CPIX14
(Workshop on Active CMOS Pixel Sensors for Particle Tracking)

X-ray Image Sensors for SACLA and Future Ultimate Storage Ring Light Sources

September 17, 2014

RIKEN*, University of Hyogo**
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Collaborators

- RIKEN, JASRI

  All members of SACLA members, especially,

  Togo Kudo, Takashi Kameshima, Shun Ono, Kyosuke Ozaki,

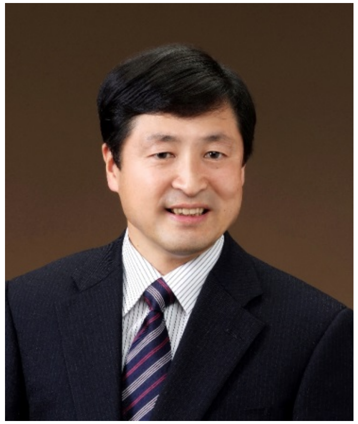
  Kazuo Kobayashi, Yoichi Kirihara, Masahiko Omodani
- Univ. of Hyogo

  Takeo Watanabe, Hiroo Kinoshita
- SOIPIX collaboration

  esp. **Yasuo Arai** (KEK), Ikuo Kurachi (KEK), Jiro Ida (Kanazawa Inst. of Technology), Takeshi Tsuru (Kyoto Univ.) , Kazuhiko Hara (Unv. of Tsukuba)
- Private Sector
  - e2v Technologies, Meisei Electric, Lapis Semiconductor, A-R-Tec Corp.
- Detector Advisory Committee
  - **Peter Denes** (Chair, LBNL), Andrew Holland (The Open Univ.), Grzegorz Deputch (Fermilab), **Yasuo Arai** (KEK)

Contents

Self-introduction



<u>Nobukazu Teranishi</u>

- 1978–2000, NEC
- 2000–2013, Panasonic
- 2013–present, U. of Hyogo, Shizuoka U., RIKEN

I have developed image sensors and cameras for 35 years since 1978.

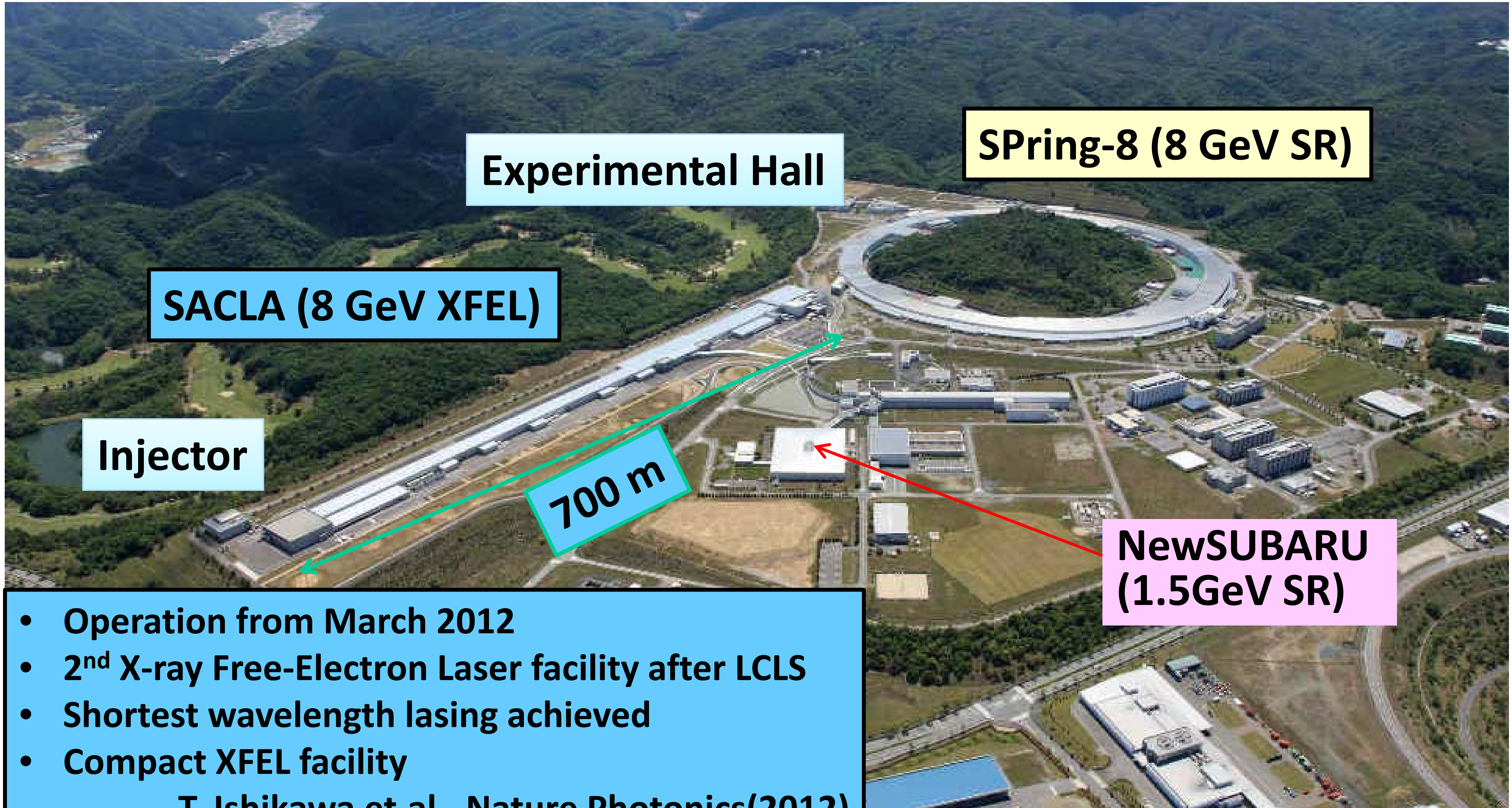
- Invented "pinned photodiode"
- Wafer process (Dark current, microlens, color filter, small pixel, …)
- Design (CCD, CMOS, noise, …)
- Camera (First USB camera, mosaic color filter arrangement, …)

Developing

- X-ray image sensors
- Visible photon counting image sensors
- Image sensors with new functions

Contents

SPring-8 Campus
SPring-8, SACLA, and NewSUBARU

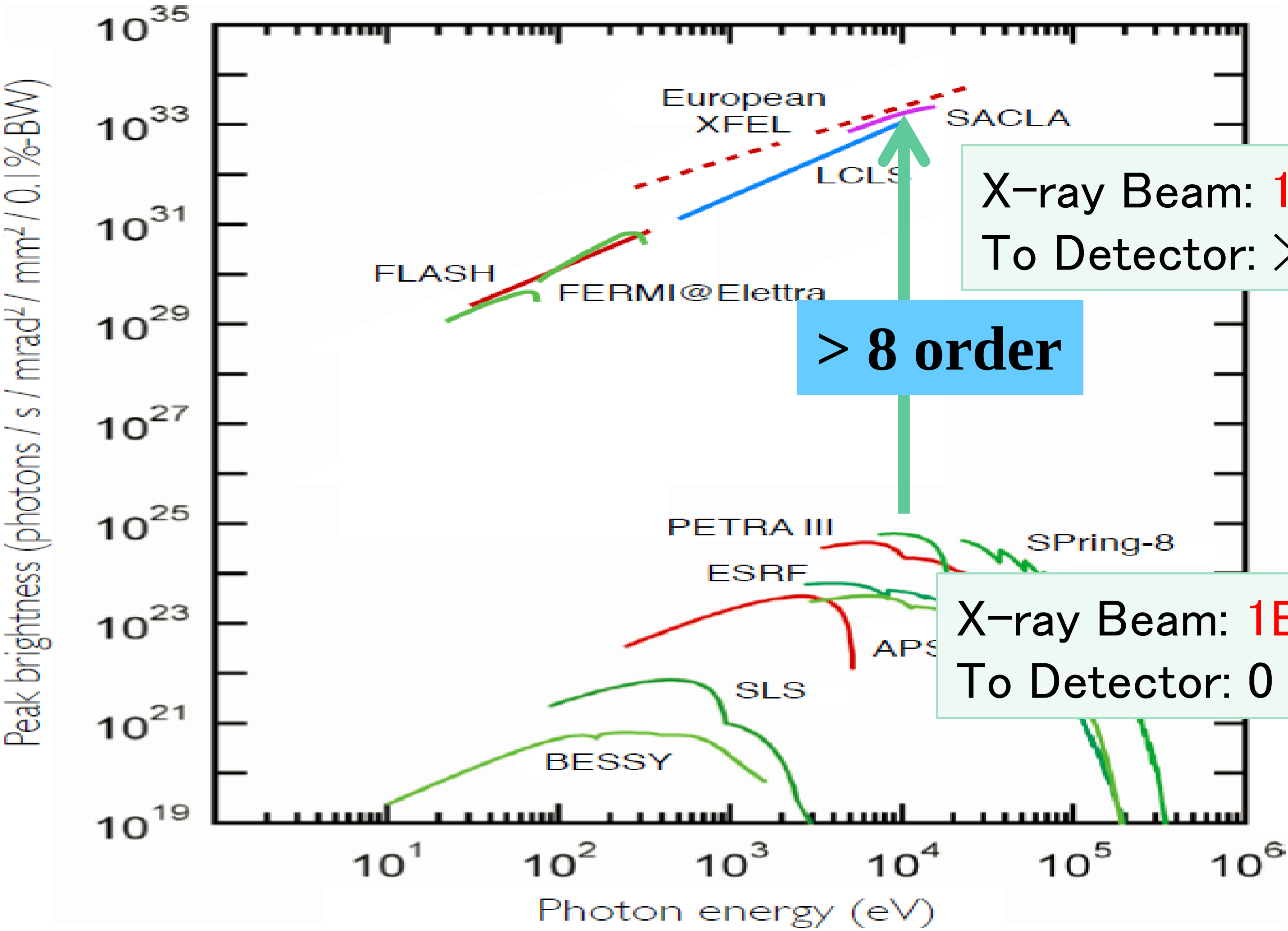


- Operation from March 2012
- 2^{nd} X-ray Free-Electron Laser facility after LCLS
- Shortest wavelength lasing achieved
- Compact XFEL facility

T. Ishikawa et.al., Nature Photonics(2012)

X-ray Free-Electron Lasers

- Integration mode X-ray image sensors are needed.



X-ray Beam: 1E11 photons in < 10 fs pulse
To Detector: >1000 ph/pulse/pixel @ 30Hz

Integration mode X-ray image sensor

X-ray Beam: 1E4 photons in 40 ps pulse
To Detector: 0 or 1 ph/pulse/pixel @ 500 MHz

Peter Schmüser, Martin Dohlus, Jörg Rossbach, Christopher Behrens
"Free-Electron Lasers in the Ultraviolet and X-Ray Regime Physical Principles, E
xperimental Results, Technical Realization" Springer Tracts in Modern Physics, Vol. 258 (2014) 2nd Eds.

Scientific Experiments at SACLA

Target: Nano scale dynamics of materials
by coherent X-ray diffraction Imaging

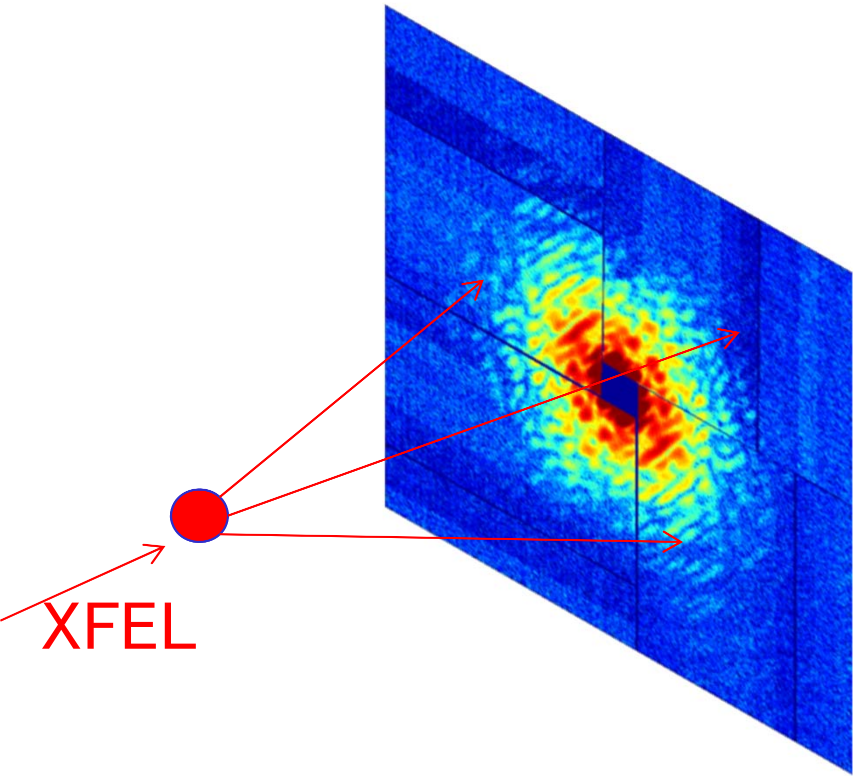
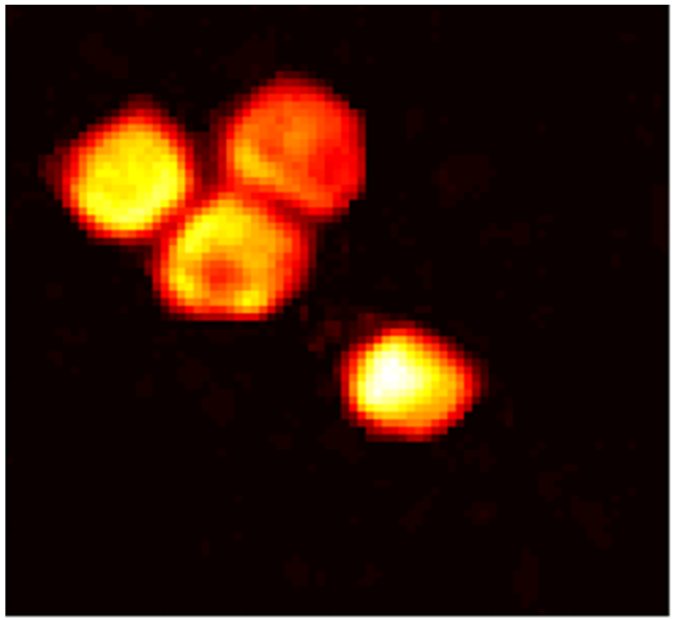


Image Reconstruction



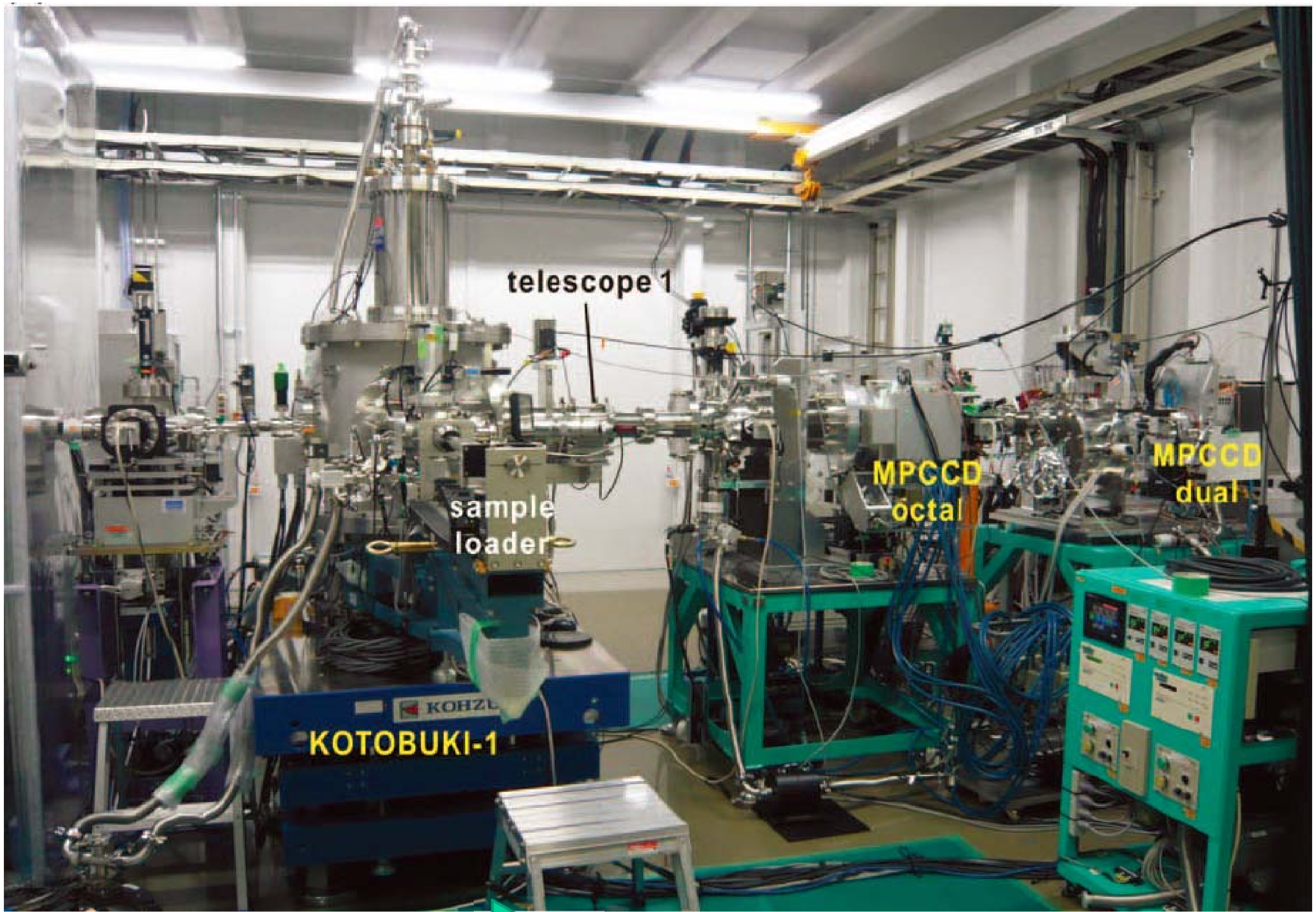
<u>Diffraction Pattern</u>

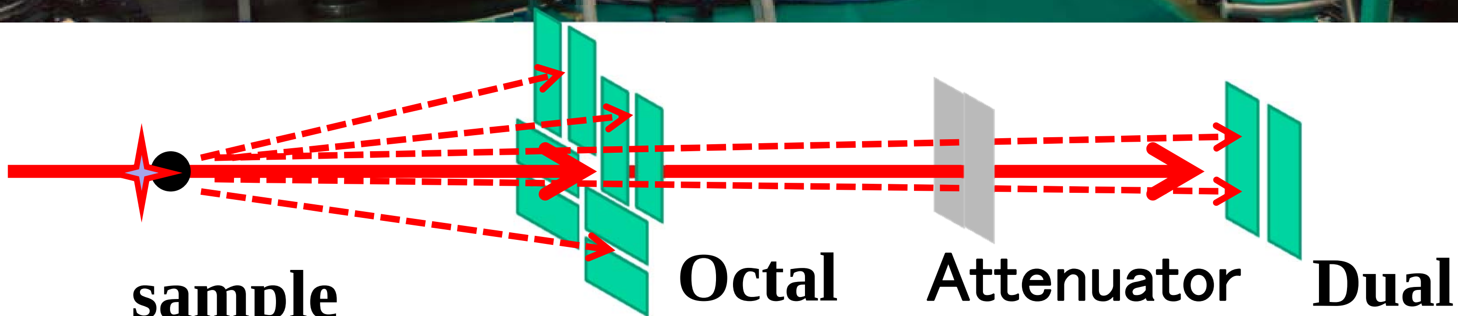
- MPCCD
  (Custom Multi-port CCD)

<u>Real Space Image</u>

- Gold nano particles
  Diameter of about 100 nm
- Spatial resolution: 8 nm
  (C. Song et.al.)

Setup with Octal and Dual MPCCD





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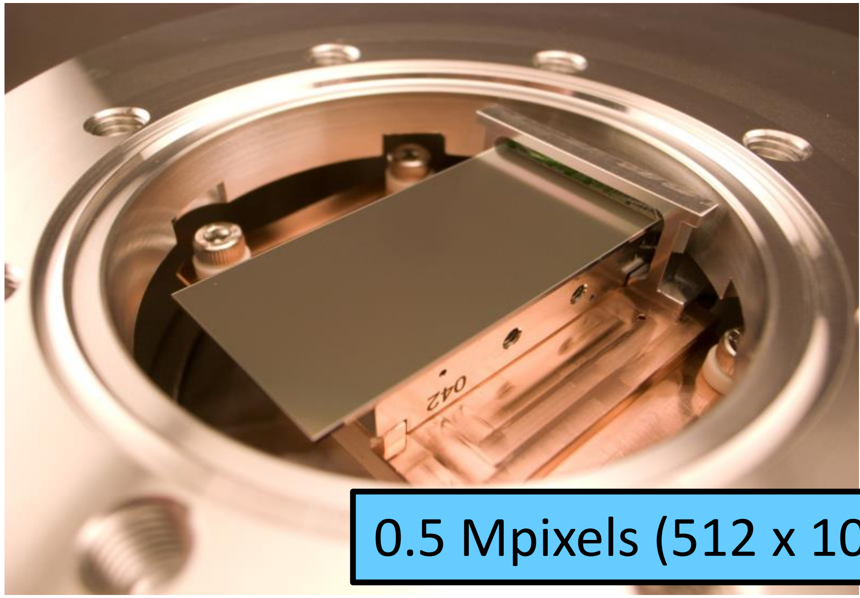
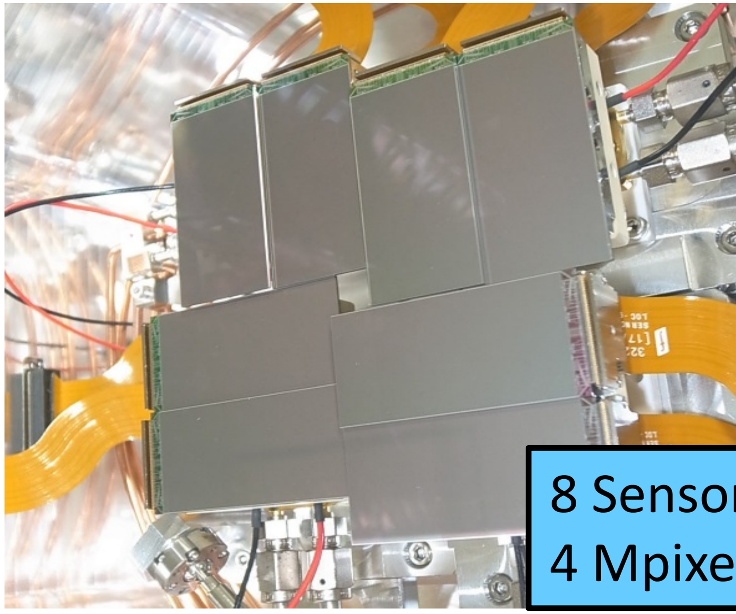
Detector Family

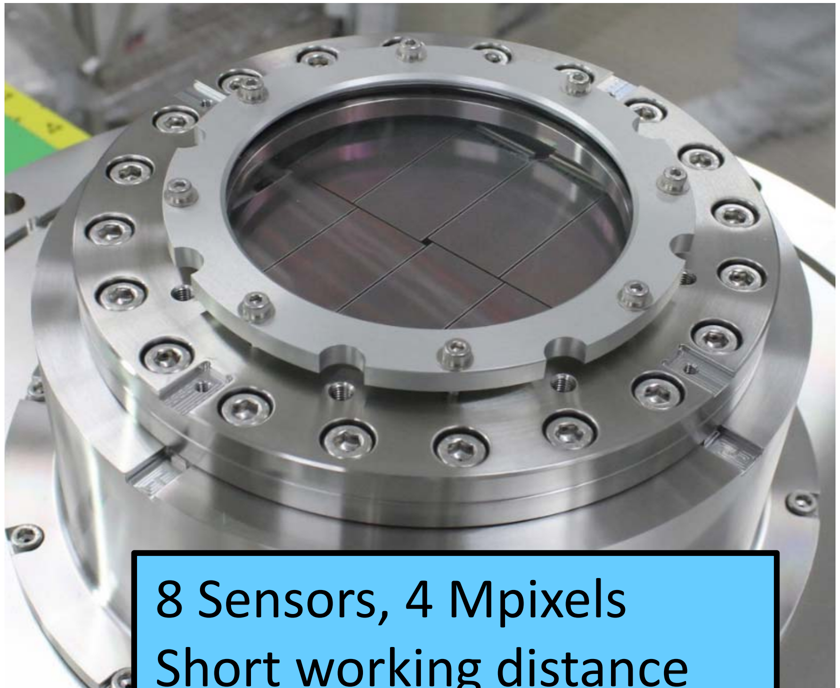
Kameshima et.al., Rev. Sci. Instrum. 85, 033110 (2014).



0.5 Mpixels (512 x 1024)



8 Sensors
4 Mpixels



8 Sensors, 4 Mpixels
Short working distance

- Current Deployment
  8 detectors (Totally 31 sensors)
  70–80% applications are covered.
- March 2015
  14 detectors (45 sensors)
- Increases at ～20 sensors/year

Imaging Live Cell in Micro-Liquid Enclosure by X-ray Laser Diffraction

(T. Kimura et.al., Nature Communications 5, Article number: 3052)

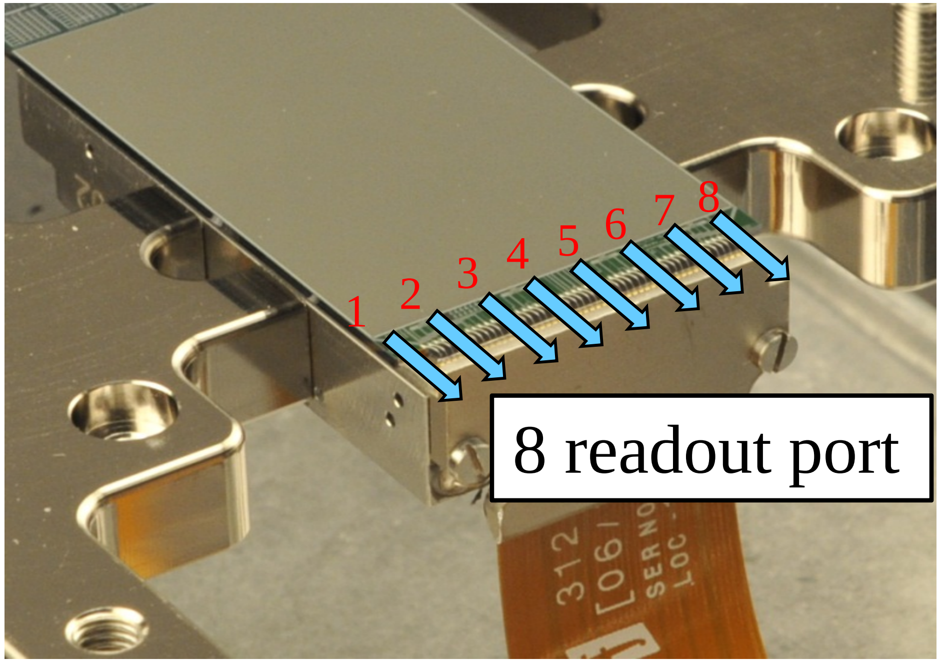
Photos are not available.

Contents

MPCCD Phase I (Multi-Port CCD)

Requirements

- Radiation hardness
- Large dynamic range
  - ✓ Single photon detection
  - ✓ Large peak signal



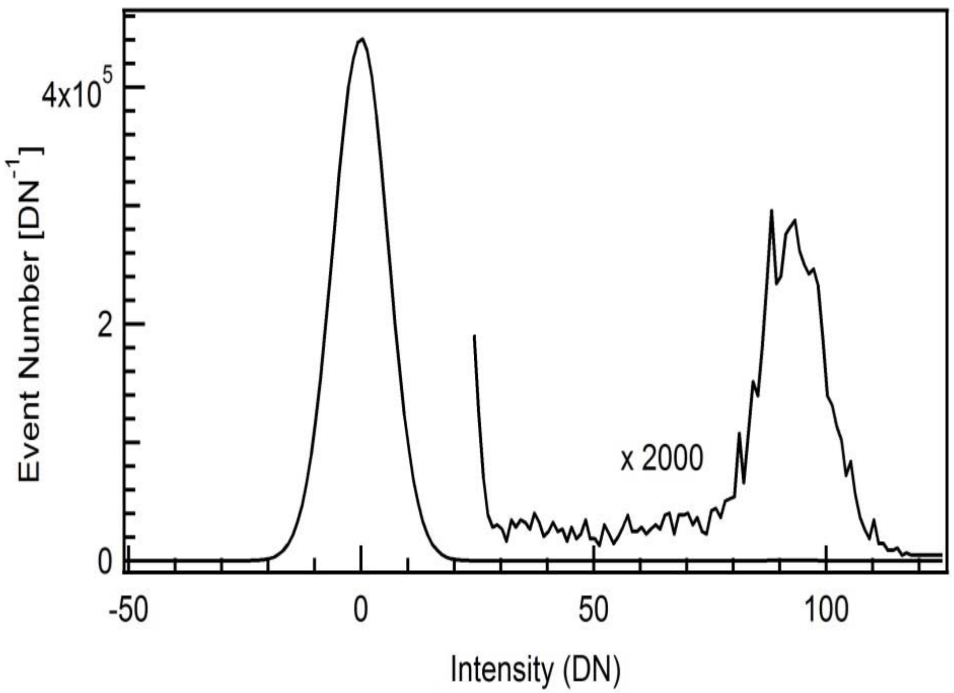
MPCCD Phase I specification

- Pixel size: 50 um□
- # of pixels: 512 (H) x 1024 (V)
- Frame rate: 60 fps
- Peak signal: 4.1–5 Me–
  2.5–3.0 kphoton@6 keV
- Detector noise: 100–250 e– rms
  0.06–0.15 photon@6 keV
- Sensor thickness: 50um
- PSF: 3 um @ 2 Me– Injection
- Radiation hardness:
  116 Mrad
  (3.2×10^{14} photon/mm^2@12 keV)

(T. Kameshima et.al., Review of Scientific Instruments, 85, 033110 (2014).

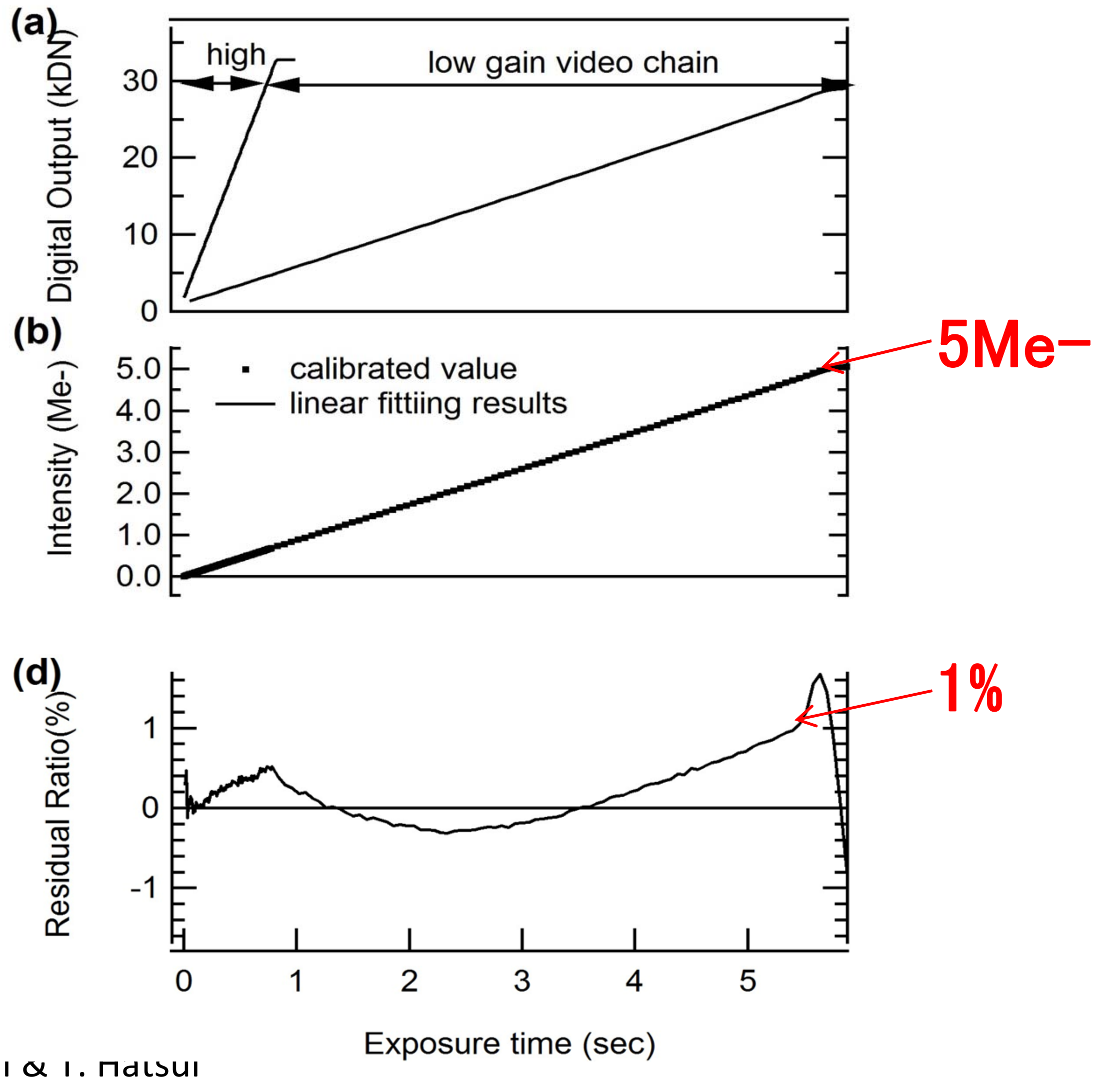
MPCCD Phase I Performance: Noise and Peak Signal

Single photon Detection
Fe55 (5.9 keV)



Peak signal and linearity

(Camera has 2 gain chains.)



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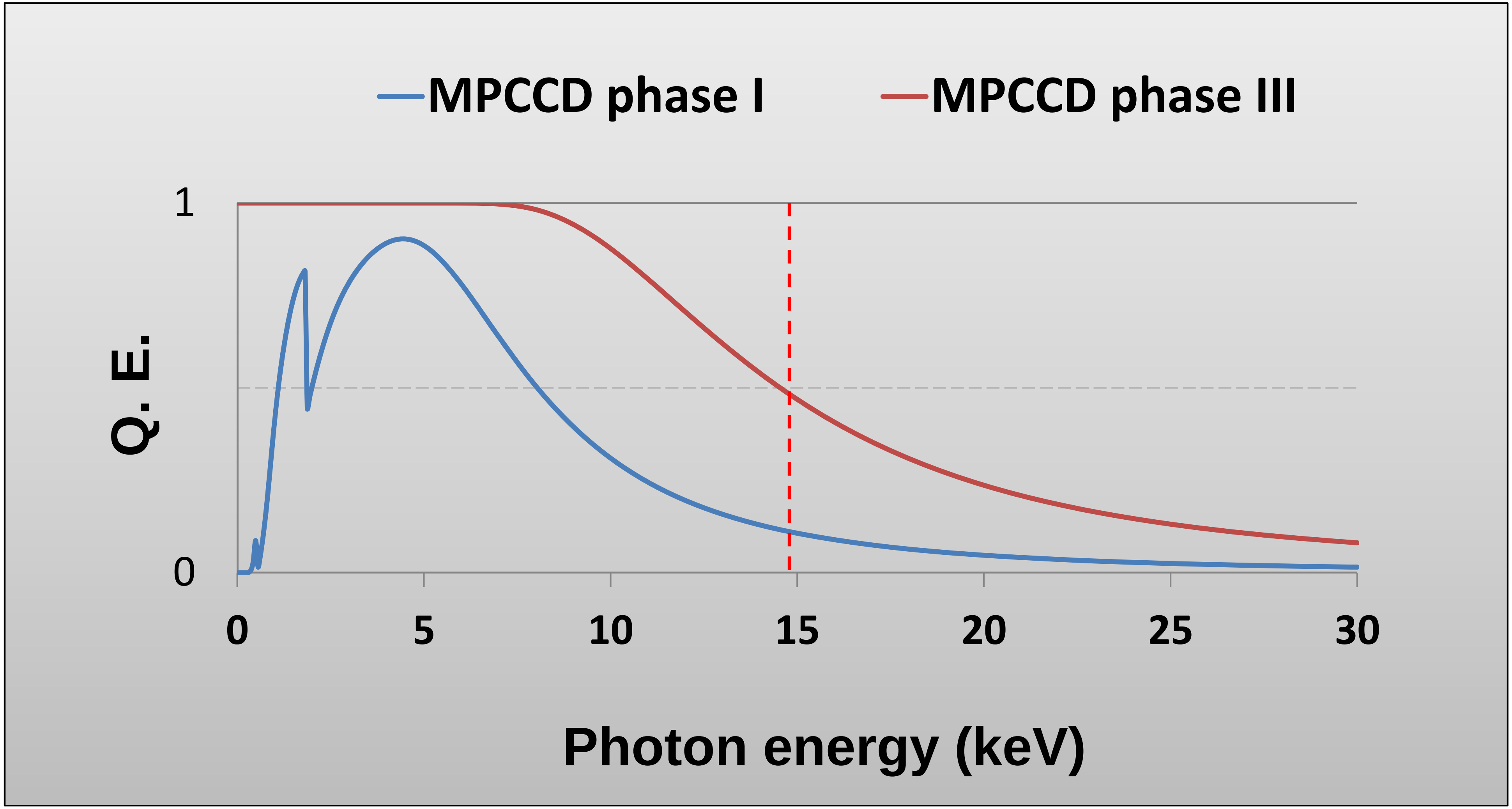
MPCCD Phase III and Phase III-L under Development

Description	Phase I*	Phase III**	Phase III-L**	Unit
Pixel Size	50 x 50			μm²
Pixel Number	1024 (V) x 512 (H)			-
Readout Port	8			-
Wafer	Epitaxial	FZ		-
Illumination Side	Front	Back		-
Sensor Thickness	50	300	300	μm
Quantum Efficiency	78	99	99	% for 6 keV
	19	73	73	% for 12 keV
Conversion Gain	0.5	0.5	2.0	μV/e-
Detection Noise	100-250	300	60	e- rms
Peak Signal	4.1-5	3.4	1.6	Me-/pixel
	16.4-20	13.6	6.4	Me-/100μm□
Radiation Hardness	1.1	1	1	MGy for 12 keV X-rays

*: T. Kameshima et.al., Review of Scientific Instruments, 85, 033110 (2014).

**: S. Ono et.al., in preparation.

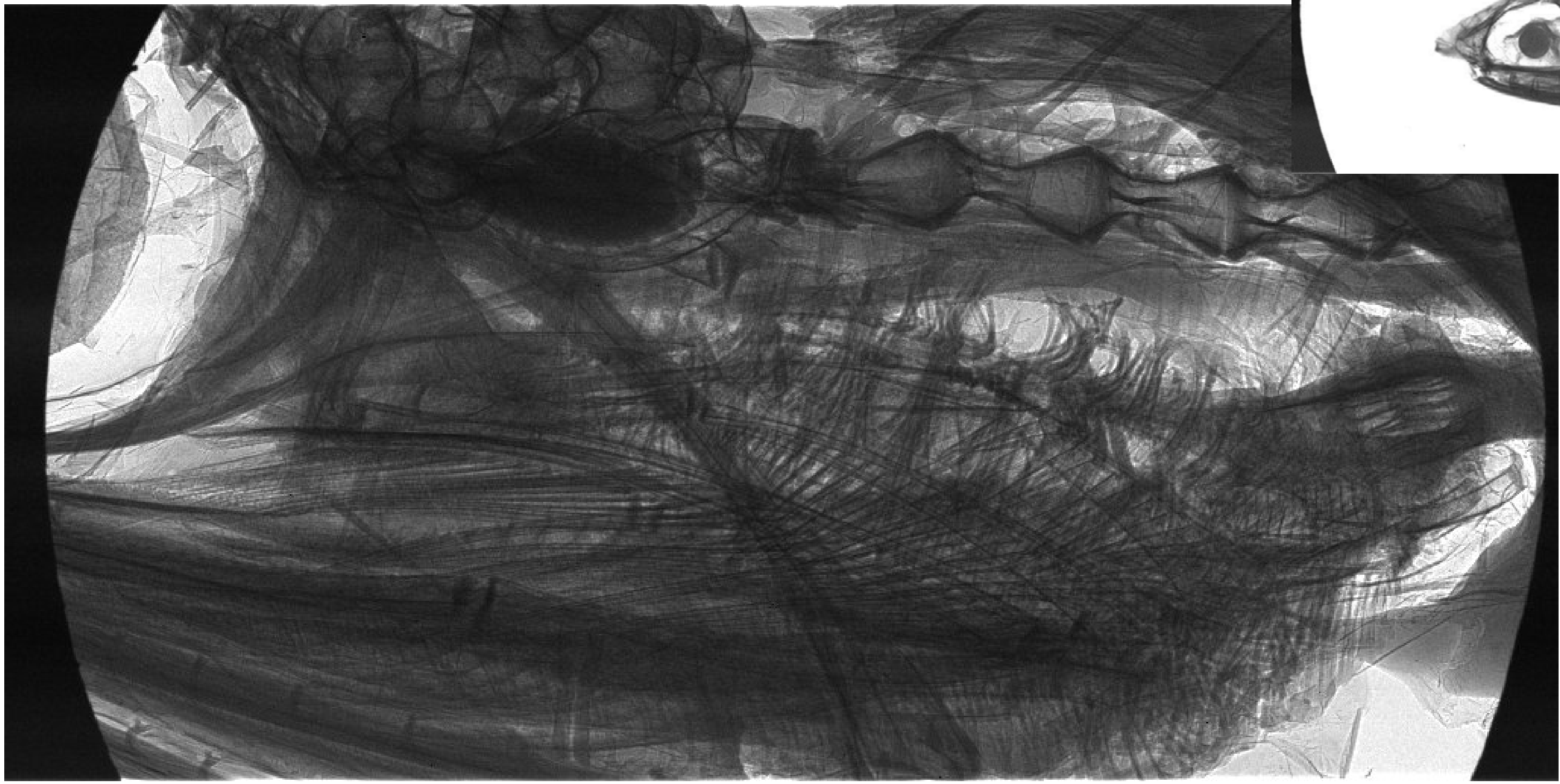
Quantum Efficiency of MPCCD Phase III



X-ray Transmission Image by MPCCD Phase III

Source-sample : 380 mm
Detector-sample : 890 mm
X-ray (Cu target) : 40 kV, 100 uA
X-ray source size : ～65 um
Exposure time : 100 msec
Temperature : −20℃

Average of 100 frames
Gain calibration among output ports
Background and flat field correction



Dried fish

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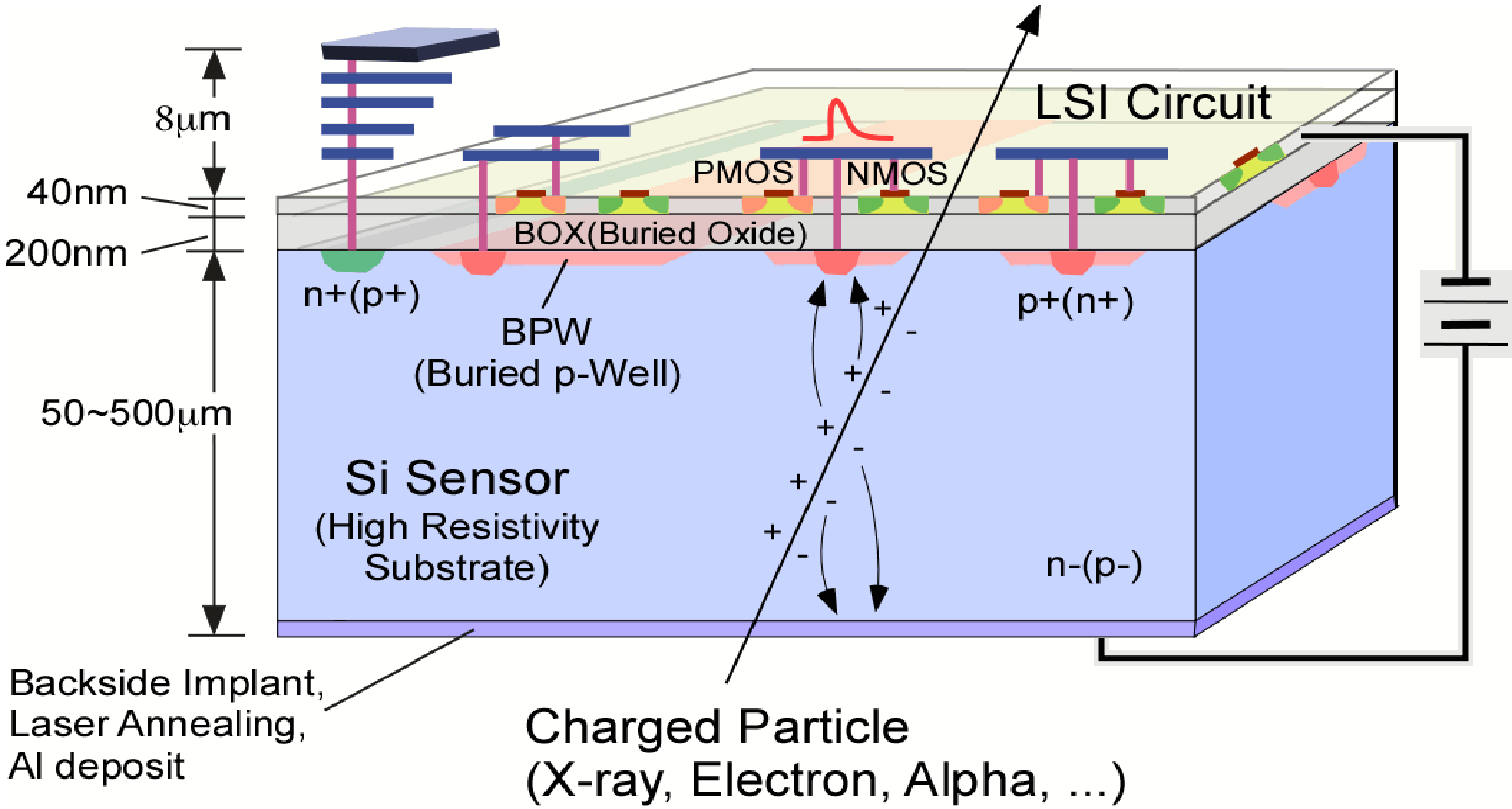
Contents

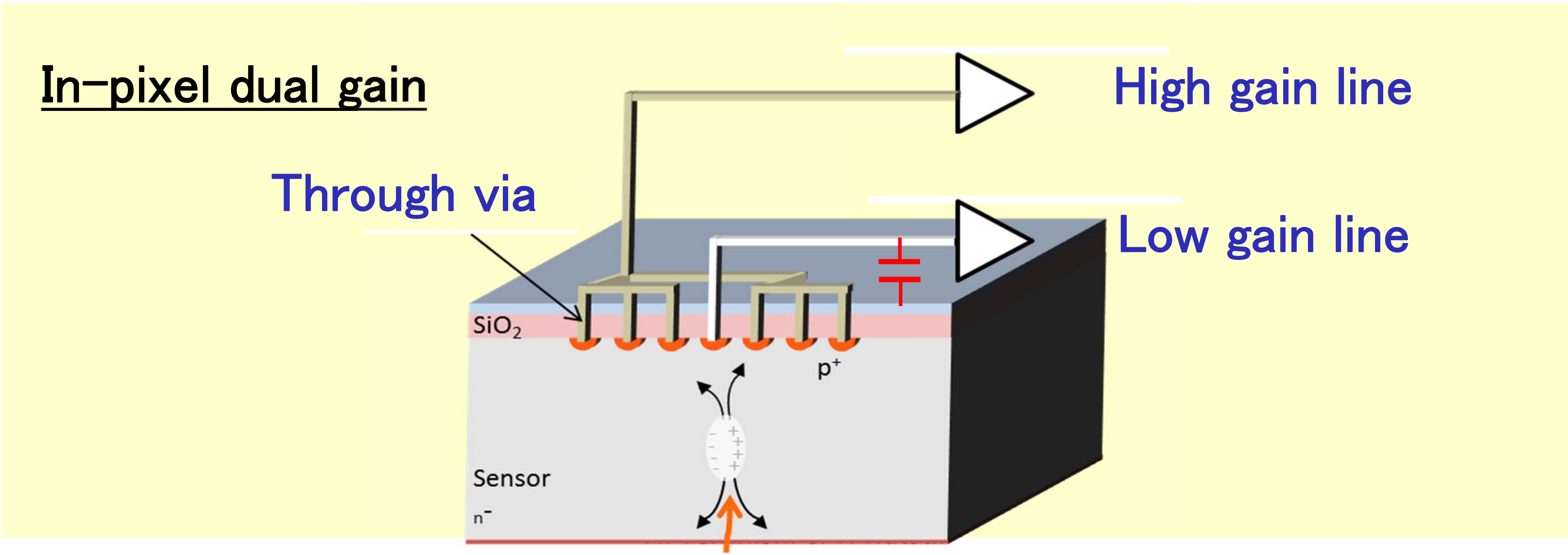
SOI Pixel Detector Architecture (SOIPIX Collaboration)



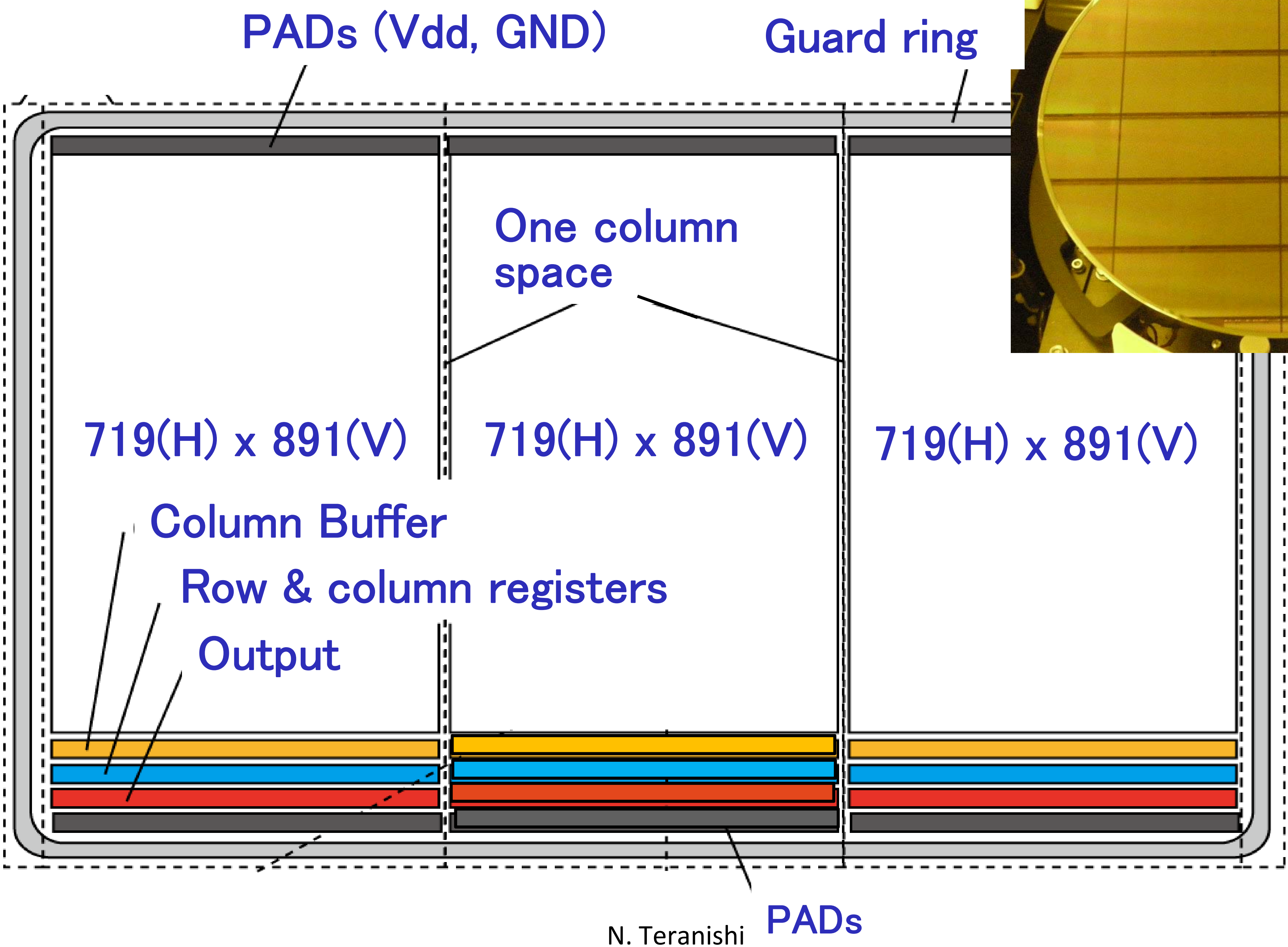
- High resistivity substrate for support → 500 um thick sensor
- Readout circuits and sensor are optimized independently
- Readout circuits can use almost all pixel area.
- Large saturation, 7 Me− by MIM and CMOS circuit

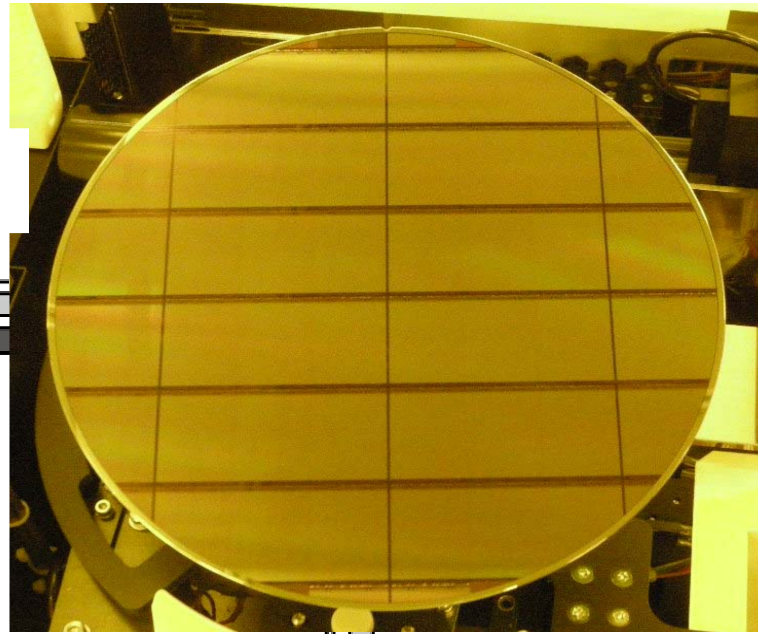
SOPHIAS (Silicon-On-Insulator Photon Imaging Array Sensor)

Specifications	SOPHIAS	MPCCD Phase I
Pixel Size	30 μm	50 μm
Pixel Number	1.9 Mpixel	0.5 Mpixel
Frame Rate	60 fps	60 fps
Dual Gain Line	In-pixel	In-Camera
Random Noise	150 e-rms @ High gain	250 e-rms
Saturation Signal	7 Me-/pixel @ low gain	4.1-5 Me-/pixel



Floor Plan





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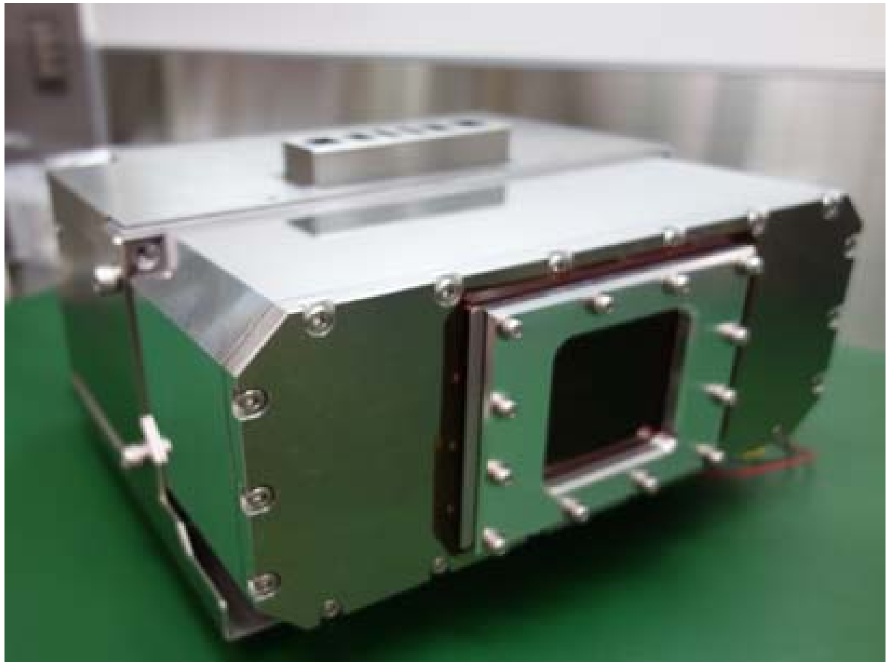
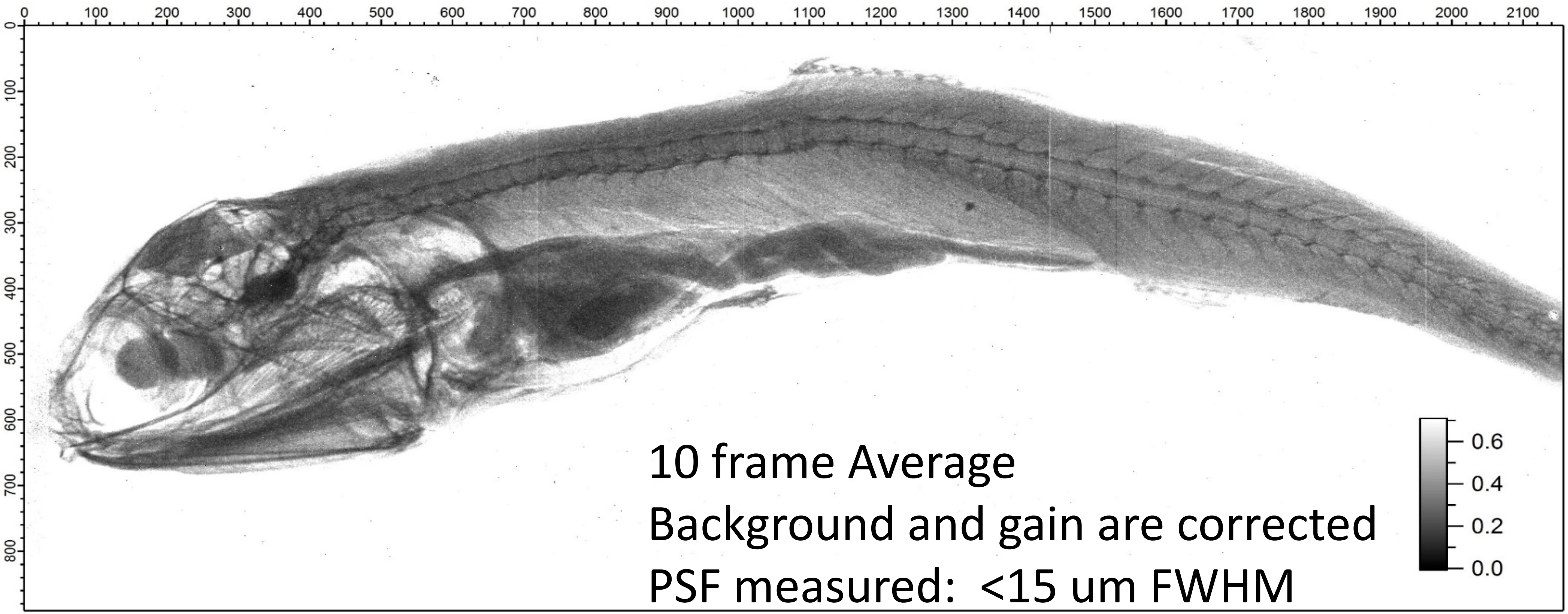
Schedule of SOPHIAS

- Now
  - Sensor evaluation & improvement
- Dual Sensor Detector
  - 3.8 Mpixels
- Target:
  - Coherent X-ray Imaging
- Fall 2014
  - In-house test campaign



Dual Sensor Detector

X-ray Transmission Image



Source-sample : 200 mm
Detector-sample : 600 mm
X-ray (Cu target) : 40 kV, 800 uA
X-ray source size : ～3 um
Exposure time : 10 msec
Temperature : Room Temp.

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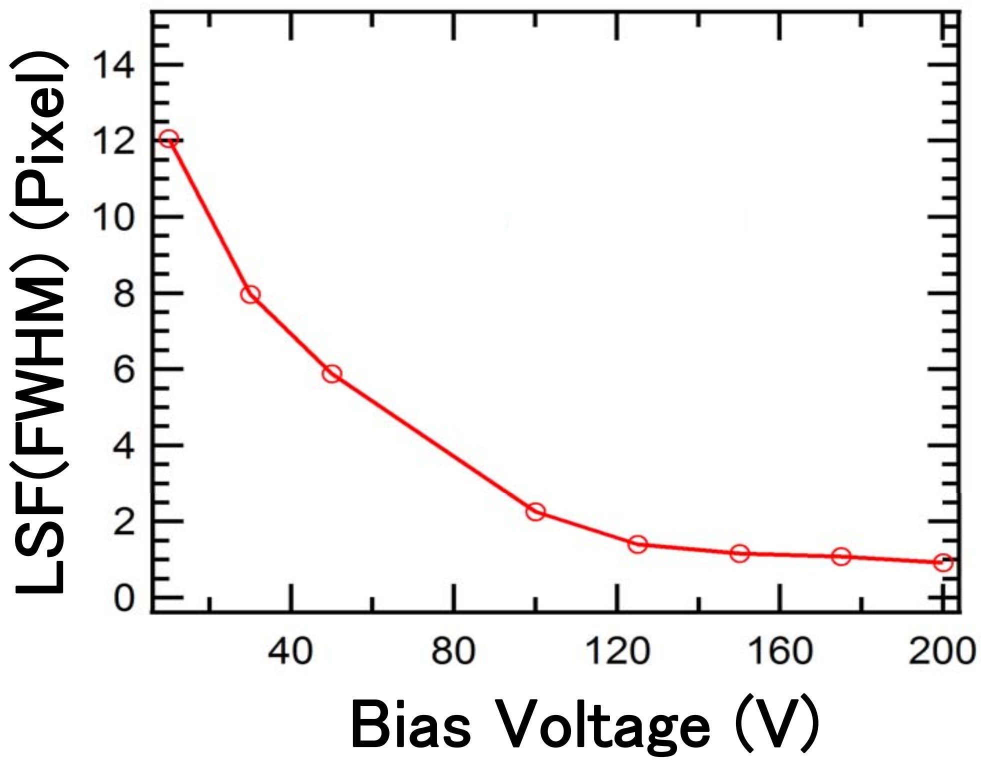
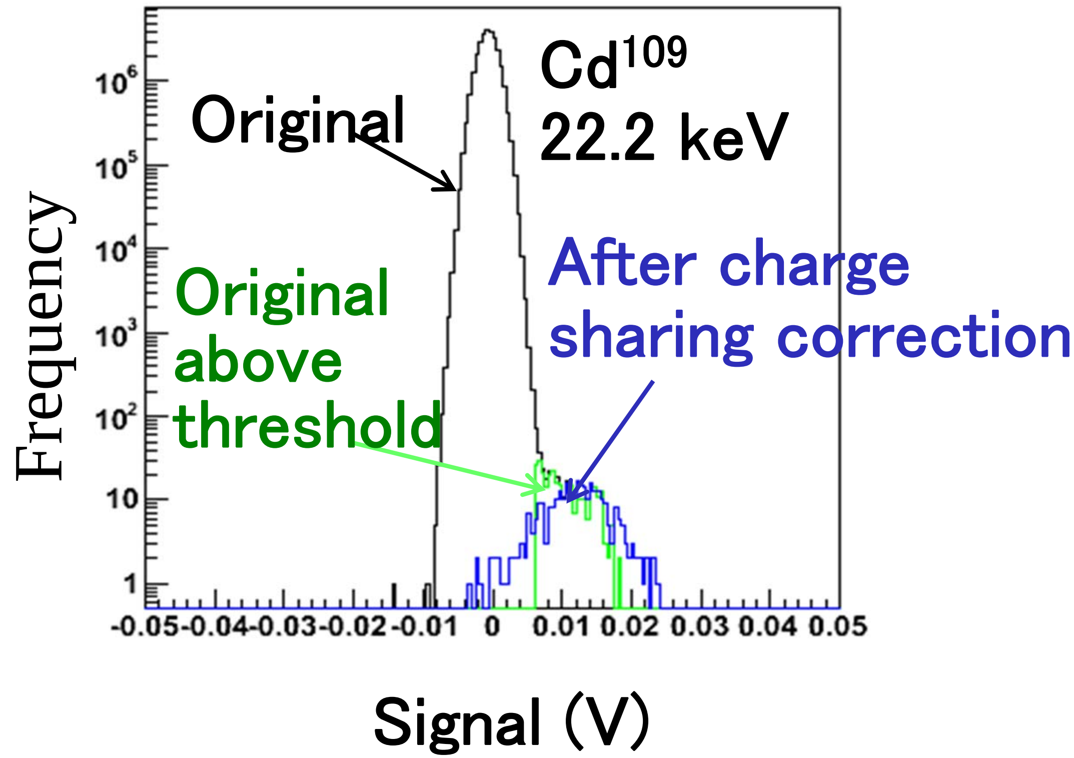
Performance Evaluated

- 7 kΩcm, 500 μm substrate is fully depleted at more than120 V.
- LSF(FWHM) : 33 μm (1.1 pixel)
- Single photon is detected, but the existence of some signal loss is suggested.



Spatial Resolution

Cu Ka irradiation 40 kV 300 uA



Single Photon Detection

Contents

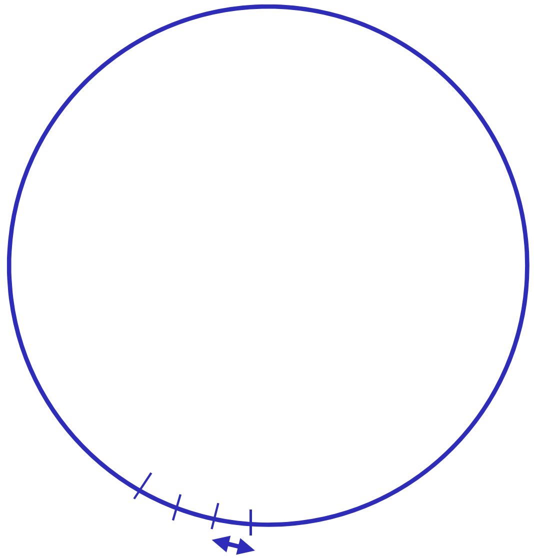
SPring-8 will Power up to be SPring-8 II

New Feature

- X-ray focus size at full irradiation : 1um → 10nm in diameter
- Coherent flux : 0.1% → 10-20%

Ring Parameters

Item	Time	Frequency
Pulse width	～50ps	
Pulse interval (bucket interval)	2ns (1.965ns)	508.810MHz
Revolution (2,436 buckets)	4.786us	208.87kHz



- 2ns interval
- 2,436 buckets on ring

Proposed schedule

Q1 2019 : SPring-8 blackout
Q2 2020 : Beam line commissioning
Q1 2021 : First science

New Image Sensor for SPring-8 II (Tentative)

- Mode A. High frame rate mode: 52.2 kfps
  To synchronize with 1/4 full revolution frequency of 208.87 kHz

- Mode B. High speed burst mode: 10 ns interval
  To observe mesoscopic dynamics at atomic scale.

- Mode C. Large full count rate mode (≡ (Saturation) x (Frame rate))
  To reduce statistical error and to shorten measuring time.

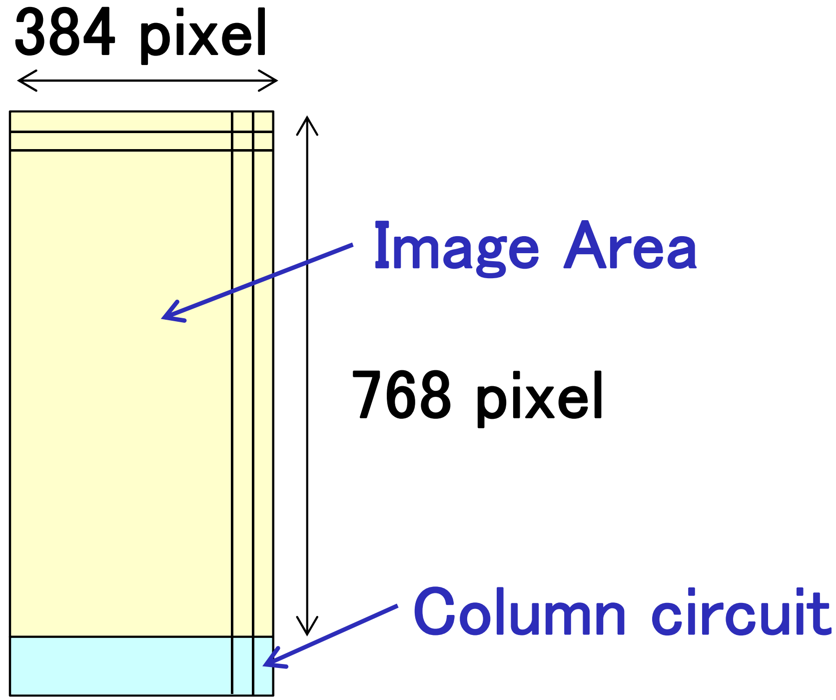
	Electron	Photon@12.4 keV
Saturation	6.25 Me−	1840 photon
Full count rate	130 Ge−/s	38 Mphoton/s

Frame rate: 20.88kfps

Data Rate (Mode A)

Assumptions:

1. Pixel number: 384 (H) x 768 (V)
2. Frame rate: 52.2 kfps
   Frame period: 19.2 ns
   Then, horizontal period (1H):
   19.2 us/768＝24.9 ns (40 MHz)
3. ADC resolution: 12 bit



Date rate from 1 column:
40 MHz x 12 bit = 480 Mbps
Date rate from 1 chip:
480 Mbps x 384 = 185 Gbps

- Date rates for Mode B & C are set as same as Mode A.

Comparison with SHV (Super Hi-Vision)

- Data rate is 3.6 times larger than SHV.
  ⇨ Digital outout is suitable.

	SHV (8k) *	New sensor Mode A	Ratio
Pixel area	2.8 um □	70 um □	625
Total pixel number	7808(H) x 4336(V)	384(H) x 768(V)	0.0087
Frame rate	120 fps	52.2 kfps	435
Saturation	7 ke− (Estimated)	140 ke−	20
ADC resolution	12 bit	12 bit	1
Random noise	3.0 e− @gain=7.5	60 e−	20
Data rate	51 Gbps	185 Gbps	3.6
Power consumption	2.67 W @gain=7.5	5 W	1.87
Year	2012	2017	−

*: Kitamura et al. (NHK, Shizuoka U., Brookman Tech.), IEEE Trans. ED, vol. 59, p. 3425 (2012).

Analog Output vs Digital Output

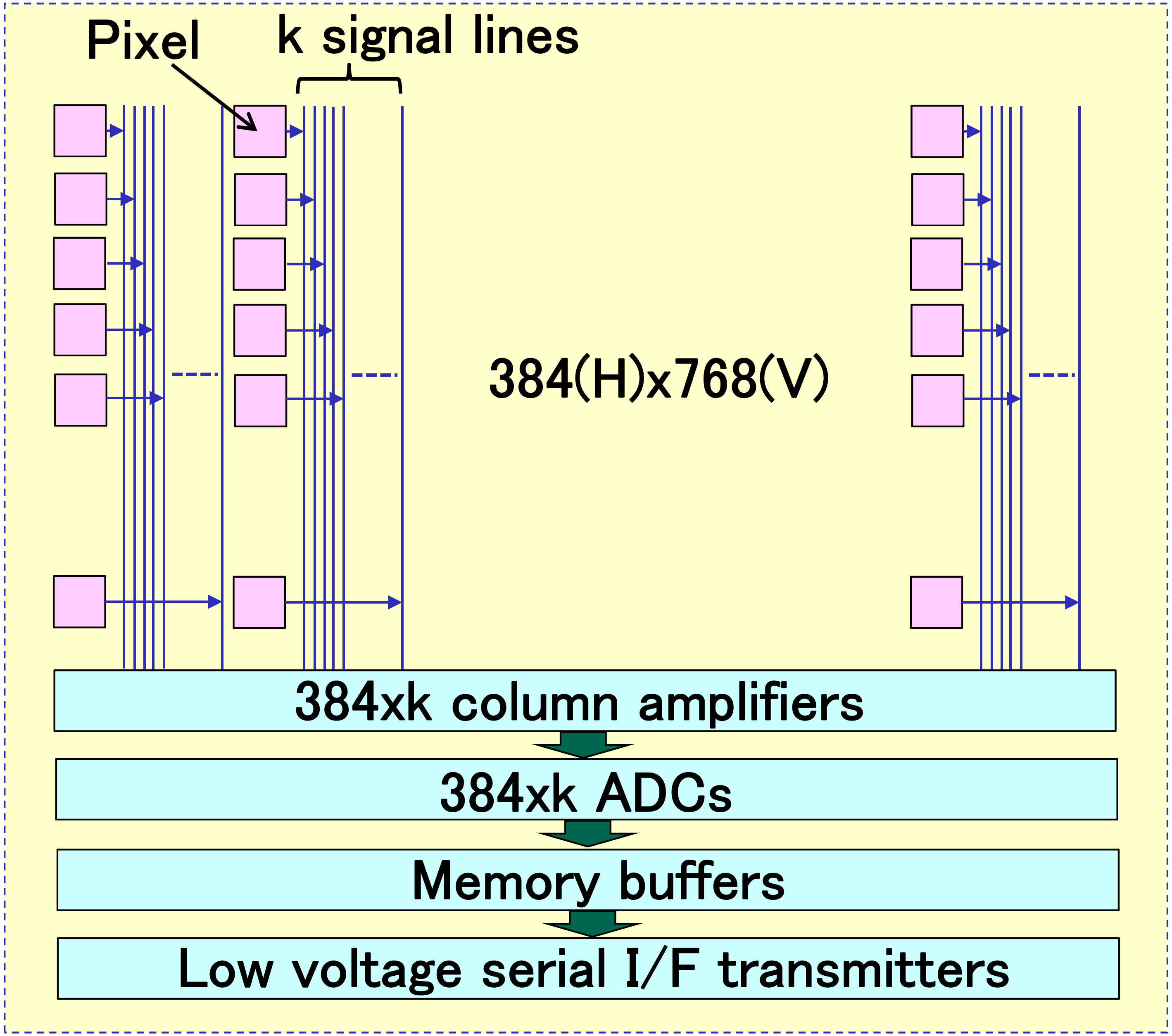
- Digital output looks better, which is main stream in industry.
- 2 or 3 times faster ADC is still needed.

	Analog	Digital
Data Rate/Port	20 MHz x 12 bit equiv.	2.3 Gbps (sub-LVDS)**
# of Port/Column	2 Port/Column	1/4 Port/Column
Power (ADC)	None	101 uW * x 70 x 384 = 2.7 W (70 ADC/Column)
(IO)	6 mW x 2 x 384 = 4.6 W	12.5 mW** x 1/4 x 384 = 1.2 W
(ADC + IO)	4.6 W	3.9 W
Chip Size (Circuit)	Smaller	Larger
(PAD)	Larger	Smaller
Crosstalk	Worse	Better

*: Kitamura et al. (NHK, Shizuoka U., Brookman Tech.), IEEE Trans. ED, vol. 59, p. 3425 (2012).
**: T. Toyama et al. (Sony), IEEE ISSCC, 23.11, p.420 (2011).

Configuration of New Sensor for SPring-8 II

- k vertical signal lines.
  - Settling time
  - ADC time
- Column parallel.
- On-chip ADC.
- High speed serial digital out.
- 3 side buttable.



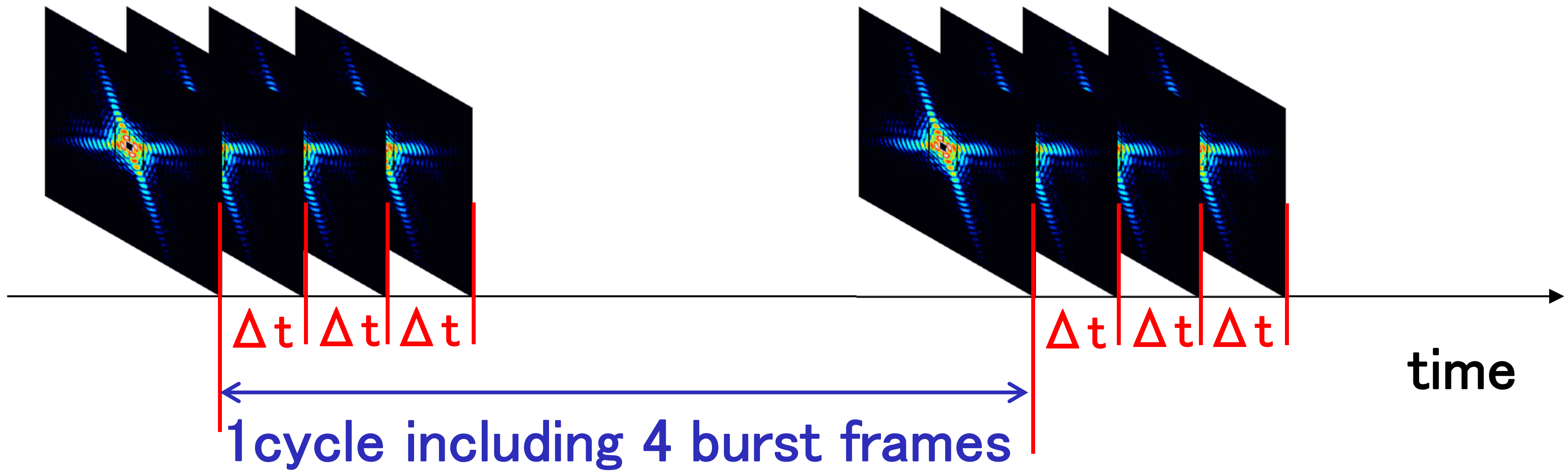
High Speed Burst Mode (Mode B)

Motivation:

- To observe mesoscopic dynamics at atomic scale.
- Diffraction correlation gives information on the atomic motion.

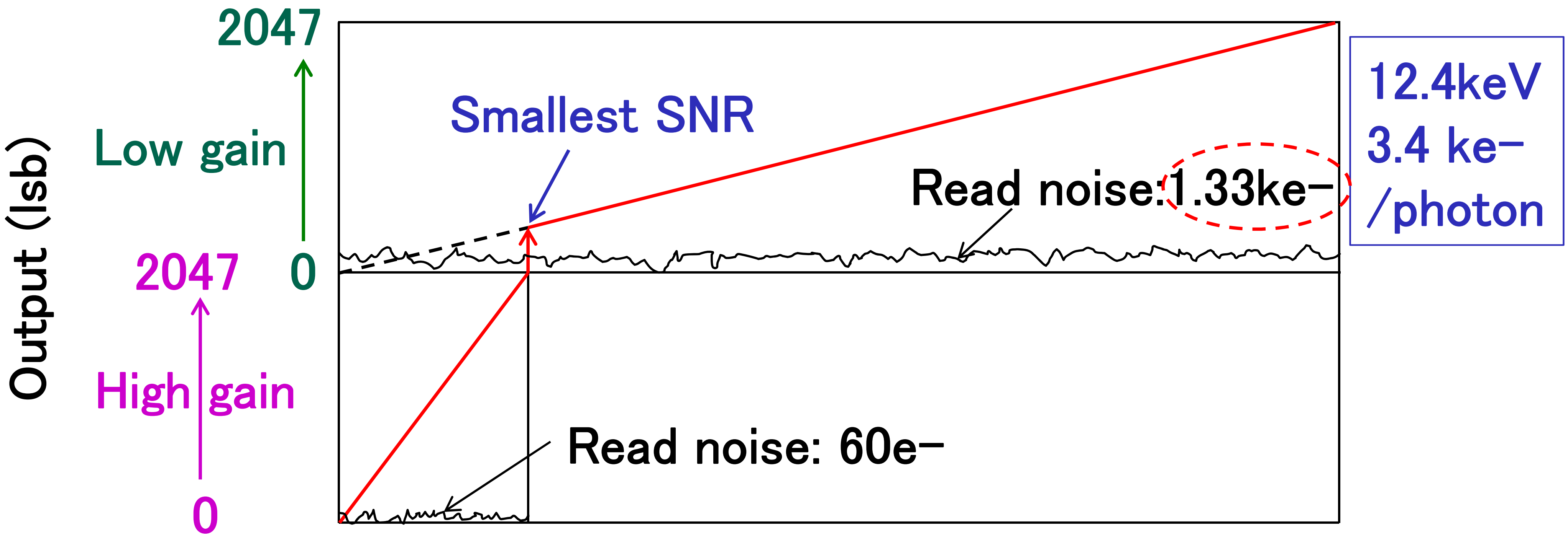
Target:

- 10 ns burst mode (Δt = 10 ns)
- # of burst frames: 2, or 4, or 8
- 1cycle = 52.2 kfps / # of burst frames



Large Full Count Rate Mode (Mode C)

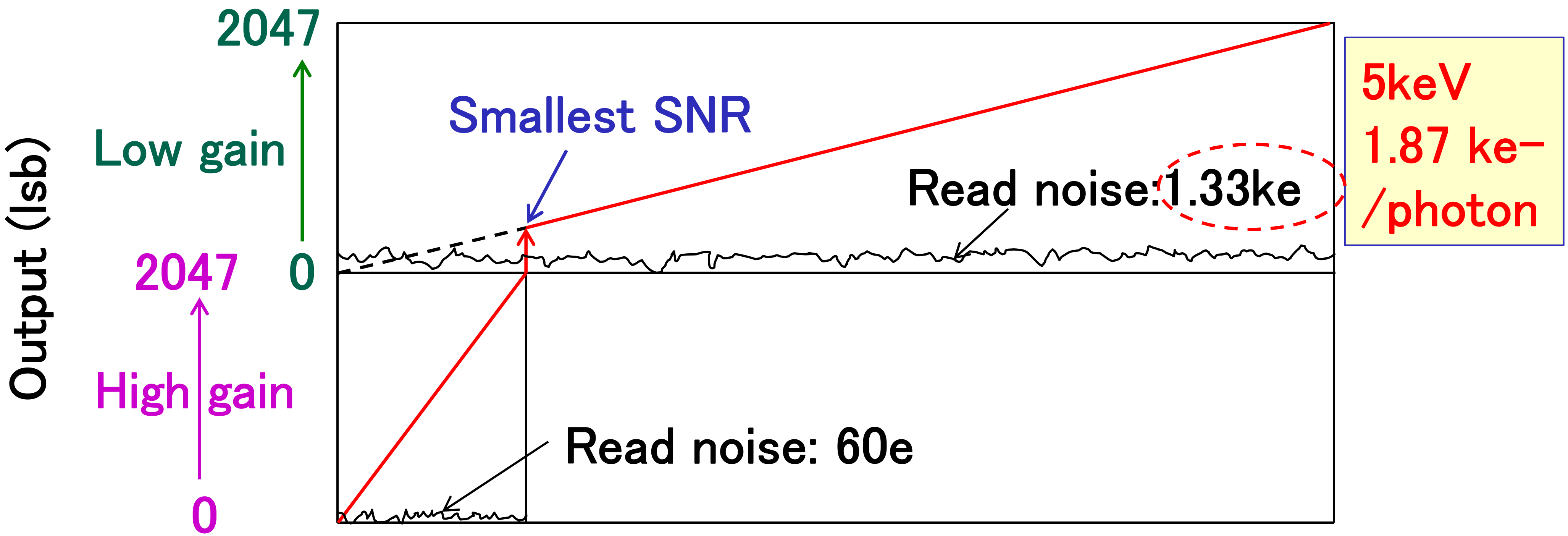
- Each pixel has 2 different detection capacitance, which realize high gain pass and low gain pass.
- Read noise is at most 9% (12.4 keV) of photon shot noise.



Signal	0 e− 0 photon	72 ke− 21.2 photon	6,250 ke− 1,840 photon
Photon shot noise		15.6 ke− 4.6 photon	146 ke− 43 photon

Large Full Count Rate Mode (Mode C)

- If incident X-ray energy is decreased, photon shot noise at electron is decreased.
- Read noise is at crossover point is 11% (5keV) of photon shot noise.

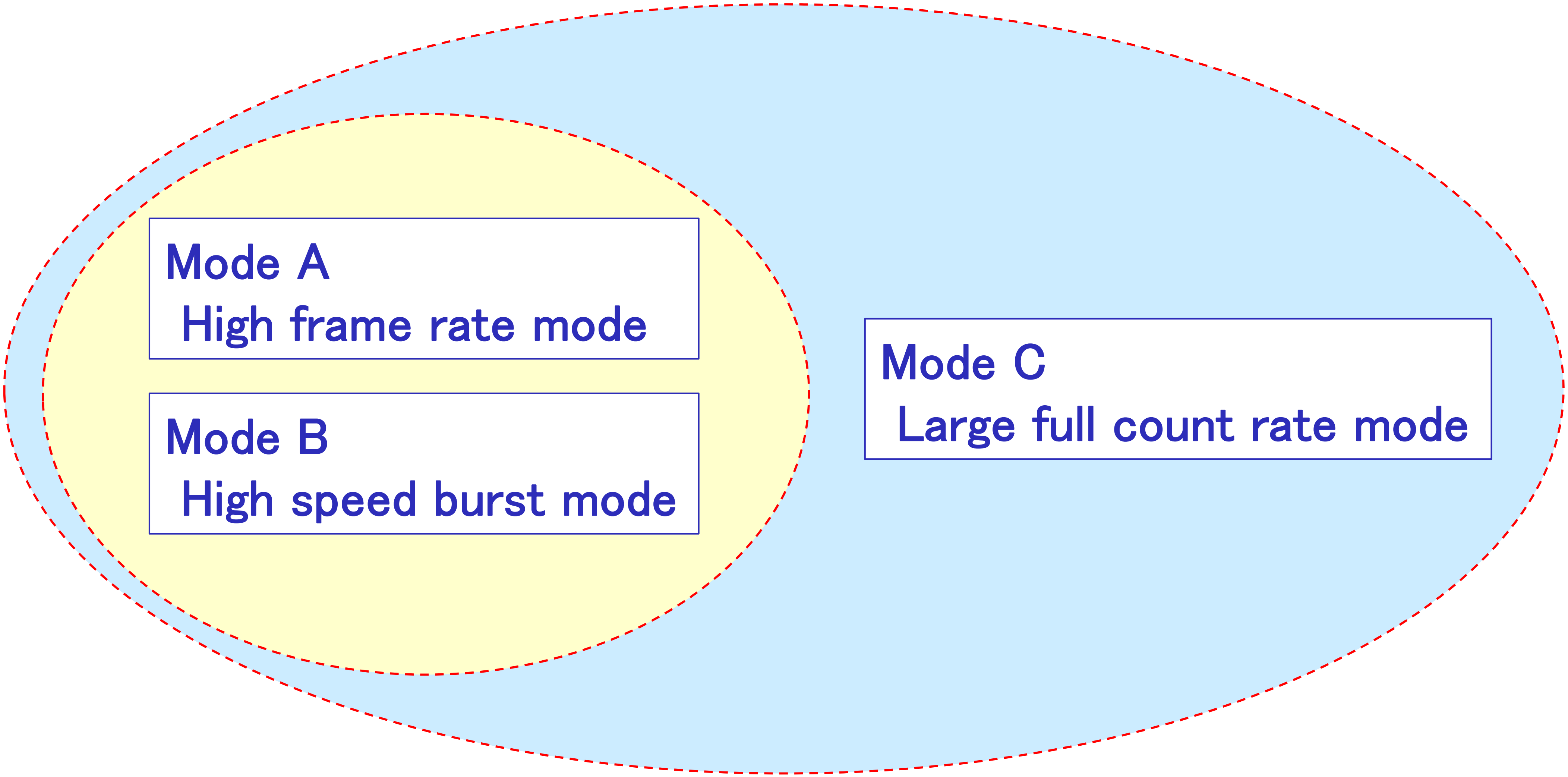


Signal	0 e− 0 photon	72 ke− 38.5 photon	6,250 ke− 3,340 photon
Photon shot noise		11.6 ke− 6.2 photon	108 ke− 58 photon

Combination of Modes

Target:

- Mode A and Mode B will be realized on one image sensor.
- Preferably, all three modes will be realized on one image sensor.



Contents

Summary

1. MPCCD
- Phase I sensor is used for 70-80 % applications at SACLA.
- Phase III sensor with 300 um depletion depth and Phase III-L with 60 e- rms noise are under development.

2. SOPHIAS is under development
- SOI Pixel Detector (SOIPIX Collaboration)
- Saturation: 7 Me- at 30 um pixel
- High gain pass & low gain pass are implemented.

3. New sensor for SPring-8 II and SACLA is under planning.
- High frame rate mode: 52.2 kfps
- High speed burst mode: 10 ns interval
- Large full count rate mode
  ≡ (Saturation) x (Frame rate): 130 Ge-/s