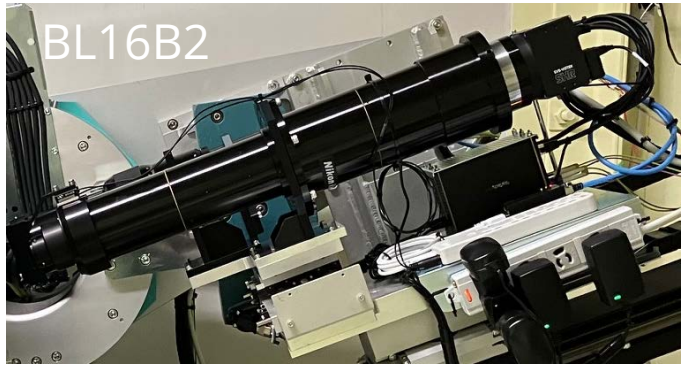
▶ **Six systems is designed to provide quasi-diffraction-limited resolution & 2 ~ 50 mm FOV.**

DIFRAS widefield series

DIFRAS-wf-1x

DIFRAS-wf-3.5x

DIFRAS-wf-7x



DIFRAS-wf-5.2x

DIFRAS-wf-10x

▶ **Five systems are available for SPring-8 and SACLA**

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Expanding the camera output bandwidth

- Scientific CMOS
  - 2048 x 2048 (**4M pixels**)
  - 30~**100 fps**
  - 16 bit
  - 2~3 electrons readout noise
- Latest machine vision CMOS
  - 19200 x 12800 (**250 Mpixels**) x60 larger
  - **12,000 fps** x120 larger
  - 12 ~ 16 bit
  - 2~3 electrons readout noise

Camera bandwidth

6.7 Gbps

~ 100 Gbps

► **Bandwidth increased by more than 10-fold**
► **Wide bandwidth DAQ is required for accepting this without data defects**

Specification

I. 100 Gbps direct recording to SSDs
II. Wide camera compatibility
III. Over 100 TB of fault-tolerant storage
IV. Instant data readout for feedback analysis

Issues for deployment

- Cost reduction for operation, implementation, and maintenance
- Connectivity to data center

DIFRAS Edge

Integrated implementation of frame-grabber, storage, NVIDIA GPU

AMD EPYC
PCIe x128

NVIDIA Mellanox NIC
25 – 100 GigE

PLIOPS
NVMe accelerator

Enterprise
NVMe SSD

NVIDIA GPU

TYAN 2U 1S server

- **One-stop system (data acquisition, recording, and analysis)**
- **Large capacity NVMe storage (100 Tbyte RAID5)**
- **Over 700 Pbyte endurance and hardware data compression**

► Shift from network distributed system to single PCIe based system (to get x10 higher bandwidth)

GCapture

GenICam Capture (**GCapture**)

- GenICam・GigEVision2・USB3Vision・CoaXPress
- Large format and bandwidth Live & Record
  - Over 150 Mpixels, ~ 100 Gbps bandwidth
- Remote control (Python interface)
- ○Trigger record
- ○External ID synchronization

Output data structure

```
run_10001
    L image_tag1234001.tif
    L image_tag1234003.tif
    L image_tag1234005.tif
    L image_tag1234007.tif

run_10002
    L image_tag1234101.tif
    L image_tag1234103.tif
    L image_tag1234105.tif
    ⋮
```

► Functions ○ provide SACLA tag synchronization.

► Direct HDF5 output and real-time data compression is to be implemented

Verified cameras

- SVS-VISTEK
  - SONY IMX411・IMX661
  - 10 GigE、25 GigE、CoaXpress
  - 14 ~ 16 bit dynamic range

→ Widefield (> 100 Mpixels)

- EVT
  - SONY Pregius S series、Gpixel Gsprint series
  - 25GigE、100 GigE

→ Fast frame rate (several 100 ~ > 10 kHz)

- Basler
  - SONY Pregius S series
  - GigE、5 GigE

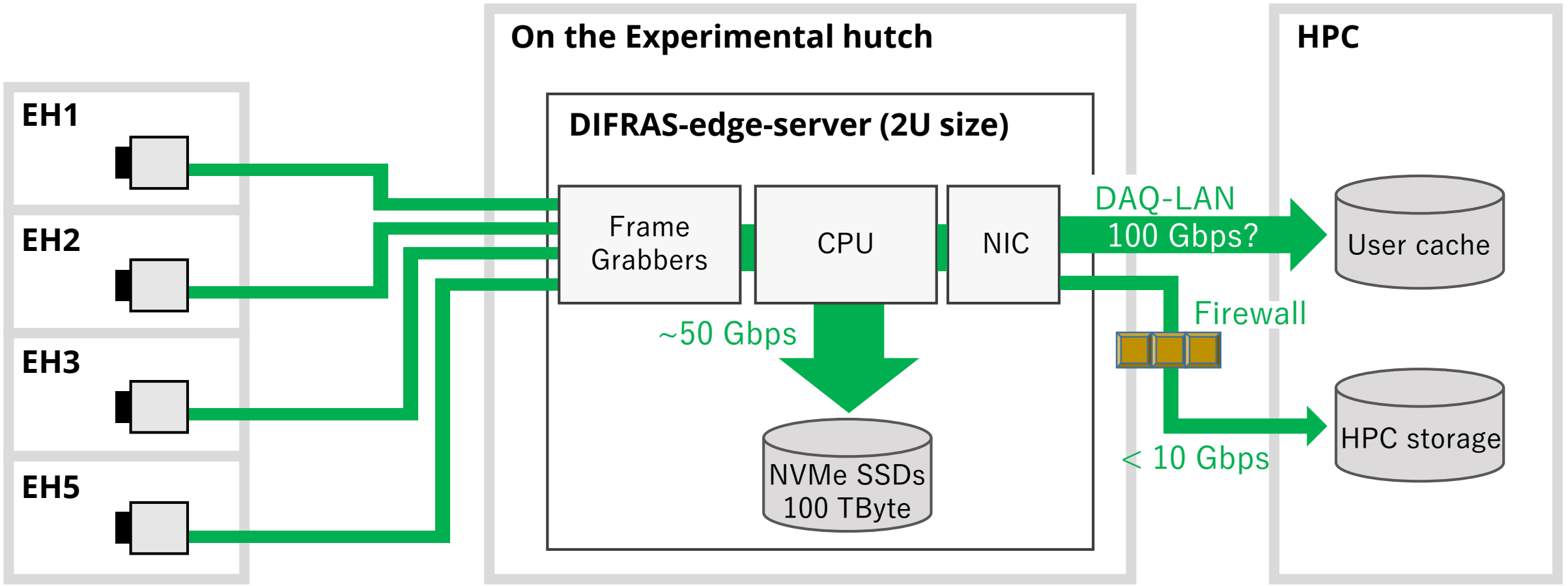
→ Cost performance (50 ~ 300k yen)

- Hamamatsu
  - CoaXpress
  - 16 bit dynamic range

→ Sensitivity (< 1 electrons)

► Wide camera compatibility. Selectable according to requirements

DIFRAS Edge installation plan



► Optical fiber distribution to whole hutches. Quick detector setup & stable operation

Summary

- DIFRAS has a resolving power close to diffraction-limit of scintillation light.
- Widefield-type camera is ready to be deployed.
- DIFRAS DAQ is designed to have 100 Gbps wide bandwidth record and wide camera compatibility in the single edge system.
- Automatic recording synchronized with SACLA DAQ is demonstrated.

Thank you for your attention.

Appendix

Deployed detector configurations

Standard unit

	Unit	100x	50x	20xHR	20x	10x	5x	2x
NA		0.85	0.7	0.7	0.45	0.3	0.15	0.06
FOV	[mm]	Φ0.21	Φ0.43	Φ1.1	Φ1.1	Φ2.1	Φ4.3	Φ11.0
Conversion*1	[photons/10 keV]	15	10	10	4	1.7	0.4	0.07
Scintillator thickness	[μm]	5	5	5	5	15	50	50
X-ray protection		**Attenuation in the 1-mm-thick LuAG support substrate (10^{-43} for 10 keV)**						

Off-axis unit

	Unit	20x	10x	5x	2x
NA		0.45	0.3	0.14	0.055
FOV	[mm]	Φ1.1	Φ2.1	Φ4.3	Φ11.0
Conversion*1	[photons/10 keV]	4	1.7	0.4	0.07
Scintillator thickness	[μm]	5	15	50	50
X-ray protection		**All lenses evacuation from X-ray optical axis**			

- So far about 10 detector systems are deployed to SPring-8/SACLA.
- These imaging units and scintillators are **commercially available from SIGMAKOKI CO.,LTD**.

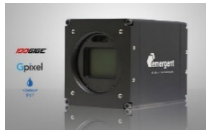
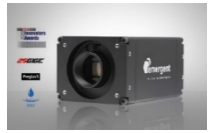
Small pixel image sensor + High NA low magnification lens

		20xHR	10xHR	5xHR	2.5xHR	1xHR
NA		0.7	0.61	0.31	0.15	0.061
Resolution(L&S)	**[μm]**	0.23	0.26	0.51	1.06	2.6
FOV with IMX530	**[mm²]**	0.73 x 0.63	1.47 x 1.27	2.94 x 2.53	5.87 x 5.08	14.7 x 12.7
Scintillator thickness	**[μm]**	2.3	3.4	13.3	56.2	342

- SONY Pregius S series (2.74 small pixel)
  - IMX530: 5320 x 4608, 2.74 μm pixels, 58 fps@12bit, diagonal 19.3 mm
  - IMX901: 8016 x 2048, 2.74 μm pixels, 91 fps@12bit, diagonal 22.7 mm

▶ 4~ 20 factor FOV increase by matching spatial resolution & sampling

List of verified cameras on GCapture

	(A) IMX411 SVS-VISTEK shr411MXGE	(B) IMX661 SVS-VISTEK shr661MCX12	(C) Gsprint4521 EVT HZ-21000-G	(D) Gsprint4502 EVT HZ-2000-G	(E) IMX530 EVT HB-25000-SB	(F) IMX547 Basler a2A2448-105g5mBAS	(G) qCMOS Hamamatsu C15550-20UP
							
Feature	**Widefield**	**Widefield/Fast**	**Wide bandwidth**	**Fastest**	**Fast**	**Low cost**	**Low noise**
Format	14,192 x 10,640	13,400 × 9,528	5120 × 4096	2048 × 1216	5320 × 4600	2472 × 2064	4096 x 2304
Frame rate	6.2 Hz	20.3 Hz	542 Hz	3426 Hz	105 Hz	106 Hz	120/5 Hz
Bit depth	12・16	8・10・12・14	8・10・12	8・10	8・12	8・12	8・16
Noise	~ 3 e-	~ 3 e-	~ 3 e-*	~ 3 e-*	~ 2 e-	~ 2 e-	0.43/0.27
Shutter	RS	RS	GS	GS	GS	GS	RS
Interface	10 GigE	CoaXPress	100 GigE	100 GigE	25 GigE	5 GigE	CoaXPress
Bandwidth	**10 Gbps**	**25 Gbps**	**91 Gbps**	**68 Gbps**	**25 Gbps**	**5 Gbps**	**17 Gbps**

* at high gain

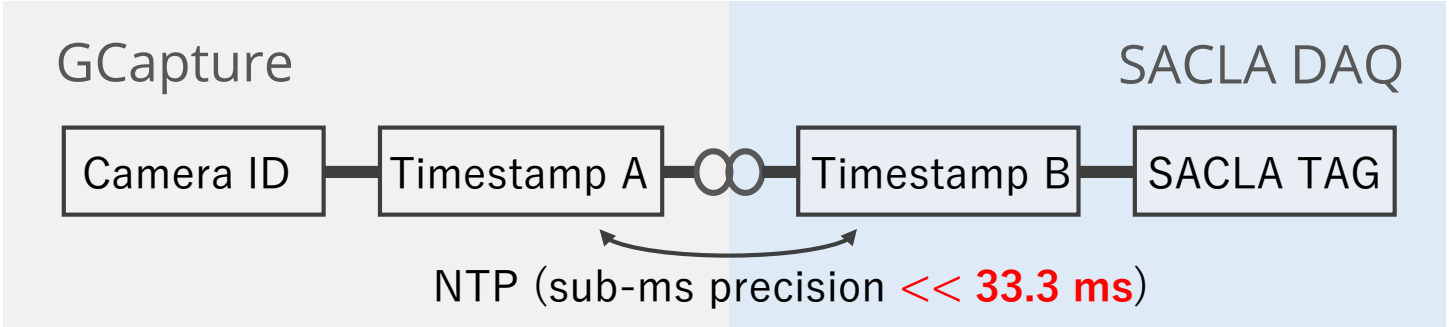
► GigE~100GigE + CoaXPress (CXP-12) are available

GCapture operation at SACLA

Output data structure

```
run_10001
    L image_tag1234001.tif
    L image_tag1234003.tif
    L image_tag1234005.tif
    L image_tag1234007.tif
    L image_tag1234009.tif
run_10002
    L image_tag1234101.tif
    L image_tag1234103.tif
    L image_tag1234105.tif
        ⋮
```

ID synchronization



- Camera ID & SACALA TAG is linked via NTP time synchronization.
- Short-period synchronization can handle master clock drift and loss.

After trigger to record past frames

- GCapture has image buffers to store frames for several seconds.
- Large latency arising from SACLA run generation is acceptable.

► GCapture can provides automatic data acquisition synchronized with SACLA run