IFDEPS 2024 - Port Jefferson, New York - March 17-20, 2024.

Commissioning and Operational detector experience at LCLS: current and coming detectors

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SLAC X-ray Detector R&D Program

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Overview:

- Evolution of detector pool and currently supported detectors;
- How are the detectors deployed;
- Process of bringing up detectors at LCLS;
- Recent commissioning and lessons learned; and
- Detectors being developed for the LCLS upgrade and their current status.

Upgrade of the detector pool over the last few years

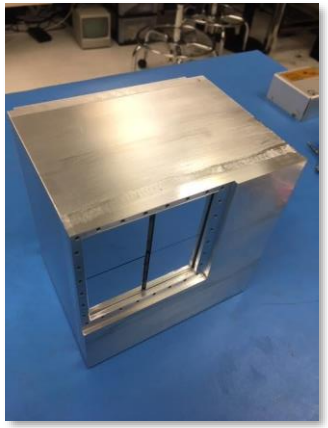
Detector	Qty
ePix10k 2.1M	2 (1 in fab)
ePix100 0.5M (side, front)	1,10
ePix10k 140k (front)	2
ePix10k 140k (side, 1mm Si)	1
ePix10k 0.5M Quad (MEC + UED + ASC)	7
Rayonix 340	1
Jungfrau 0.5M	1
Jungfrau 1M	1
Jungfrau 4M	1
CSPAD 2.3M	2

- Last IFDEPS (2017) the primary cameras in use were CSPAD's, pnCCD, Rayonix's, ePix100's.
- The pool has evolved towards a more ePix100, ePix10k, and Jungfrau focus.
- In the next decade, the facility will increase its rep rates. Detector technology must advance accordingly to match this pace, and the data systems need to manage the increased data from the new cameras

Operational use of the detectors at LCLS

ePix Family of detectors

ePix10k 140k/ ePix100



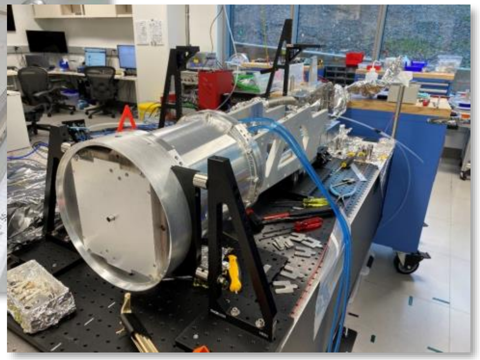
ePix10kQuad

ePix10k2M

- Come in various sizes;
- Some are permanently installed at a specific station while others are moved around with roughly 2-3 new experimental configurations requested per week.
- Require a robust and flexible design to allow for use in “the wild”.

Jungfrau family of detectors

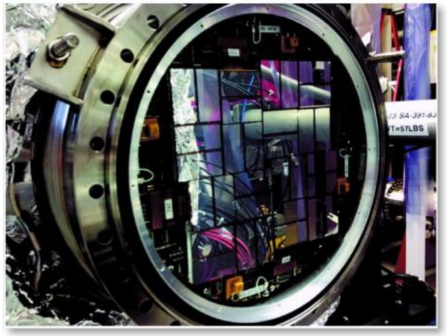
Jungfrau 0.5M and 1M



Jungfrau 4M

Others

Rayonix MX340



CSPAD

Additional “low rate” cameras coming in the next year:

- Jungfrau 15M (MFX)
- RIXSccd (qRIXS)
- ePix10kQuad1kHz (UED)

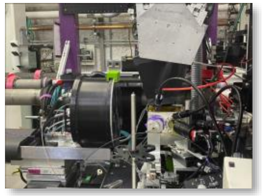
The process of bringing up a new detectors at LCLS

Detector/Camera development

Create the needed technologies

- Development of the needed sensor, ASICs, readout systems and mechanicals.
- Many year process that span R&D and camera development.

Calibration scheme development



Linking detector response to a physical reality.

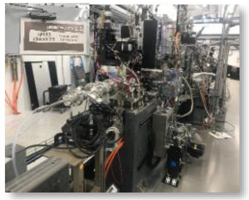
- Map the electronic response to physical reality.
- Often includes understanding how to accurately determine per pixel pedestals, gains, offsets, and geometrical corrections.

Verification cycle

Verifying that the specs meet the requirements.

- Ensure that the performance of the delivered detector meets the targeted requirements.
- Measurements to determine the specs of the detector. Combination of lab and beamline-based measurements.

Validation cycle



Validating that the detector meets the needs of the science.

- Incorporate the detector into a representative use case measurement to see that the detector is able to provide science-grade data.

Commissioning

Operationalize the camera.

- Ensure the camera is ready for use in the intended environment.
- Include development of IOC’s, physical installation at end station, ensure deployment of calibration constants, implementation of bad pixel masking, on the fly corrections, and training beamline personel.

Operation

Deploy and support the camera in user experiments.

- Deploy and continuously support the use of the detector in science campaigns, as needed by the facility.

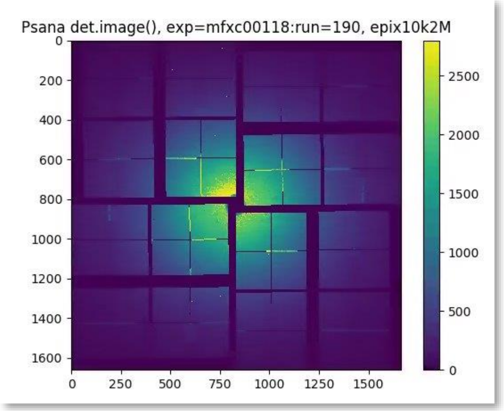
- The number of steps that need to be performed at SLAC to bring a camera to operation varies depending on if it is developed in-house or procured from an external supplier.
- The steps are often interleaved and can require iterations as you go along.

Commissioning and operation

* See Jana Thayer's presentation

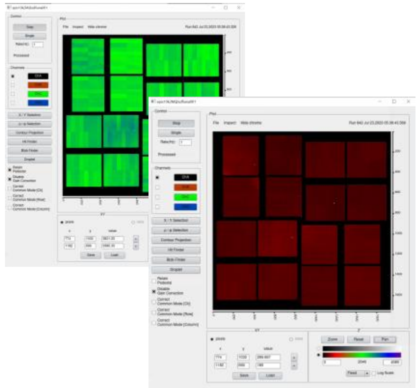
Getting the detector running in the LCLS environment

DAQ integrating



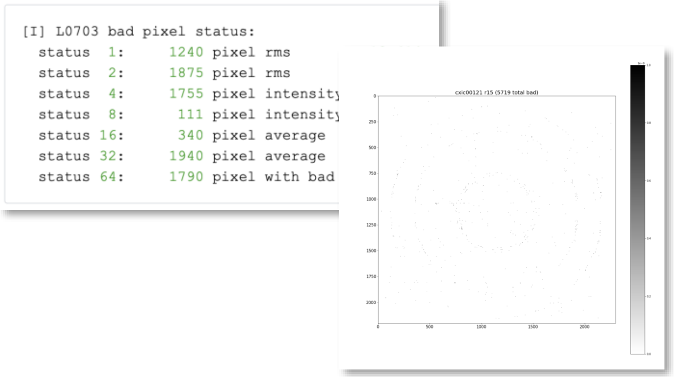
- Enable running in the LCLS DAQ environment*

Calibration and data access



- Raw and calibrated data offline (psana) and online (AMI).*

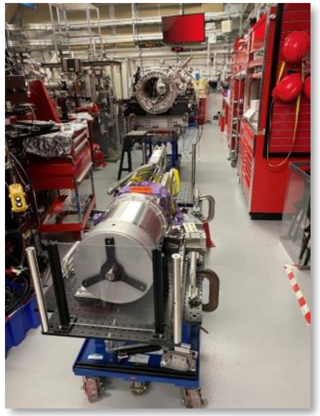
Bad pixel mapping



```
[I] L0703 bad pixel status:
  status  1:     1240 pixel rms
  status  2:     1875 pixel rms
  status  4:     1755 pixel intensity
  status  8:      111 pixel intensity
  status 16:      340 pixel average
  status 32:     1940 pixel average
  status 64:     1790 pixel with bad
```

- Exclude pixels that are not behaving properly from user analysis

Installation



- Install detector and support equipment at the endstation

* See talk from Jana Thayer

Safe operation and remote monitoring

IOC development

- Interlock detector for automatic shutdown in case key PVs trip.
- Monitors vacuum levels, current and voltages, temperatures, and humidities.

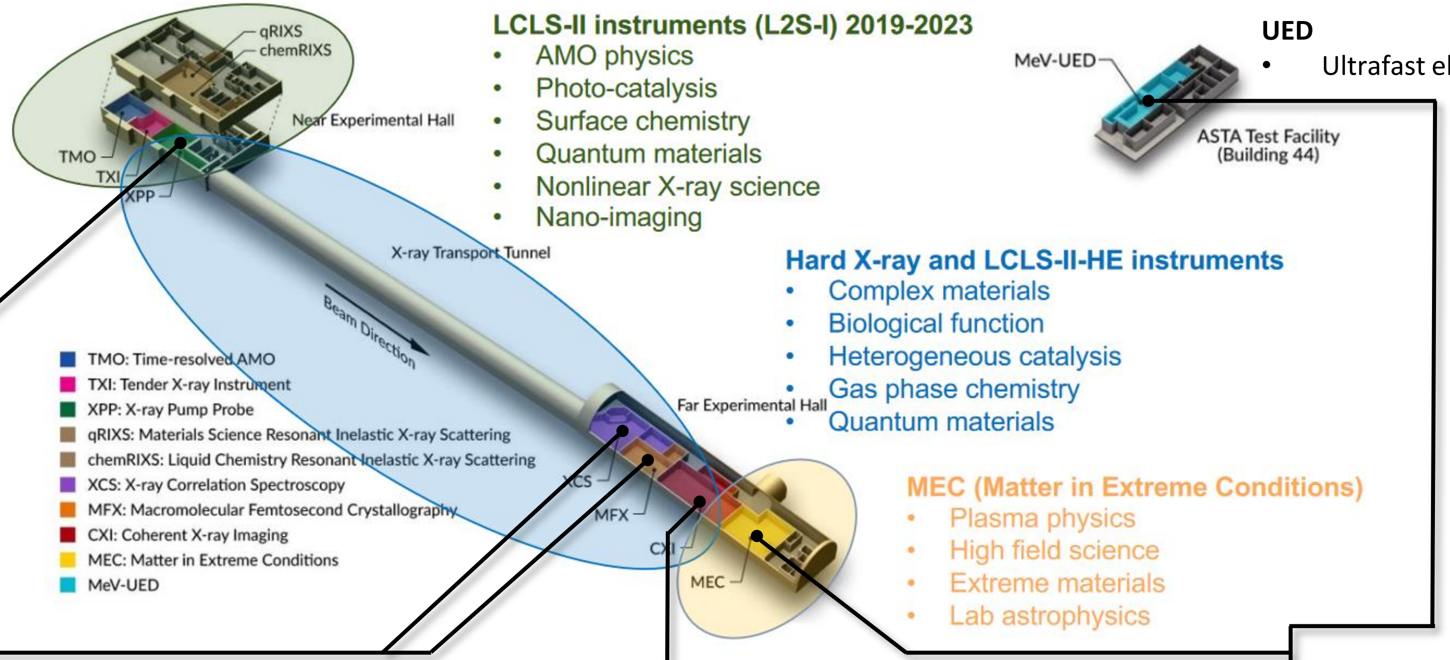
Remote monitoring and parameter logging

Dashboard summary hutches

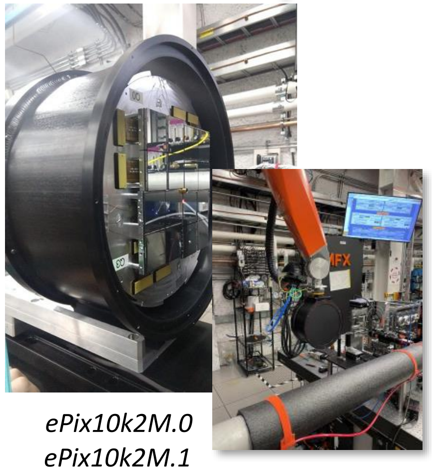
Live status of each detector

- Allow for live status checking on the detectors and PV value logging for initial diagnostics
- Alerts can be programmed to bring attention to off-nominal performance.

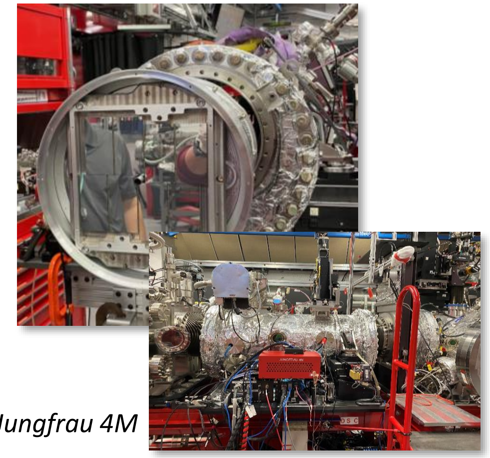
Commissioning case studies and lessons learnt in operation



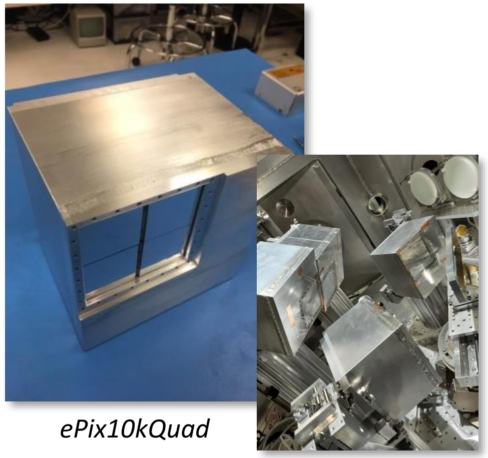
UED
- Ultrafast electron Diffraction



ePix10k2M.0
ePix10k2M.1

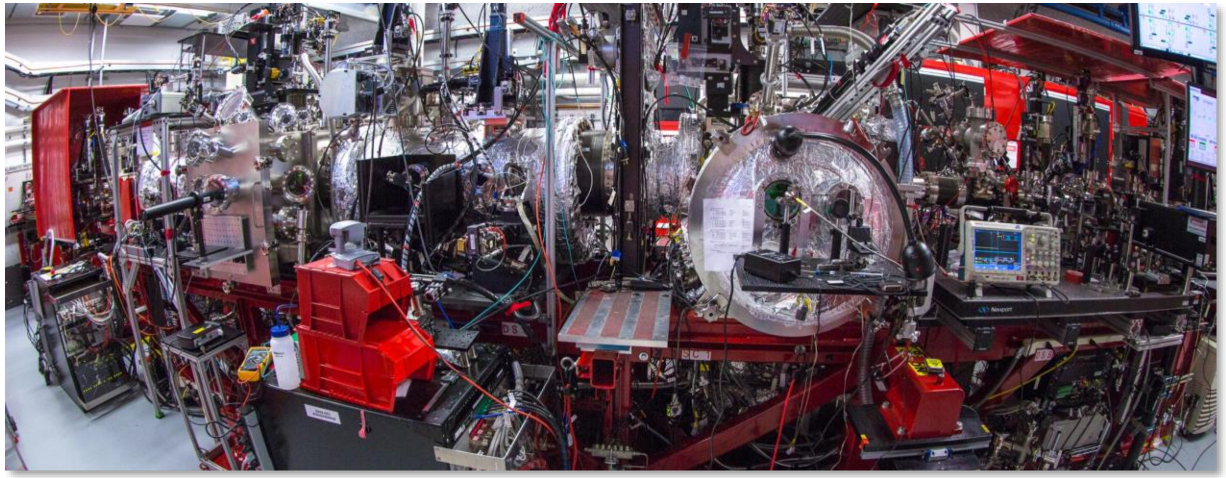


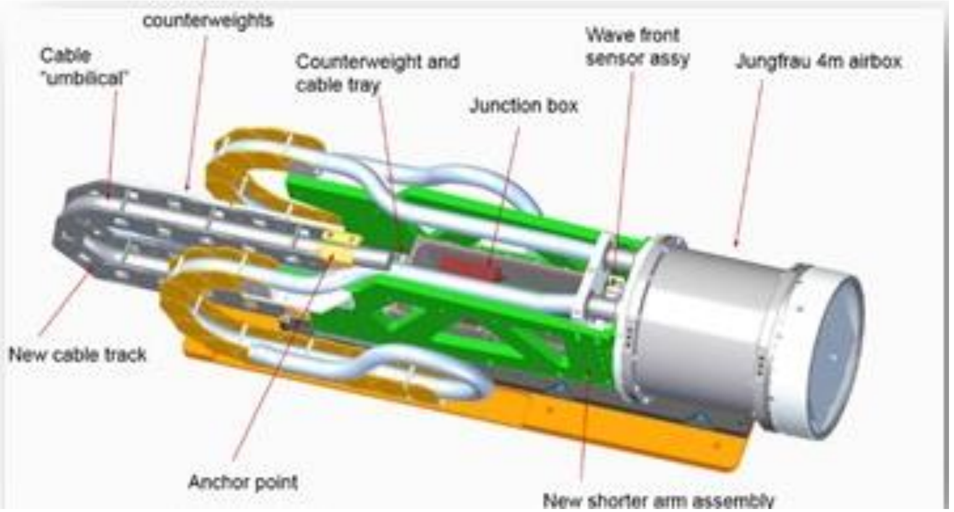
Jungfrau 4M



ePix10kQuad

Jungfrau 4M – Coherent X-ray Imaging end station





CXI

- CXI instrument consists of a highly flexible instrumentation suite to make use of hard X-rays primarily in a vacuum sample environment;
- CXI is suitable for forward scattering experiments requiring, or benefiting from, a vacuum sample environment that provides extremely low background, particularly beneficial for weakly scattering systems.
- CXI has hosted experiments for many scientific fields, including structural biology, materials science, materials in extreme conditions, atomic molecular and optical physics, chemistry, soft condensed matter, and high-field X-ray science.

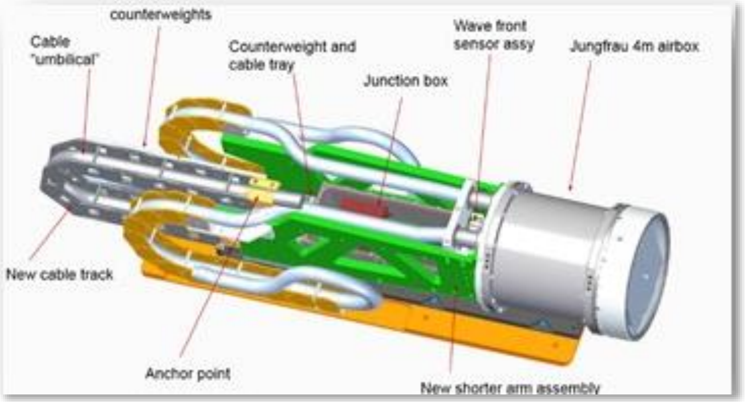
Jungfrau 4M

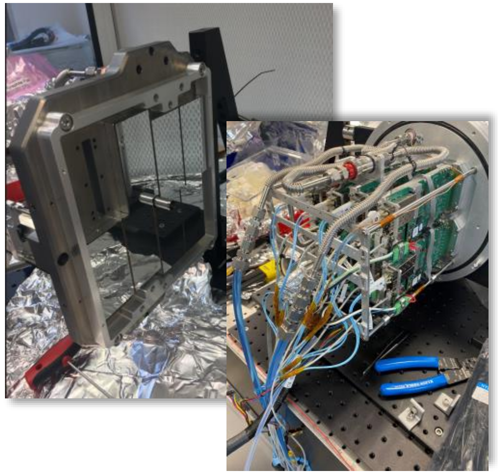
- In-vacuum, 4M pixel charge integrating detector;
- Operates in gain-switching mode with 3 gain regions covering the full dynamic range.

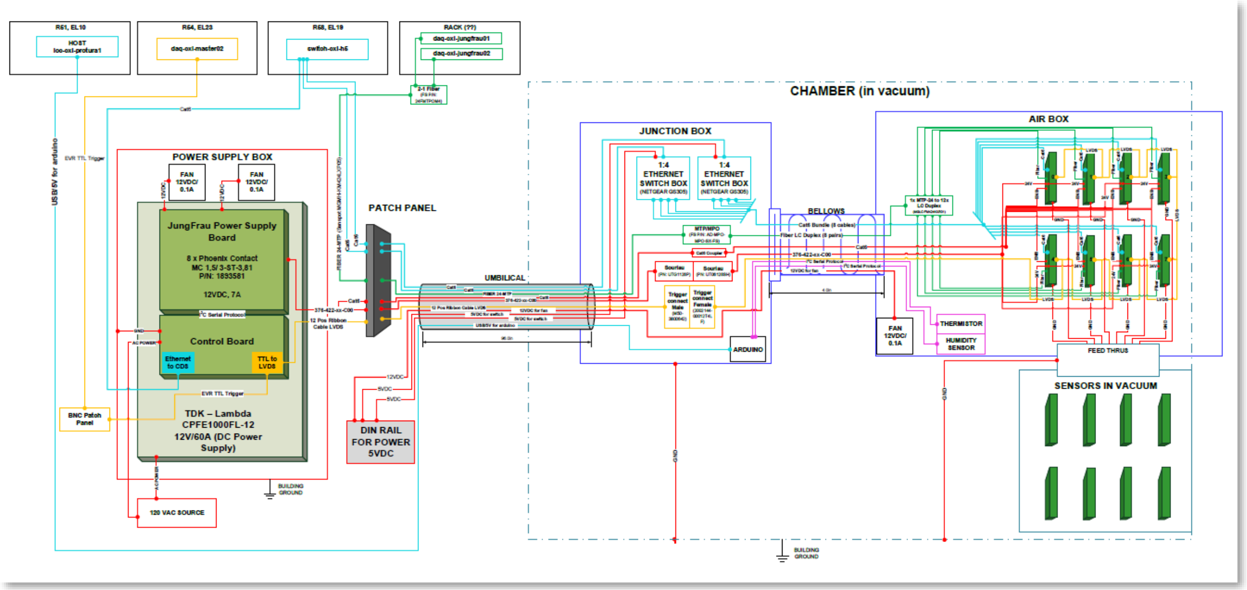
Jungfrau 4M specs

Pixels per module	1024 x 512 (8 modules)
Pitch (um)	75
Noise (RMS) (eV)	180-270
Max Signal (8keV photons)	15000
Frame rate (Hz)	120 (2kHz)

Camera structure, IOC and performance







Camera structure

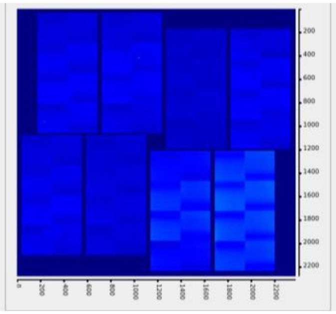
- Sensors and readout boards separated to be on opposite side of vacuum to ensure the readout boards are not overheated.
- Communication, power, and chiller lines routed through the in-air umbilical, out to the servers and power supplies.

IOC

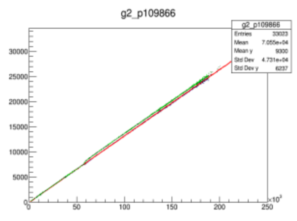
Software interlocks implemented to keep detectors within operating range:

- Water chiller failure
- Sensor + electronics over-temperature
- Electronics under-temperature + humidity
- Over-current/over-voltage

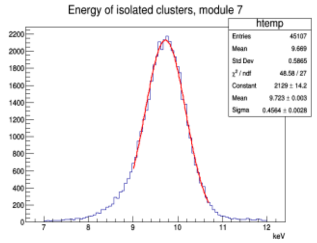
Performance



Noise map



Gain Switching



SP response 9.76keV

	Pedestals (ADU)	Noise (ADU)	Noise (keV)	SP limit (keV) (5σ)
Gain 0	2400	12.9	0.32	1.55
Gain 1	13600	6.6	4.7	23.5
Gain 2	14200	6.2	56	280

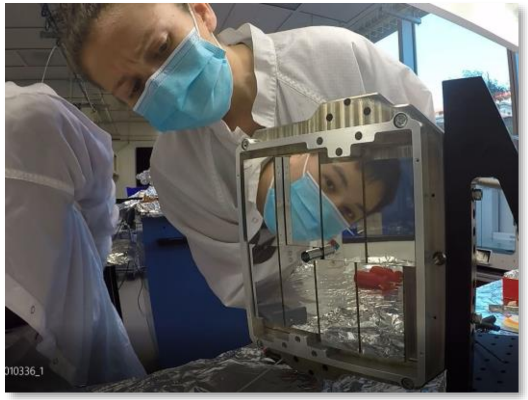
Timeline for camera assembly, commissioning and operation

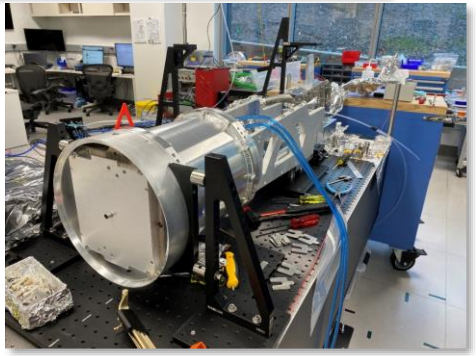
Sensor arrival and camera assembly start (Dec 2019)

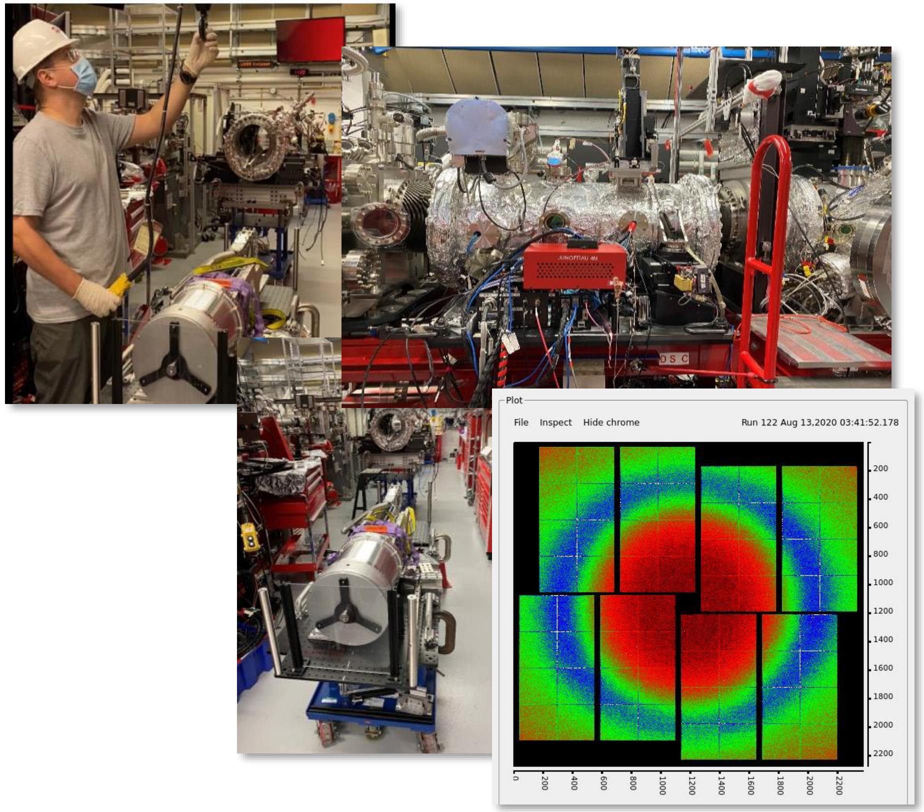
Final in lab testing and transport to station (March 2020)

Vacuum assembly and beamline installation (July 2020)

Operation (On-going)

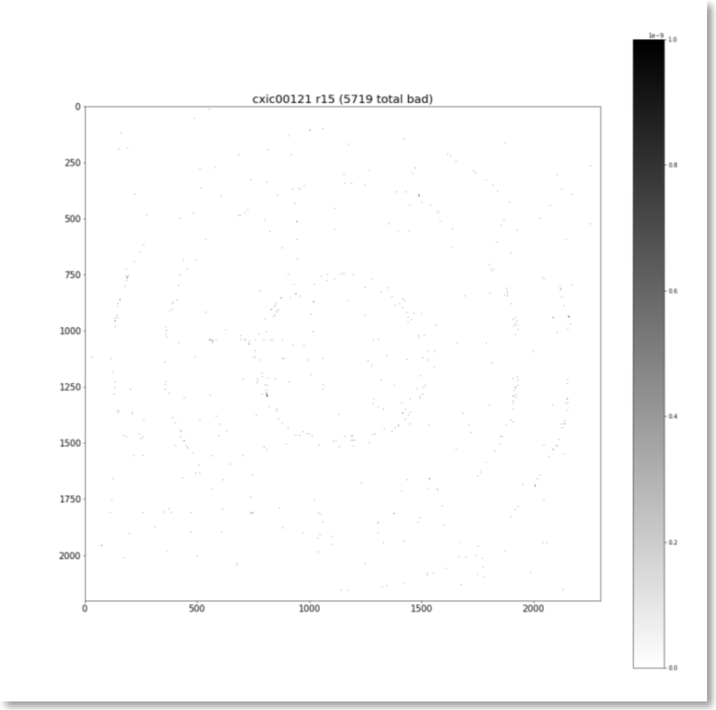




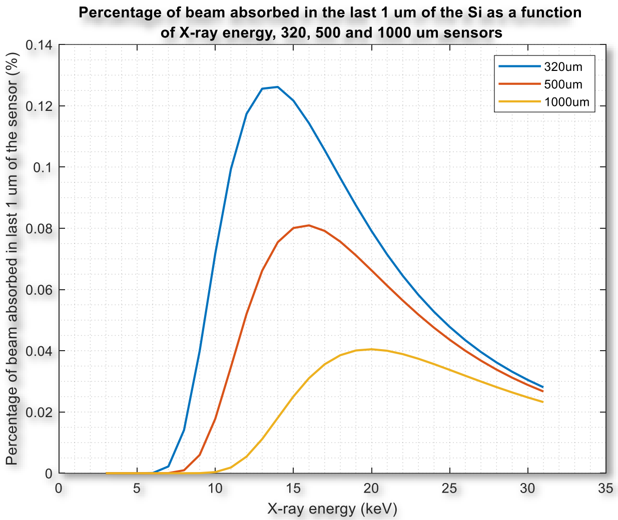


Lessons learnt

Operational lesson 1: Radiation damage and large pulse exposure

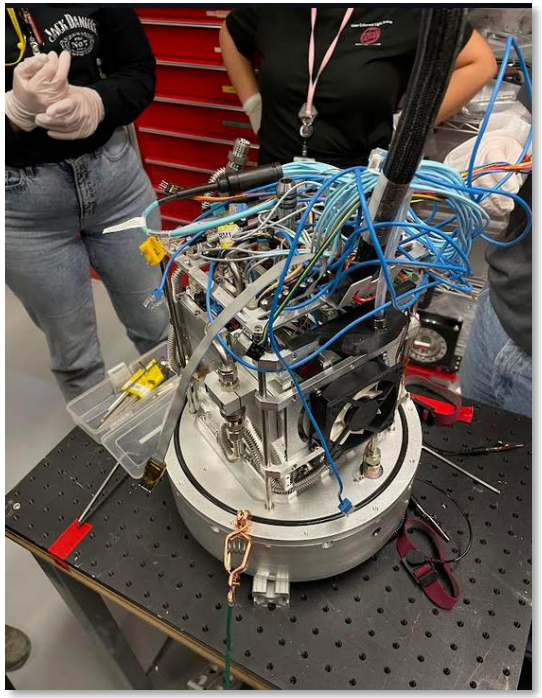



```
[I] L0703 bad pixel status:
  status  1:     1240 pixel rms        > 19.414
  status  2:     1875 pixel rms        < 0.611
  status  4:     1755 pixel intensity > 16000 in more than 0.1 fraction of events
  status  8:      111 pixel intensity < 1 in more than 0.1 fraction of events
  status 16:      340 pixel average    > 3761.95
  status 32:     1940 pixel average    < 1226.6
  status 64:     1790 pixel with bad gain mode switch
```



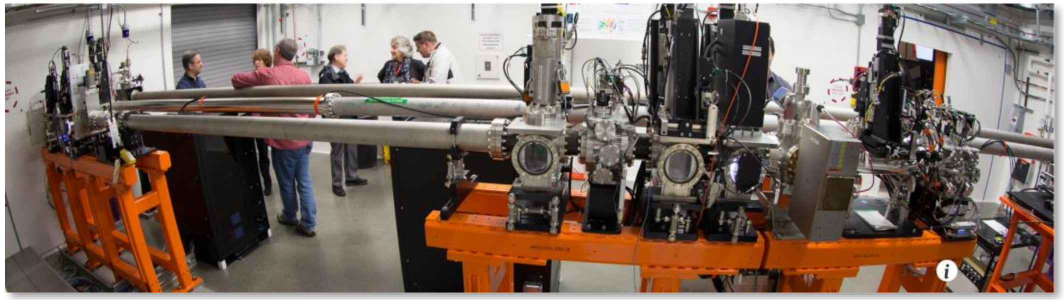
- Used in >50 experiments since going into operation;
- Number of bad pixels observed show clear correlation to water ring locations;
- Attributed to very large diffraction signals and radiation damage;
- *Implemented software saturation protection turning off the camera if large number of extreme diffraction peaks are observed;*
- *Radiation damage consideration when moving to higher energies and rep-rates clear.*

Operational lesson 2: Heartbeat monitor

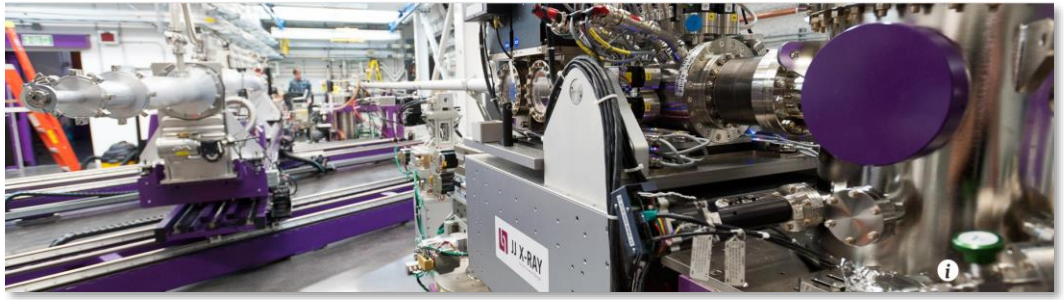


- IOC lost network connection resulting in readings not being updated;
- Perfect storm resulted in overheating of air-box and damage of one of the readout boards;
- Resulted in the need to reschedule user program and uninstall the camera from vacuum enclosure for repairs.
- *Heartbeat monitor to monitor that the noise level of reading are changing was implemented to ensure this does not happen in future.*

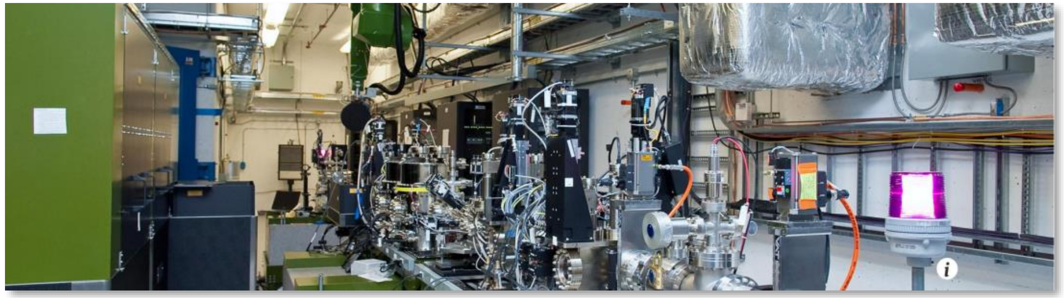
ePix10k2M– MFX, XCS, and XPP



MFX – Macromolecular Femtosecond X-ray Crystallography end station.



XCS – X-ray Correlation Spectroscopy end-station.



XPP – X-ray Pump and Probe end-station.

MFX

- The MFX instrument is primarily focused on macromolecular crystallography at atmospheric pressure, utilizing the widely developed techniques from synchrotron sources
- The instrument primarily make use of the ability for short pulses of X-rays to limit damage to samples during the exposure. The "diffraction-before-destruction" concept can enable high resolution data to be collected on radiation-sensitive samples, primarily biological samples.

XCS

- XCS is primarily focused on the observation of dynamical changes of large groups of atoms in condensed matter systems over a wide range of time scales using Coherent X-ray Scattering (CXS) in general and X-ray Photon Correlation Spectroscopy (XPCS) in particular. The X-ray Correlation Spectroscopy (XCS) instrument at the LCLS allows the study of equilibrium- and non-equilibrium dynamics in disordered or modulated materials.

XPP

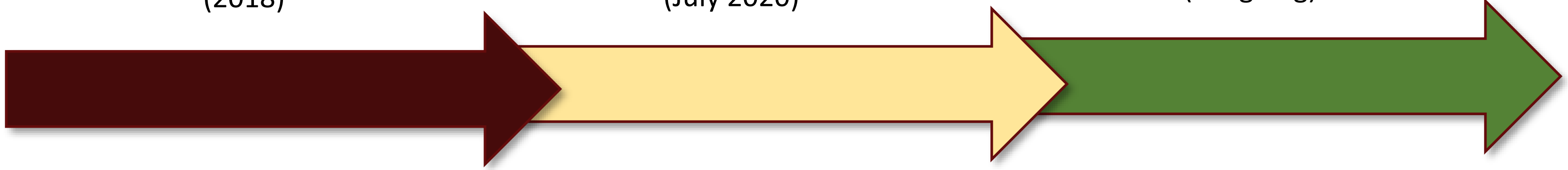
- The XPP instrument predominantly uses ultrashort optical laser pulses to generate transient states of matter which are subsequently probed by hard X-ray pulses from the LCLS. The X-ray pulses help to reveal structural dynamics initiated by the laser excitation at the timescale of atomic motions in solid, liquid and gaseous specimens.
- X-ray absorption and emission spectroscopy, diffraction and scattering are typical tools for probing the laser-induced structural changes at this station.

Timeline, camera structure and IOC – ePix10k2M

Initial evaluation of the first copy (2018)

Commissioning and deployment (July 2020)

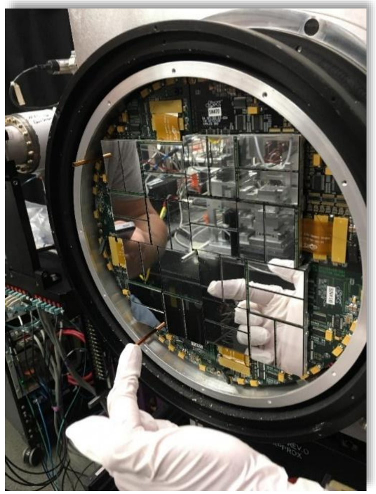
Operation (On-going)

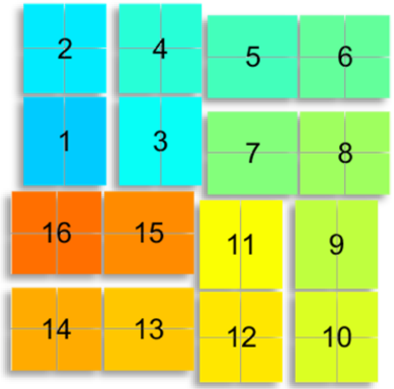


ePix10k2M

- In-air, 2M pixel charge integrating detector;
- Aimed at replacing the legacy CSPAD detector;
- Have 5 operational modes, 3 fixed gain modes and 2 auto-ranging. The mode used varies on the station:
    - MFX: Fixed or auto-ranging;
    - XCS – Fixed mixed;
    - XPP - Fixed

Parameter	CSPAD	ePix10k
Gain modes	2 - Fixed	3 – Fixed; 2 - Auto ranging
Maximum signal (keV)	20,000	88.000
Noise in high gain (eV)	1,100	390/290*
Frame rate (Hz)	120	120
Standard Sensor (Si) Thickness (µm)	500	500
Pixel pitch (µm)	110	100
Pixels/ASIC (#)	194x185	192x176





Camera structure

- Full camera made up of 16 modules, each consisting of 4 ASICs covered by a single sensor;
- Mounted on circular readout boards and power, communication and cooling fed back through the rear of the camera.

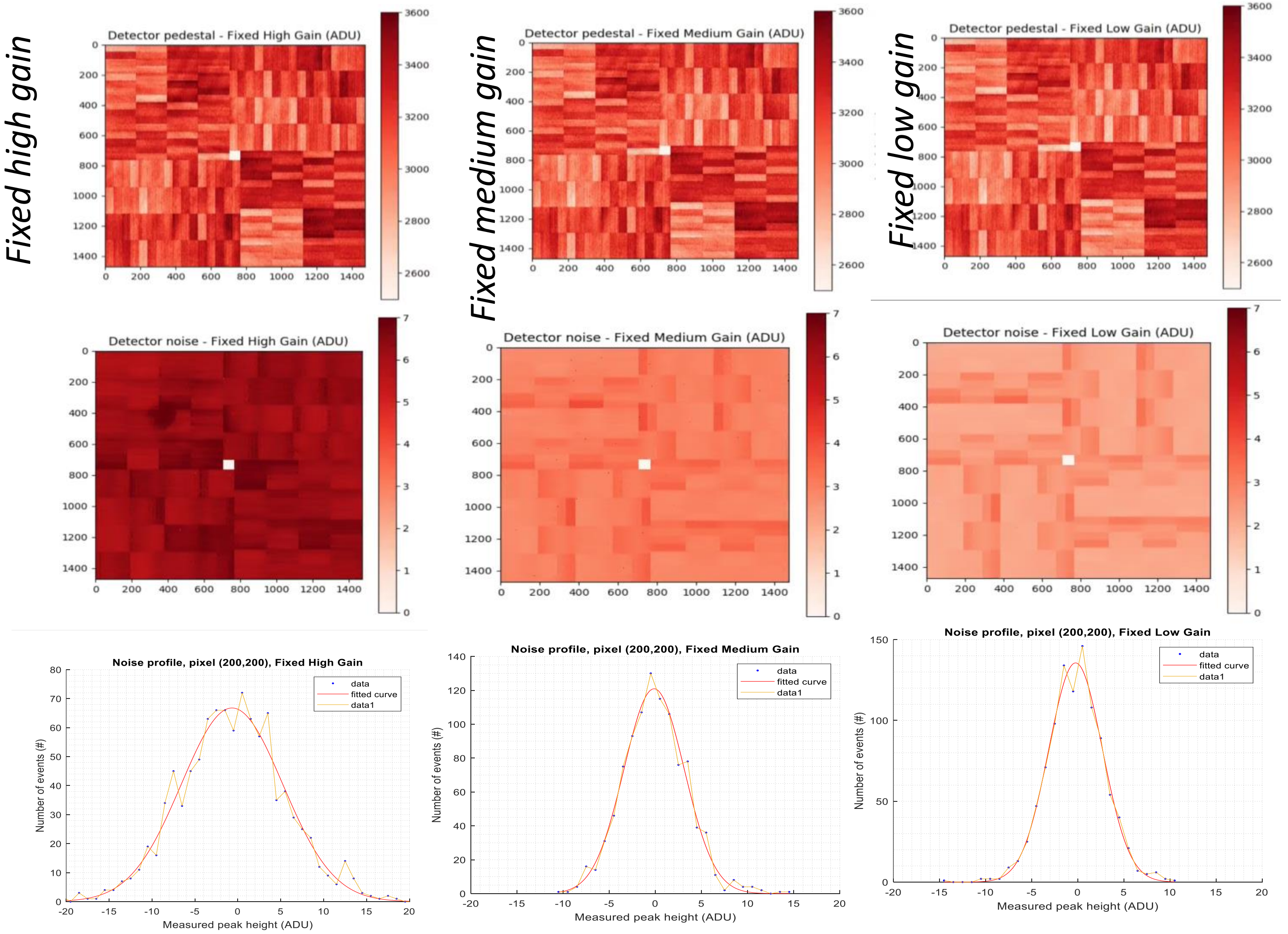
IOC

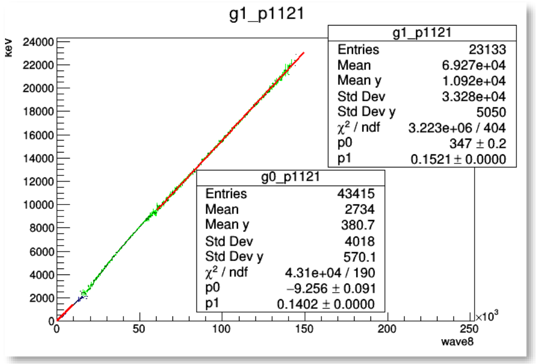
Software interlocks implemented to keep detectors within operating range:

- Water chiller failure
- Sensor + electronics over-temperature
- Electronics under-temperature + humidity
- Over-current/over-voltage
- Over intensity protection

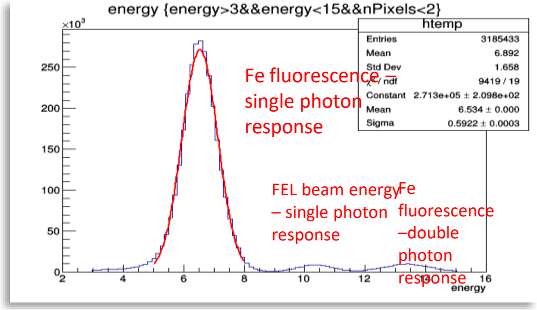
Performance ePix10k2M

Performance

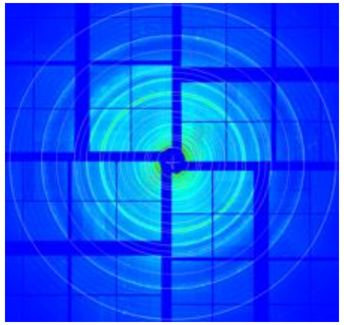




Gain switching



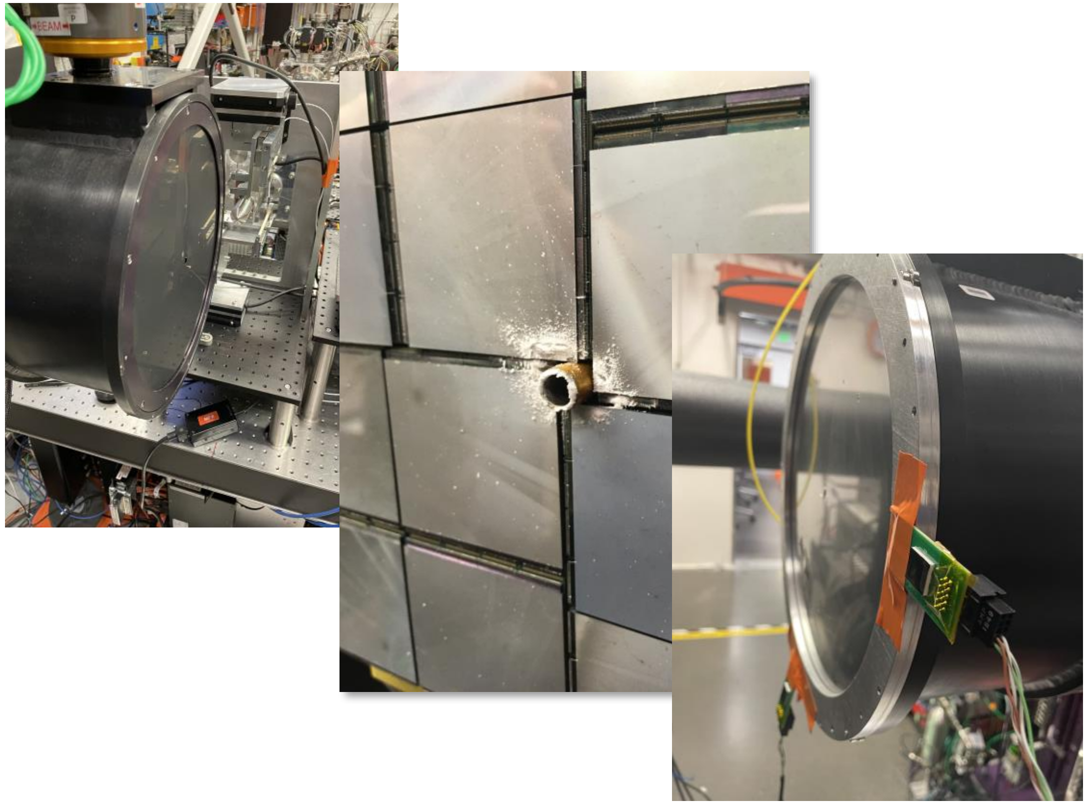
SP response – Fe fluorescence



Diffraction pattern measured at XCS.

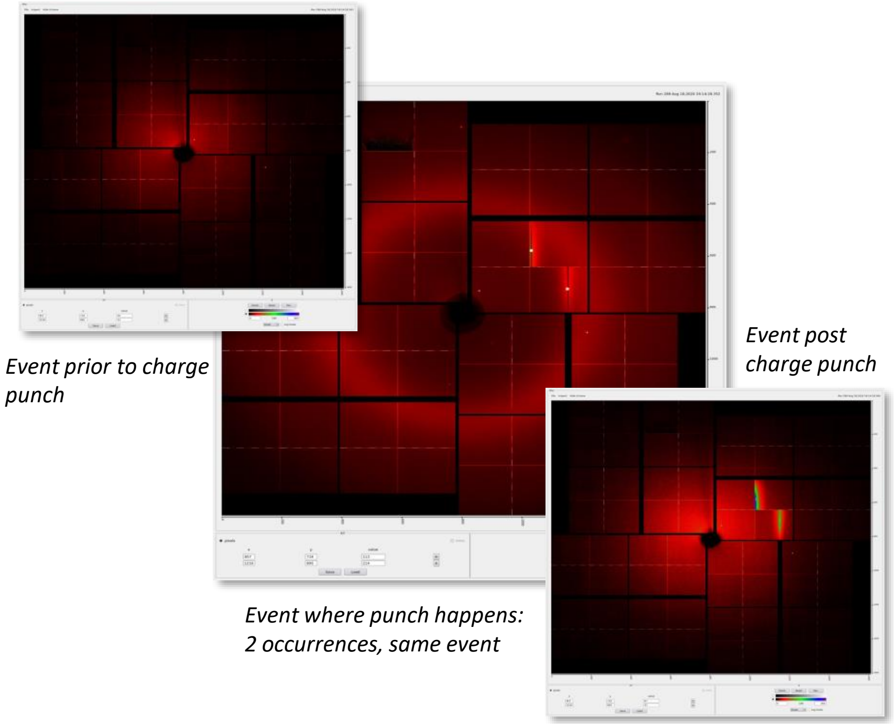
Lessons learnt

Operational lesson 3: Sample environment conditions



- Detector incorporated into experimental setup using jet-based sample delivery system in a helium environment;
- Gas flow outlet not sufficient – Detector beam pipe path became an exhaust
- *Pay attention to sample environments the detectors are going into, especially for detectors that move, since the experimental conditions can vary significantly.*

Operational lesson 1 (repeat): Large X-ray pulse exposure



Event prior to charge punch

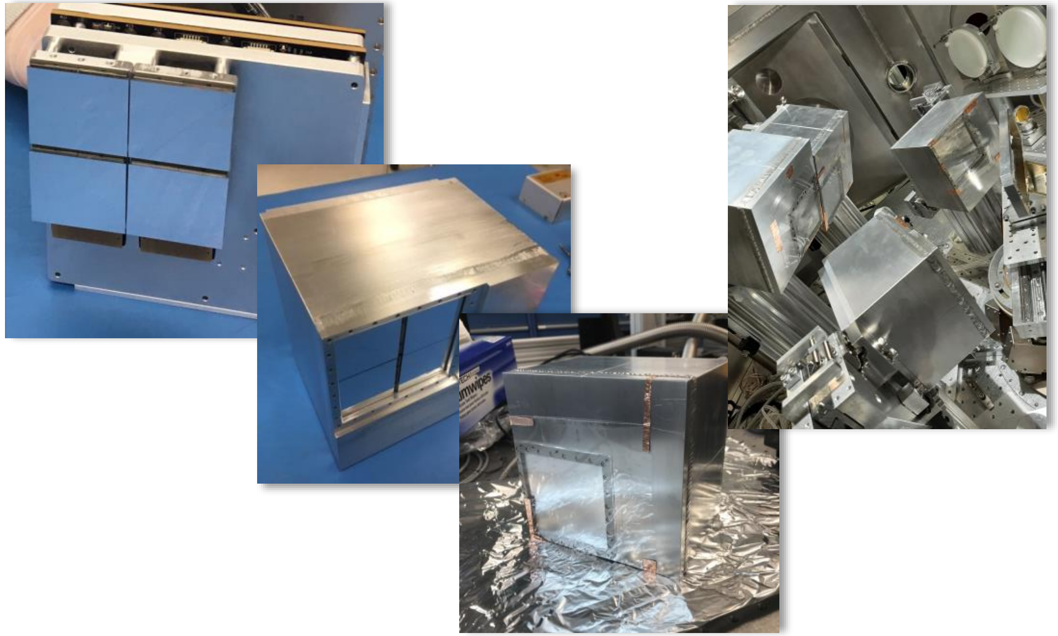
Event post charge punch

Event where punch happens: 2 occurrences, same event

- Detector incorporated into experimental setup using jet-based sample delivery;
- Formation of ice crystals in the sample delivery system resulted in locally extreme pulses (Bragg peaks) exceeding what the pixel was designed for;
- *Implemented software saturation protection turning off the camera if a large number of extreme diffraction peaks are observed;*

ePix10kQuad– Matter under Extreme Conditions end station

MEC – Matter under Extreme Conditions end-station.



MEC

- MEC is dedicated to investigating the dynamic behavior of matter under extreme conditions. The instrument excels in harnessing the distinctive LCLS beam alongside high-power optical laser beams, complemented by a specialized suite of diagnostics finely tuned for this realm of scientific exploration. Research conducted at MEC encompasses a broad spectrum, spanning Warm Dense Matter physics, high-pressure studies, shock physics, and fundamental research into inertial fusion energy.

Camera structure

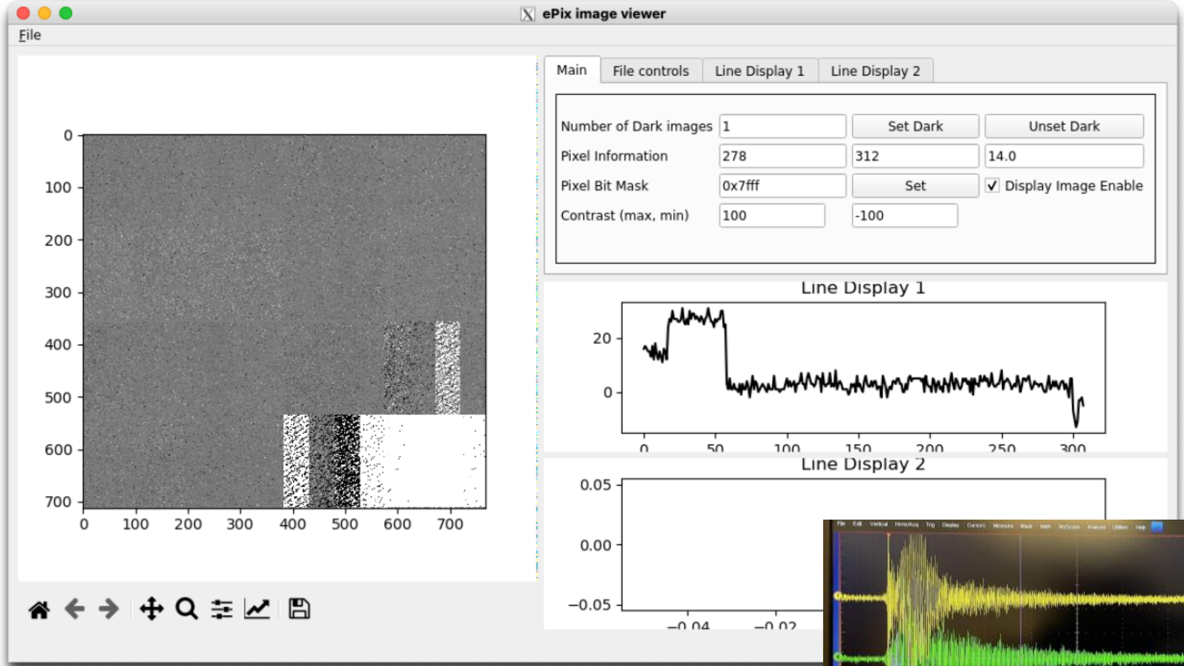
- Based on the ePix10k ASIC, has the active area of ¼ of the ePix10k2M;
- Readout board design re-used from the 2M, hence the camera larger than active sensor area;
- Mounted on circular readout boards and power, communication and cooling fed back through the rear of the camera;
- Fully metalized body (including debris shield) in order to mitigate EMP pulses created by the laser pulsing (Faraday cage).

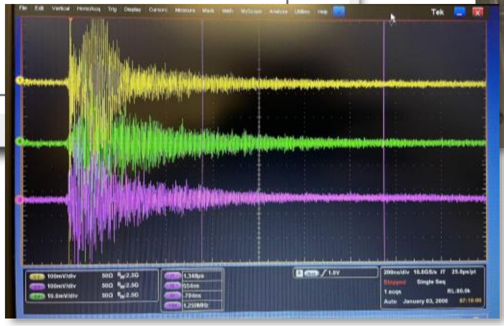
IOC

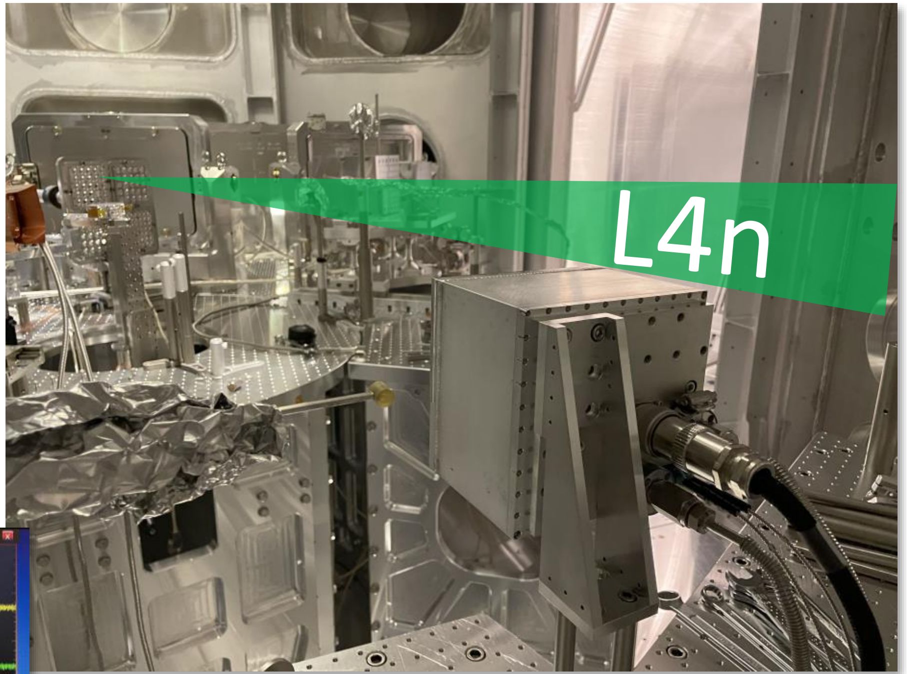
Software interlocks implemented to keep detectors within operating range:

- Water chiller failure
- Sensor + electronics over-temperature
- Electronics under-temperature + humidity
- Over-current/over-voltage
- Over intensity protection

Lessons learnt





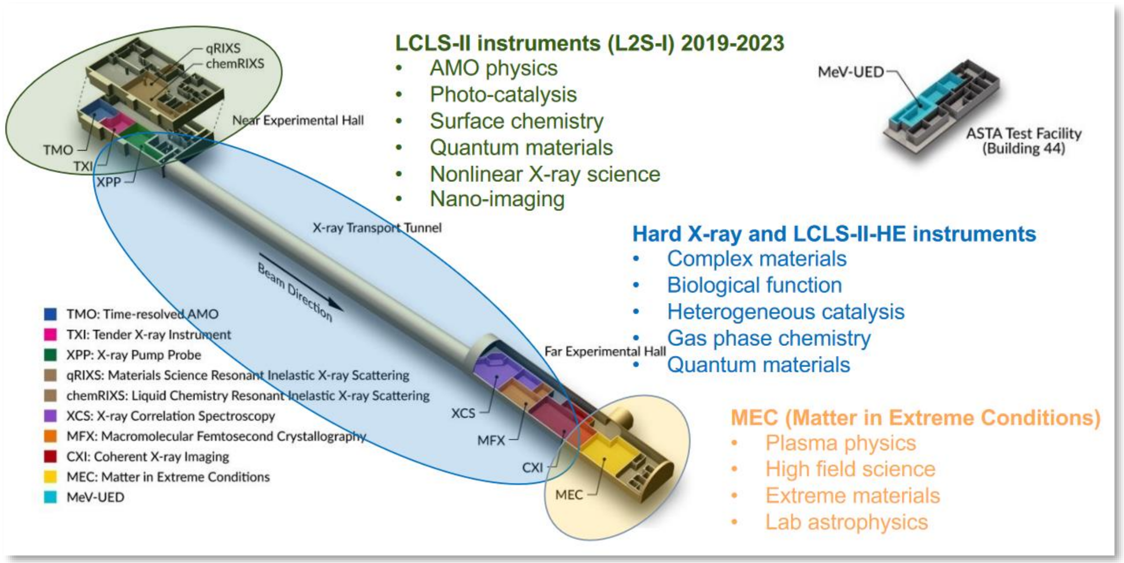


Operational lesson 4: EMP resistance for operation in harsh environments:

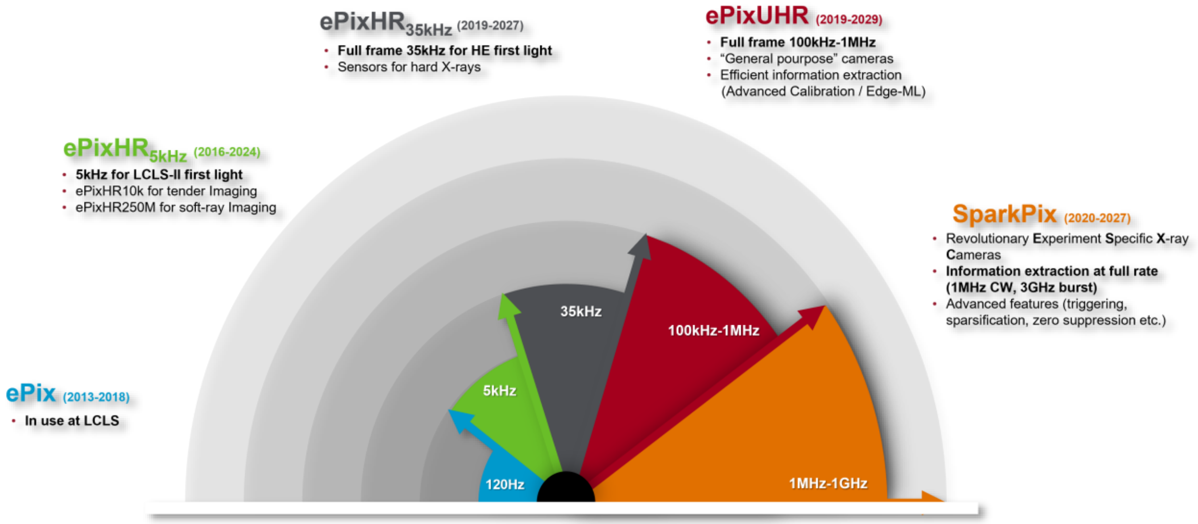
- EMP pulses created by laser/matter interactions; knock out the detector (Pedestal shifts, HV trips, Read out failures);
- Full Faraday cage layout for the detector housing as well as the cabling, has to be designed;
- Decouple the electronics from the detector housing;
- Successful operation of detectors at 200J, 1m for large pulse durations (60J in 2016). Much harsher environments are envisioned for MEC-U in the kJ region.
- *Detector EMP resistance must be considered in the design of the detector when operating under harsh experimental conditions.*

Coming facility upgrade and detector development roadmap

Facility upgrade



Detector development roadmap for increased rep rate



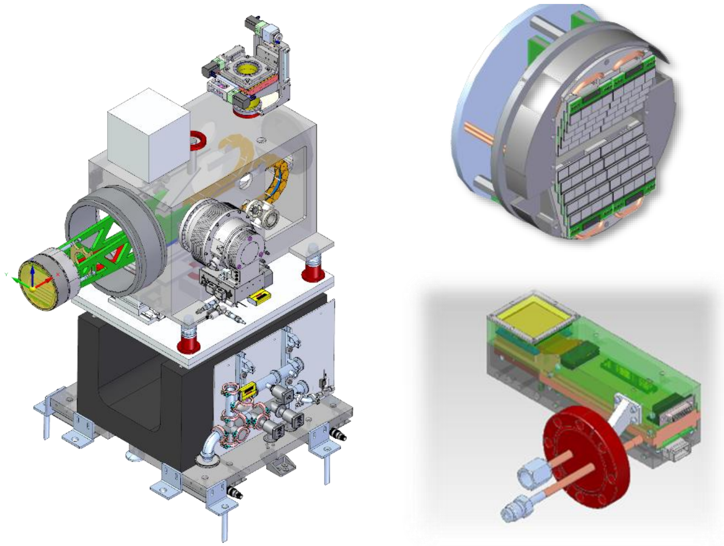
Facility upgrade	Detector	Notes
LCLS-II		
Superconducting LINAC serving the soft and tender x-ray beamlines allowing for high-rep rate operation (TMO, TXI, qRIXS, chemRIXS).	$ePixHR_{5kHz}$*	Tender X-ray detector (>5keV) operating at 5kHz for TXI end station.
	$ePixHRM_{5kHz}$*	Soft X-ray detector (<250 eV) operating at 5kHz for RIXS end stations.
	RICSccd	Soft X-ray detector, (<250 eV) , 200Hz operation in 1D mode.
LCLS-II-HE (2026-2027)		
Extension of the energy range for the Superconducting LINAC to allow for hard x-ray stations to be operated (XPP, MFX, CXI, and XCS(DXS)).	$ePixHR_{35kHz}$*	Hard X-ray detector operating at 35 kHz for the Hard X–ray instruments.
	ePixUHR**	Hard X-ray detector operating at 100 kHz for the Hard X–ray instruments.
	SparkPix Family**	Hard X-ray detector operating at up to 1MHz for the Hard X–ray instruments. Experimental specific detector designs, and data reduction close to detector to allow for the increasing data rates.

Additional cameras being evaluated for future facility use:

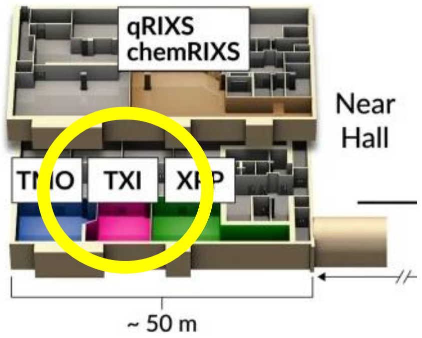
1. UXI family of detectors;
2. CITIUS;
3. Tixel (LGAD).

*See talk from Dionisio Doering;
** See talk from Lorenzo Rota

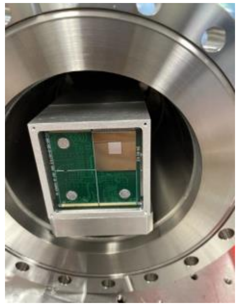
ePixHR$_{5kHz}$ – Tender X-ray imager for TXI endstation



Left: Model of the large TXI camera installed in instrument. Top right: internal view of the large TXI camera. Bottom right: Small form factor TXI camera.

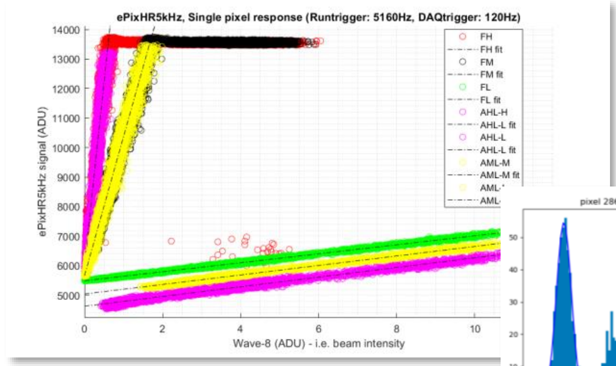


TXI end station in the Near Hall.

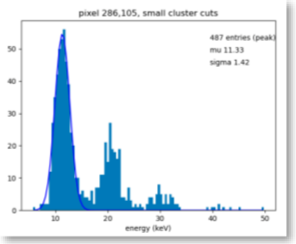


Prototype detector.

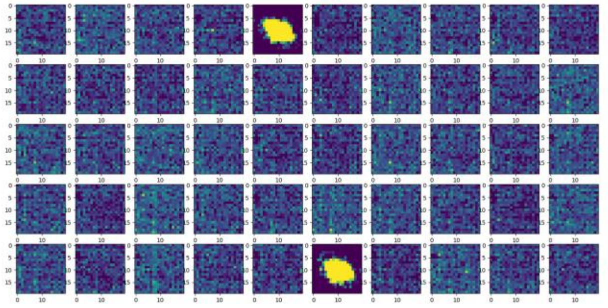
- Soft X-ray detector, sensitive to X-ray below 5 keV, running at 5kHz,
- 1 large and two small format cameras to be delivered within the year.
- Primarily targeted at spectroscopy and SAXS/XAFS.
- Currently undergoing camera/ calibration scheme development stage.

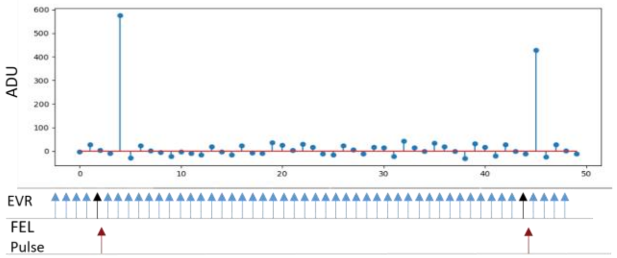


Measured linearity for different gain modes at 5160 Hz.



Single, double and triple photon peak.





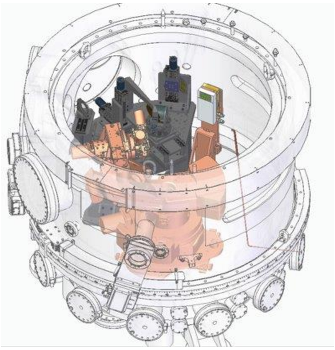
Pulse response when running detector at 4920 Hz, beam 120 Hz.

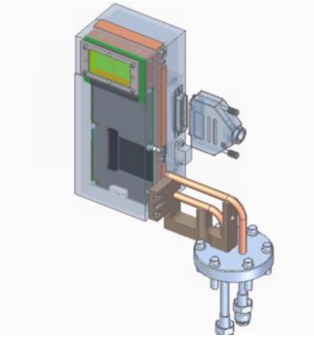
ePixHRM$_{5kHz}$ – soft X-ray imager for the end station 2.2

chemRIXS, REXS - ePixM

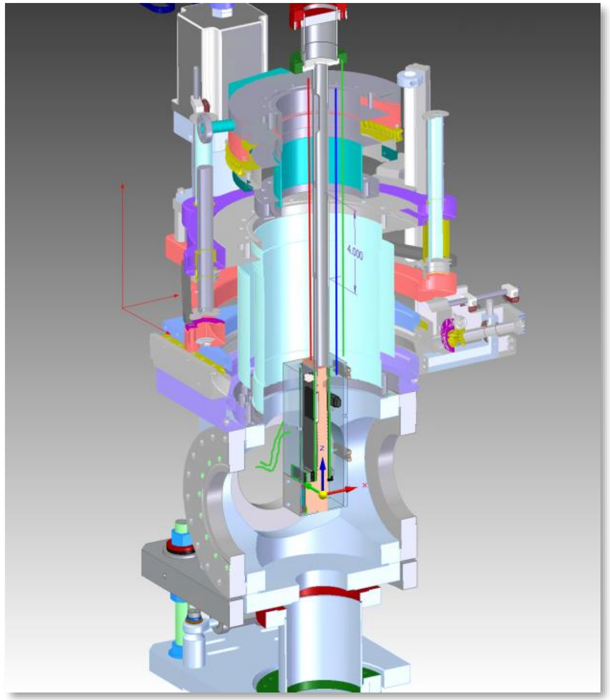
Model of the REXS chamber with the position ePixM position visible.

Picture of REXS camber at the RIXS station

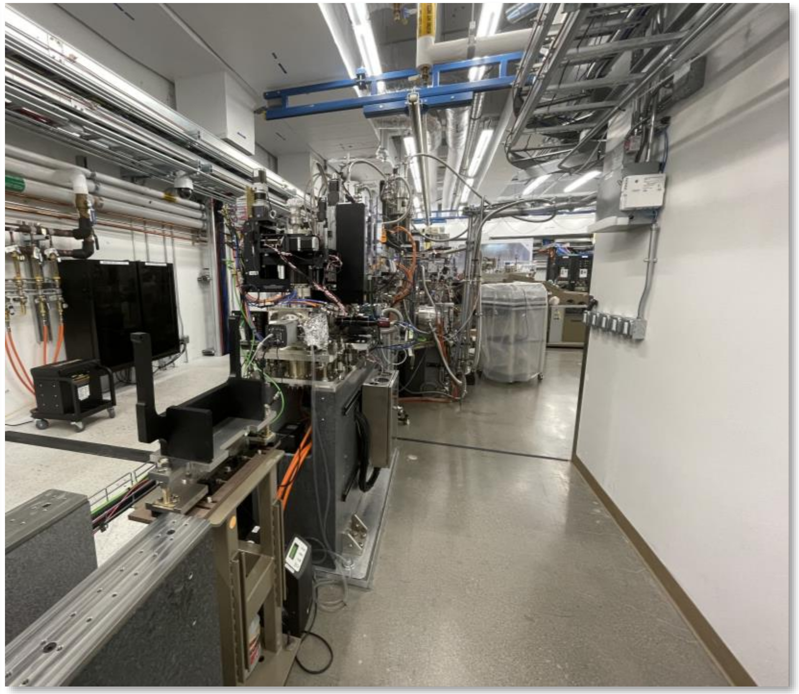




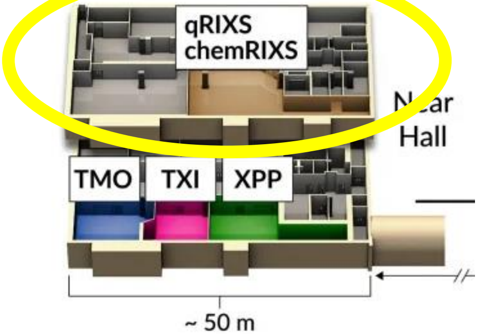
Model of the ePixM camera as designed for the REXS chamber



Model of the chemRIXS chamber with the position ePixM position visible.



Picture of the ChemRIXS station where one of the cameras will be installed.

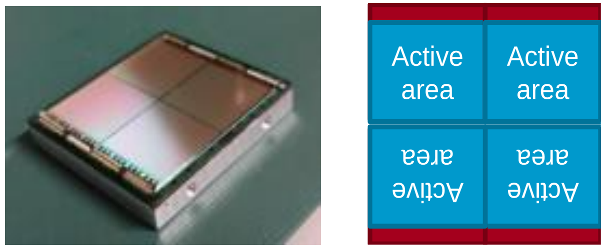


ePixM prototype

- Soft X-ray detector, sensitive to X-ray below 2 keV, running at 5kHz,
- Three small format cameras to be delivered within the year.
- Primarily targeted at spectroscopy, XAS/REXS, and XPCS (XPFS).
- Currently undergoing camera/calibration scheme development stage.

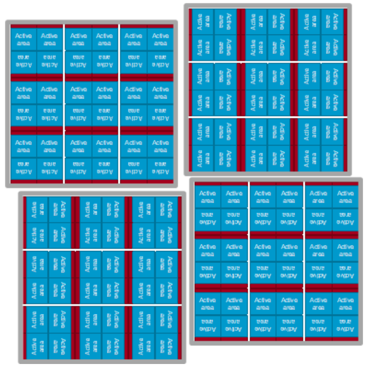
ePixHR$_{35khz}$ – Hard X-ray imager for LCLS-II-HE

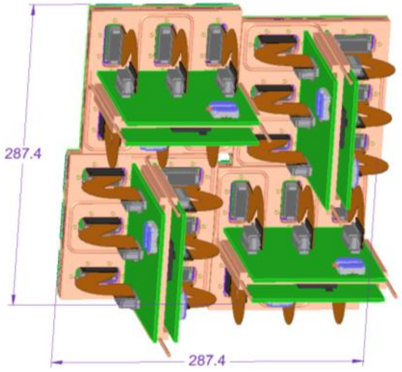
ePixHR/UHR – 140k



5cm x 5cm

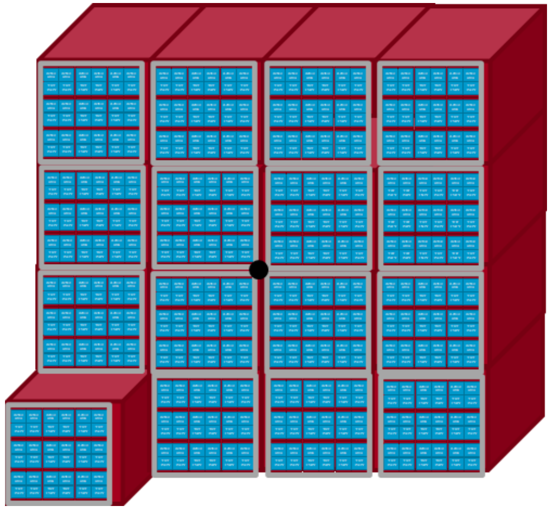
ePixHR/UHR – 4M





28cm x 28cm

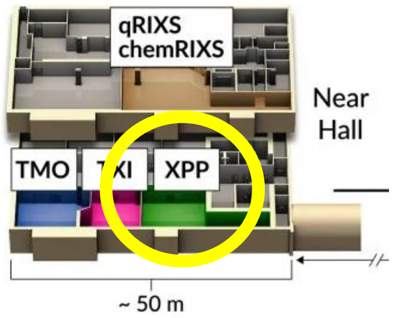
ePixHR/UHR – 16M

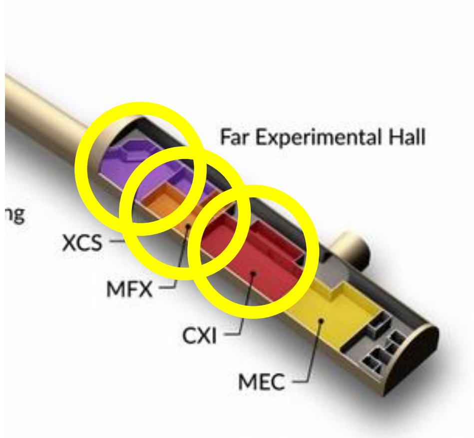


56cm x 56cm

ePixHR/UHR – 1M

14cm x 14cm





- Modular design, capable of producing different size cameras;
- Targeted at all the LCLS-II-HE hard X-ray hutches: DXS (XCS), MFX, CXI, and XPP.
- Currently undergoing development stage.
- First delivery for early 2026.

Summary:

1. The Detector pool supported by the LCLS detector department has evolved over the last year and this will continue in the coming year as LCLS undergoes its planned upgrades.
2. Four operational lessons learned where covered for the commissioning case studies:
   a) Radiation damage and large pulse exposure;
   b) Heartbeat monitor;
   c) Operating the detector in the sample environment;
   d) EMP resistance of detectors operating in harsh laser environments.
3. A brief overview of the coming high-rate detectors was covered.