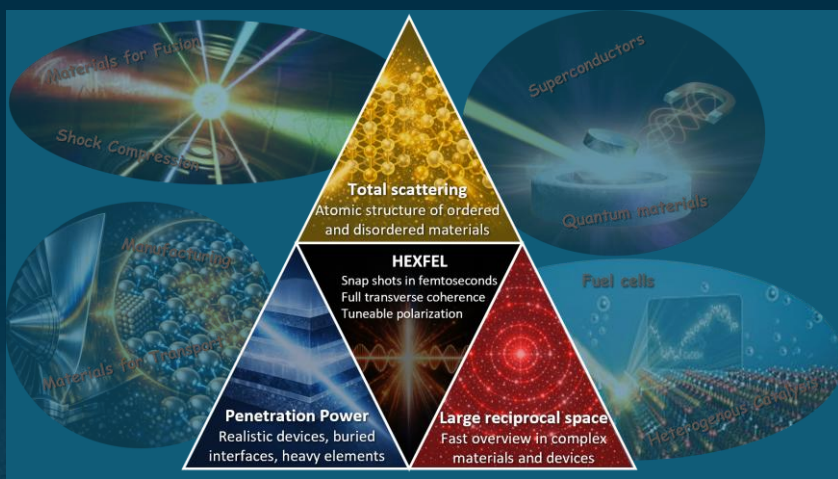




High-Energy X-rays: detectors challenges and opportunities

Gabriella A. Carini...with contributions from the broader detector and sensor materials community

20260829

The lay of the land

XFELs detectors – some examples

Historical evolution

Pixelated detectors

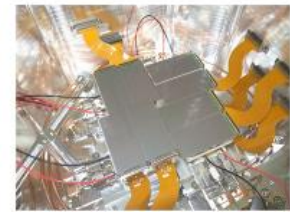
CCDs changed the way we see the world



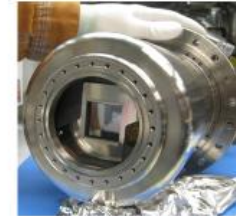
Invention of the CCD in 1969



scintillator fiber coupled to CCD

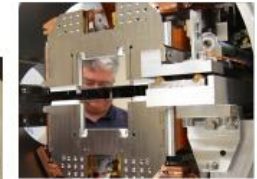
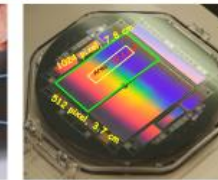
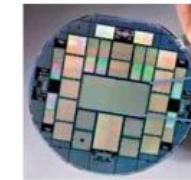


MPCCD, Riken, Japan



Brookhaven National Laboratory

FCCD, LBNL



pnCCD, MPG-HLL

Pixel Array Detectors

It consists of a segmented sensor bonded to a dedicated integrated circuit

History:

- Counters: charge is shaped and compared to a threshold (minimum detectable value)
 - PILATUS, Medipix(-based), XPAD, EIGER, etc.
- Integrating detectors: charge is integrated and measured
 - CS-PAD, KECK, JUNGFR AU, AGIPD, LPD, MMPAD, ePIX, MOENCH, etc.

Today many groups are working on that

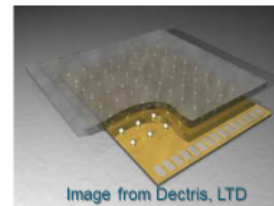
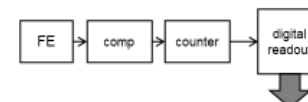
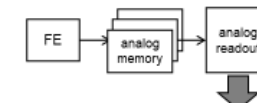


Image from Dectris, LTD

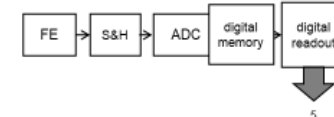
counting chip



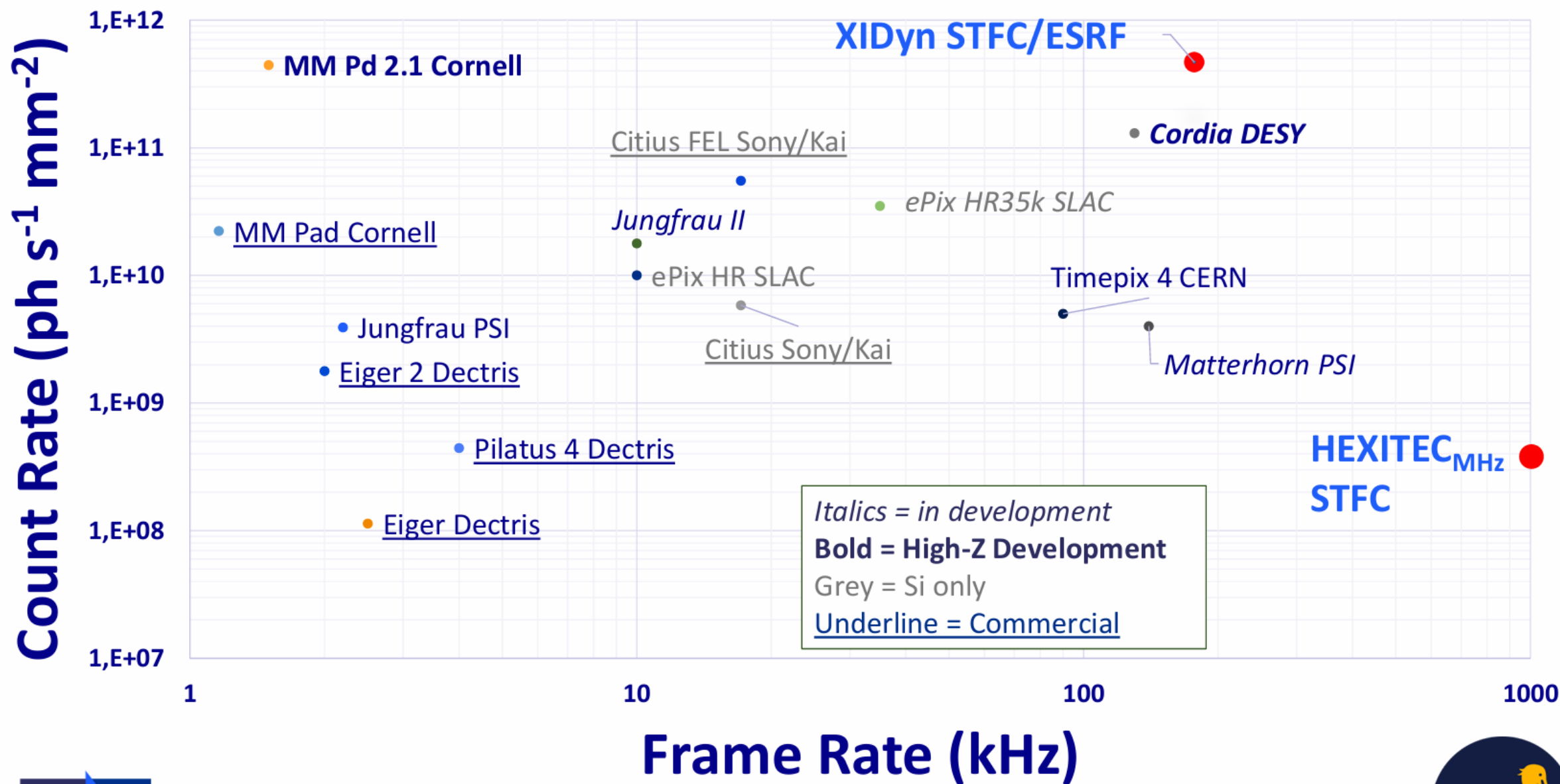
analog integrating – analog readout

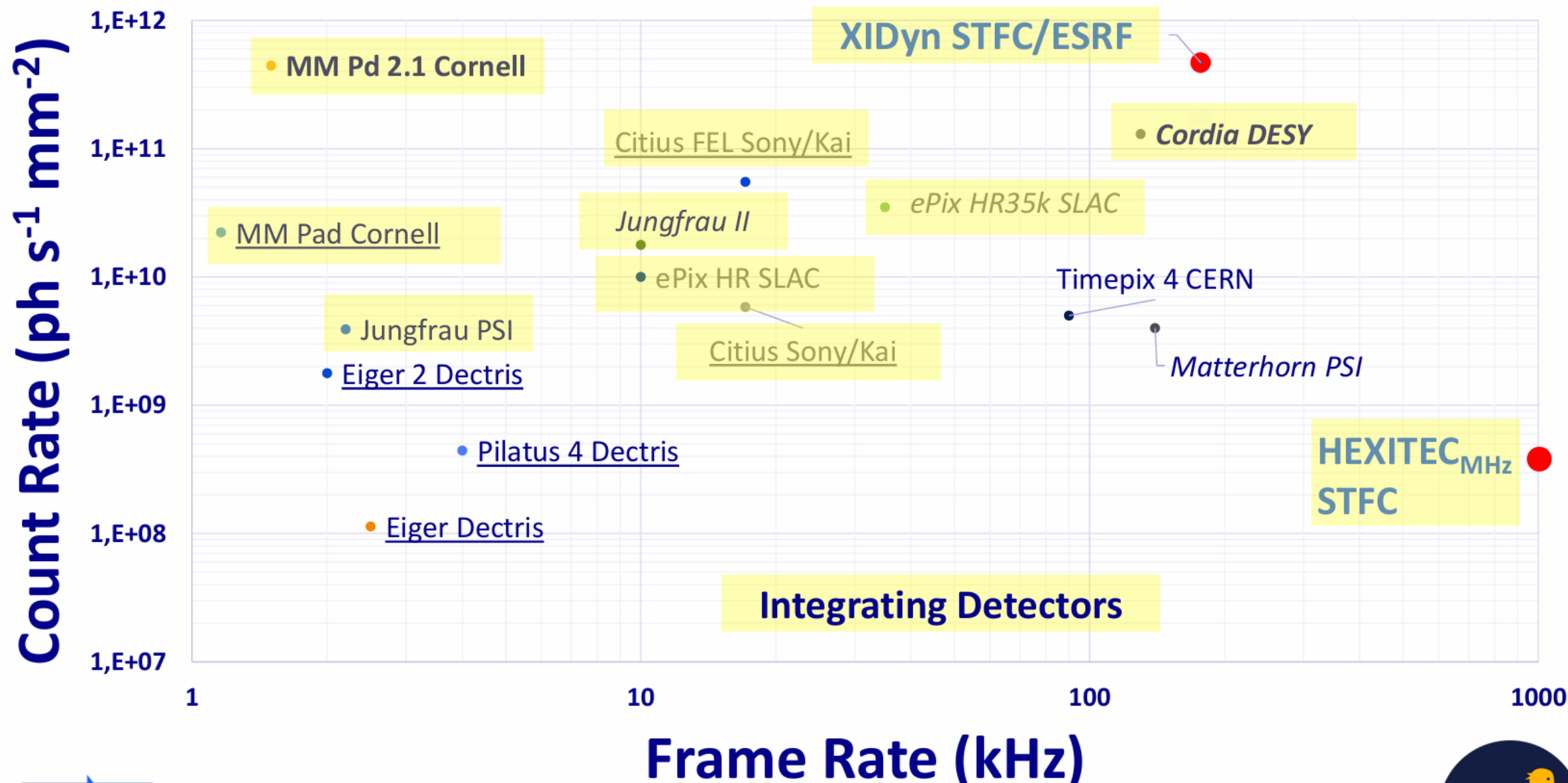


analog integrating – digital readout



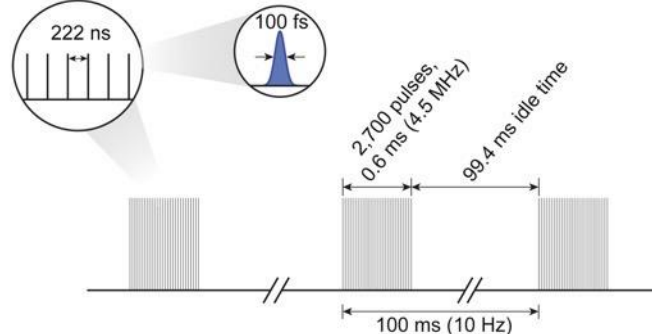
Brookhaven National Laboratory





XSPA – Rigaku: Nakaye, Y., Sakumura, T., Sakuma, Y., Mikusu, S., Dawiec, A., Orsini, F., Grybos, P., Szczygiel, R., Maj, P., Ferrara, J. D. & Taguchi, T. (2021). J. Synchrotron Rad. 28, 439-447.

SELUN - Dectris: Montemurro, G. V., Grimm, S., Donath, T. & Zambon, P. (2026). J. Synchrotron Rad. 33, 98-105.



Detectors for EuXFEL

**X-ray
energy**

Hard
X-rays
6-25 keV



ePix100 (2 instruments)

Noise: 50 e⁻ (HG)
Dyn range: 100 8 keV ph



Jungfrau x 18 (all hard X-ray inst.)

Noise: 80 e⁻ (HG)
Dyn range: 10⁴ 12 keV ph

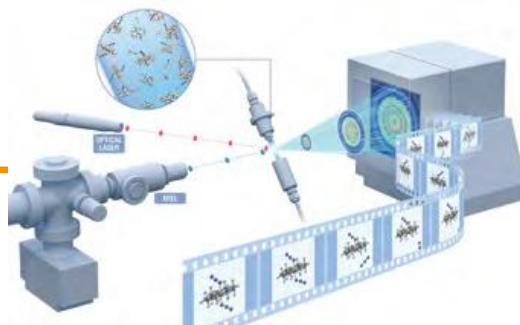
pnCCD (1 instrument)



Soft
X-rays
0.5-3 keV

10 Hz

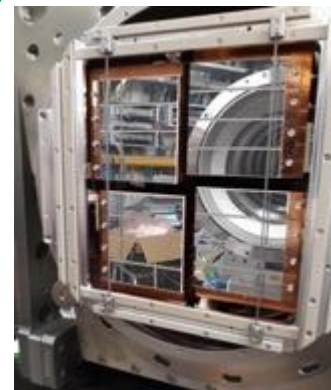
Low noise to see low energy photons
High dynamic range to see many
photons in the same pixel



Noise: 3 e⁻
Dyn range:
1500-3000 1 keV ph

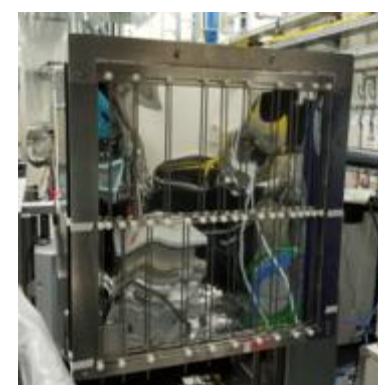


AGIPD (3 instruments)



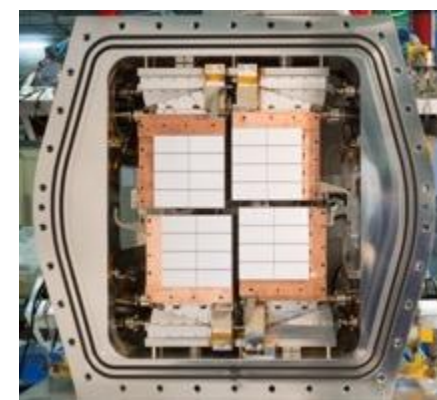
Noise: 350 e⁻ (HG)
Dyn range: 10⁴ 12 keV ph

LPD (1 instrument)



Noise: 2010 e⁻ (HG)
Dyn range: 10⁵ 12 keV ph

DSSC (2 instruments)



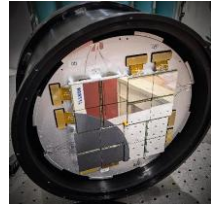
Noise: 40/60 e⁻ (DSSC1)
< 10 e⁻ (DSSC2)
Dyn range:
N x 256 ph @ 4.5 Mhz –
N x 512 @ f ≤ 2.2 MHz
N ≤ 1 for single ph sens.

4.5 MHz

Rate

**EuXFEL
specific!**

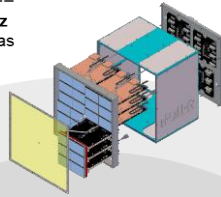
Ultra high-rate X-ray detectors for LCLS-II-HE



ePixHR_{5kHz} (2016-2025)
 • 5kHz for LCLS-II first light
 • ePixHR250M for soft-ray Imaging

ePixUHR_{35-100kHz} (2019-2028)

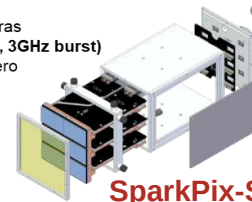
- Full frame 35kHz-100kHz
- "General purpose" cameras
- 35kHz for HE first light
- Sensors for hard X-rays



ePixUHR – 4M

SparkPix (2020-2028)

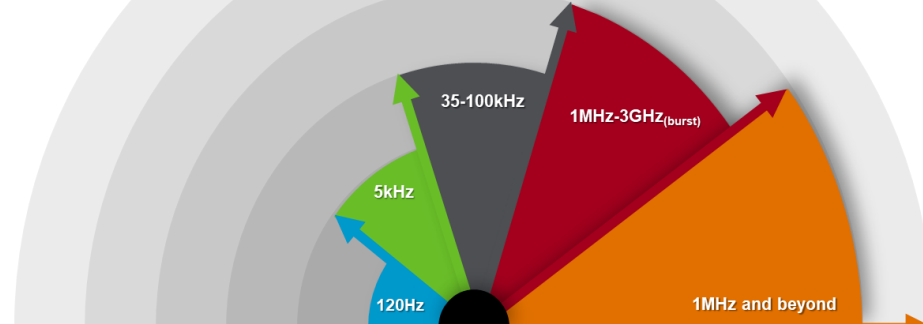
- Revolutionary Experiment Specific X-ray Cameras
- Information extraction at full rate (1MHz CW, 3GHz burst)
- Advanced features (triggering, sparsification, zero suppression etc.)



SparkPix-S

Morpheus (2025-2032)

- Data-driven intelligent Detector with distributed real-time processing at the sensor
- Ultra-high frame rate (programmable patterns)
- Trainable Energy-efficient real-time information extraction
 - Advanced Calibration / Edge-AI/ML
 - Validated algorithms – no loss of information
- Adaptive resolution (spatial, energy, and time) for experimental steering



ePix (2013-2018)
 • In use at LCLS

Development of high-rate X-ray area detectors, up to MHz readout is on-track, allowing >35 kHz from day one of LCLS-II-HE

R&D on Intelligent detectors with adaptive real-time processing



SPARKPIX-RT:

Real-time data compression engines for MHz detectors

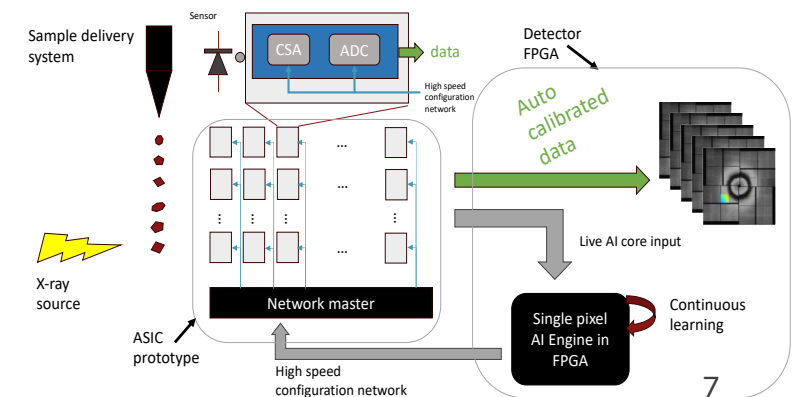
- Solve data transmission bottleneck by demonstrating on-chip compression in detector front-ends
- Digital multiplication (custom 9b FP) and "division" operations to support "photonization" on either a global or per-pixel basis
- First X-ray detector with compression and on-chip calibration!



Detector enclosure

TOWARD MORPHEUS: Real-time hardware-based AI engines for MHz data-driven detectors

- On detector Edge-AI/ML for auto calibration
- Prototype adaptive front-end with fast feedback
- Framework for algorithm validation



CITIUS detector

17.4 kframes/s and 1 Gcps with 72.6 μ m pixel



CITIUS detector for synchrotron radiation

Architecture [1-3]

Integrating Pixel & High Frame Rate

Feature

High Dynamic Range	Ultralow Systematic Error	Spectro-Imaging
--------------------	---------------------------	-----------------

Detector Performance

Parameters		Value
Sensor	Thickness	Si 650
	Pixel Size	72.6
	Pixel Number	0.28 Mpix
	Noise	0.027 phs./@
	Peak Signal	1,800 phs.
	Frame Rate	17.4
Largest System	Sat. Count Rate @12 keV	30 or 60
	Pixel Number	20.2 M
Image Area		325 x 3

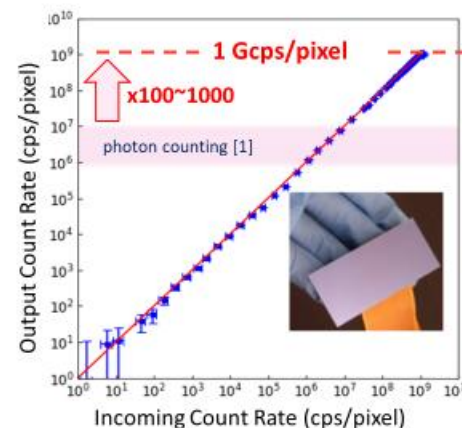
20.2M at SACLA FEL



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

CITIUS detector

17.4 kframes/s and 1 Gcps with 72.6 μ m pixel

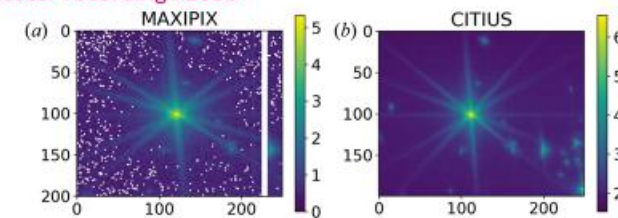


RIKEN-Sony Collab.
Invited Talk by T. Hatsui, Friday morning

- [1] Y. Imai and T. Hatsui, J. Synchrotron Rad. 31(2) (2024) 295.
- [2] M. Grimes et.al., J. Appl. Cryst. 56(4) (2023) 1032.
- [2] Y. Takahashi et.al., J. Synchrotron Rad. Vol. 30(5) (2023) 989.

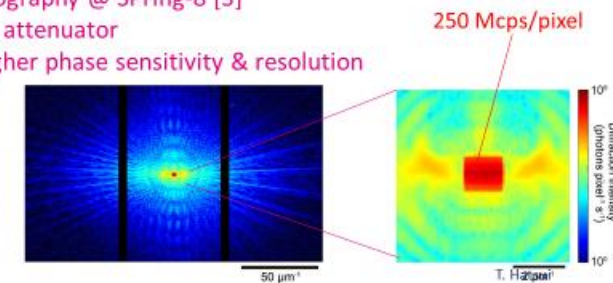
Bragg CDI @ ESRF [2]

- faster recording x1000



ptychography @ SPRING-8 [3]

- no attenuator
- higher phase sensitivity & resolution

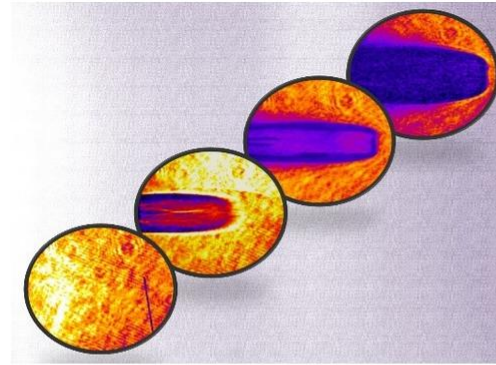
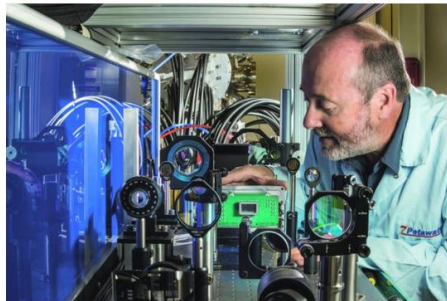


Other 'fast' detectors

Ultra-Fast Digital X-Ray Imager

High Energy Density (HED) physics and inertial confinement fusion experiments rely on successively monitored images for data collection

High Energy Density (HED) physics and inertial confinement fusion experiments rely on successively monitored images for data collection. Currently, gated X-ray imaging and spectroscopy in the 0.1-10 nanosecond (ns) time scale in HED physics utilize Micro-Channel Plate (MCP) detectors. Unfortunately, MCP detectors suffer from small to moderate dynamic range, difficulty in calibration, and can only capture a single frame along each line of site. HED experiments carried out at Sandia's Z-Machine facility led to the development of the Ultra-Fast Digital X-Ray Imager (UXI)—a high speed, multiframe, time-gated Read Out Integrated Circuit (ROIC)—as a more efficient replacement for MCP detectors. UXI is capable of taking images with an exposure time of only 1.5 ns, and taking extremely close sequential images within the same experiment.



UXI was developed to take two, 2 ns X-ray images with high, 25 μm , spatial resolution. It consists of a 1024 x 448-pixel array of 25 μm pixels with two frames of 1.5 million electron in-situ pixel storage, the associated readout decode circuitry, parallel output analog buffering for pixel data read off and high-speed timing generation and distribution blocks. The system is designed to be completely configurable based on the specific experimenters needs. Various shutter speeds can be set based on experiment parameters, as well as scalability to a greater number of frames for future

iterations of imagers. The current silicon detector used on Furi is sensitive to 4-6 keV X-rays or 532 nm visible light. The detector is bonded to the ROIC using a 3-dimensional interconnect. This allows different detectors to be bonded to the ROIC enabling the camera to be used in a wider area of applications. This novel high-speed camera will allow researchers the new ability to view a succession of chemical, nuclear, or biological reactions that occur in nanoseconds—making it a valuable research tool for industry or universities.

The existing Icarus form factor comprises a 1024 x 512 pixel array at 25 μm pitch, giving a total active area of 25.6 mm x 12.8 mm

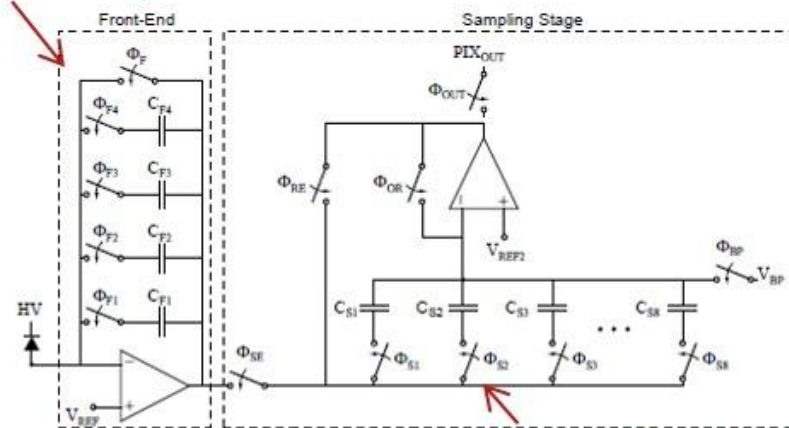
Overview

The Keck-PAD is a photon-integrating area detector compatible with **single-bunch(-train) imaging** at storage ring sources. 256x384 pixel prototype cameras are available for use through the Cornell Detector Group, and 512x512 pixel cameras have been commercialized by Sydor Technologies. Both **Si** and **CdTe** sensors are available.

Keck-PAD specifications	
Burst mode framing	8 consecutive frames with minimum separation ~100 ns
Read time	0.86 ms/stored frame
Frame timing	Programmable to 10ns resolution
Pixel size	150 μm x 150 μm
Format	256 x 384 pixel and 512 x 512 pixel units
Read noise	1 photon @ 8 keV (high gain) 4 photons @ 8 keV (low gain)
Well capacity	~1100 photons @ 8 keV (HG) ~7300 photons @ 8 keV (LG)

Programmable gain

Pixel schematic

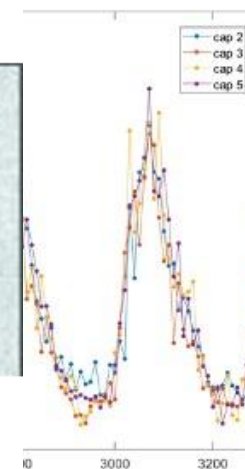
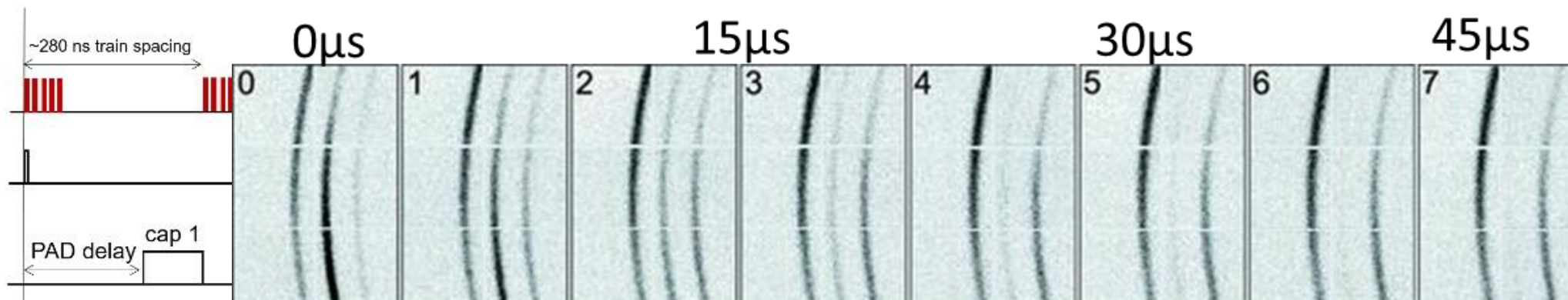


Frame storage capacitors

Potential applications

- Warm dense matter properties in magnetic pinch and impact experiments
- Crack propagation
 - Turbulence
 - Shock waves
 -

Demonstration of single-bunch-train imaging with the Sydor 512x512 CdTe-Keck-PAD @ CHESS MSN-C



New 77 ns 16 frame burst-rate detector is currently being designed for use at Advanced Photon Source (APS)

**Good news: we don't need
new crazy fast detectors!**

**Bad news: we need better
sensor materials!**

Detector sensing medium: a material challenge

Photon absorption depth in Silicon

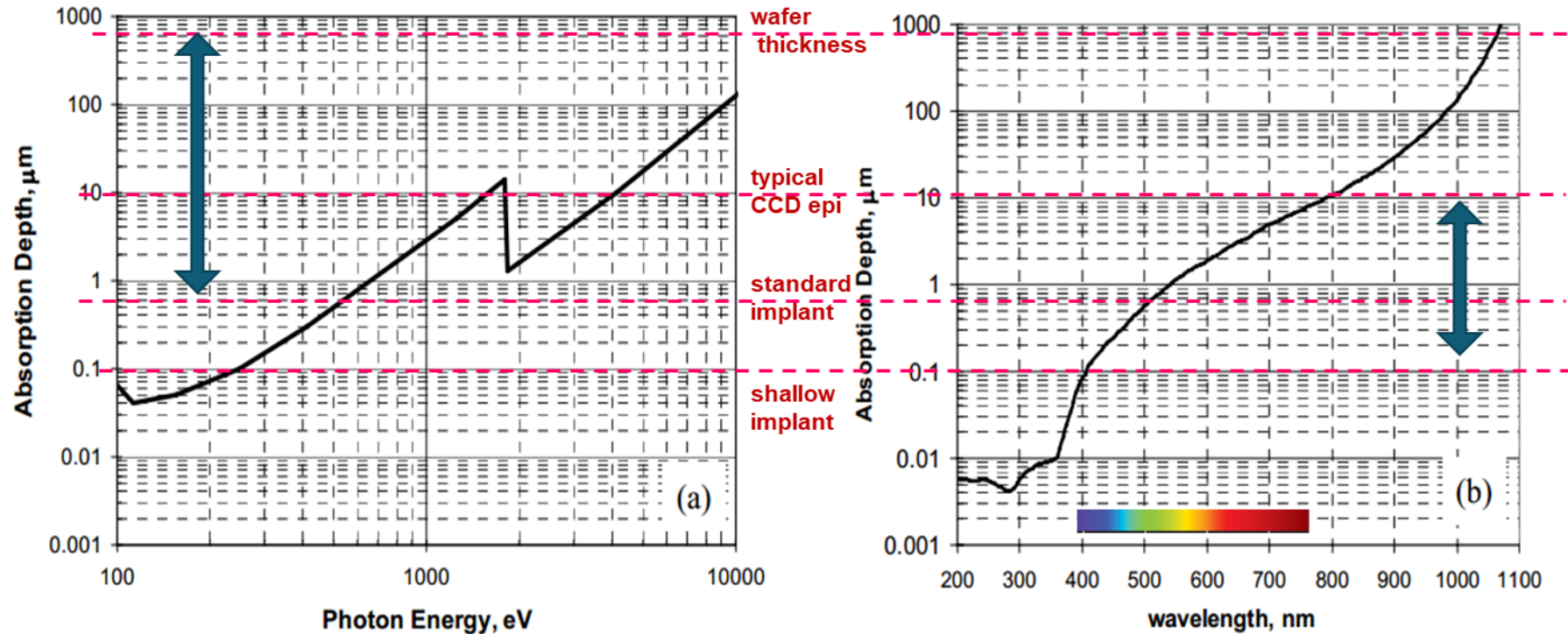


Fig. 7: Absorption depth of photons in silicon as a function of: (a) X-ray energy and, (b) the wavelengths from UV to NIR

- hard x-ray cameras need thick sensors
- soft x-ray cameras need thin entrance windows

'Beyond' silicon: materials challenge

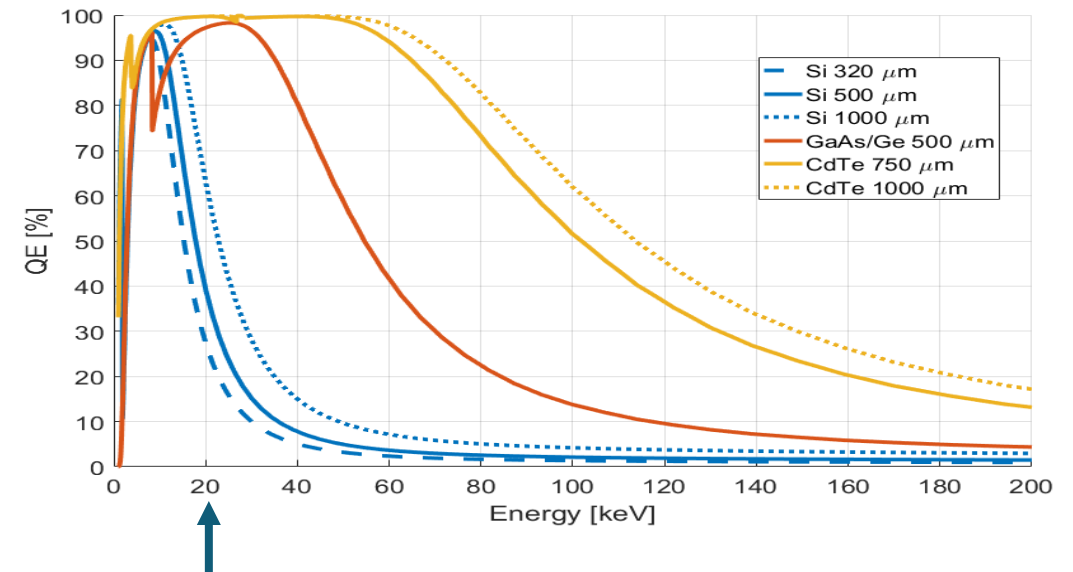
J. Thom (Cornell)

Hard x-rays need better stopping power (high-Z materials)

Physical characteristics of the semiconductors

Semi-conductor	ρ [g/cm ³]	Z	E_{gap} [eV]	ϵ [eV]	T_{working} [K]	K-edge [keV]	ρ_e [Ω cm]	$\mu_{e,h} \tau_{e,h}$ [cm ² /V]
Si	2.33	14	1.12	3.6 [1]	300	1.8	$\approx 10^3$	0.42, 0.22
Ge	5.33	32	0.67	2.9 [3]	77	11.1	$\approx 10^2$	0.72, 0.84
GaSe	4.55	31, 34	2.03	4.5 [4]	300	10.3, 12.6		$10^{-7}, 10^{-7}$ $1.5 \times 10^{-6}, 2.5 \times 10^{-6}$
InP	4.78	49, 15	1.30	4.2 [6]	300	27.9, 2.1	$\approx 10^7$	$4.8 \times 10^{-6}, \leq 10^{-7}$
CdS	4.84	48, 16	2.60	7.3 [15]	300	26.7, 2.4		
GaAs	5.32	31, 33	1.43	4.3 [3]	300	10.3, 11.8	$\approx 10^7$	$8.6 \times 10^{-6}, 4.0 \times 10^{-5}$ $8.6 \times 10^{-5}, 4.0 \times 10^{-4}$
InSb	5.77	49, 51	0.20	0.6 [15]	4	27.9, 30.4		$10^{-5}, 7.5 \times 10^{-6}$
CdSe	5.80	48, 34	1.73	5.5 ^a	300	26.7, 12.6		$2.0 \times 10^{-5}, 1.5 \times 10^{-4}$
CdTe	6.20	48, 52	1.44	4.7 [3]	300	26.7, 31.8	$\approx 10^9$	$2.0 \times 10^{-3}, 4.0 \times 10^{-4}$
PbI ₂	6.20	82, 53	2.55	7.7 ^a	300	88.0, 33.2	$> 10^{13}$	$8.0 \times 10^{-6}, 2.0 \times 10^{-5}$
HgI ₂	6.40	80, 53	2.13	4.2 [7]	300	83.1, 33.2	10^{13}	$10^{-4}, 10^{-5}$
TlBr	7.56	81, 35	2.68	6.5 [18]	300	85.5, 13.5	$\approx 10^{12}$	$1.6 \times 10^{-5}, 1.5 \times 10^{-4}$

From Bencivelli et al., Nucl. Instr. Meth. Phys. Res. A310 (1991) 210-214



Every common higher-Z sensor has problems!

Availability & quality, fluorescence, trapping, recombination lifetime, carrier mobility, radiation hardness, dark current, physical properties.

High-flux CZT

- Development driven by CT applications (medical and security)
- '*Small*' pixel pitch ($\sim 100\text{s um}$)
- '*High*' flux ($> 10^6 \text{ ph s}^{-1} \text{ mm}^{-2}$)
- Redlen introduces HF – CZT in 2016-2017

High-flux CZT

*Turning up the heat:
up to 10^{12} ph s⁻¹ mm⁻²*

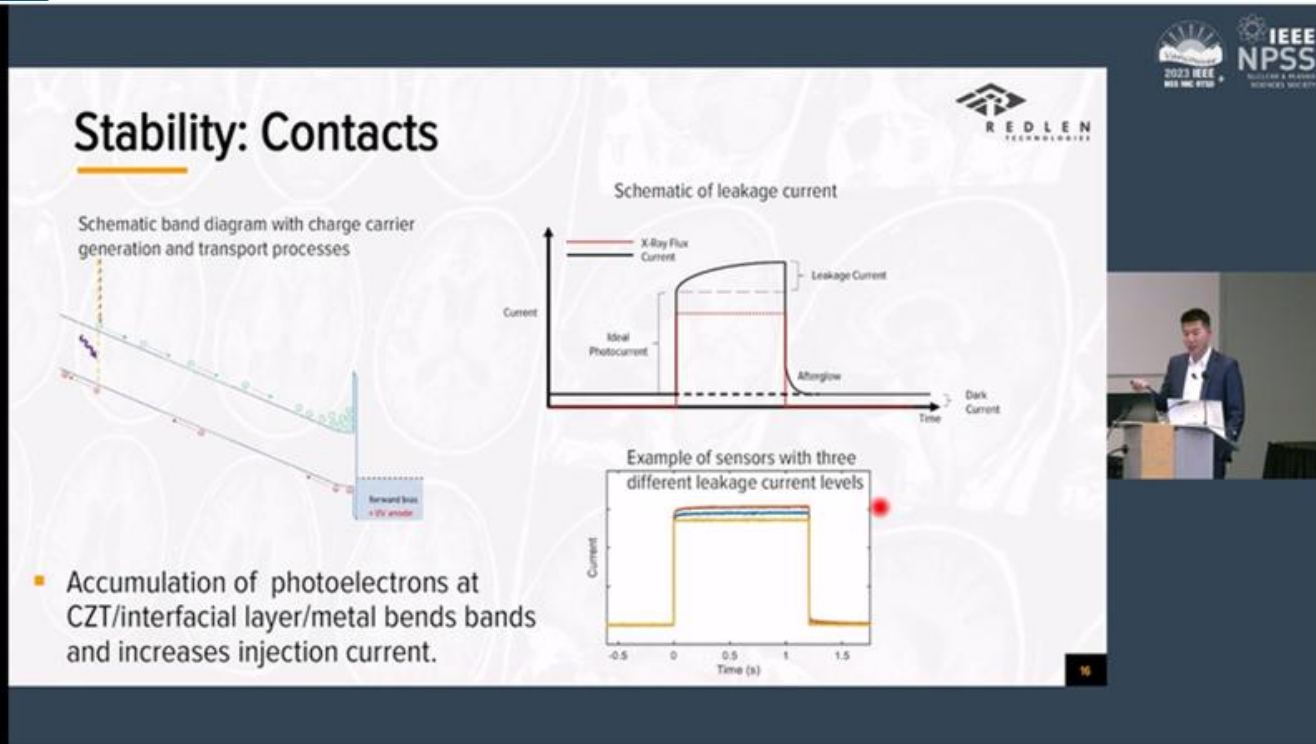
Table 1. A summary of the measured charge transport properties of three “high-flux” Redlen CdZnTe detectors [14, 16].

	$\mu_e \tau_e$ ($\times 10^{-4}$ cm ² V ⁻¹)	μ_e (cm ² V ⁻¹ s ⁻¹)	τ_e ($\times 10^{-6}$ s)	$\mu_h \tau_h$ ($\times 10^{-4}$ cm ² V ⁻¹)	μ_h (cm ² V ⁻¹ s ⁻¹)	τ_h ($\times 10^{-6}$ s)
High Flux CdZnTe	11 ± 6	940 ± 190	1.2 ± 0.8	2.9 ± 1.4	114 ± 22	2.5 ± 1.4
Standard CdZnTe	100	1100	11	0.2	88	0.2

B. Thomas et al. *Characterisation of Redlen high-flux CdZnTe*, 2017 JINST 12 C12045

*Characterization of High-Flux CdZnTe with optimized electrodes for 4th
generation synchrotrons, O. Baussens et al 2022 JINST 17 C11008*

Contacts



A Bolotnikov et al. 'Properties of Pt Schottky type contacts on high-resistivity CdZnTe detectors, NIM A, Vol. 482 (1–2), 2002

Characterisation of Redlen HF-CdZnTe at $> 10^6 \text{ ph s}^{-1} \text{ mm}^{-2}$ using HEXITEC_{MHZ}, B.D. Cline *et al* 2024 *JINST* **19** P04028

- A 2mm thick HF-CZT sensor + HEXITEC_{MHZ} ASIC was characterized at the DLS synchrotron's B16 Test Beamline using a uniform and monochromatic beam.
- ***Excess leakage current was generated in the detector following the initial application of a specific X-ray flux.*** Observed a temporary shift in raw spectra to higher ADU values (changing position of the 0γ peak).
- Effect's dynamics is ***highly localised***, with pixels unaffected by the irradiation of their nearest neighbours, and intensity-dependent.
- Comparison to Si suggests this is a ***CZT-specific phenomenon*** and thought to result from ***charge trapping at the electrode-CZT interface***. This results in the localised build-up of space charge and modification of the contact potential barrier.
- **More tests are needed!**

CdZnTe (CZT) as a Material for Detecting Hard X-rays at Synchrotrons and FELs

J. Mulvey, D. Greiffenberg, K. A. Paton, C. Posata Soto, B. Schmitt, A. Bergamaschi, M. Brückner, M. Carulla, R. Dinapoli, S. Ebner, K. Ferjaoui, E. Fröjd, V. Gautam, S. Hasanaj, J. Heymes, V. Hinger, V. Kedysh, T. King, S. Li, C. Loper Cuenca, A. Mazzoleni, D. Mezza, K. Moustakas, A. Mozzanica, M. Müller, C. Ruder, S. Silletta, D. Thattil, X. Xie, J. Zhang

PSI Center for Photon Science, 5232 Villigen PSI, Switzerland

iWoRiD, Bratislava, Slovakia, 6–10 Jul 2025

Summary

CZT performs impressively compared to GaAs and CdTe

High-Flux & Spectroscopic demonstrate a remarkably **low leakage current per pixel (< 5 pA)**, and the MPV is 2-3 orders of magnitude lower than that observed for GaAs

Energy resolution at 59.5 keV appears to comparable with GaAs

- **High-Flux CZT is better than Spectroscopic CZT**

High-Flux CZT has a better $\mu_e \cdot \tau_e$ than reported for GaAs and CdTe

- Inconclusive for Spectroscopic CZT
- **CCE of Spectroscopic CZT is > 97% at -20 V**

New CZT Assemblies

CZT + JF1.2

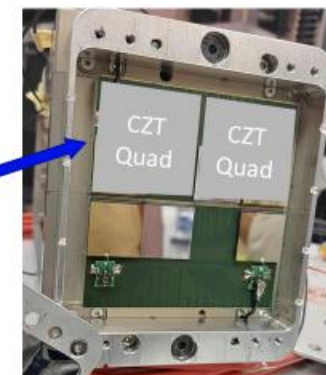
- Testing **dynamic gain switching with electrons**

Full CZT Module (2x Quads) + JF1.2

- 0.5M **uniformity** and **pilot experiments** at beamlines
- Expected later this year

CZT + Matterhorn

- Photon counting with high-Z
- MH optimised for high count rates (20 MHz/Pixel)
- Aims to **mitigate afterglow** with thresholding and fast shaping
- **Higher bias** and **thinner sensors** are preferred (GaAs?)
- Initially **larger pixels** for CZT (150 μm pitch)
- First MH1.0 wafers expected at the end of the year



E. Fröjd, 2023 [6]

18

PSI Center for Photon Science

06.07.2025

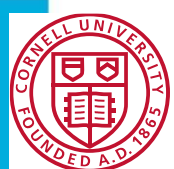
Evaluation of Hi-Z Detector Materials for X-ray Science

Nino Miceli (ANL), Mercouri Kanatzidis, Duck Young Chung
(Northwestern University)

Abdul Rumaiz, Gabriella Carini, Peter Siddons (BNL)

Julia Thom-Levy, Sol Gruner, Mark Tate (Cornell University)

Julie Segal, Connie Hanson, Chris Kenney (SLAC)



Cornell University



Northwestern
University

Argonne
NATIONAL LABORATORY



Brookhaven
National Laboratory

SLAC

NATIONAL
ACCELERATOR
LABORATORY

Sensor materials under investigation

Relatively established hi-Z materials:

- Germanium (wafers and sensors)
- Cadmium Zinc Telluride (Redlen Technologies)
- CdTe (Acrorad)

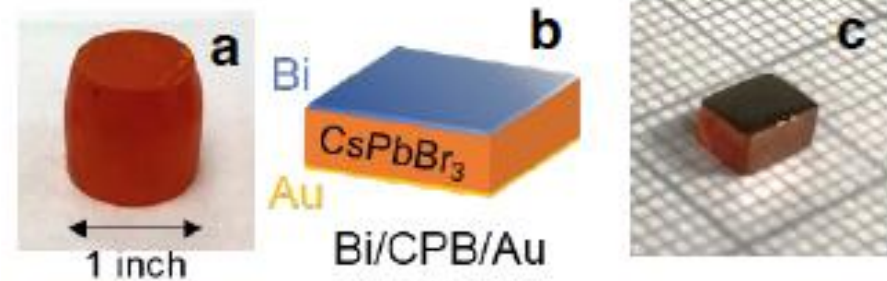
Newer hi-Z materials:

- Perovskite CsPbBr_3 (ANL/NWU)
- a-Se (BNL), CZTS (BNL)
- and recently GaAs (Advafab)

Germanium sensor (Umicore) fabricated at BNL

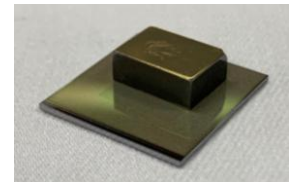


Germanium sensor wafer from Mirion/SLAC



1-inch diameter CsPbBr_3 wafer grown at NWU/ANL

CZTS grown at BNL



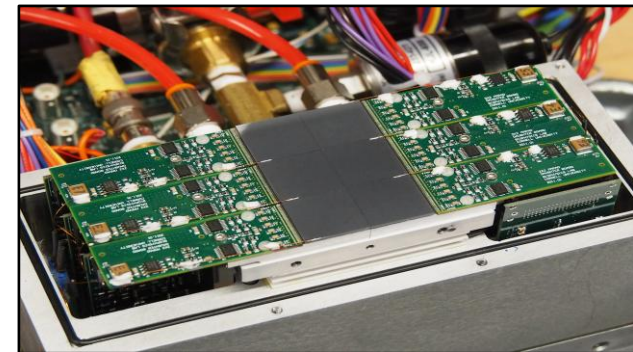
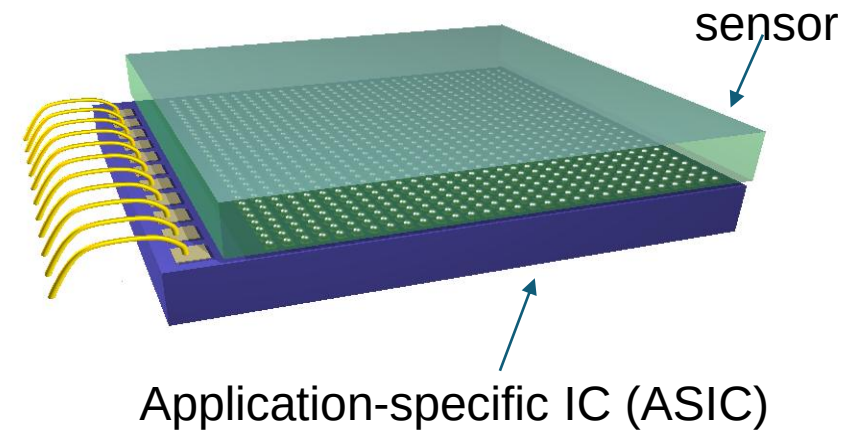
Major research project goals

Evaluate and develop high quantum efficiency sensors for very hard X-rays (energies >20 keV) at XFELs and storage rings.

Ingredients:

1. Sensors
2. Mature and representative detector readout ASICs and testing platforms
3. Full characterization using lab x-ray sources and high flux synchrotron radiation (SLAC, CHESS, ANL, BNL)

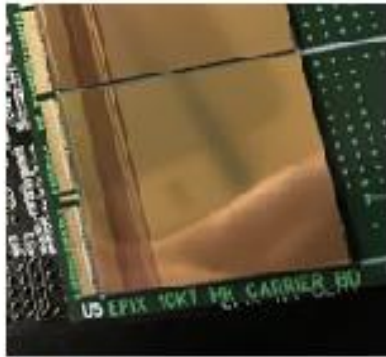
Hybrid pixel array detectors:



Detector Readout ASICs and testing platforms

SLAC ePix10k: (a) Image of the chip. (b) 135k Pix Detector

Focus on very high dynamic range

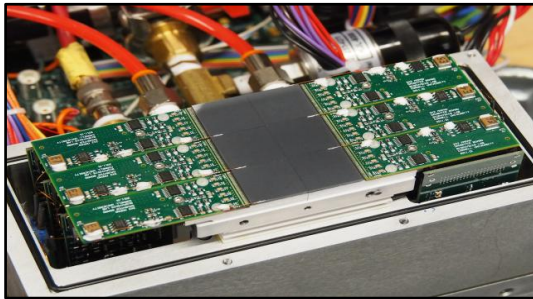


(a)

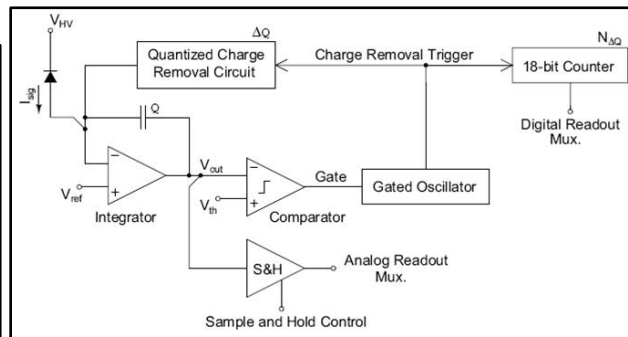


(b)

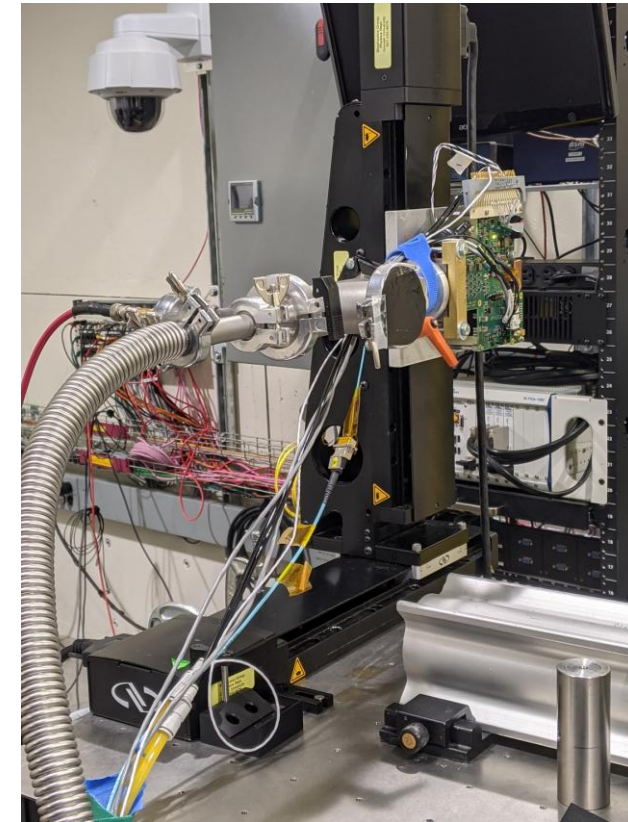
Cornell MM-Pad: (a) tiled array. (b) analog and digital readout



(a)



(b)



MM-PAD detector system at a beamline

Detector Readout ASICs and testing platforms

SLAC ePix10k: (a) Image of the chip. (b) 135k Pix Detector



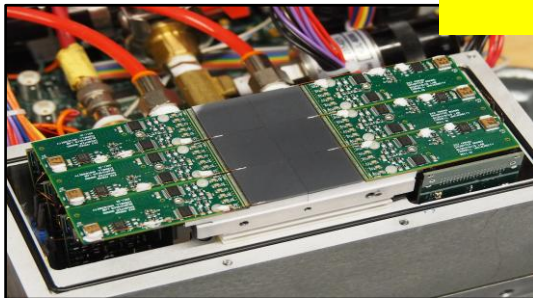
(a)



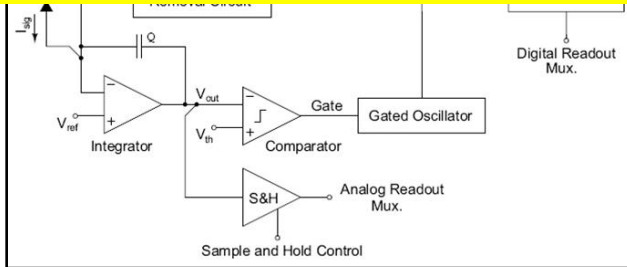
New versions with capability to process negative polarity now available (e- collecting)

Types (pixels)	135k, 2M
# of Pixels/module	384 x 352
Pixel Size	100 μm
Active Area Dimensions	38.4 x 35.2 mm^2
Operating Temperature Range	4C to 20C (constant: must be above dew point)
Operating Pressure Range	Air or Vacuum
Operating Humidity Range	Avoid condensation on sensor plane
Max signal (8 keV photons)	11000
	Water-cooled/Peltier (small cameras)
	120 Hz

Cornell MM-Pad: (a) til



(a)



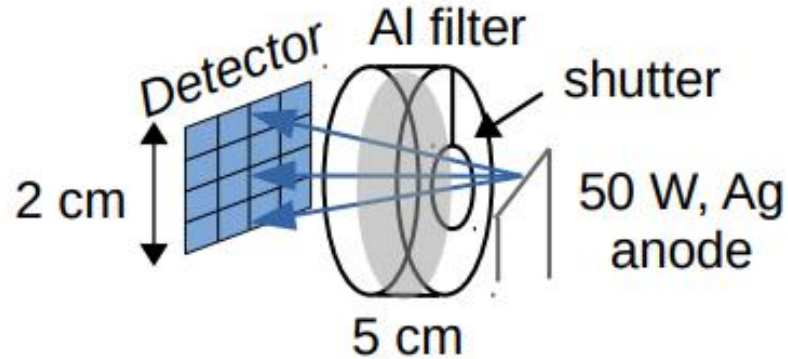
(b)

count rate limit of 10^8 8-keV

- charge removal architecture with an emphasis on sustained count rate
- E.g. 500 μs integration time corresponding to a frame rate of ca. 2 kHz
- 150 μm x 150 μm pixel size

Characterization and beam testing

In the lab (Cornell):



Common detector testing framework for systematic exploration:

- Determine operating conditions, corrections and calibrations
- Measure flat field and single photon response histogram
- Measure charge collection efficiency and gain calibration vs. x-ray energy
- Resolution (edge response and probe distortion due to accumulated space charge)



CHESS 29keV energy, single bunch mode



APS beamlines 1-BM-B and 11-ID-B

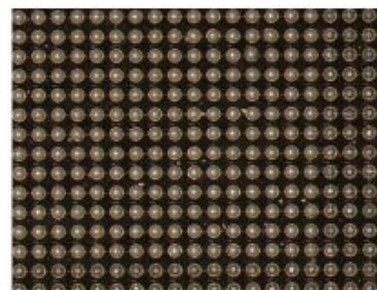


LCLS at SLAC

Trying to solve a similar puzzle

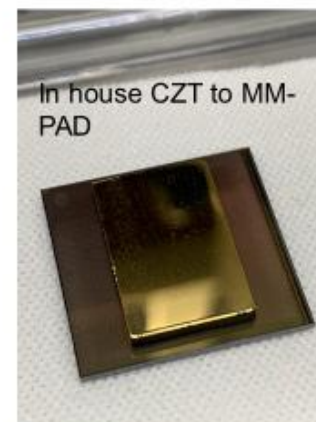
- Despite same contact material on both sides, (Pt:CZT:Pt), CZT exhibits Schottky IV-behavior
 - Thought to be the result of Cd vs Te rich side
- Lag/ afterglow: we observe voltage dependent level/time
- Possible dead layer?
- IR illumination improves response speed
- IR Light Polarization

'High-flux' CZT sensors from Redlen



Brookhaven
National Laboratory

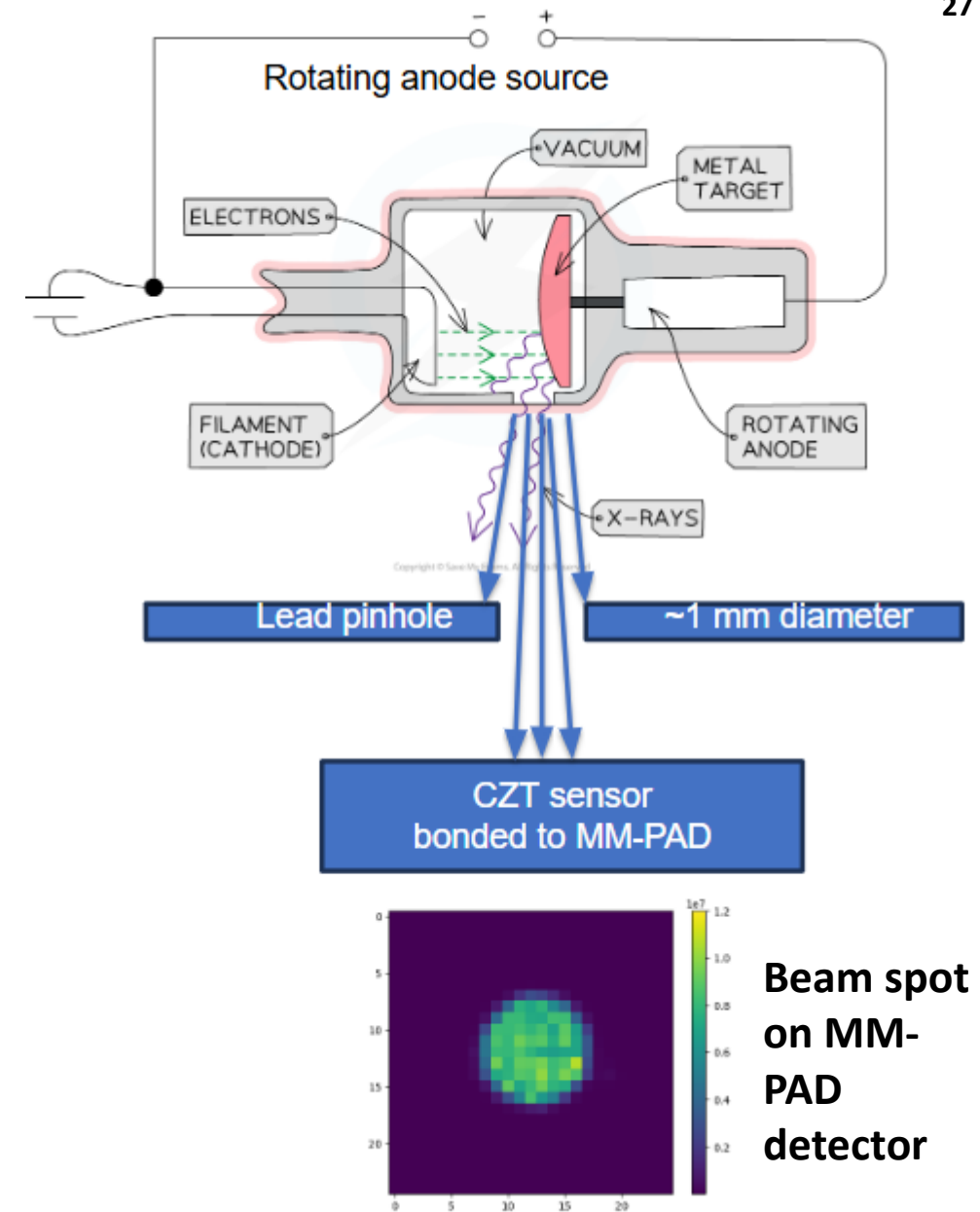
Conductive
Epoxy Bumps



Redlen CZT
Bonded to an
MM-PAD at BNL:
~ 12.2 mm x 8.7 mm
area
2 mm thickness
75 x 52 pixels
300 um guardring

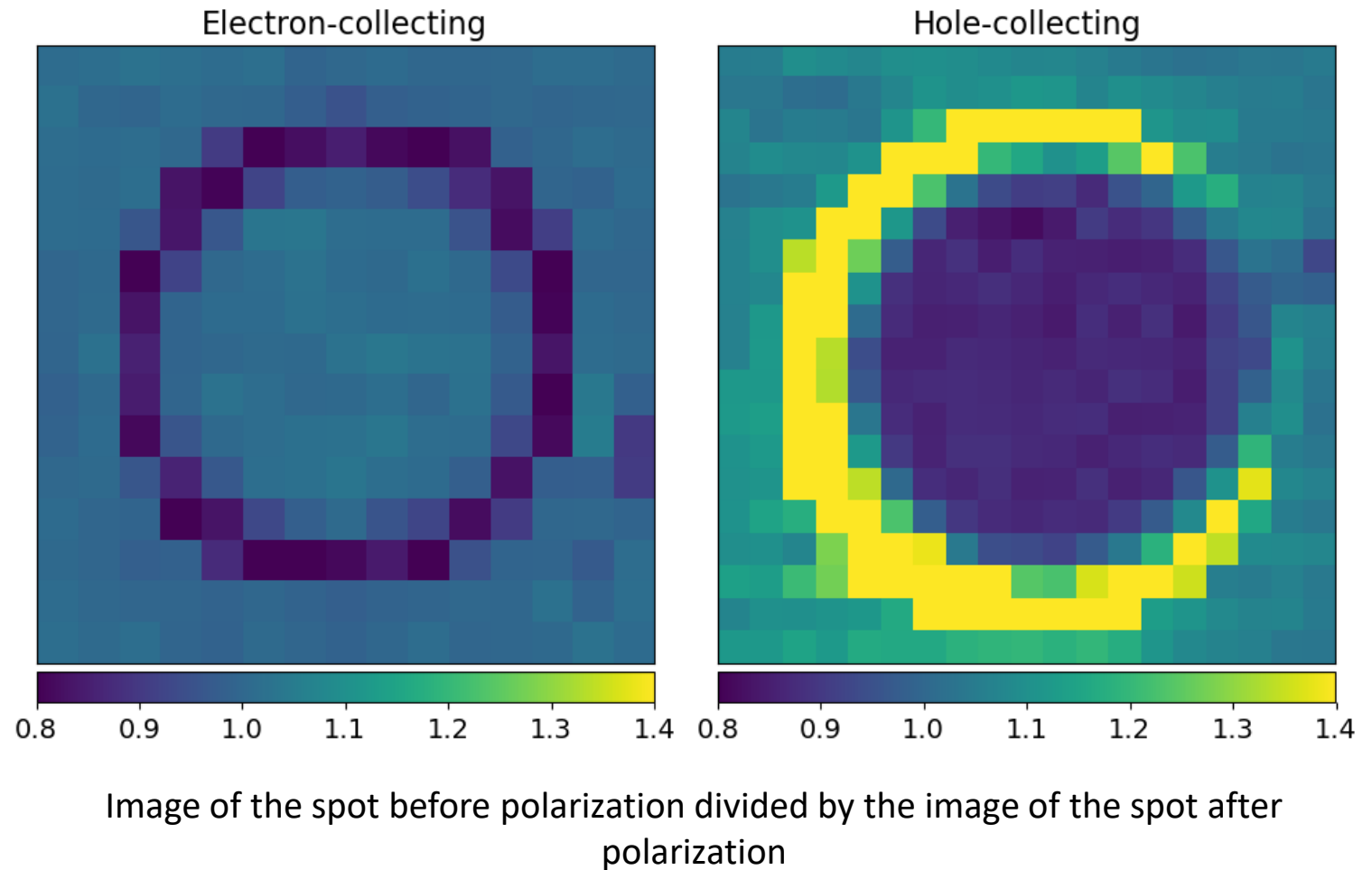
Polarization – Preliminary Results

- Preliminary: only conducted with in-lab source which provides no more than 10^9 ph/mm²/s
- Some change in total spot intensity at high fluxes of low-energy (<20 keV) X-rays
- Improvement over CdTe (at same E-field)



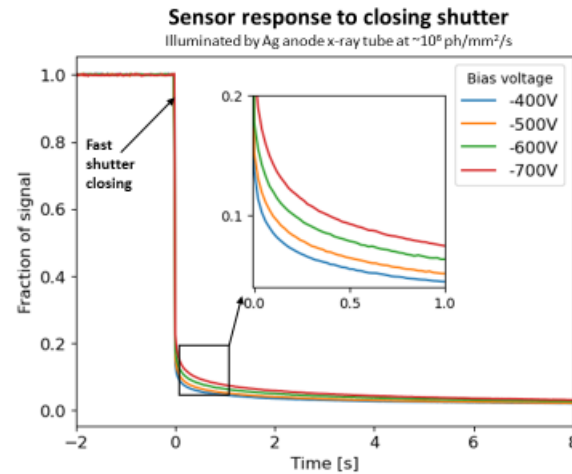
Changes in spot shape

- Spot shape changes slightly as dose is absorbed, even if total spot intensity doesn't change
- Electron collecting spot shrinks slightly, hole-collecting spot grows slightly



Afterglow

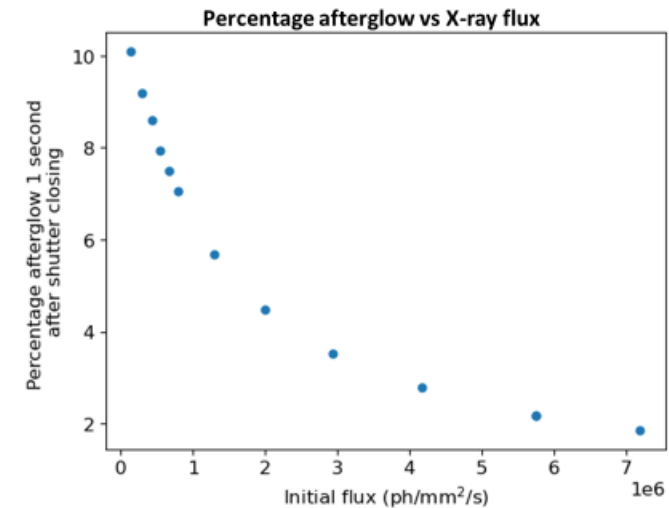
- Significant afterglow observed at low to moderate fluxes
- Afterglow magnitude increases with applied bias



Is afterglow due primarily to bulk traps, surface traps, or a combination of both?

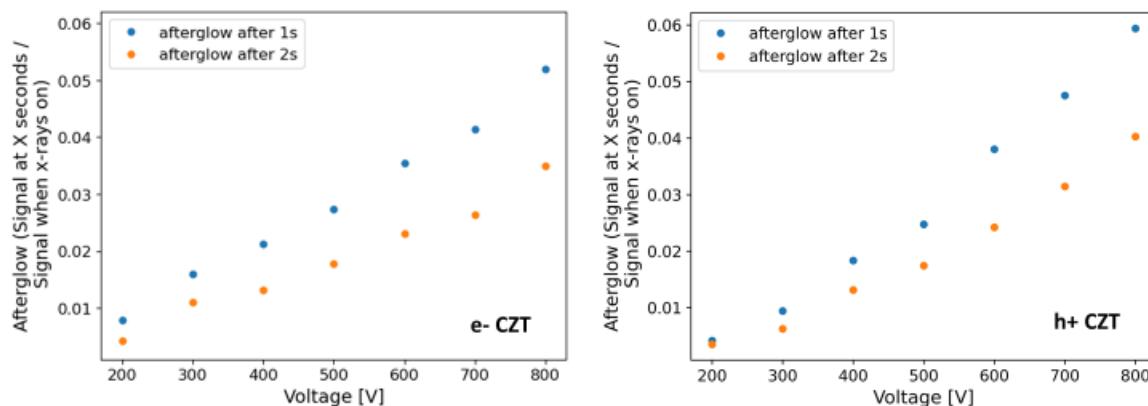
Afterglow vs Flux

- As traps fill, afterglow signal (relative to initial signal) decreases
- Promising for high flux ($>10^7$ ph/mm²/s) applications



X-rays from Ag anode X-ray source, tube bias 40kV

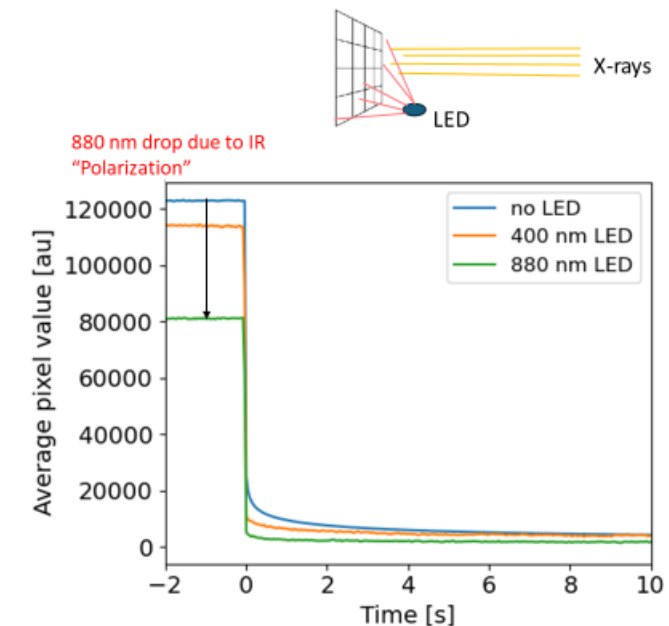
Afterglow – electron vs hole collection



Electron and hole collecting sensors exhibit similar magnitude and duration of afterglow

Mitigating afterglow with LED illumination

- Can LED illumination of different wavelengths reveal the depth profile of afterglow-causing traps?
- Illuminated with 400 nm light (absorbed in top ~ 0.1 μ m) and 880 nm light (absorbed fairly uniformly)



Modeling detector response

‘coupling material, detector geometry, operating condition, and shaping electronics parameters’

Carrier dynamics in CdZnTe under high-flux x-ray irradiation: application to device polarization and temporal response

Dynamic Lateral Polarization



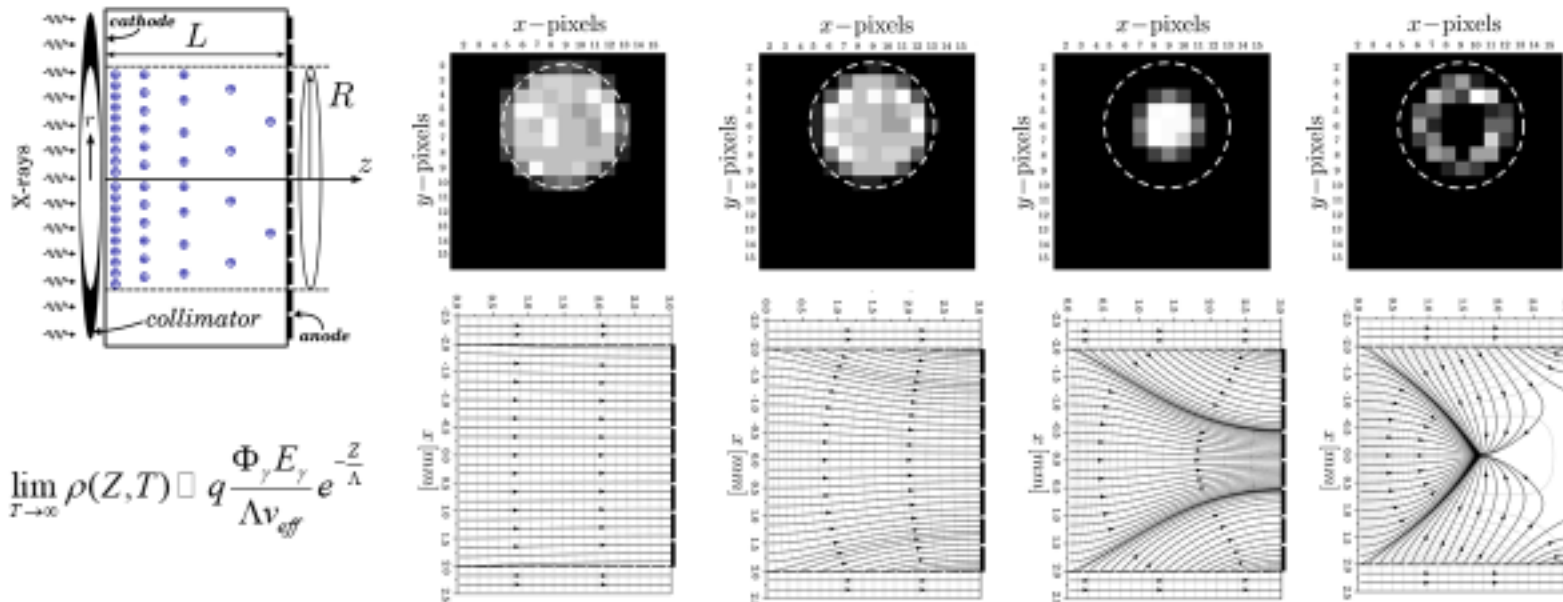
(2008)

- it was observed in practice that pixilated detectors fabricated from low-hole transport material exhibited a dynamic focusing of counts when subjected to a collimated beam of high-flux x-rays

- S.A.Soldner, D.S. Bale, and Cs. Szeles, *IEEE Trans. Nucl. Sci.* 54 (2007)

- We have shown that such focusing of the counts is consistent with the electric field lines due to the time-asymptotic positive charge density derived from the multiple scale analysis

- D.S. Bale, S.A. Soldner, and Cs. Szeles, *Appl. Phys. Lett.* 92, 2101 (2008)



$$\lim_{T \rightarrow \infty} \rho(Z, T) \approx q \frac{\Phi_\gamma E_\gamma}{\Lambda v_{eff}} e^{-\frac{Z}{\Lambda}}$$

Courtesy of Derek Bale

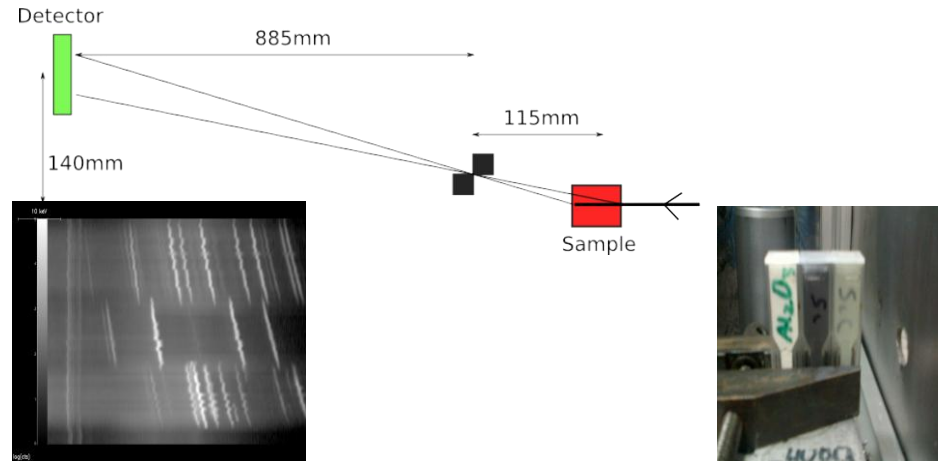
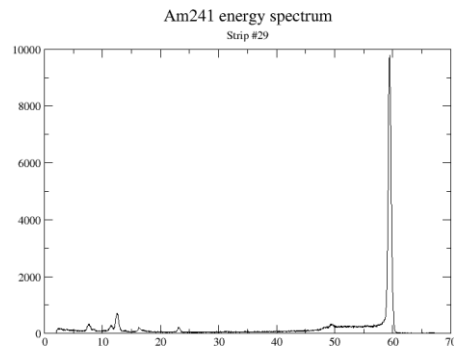
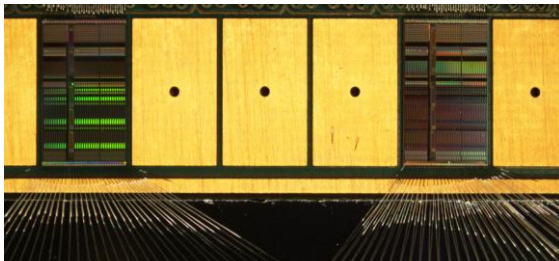
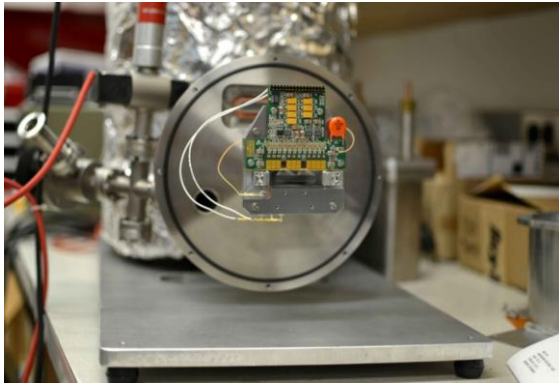
We have developed a model for the loss of counts due to diminished charge induction conditions (i.e. polarization) in the high-flux steady state within the crystal

- D.S. Bale and Cs. Szeles *Phys. Rev. B* 77 035205 (2008)

Classic, old germanium?

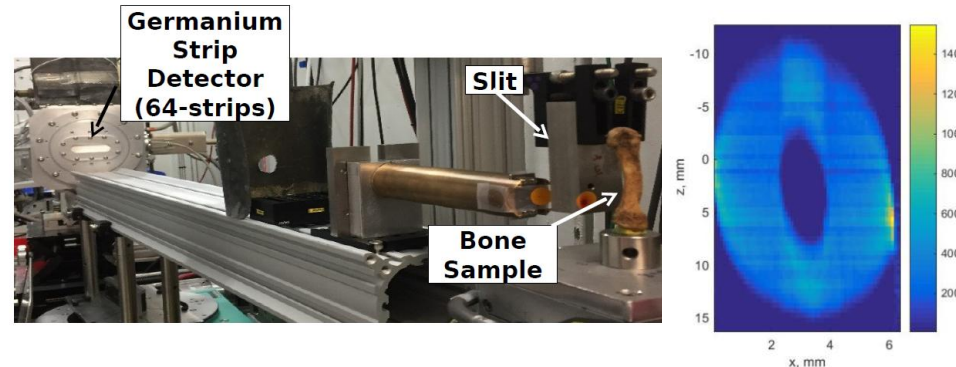
Germanium Detector BNL

First prototype 64-strip Ge (2013) - Dispersive Diffraction and Diffraction Imaging (2014 & 2017) - HEX at NSLS II (current)

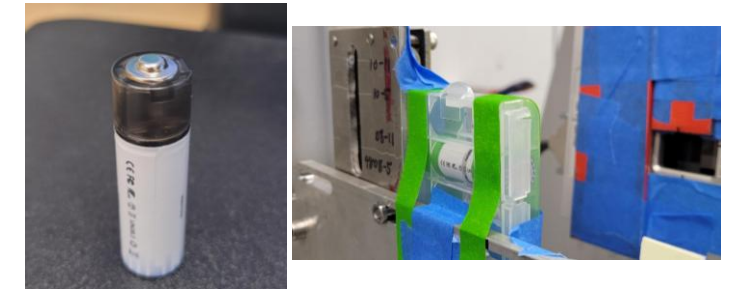
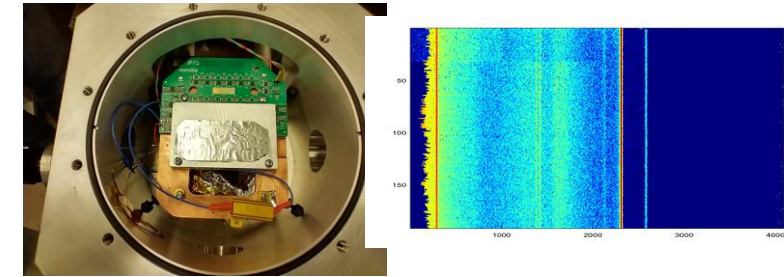


- 100um white beam enters from right
- Slit projects scattered beams onto strip detector
- Each detector element collects spectra (i.e. diffraction pattern) from one region of sample.

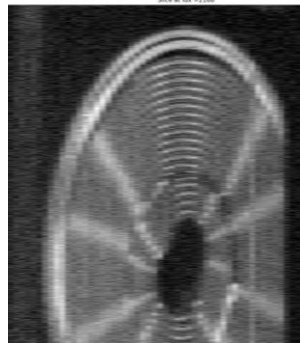
A.K. Rumaiz, T. Krings, D.P. Siddons, A.J. Kuczewski, D. Protic, C. Ross, Ge De Geronimo, Z. Zhong, IEEE TNS, 61, 3721 (2014).



S.R. Stock et al., SPIE Proceedings 10391, Developments in X-ray Tomography, 103910A (2017).

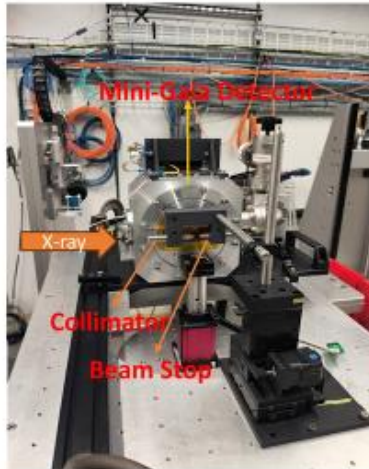
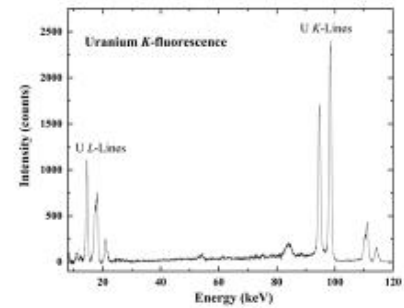


- 192-strip detector for HEX beamline at NSLS II
- Up to 200 keV with 1% energy resolution
- New chip HE-MARS with lower gain

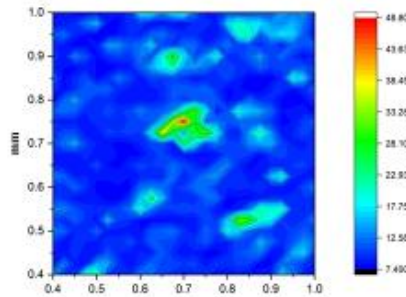


Germanium: pixelated and drift detectors

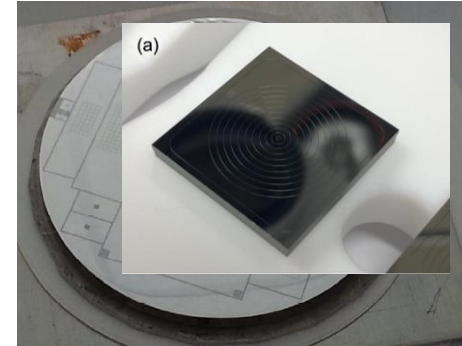
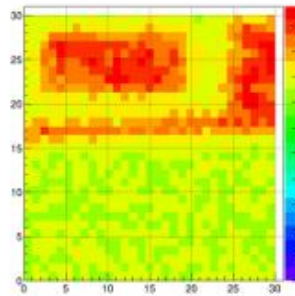
Mini-Gaia at HEX Beamline at NSLS II



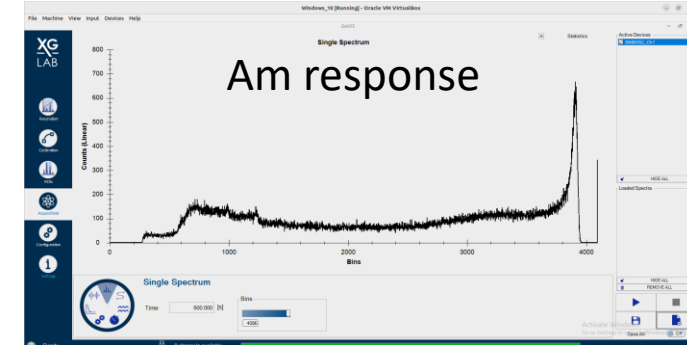
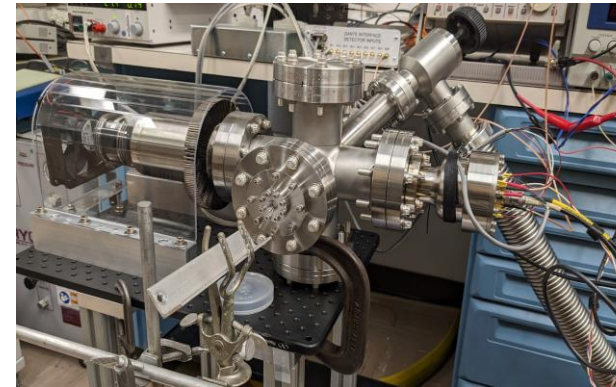
UO_x sample, fluorescence map



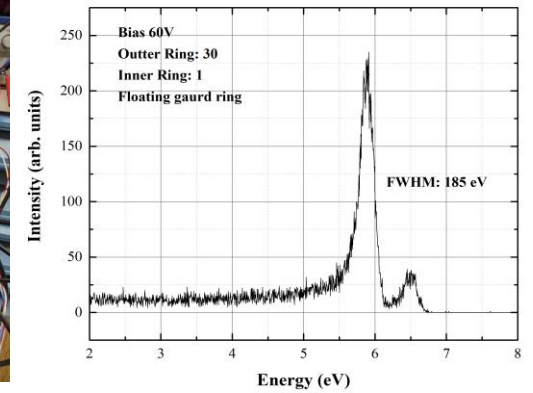
2D Element Map of Au



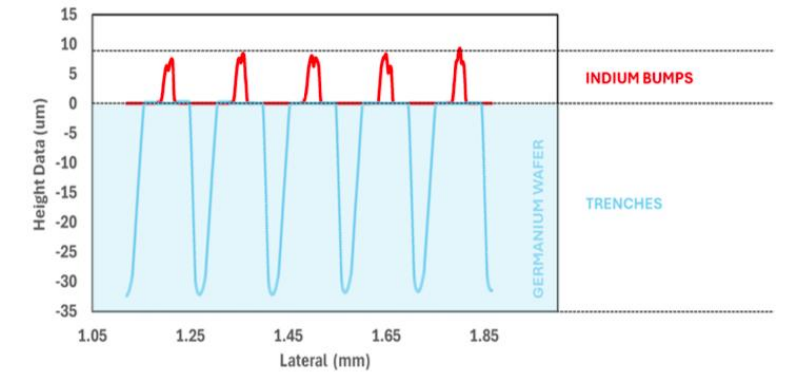
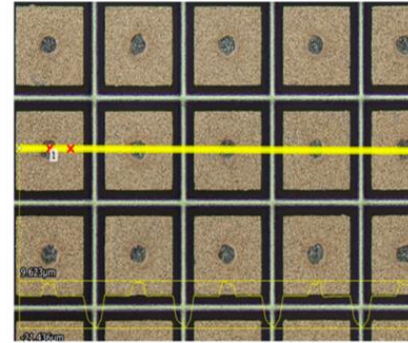
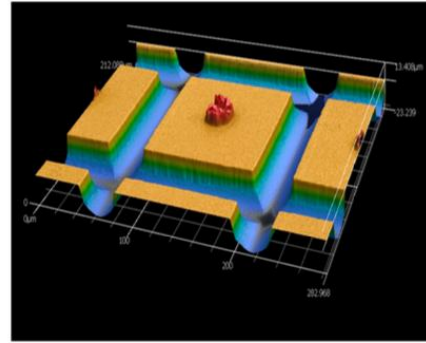
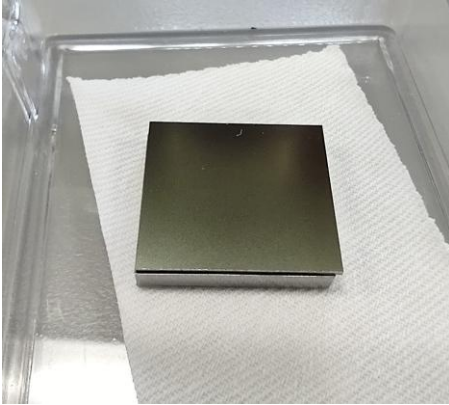
Full system GDD



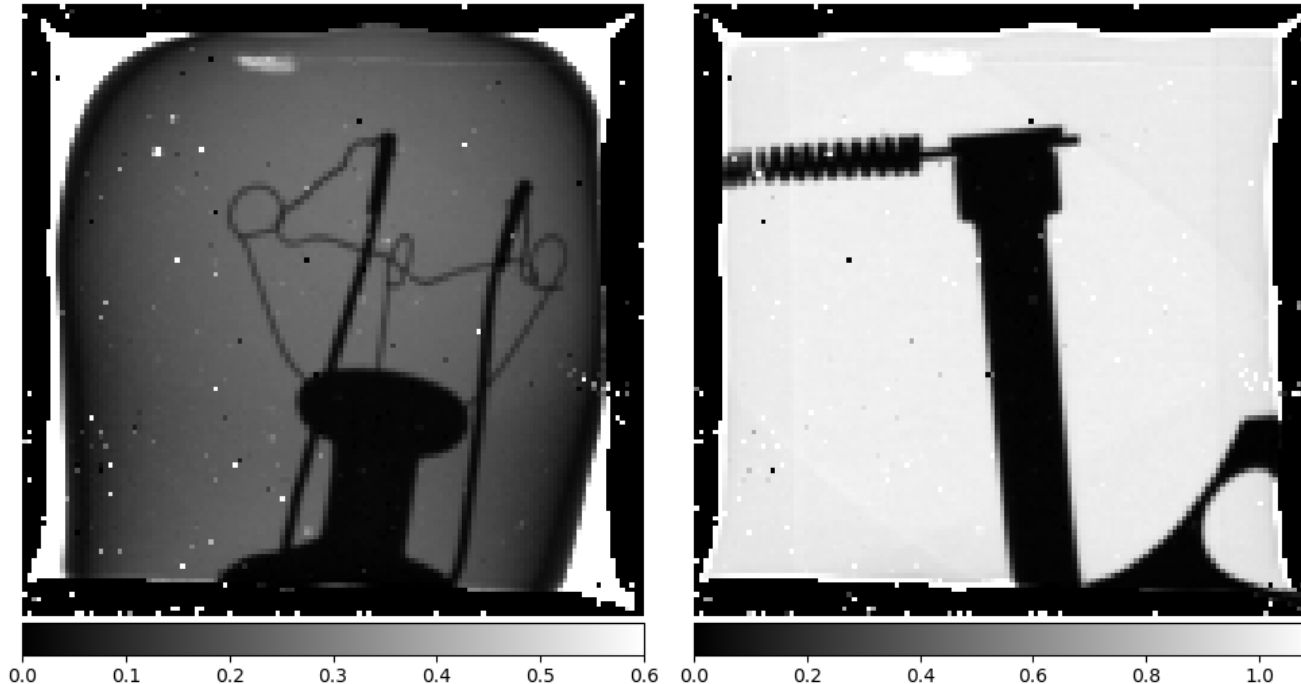
Fe⁵⁵ response



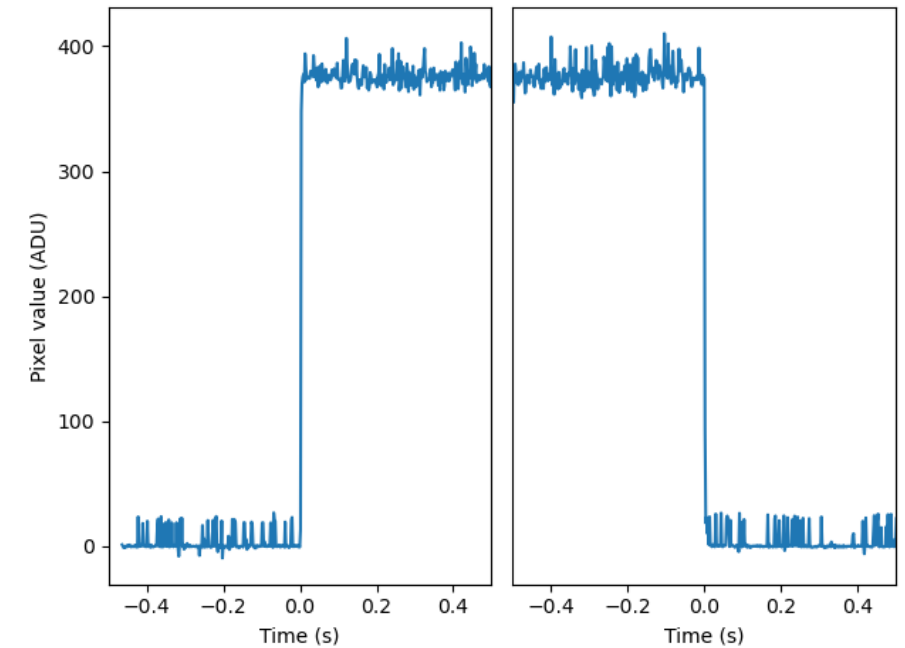
MM-PAD with Ge (New Results!)



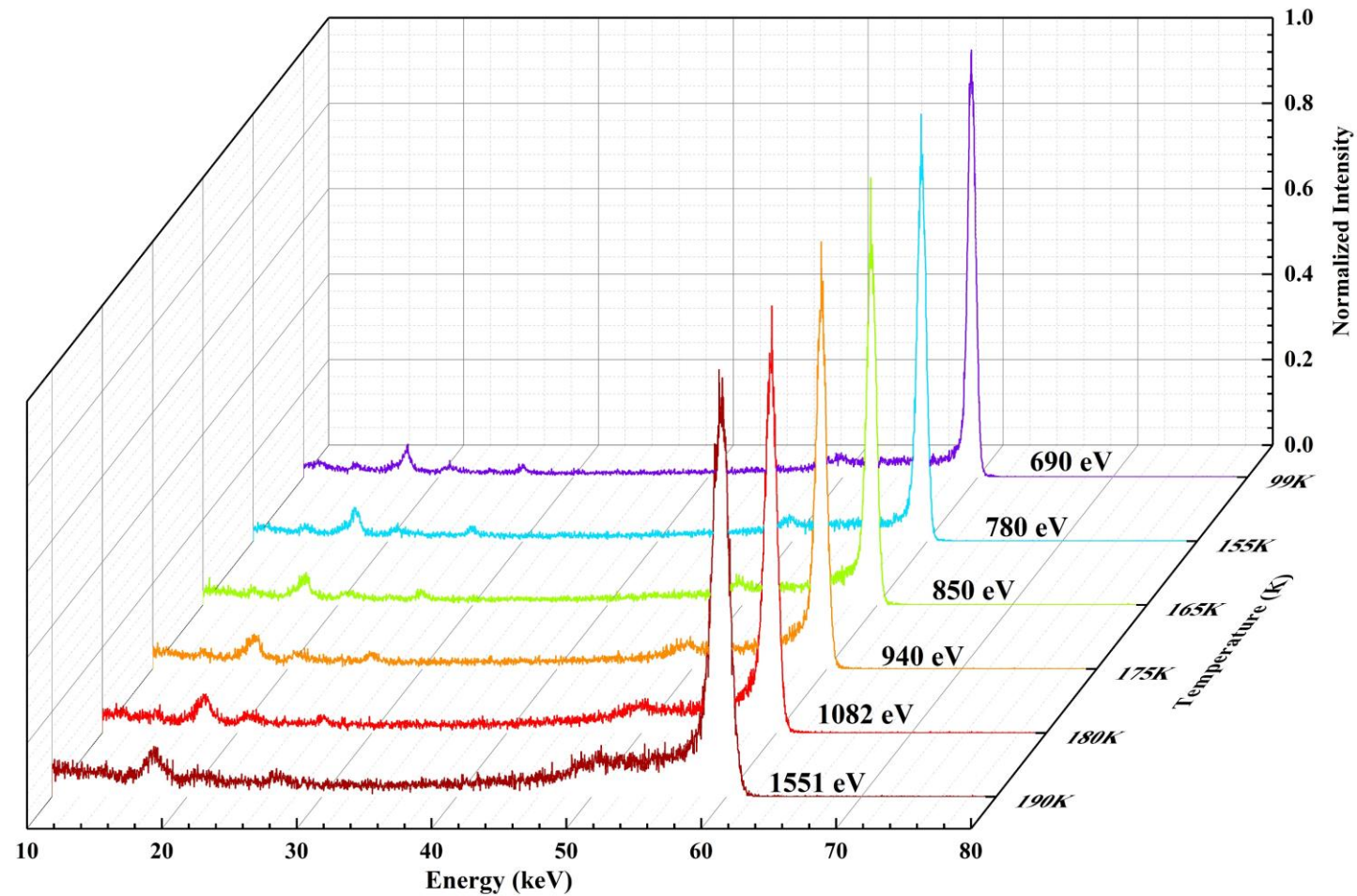
Radiograph



Dynamic Response



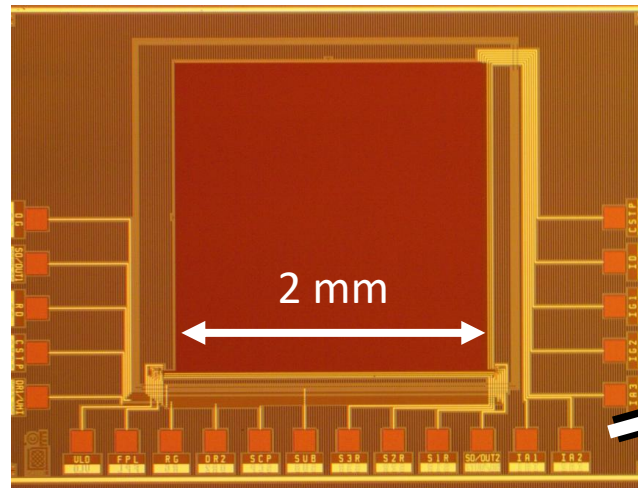
How cold do we need to go ?



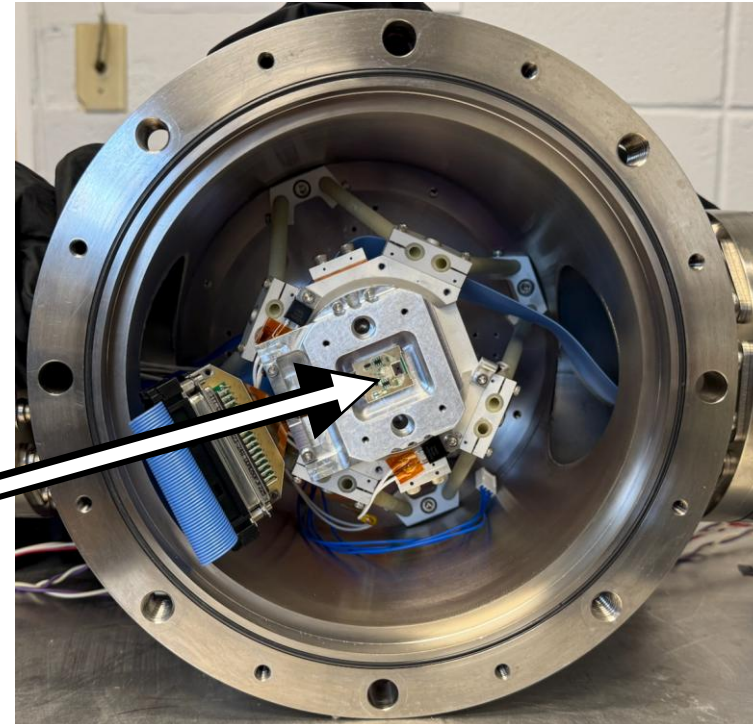
Germanium Charge-Coupled Device Development

- Collaborated with MIT-LL and MIT-Kavli on developing the germanium CCD
- Developed the packaging, sequencer, cryogenic characterization system, autonomous data acquisition system and analysis software for germanium CCD by leveraging the LSST heritage

Microscopic image



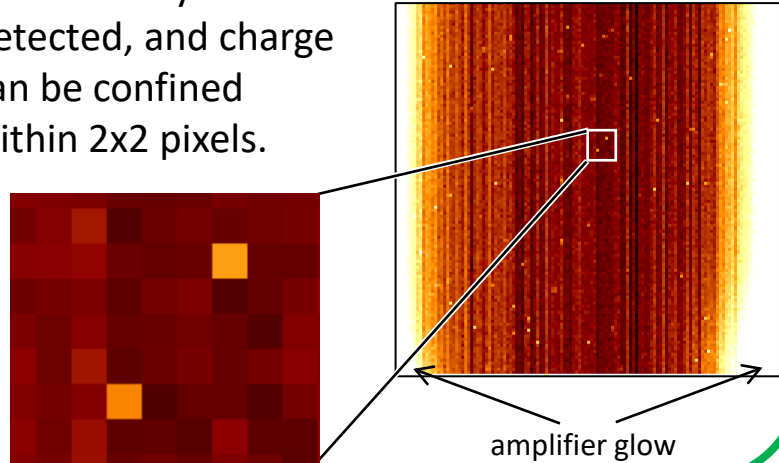
Front-illuminated
128×128 pixels
8.1×8.1 μm^2



Germanium Charge-Coupled Device Characterization

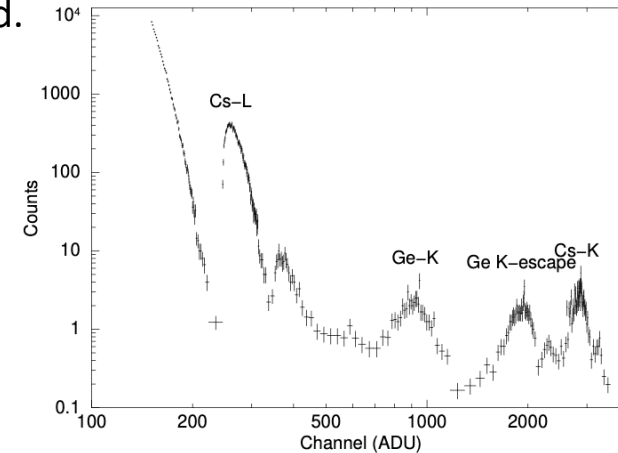
^{55}Fe irradiation

~6 keV X-rays can be detected, and charge can be confined within 2x2 pixels.



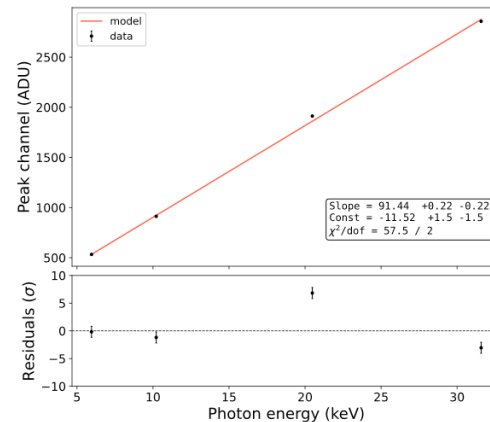
^{133}Ba irradiation

Cs-L (~5 keV) up to Cs-K (31 keV) can be clearly resolved.



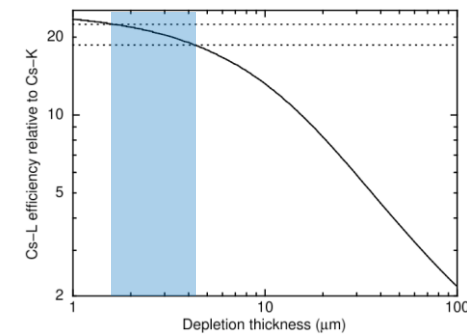
Energy-Pulse height relationship

Excellent linearity is achieved from 6 keV to 31 keV, demonstrating that the germanium CCD can be used as an X-ray spectrometer.

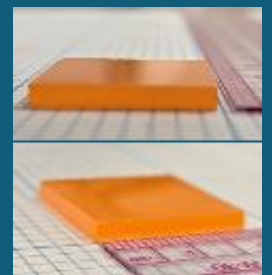


Estimate depletion thickness

The observed Cs-L to Cs-K count ratio deviates from the expected intrinsic branching ratio because of germanium's absorption efficiency. Since this efficiency depends directly on the depletion thickness, comparing the observed and intrinsic ratios allows us to calculate that thickness to be 1.6~4.3 μm .



Perovskites and amorphous selenium? CZTS*? It depends...



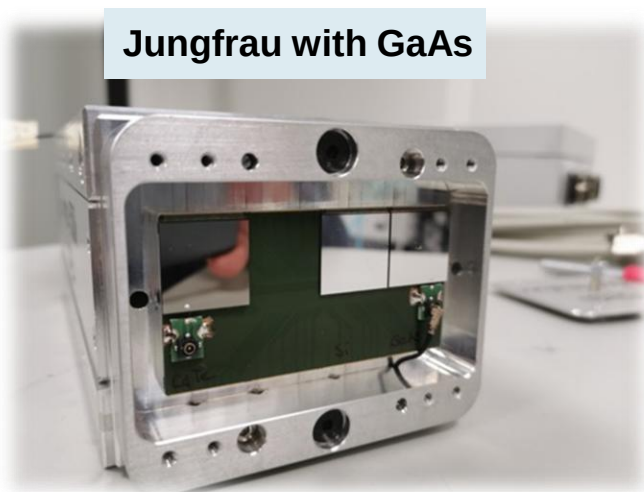
ePix CsPbBr₃ Perovskite



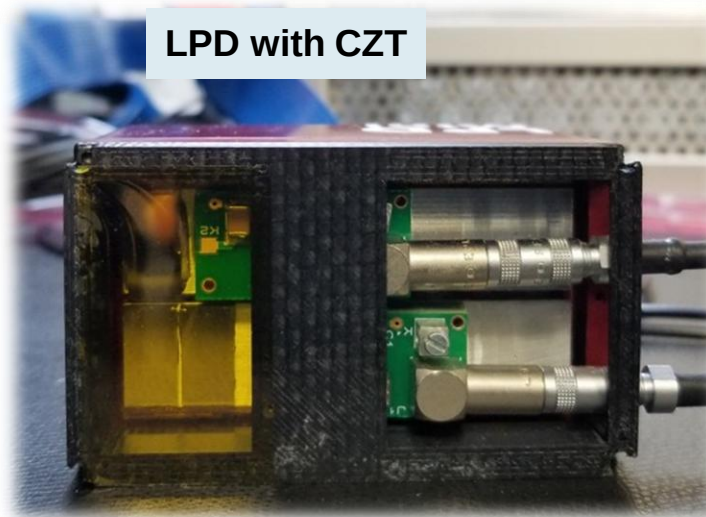
Running the EuXFEL with harder X-rays: now!

- The recent week in which the machine provided 23 keV photons made very clear the limitations of silicon:
 - only ca 20% of the radiation is absorbed by the sensor
 - electronics damage on the ASIC becomes likely
 - ▶ need materials able to absorb these photons: GaAs, Cd(Zn)Te
 - ▶ the worldwide community is looking for a solution to this problem
 - ▶ EuXFEL to provide beam and joining sensor qualification activities

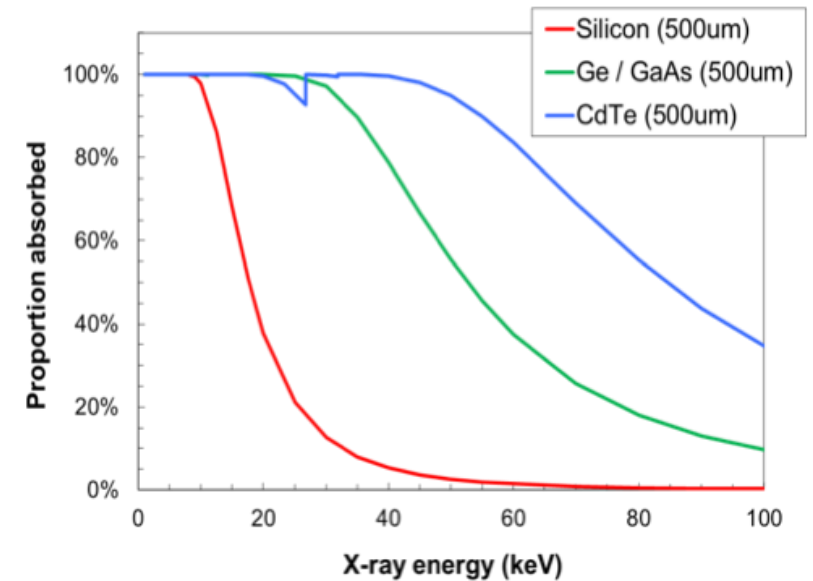
Jungfrau with GaAs



LPD with CZT

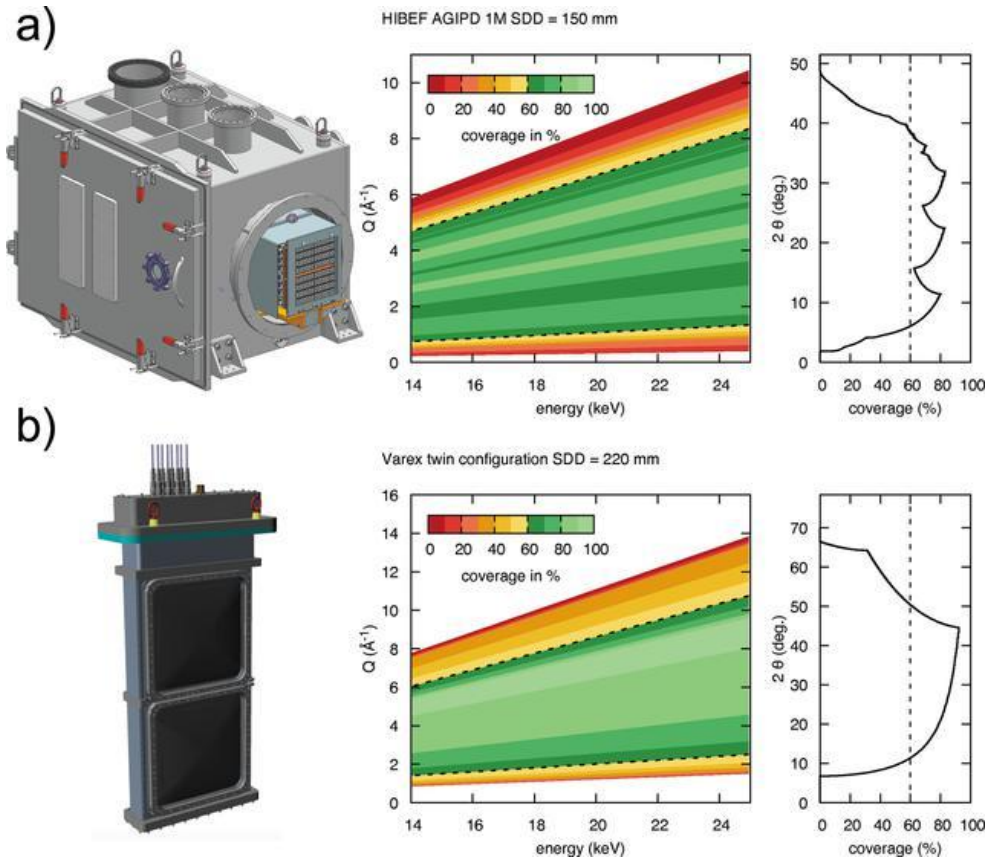


Photoelectric absorption of X-rays



EuXFEL is joining the community of scientists active in this topic

Large areas: direct detection and scintillators



The High Energy Density Scientific Instrument at the European XFEL

(a) HIBEF AGIPD 1M detector and coverage as a function of X-ray energy. (b) Varex twin detector system and coverage as a function of X-ray energy for the downstream position.

The AGIPD 1 megapixel version consists of sixteen 128×512 -pixel modules in an 8×2 arrangement.

Varex XRD 4343 CT flat-panel detectors with scintillator panels consisting of **CsI:TI** oriented needle crystals which are bonded to a 2880×2880 pixel ($140 \mu\text{m} \times 140 \mu\text{m}$) TFT-diode array with an active surface of $432 \text{ mm} \times 432 \text{ mm}$.

U. Zastrau et al J. Synchrotron Rad. 28, 1393-1416 (2021).

- **Commercial solid-state scintillators**, e.g., NaI(Tl), Bi₄Ge₃O₁₂ (BGO), and **Ce³⁺-activated crystals** such as (LuY)₂SiO₅ (LYSO), (LuY)AlO₃ (LuYAP), and Gd₃(Al,Ga)₅O₁₂ (GAGG), have demonstrated **superior performance in high light yield** (LY) ($\sim 10^4$ photons/MeV) and **excellent energy resolution** (ER < 10%).
- **Progress on crystalline scintillator technology** (e.g., electronic band structures and defect-mediated scintillation mechanisms) **has been enabled by robust computational frameworks** (DFT and first-principles calculations), and more recently, **data-driven approaches integrating physics-informed machine learning**.
- **Glass scintillators offer 3 main advantages:**
 - 1 - compatibility with industrial-scale production techniques enables **cost-effective fabrication** of large-format components (≥ 30 cm³) tuned to specific applications.
 - 2 - **raw material costs** remain substantially lower, typically 10% of BGO crystal expenses.
 - 3 - their unique viscoelastic properties during fabrication permit **structural customization** into complex geometries (fibers, tapered rods, conformal coatings) for deployment in extreme environments such as nuclear reactor cores or deep-space probes

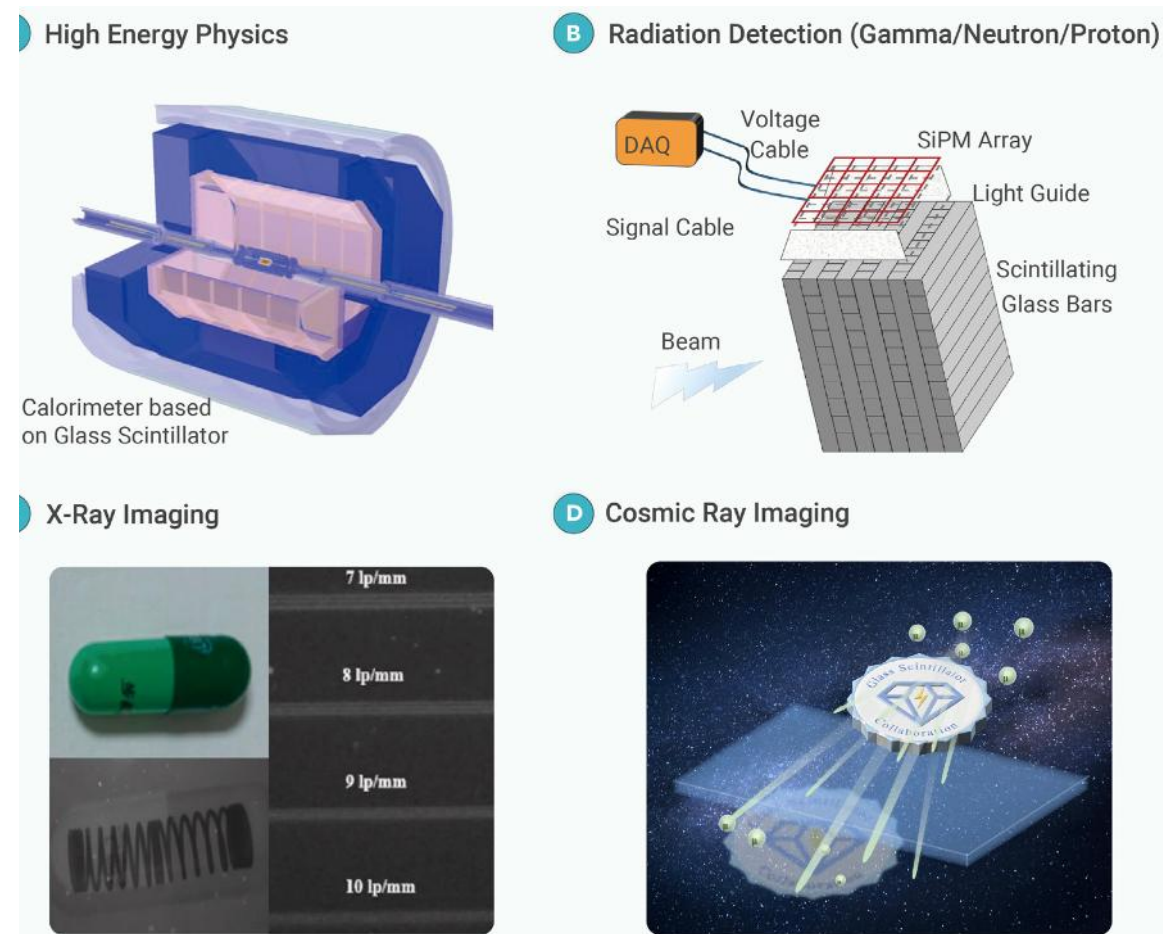


Figure 10. Applications of glass scintillators (A) High-energy physics.¹⁵ (B) Radiation detection.¹²⁸ (C) X-ray imaging.¹²⁹ (D) Cosmic ray imaging.

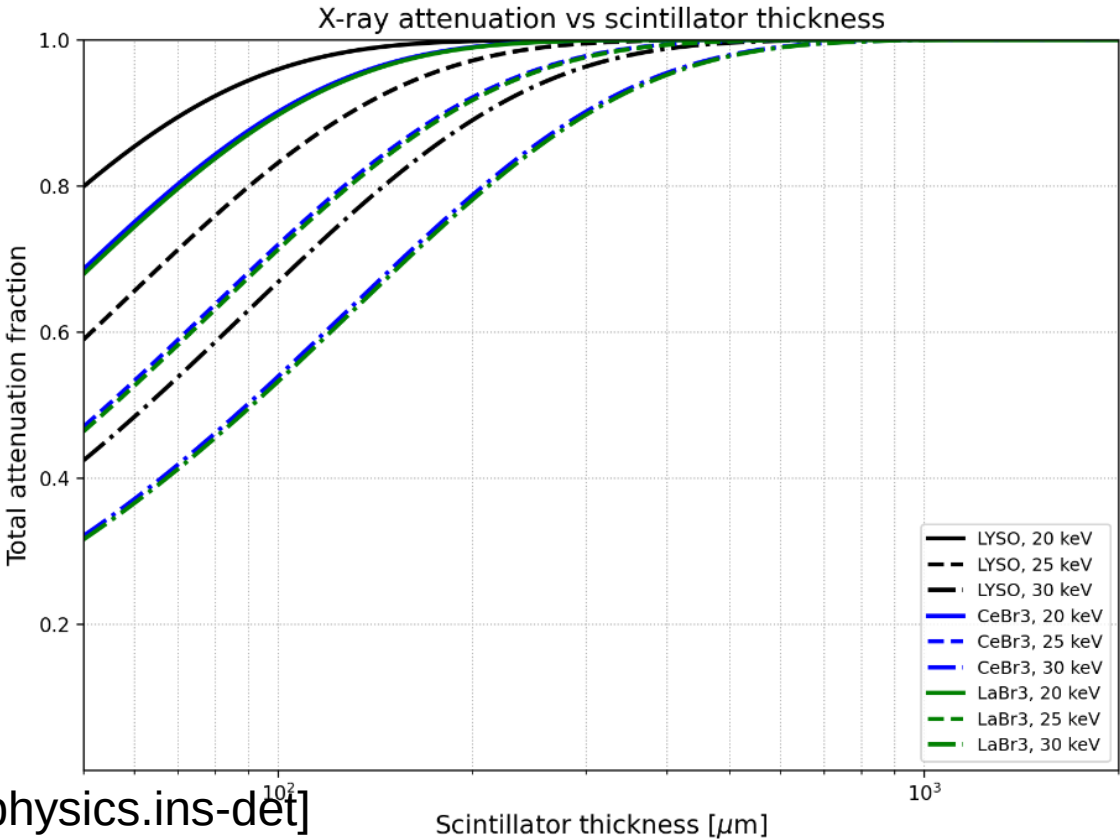
good efficiency for high energies >>
ing spatial resolution. Ce³⁺-doped

Fast and bright scintillators for ultrafast materials dynamics using 4th generation synchrotron

Material	Density (g/cm ⁻³)	Decay time (ns)	Light yield (ph/keV)	Emission Peak λ (nm)	Refractive index	25-keV X-ray Attenuation length (μ m)
LYSO:Ce	7.1-7.25	36-45	30-33	420	1.81-1.83	50–51
LaBr ₃ :Ce	5.08	16-25	60-70	380	1.90-1.95	71–72
CeBr ₃	5.1-5.2	17–22	60-68	380	2.09-2.1	68–70

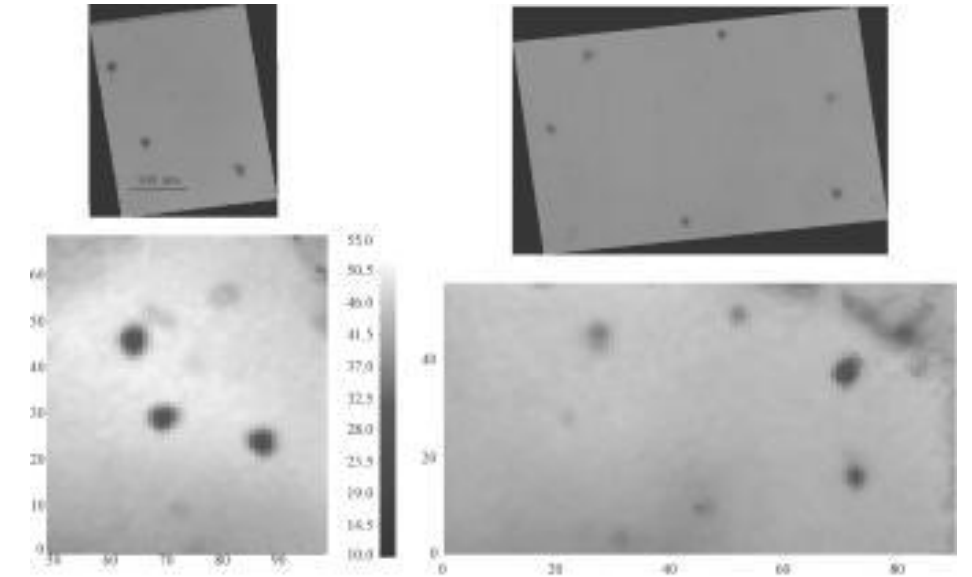
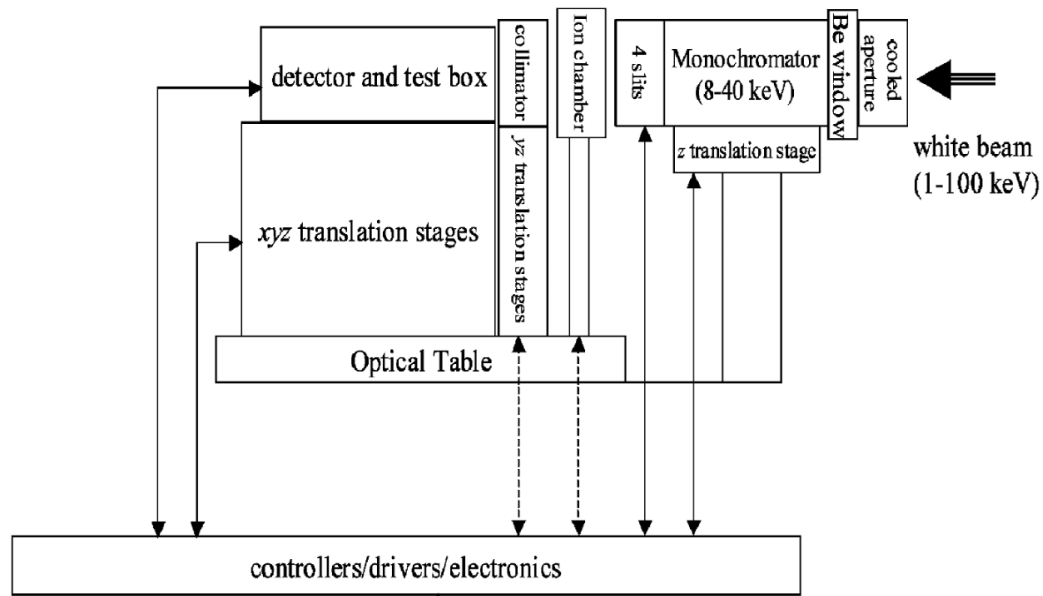
Observed material limitations due to: hygroscopicity, efficient optical coupling to imaging systems, and high quantum efficiency for conversion of scintillation light, predominantly at wavelengths below 400 nm, into detectable electronic signals.

Fig. 2. Theoretical X-ray attenuation as a function of scintillator materials type (LYSO, LaBr3:Ce, and CeBr3), thickness (50 to 1000 μ m) and X-ray energies (20, 25 and 30 keV). Thicknesses in the range of 200 - 500 μ m scintillator crystal are sufficient for efficient absorption of X-rays and imaging at APS-U



Using light sources to understand material limitations

2006



Examples of correlations between x-ray (bottom) and IR (top) transmission maps measured for a 1mm thick CZT planar device. The scans were performed by using a $10 \times 10 \mu\text{m}^2$ size, 85keV x-ray beam. In some cases, the typical triangular shapes of precipitates are recognizable in the x-ray maps.

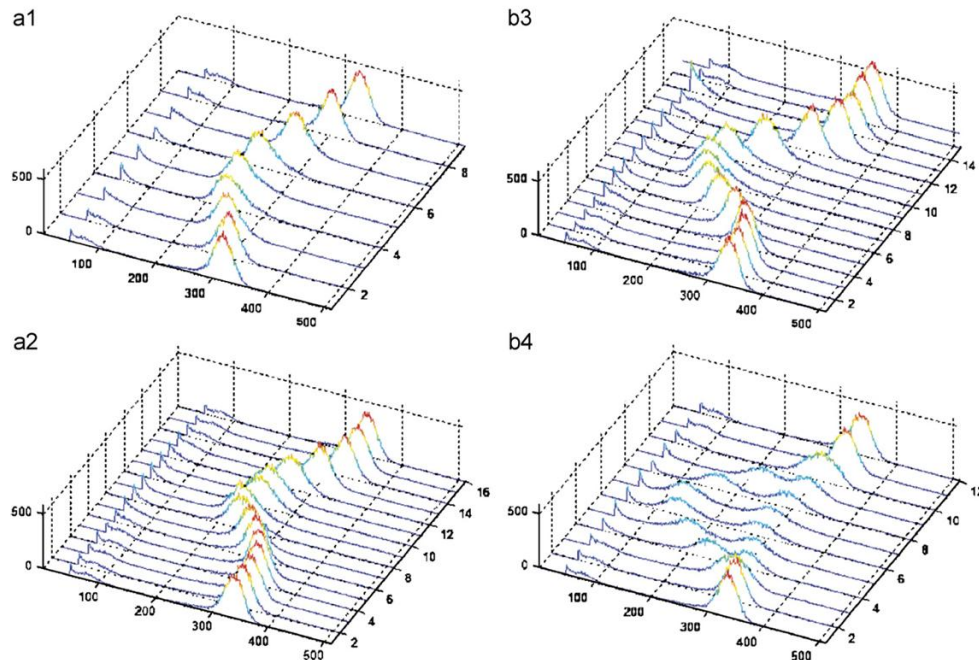
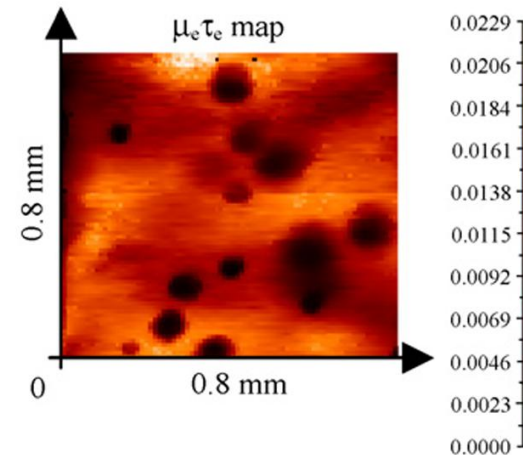


Fig. 4. Spectra along lines crossing through the center of the selected spots. The lines were horizontal to the map. Each spectrum corresponds to a 6- μm distance.



Resolution mte map of 10mm. The mu-tau values fluctuate over a large range between 0.2 and 20.0 $10^3 \text{cm}^2/\text{V}$, while the average value, as calculated for the region shown in the figure, is 1.1 $10^3 \text{cm}^2/\text{V}$.

G.A. Carini et al. High-resolution X-ray mapping of CdZnTe detectors, NIM A579 (2007) 120–124
 G.A. Carini et al. Effect of Te precipitates on the performance of CdZnTe detectors, Appl. Phys. Lett. 88, 143515 (2006)

Summary of beamtime allocated for detector studies since last DAC

- HighZ JUNGFRAU at SPB/SFX: 6 night shifts
- HighZ AGIPD at HED: 3 shifts in Nov 2024, 2 shifts in Feb 2025
- LGAD JUNGFRAU at SCS: 6 shifts in Nov 2024
- DSSC DEPFET at SCS: 11 shifts, as the first ~7 shifts were essentially lost due non-detector-related issues
- New procedure to allocate beam time for detector development (in beam delivery weeks)
 - Plans and mini-proposals to be submitted before the PRP
 - Instruments will have the possibility to have the full overview of what needs to be allocated
 - Beam delivery days also for detector development

How to move fast forward? Collaboration

Outlook

- We are better together...
- Coordinated purchase and characterisation of CdZnTe
- Redlen developments:
 - 'Best Practice 9' Ti electrodes
 - Passivation
 - Edge polishing
- Do they work? Lets see!





International Forum on Detectors for Photon Science

- IFDEPS 2016 – Lake Kawaguchi, Japan – March 28-April 1
- IFDEPS 2018 – Annecy, France – March 11-14
- IFDEPS 2020 – CANCELLED due to Covid-19
- IFDEPS 2024 – Port Jefferson, NY USA – March 17-20
- IFDEPS 2026 – Kyoto, Japan
March 10-13
- The IFDEPS Virtual Thursdays March-April 2021



Thank you!

