Evolution of Semiconductor Detectors in Photon Science

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MPG HLL Semiconductor Symposium

@BrookhavenLab

Photon Science: accelerator-based x-ray sources

https://doi.org/10.1098/rsta.2018.0231
Tetsuya Ishikawa (29 April 2019)

Synchrotron Radiation and Free-Electron Laser Facilities

Light sources of the world

There are more than 50 light sources in the world (operational, or under construction). This page lists all the members of the lightsources.org collaboration.

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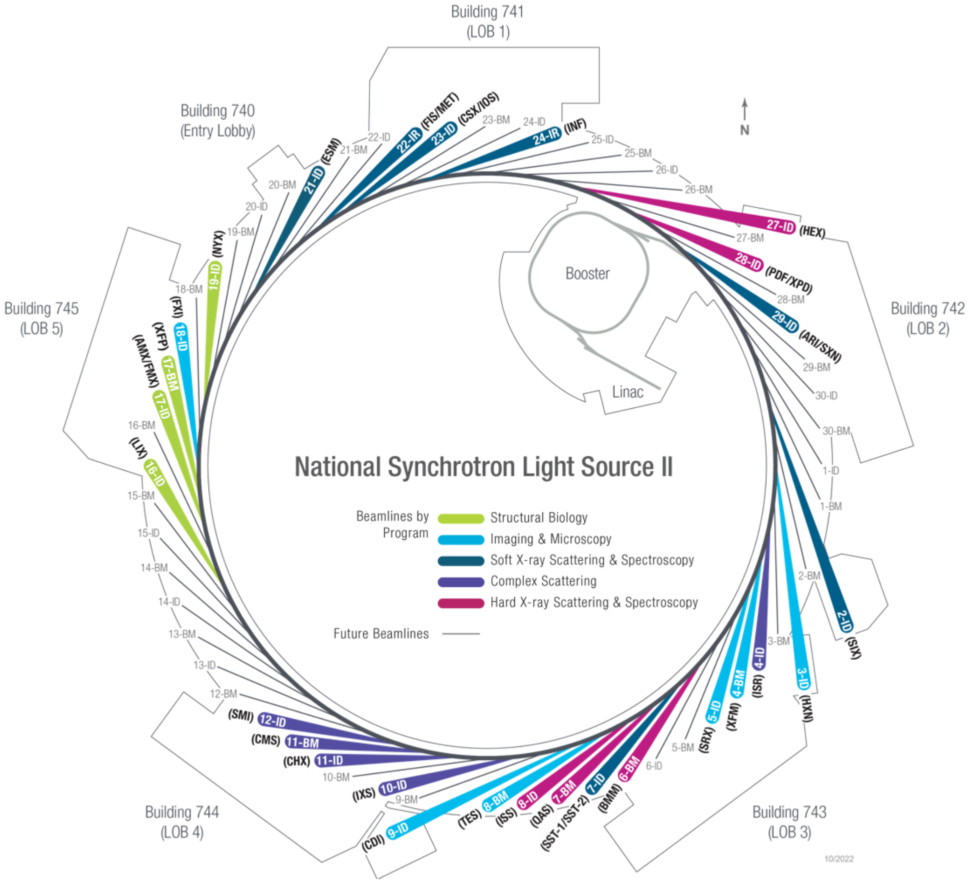
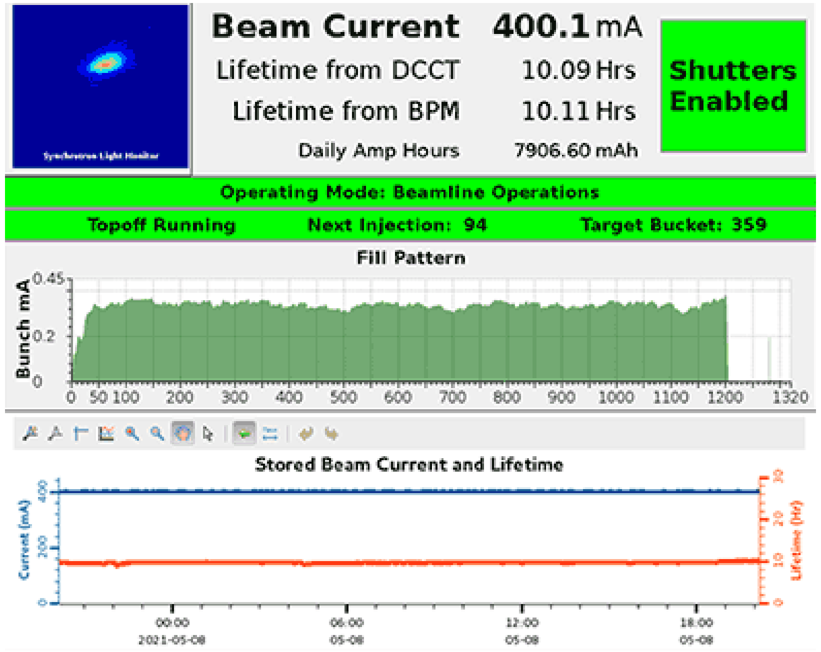
Synchrotron Radiation Facilities

Sources of ‘continuous’ x-ray beams





Offering world-leading spectral brightness from infrared light to hard x-rays (0.6 meV - 117 keV)

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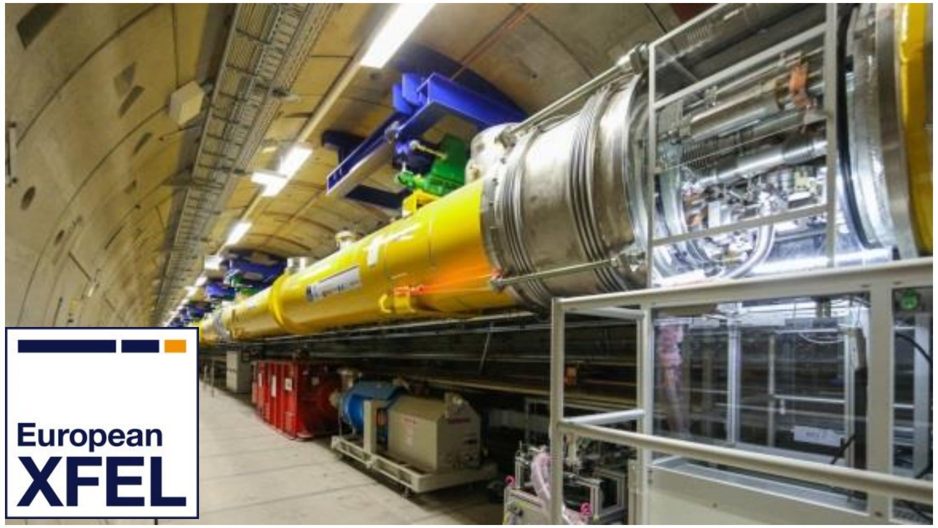
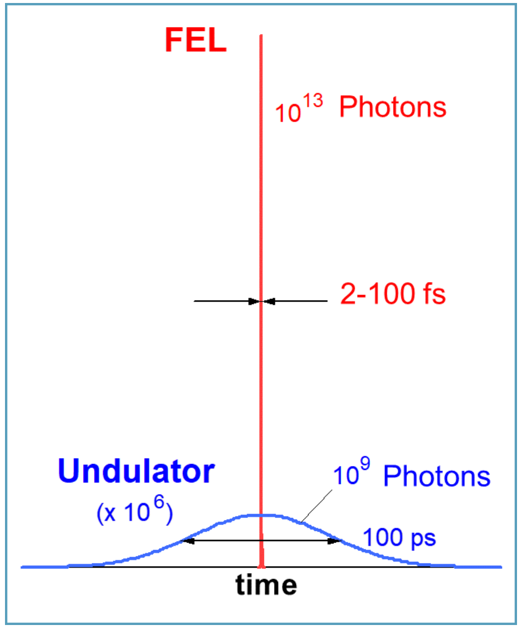
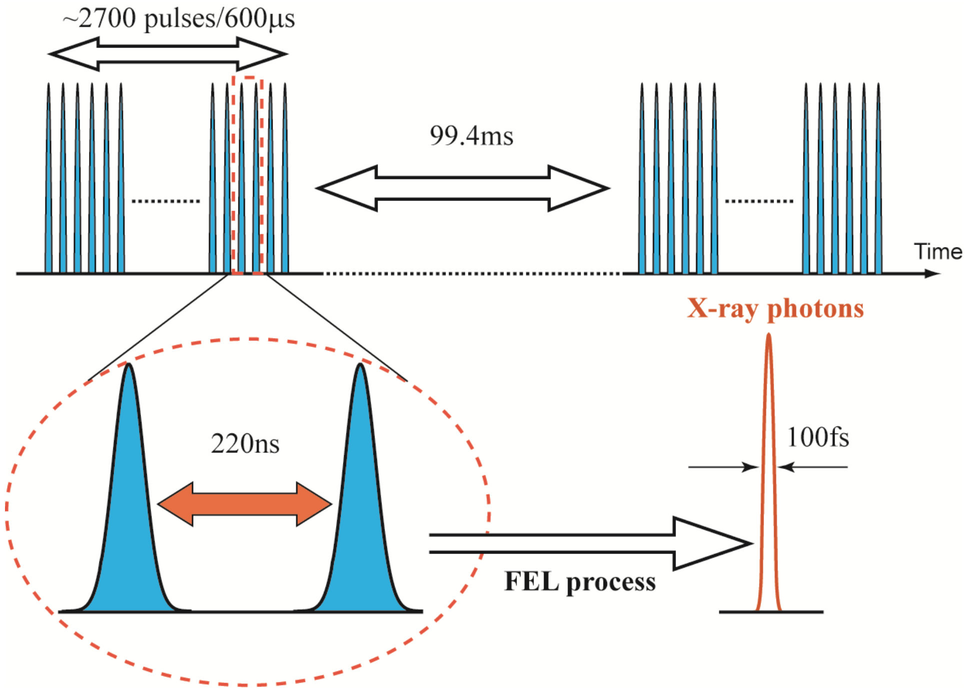
Typically detectors accumulate information

Free-Electron Laser Facilities



- Follows from pulsed RF system
- Trains of e-/x-ray pulses
- Max. = 2.700 per train/27.000 /s
- Electron Energy: 8.5 – 17.5 GeV
- Photon Energy: 0.26 - >25 keV
- Pulse Duration: 2 – 100 fs





https://www.xfel.eu/facility/overview/index_eng.html

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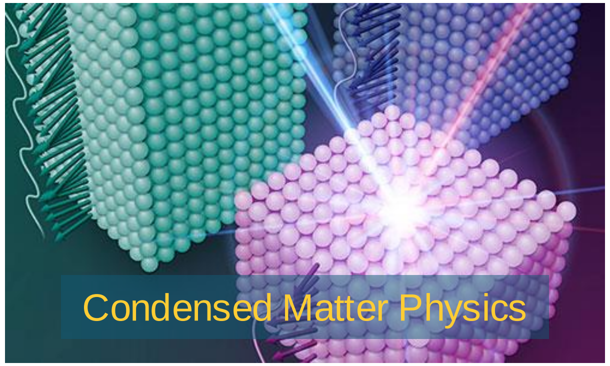
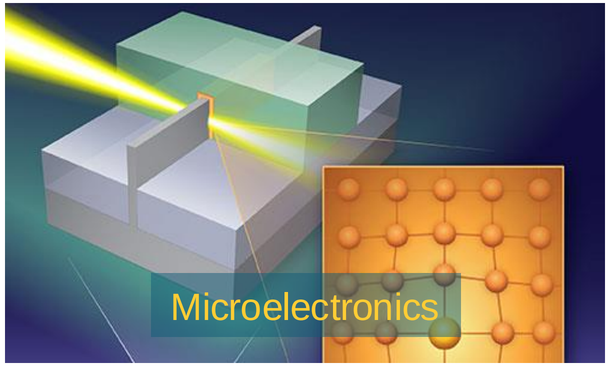
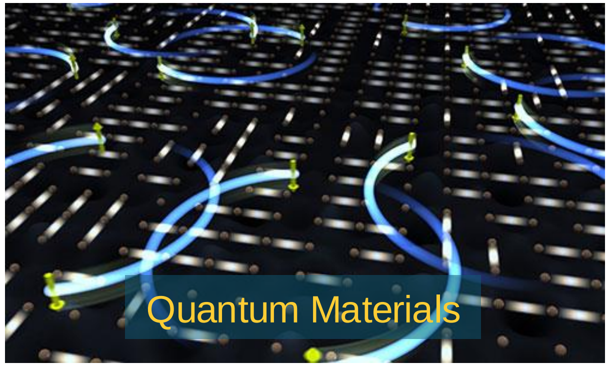
Photons arrive at once: information per pulse

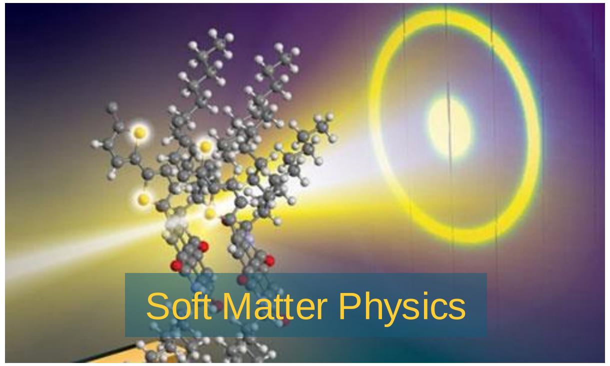
Photon Science: experimental techniques and detector tradeoffs

Research at Synchrotrons









https://www.bnl.gov/nsls2/research/

BNL - NSLS-II

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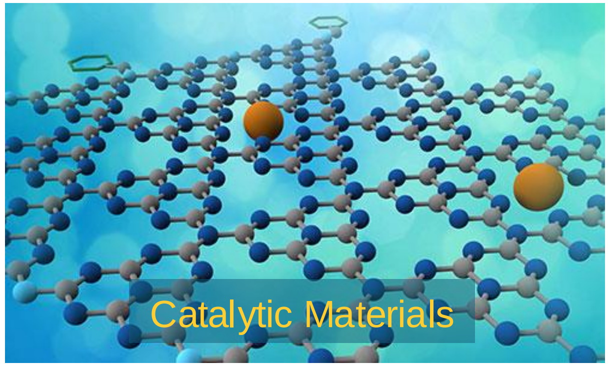
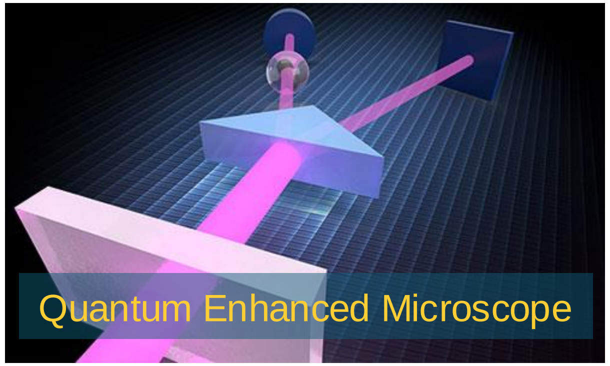
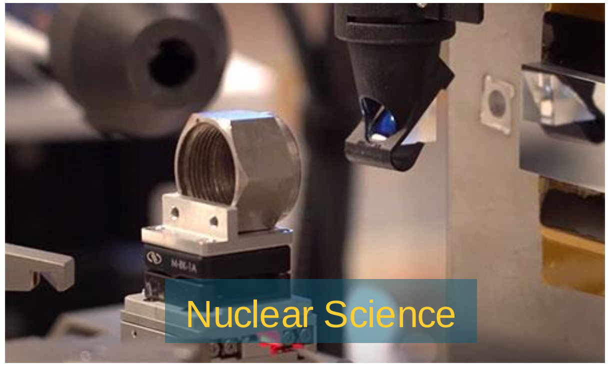
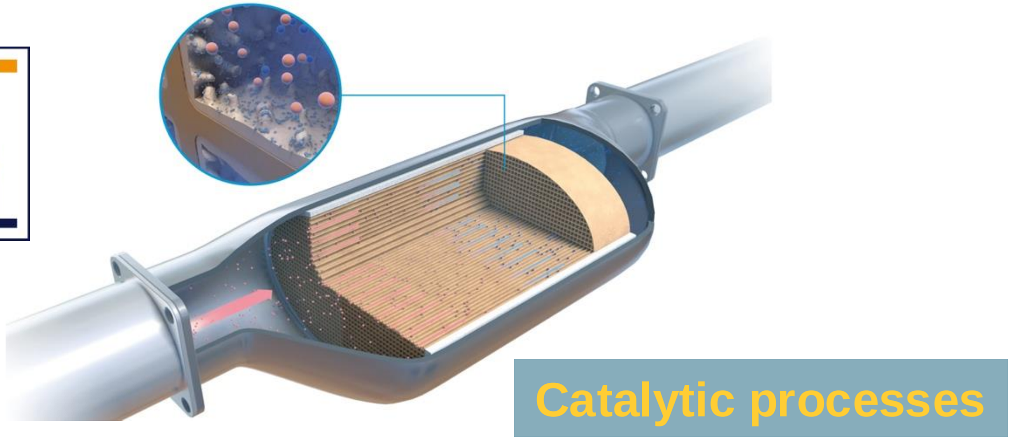






Research at Free-Electron Lasers

European XFEL



https://www.xfel.eu/science/index_eng.html

Detectors in photon science

R&D drivers

Detector development in science

- Particle Physics
- Astrophysics
- Consumer markets

Main drivers in photon science

- Macromolecular Crystallography
- X-FELs

Technology drivers

- Difficult to access new technology

Experimental techniques

Imaging/scattering:

- Good spatial resolution
- Dynamic range
- Fast and "smart"

Spectroscopy:

- Very high energy-resolution
- High speed

…other common needs

Efficiency and sensitivity

- Good entrance window for soft x-rays
- High stopping power material for hard x-rays

Fast

- Detector speed (temporal resolution)
- Readout speed (frames/second)

Large solid angle (large area)

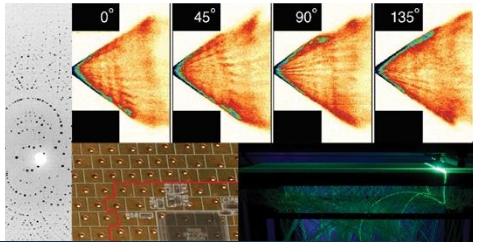
- Scalability

Radiation tolerant

Affordable

Easy to use

Evolution – a decade of progress



	Brighter Sources	with better energy resolution	with better spatial resolution	with better temporal resolution
δT Speed	X	X	X	X
ε Efficiency	X	X	X	X
δE Resolution		X		
δt Time				X
Q Intensity	X		X	
δx Size		X	X	

October 2023

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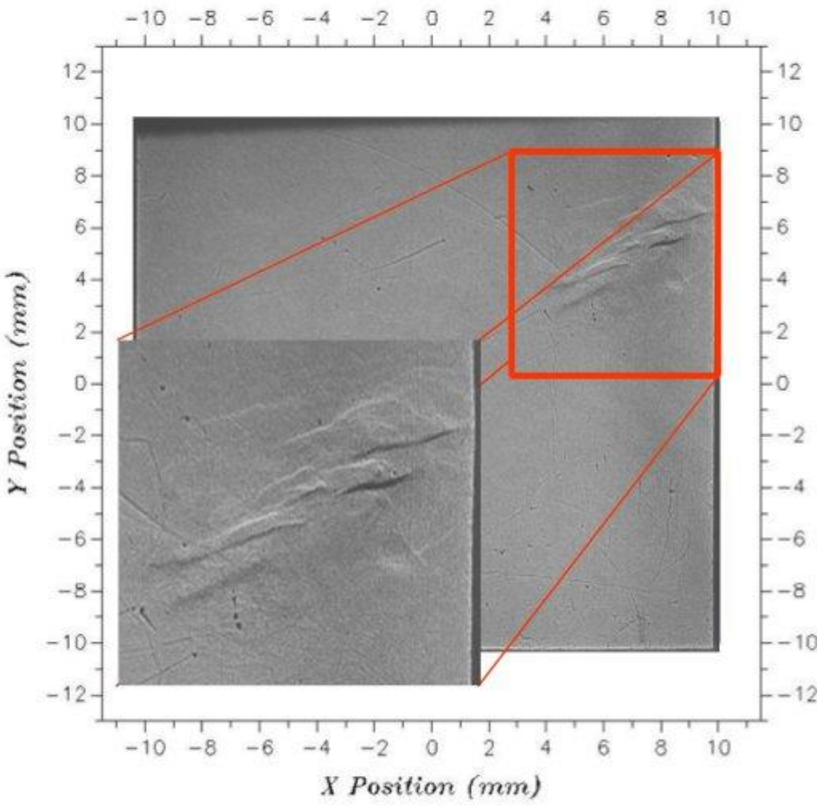
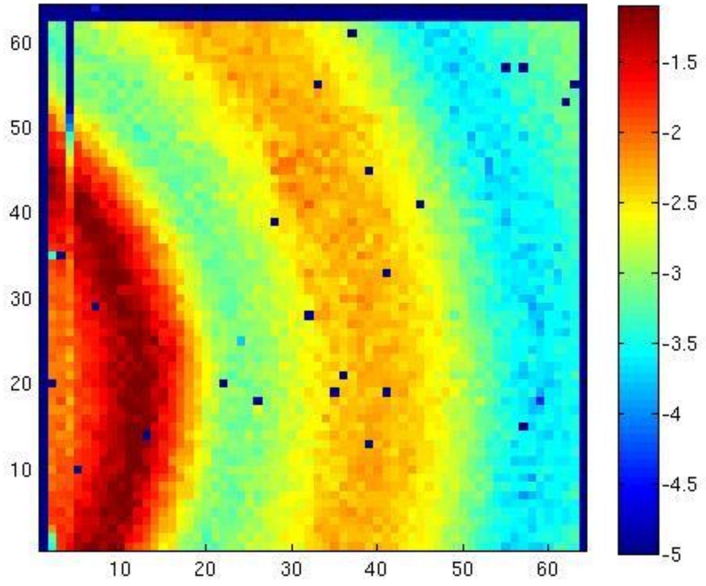
On a personal note





CdZnTe substrate - NSLS
White Beam X-ray Topography @ X19C
Beam energy: 6 keV to 50 keV
Film
(111) Reflection

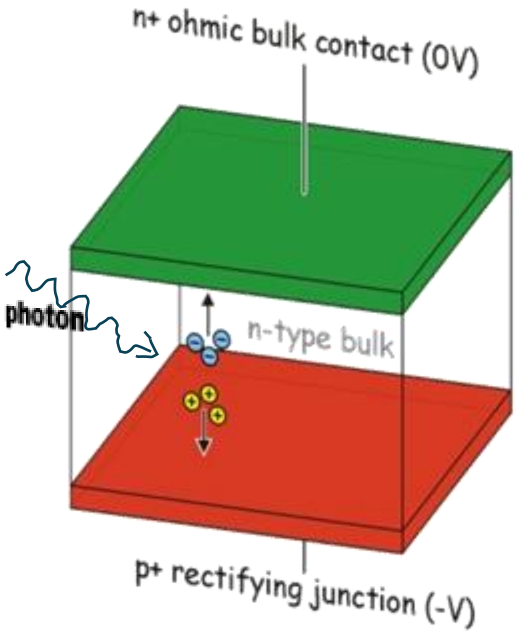
2004

Latex suspension – APS
XPCS @ 8-ID-I
Beam energy: 10 keV
VIPIC prototype

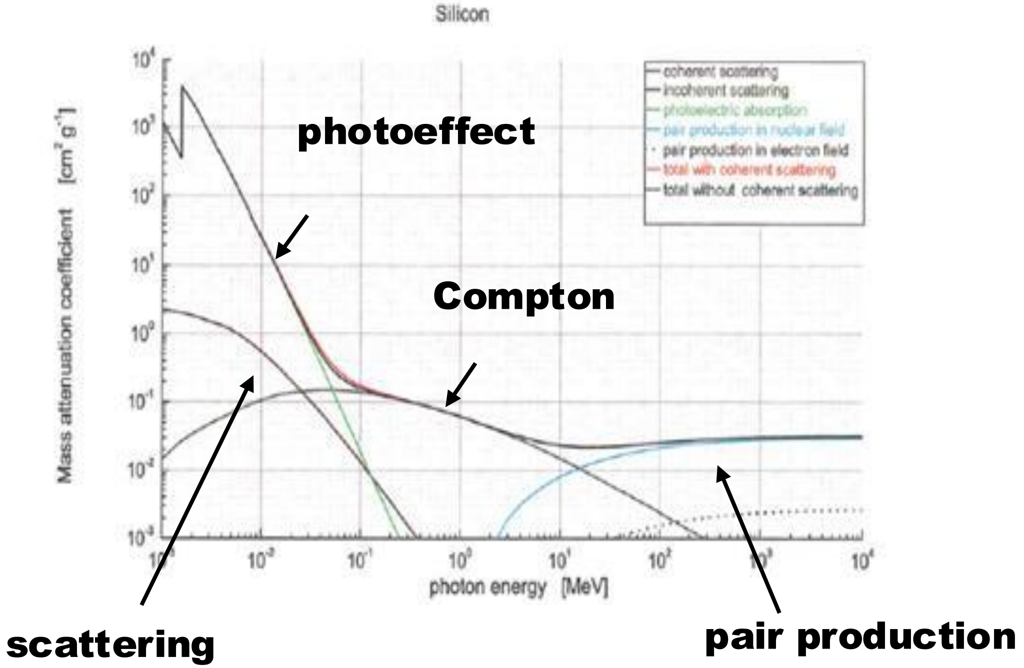
2014

Materials challenges

Silicon is an excellent material for direct conversion



PIN diode scheme



- Below ca. 40 keV photoeffect dominates in silicon
- $N_{\text{e-h pairs}} = E_{\text{x-ray}} / 3.65\text{eV}$
- Variance: $\sigma = \sqrt{(F \times N)}$
  - Fano factor: F= 1 pure Poisson process
    F= 0.115 - 0.117 for silicon

5.9keV (Fe^{55}) → 1616 e^- mean → 13.7 e^- sigma → 50.2eV sigma → 118eV FWHM

/3.65 *3.65 *2.35

Photon absorption depth in Silicon

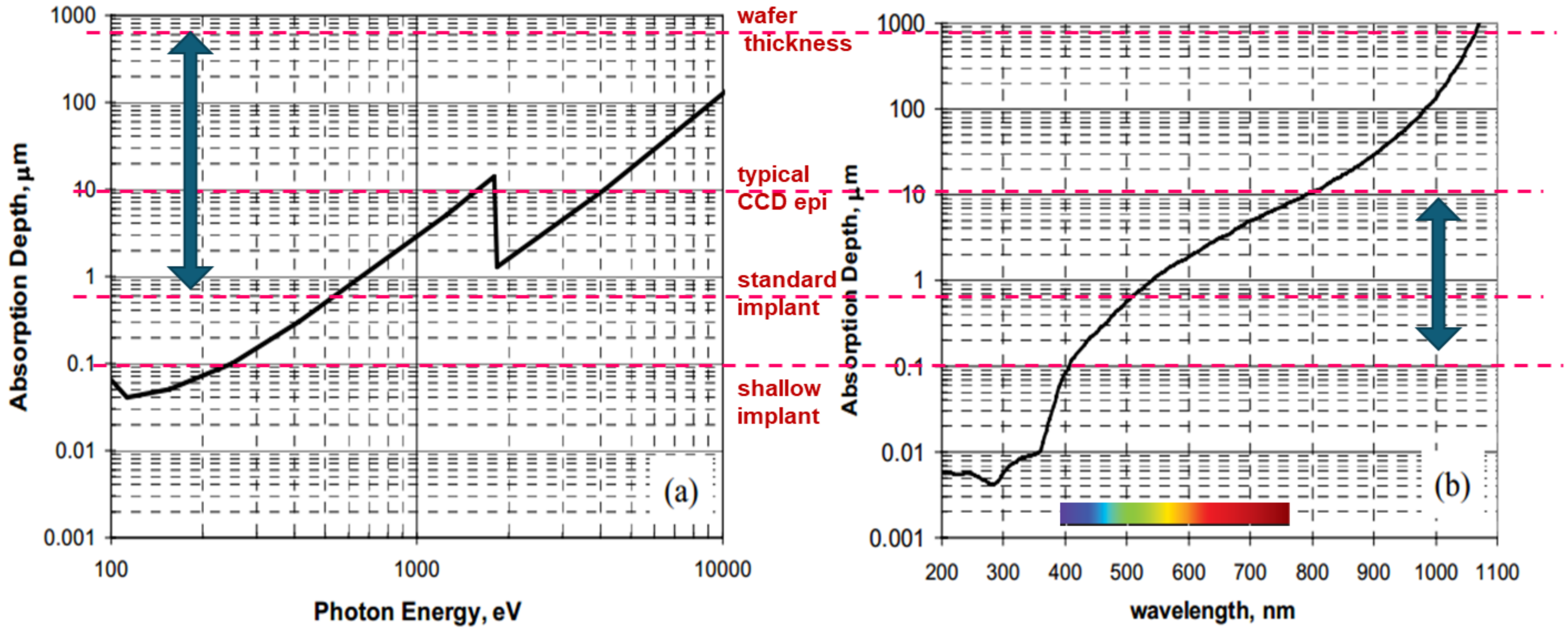


Fig. 7: Absorption depth of photons in silicon as a function of: (a) X-ray energy and, (b) the wavelengths from UV to NIR

- **hard x-ray cameras need tick sensors**
- **soft x-ray cameras need thin entrance windows**

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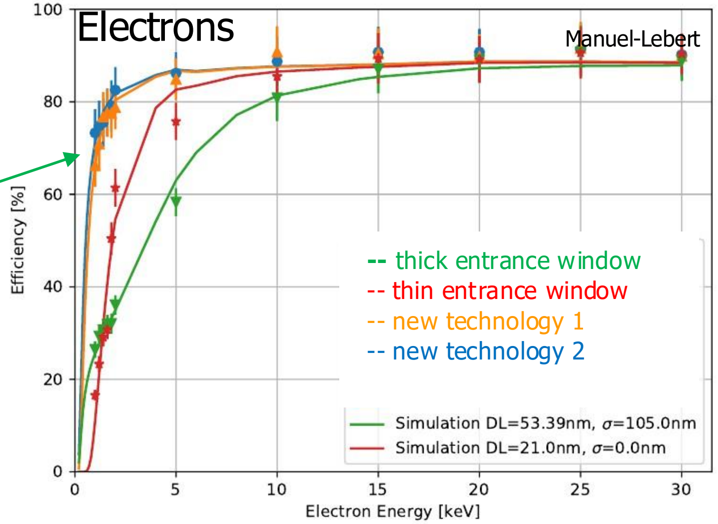
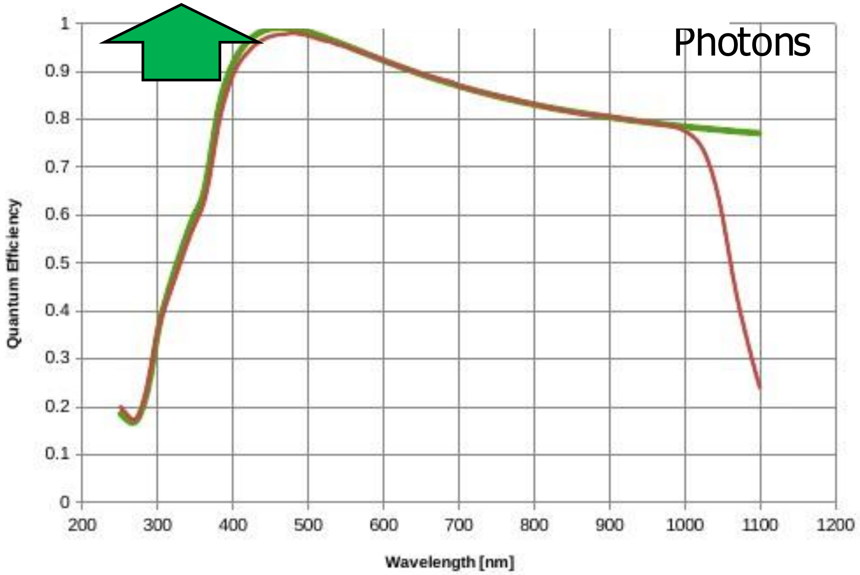
Yibin Bai et al, *Teledyne Imaging Sensors: Silicon CMOS imaging technologies for x-ray, UV, visible and near infrared*, SPIE Vol. 7021 (2008)

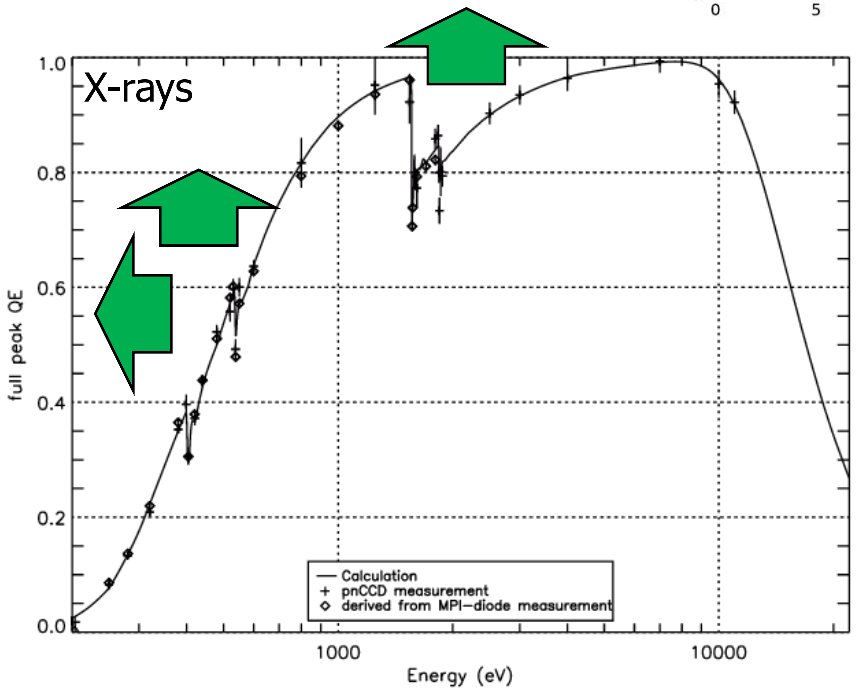
Entrance window engineering – application optimization

- anti-reflective coating (ARC)
  - ▷ sequence of dielectric layers deposited on the entrance window
  - ▷ variation of material and thickness
  - ▷ transmittance tuning to application needs
  - ▷ blocking filters
  - ▷ mechanical protection
  - ▷ optical coupling



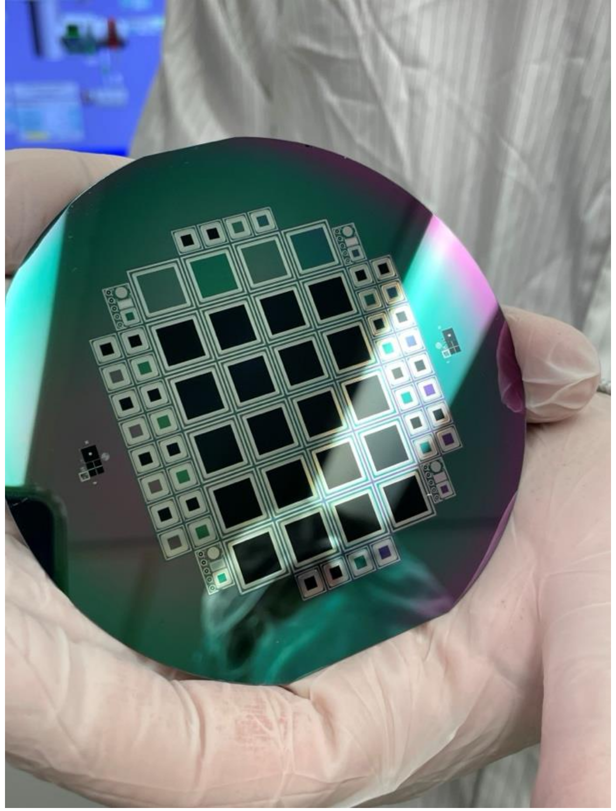
Ongoing developments
Reduction of dead layer to < 20nm

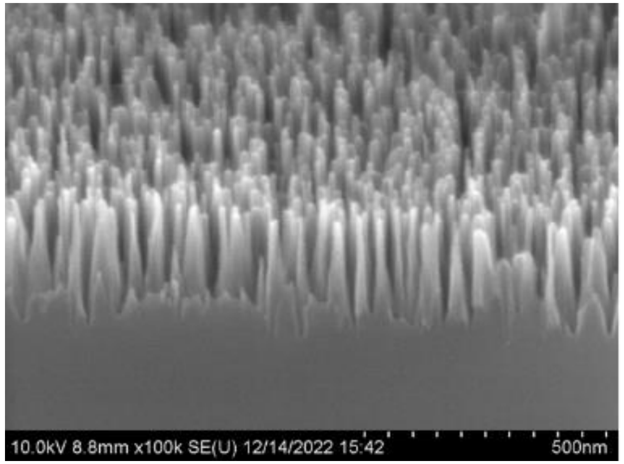


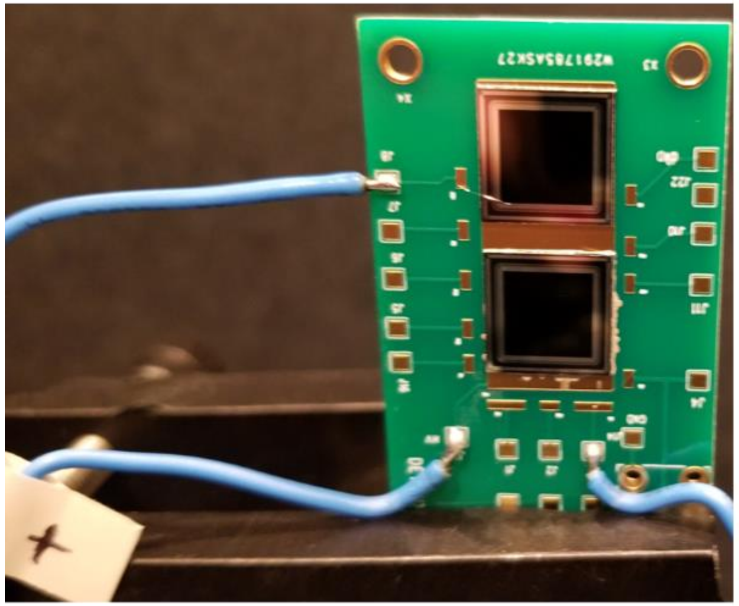


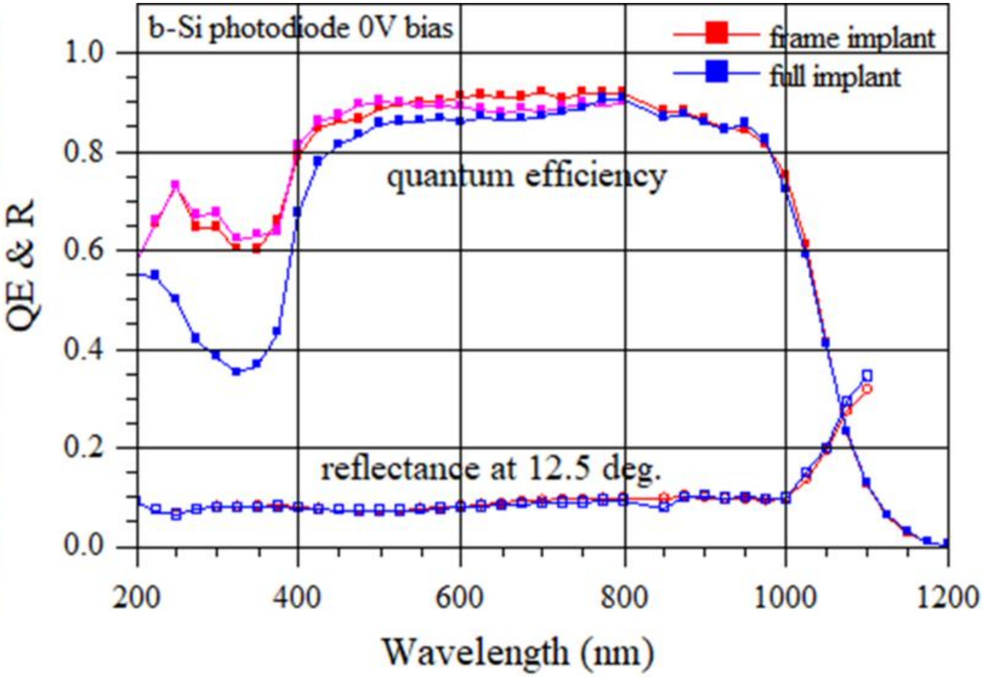
Black silicon

- Black silicon obtained by RIE etching of silicon surface
- Passivation with alumina
- High QE on wide wavelength range









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‘Beyond’ silicon: materials challenge

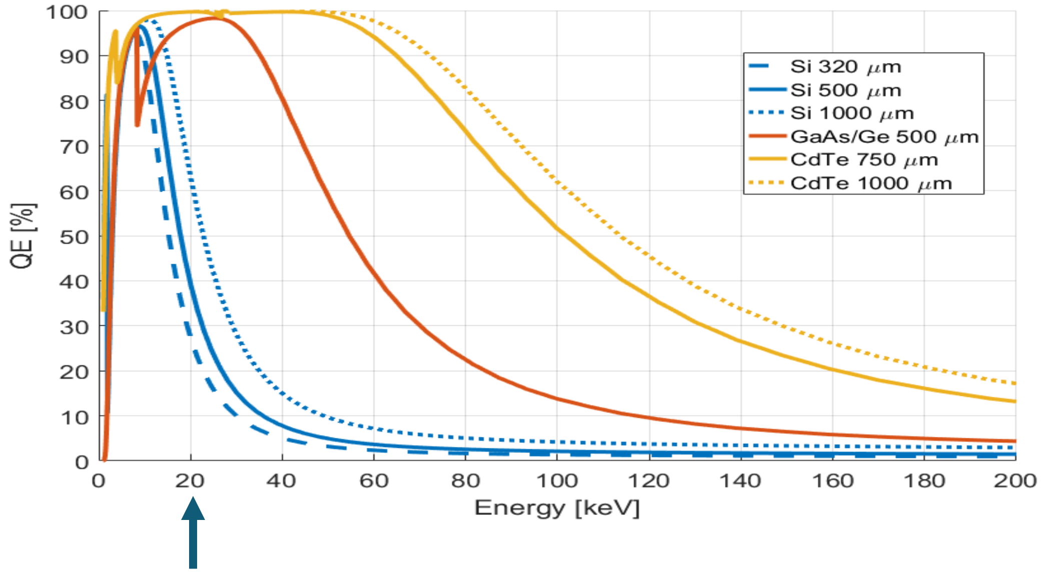
J. Thom (Cornell)

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}
								1.5×10^{-6}, 2.5×10
InP	4.78	49, 15	1.30	4.2 [6]	300	27.9, 2.1	$\approx 10^7$	4.8×10^{-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	$\approx 10^7$	8.6×10^{-6}, 4.0×10
								8.6×10^{-5}, 4.0×10
InSb	5.77	49, 51	0.20	0.6 [15]	4	27.9, 30.4		10^{-5}, 7.5×10^{-6}
CdSe	5.80	48, 34	1.73	5.5 [a]	300	26.7, 12.6		2.0×10^{-5}, 1.5×10
CdTe	6.20	48, 52	1.44	4.7 [3]	300	26.7, 31.8	$\approx 10^9$	2.0×10^{-3}, 4.0×10
PbI_2	6.20	82, 53	2.55	7.7 [a]	300	88.0, 33.2	$> 10^{13}$	8.0×10^{-6}, 2.0×10
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	$\approx 10^{12}$	1.6×10^{-5}, 1.5×10

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



Every common higher-Z sensor has problems!

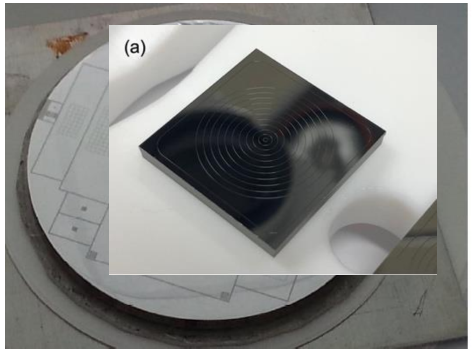
Availability & quality, fluorescence, trapping, recombination lifetime, carrier mobility, radiation hardness, dark current, physical properties.

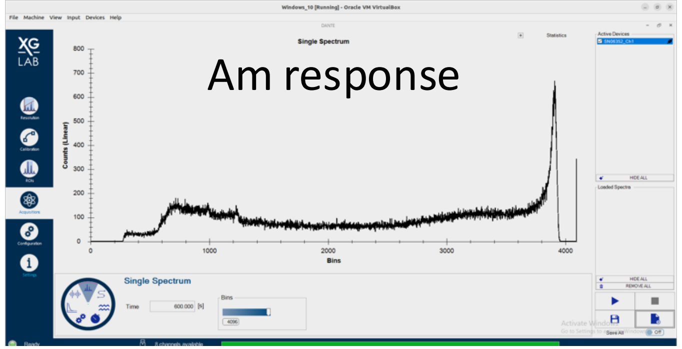
Classic ‘old’ Germanium or more ‘exotic’ options?

Efforts to evaluate different type of materials are ongoing around the world – the community is trying to maintain a good level of communication & coordination

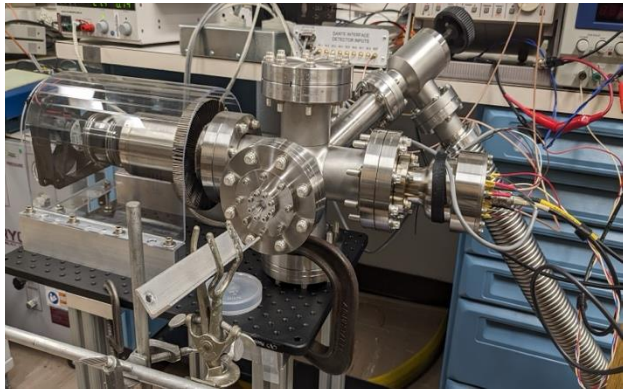
Germanium

Courtesy of A. Rumaiz

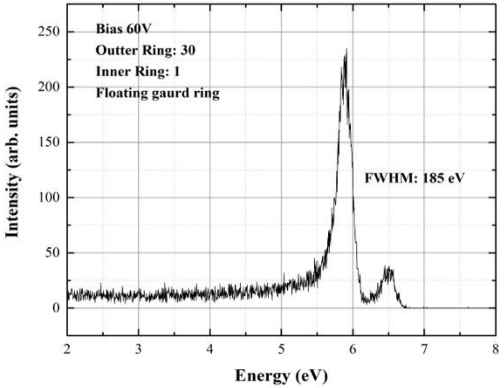




Full system GDD



Fe^{55} response



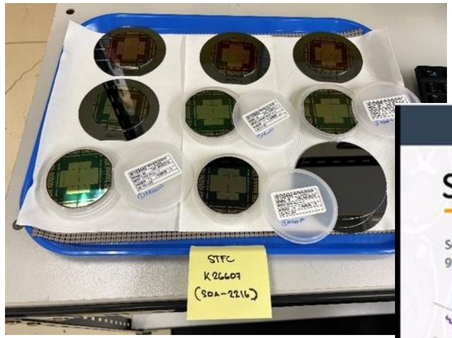
High-flux CZT

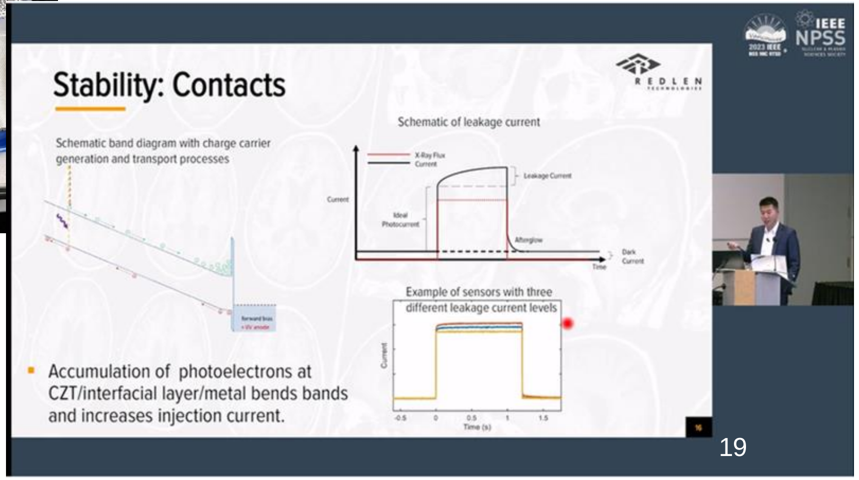
Courtesy of M. Veale

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

	$\mu_e\tau_e$ ($\times10^{-4}$ cm^{2}V^{-1})	μ_e (cm^{2}V^{-1}s^{-1})	τ_e ($\times10^{-6}$ s)	$\mu_h\tau_h$ ($\times10^{-4}$ cm^{2}V^{-1})	μ_h (cm^{2}V^{-1}s^{-1})	τ_h ($\times10^{-6}$ 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

DOI: 10.1088/1748-0221/12/12/C12045





Cornell University Northwestern University Argonne National Laboratory Brookhaven National Laboratory SLAC National Accelerator Laboratory

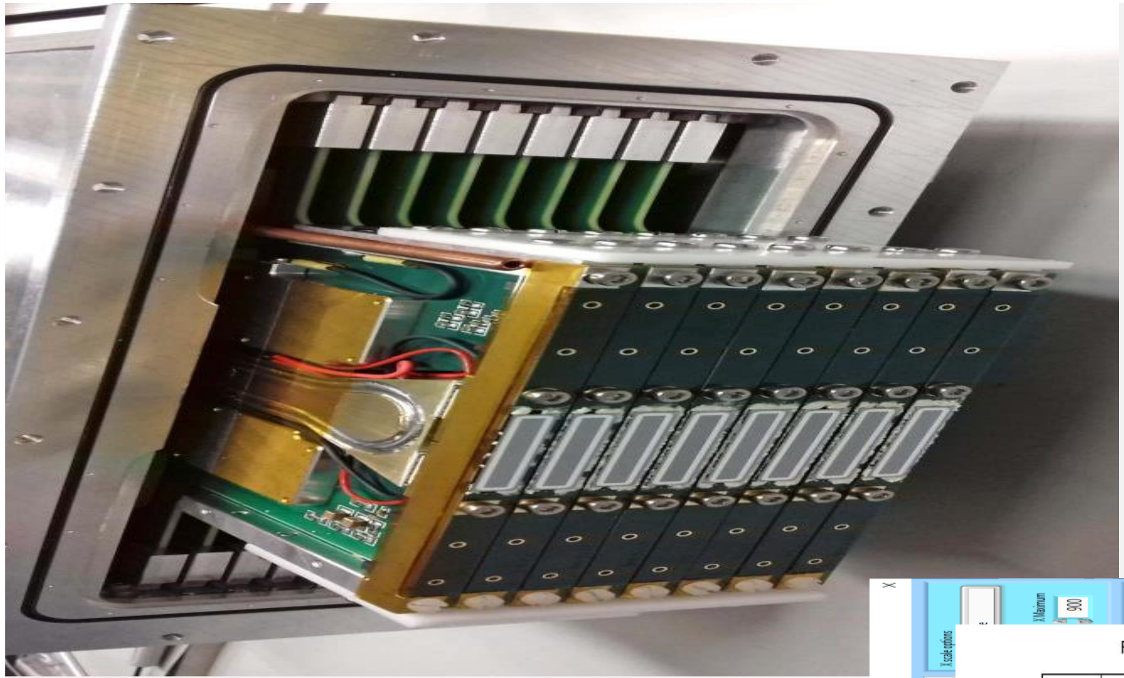
Energy resolving detectors

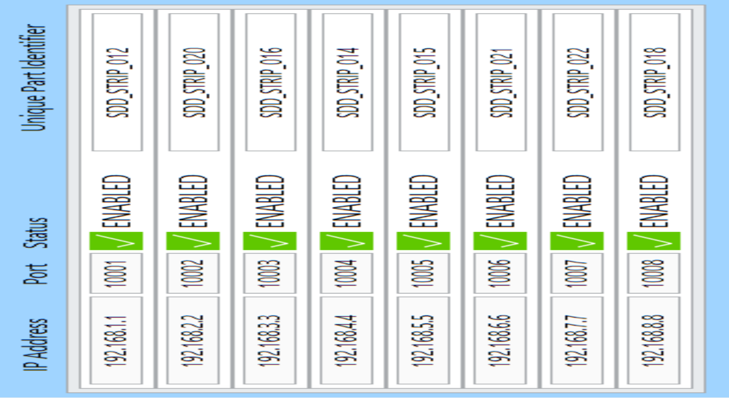
High throughput spectroscopy with semiconductor detectors

Courtesy of Ralf Menk

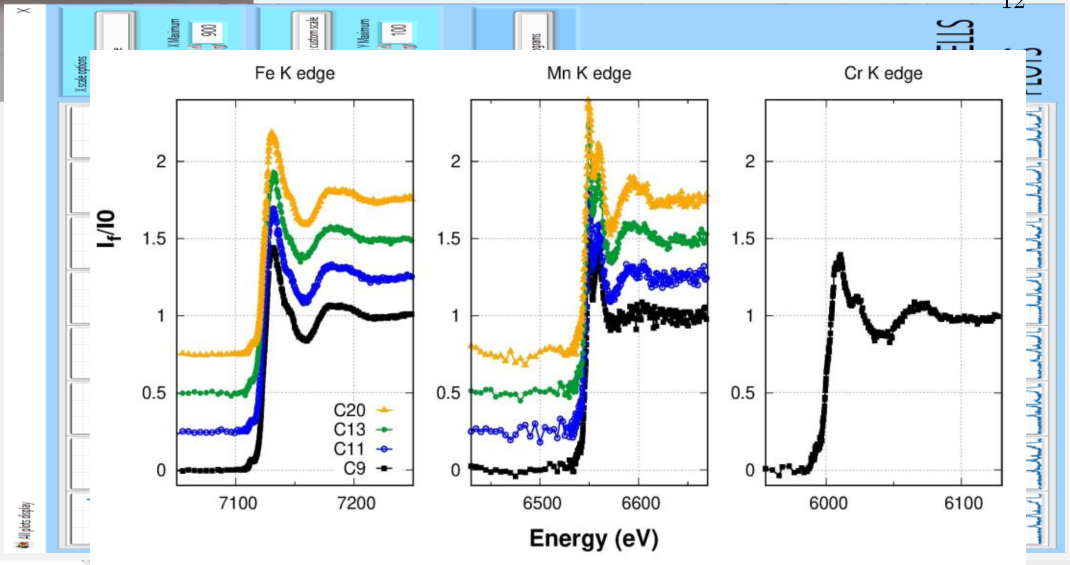
Elettra Sincrotrone Trieste

EXAFS SDD Sesame and Elettra

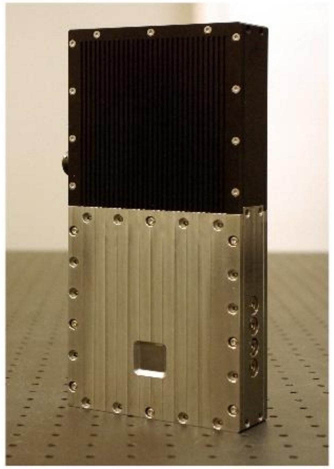




- 8 strips
- 64 channels
- 576 mm^2 active area



Maia detector: a fresh approach to x-ray fluorescence microscopy (XFM) imaging

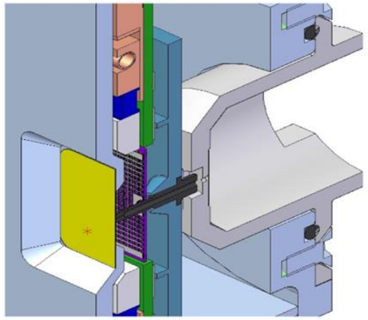


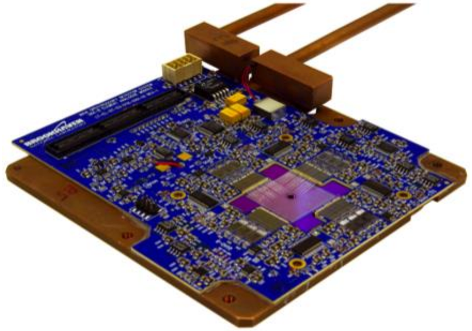
- massively parallel detector architecture
- dedicated pulse shaping and capture on each channel
- asynchronous acquisition of x-rays as an event stream
- real-time processing of the event data

2011 R&D 100 Award

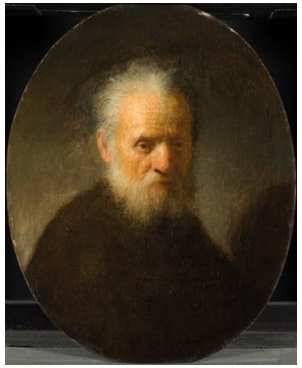
With Fly scan it is possible to achieve 100 M pixels with a collection time of few hours and time per pixel as low as 50 μs

Sensor, readout electronics developed at BNL, s/w for fly scan, on the fly DA analysis with GeoPIXE developed by CSIRO

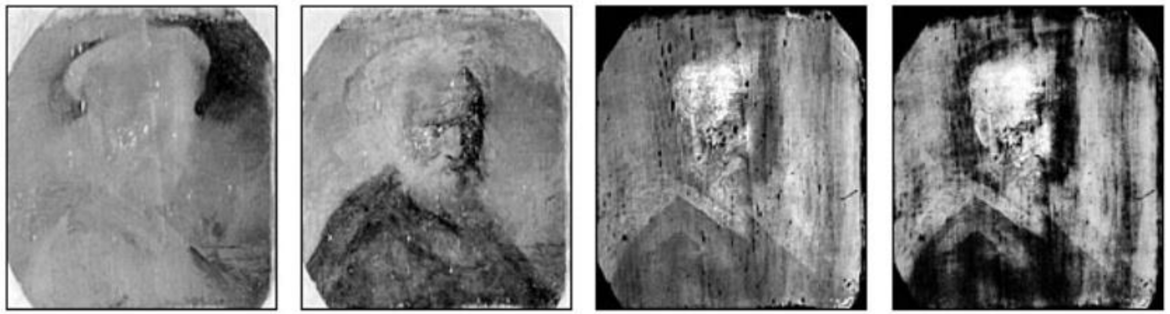




Energy resolution	~270 eV (2 μs) / ~350 eV (0.5 μs) – at 6 keV
Count rate	~30 k (2 μs) / ~100 k (0.5 μs) – per pixel
Element	384
Area	3.84 cm^2



Rembrandt's "Old Man With a Beard." Courtesy Rembrandt House.



Maia produced high-definition maps of the spatial distribution of different chemical elements in the painting. From left to right: copper, iron, lead, mercury.

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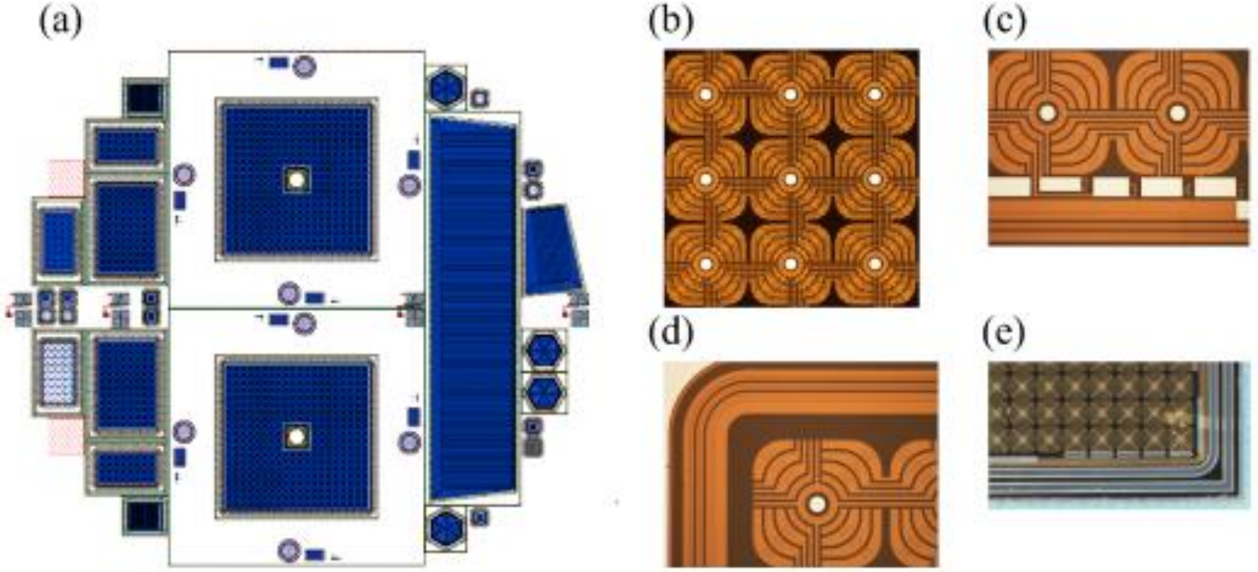
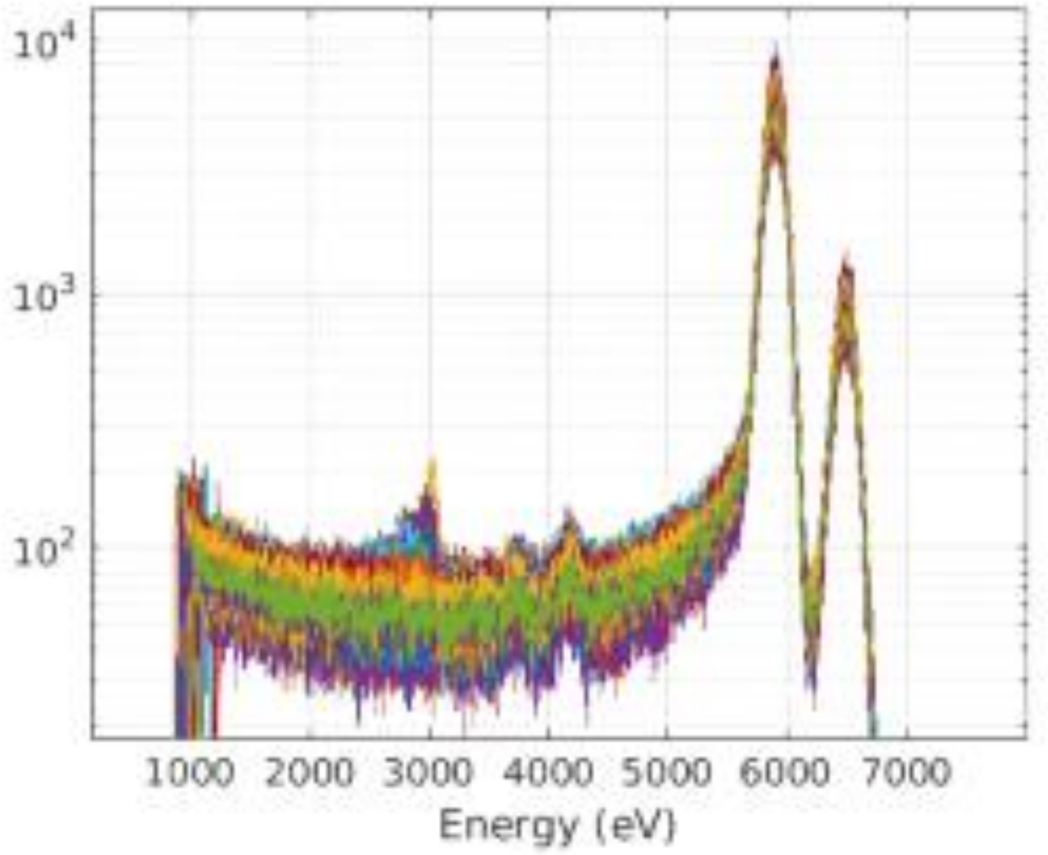
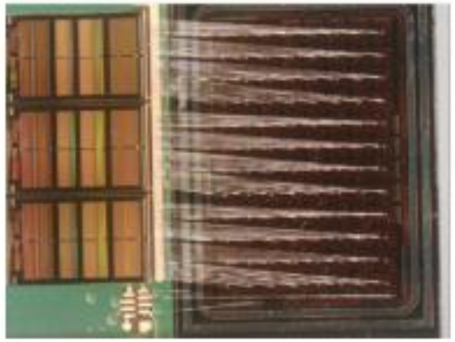
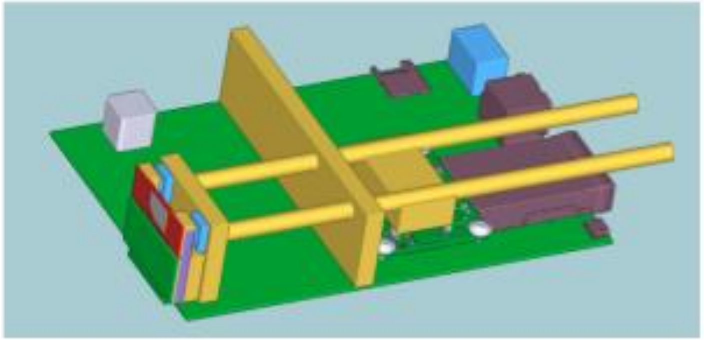
D P Siddons et al 2014 J. Phys.: Conf. Ser.499 012001

HERA a SDD version of Maia Detector









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W.Chen et al. J. Inst. 18 P01016 (2023)

Imaging detectors

…and not only

Pixel detectors: two approaches

Monolithic

CCD

CMOS imagers

- CMOS Monolithic Active Pixel Sensors (MAPS)
- CMOS Silicon On Insulator (SOI)

Hybrid pixel detectors

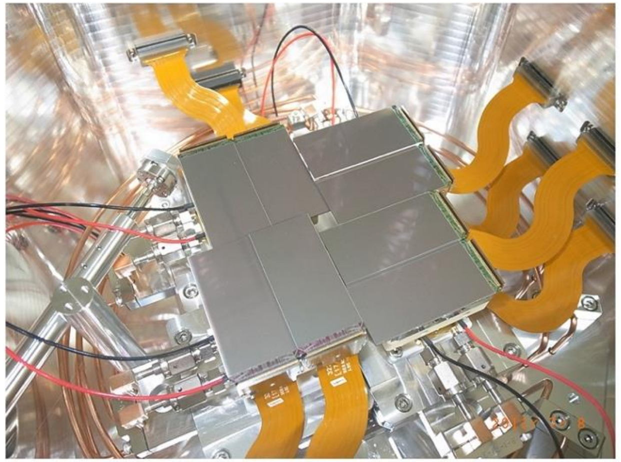
- Sensors in high resistivity silicon: e.g., Pixel Array Detectors (PADs), Silicon Drift Detectors (SDDs), Low-Gain Avalanche Diodes (LGADs), DEpleted P-channel Field Effect Transistors (DEPFETs),
- Readout chip in low resistivity silicon - standard IC technology

…and combination of the above

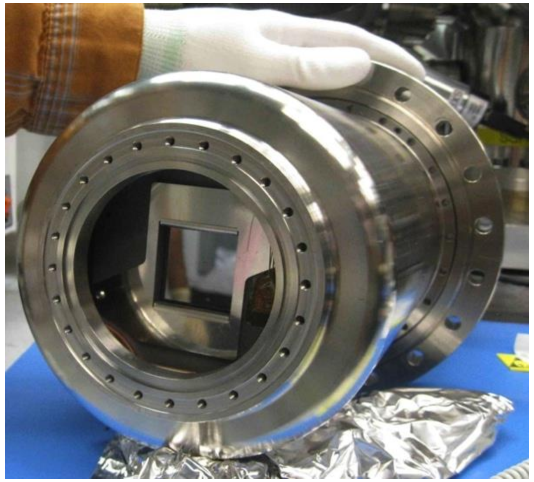
CCDs changed the way we see the world

Invention of
the CCD in 1969

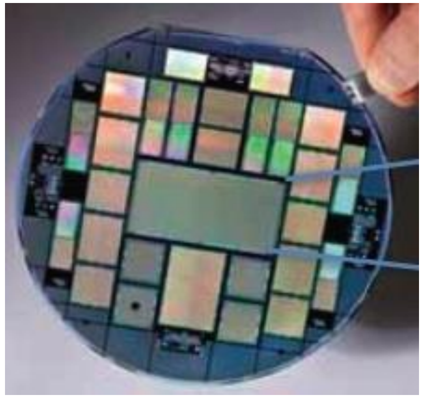
scintillator
fiber coupled
to CCD

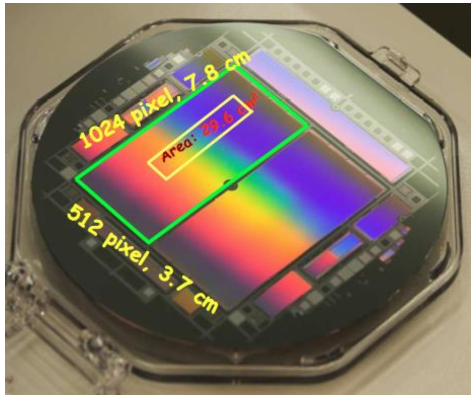


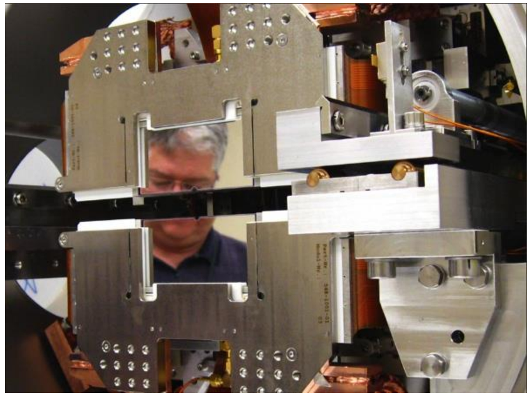
MPCCD, Riken, Japan



FCCD, LBNL





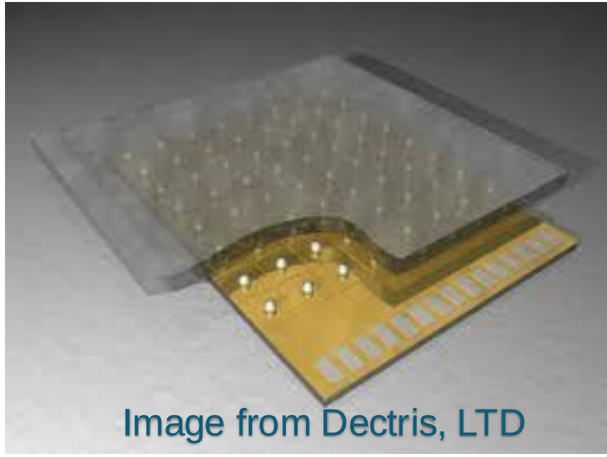


pnCCD,
MPG-HLL

Brookhaven National Laboratory

Pixel Array Detectors

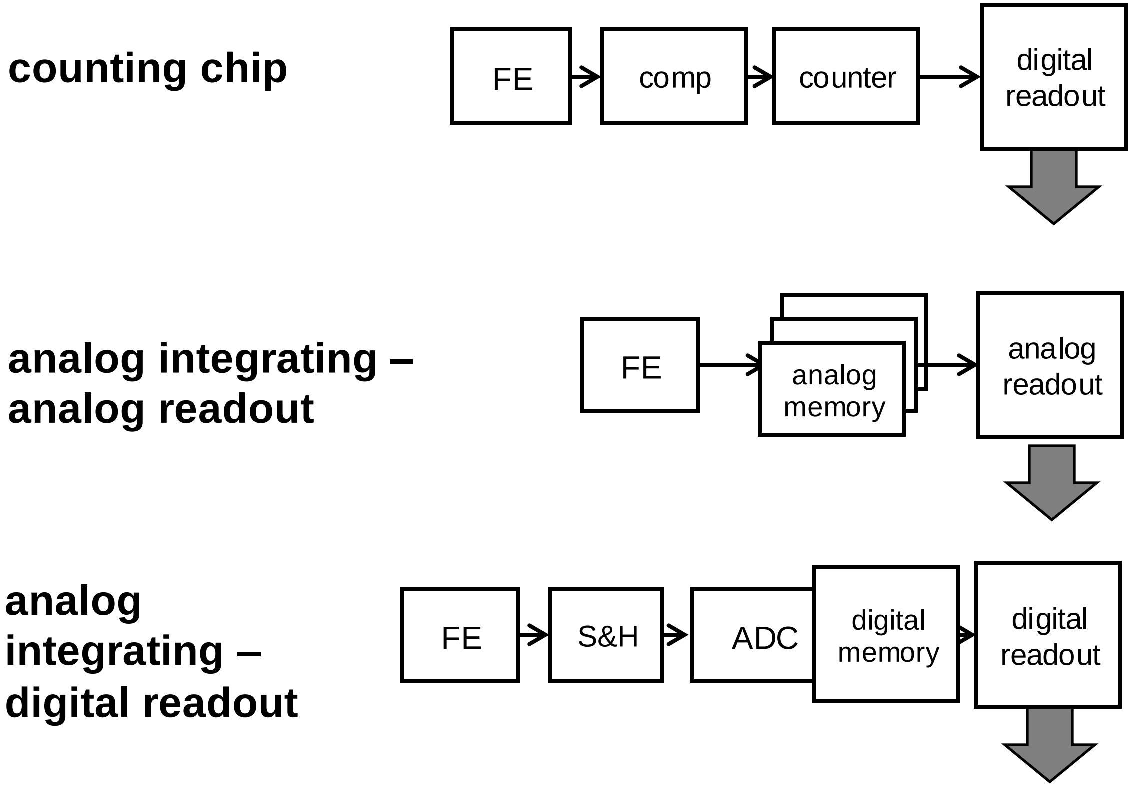
It consists of a segmented sensor bonded to a dedicated integrated circuit



History:

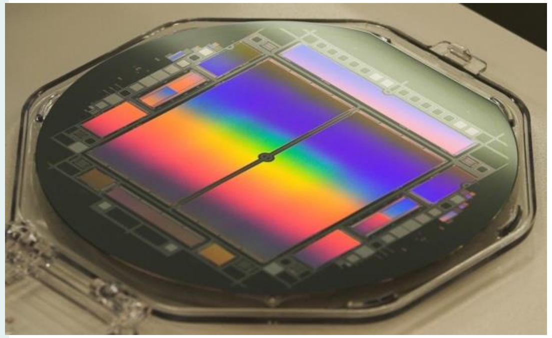
- Integrating detectors: charge is integrated and measured
  - CS-PAD, KECK, JUNGFRAU, AGIPD, LPD, MMPAD, ePIX, MOENCH, etc.
- Counters: charge is shaped and compared to a threshold (minimum detectable value)
  - PILATUS, Medipix(-based), XPAD, EIGER, etc.

Today many groups are working on that



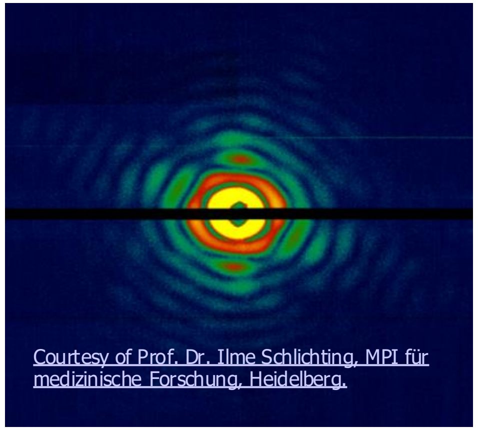
Soft X-ray detectors - Highlights from the past

CAMP / LAMP
(pnCCD sensor)



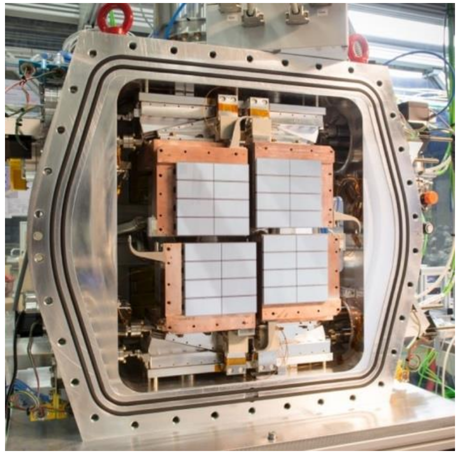
Sensor: 3.7 x 7.8 cm^2
1024 × 512 pixels.

Pixel size: 75 x 75 μm^2
Frame time: 8 msec (up to 120Hz)



Courtesy of Prof. Dr. Ilme Schlichting, MPI für medizinische Forschung, Heidelberg.

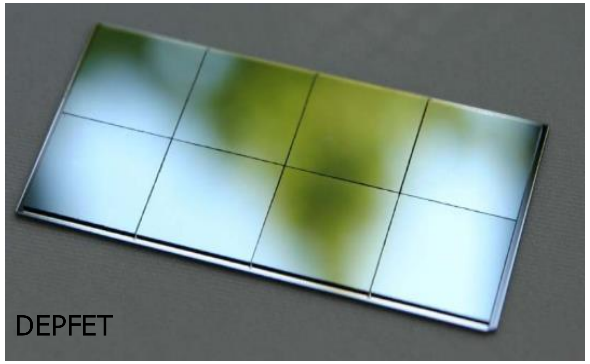
Mini SDD @ EuXFEL
(SDD sensor)



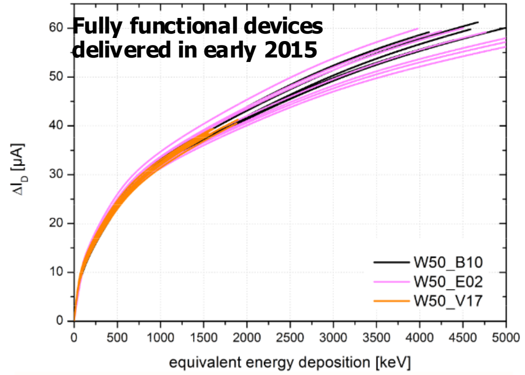
M. Porro et al., *The MiniSDD-based 1-Megapixel Camera of the DSSC Project for the European XFEL*, IEEE TNS 68(6), pp. 1334 - 1350, June 2021

camera	**1024 x 1024 pixels**
	21 x 21 cm^2
	32 sensor chips
	4 quadrants
	central hole for direct beam
sensor	mini-SDD cells
	128 x 256 pixels
	3.0 x 6.2 cm^2 (chip)
hex. pixel pitch	204 µm × 236 µm
energy range	**0.25 keV – 6 keV**
noise	60 el. r.m.s.
peak frame rate	**4.5 MHz**
frame storage	800 frames

DSSC @ EuXFEL
DEPFET **S**ensor with **S**ignal **C**ompression



Sensor **2.56 x 10.24 cm^2**
512 × 128 pixels
Hybrid detector
with 8 readout ASICs (64x64)
Pixel size: 204 x 236 μm^2
Frame time: **220ns (4.5MHz)**



DSSC Detector for EuXFEL

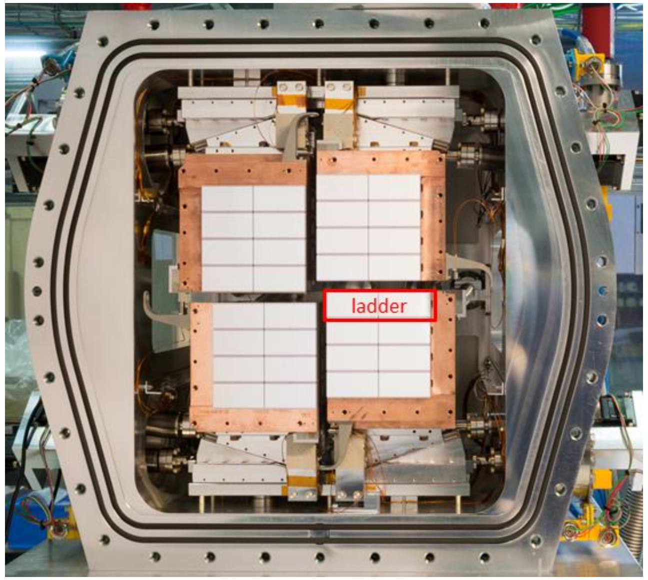
P.I.: Matteo Porro (EuXFEL)

Parameter		Value
Target energy range		0.25 keV – 6 keV
Pixel count		1024 × 1024
Pixel shape		hexagonal
Sensor pixel pitch		~204 µm × 236 µm
Active area		~ 21 cm × 21 cm
Input photon range / pixel / pulse (*)	MiniSDD (*)	2^n × N -1
	DEPFET (**)	*>10^4*
Achievable noise	MiniSDD	~ 40 - 60 e- r.m.s.
	DEPFET	*~ 10 e- r.m.s.*
Peak frame rate		1.1 MHz - 4.5 MHz
Stored frames per X-ray train		800
Average / peak data rate		134/ 144 Gbit / s
Average power consumption		~ 260 W
Operating temperature		-20º C optimum, room T possible

(*) The MiniSDD camera has been installed in 2019 and is routinely used for user experiments

(**) The DEPFET camera is under assembly and will be available at the end of the year. Performance have been tested on submodules, which contain the complete readout chain

M. Porro et al., "The MiniSDD-Based 1-Mpixel Camera of the DSSC Project for the European XFEL," in IEEE Transactions on Nuclear Science, vol. 68, no. 6, pp. 1334-1350, June 2021, doi: 10.1109/TNS.2021.3076602.



- 1 Megapixel camera **4.5 MHz peak frame rate**
  - 4 quadrants (512 x 512)
  - **16 ladders (512 x 128)**
  - 32 monolithic sensors 128x256
  - 256 Readout ASICs 64 x64
- Sensors:
  - **MiniSDD arrays - 1st camera**
  - DEPFET non-linear active pixel arrays - 2nd camera (Jan 25)
- Readout concept
  - **Full parallel readout**
  - **In pixel ADC**
  - **In pixel digital storage** (800 frames) with the possibility to overwrite non-valid frames (VETO)
  - Output average **data rate: 134.4 Gbit/s**
- Instruments:
  - The camera is being used and the **Spectroscopy and Coherent Scattering** (SCS) and **Small Quantum Systems** (SQS)
  - First camera was commissioned in 2019
  - So far **31 user experiments** have been **successfully performed**. *Time resolved Holography, Time resolved scattering, Time resolved XAS, Time resolved XPCS,* ***Single Particle Imaging***

Example of Application: Tender X-ray Single-Particle Imaging of Anisotropic AuNPs at SQS

- **Small and Quantum Systems (SQS) Instrument**
- Au octahedra used as test samples
- E = **3 keV**, Edge resolution ~1.5 nm
- 440 pulses/train DSSC
- **readout rate: 2.2 MHz**
- Total **320k good hits out of 500k hits collected in 30 minutes** at 0.5 MHz (to avoid melting of AuNPs)

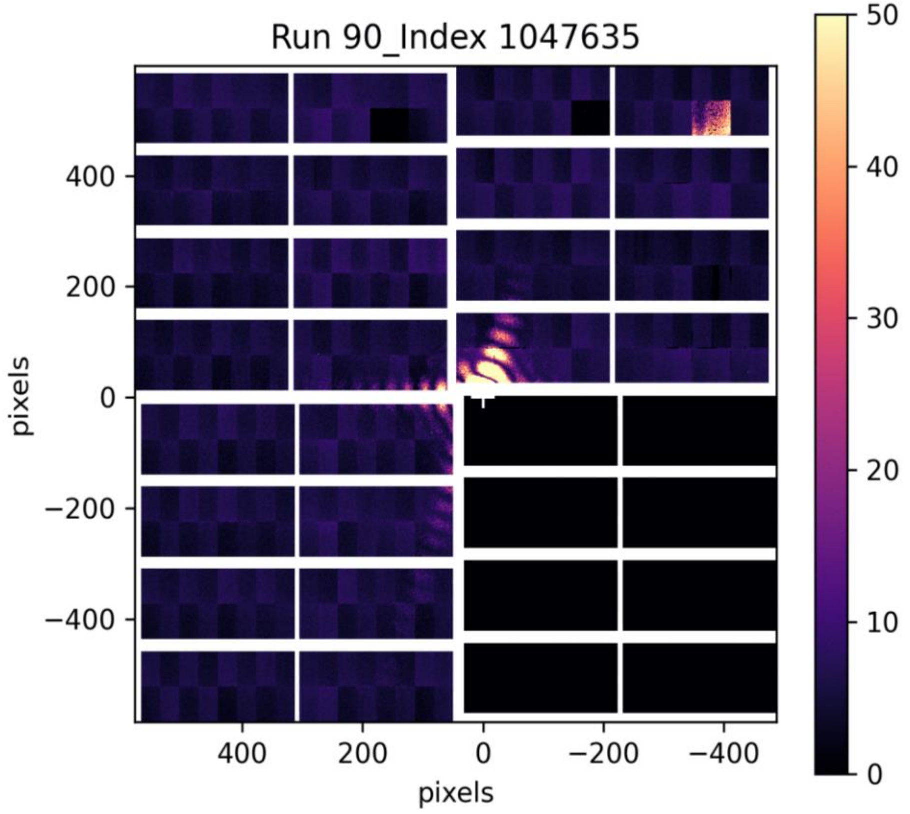
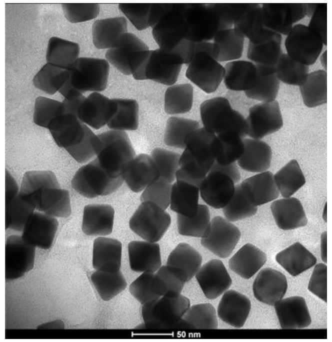
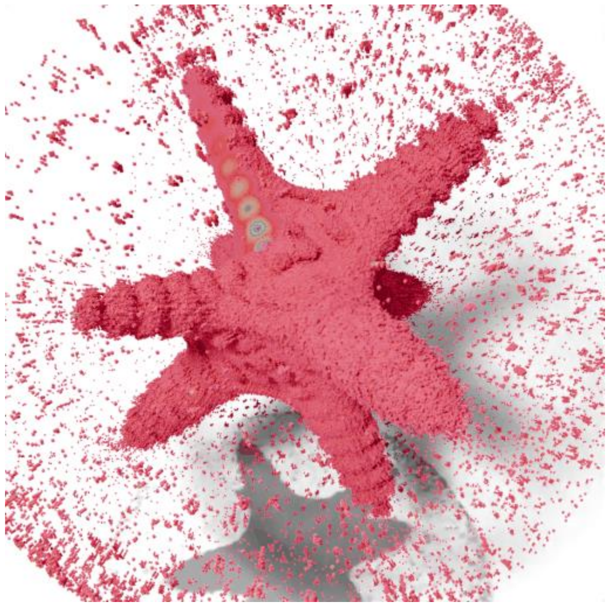
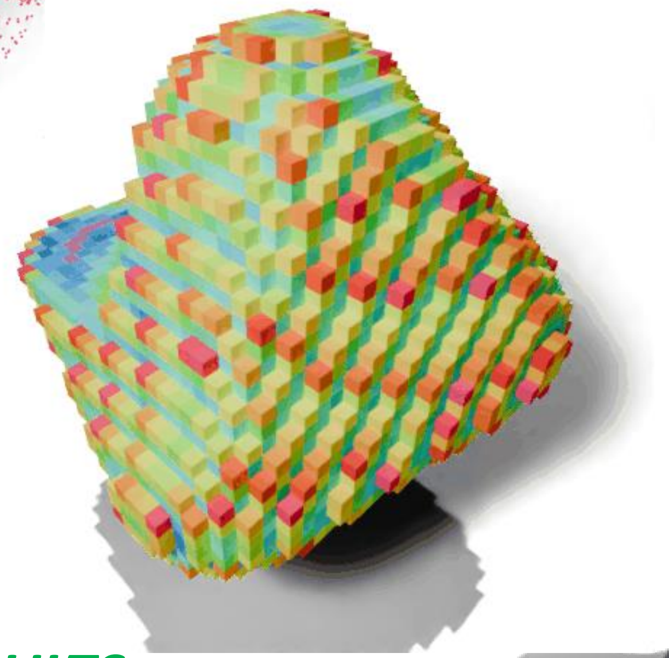


Fig: P.L. Xavier/A. Morgan



Au octahedra with edge length ~30 nm





PRELIMINARY RESULTS

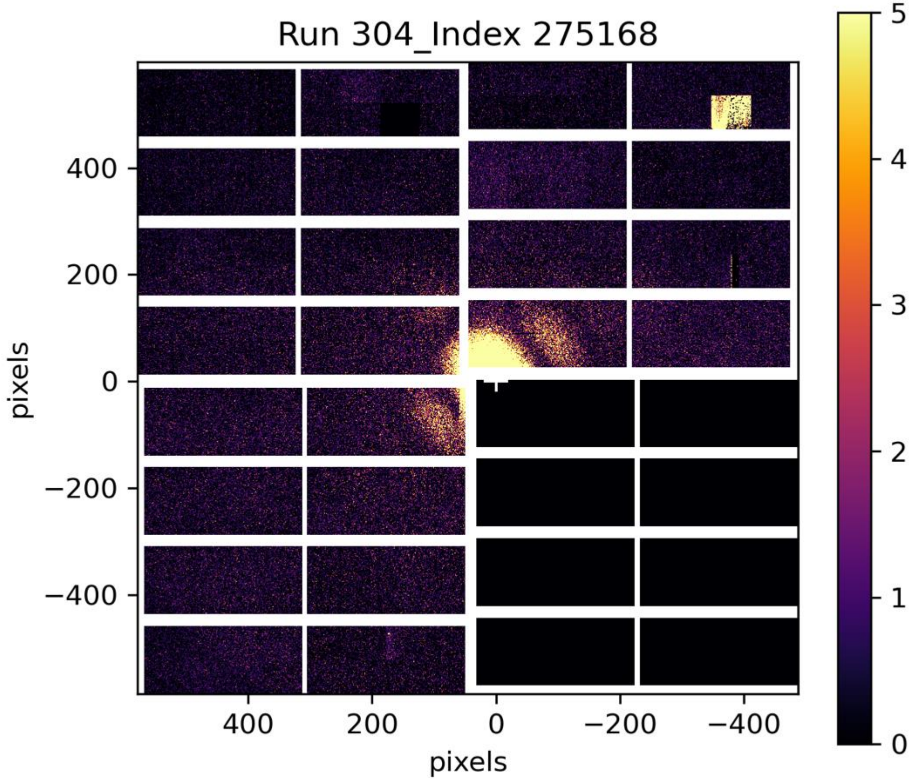
Expt: P3004 Xavier/Chapman

Soft X-ray Single-Particle Diffractive Imaging of Giant-Hemeprotein at SQS

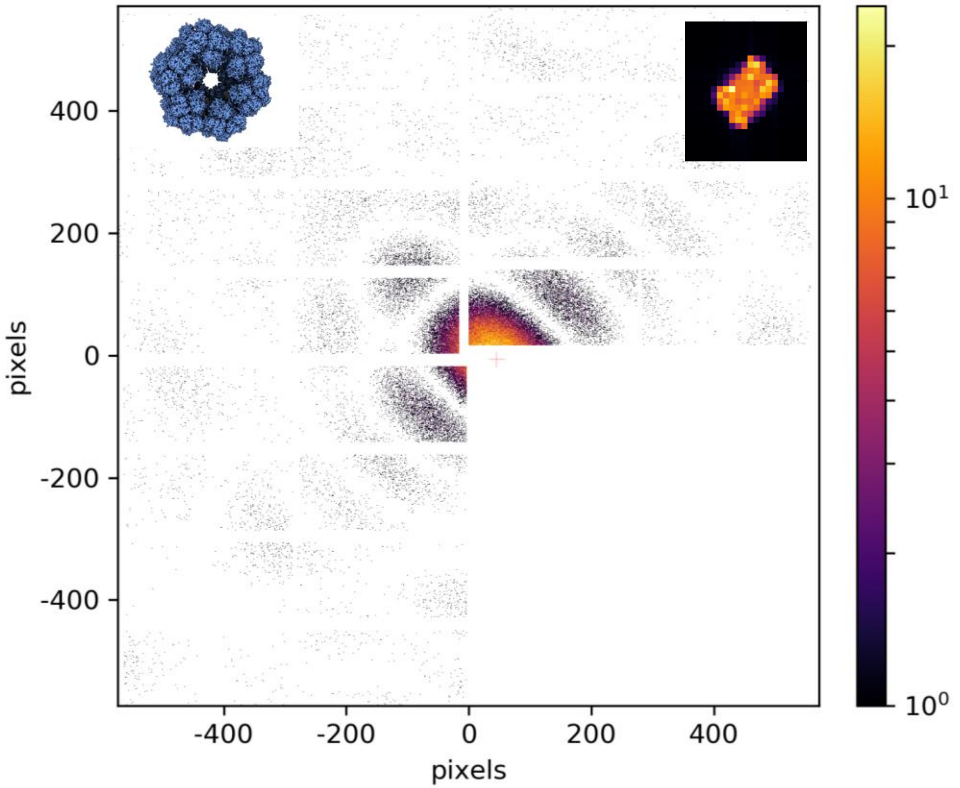
- **E = 1.2 keV**
- 440 pulses/train DSSC
- gain: 5 ADU/ph
- **readout rate: 2.2 MHz**

First ever recorded single-particle diffraction pattern of a photoactive protein system relevant to XFELs exhibiting ps/fs dynamics

Experimental



Simulation



1.2 keV 536 mm detector distance

- Single-particle diffraction patters with soft X-rays have been recorded also for:
  - *De-novo protein complexes*
  - *DNA origamis*
  - *Photosystem I*
- The average noise was ~ 45 el. rms
- Better performance is expected with the DEPFET camera: ~10 el rms
- The DEPFET camera has been assembled and can be available for user experiments in Jan 2025

Xavier/Chapman P3004

Vertically Integrated Photon Imaging Chip (VIPIC)

Pixelated detector for XPCS based on ‘3D’ also known as ‘Vertical Integration’ technology

The stack consist of:

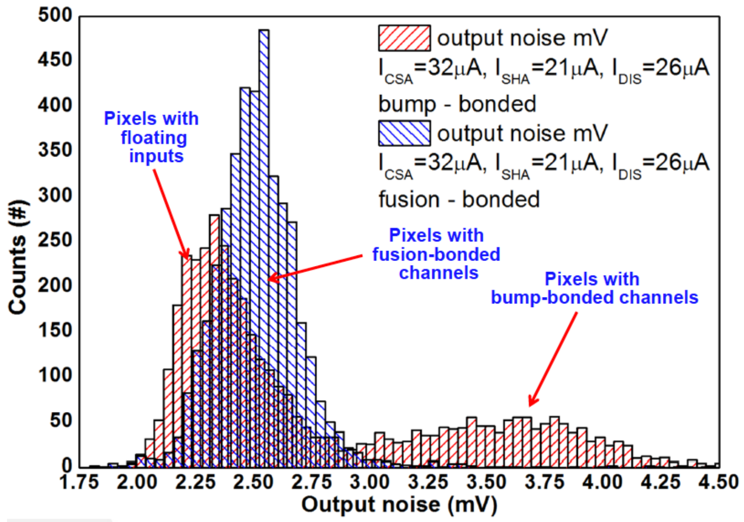
- a 500 µm thick silicon sensor
- a two-tier, 34 µm-thick integrated circuit
- a host printed circuit board

Different advanced interconnects technologies:

- The 80 µm-pixel-pitch sensor was Ni-DBI® bonded to the integrated circuit
- The integrated circuit tiers were bonded using Cu-DBI® technology (1 µm diameter through silicon vias).
- The stack was mounted on the board using Sn-Pb balls placed on a 320 µm pitch

Entirely wire-bond-less structure

How technology impacts performance



- Low interconnect capacitance associated with oxide bond
- Lower capacitance is also reflected by larger gain

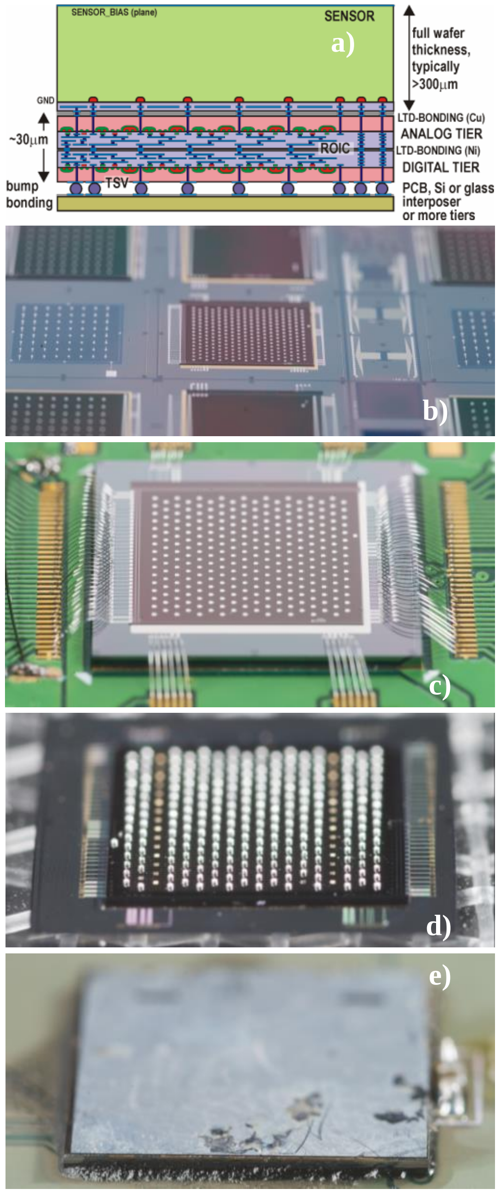


Fig. 1. a) Cartoon of a fully 3D-integrated pixel detector, b) VIPIC1 LTD-bonded on the sensor wafer with back-side bump-bonding pads exposed before wafer dicing, c) VIPIC1 LTD-bonded on the sensor with wire-bonding connections to PCB using traces on the sensor, d) VIPIC1 LTD-bonded to the sensor with bump-bonding Sn-Pb balls deposited on the back, e) VIPIC1 LTD-bonded on the sensor bump-bonded upside down on the precision PCB.

Brookhaven National Laboratory   Fermilab   AGH

G. Deptuch et al IEEE Transactions on Electron, 63 (1), 2016

Detectors development: from MPCCD to CITIUS

Silicon Integrating-pixel detectors

[Hatsui IFDEPS2021]

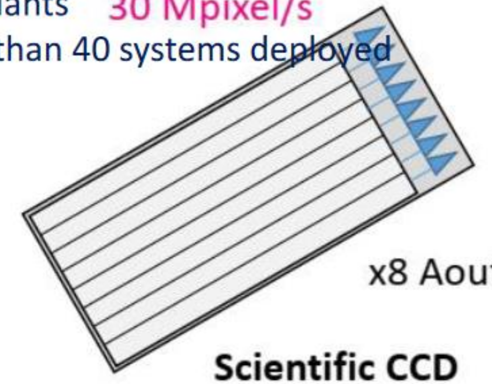
X-ray imager for SACLA

2009-2011

0.5 Mpixel 60 Hz

14 variants 30 Mpixel/s

More than 40 systems deployed



Scientific CCD with Teledyne e2v

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

Wide dynamic range imager

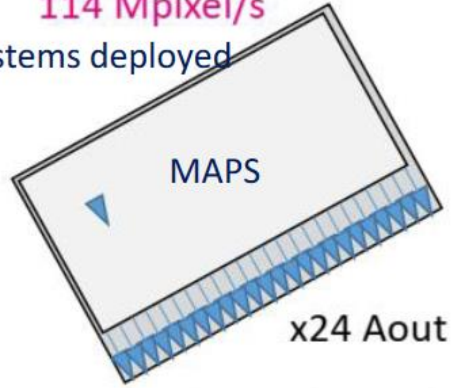
2009-2014

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

2013-

XFEL variant

0.28 Mpixel 5,000 Hz

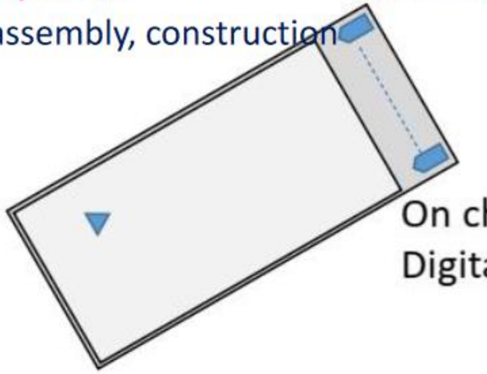
1400 Mpixel/s

SR variant

0.28 Mpixel 17,400 Hz

4872 Mpixel/s

Under assembly, construction



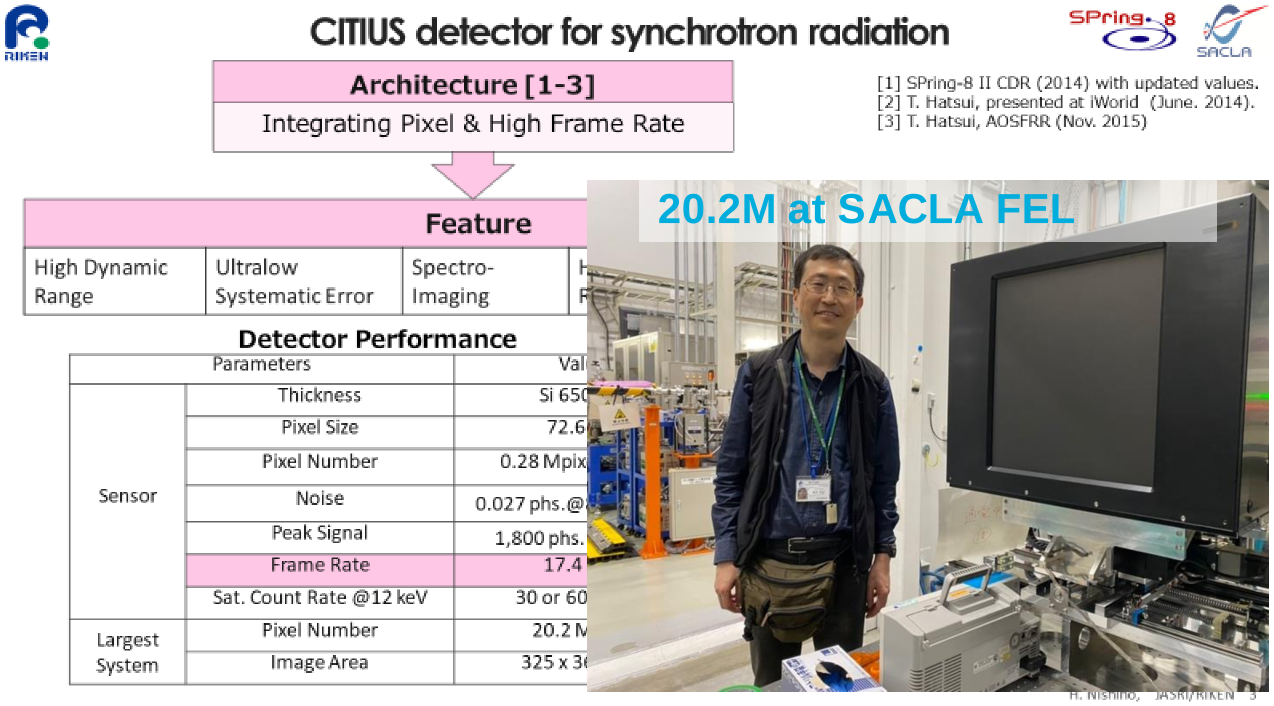
Dedicated CMOS Image Sensor with Sony

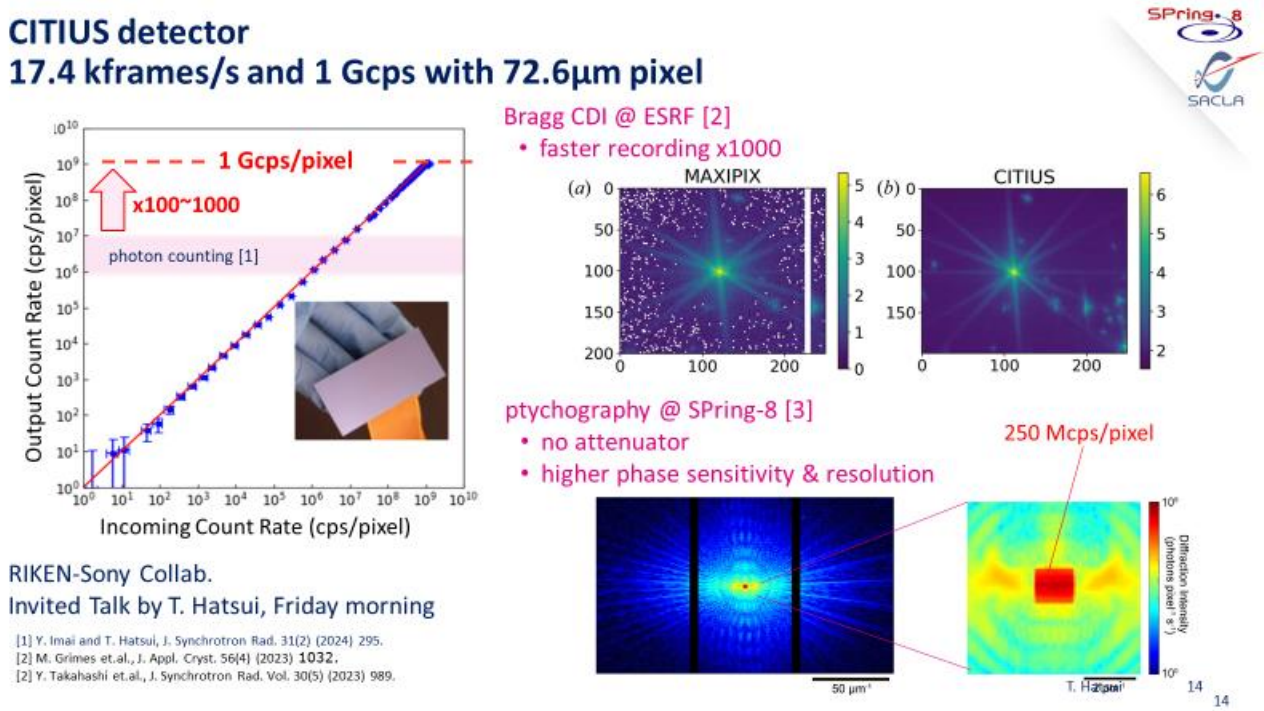
T. Hatsui, et.al., in preparation

From Fabienne Orsini's presentation

CITIUS detector
17.4 kframes/s and 1 Gcps with 72.6µm pixel

Courtesy of T. Hatsui's



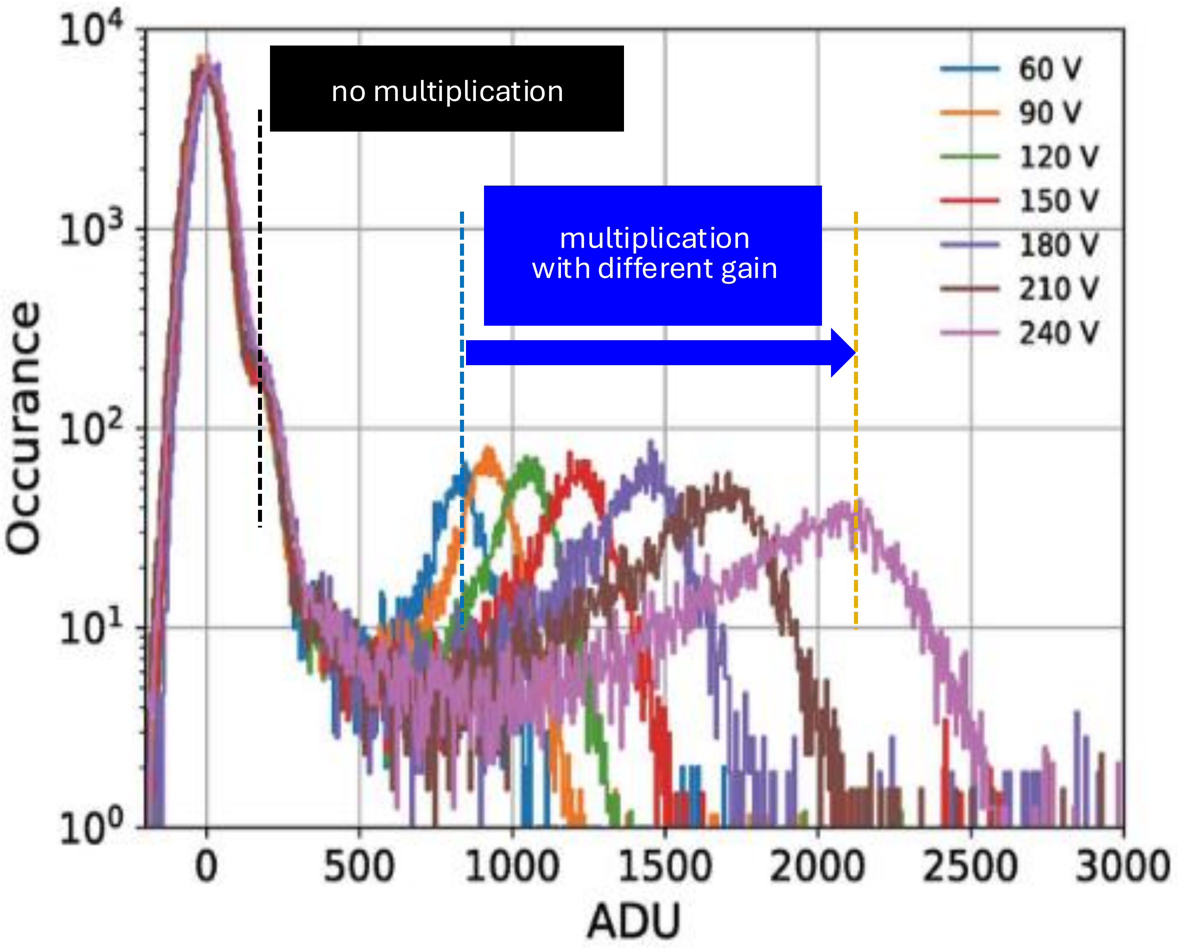


Technology has been partly transferred to kai scientific

Soft x-rays: boosting the signal

Sensors with moderate gain + ‘standard’ readouts

SNR improvements with LGAD sensor (G-1.7, 8 keV)



M. Andrae et al., *J. Synchrotron Rad.* ***26*(4)**, 1226-1237 (2019)

→ Single photon counting and charge integrating detectors down to low energies

Low Gain Avalanche Diodes (LGADs)

Producers

HAMAMATSU

FONDAZIONE BRUNO KESSLER

Centre Nacional de Microelectrònica IMB

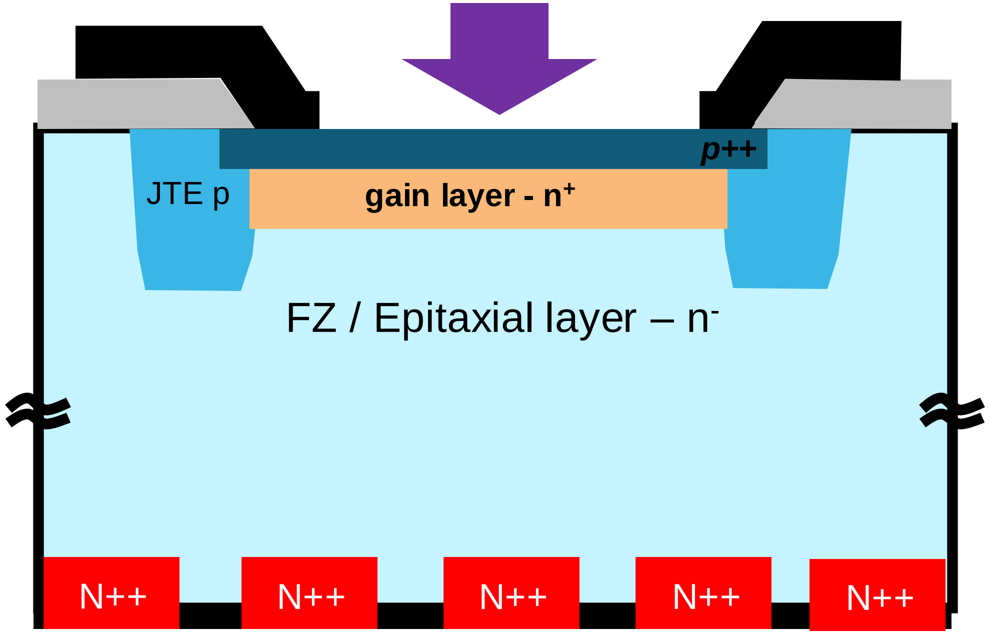
Brookhaven National Laboratory

SINTEF

MICRON SEMICONDUCTOR LIMITED

NDL High Energy Physics (IHEP) Chinese Academic Science

BNL nLGAD

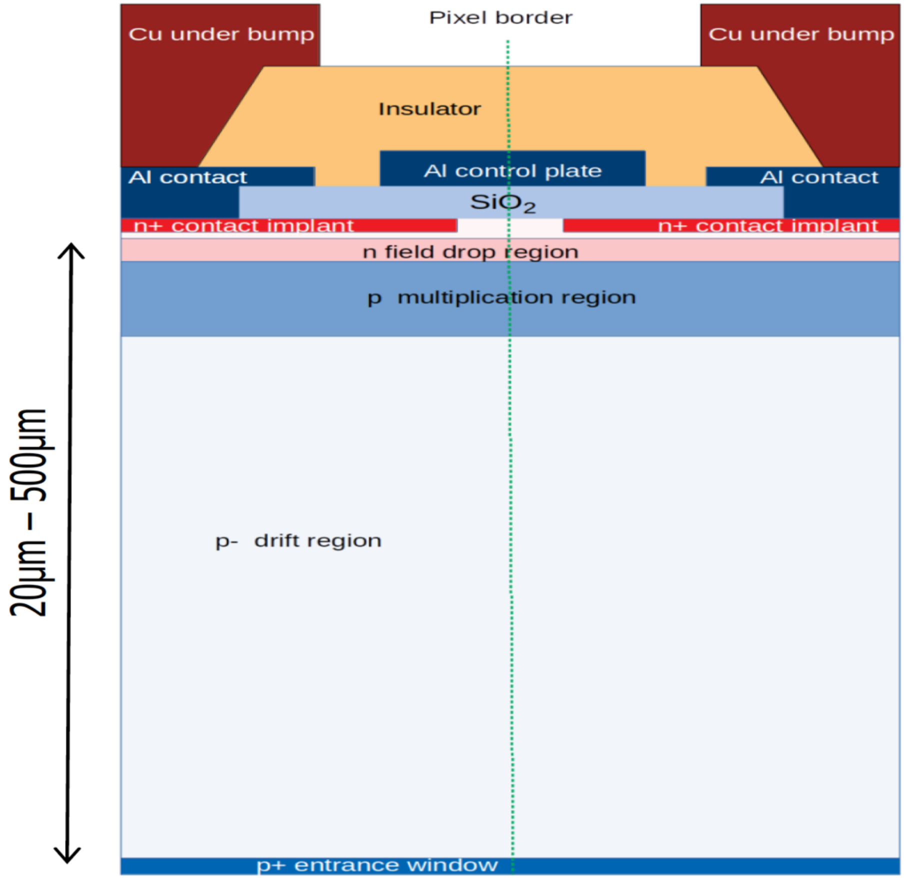


- Pioneered by CNM (Barcelona, Spain), funded by RD50 collaboration in 2021 (CERN R&D for Radiation hard semiconductor devices for very high luminosity colliders)
  - Tailored for the detection of mips in HEP

- UV, low-energy electrons, soft X-rays have small penetration depth in silicon:
  - signal electrons cross the high field to be collected by the n+ on the back
  - requires thin entrance window

MARTHA - **M**onolytic **A**rray of **R**each **T**hrough **A**PDs

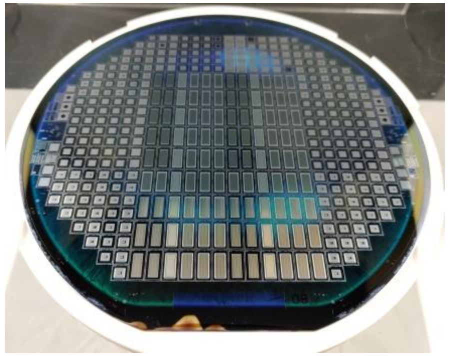
Initial motivation – develop low gain avalanche device with high fill factor for photon science applications



Expected features:
Gain up to 20
Collection efficiencies: **> 99%**
Pixel pitch: given by bump bond technology
and read out electronics space consumption (ATLAS 50µm)
Position resolution: $<< \frac{pitch}{\sqrt{12}}$ ($<< 10\mu m$)
Time resolution:
Application dependent
Leading edge trigger: <50ps
Full signal formation 50ns (for thickness 500µm)

Proof of principle production on standard thick material finalized Oct 2023

Designed structures:
- Pixel arrays
- Strip sensors
- Diodes
- Multi Guard Ring Test diodes



Data, data, data…

Data reduction: an end-to-end collaboration

***The perfect storm*:**

- increases in detector speed, frame rates, and pixel number
- evolution of multimodal and concurrent techniques

Detectors and data reduction methods are not tightly integrated:

- flood of data also limits the ability to extract actionable insights to steer experiments

*U.S. light sources will generate exabytes (EB) of data over the next decade, requiring tens to 1,000 PFLOPS of peak on-demand computing resources, and utilization of billions of core hours per year**

Data reduction is a must:

- several tradeoffs should be considered when choosing how early data reduction can be implemented effectively
- do not loose important information!
- lossy compression is very much experiment-specific >> requires user involvement to evaluate quality and value of the different implementations.

*N. Schwarz *et al.* doi.org/10.1007/978-3-030-63393-6_10

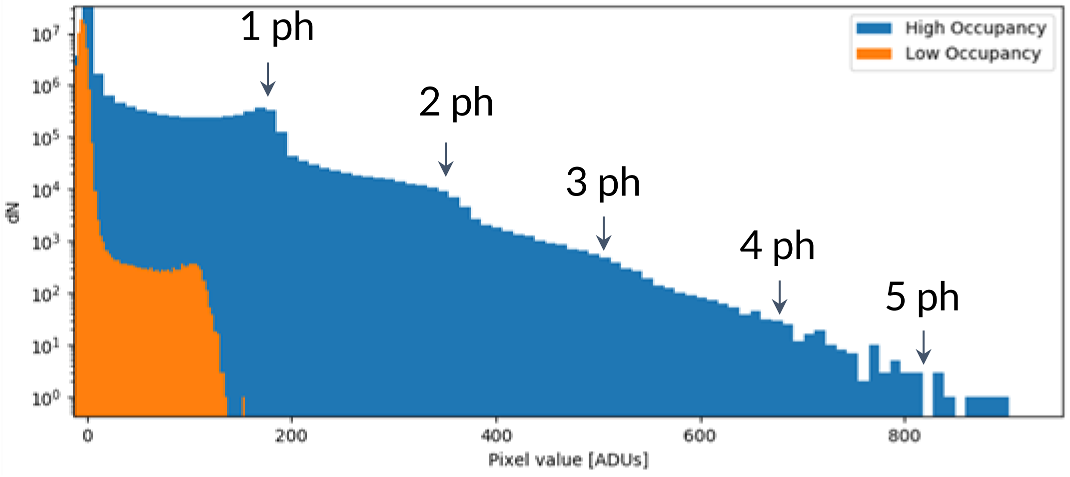
Smart Sensors: SparkPix-S and SparkPix-RT

A. Dragone (SLAC)

Detectors with sparsified readout at ASIC enable leap from 100 kHz detector rates to 1 MHz

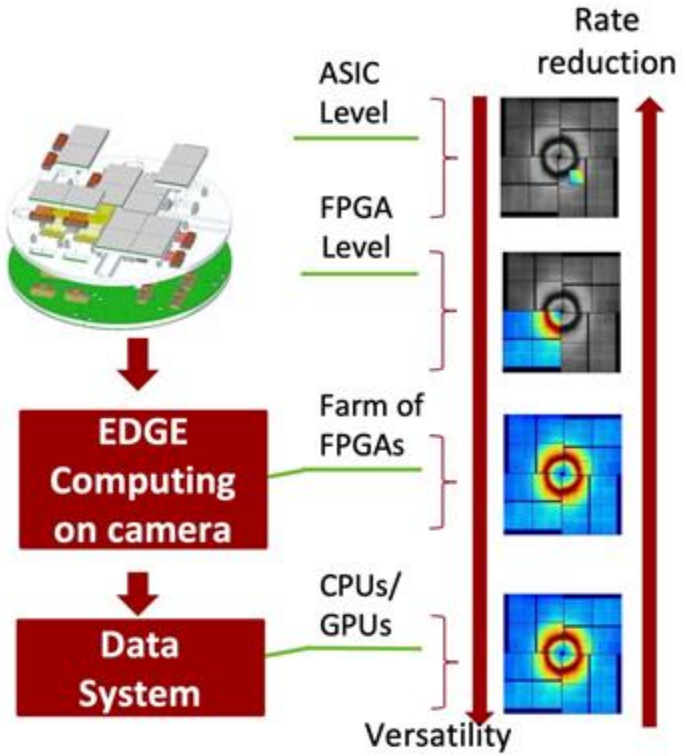
SparkPix-S: Pixel-threshold

- Information in both XPCS and XSVS experiments is “**sparse**” and confined in a limited # of pixels/frame, each pixel containing a limited # of photons
- 2D detector with fine spatial resolution, operating at the full rate of the machine, and discriminating between 0, 1, 2, 3.... photons/pixel/frame with high QE



SparkPix-RT (SLAC/ANL)

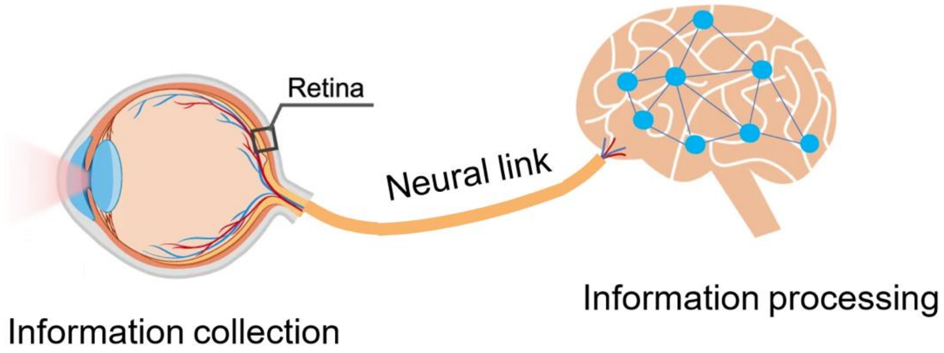
- Solve data transmission bottleneck by implementing compression algorithm solutions in ASIC
  - bit-level compression
  - auto-correction techniques (pedestal)
- R&D needed to deal with calibration and segmentation

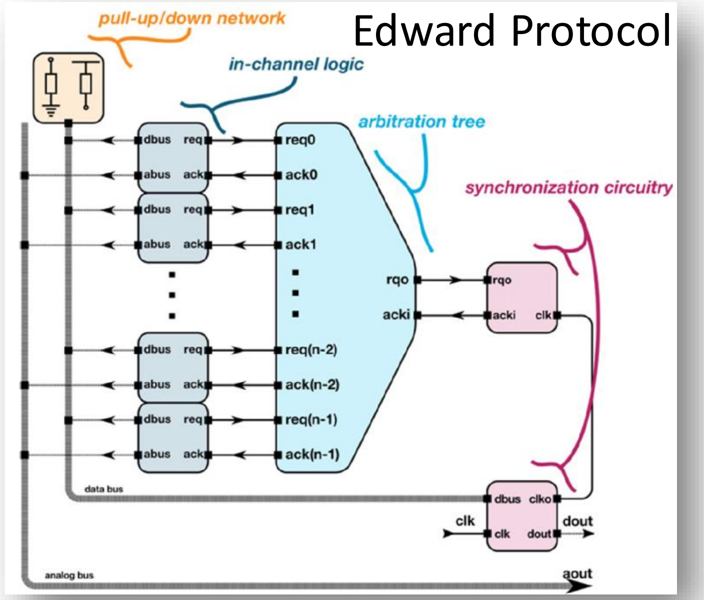


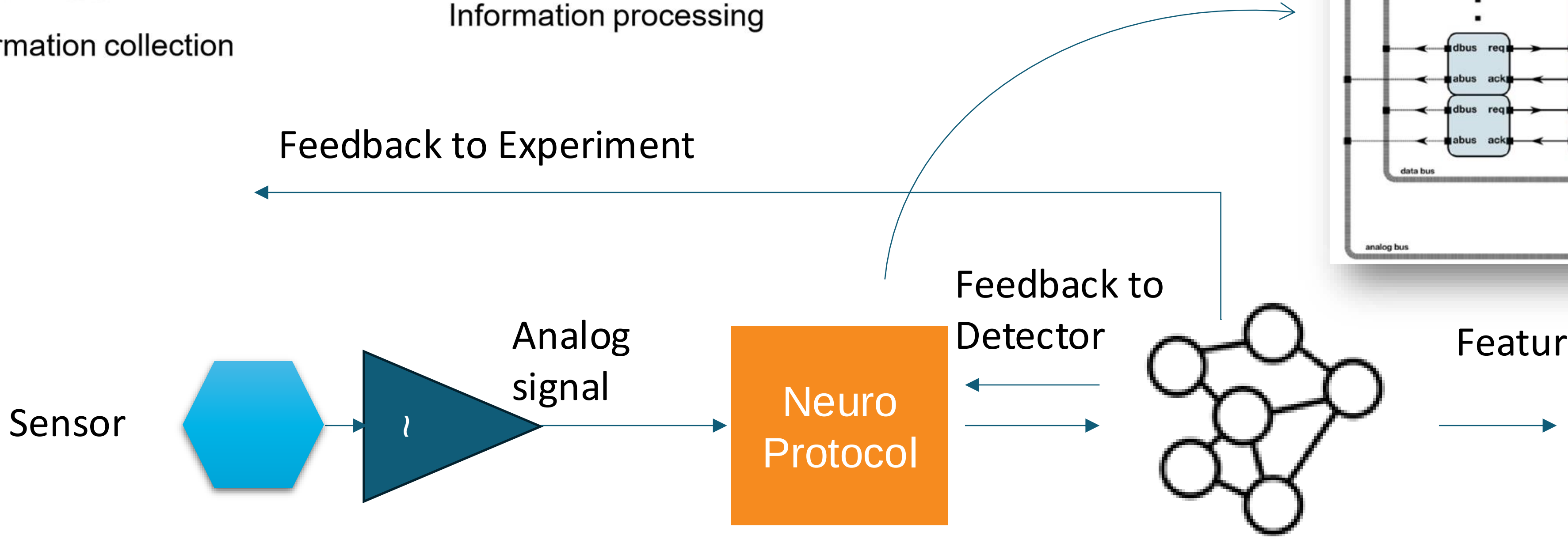
New Concept of a Smart Detector

P. Maj (BNL)

Mimicking biology system by placing the neuromorphic computing (brain) outside the focal plane improves single pixel size, energy consumption and crosstalk and thermal noise.







Binary Readout
High occupancy (10 Mcps)
Low noise (10 el.)
Low Power (100nW)
Small Area (20um)

Biologically inspired
Event based
Frameless
Low Latency
Single Pixel access

Neuromorphic Processor - “brain” of the detector
Event / Address protocol (supported by SNN)
Real-time features extraction

Community building: international forum

IFDEPS

International Forum on Detectors for Photon Science

- IFDEPS 2016 – Lake Kawaguchi, Japan – March 28-April 1
  - Highlight topic: CMOS image sensor technology for X-ray detection

- IFDEPS 2018 – Annecy, France – March 11-14
  - Highlight topic: Energy dispersive X-ray detector systems

- IFDEPS 2020 – CANCELLED due to Covid-19

- IFDEPS 2024 – Port Jefferson, NY USA – March 17-20
  - Highlight topic: Single-photon sensitive charge integrating detectors for storage rings and XFELs

- The IFDEPS Virtual Thursdays March-April 2021

Final thoughts

- Semiconductor detectors have evolved and enabled significant advances in Photon Science
- When developing new detectors we always have to keep in mind: energy efficiency, integration, and calibration

The best detector is the one **easy to** use!

Brookhaven National Laboratory

Thank you!