# Detector report

**Working group**

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN SCIENCE ASSOCIATES

# Motivation

- ***The 5-way Light Sources Detector Working Group*** was chartered by the Directors at the April 2018 5-way meeting.

- The ***charge*** to the Working Group was to ***survey the detector needs*** of the Light Sources complex over the next 5 - 10 years, ***broken down according to X-ray energy range and scientific technique***.

- High-level detector ***requirements*** to meet the identified needs were to be estimated, and potential detector ***technologies*** to meet those requirements identified.

# **Tender/hard x-rays** (2-20 keV) - APS/NSLS-II

| Storage rings | Pulsed sources | Technique | Requirements | Existing technologies | Ongoing R&D | Gaps | Comments |
|---|---|---|---|---|---|---|---|
| | | CDI (Ptychography, Bragg/Surface) | Bragg: 50-100 kHz, > 10^6 ph/px/s (20-bits); Ptychography: 1 MHz; moderated dynamic range (12-bits) | Eiger; Jungfrau, Medipix | MM-PAD, ePix, hybrid CMOS, DESY 100 kHz concept, | Rate, dynamic range | Pixel size ~ 50 µm Single photon sensitivity, small dead area, short dead time |
| | | XPCS | 100 ns resolution, few photons per frame (≤ 2-bits) | Eiger, Medipix:, Timepix, UFXC32k | VIPIC | Rate, noise | Pixel size ~ 50 µm Single photon sensitivity, small dead area |
| | | Scattering & Diffraction | 50-100 kHz, > 10^4 ph/px/s (14-bits) | Eiger; Jungfrau, Medipix | MM-PAD, ePix, hybrid CMOS, DESY 100 kHz concept | Rate, dynamic range | Pixel size ~ 50 µm Single photon sensitivity |
| | | Scattering & Diffraction (Pump-probe) | 11 or 75 ns (gateable); on-chip accumulation of “laser-on/laser-off” | Pilatus | sCMOS, Eiger2, Cpix | Fast gate | Pixel size ~ 50 µm Single photon sensitivity |
| | | Full-field Imaging | 50 kHz at 12-bits | Scintillator-based systems | MÖNCH | | Pixel size ~ 1 µm |

# (DL)SR and XFELs

We would also like to comment on one of the main differences between (DL)SRs and XFELs.

- The quasi-continuous nature of (DL)SRs requires the detector deadtime to be as short as possible.
- While the pulsed natured of XFELs allows for detectors with low duty cycles since the integration time can be short and a long time is available for signal progressing and readout.

# Appendix B

This appendix summarizes the existing detectors used at the facilities.

## Tender/hard x-rays (2-20 keV)

| Detector type | NSLS-II | ALS | APS | LCLS |
|---|---|---|---|---|
| Photodiodes (thin window or bias front grid) | X | X | | |
| Strip detectors (1-D)<br>• BNL strip detector (commercially available, Sydor)<br>• Mythen | X | | X | |
| Silicon Drift Detectors (single and multiple channels) + Xspress3/FalconX | X | | X | |
| Maia | X | | | |
| Pilatus | X | X | X | |
| Eiger | X | | X | |
| Timepix | X | | X | |
| Medipix (Lambda, Merlin, etc) | X | | X | |
| fCCD | | | X | |
| pnCCD | | | | X |
| UFXC32k | | | X | |
| ePix100 | | | | X |
| Crystal analyzer | | | X | |
| Flat panel amorphous silicon detector | X | X | X | |
| Transition edge sensor (TES) | | | X | |
| Scientific CCD (Andor) | X | | X | |
| Tagma (pseudo 2D strip detector) | X | | | |
| Scientific CMOS (Bruker) | | X | | |
| Vortex XRF | | X | X | |
| Fast SDD (Amptek) | | X | X | |
| Mar 345 image plate detector | | X | X | |
| CSPAD | | | | X |
| ePix10k | | | | X |
| Rayonix MX340 | | | | X |

# **Soft x-rays** (<2 keV)

| SRs/DLSRs | |
|---|---|
| **Technique** | Detector Needs |
| **Photoelectron Spectroscopy (PES)** | • Direct electron detection<br>• Biased to 1 kV relative to ground<br>• UHV compatible, bakeable up to 120 $^{o}$C<br>• 2k x 2k pixel array with < 40 um pixels<br>• Time resolution < 1 ns (~ 60 ps to match the ALS time structure) |
| **Photoelectron Microscopy (PEEM)** | • Direct electron detection<br>• Biased at very high voltage relative to ground<br>• UHV compatible, bakeable up to 120 $^{o}$C<br>• 8k X 8k pixel array with < 20 um pixels (prefer 10 um)<br>• High count rate, $10^{10}$ electrons/second/frame<br>• Time resolution < 1 ns (~ 60 ps to match the ALS time structure) |
| **Ptychography / Coherent Diffraction Imaging (CDI)** | • Frame rate ideally 100 kHz.<br>• 1k x 1k pixel (or 2k x 2k) array with ~ 30 um pixels<br>• High count rate, $10^{5}$ photons/second/pixel at 1 keV.<br>• Single photon sensitivity<br>• Synchronization<br>• Hardware data pre-process such as filtering, noise reduction, binning, averaging. |
| **X-ray Photon Correlation Spectroscopy (XPCS)** | • Sparsified data train like (x, y, t)<br>• 2k x 2k pixel array with ~ 30 um pixels<br>• Single photon sensitivity<br>• High time resolution <10 ns (ideally 2 ns).<br>• Hardware data pre-processing capability (algorithm TBD). |
| **Spectromicroscopy (STXM)** | • Large dynamic range $10^{6}$ photons/pixel @ 1 keV<br>• Fast readout > 1 kHz<br>• Detector capable to work under magnetic field |
| **Resonant Inelastic X-ray Scattering (RIXS)** | • High spatial resolution <5 um (ideally 2 um)<br>• Single photon sensitivity<br>• 5k x 5k pixel array<br>• Large dynamic range (linear) $10^{4}$ photons/pixel @ 1 keV |
| **Resonant Elastic X-Ray Scattering (REXS)** | • High count rate $10^{5}$ photons/second/pixel @ 1 keV<br>• High frame rate (several MHz) |

# Preliminary findings

- When we started this work, our goal was to define two areas: common needs and key developments with high scientific impact.
- Mapping the various experimental techniques available and being developed at the five light sources, we found a number of distinct needs.
- Detector requirements are very specific, derived hence closely coupled to a class of experiments. Nevertheless, some clear unmet needs could be identified and are summarized, at a very high level, as follows:
  - Sensors with high quantum efficiency for very hard X-rays for APS, NSLS-II, LCLS-II/HE
  - Area detectors with (All)
    - high dynamic range
    - high frame rate readouts
    - high spatial resolution
  - Some area detectors would benefit from sparsified readouts
  - Energy-resolving detectors with (All)
    - high speed
    - very high energy resolution

# Preliminary findings

- Unmet needs have vastly **different technological solutions for soft and hard X-ray energies**.
- The **pulsed nature of the LCLS** also requires certain **distinct technological solutions** from the **storage ring light sources**.
- **Common need** for **high frame rate area detectors** is potential area for standardization and **co-development**.
  - *high-speed data transmission off the detector ASIC is common needs across all the light sources*.

- Integration, beyond the mechanical interface, in the experimental environment.
- The increasing complexity of experiments, often demanding the use of concurrent techniques with multiple stimuli and probes, can only be managed by suitable **data collection strategies**.
- **Synchronization and event time information** (timestamp) together with good **diagnostics** (e.g. beam monitors) are therefore other important components of the detection system.

# Preliminary findings

- **Data management and analytics are becoming integral part of detector development**.
- Current detectors have already outran the ability of common data storage systems to handle the data rate.
- In the future we will need to find ways of **analyzing**, at least partially the data in real-time, and **reduce data on-detector**.

**Next steps**

- Continue working group effort
- Add international landscape
- Work on priorities with the facilities
- Identify/develop focused collaborations

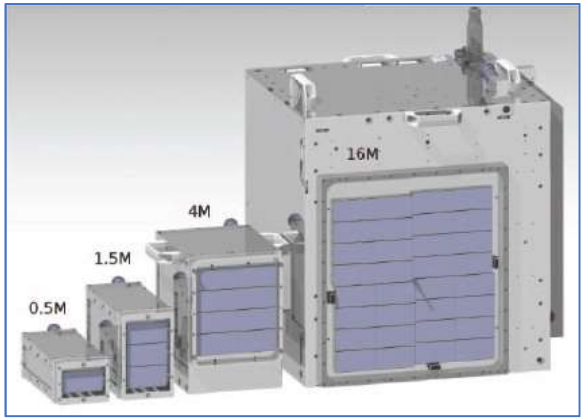
# Landscape - Europe

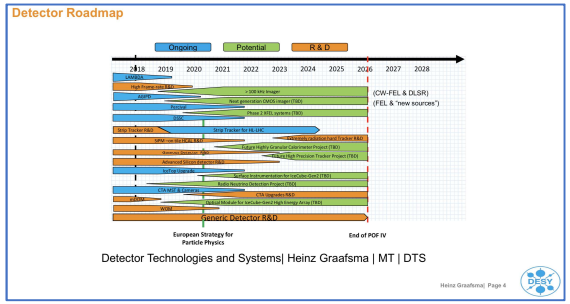
- Several strong developments
- Two main models:
  - Facility-focused development with uninterrupted funding
  - Large collaborations (consortia) for specific projects
- Several commercialization models
  - Successful and effective

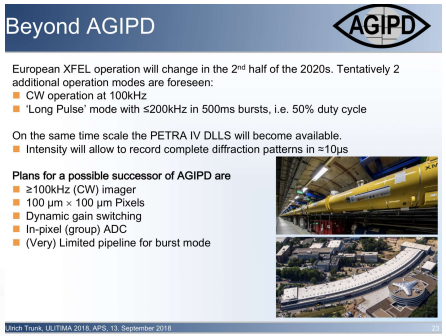
# Landscape - Europe

## PSI

- Eiger3 49M -- Single photon counting detector for high count rates – SLSII 2023
  - So large that there's no need to move the detector to cover Q range (e.g., no big SAXS flight tubes)
- Jungfrau
  - Several many Mpixels (up to 16M) SwissFEL and SLS (PX), LCLS, and Eu-XFEL
  - 75 um, large dynamic range, up to 2 kHz
- Mönch
  - 25-mm pixels, 30 e- noise,  hybrid pixel detector, up to 6 kHz
- Investigating LGAD sensors for soft x-rays
- Reference: [http://www.esrf.eu/files/live/sites/www/files/events/conferences/2018/IFDEPS/S2.13.PSI.Schmitt.pdf](http://www.esrf.eu/files/live/sites/www/files/events/conferences/2018/IFDEPS/S2.13.PSI.Schmitt.pdf)



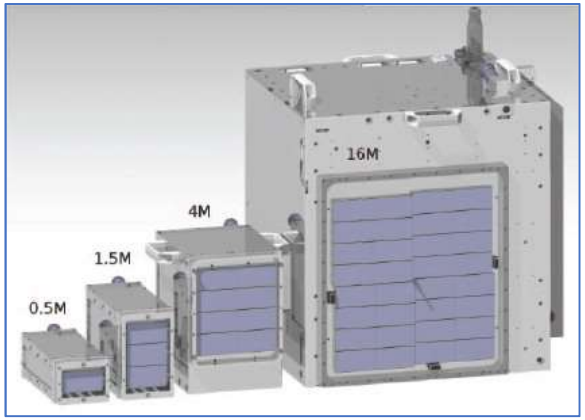



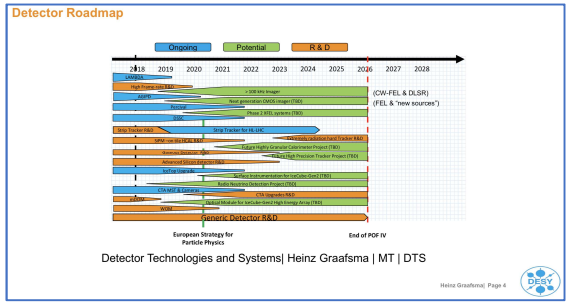



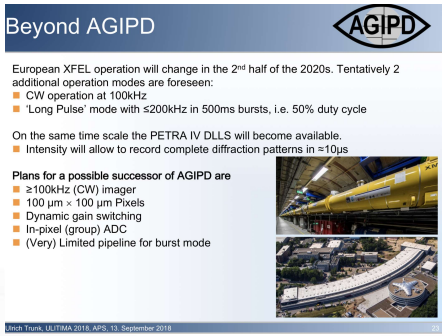
# Landscape - Europe

## DESY (collaborations led by)

- AGIPD for EU-XFEL
  - 4M AGIPD for SFX & (GaAs/CdTe) 1M for HiBEF
- >100 kHz imager conceptual studies
- Percival 2M pixel monolithic CMOS
  - 27-um pixels, 300 Hz, 250 eV - 1 keV, 15 e- noise, > $5\times10^4$ photons @ 250 eV)
- References:
- https://aip.scitation.org/doi/pdf/10.1063/1.5084702?class=pdf
- http://www.esrf.eu/files/live/sites/www/files/events/conferences/2018/IFDEPS/S2.05.DESY.Graafsma.pdf
- https://indico.fnal.gov/event/ANLHEP1390/session/9/contribution/70/material/slides/0.pptx



# Landscape - Europe

## ESRF

- Conceptual studies of a new high-dynamic range detector XIDER detector ([https://doi.org/10.1088/1748-0221/15/01/C01040](https://doi.org/10.1088/1748-0221/15/01/C01040))
  - Potential competition for MM-PAD

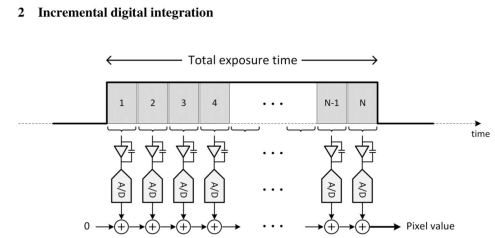



**Figure 1.** Basic principle of the incremental digital integration scheme: the input signal is integrated in N subsequent intervals (subframes), the result of each subframe integration is digitized and the digital values are summed sequentially to produce the final pixel value.

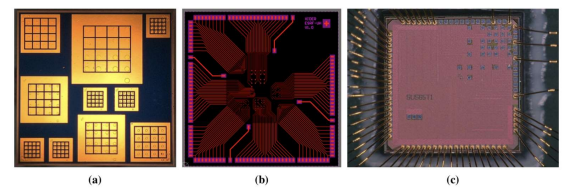


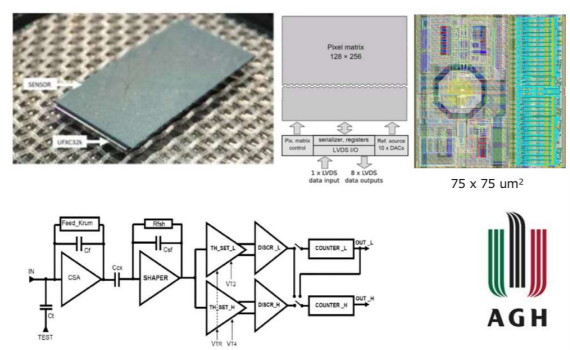

**Figure 4.** Components of the first XIDER test prototypes. The CdTe sensors (a) include several 4 × 4 pixel matrices with three different pixel pitches (100, 200 and 300 µm) that can be connected either via a silicon interposer (b) or by direct bump bonding onto the test readout ASIC (c).

## Other EU-XFEL consortia

- STFC-RAL (LPD detector), EU-XFEL (DSSC)

## AGH University of Science and Technology (Poland)

- Photon counting UFXC → Rigaku UHSS commercialization
- Eiger/Lambda competition




UFXC 32k Chip used in UHSS-500k detector

Rigaku

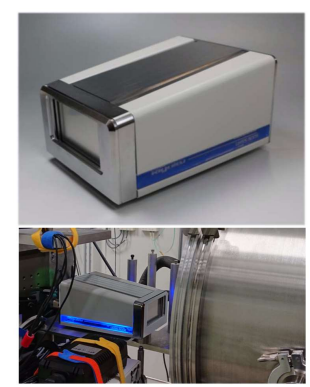


Photo of the UHSS-500k detector (pre-production model.) Now under final test before launch at Argonne National Laboratory (APS 8 ID-I.)

Argonne

# Landscape - Asia

Mainly Japan

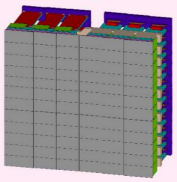
- Strong partnership with industry
  - Stable uninterrupted funding
- Two main models
  - Facility focused
  - Technology oriented

# Landscape - Asia

- SACLA/Spring-8:
- MPCCD and Sophias
- Now **CITIUS detector**
  - 17 kfps

## Data Rate Estimation

**Citius 20 Mpixels@17.4 kfps**



**Calibrated data stream**
32 bits/pixel, 20 Mpixels, 17,400 frames/s

→ 0.348 Tpixels/s, 11.1 Tbps, **1.4 TB/s**

**SPring-8 Operation senario**
4000 hours/year
30 % data acquisition duty ratio

→ **6.0 EB/year**

**SACLA Computer room**

**"Raw Data" Storage**

↓

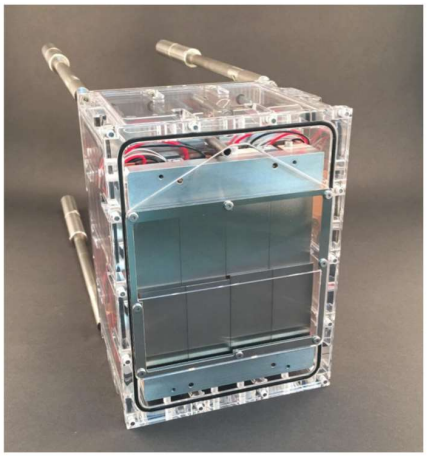
**Store Processed Data (eg.) "Accumulated" data**

Three-way meeting Feb. 10th, 2020 11

2.28 Mpixel Camera Head (Mock-up)

| | | |
|---|---|---|
| Sensor Module | Pixel Size | 72.6 μm |
| | Pixel number | 0.28 Mpixel/sensor |
| | Peak Signal | 1800 phs.@12 keV |
| | Noise | 0.02 phs.@12 keV |
| | Frame Rate | 17.4 kHz |
| | Saturation Count rate | 30 (600) Mcps |

| | | |
|---|---|---|
| Detector System | Pixel Number | Max. 20 Mpixel |
| | Imagine area | Max. 32 x 32 cm$^2$ |



Three-way meeting Feb. 10th, 2020 T. Hatsui, RIKEN 4

## Dedicated Data-Processing FPGA board

**Custom FPGA board**
**Arria 10 FPGA: 3 pcs**

In 146 Gbps : 17.4 kfps equivalent
Out 96 Gbps : 6 kfps equivalent

Final Verification of the

Three-way meeting Feb. 10th, 2020 1

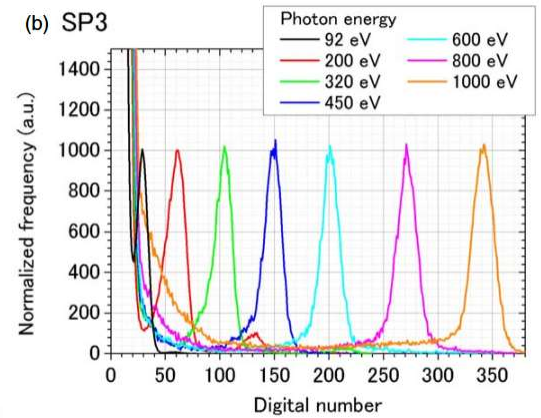
# Landscape - Asia

*High-exposure-durability, high-quantum-efficiency (>90%) backside-illuminated soft-X-ray CMOS sensor*

Tetsuo Harada, Nobukazu Teranishi, Takeo Watanabe, Quan Zhou, Jan Bogaerts, and Xinyang Wang

University of Hyogo, Shizuoka University, Hamamatsu, Gpixel Inc. (China)

- BSI CMOS detector for soft X-rays
  - Low noise, small pixel (11 um), 48 fps



# Needs: identified gaps per facility

# Needs: identified gaps per facility - ALS

- Detector with small pixels at grazing incidence ( < 5 degrees & < 2.5 um square pixels)
  - e.g. CMOS development
- Faster time-resolved x-ray detector
  - E.g. Timepix 4; specs the same as Timepix 3 but with 200 ps temporal resolution; event trigger sparsified readout in-parallel with centroiding capability.
- Electron detectors
  - e.g. electron detection with Timepix 3, biased above 2.5 kV for phase 1 (ARPES, APXPS); biased up to higher voltage for PEEM app.

# Needs: identified gaps per facility - APS

## Pixel Detectors

- **1-10 kHz Ultra-wide dynamic range,** ≥2 Megapixel (i.e., large), Si and CdTe/Ge/etc
  - Ultra-wide dynamic range ≈ $10^8$ photons/pixel/frame (MM-PAD-like)
  - Coherent Surface Scattering Imaging (CSSI < 25 keV) & High-Energy X-ray Microscopy (HEXM > 50 keV) Others: Bragg-Diffuse scattering, beamstop-free SAXS
  - Alternatives: Dectris Eiger2 16M (Si and CdTe) with compromise on dynamic range?
- ≥ **0.1 MHz CW detector**, ≥ 0.5 Megapixels (i.e., medium) , Si and CdTe/Ge/etc
  - High dynamic range ≈ $10^5$ photons/pixel/frame
  - PtychoProbe, In Situ Probe, ATOMIC/Bragg CDI, CNM 4D Nanoprobe, BioNanoprobe-2, XPCS
  - Alternatives: ??

## Spectroscopy Detectors

- **XAS** ($\Delta E \approx 30$ eV, <20 keV, 100 kcps, Peak-to-Background > $10^4$)
  - e.g., TESs
  - XAS beamlines
  - Alternatives: Crystal analyzers
- **XRF** ($\Delta E \approx 150$ eV, <20 keV, ≈ 1000 photons/1μs)
  - e.g., Maia v2
  - PtychoProbe, In Situ Probe, micro/nanoprobes XRF beamlines
  - Alternatives: commercial SDDs and digital pulse processors

# Needs: identified gaps per facility - NSLS-II

- **Soft x-rays**: detectors for REXS/XPCS and CDI/STXM (for RIXS commercial options could work).
  - Fast readout, low noise, small pixels, robust operation, vacuum integration.
  - Large dynamic range or high temporal resolution (XPCS).
  - Started discussions with ALS and the soft x-rays community.
- **Tender x-rays**: improve noise wrt deployed detectors (e.g. Eiger) for real photon-counting capability.
  - Perhaps new Rigaku detector.
- **Hard x-rays**:
  - pixel detectors with spatial (100 um and smaller) and energy resolution. Large area depending on application. Needed for a broad range of energies (4 -100 keV)
    - e.g. FFFI and Galahad
  - fast pixel detectors with high count rate (50 - 100 um) and large area (300 mm)
    - combined with techniques for data reduction: “on-the-fly” and lossy compression
  - high time resolution with small pixels ( ~ 50 um) and sparsified readout integrated in beamline instrumentation for efficient processing
    - e.g. VIPIC
  - Desire to replace flat panel detectors for very hard x-rays
  - Better scintillators for hard x-rays microscopy

# Needs: identified *gaps* per facility - LCLS (SXR)

| Technique | Detector requirements | Comment |
|---|---|---|
| Med-res RIXS (grating) | <20um pixel, 50mm 2d array, >200Hz frame rate, 5e noise | System efficiency limits science return. Signal can be integrated for a range of experiments. |
| Med-res RIXS (energy-resolving detector) | 0.5eV energy resolution, 10kHz frame rate, 1k pix | Eliminating grating increases efficiency. Fast detector allows wider range of shot-by-shot science. |
| XPCS | 2D, photon-counting,2d array, 50umpitch, >5 kHz frame rate | Very challenging with present detectors. |
| Hi res RIXS | <10um spatial resolution, photon coun ting @250eV | System efficiency limits science return. Signal can be integrated for a range of experiments. Higher rate enables wider range of shot-by-shot science. |
| REXS | <50 um spatial resolution, high rate | Readout rate faster than timing drifts, can integrate signal if jitter is small. |
| 2P X-ray Speckle Visibility Spectroscopy | High rate, single-photon sensitivity @250eV | Need to distinguish 1, 2, and 3-photon events. |
| Particle detection (Auger, streak cameras for atto-sec) | ToF detectors | Pixellated momentum-resolving detectors allow study of more complex systems. |

# Needs: identified *gaps* per facility - LCLS (TXR/HXR)

| Technique | Detector requirements |
|---|---|
| XPP Coincidence Catalysis | 0.5 Mp area array, >5 kHz frame rate, single-photon @2keV |
| Spectroscopy (photon in/photon out, TXR/HXR) | <150um pitch, >0.1Mp area array, single photon @2keV, >10kHz frame rate, 300 photon capacity/pulse |
| HXR Diffraction/ Crystallography | 2Mp area array, 100um pitch, 10k photon capacity, single-photon @6keV, NEE <500eV |
| HXR Inelastic Scattering | 25um pitch, 400x400 pixels 1k ph/pix-s rate, single photon @5keV, NEE <500eV |
| HXR XPCS | <50um pitch, 4Mp area array, 10kHz frame rate, single-photon @8keV, 100 ph/pix-pulse |
| HXR Liquid Scattering | 110um pitch, 2Mp area array, 10kHz frame rate, 10kph/pix-shot |
| HXR Diffraction | 100um spatial resolution, 2Mp area array, single photon @5keV, high QE @25keV |
| Liquid-Liquid transition Ejecta Studies | 100um spatial resolution, 2Mp area array, single photon @5keV, high QE @25keV |
| In situ decoupling of line-broadening effects | Ns-scale time resolution, gated/framing camera |

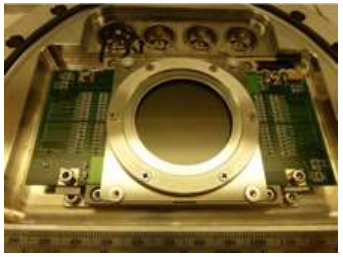
# Technology readiness

The following tables summarize technologies being considered or supported at the facilities and their assessed readiness

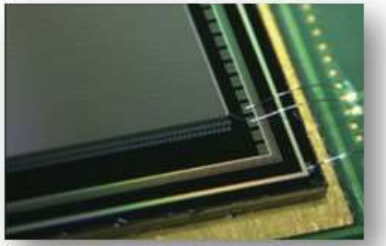
# Technology readiness - ALS

| platform | Characteristics | readiness |
|---|---|---|
| QERLIN CMOS | 5 um square, 2K*4K array, < 25 Hz, Normal incidence, full package | 2020 (packaging) |
| QERLIN CMOS | 5 um square, 2K*4K array, < 25 Hz, grazing incidence | ~ 2023 – 2025 (in development) |
| Small pixel CMOS | < 2.5 um | > 2025 (conceptual?) |
| SpectroCCD | 5 * 45 um, 6K * 1450, < 1 Hz, normal incidence | 2020 (delivered, testing) |
| VFCCD | 48um square, 0.25Mp area array, 5 KHz | 2020 (testing)? |
| Timepix 3 | 6 um MCP with 55 um CMOS, 256 * 256 array, 1 ns temporal resolution, one sensor | 2022 (in development) |
| Timepix 3 | 4 sensor with on-chip FPGA for data reduction | > 2022 (in development) |
| Timepix 4 | Similar specs with Timepix 3, 200 ps temporal resolution | > 2025 (sensor design) |
| Electron detector | Timepix 3 biased above 2.5 kV | > 2025 (R&D for insulation between MCP and CMOS) |
| | | |

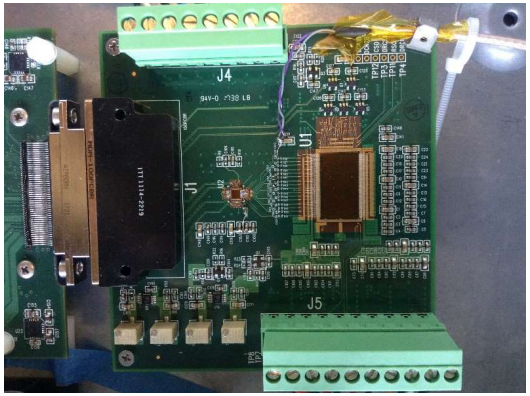
# Technology readiness - ALS



TimePix3-MCP



VFCCD



$(5\ \mu m)^2$, 8 Megapixel CMOS Sensor

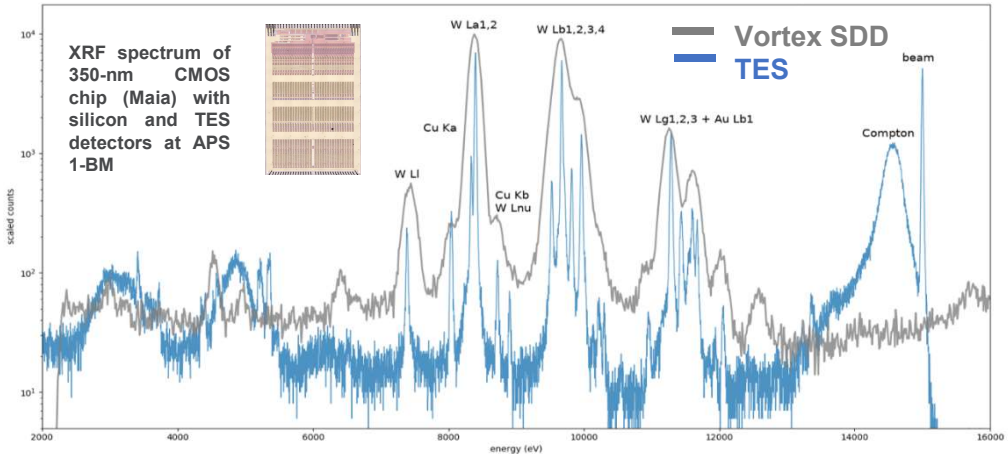
SpectroCCD

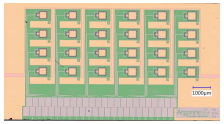
# Technology readiness - APS

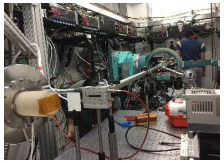
| Platform | Characteristics | Readiness |
|---|---|---|
| MM-PAD v1 (Cornell) | 150 μm, 384x256, 1 kHz (0.86 ms/frame, not double buffered) , CdTe | Done |
| MM-PAD v1 (Sydor) | 150 μm, 512x512, 1 kHz | ~2021 (Si) 2022 (CdTe) |
| MM-PAD v2.1 (CU/APS) | 150 μm, 384x256, Compatible with 10 kHz (double buffered), CdTe | 2020 |
| MM-PAD v2.2 (Sydor) | 150 μm, 2M, 10 kHz | ~ 2024 |
| ≥ 0.1 MHz CW detector v1 | 75-100 μm, 256x256=0.065M | ~2024 |
| ≥ 0.1 MHz CW detector v2 | 75-100 μm, 0.5M | ~2028 |
| TES XAS v1 | $\Delta E \approx 30$ eV, <20 keV, 1 kcps | 2020 |
| TES XAS v2 | $\Delta E \approx 30$ eV, <20 keV, 10 kcps | 2024 |
| TES XAS v3 | $\Delta E \approx 30$ eV, <20 keV, 100 kcps | 2028 |

# Technology readiness - APS

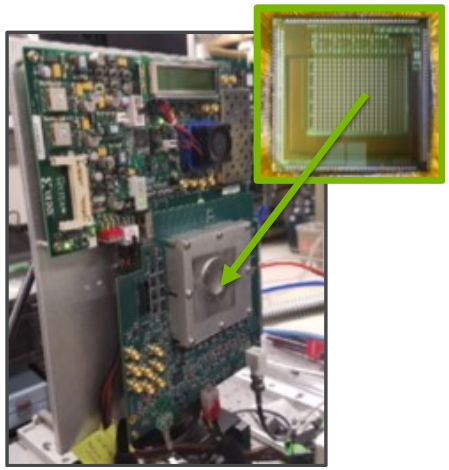
**First light for TES hard X-ray detector @ APS 1-BM-C, November, 2019**

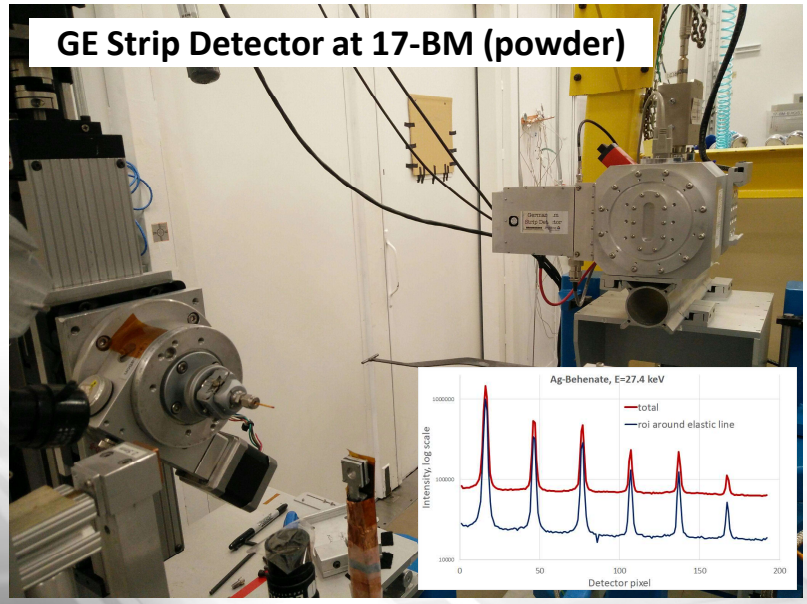




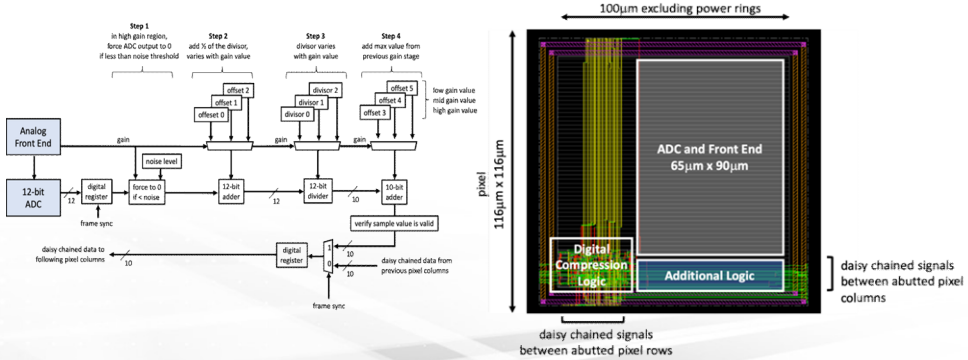


## MM-PAD v2.0





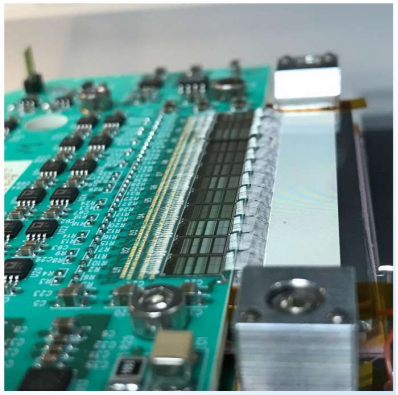

## On-chip data compression



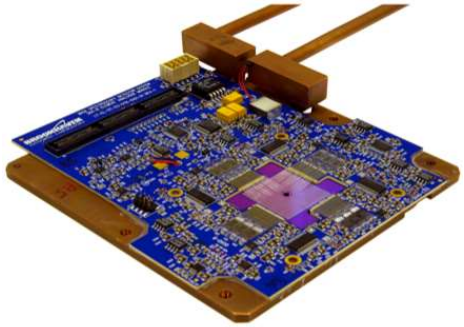
# Technology readiness – NSLS-II

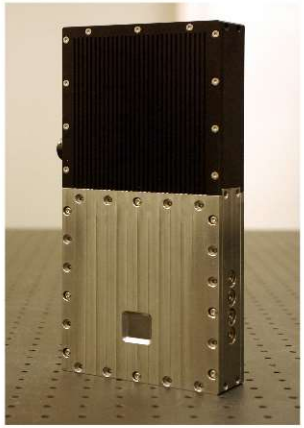
| Platform | Characteristics | Readiness |
|---|---|---|
| Silicon sensor foundry | Fabrication of custom sensors on up to 6” wafers. Pad, strip and SDD devices. LGADs | Now |
| Germanium sensor foundry | Fabrication of custom sensors on up to 4” wafers, custom thicknesses. Pad and Strip structures. Germanium drift detectors: 1cm diameter, 3mm thick | Now, drift detector in development (2021) |
| CZT/CZTS sensor | Crystal grow and fabrication of custom sensors, custom thickness. Pad and strip structures. | In development (2020) |
| Selenium | Amorphous selenium deposited directly on a CMOS ASIC. | Concept |
| Maia | 384 silicon pad detectors, each 1mm x 1mm. ~250eV energy resolution, >10M/s | Now |
| Tagma | Silicon 2 x 32 strip, 80um pitch x 3mm long, quasi-2D. | Now |
| Hera | 96 SDDs, (8 x 12 array) each 1mm x 1mm, ~175eV resolution | In development (2021) |
| 3FI | Photon-counting hybrid pixel detector with energy resolution of ~200eV. 100um hexagonal pixels. 3KeV – 14 keV. 200 x 200 pixels. | In development (2023) |
| GALAHAD | Photon-counting hybrid pixel detector with germanium sensor, with energy resolution ~500eV. 20keV – 200 keV. Operated at LN2 temperature. First device 200 x 200 pixels. | In development (2023) |
| VIPIC | Hybrid pixel detector with time-stamp capability (10 us), small pixel (65 um), and sparsified readout. 1 Mpixel. | In development (2021) |
| FLORA | Fast imaging detector with active sensor. 50 um pixel size, low noise, 40 kHz readout | Prototype testing |

# Technology readiness – NSLS-II

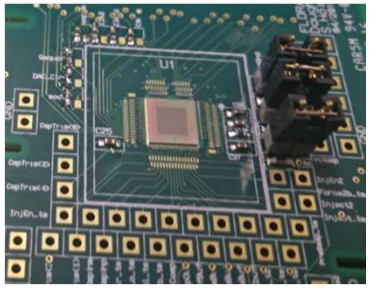


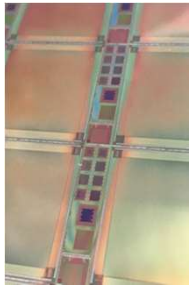
384-strip germanium detector wire-bonded to 12 MARS ASICs



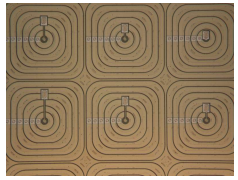


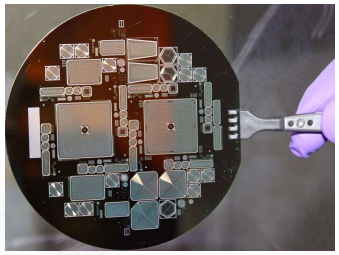
Maia





FLORA





SDD and pixel arrays

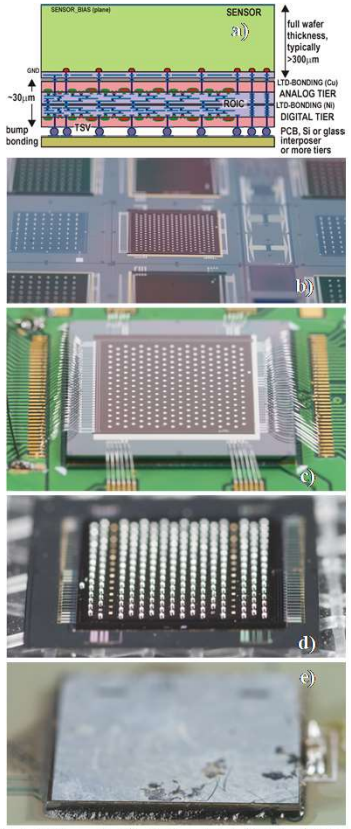



Fig. 1. a) Cartoon of a fully 3D-integrated pixel detector, b) VIPIC1 LTD-bonded on the sensor wafer with back-side bump-bonding pads exposed before wafer dicing, c) VIPIC1 LTD-bonded on the sensor with wire-bonding connections to PCB using traces on the sensor, d) VIPIC1 LTD-bonded to the sensor with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

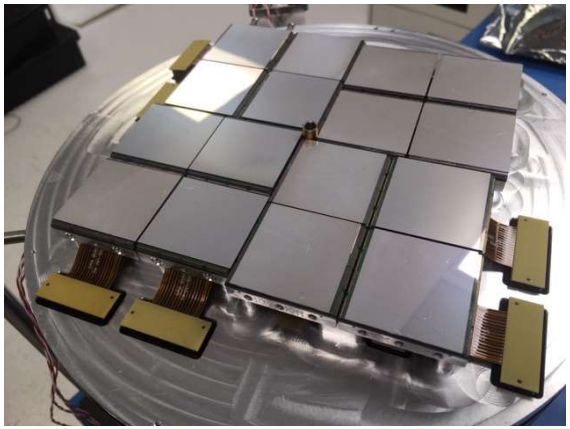
VIPIC

Developing a germanium and a silicon pixelated detector with very high photon energy and spatial resolutions

# Technology Readiness - LCLS

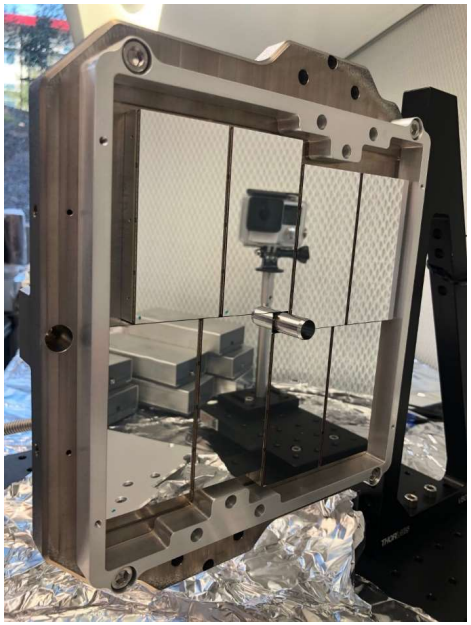
| Platform | Characteristics | |
|---|---|---|
| ePix 100 | 50um pitch, 0.5 Mp area array, 120 Hz frame rate, single-photon @2keV, 100 8leV photons | Deployed (HXR) |
| ePix10k | 100um pitch, 2Mp area array, single photon @2keV, >1kHz frame rate, 11k 8keV photons | Deployed (TXR-HXR) |
| ePix10kHR | 100um pitch, 0.14Mp area array, single photon @2keV, 5kHz frame rate, 11k 8keV photons | 2020 (prototype in test) |
| VFCCD | 48um pitch, 0.25Mp area array, single photon @250eV, 5kHz frame rate, 1k photons @500eV | 2021 (in development) |
| ePixM | 50um pitch, 0.25Mp area array, single photon @250eV, 5Hz frame rate, 1k photons @500eV | 2021 (in development) |
| Hi-Z | Materials development for high QE above 20keV | 2025 (collaboration) |
| ePixHR2.5d | 100um pitch, 2Mp area array, single photon @2keV, 25kHz frame rate, 11k 8keV photons | 2025 (in development) |
| TES | 200um pitch, 1kpix energy-resolving area array, R=2000 @1keV, 10kHz frame rate | ~2025 ( in development) |
| ePixUHR | 100um pitch, 2Mp area array, single photon @2keV, ~100kHz frame rate, 11k 8keV photons | ~2028 (concept) |
| UXI/Icarus | Fast-framing, ~ns time resolution, four stored frames, 25um pitch | NNSA development |

# Technology readiness - LCLS

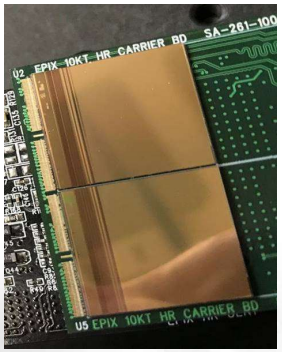


ePix10k
2M

RIXS
CCD

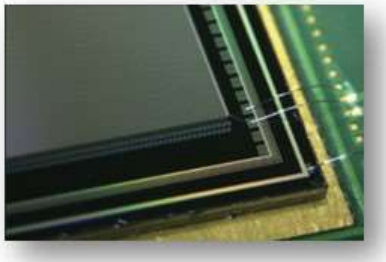


Jungfrau 4M




ePixHR

ePixM



VFCCD

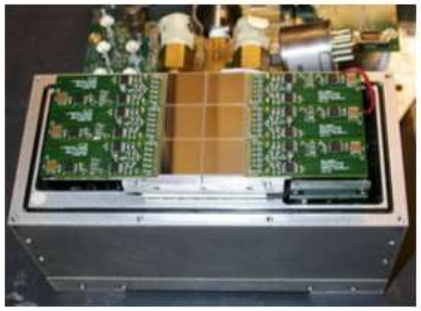
# Hurdles

- Funding
  - limited and not continuous
  - often focused on R&D only with not much support for large scale, beamline-ready systems
- Integration with the beamlines
  - facility dependent
- Limited commercialization options
  - market often too small to attract strong industrial developers

# Models to bring detector to fruition

Research → Development → Commercialization

**MM-PAD 100K (CU)**



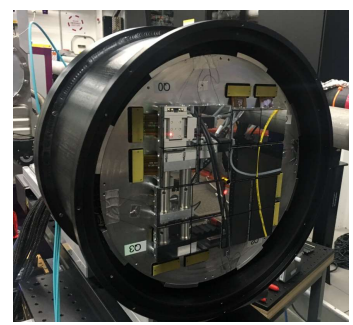
**Pilatus 6M (PSI → Dectris)**

**PSI Pilatus 100K (2005)**

**Dectris Pilatus (2006)**

- SBIR companies only have a financial interest and typically no strong ties to the technology.
  - Only success stories for large detectors are those with big markets (e.g., MX)
  - Most of the detectors being developed probably don't have huge markets.
    - SBIR companies will need to charge a lot of money for each detector to make it worth their while.
  - Hard to ask an SBIR to take a box of parts (e.g., MM-PAD 100K) and scale up to megapixels.
  - other SBIR examples: Cornell KeckPad and SLAC CPix
- Lab staff could start new companies (e.g., Dectris (CH), X-Spectrum (DE)).
- University groups do not have the base funding to do this.
- The labs could just do themselves, but SUF/ADR won't fund this!
- The facilities should probably to do this
  - some examples: BNL linear and diamond detector, LBNL fCCD and SpectroCCD, SLAC ePix10k 2M

**SLAC ePix10k 2M**



BROOKHAVEN NATIONAL LABORATORY

# Models to bring detector to fruition

- Facility focused/initiated efforts (unilateral)
  - ePix (SLAC)
  - Maia (BNL)
  - **Pro**: Focused and undistracted efforts
  - **Con**: Requires extra effort to get buy-in from the other facilities; other facilities see the development as another vendor
- Collaboration (bilateral efforts)
  - FCCD 1 & 2 (LBNL/ANL)
  - VIPIC (BNL/FNAL/ANL)
  - Ge Strips (BNL/ANL)
  - MM-PAD v2.0 (Cornell/ANL)
  - VFCCD (LBNL/SLAC)
  - TES (NIST/SLAC/ANL)
  - **Pro**: At least 2 facilities have a vested interested in seeing the project succeed.
  - **Con**: Requires extra effort to coordinate efforts at 2 or more facilities.

# New collaborative effort

First identified need: high-Z sensors

- Working on a collaborative effort
  - ANL, BNL, CU, SLAC
  - Other collaborators: Northwestern University, Stony Brook University, AGH University (Poland), Spring8 (Japan)

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

- Finalizing white paper

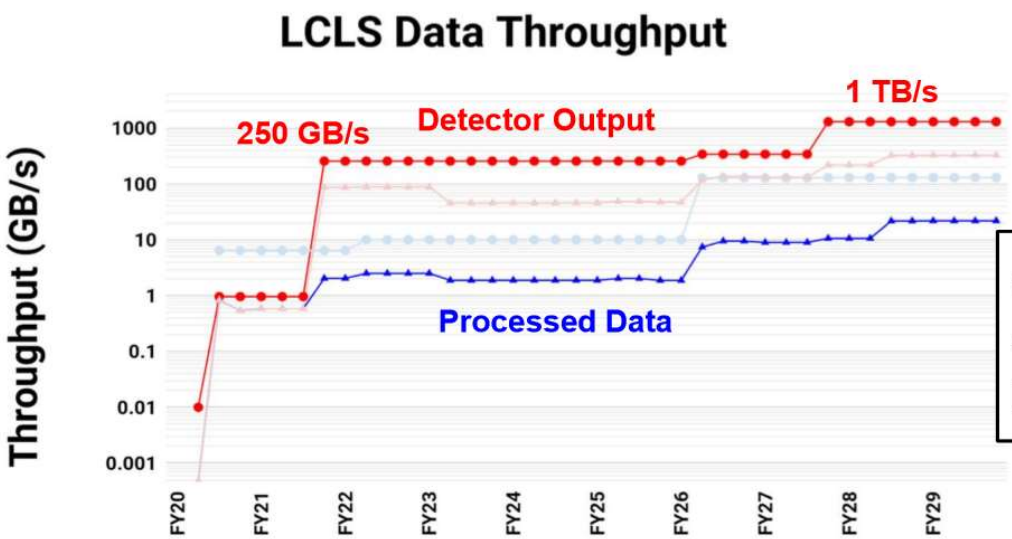
# Summary

- Working group found working together beneficial
  - To inform and plan activities
- Several developments are needed
  - Workhorse detectors have larger distribution and can be commercialized
    - Better models for commercialization needed
  - Specific detectors for high-end applications
    - Will remain facility-owned – few detectors
  - Soft x-rays: additional constraints
    - Limit their commercialization opportunities
  - Data produced by the detector will be unmanageable
    - Data reduction techniques needed (being developed)

# Summary

## LCLS-II Data before/after real time processing

SLAC




**Synchrotrons: MB/s → GB/s**

**ATLAS: 1.5* GB/s → 20* GB/s**

**LCLS: 5 GB/s → 250 GB/s → 20 GB/s**

Zero-suppressed data for one fixed experiment setup

**This scale of real-time data production is unprecedented**

- Data produced by the detector will be unmanageable
  - Data reduction techniques needed (being developed)