Integrating-pixel detectors development at SPring-8 and SACLA

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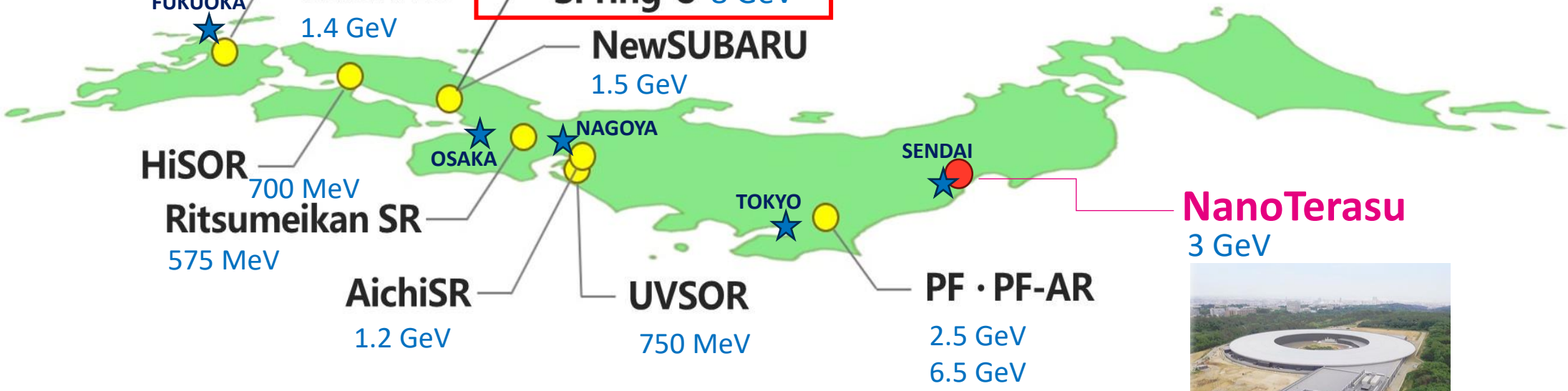
RIKEN SPring-8 Center

With materials from T. Ishikawa (SPring-8/SACLA), T. Yabuuchi (SACLA), T. Hatsui (Detectors)

XDEP workshop
6th February 2024

SR light sources and XFEL in JAPAN



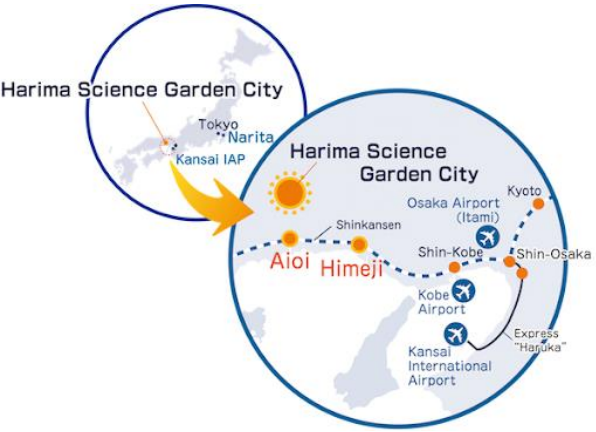
- 9 Synchrotron Light Sources
- 1 XFEL

FY2024: Start of operation

SPring-8 and SACLA

http://www.spring8.or.jp/en/

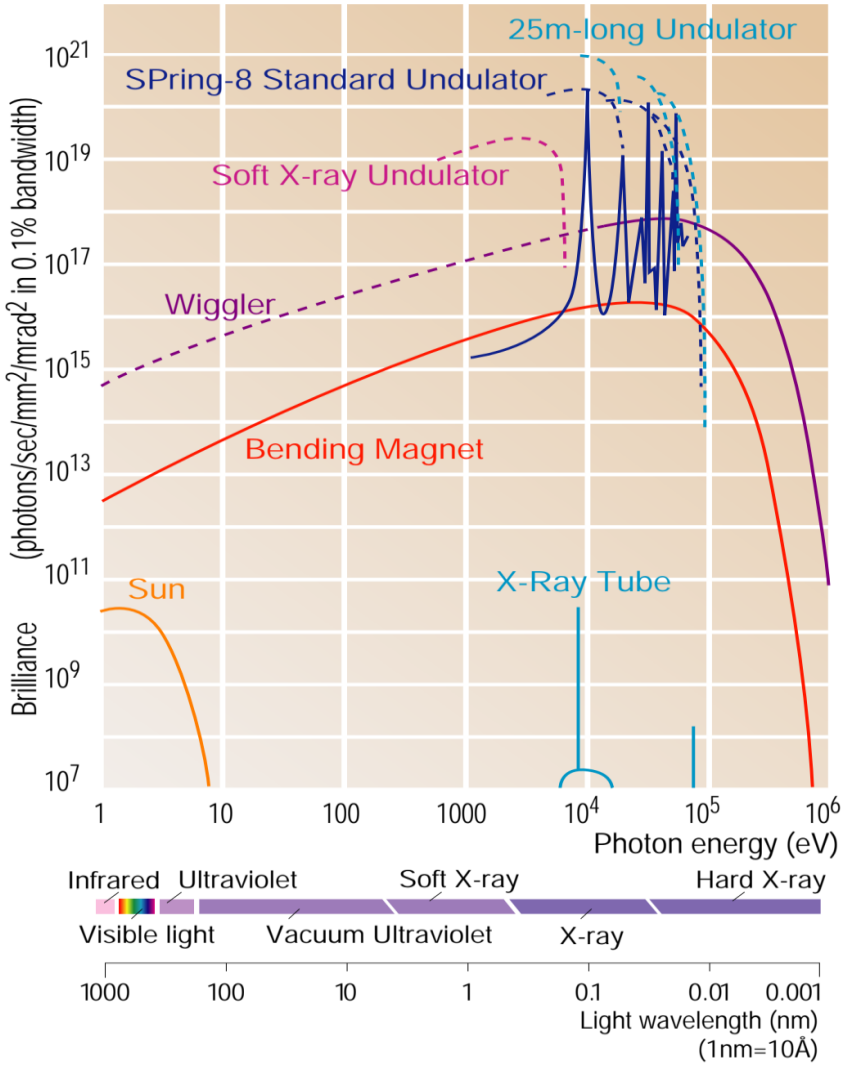
In HYOGO prefecture



- ~40 km from HIMEJI
- ~130 km from OSAKA
- ~600 km from TOKYO

General Features of SPring-8

http://www.spring8.or.jp/en/

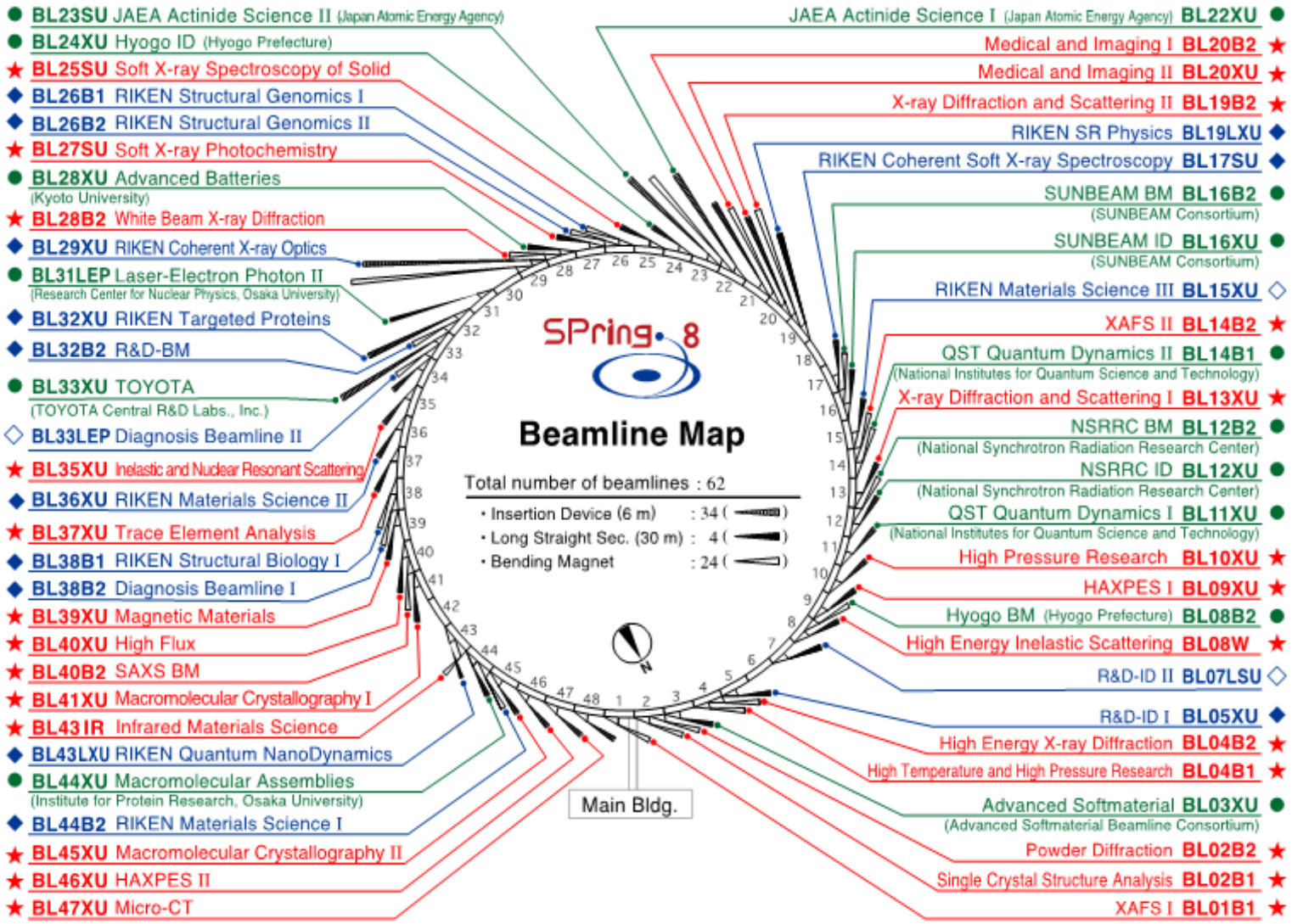


Construction: 1991-1997
Operation: 1997- …
8 GeV, Circumference: 1436 m

- Synchrotron radiation ranging from the soft X-ray (photon energy 300 eV) to hard X-ray region (300 keV) with the highest brilliance in the world. High-energy gamma rays (1.5-2.9 GeV) and infrared radiation are also available
- Many undulators (up to 38) can be installed and they can be used independently
- Advanced experimental facilities (medium-length beamline Facility, 1 km-long Beamline Facility)

SPring-8 beamlines

Number of beamlines in 2023: **57** *(62 possible)*



◆ RIKEN Beamline (16)

Mainly used for RIKEN's own research activities with partial availability for public use

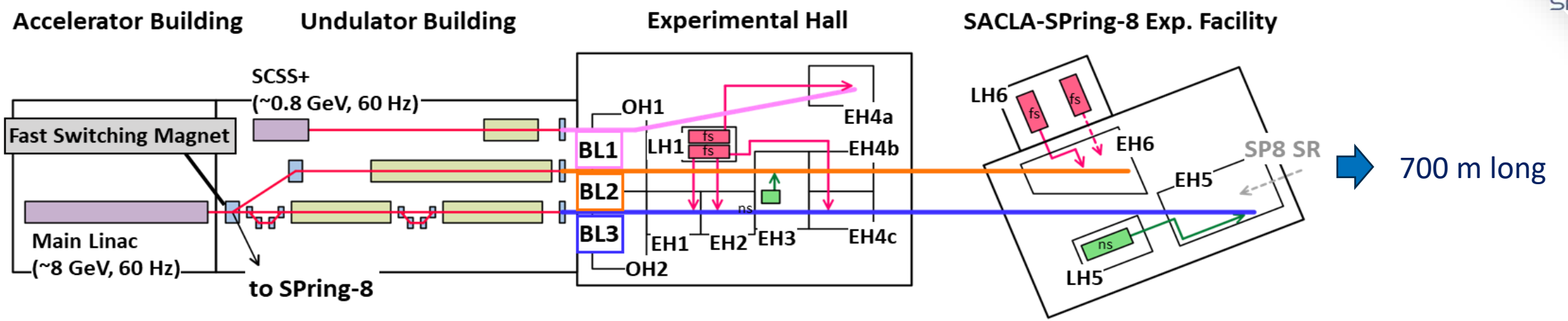
★ Public Beamline (26)

80% of operation time provided for the public use (20% for coordination)

● Contract Beamline (15)

Constructed by industrial, academic or governmental organizations in Japan and abroad. Contract beamlines are used by themselves.

SACLA beamlines



	BL1 (SXFEL)	BL2 (HXFEL)	BL3 (HXFEL)
FEL Operation for Users	Since July 2016	Since April 2015	Since March 2012
Photon Energy	**40-150 eV**	**4-22 keV**	**4-22 keV**
Pulse Duration	~30 fs	<10 fs	<10 fs
Band Width (Pink)	~10^{-2}	~3×10^{-3}	~3×10^{-3}
Pulse Energy	~50 μJ@100 eV	~500 μJ@10 keV	~700 μJ@10 keV
Photon Number (/pulse)	~3×10^{12}@100 eV	~3×10^{11}@10 keV	~4×10^{11}@10 keV
Repetition Rate	60 Hz	30 Hz (Max. 60 Hz)	30 Hz (Max. 60 Hz)

Fast switching magnet delivers electron beam to desired path in a pulse-by-pulse manner (to SACLA BL2/3 and SPring-8)

Pulse number per second: 60 pps

SACLA has been operating for 10+ years, providing access to users (~100 user experiments per year)

SR Science at SPring-8 / SACLA

Various fields of thematic in fundamental and applied research

Material science	Metal material Non-metal material Magnetic materials Semiconductors & Electronics Crystal structure & Molecular structure
Life Science / Medicine	Life science Drug discovery Medecine and Health Care
Environmental science	Living Environment Energy
Earth Science / Astronomy	Earth materials, meteorite's structure and cosmic dust
Industrial use	Material evaluation in the industrial world

+ Nuclear physics

In 2022, a booklet has been published illustrating latest press-release of SPring-8 / SACLA achievements in relation to Sustainable Development Goals

➡ Specific innovative instrumentation and services are also developed:

accelerator components, optics, **DETECTORS**, sample environment, automation, data center, etc

Detectors development: from MPCCD to CITIUS

Silicon Integrating-pixel detectors

[Hatsui IFDEPS2021]

X-ray imager for SACLA

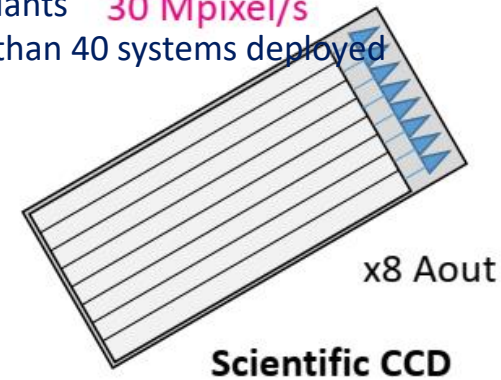
2009-2011

0.5 Mpixel 60 Hz

30 Mpixel/s

14 variants

More than 40 systems deployed



Scientific CCD with Teledyne e2v

T. Kameshima et al., Rev. Sci. Instrum. 85, 033110 (2014).

Wide dynamic range imager

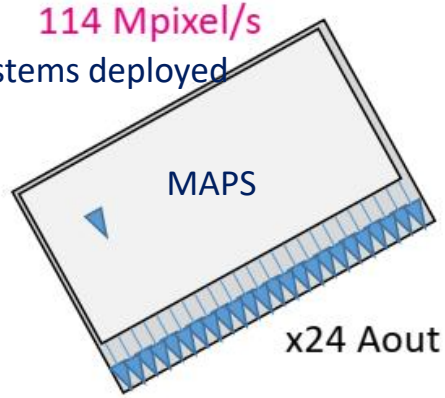
2009-2014

Peak signal 18.7 Me-/pixel

1.9 Mpixel 60 Hz

114 Mpixel/s

10 systems deployed



SOIPIX with Lapis Semiconductor

Installed to 10 BLs at SPring-8

T. Hatsui, et.al., IISW proc. 2013

High speed X-ray imager

XFEL variant 2013-

0.28 Mpixel 5,000 Hz

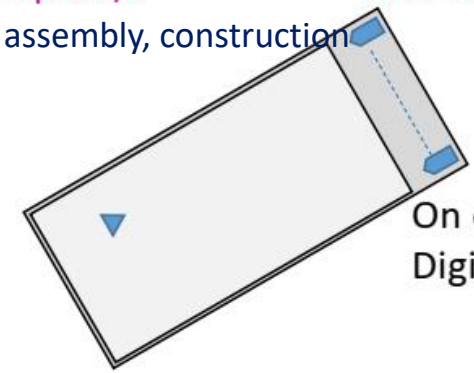
1400 Mpixel/s

Under assembly, construction

SR variant

0.28 Mpixel 17,400 Hz

4872 Mpixel/s



Dedicated CMOS Image Sensor with Sony

T. Hatsui, et.al., in preparation

CITIUS performances

[Hatsui ULiTiMA2023]

Architecture [1-3]
Integrating Pixel & High Frame Rate

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

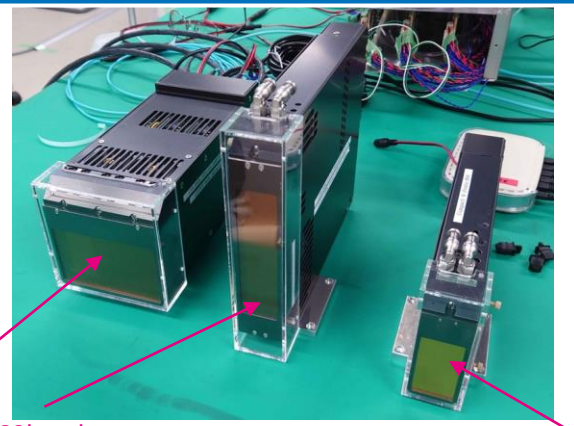
Features				
High Dynamic Range	Ultralow Systematic Error	Single Photon Sensitivity	Spectro-Imaging	High Spatial Resolution

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	17,000 phs @ 6 keV
	Frame Rate	17.4 kfps	5 kfps
	Sat. Count Rate @12 keV	30 or 600 Mcps	-
Largest System	Pixel Number	20.2 Mpixel	
	Image Area	325 × 363 mm	

SR variants

XFEL variants

840k, 560k and 280k detectors

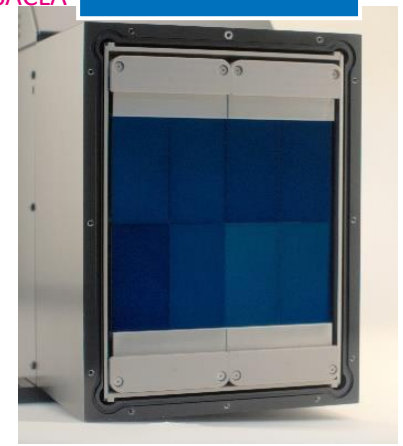


840k to be deployed on BL13XU

560k to be deployed at SACLA

280k shipped at ESRF

2.2 M detector



Proto 2.2M installed on BL29XU

CITIUS architecture choice

[Hatsui PIXEL2022]

Fully exploit CMOS image sensor process/circuitries

Chip level

On-chip ADC
- Benchmark on performance / power dissipation (techno of 2014)

Vertical signal lines
- Massively parallel

Pixel

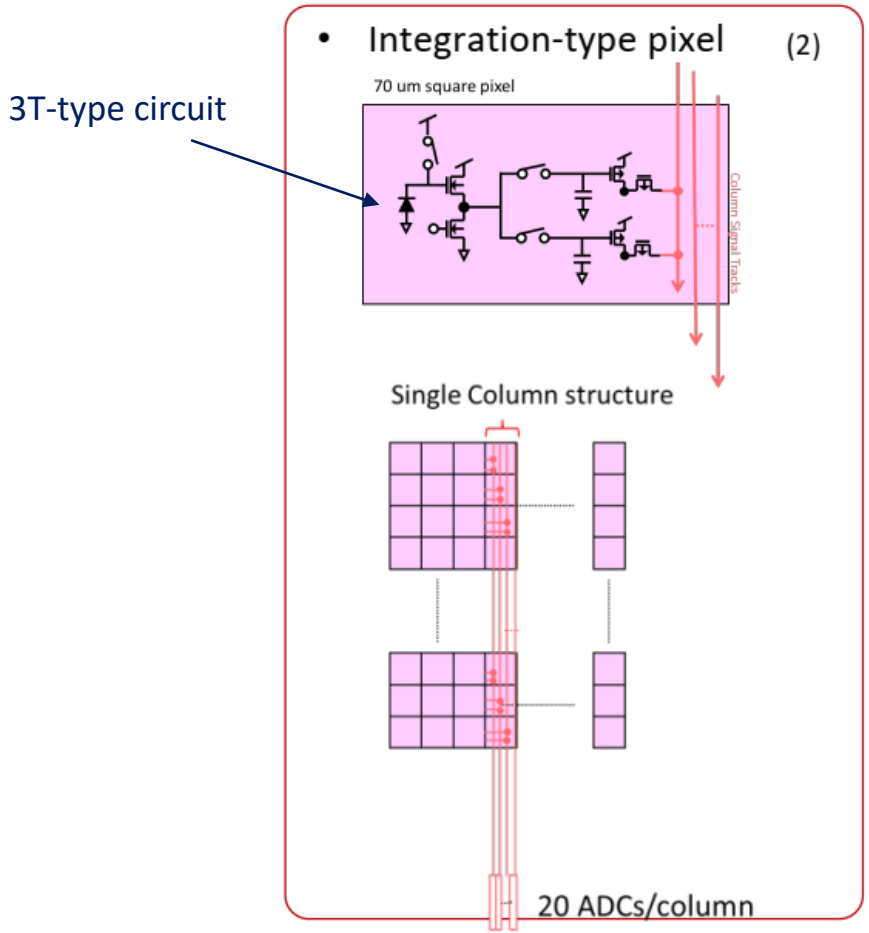
Sensor: Silicon

Global shutter operation

Multi-gain pixel circuitry without switching
- Similar to lateral overflow scheme
- No charge amplifier
- Gain selection at the periphery

Radiation hard pixel design

Power consumption: 3.6 µW/pixel



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

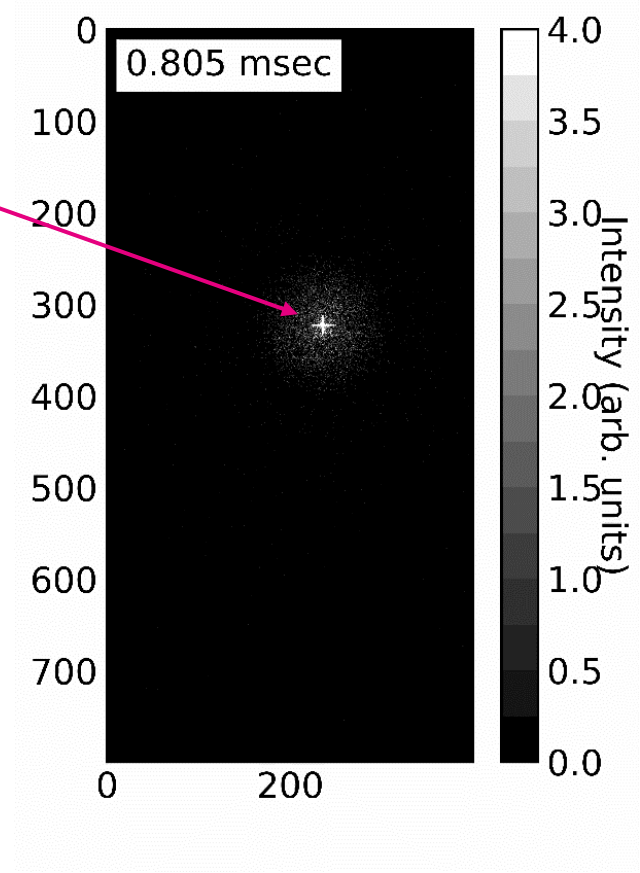
CITIUS: demonstrated performances

(not exhaustive)

[Hatsui ULiTiMA2023]

Frame Rate of 17.4 kHz demonstrated in XPCS experiments

BL29XU EH3 in July 2021
XPCS @ 8 keV
Photon flux: 2×10^9 ph/s
Direct beam was also detected



<u>CITIUS:</u>
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 0.5 mm capillary

CITIUS: demonstrated performances

(not exhaustive)

[Hatsui ULiTiMA2023]

Count rate capability and linearity

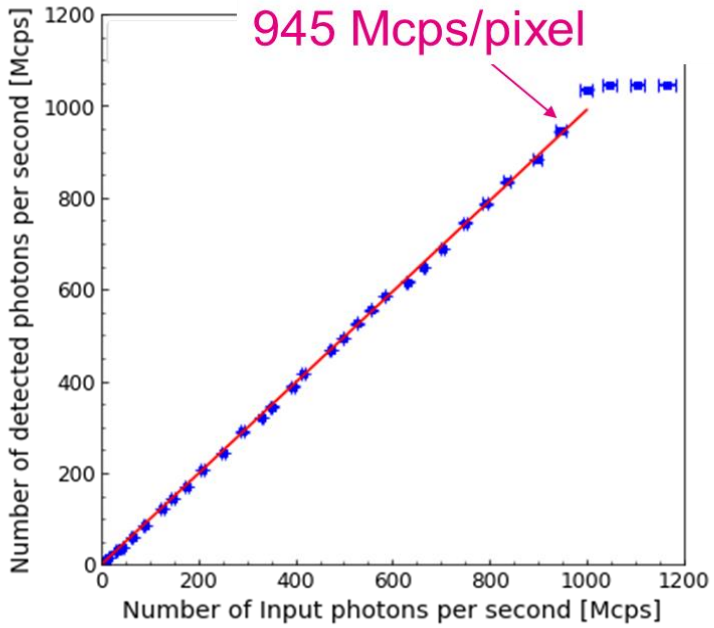
BL29XU

E = 10 keV

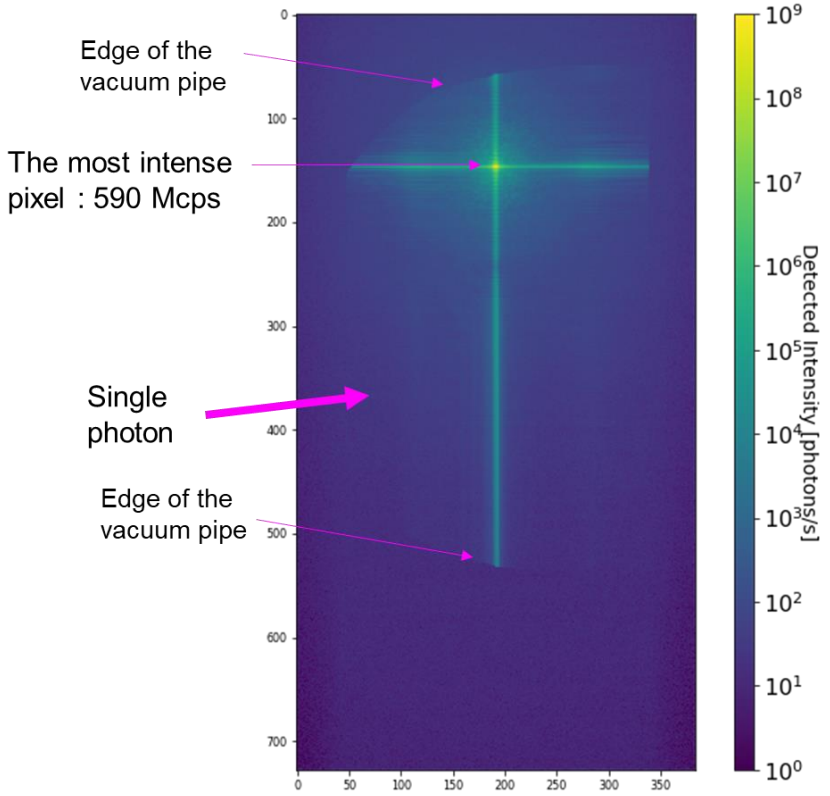
Slit to CITIUS: 15 m / Slit size: 20×20 µm

→ 8 to 9 order of magnitude observed inside a single chip

Photon Energy = 10 keV



Slit pattern observed at the extremity of the beam pipe



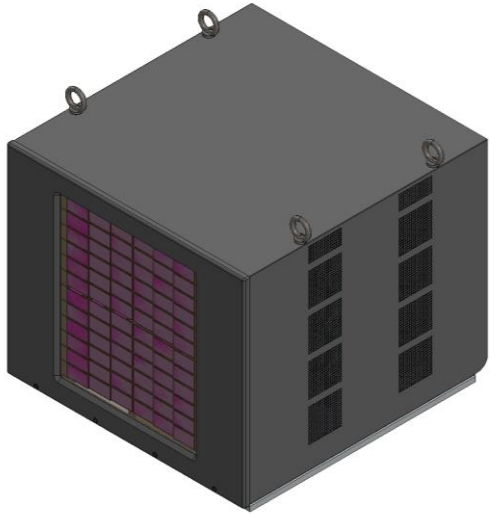
Linear response observed up to ~ 1 Gcps/pixel

CITIUS 20.2M for SACLA: deployment status

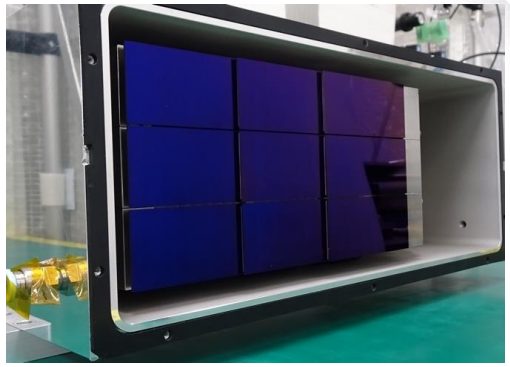
[Hatsui ULiTiMA2023]

CITIUS 20.2M to be integrated to SACLA

- 20.2 Mpixel @ 60 frames/s
- Total 1.5 kW/camera head
- About 30,000 components/system
  - 72 sensors (good yield demonstrated)
  - composed of 8 subsystems
  - 2.52 Mpixel/subsystem



General layout of CITIUS 20.2M



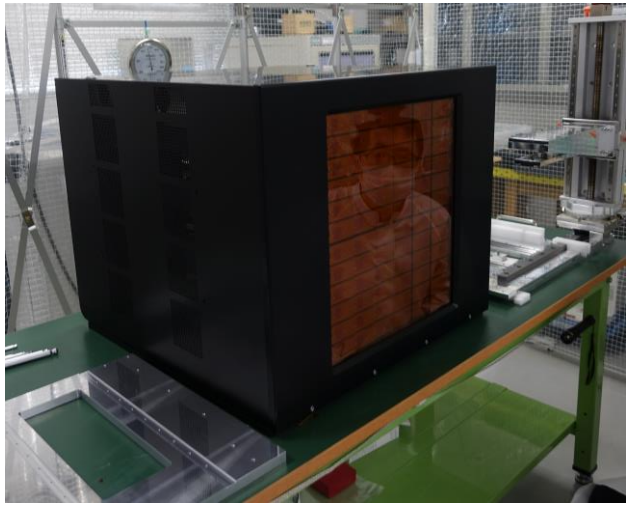
Sensors sub-system under calibration

Dedicated Data Acquisition System

- Feasibility study with 580k and 2.52 Mpixels are in progress
- Data flow management is under study (‘data deluge’)

Schedule

- Assembly and testing of the 1st subsystem were completed in July 2023
- User operation in 2024



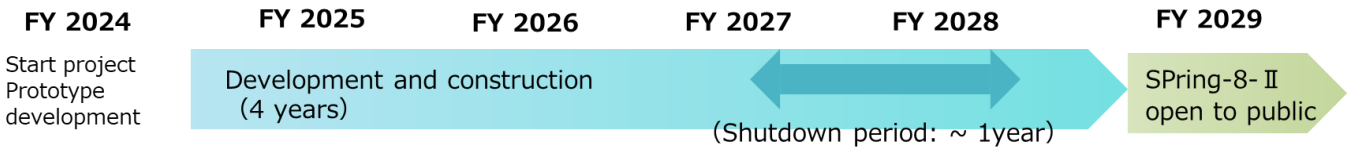
Mechanical Model under thermal testing

Summary and future plans

Detectors plan

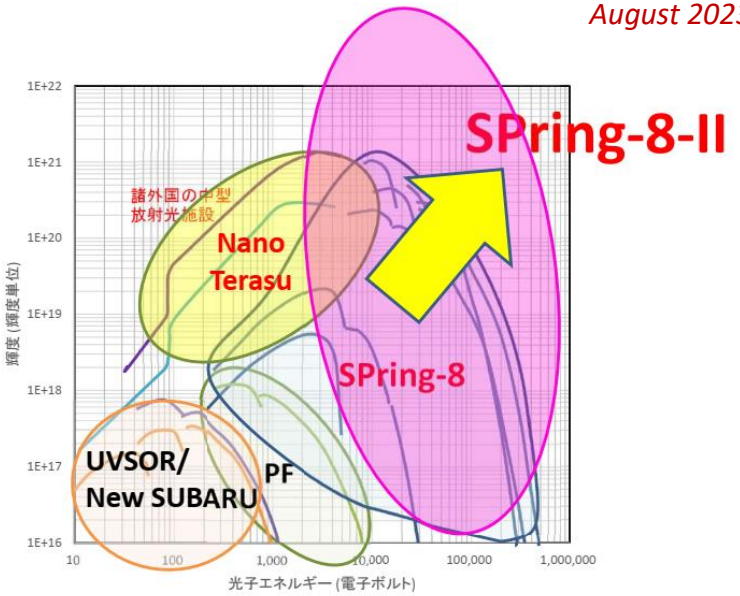
- CITIUS camera variants are under assembly and are planned to be deployed progressively for various experiments in SPring-8 and SACLA (e.g. SFX on XFEL, WAXS, ptychography, etc)
- CITIUS is under discussion for several beamline upgrades
- Other ‘commercial’ detectors are also under evaluation tests *(with high-Z material for the sensor part)*

Upgrade of SPring-8 → SPring-8-II and beyond



- SPring-8-II will be a 6 GeV storage ring-based light source with 50 pmrad horizontal emittance
- After the SPring-8-II will come SACLA-II, with 100 times more rep-rate than the present SACLA

[T. Ishikawa, SPring-8-II Symposium, August 2023]



https://new.spring8.or.jp/

Thank you for your attention