Development of 20.2 Mpixel CITIUS detector for the XFEL facility SACLA

Haruki Nishino[1,2], Kyosuke Ozaki[2], Yoshiaki Honjo[2], Toshiyuki Hiraki[2], Kazuo Kobayashi[1,2], Koji Motomura[2], Takashi Sugimoto[1,2], Mitsuhiro Yamaga[1,2], Yasumasa Joti[1,2], Takaki Hatsui[2]

JASRI[1]、RIKEN[2]

Use Case of CITIUS for X-rays

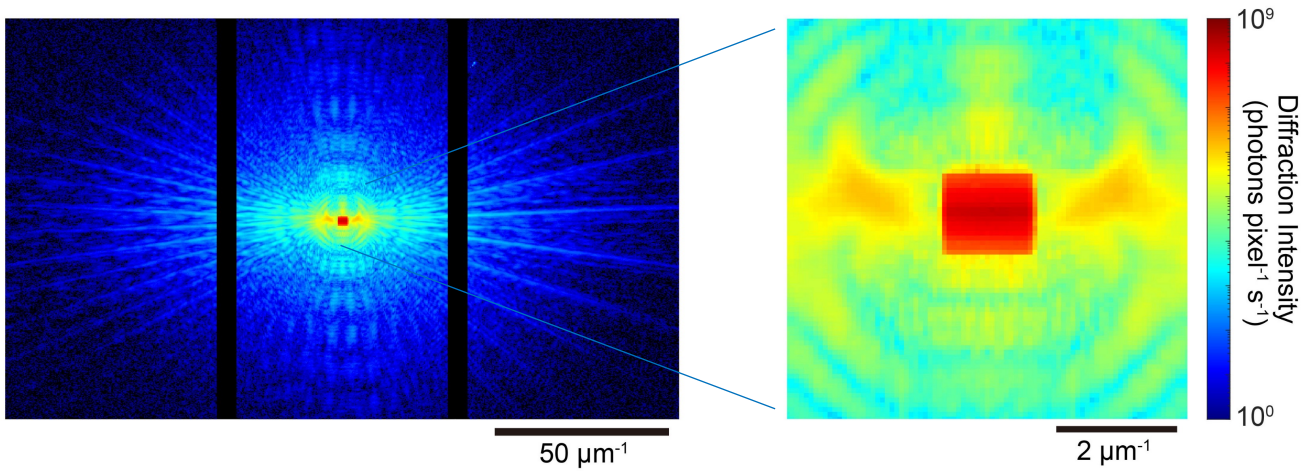
Intensity Mapping

- Number of Photons for each pixel
- Single Photon Sensitivity
  - noise << 0.018 phs rms @ 8 keV
- Ultra-high dynamic range
  - continuous X-rays: 1 Gphotons/s/pixel
  - pulsed X-rays for 6 keV
    - 1/66 photon noise (25 e-rms)
    - 17,000 photons/pixel/pulse (28 Me-)
    - S/N = 1.12 x 10^6, best in class

This talk

Max. Intensity at detector: 250 Mcps/pixel

Low-Q Region



Conceptual Design: 2023-2024
Sensor Module Development: 2025-2020
Integration: 2021-

Pixel Cross Section (72.6 μm)

p-in-n
3D integration: Sensor + ASIC
Drain terminal to collect interface leakage current
1 nA/cm^2 @ room temperature

Pixel schematic not shown due to restrictions.

Pixel Circuitry

Circuitry
- similar to lateral overflow
- no charge amplifier

Gain
- All the gains are converted sequentially
- No in-pixel gain switching

Gain selection
- High/Mid. : Selected by an on-chip logic.
- High/Mid/Low: selected by off-chip logic

In-pixel buffer
- 3 Gains: read then exposure (for pulsed X-rays)
- 2 Gains: read while exposure (for continuous X-rays)
- 1 gain: read while exposure (event recording)

Shutter
- Global shutter operation

Power consumption
- 3.6 uW/pixel
- Total power incl. on-chip ADCs, 8 W/280k pixels (0.54 W/cm2)

Pixel schematic not shown due to restrictions.

Readout Noise Reduction by Multi-Sampling

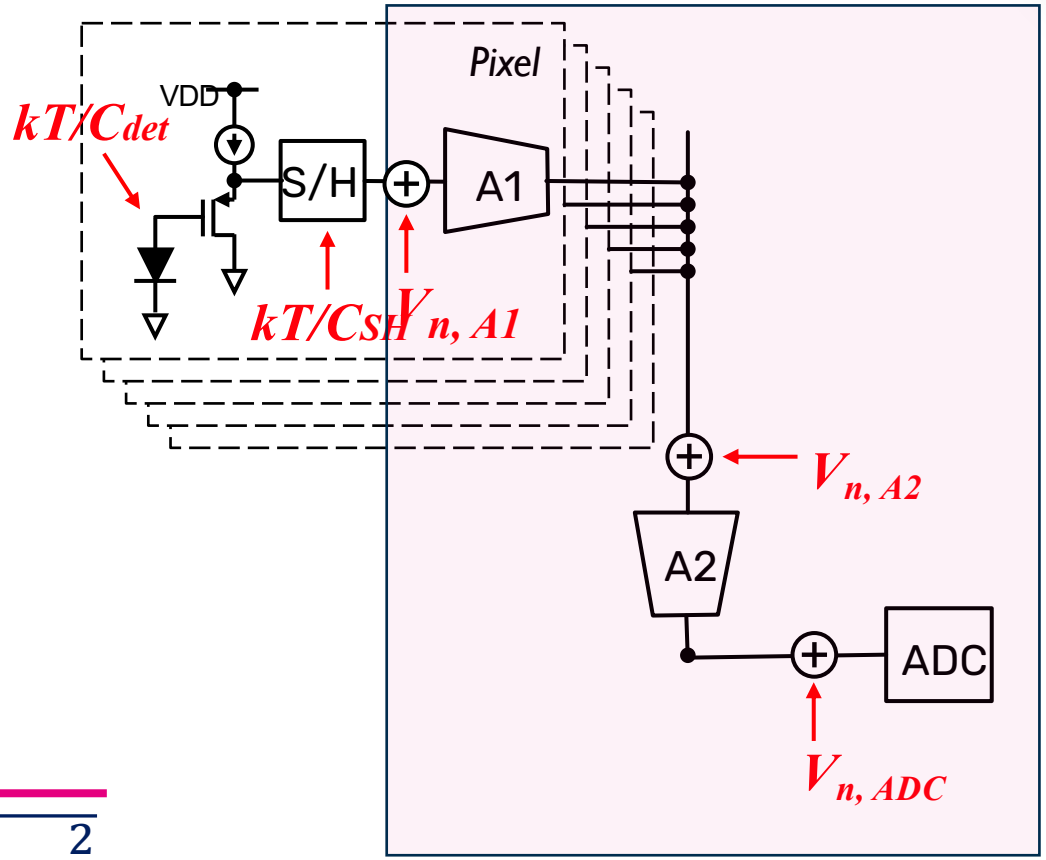
CITIUS: one ADC for 8 pixels

Multi-sampling: an established approach in consumer CMOS image sensors [1].

One can design as

$kT/C_{det} >> kT/C_{SH}$

For m-time sampling, noise $V_{n,total}$ is reduced as



$$\overline{V_{n,total}}^2 \cong \overline{V_{kTC_{det}}}^2 + \sqrt[m]{\overline{V_{n,A1}}^2 + \overline{V_{n,A2}}^2 + \overline{V_{n,ADC}}^2}$$

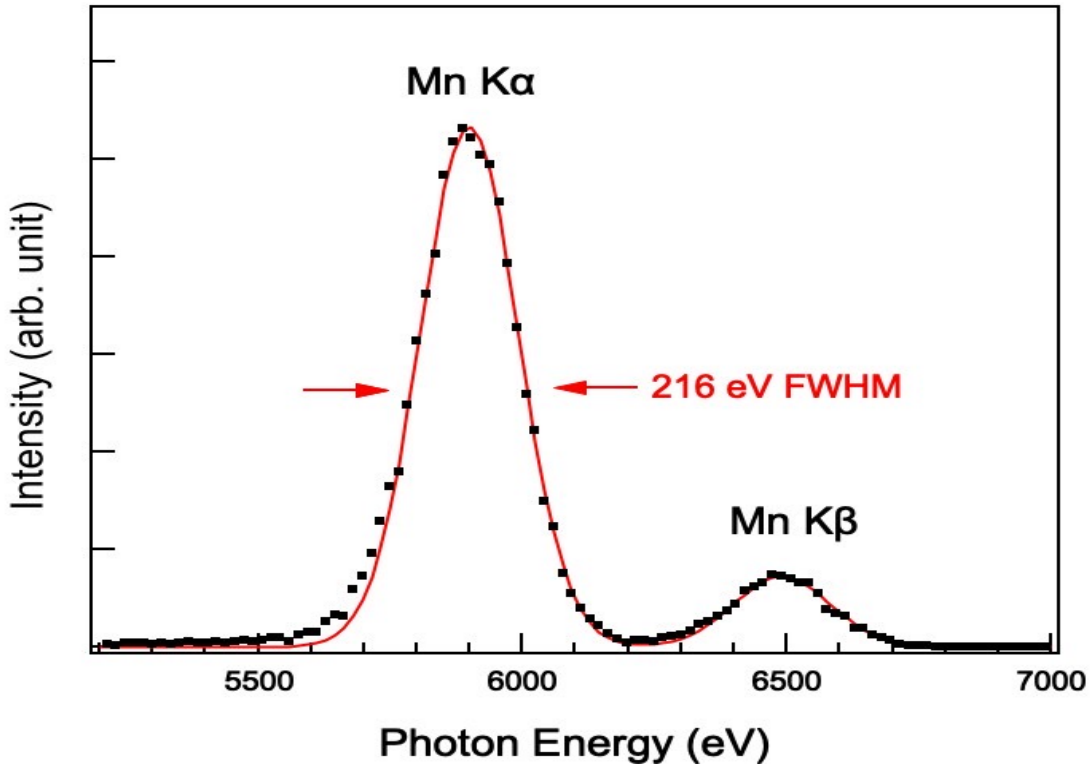
Circuit noise, except for kT/C noise, can be reduced at the slower frame rate

1) Kawahito, S. (2011). Architectures for Low-noise CMOS Electronic Imaging. In: Seitz, P., Theuwissen, A. (eds) Single-Photon Imaging. Springer Series in Optical Sciences, vol 160. Springer, Berlin, Heidelberg.

8-Sampling Results

Energy Resolution @ 5.9 keV

- Single sampling @ 26.1 kframes/s — 360 eV FWHM (40 e-rms)
- 8-sampling @ 2.2 kframes/s — 216 eV FWHM (22 e-rms)



Demonstrated Performance

Parameters		Value		unit
		CITIUS for XFEL (SACLA)	MPCCD (Phase III)	
Sensor	Sensor Material	Silicon		N/A
	Thickness	650	300	μm
	Pixel Size	72.6	50	μm
	Pixel Number	0.28	0.5	Mpixels/sensor module
	Peak Signal	17,000	2,400	phs/pixel@6 keV
		28	4	Me-/pixel
	Typical noise	25	250	e-rms
	Frame Rate	60*	60	Hz
	Data Rate	1.6**	0.06	GB/s @ digital out
System	Imaging area	321 × 393	100 × 100	mm^2
	Pixel Number	20.2	4	Mpixels
	Data Rate	107*	0.48	GB/s @digital out

x 2.1

x 1.5

x 0.6

x 7

x < 1/7

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:

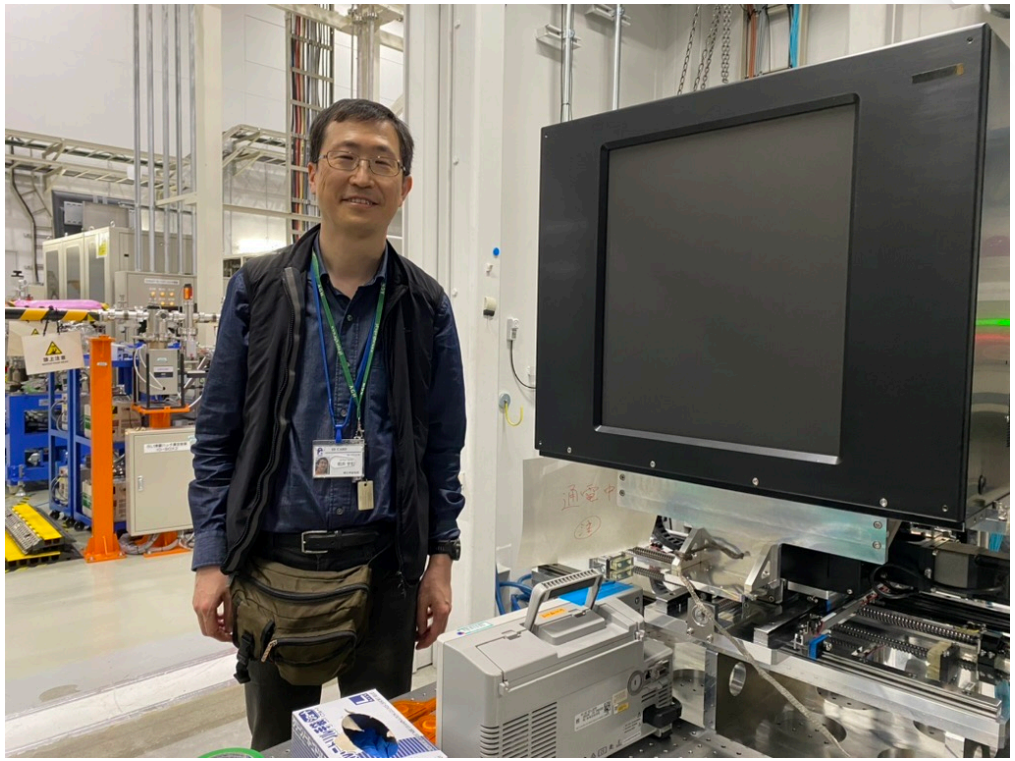
620 Gbps @ 32 bit/pixel

107 GB/s

9 PB/day, when operated continously

First Beam Test:

July 2024

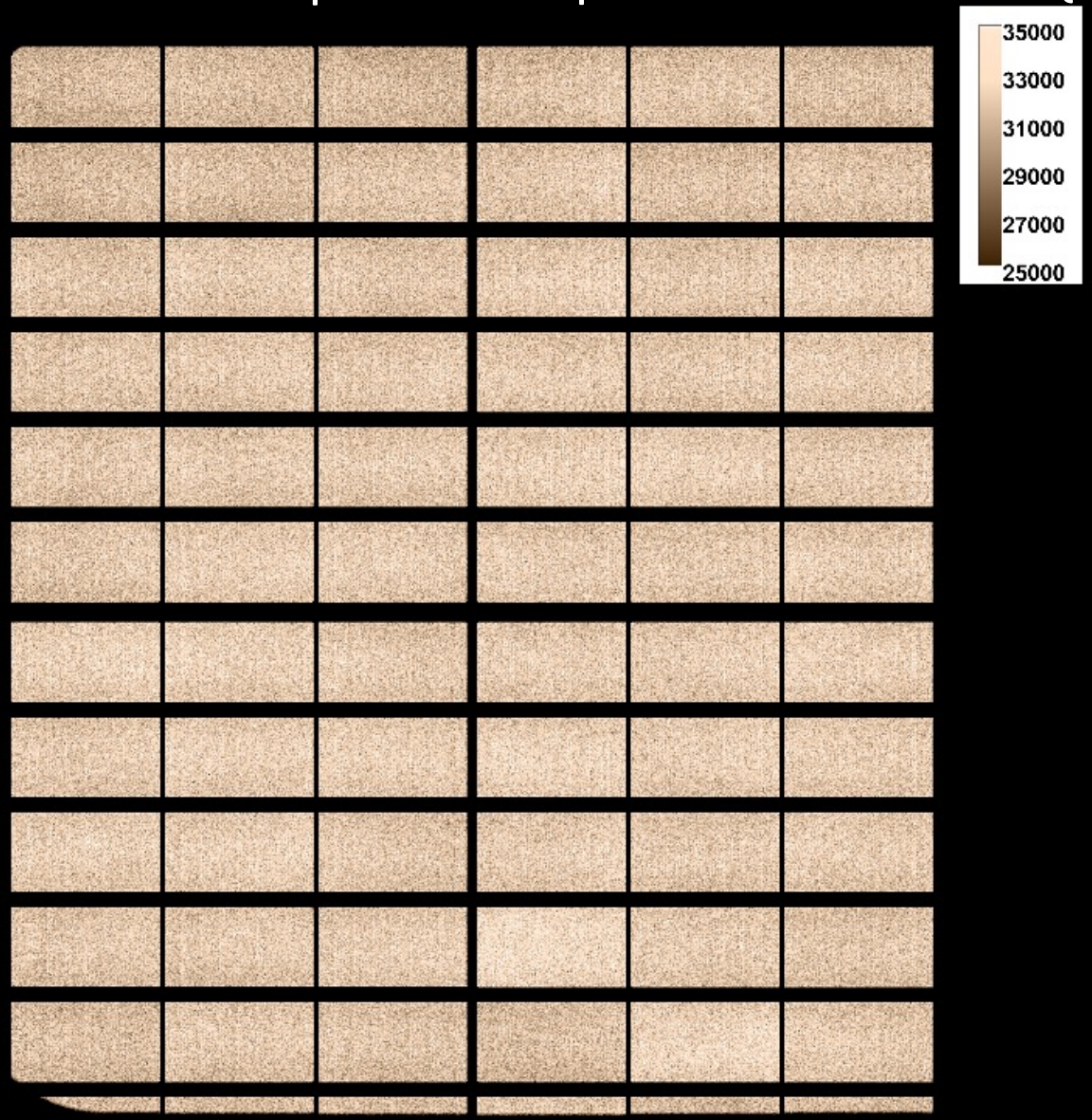


# of components: 12,586/system

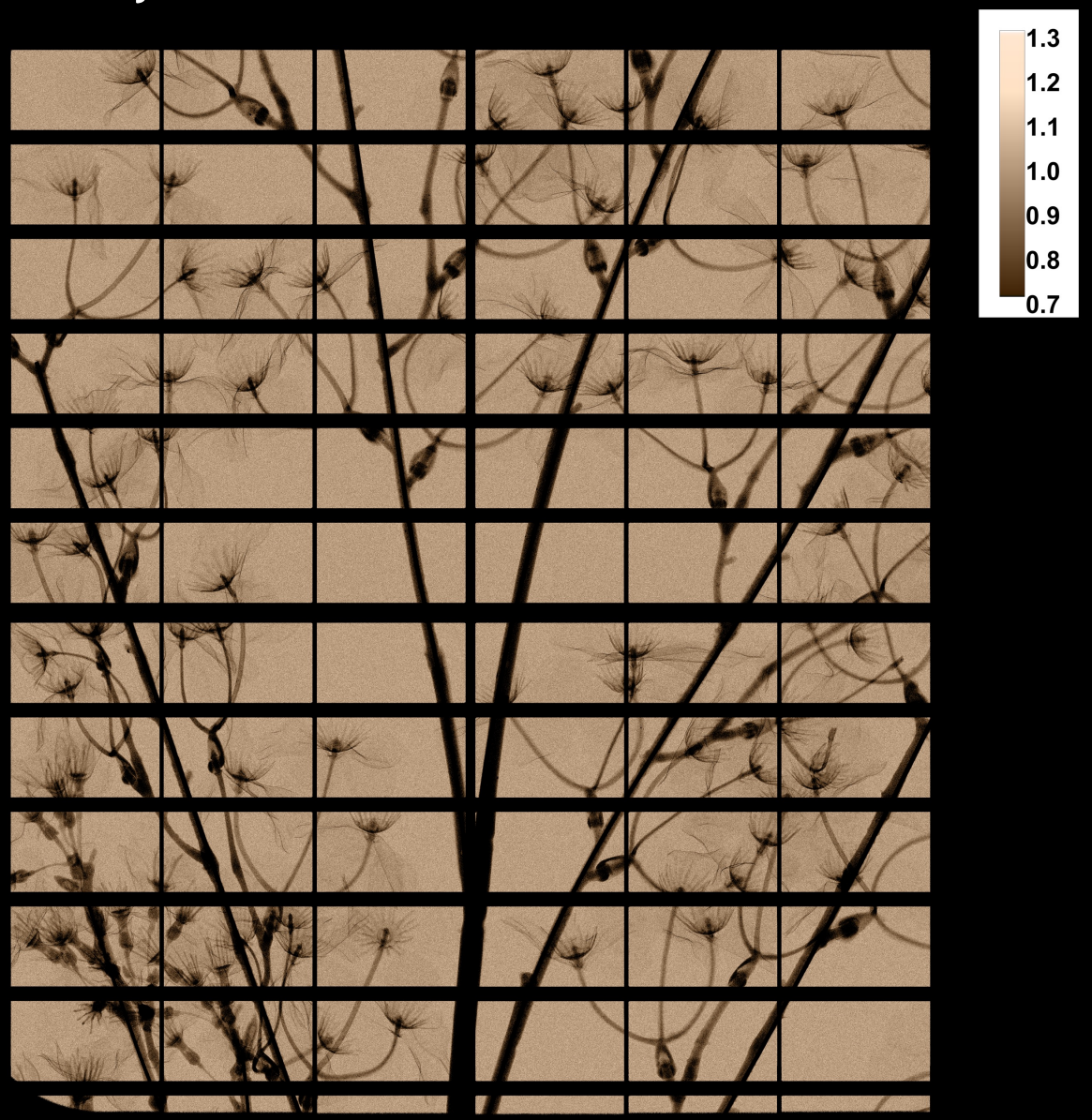
Engineering intensive project

The outcome of a large collaboration.

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

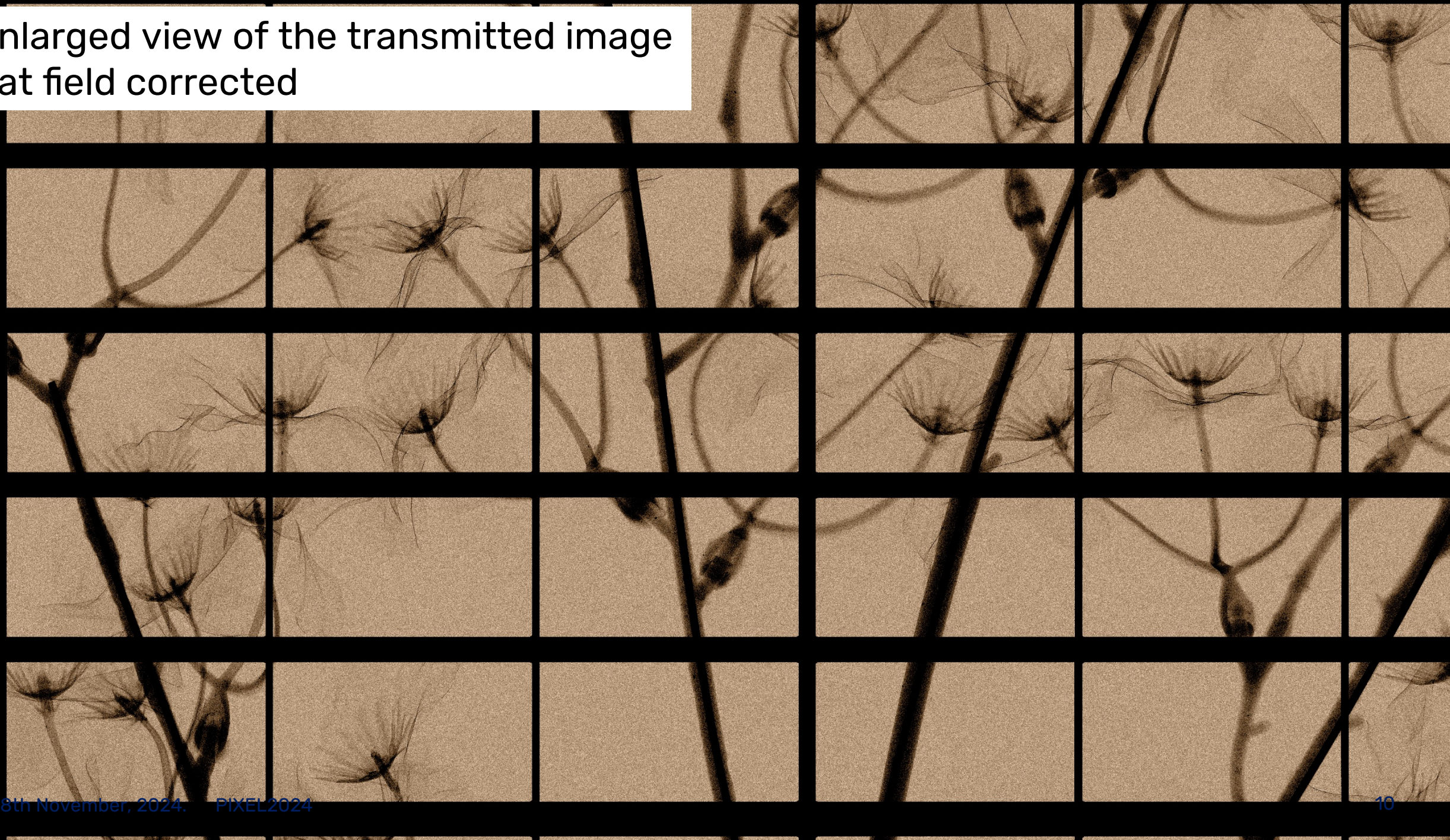


flat field image
dark subtracted

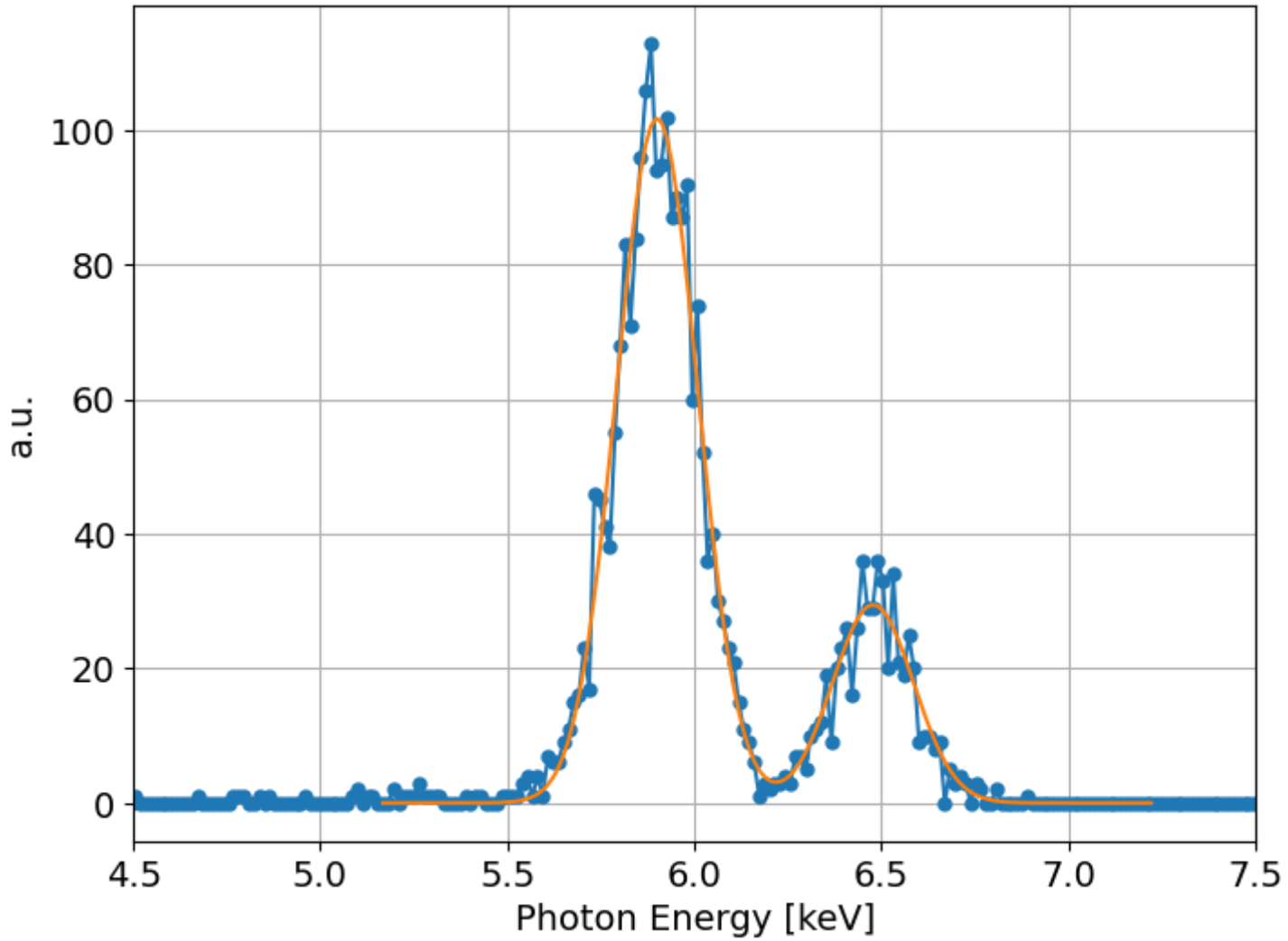


transmitted image
flat field corrected

Enlarged view of the transmitted image flat field corrected



Noise and Energy Resolution

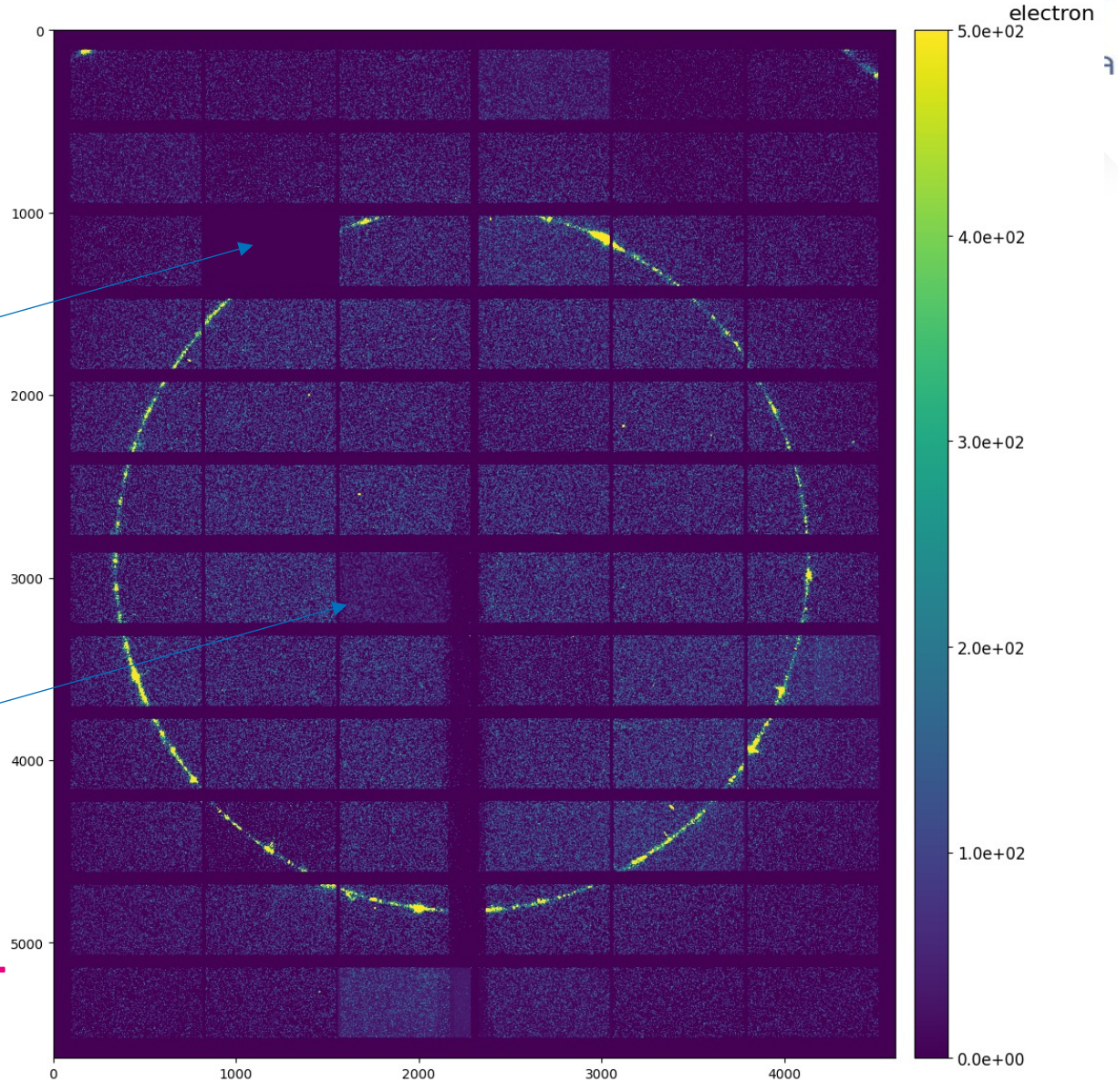


XFEL mode, 16-sampling

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

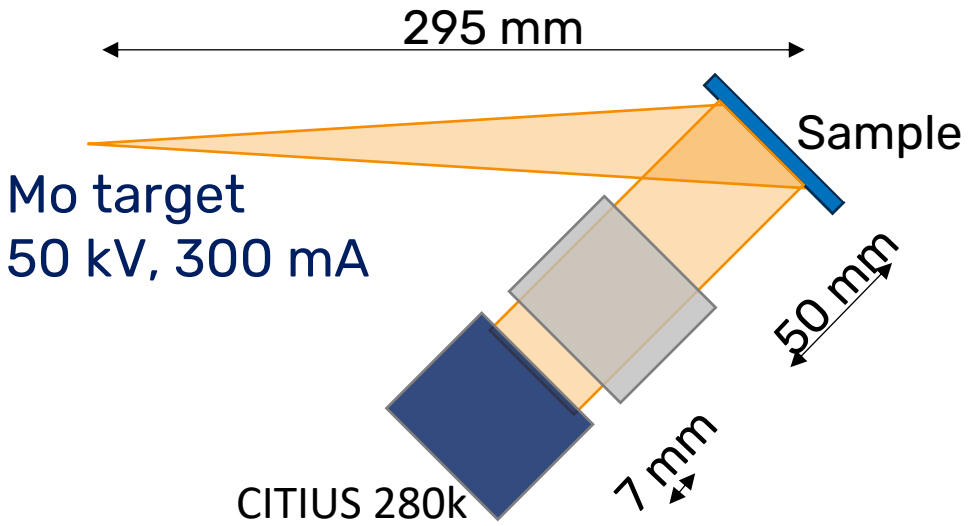


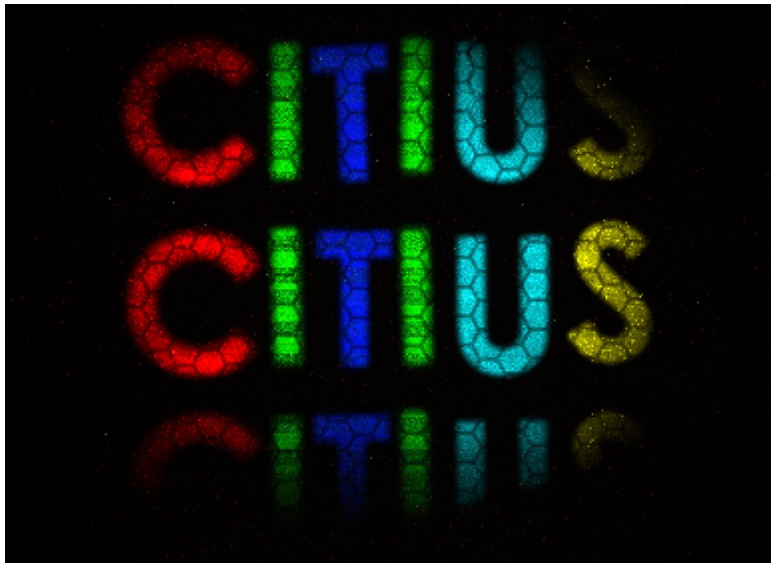
failure during commissioning

one sensor damaged
by direct beam during experiments

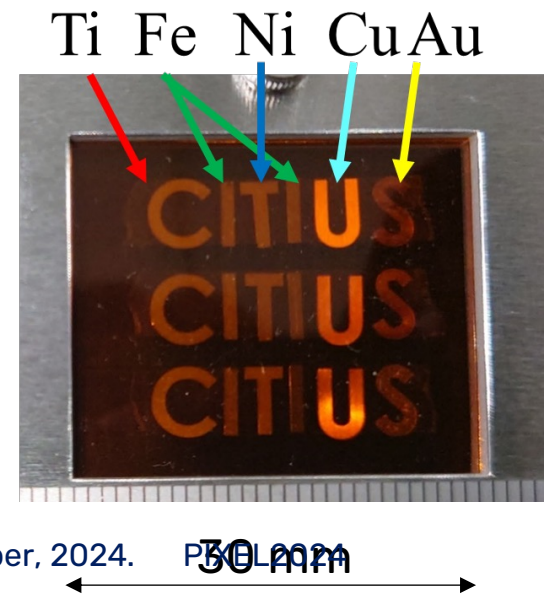
Successful structure determination demonstrated.
The first science experiments were carried out!

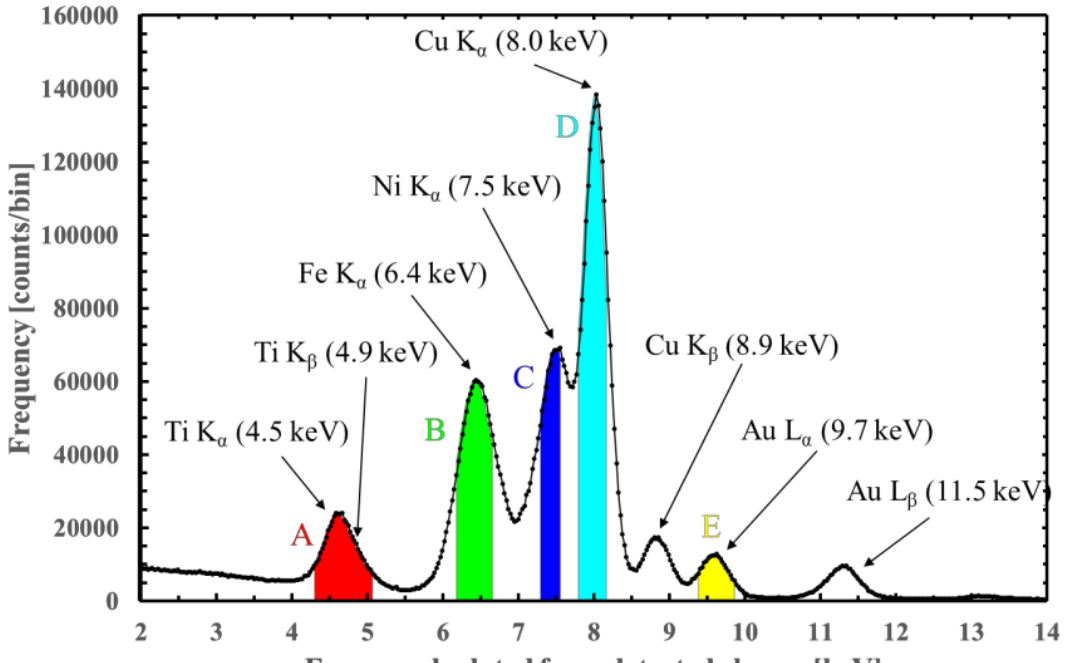
X-ray Spectro-imaging by using a Lab. X-ray source





CITIUS
8.5 Mframes
326 s
8.5 GB
at 26.1 kframes/s





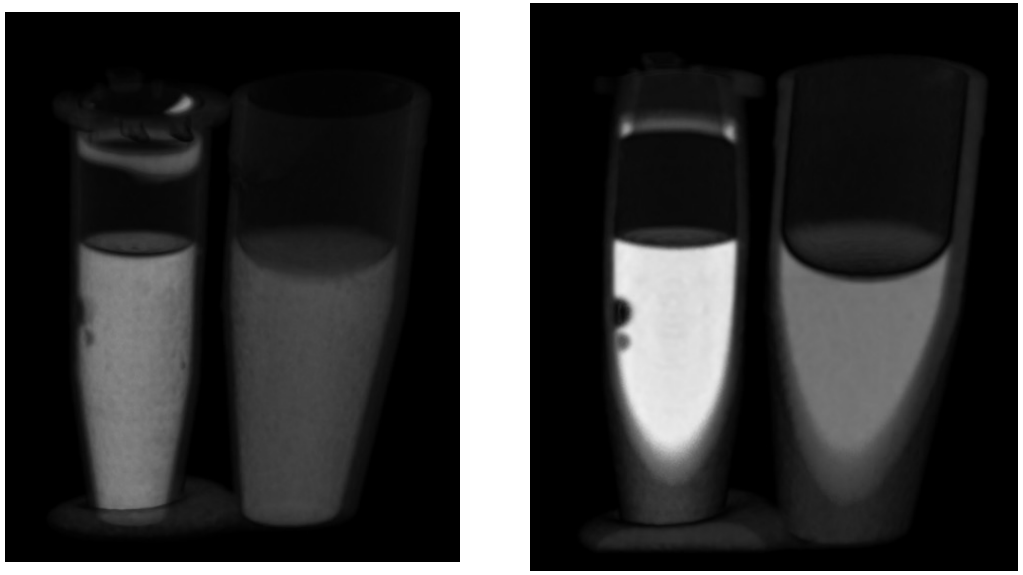
Laboratory based Spectral CT

V. Di Trapani[1,2*], F. De Marco[1,2], F. Arfelli[1,3], Y. Honjo[5], K. Ozaki[5], H. Nishino[5,6], Y. Joti[5,6], T. Hatsui[5], F. Orsini[5], P. Thibault[1,2], R. H. Menk[2,3,4]

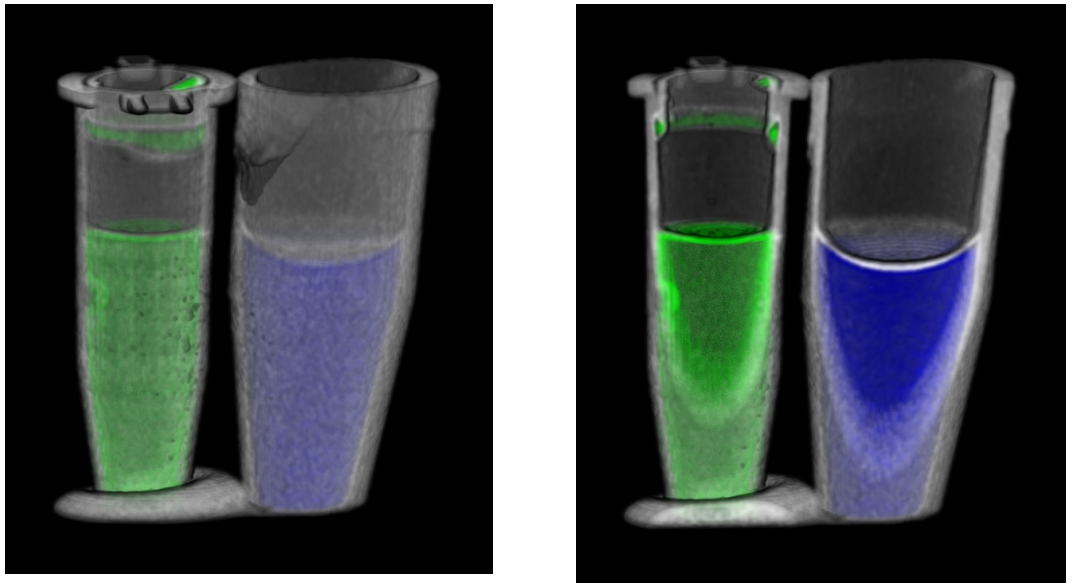
1) University of Trieste, 2) Elettra Sincrotrone 3) INFN Trieste, 4) Mid Sweden Univ., 5) RIKEN 6) JASRI

presented at iWoRiD 2024

Conventional CT



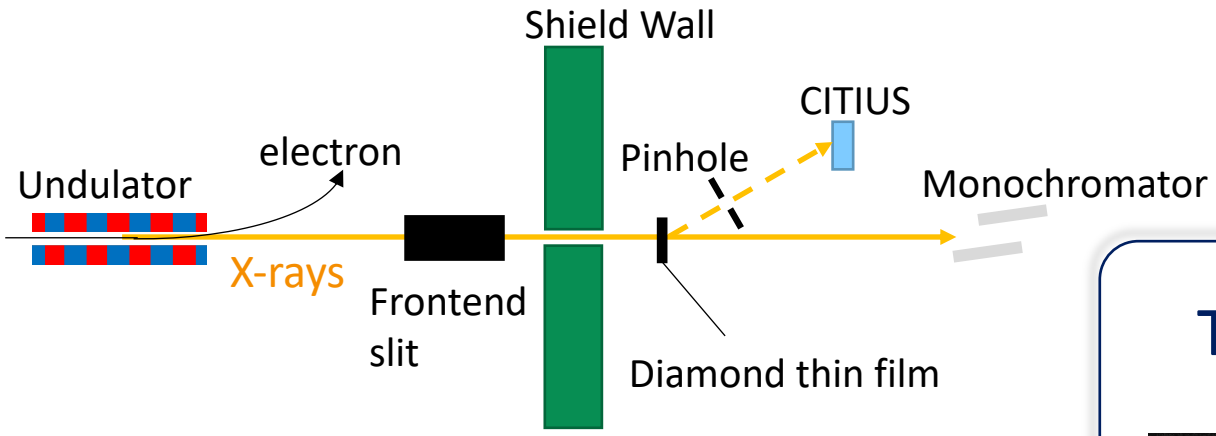
Spectral decomposed CT
(blue Ag, green KBr Gray polyethylene)



Analyzed Spectral Resolution in this experiments.

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

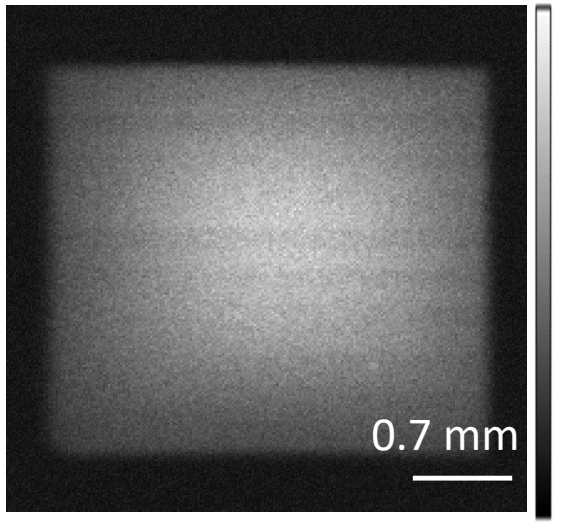
Non-Destructive X-ray Beam Monitor for SPring-8-II
Demonstration



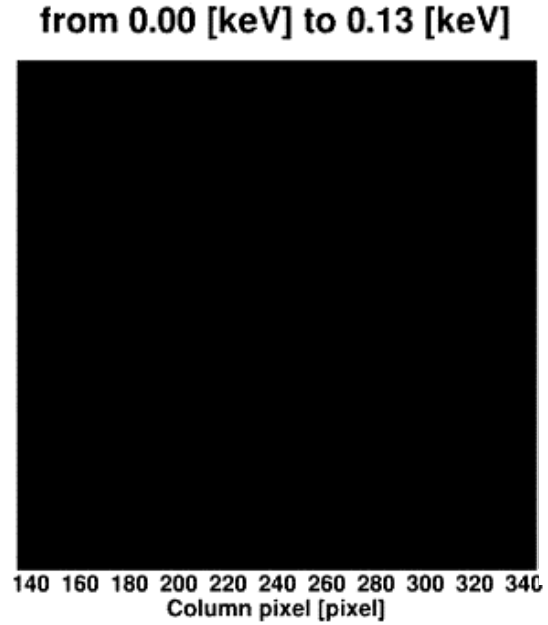
BL03XU Optical Hutch
Ring Current: 10 mA
Front end slit: 3.2 mm (h.) × 2.8 mm (vert.)
Gap: : 17.76 mm (fundamental at 12.4 keV)

CITIUS 280k
1.4 Mframes
54 s
1.4 GB
at 26.1 kframes/s

Total Intensity



Spectro-Imaging

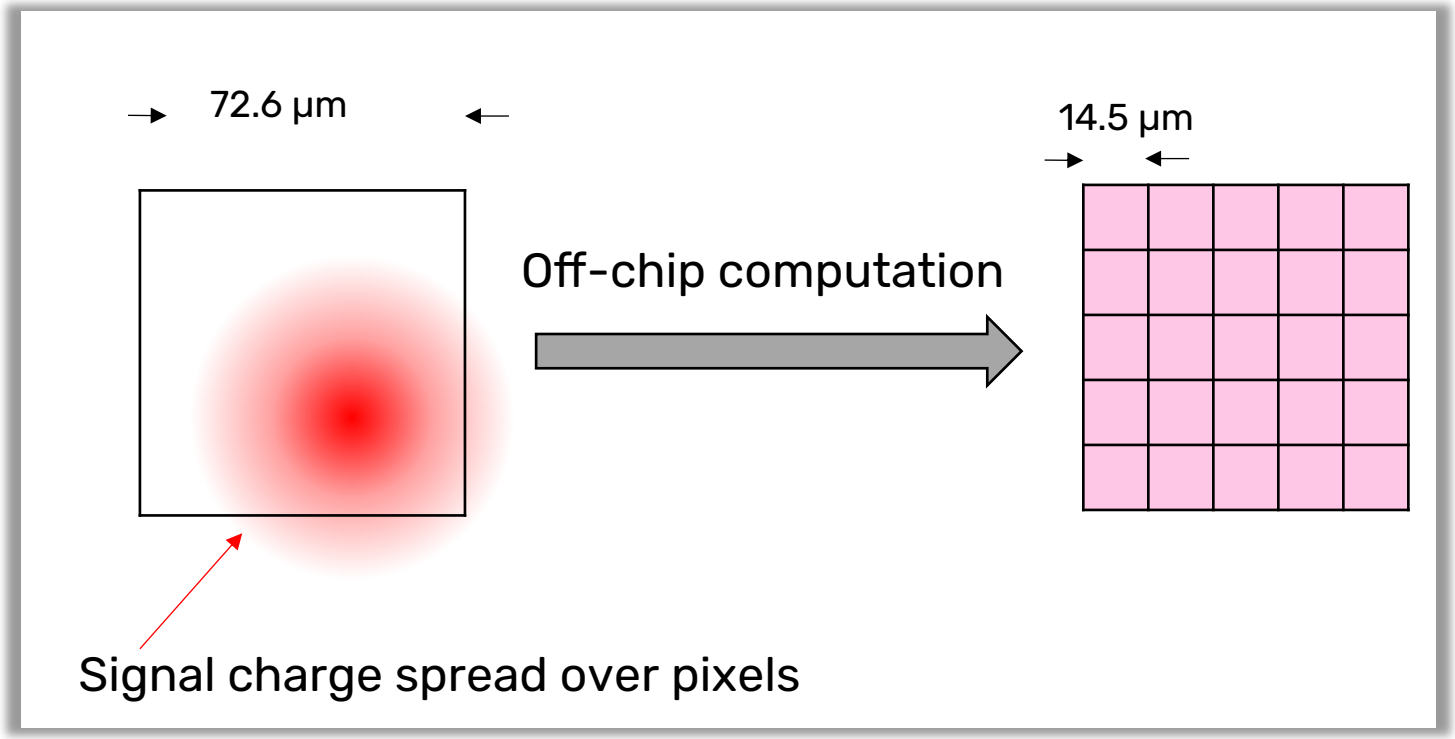


Sub-Pixel Imaging at virtual 14.5 μm Pixel Resolution

Method used in this sub-pixel imaging

R. Hosono, et.al., Opt Express, Vol 26(16) (2018). 21044.

Data were taken at 26.1 kframes/s



Yanwen Sun, Mario Balcazar, Zhu Diling, Takahiro Sato, Sanghoon Song, Tim B. van Driel, Vincent Esposito, Conny Hansson, Alex Halavanau, Kazutaka Nakahara, Jana B. Thayer, Angelo Dragone, Mark Sutton, Paul Fuoss

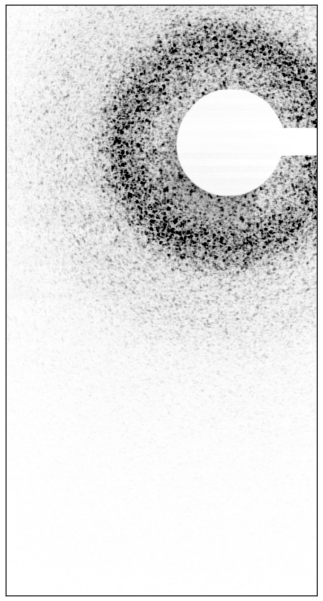
"Spectral Streaking"
Measure arrival time from the detected charge

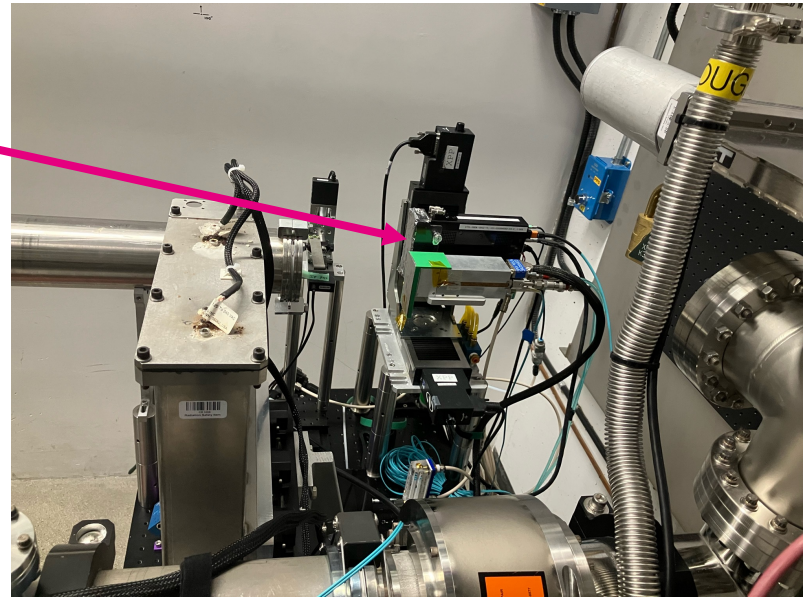
LCLS: has a unique operation mode of double XFEL pulse.

CITIUS: a double shutter mode for acquiring two successive pulses.

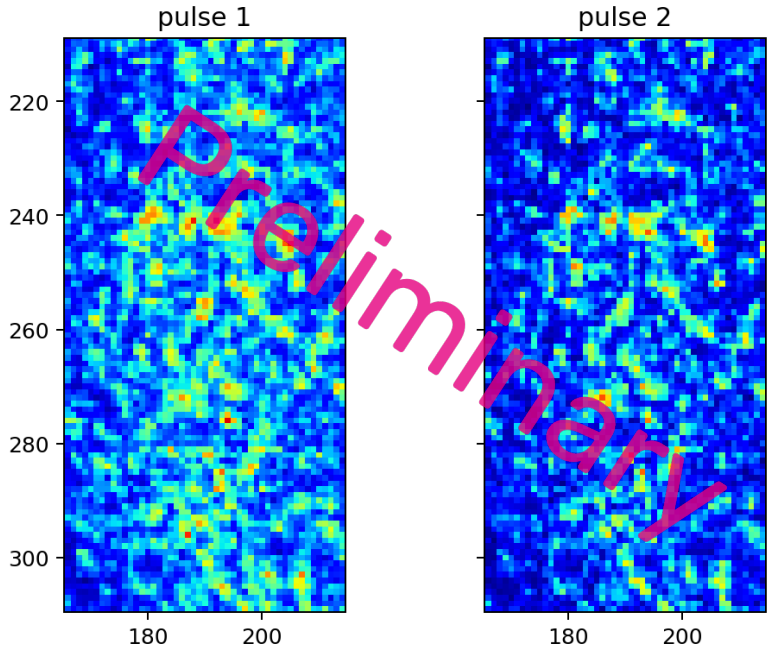
Shutter Opening/closing takes 100-150 ns.

280k sensor





CITIUS distinguished two pulses with 75 ns separation.



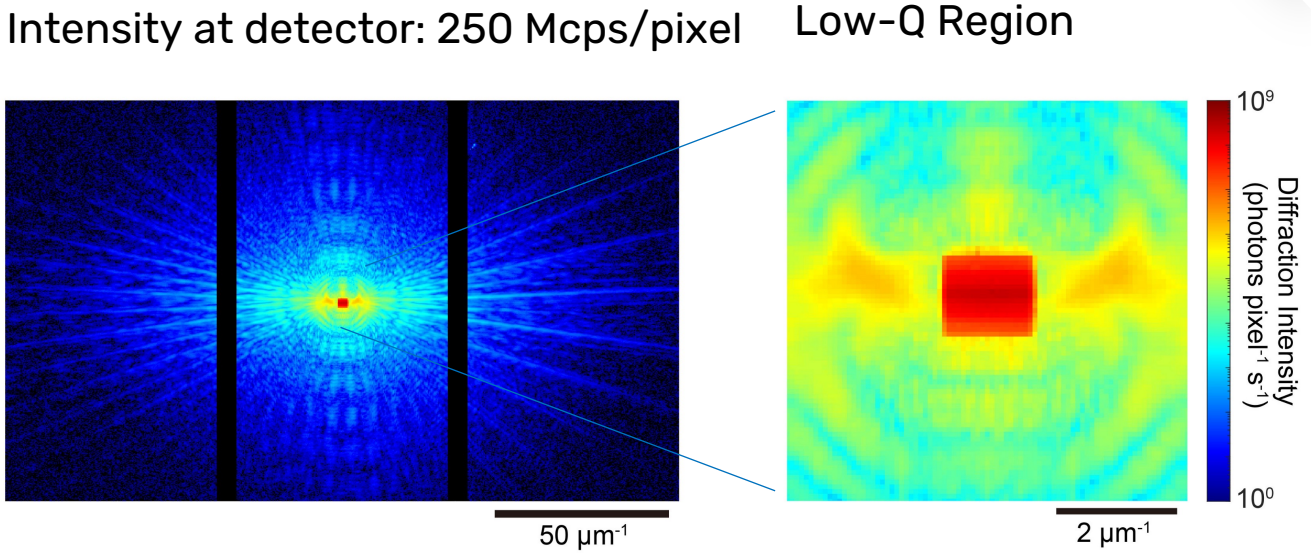
Analysis was done by taking the shutter open/close time constant of about 100-150 ns

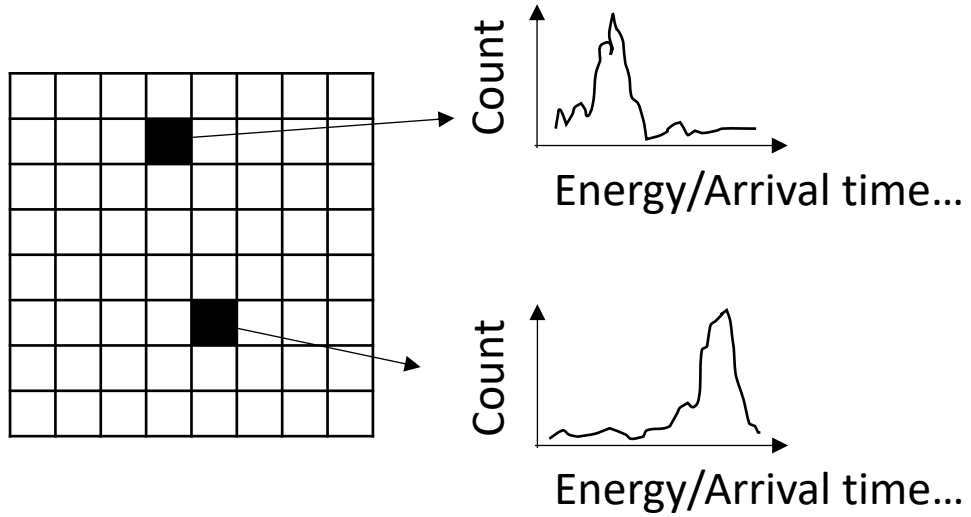
Use Case of CITIUS for X-rays

Intensity Mapping
- Number of Photons for each pixel
- Single Photon Sensitivity
  - noise << 0.018 phs rms @ 8 keV
- Ultra-high dynamic range
  - continuous X-rays: 1 Gphotons/s/pixel
  - pulsed X-rays for 6 keV
    - 1/66 photon noise (25 e-rms) *This talk*
    - 17,000 photons/pixel/pulse (28 Me-)
    - S/N = 1.12 x 10^6, best in class

Photon Event Recording
- Condition
  - Flux Density < 1 phs/pixel/frame
- Photon Event data
  - Photon energy from charge (Spectro-Imaging) *This talk*
  - Sub-pixel imaging ("Super-resolution") *This talk*
  - Polarization from *Auger electrons*
  - Direction *from Compton scattered electrons*
  - "Spectral streaking" *This talk*

Max. Intensity at detector: 250 Mcps/pixel





Acknowledgment

RIKEN and JASRI Team

- Kazuo Kobayashi, Koji Motomura, Kyo Nakajima, 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.