Detectors at MAX IV

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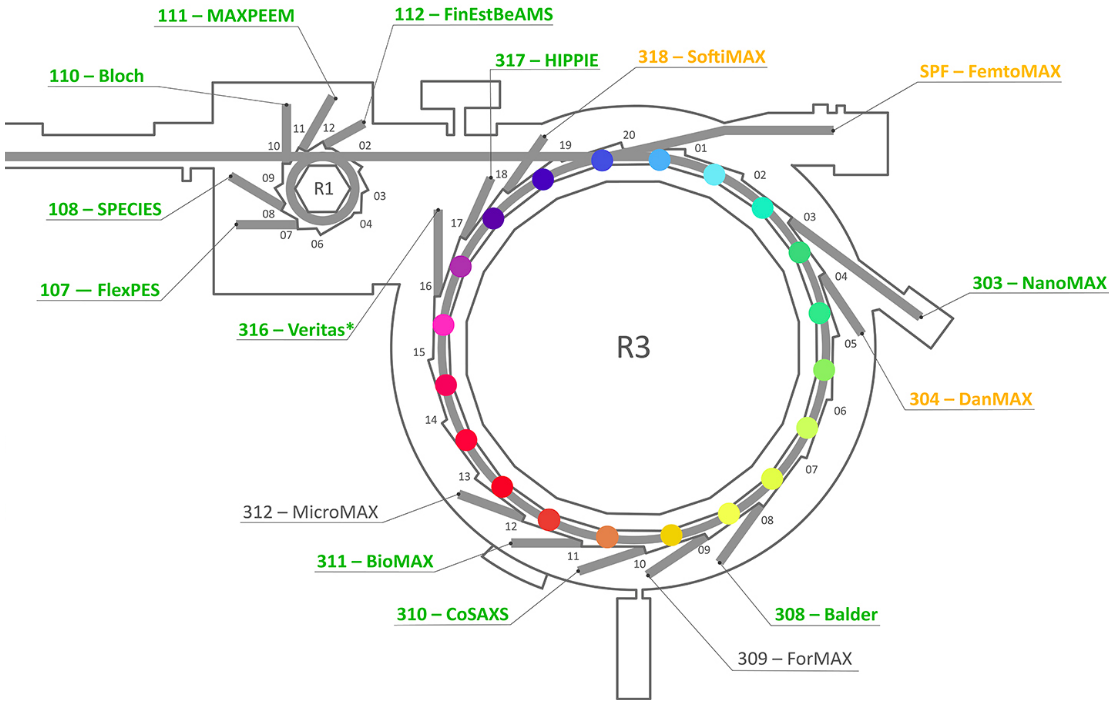
MAX IV, Detectors and Scientific Software group

Summary

- Overview
  - Facility status
  - Detector etc. group
- Detector/camera technologies
- Detector test and calibration
- DAQ and control systems
  - Slow control (Tango)
  - Data acquisition
  - Storage

Overview

- 3 GeV and 1.5 GeV storage rings
- full energy linac with Short Pulse Facility
- First beamline user operation 2016, now 11 beamlines in operation, 5 in commissioning, photon energies from 275 eV to 40KeV



Detectors and Scientific Software Group

- approx 50% det and 50% sci-sw
- Detectors half
  - Advise beamlines during procurement
  - Liaise with companies
  - Site Acceptance Tests + characterization and performance
  - Trouble shooting and updates
  - Work with rest of KITS on control and DAQ integration
  - Bring in non-commercial solutions

DETECTOR TECHNOLOGY

Pixel detector requirements

Typical (competing) requirements 2D detectors must satisfy:

- Provide good spatial resolution (100 - 5 um)
- Handle high incoming flux (~1E9 photons/s/mm^2)
- Allow high frame rate (kHz)
- Suitable energy range (1 to 40 KeV)
- Provide high dynamic range (12 – 32 bits)

Spectroscopy detectors and delay lines are left for a future meeting

Pixel Area Detectors

- General term for any pixelated solid state 2D X-ray photon detector
- Can use direct or indirect detection and be photon counting or charge integrating

Direct - hybrid detectors (separate sensor and electronics) - X-ray photons deposit their energy in the detector material (e.g. Si) directly

Indirect - eg sCMOS cameras for visible range - first a conversion is needed from X-rays to visible light (phosphorus) or electrons (MCP)

Pixel Area Detectors

Charge Integrating - energy of the detected photons integrated over an exposure time.

+ Can accept high incoming flux

- Information contained in the energy of the individual photon is lost

- Noise sources such as dark current are included in the integral

- Limited dynamic range (saturation), multiple gains required

Photon counting - readout electronics processes each single X-ray photon.

+ Threshold(s) allow noise free acquisition (any exp.)

+ Linear behaviour over the entire dynamic range as long as the counter depth is sufficient.

- Limited by incoming flux

- Charge sharing means photons lost at pixel corners

Direct detection + photon counting → hybrid photon counting detectors (HPCs) = current standard

Technologies

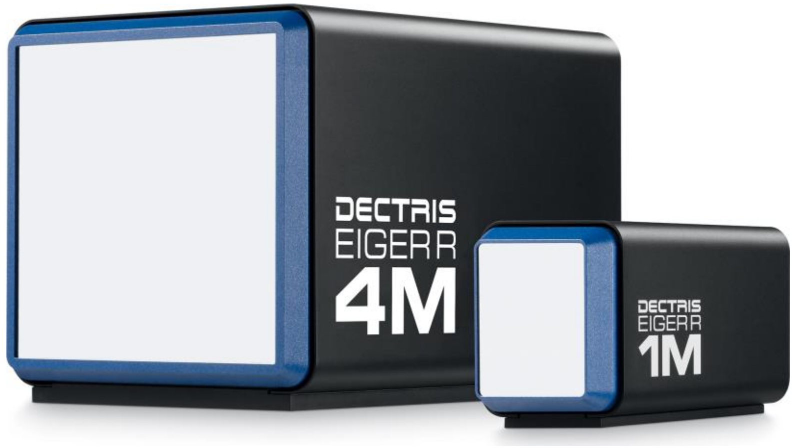
Come in several different types, e.g.:

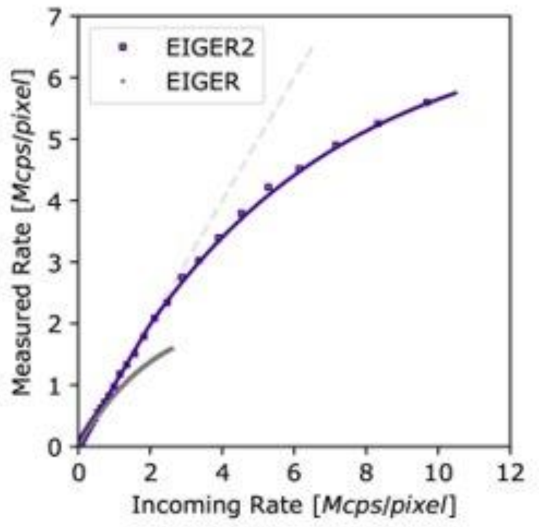
- **(s)CMOS** "cameras" (Andor Zyla, Tucsen Dhyana...)
  - usually require conversion (works with soft x-ray)
  - charge integrating → no limit on incoming flux
  - sCMOS is "low noise" but not zero (→ dark current)
  - limited frame rate (~10s of Hz)
  - small pixels

- **Hybrid Pixel (or Photon) Counting (HPC)** detectors (Eiger, Pilatus, Medipix...)
  - zero noise
  - high frame rate
  - hard X rays only (> ~4 KeV)
  - non-linearity at high flux (count rate)
  - pixel edge effects

HPC examples – Dectris Eiger & Eiger2

- Several examples at MAX IV, both Eiger and Eiger2
- 500Hz max frame rate (E2-4M)
- **Eiger**: 3ms dead time, max 10^6 photons/pixel/s
- **Eiger2**: ”continuous readout” (double counters), max 10^7 photons/pixel/s (retriggering)
- Two energy thresholds per channel
- http interface for control, data written to DCU or streamed via ZMQ.
- Throughput 1GB/s (E2-4M)





DETECTOR CALIBRATION

HPC Site Acceptance Test- Custom X-Spectrum Lambda

Medipix3: CERN technology commercialized via research-industry consortium

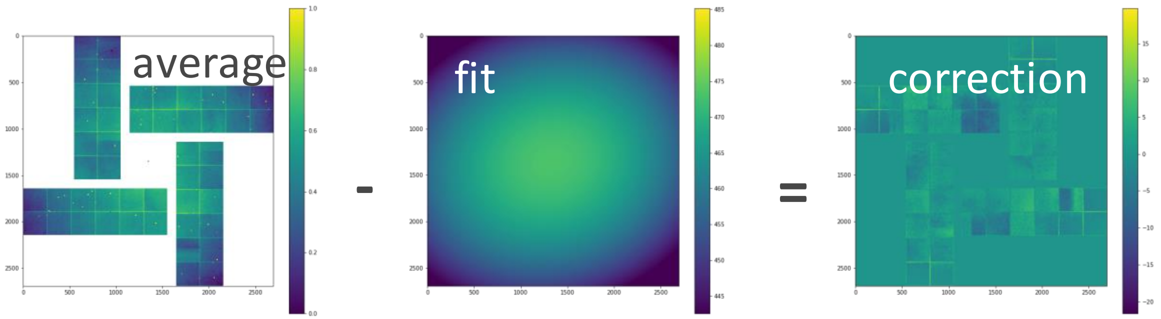
- 4 X-Spectrum modules in "windmill" pattern with center hole
  - 4x 750Kpx modules = 3Mpx
  - 2X DCU working in parallel
- 55 µm pixel pitch
- E > 5 KeV
- 12bit, 2kHz (faster with smaller counter) → 4x 18GB/s

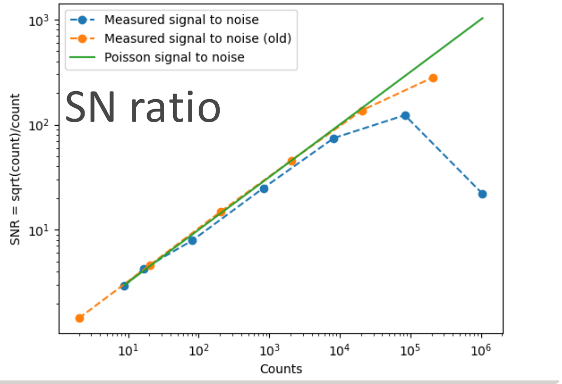
MAX IV

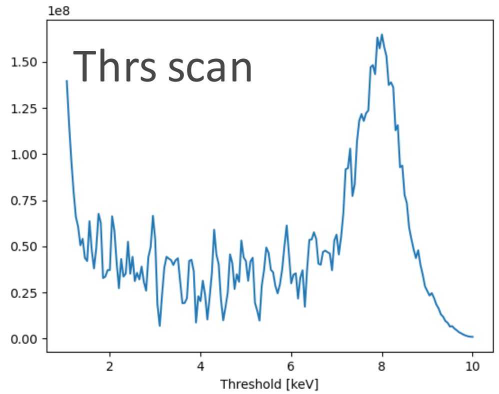
HPC Site Acceptance Test- Custom Xspectrum Lambda

- Flat field correction
  - Subtract beam profile to estimate deviations
- Signal to noise ratio
  - (Mean)/(std dev) ≈ √N
- Threshold scan
  - ΔE / Δthrs
  - Width of peak gives thrs. dispersion

Flat field correction







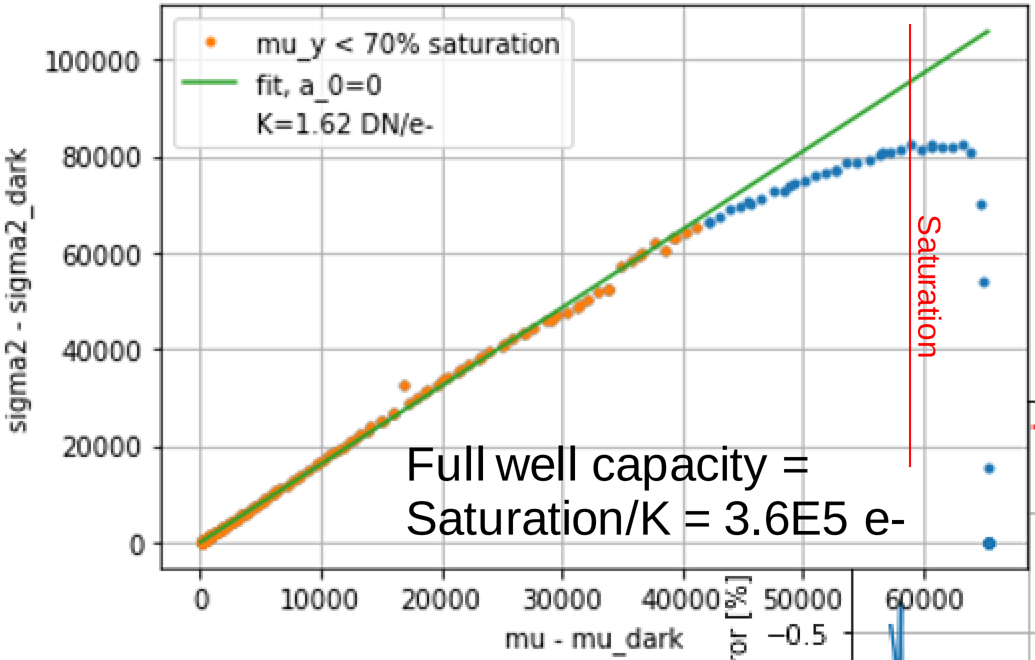
sCMOS Site Acceptance Test – Hamamatsu Orca

- 5.5µm pixel pitch, 12 Mpx
- 120Hz max at 12 bit = 2 GB / s data rate
- Readout to frame grabber card is 4 lane CoaXPress
- To be used for tomography station

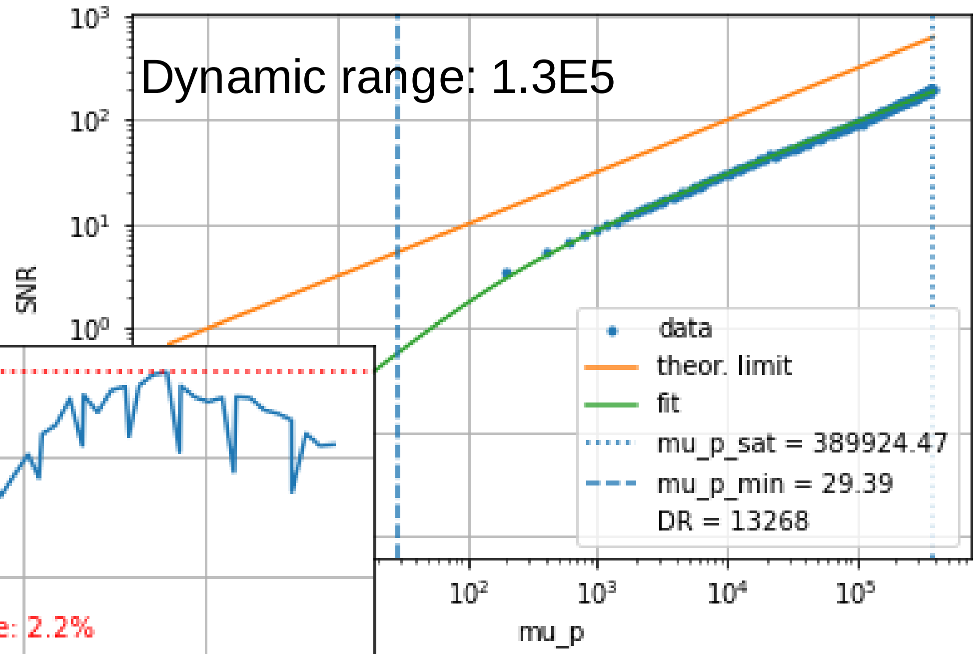
EMVA 1288 test

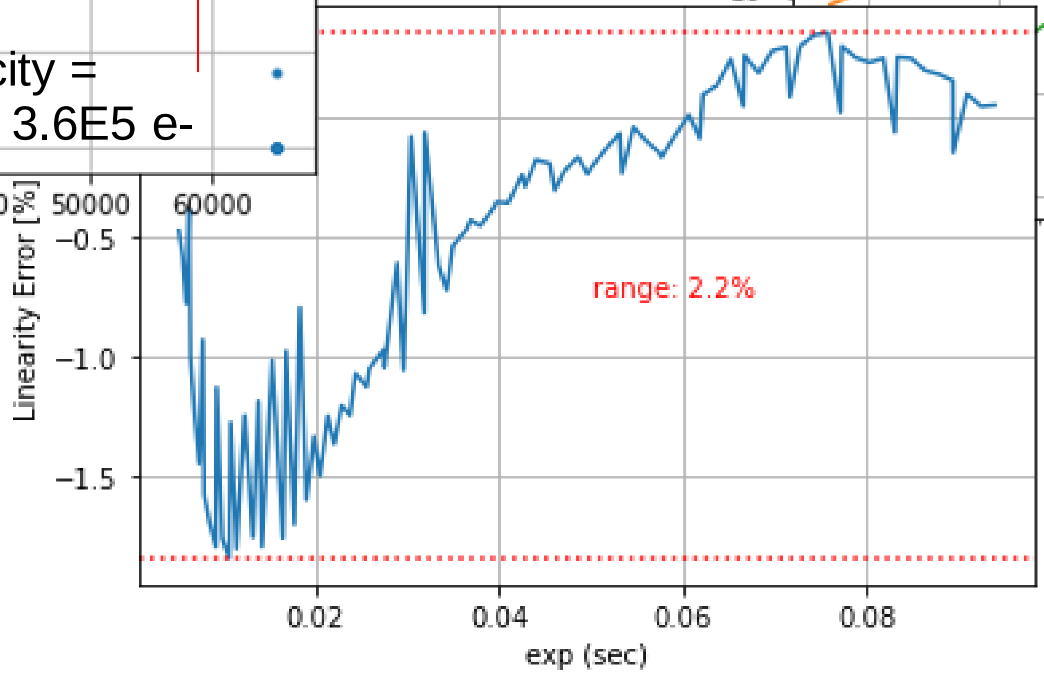
- Exposure scan with uniform illumination OR fix exposure and vary light intensity
- Let you determine:
  - Gain (ADC / e-)
  - Full well capacity
  - Linearity
  - SNR → Dynamic range
- Analysis is 90% automatic

sCMOS Site Acceptance Test – Hamamatsu Orca



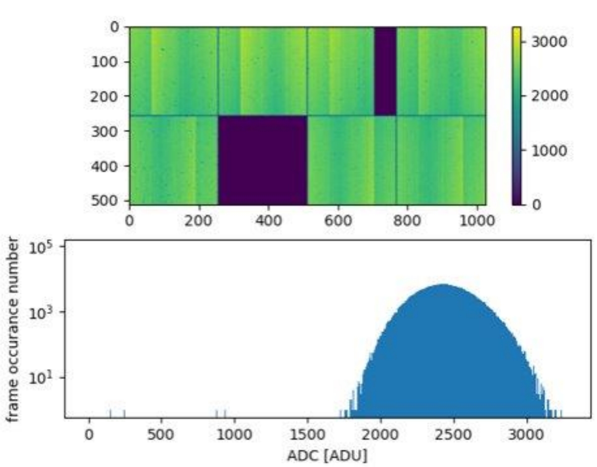
EMVA v3.0

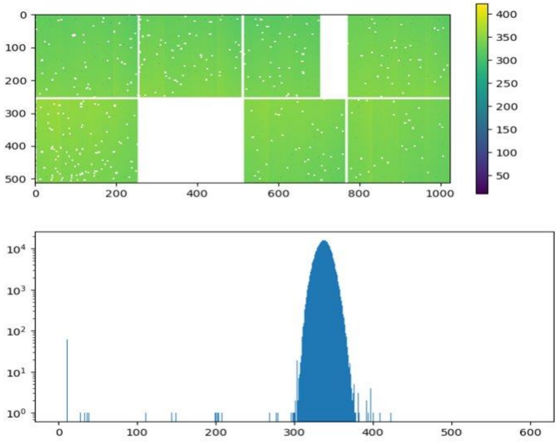




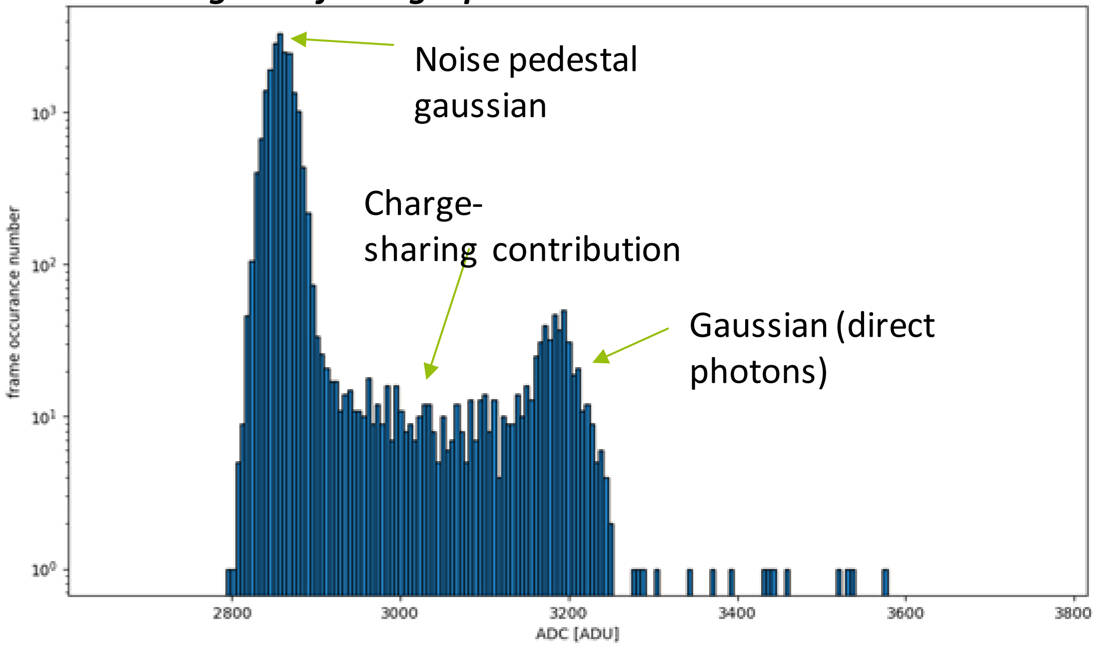
Non-commercial example: JUNGFRAU

- Direct detection CMOS for SwissFEL
- Charge integrating, multi gain, 1.1KHz
- 4Mpx detector planned for MicroMAX
- Pixel to pixel calibration using single photons



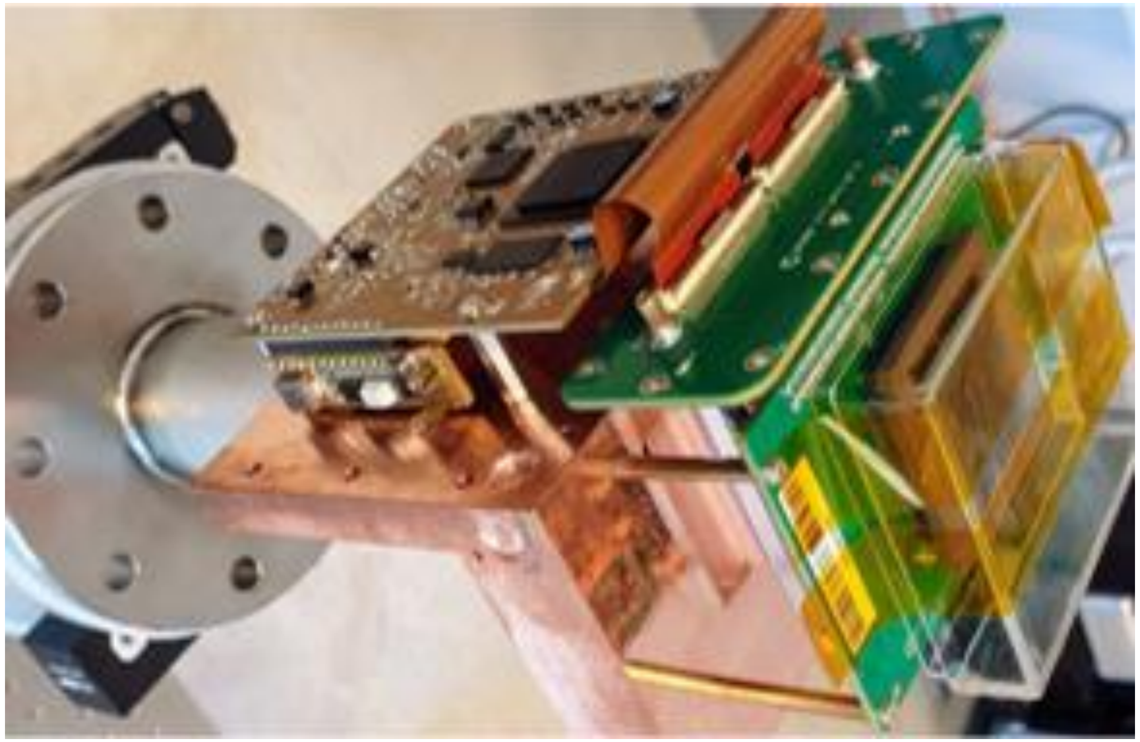


Histogram of a single pixel



Other non-commercial solutions

- Tristan
  - 1Mpx, Timepix3 based; developed at Diamond
- Dhyana
  - commercial back-illuminated sCMOS, sensitive to Xrays
  - Adapted for vacuum
- Full speed Timepix3 readout R&D
  - With Sunsval



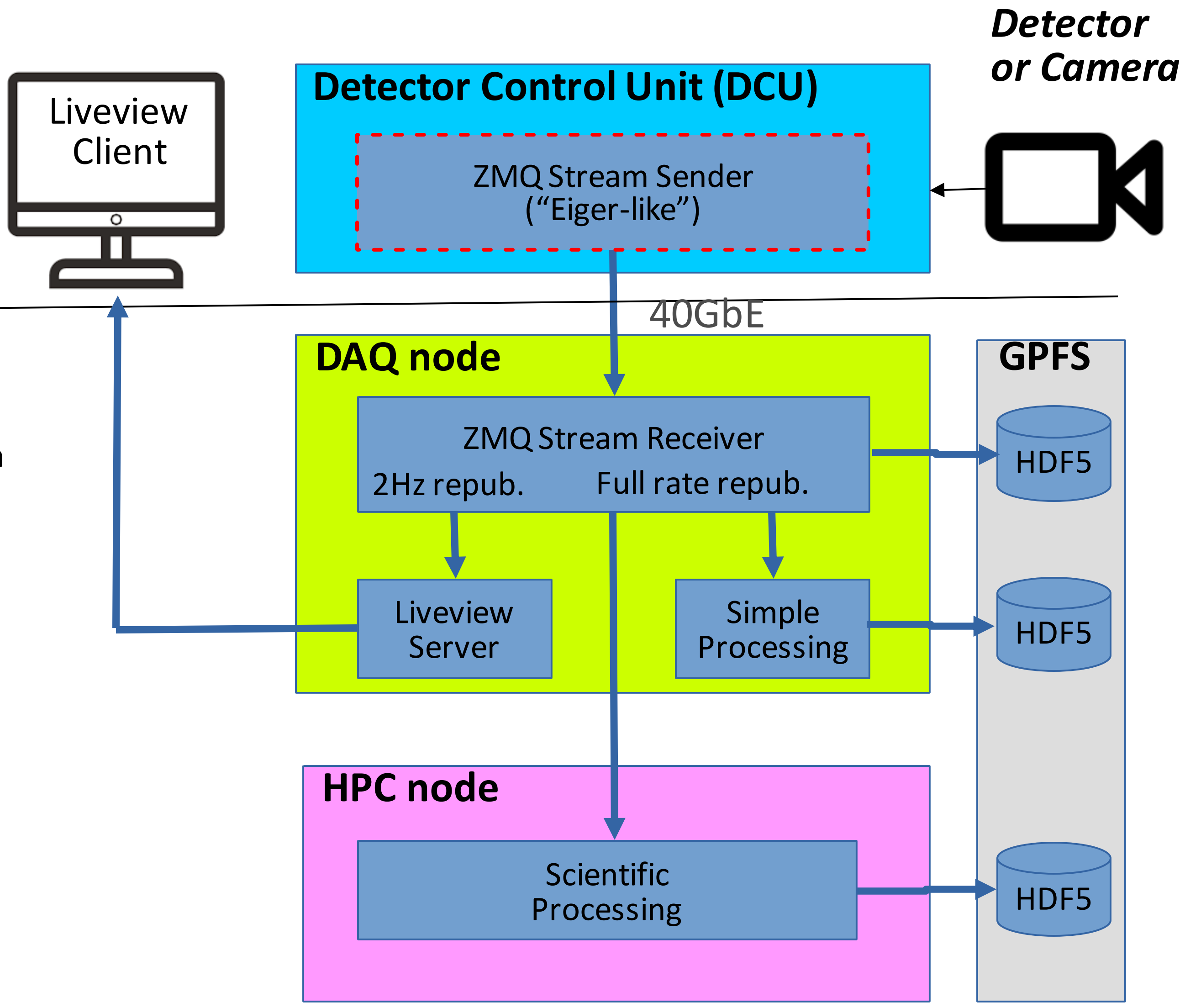
CONTROL SYSTEMS

MAX IV DAQ flow scheme

Beamline

Server room

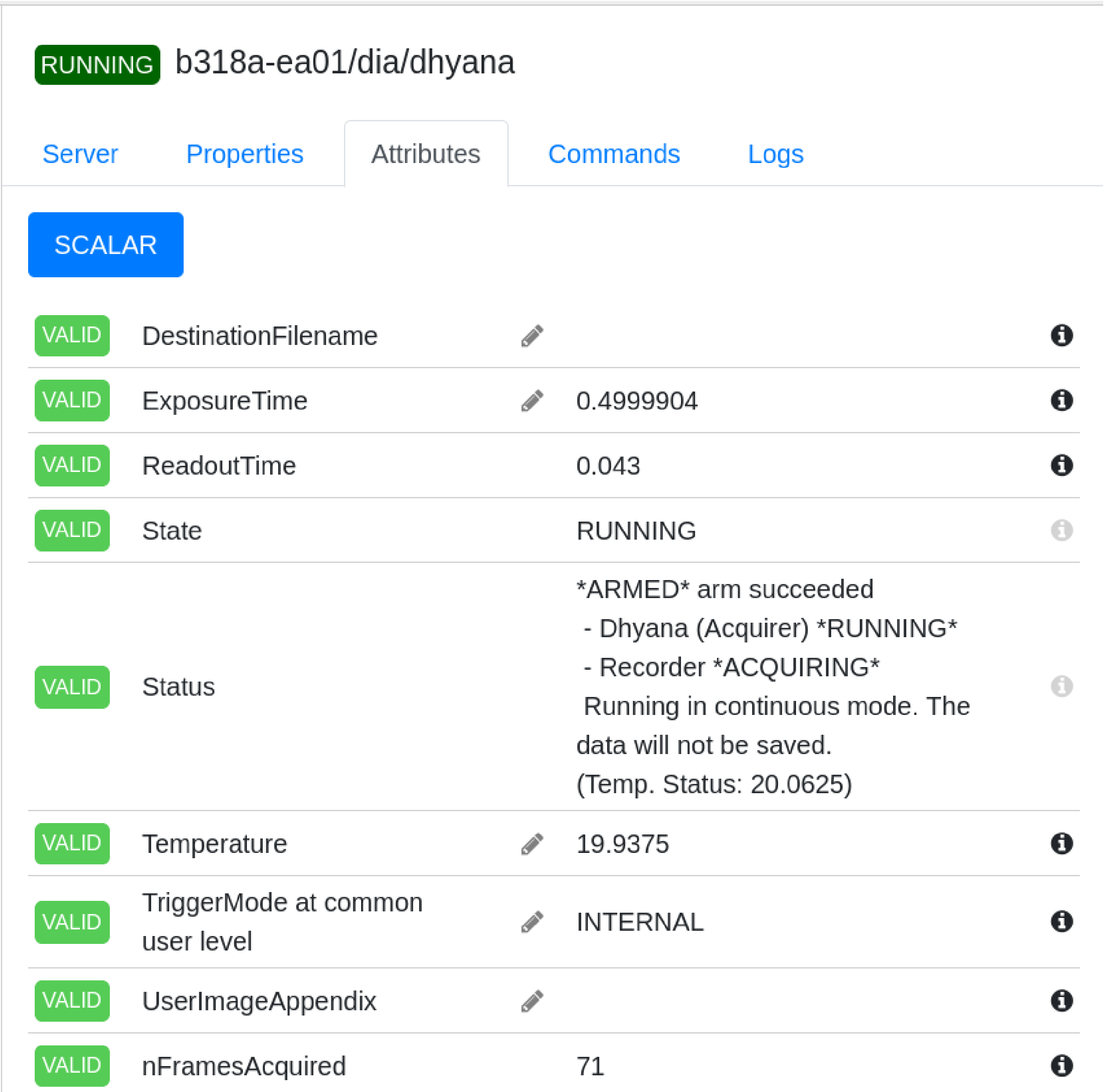
NB Control layer (Tango) not shown

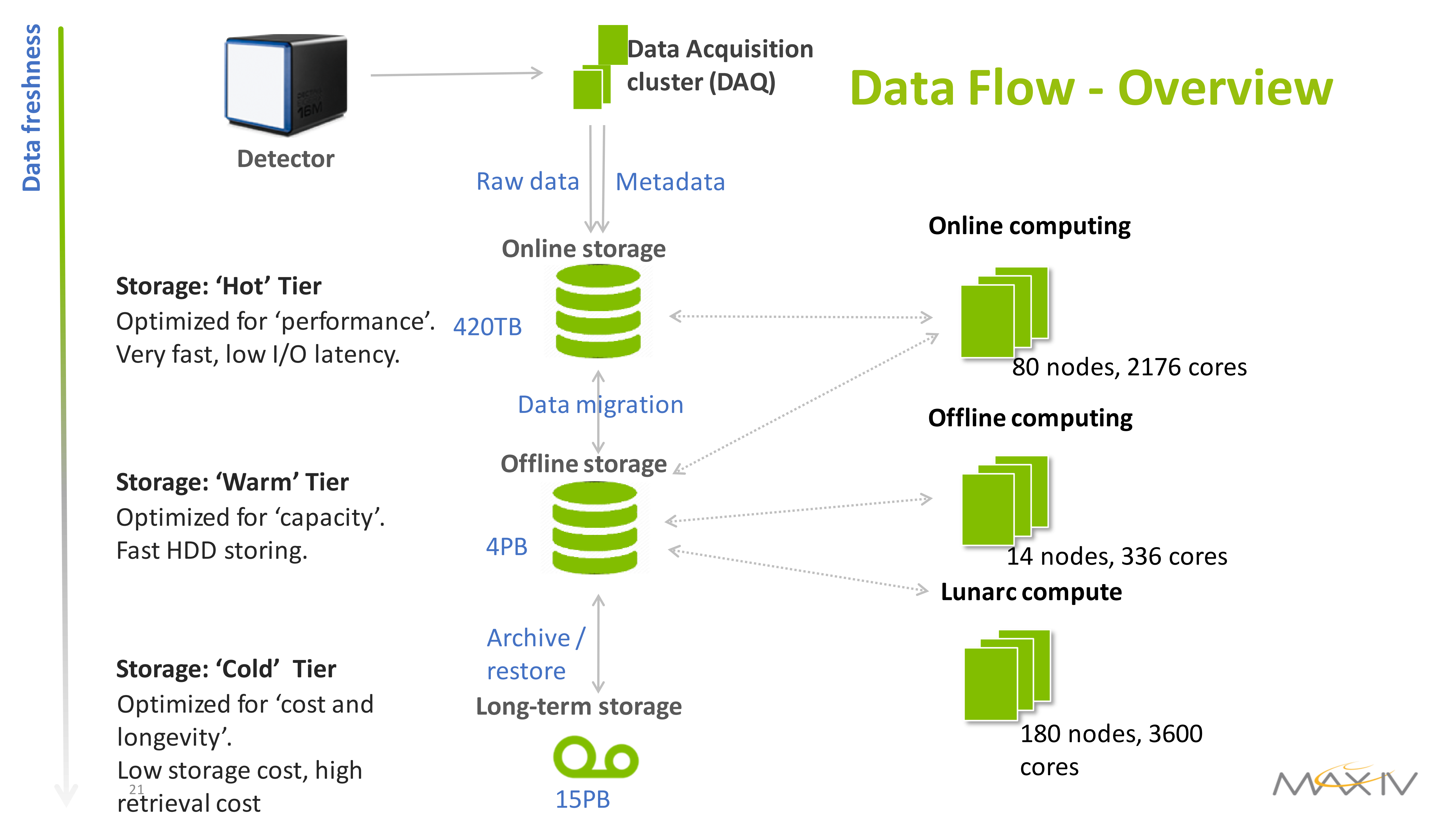


- ***Design: ZMQ streaming where needed***
- 40GbE connection DCU to DAQ cluster from where data saved to hdf5 (GPFS)
- **Done**: Eiger2, Pilatus, Andor, Dhyana...

Typical detector device

- Devices: standard interface to systems
  - state
  - commands
  - attributes
- Uniform interface to wildly different detectors
  - Space for det specific properties
- Can be used directly or as ground layer for orchestration




Data Flow - Overview
Data freshness
Detector
Data Acquisition cluster (DAQ)
Raw data
Metadata
Online storage
Storage: 'Hot' Tier
Optimized for 'performance'.
Very fast, low I/O latency.
420TB
Online computing
80 nodes, 2176 cores
Data migration
Offline computing
Offline storage
Storage: 'Warm' Tier
Optimized for 'capacity'.
Fast HDD storing.
4PB
14 nodes, 336 cores
Lunarc compute
Archive / restore
Long-term storage
Storage: 'Cold' Tier
Optimized for 'cost and longevity'.
Low storage cost, high retrieval cost
15PB
180 nodes, 3600 cores

Summary

- Range of energies x range of requirements = range of detectors
  - sCMOS and HPC
  - Commercial vs research
  - ...
- Detector specific DCU + standardized DAQ and control
- Detectors drive infrastructure requirements


MAX IV

When commercial solutions are not enough...

- MicroMAX beamline expects 10^4 photons/pixel/10μs:
  → requires a charge integrating detector
- **JungFrau** 1M on loan from PSI: preparation of DAQ scheme, understand and characterise detector
- 4M **JungFrau** array being planned

- Strong interest in developing coherent techniques such as **X-ray Photon Correlation Spectroscopy (XPCS)** → requires time resolution
- Planning to loan a Timepix3-based **TRISTAN** 1M from DLS this year to run a demonstration XPCS experiment at the NanoMAX beamline

- Soft X-ray XPCS a further challenge (photon counting in general for soft X-rays)
- *→ exploring collaboration with Mid Sweden University and Uppsala University on development of small pixel sized LGADs for readout wit Timepix3 or Medipix3*

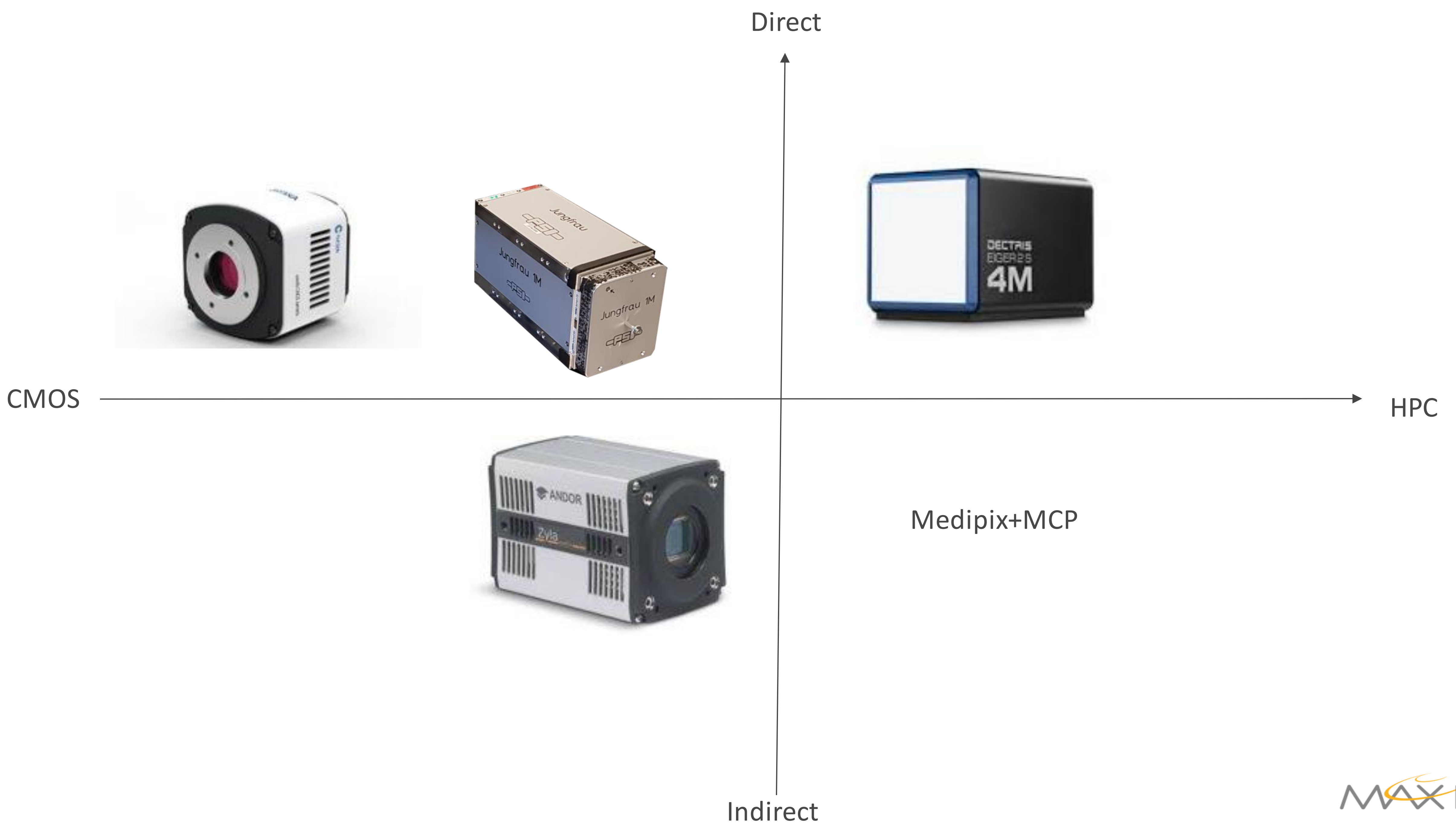
MAX IV

Commercial detectors

- **HPCs**
  - 3x Dectris Eiger2 4M, 3x Eiger1 1M, 1x Eiger1 16M
  - 1x Dectris Pilatus3 2M, 1x Pilatus2 1M
  - 1x Dectris Pilatus3 2M (WAXS L-shaped)
  - 1x XSpectrum Lamdba 3M (WAXS centre hole)
  - 1x Dectris Mythen
  - 1x QD Merlin Quad
- **sCMOS**
  - Numerous Andor Zyla, 1x Andor Balor
  - 1x Tucsen "DhyanaX" (NB: Adapted for vacuum following Soleil)
- **Spectroscopy**
  - 2x Amptek XR-100 SDD via QD Xspress3
  - 2x Rayspec SDD via QD Xspress3
  - 1x Canberra/Mirion 7 element SDD / HPGe via QD Xspress3
  - 1x Rayspec SDD Xia FalconX

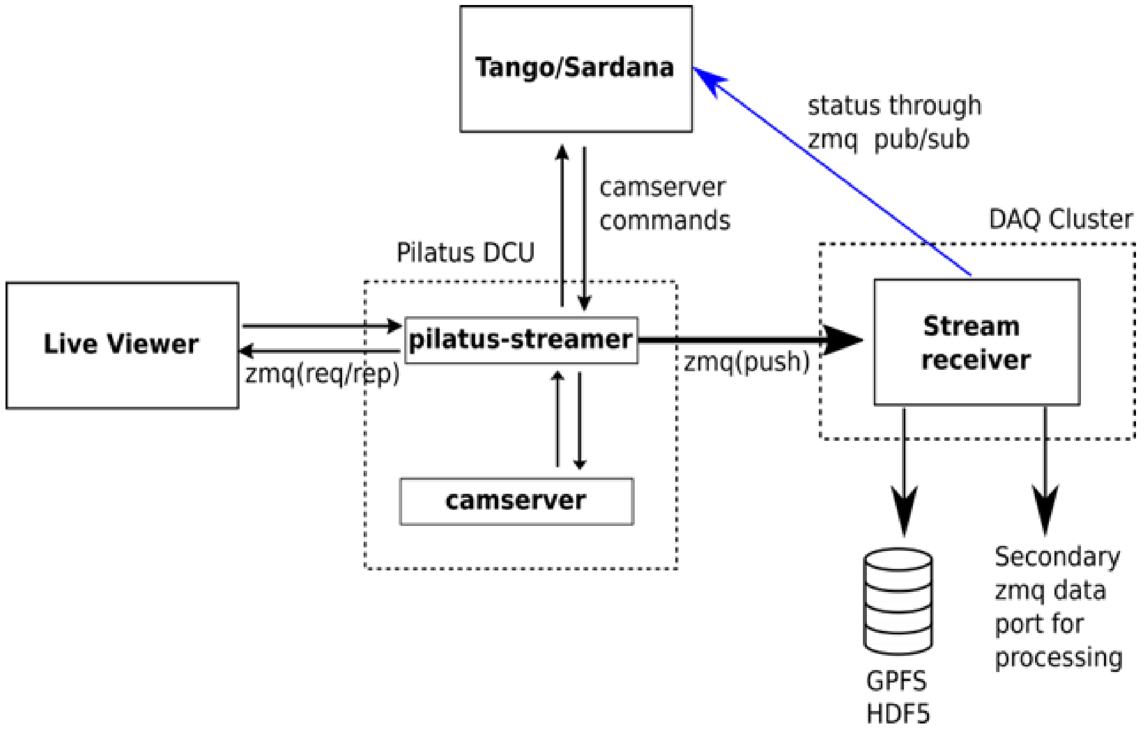
MAX IV


Flux
Rate
ANDOR
Jungfrau
Jungfrau 1M
Jungfrau 1M
DECTRIS
EIGER2 S
4M


Direct
CMOS
HPC
Indirect
Medipix+MCP
Jungfrau
Jungfrau 1M
Jungfrau 1M
DECTRIS
EIGER2 S
4M
ANDOR
Zyla

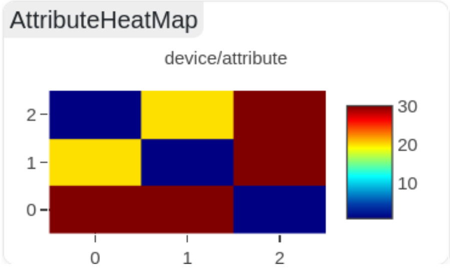
Control and DAQ example: Pilatus

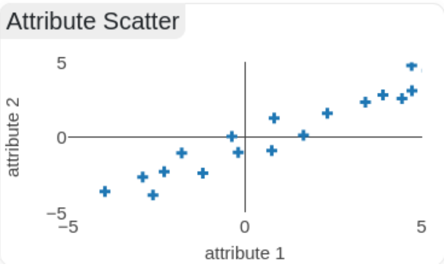
- Tango: based on actor model
  - Protocol
  - API
  - tools
- Devices: standard interface to systems
  - state
  - commands
  - attributes

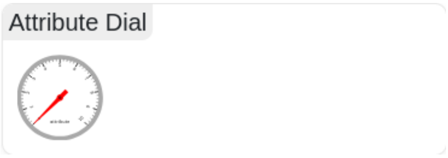


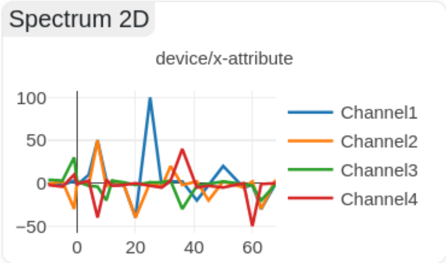
Webjive / Taranta

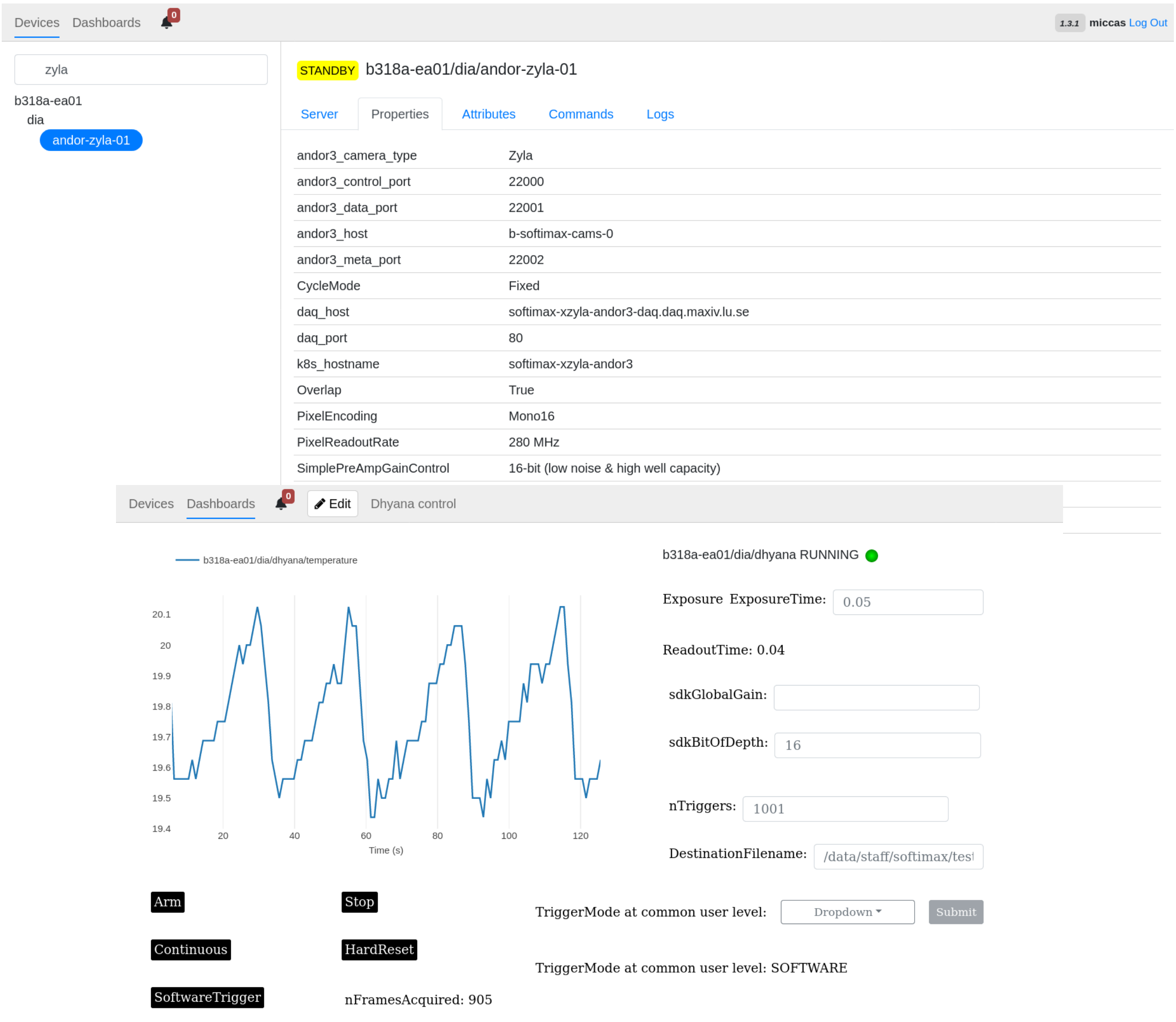
- Taranta: a web application to interact with Tango devices.
- Access to properties and commands (Webjive)
- Customizable dashboards:
  - Charts, indicators, dials...











CMOS and sCMOS cameras

- sCMOS = "scientific CMOS", next generation fabrication method, less noise and higher frame rates (NB still not very fast for us – 10s of Hz / fps)
- Also generally known as **Active Pixel Sensors** (APS)
- Operating principle:
  - each pixel is a photo diode
  - incident photon generates electron-hole pairs
  - electrons accumulated in a potential well
  - each pixel does its own digitisation (faster than **CCDs**)
- (s)CMOS cameras are fundamentally **charge integrating** not **photon counting:**
  - Signal proportional to sum of photon energies.
  - Noise sources such as dark current are also included in the integral
  - Counter is arbitrary scale (requires calibration)

Anatomy of the Active Pixel Sensor Photodiode

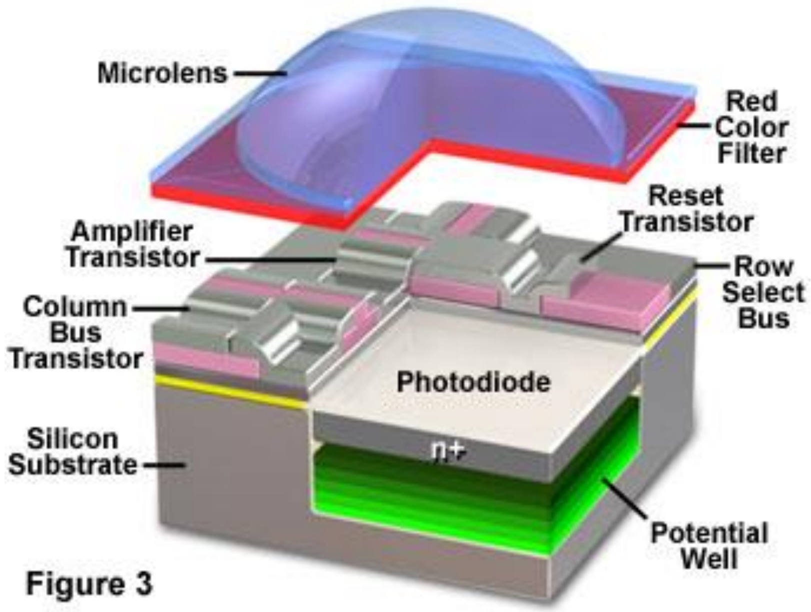
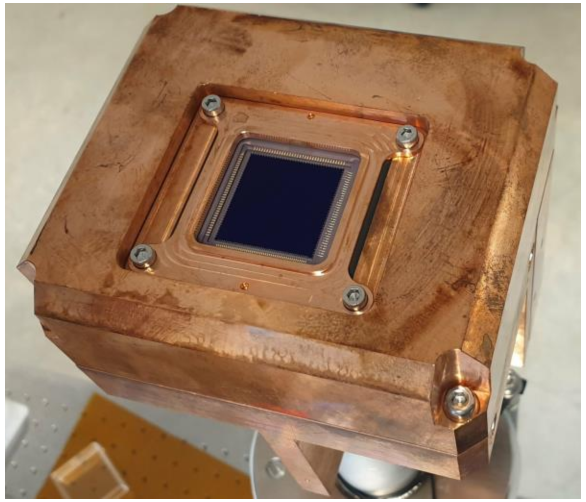


Figure 3

CMOS and sCMOS cameras

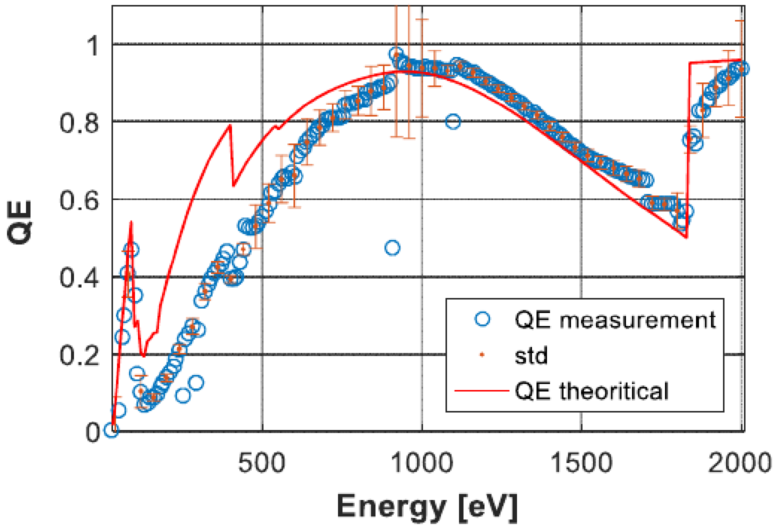


Reference parameters:

- - “**noise**” (dark noise and read noise components)
- - **pixel well depth**: how much charge can be accumulated in each pixel
- - **dynamic range** = ratio of well depth to noise (i.e. brightest to just discernible)

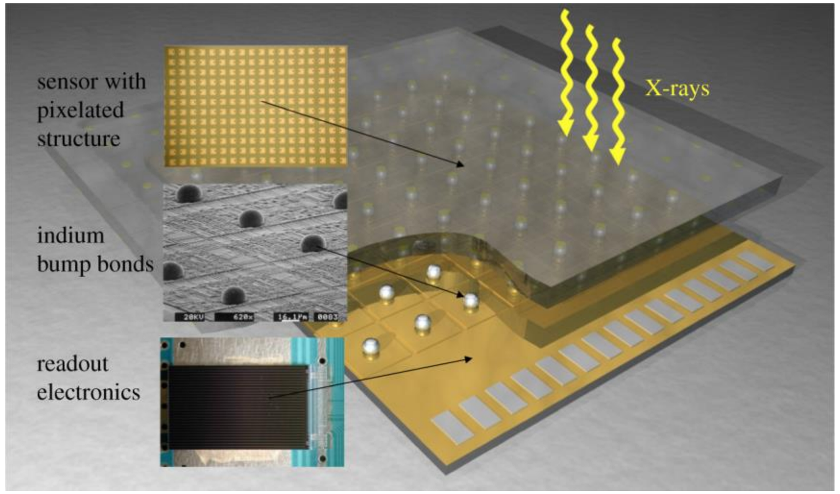
Direct/indirect :

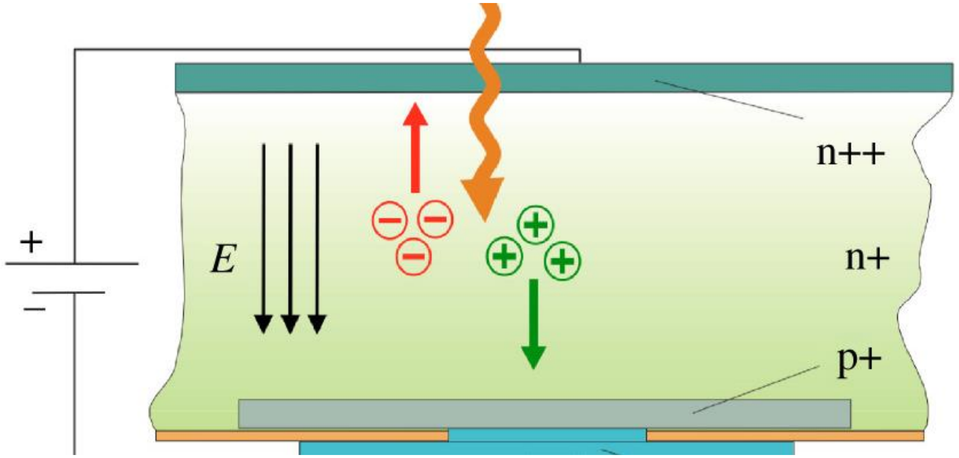
- (s)CMOS cameras are sensitive to photons in the visible range. X ray photons are detected “**indirectly**”, with some scintillator first generating visible light (e.g. the phosphor coating on the Andor Zyla camera at Softimax).
- May be **front** or **back illuminated** – back illuminated gives higher efficiency as incident photons do not first have to pass through the circuitry (e.g. Dyhana camera at Softimax)



Hybrid Photon Counting Detectors (HPCs)

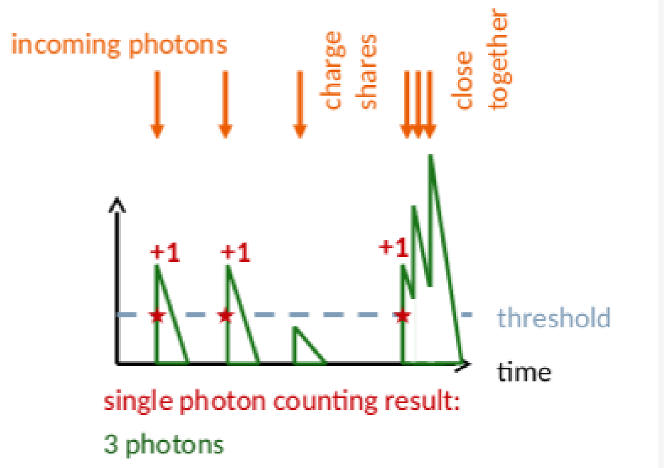
- Principle: separate high resistivity sensor (**direct detection** of X-ray photons with high efficiency) from low resistivity CMOS electronics (ASICs for signal processing, storage and output)
- Readout electronics process each single X-ray photon
- Final output is a photon count in each pixel
- (Dynamic range simply = counter depth now)
- Fast, so high frame rate (to kHz range)





Separate high resistivity sensor (direct detection) from low

ASICs for HPCs



- Basic role of ASIC:
  - Amplify detected charge
  - Compare to threshold
  - Increment counter
- ASICS/sensors typically combined in modules to give larger areas
- **Main players at MAX IV in hard X ray region, approx 5-40keV:**
- Pilatus (PSI/Dectris)
  - Pilatus1 originated from CERN CMS collaboration via PSI
  - Pilatus2 PSI/Dectris: 497x192 pixels, 172µm square, 20 bit depth counter
  - Pilatus3 increases max count rate with retriggering feature (++counter if over threshold for extended period),

Photon Counting pros and cons

+ The threshold is set above the electronics noise so long acquisition times with “zero noise” are possible

+ Linear behaviour over the entire dynamic range as long as the counter depth is sufficient.

+ High frame rate up to kHz

+ Can swap Si for some other material more efficient at high energy

- Limit on incoming flux, say $1\text{x}10^7$ photons/pixel/s (no such limit if charge integrating) (counting may not be linear with incoming flux)

- Charge sharing means photons lost at pixel corners (set threshold to be half the energy so that on boundary photon is counted in one pixel or the other)

- Relatively large pixel size (~10x) compared to CMOS cameras

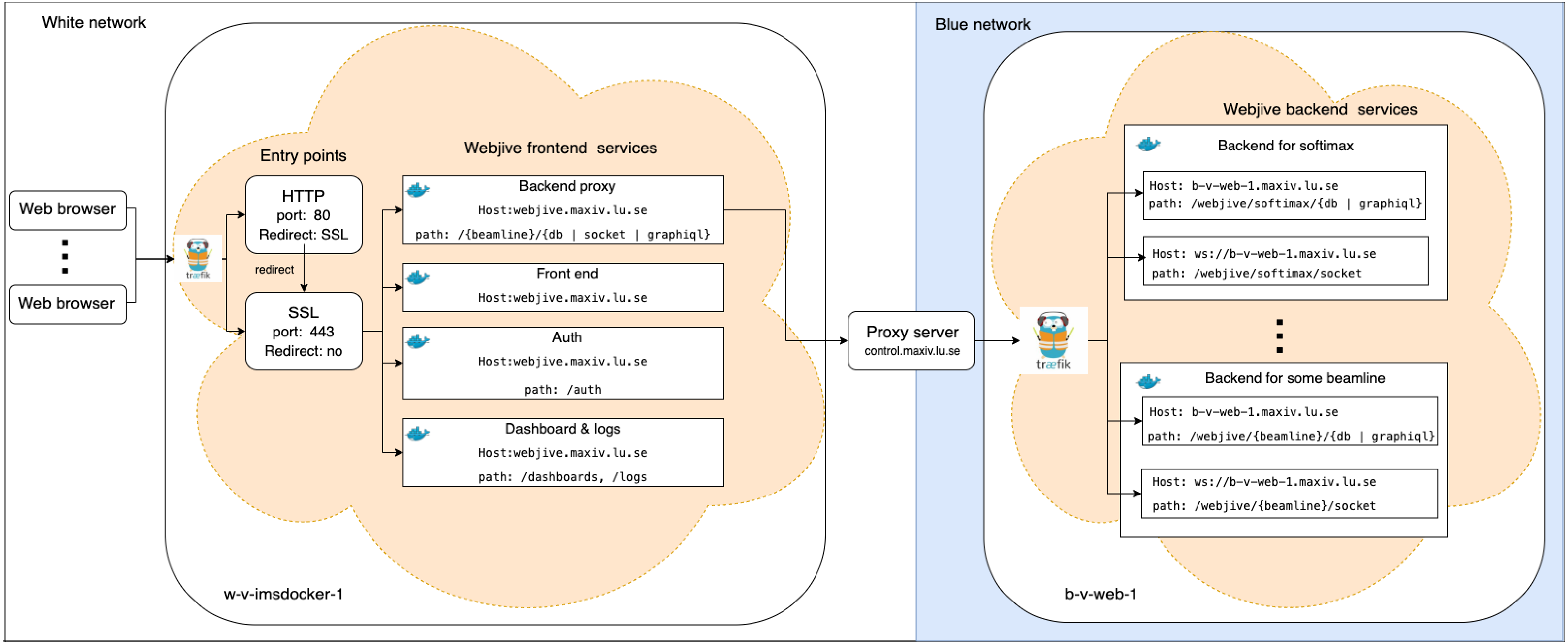
HPC examples – Dectris Pilatus 3

- e.g. 2M example at DanMAX, CoSAXs to receive another this year
- Max frame rate 500 Hz at 20 bit
- 0.94ms readout time between frames
- Max incoming flux 1×10^7 photons/pixel/s
- Comes with a dedicated Detector Control Computer (DCU)
- Writes image data to files on DCU

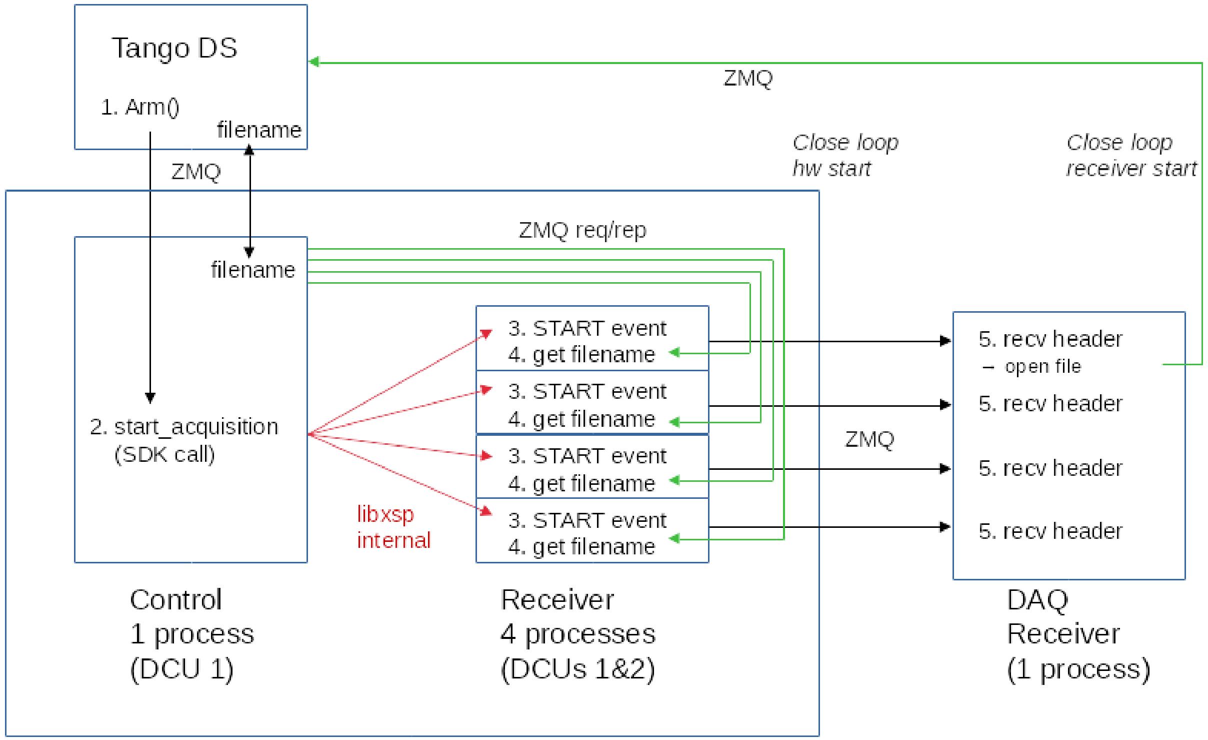
Our DAQ: open image files and stream out over ZMQ to DAQ cluster

- Count rate (max flux) increased over Pilatus2 via retriggering feature

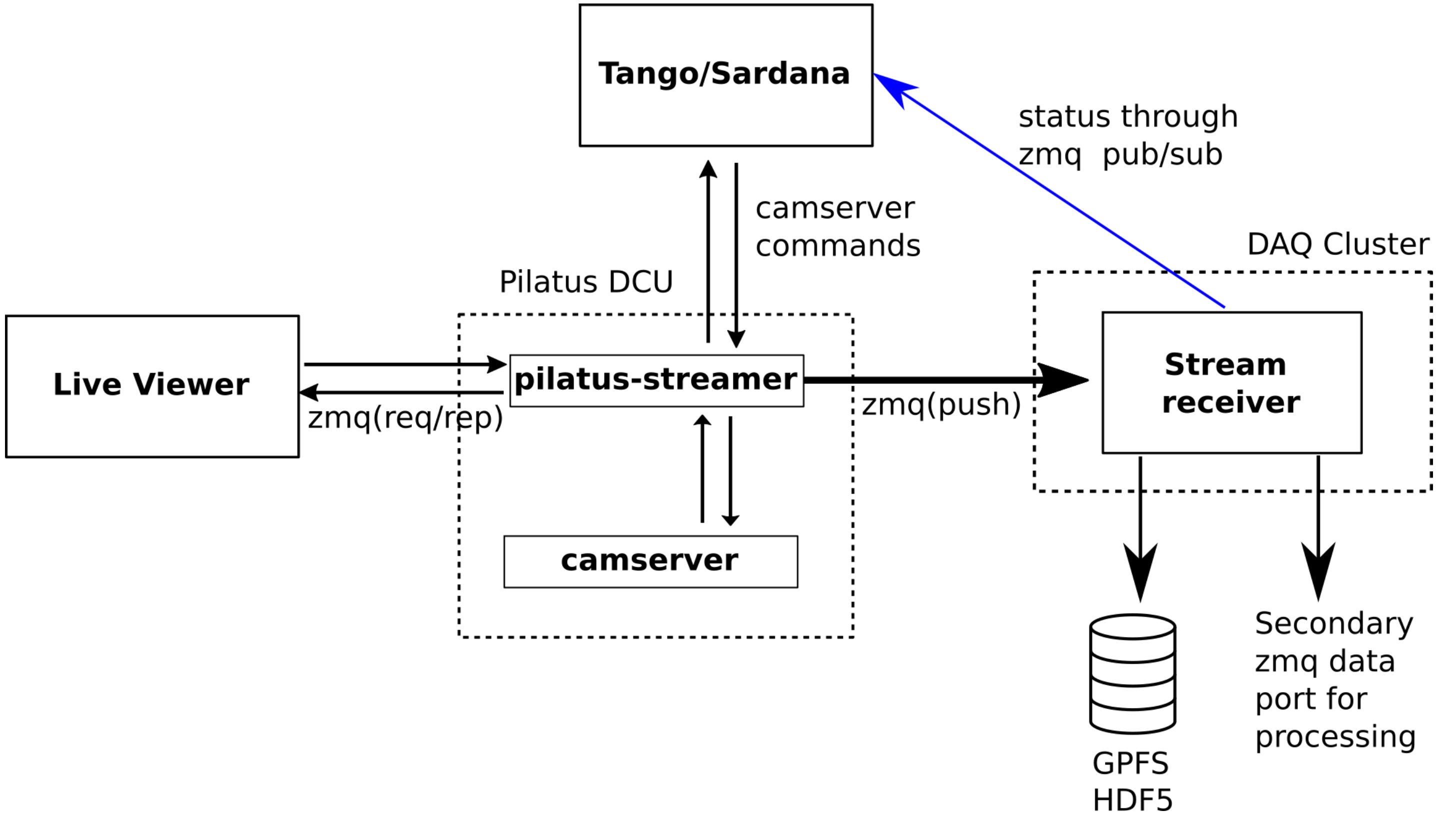
Tango: webJive



Lambda "windmill" control scheme

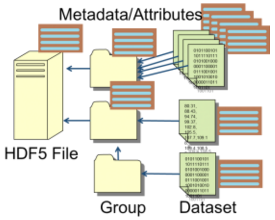


Control and DAQ example: Pilatus



Experiment Orchestration with SARDANA

SCAN ORCHESTRATION



peristaltic pump

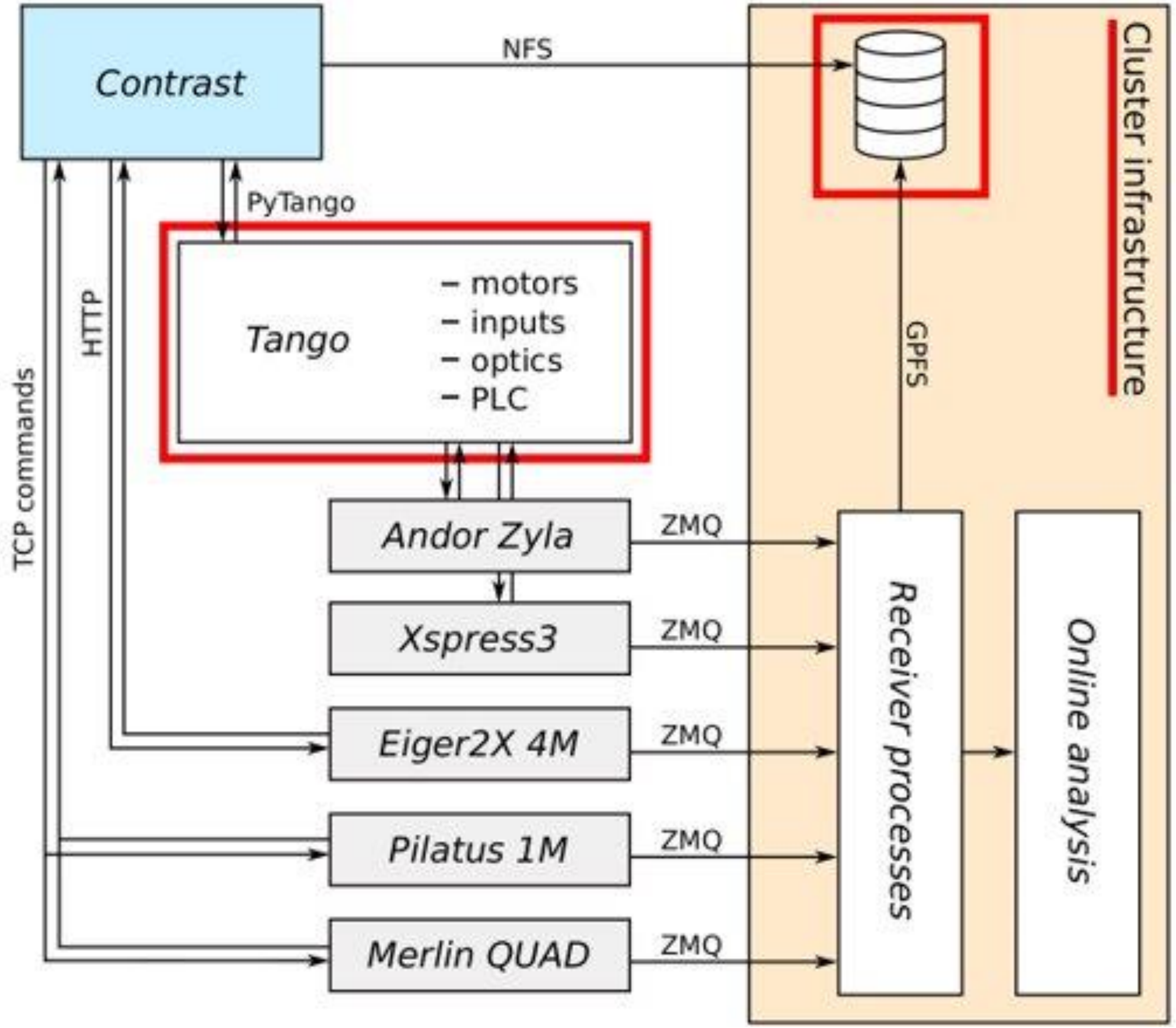
detector

START DATA RECORD → RUN PRE-SCAN HOOKS → PREPARE EQUIPMENTS → DATA ACQUISITION

DATA ACQUISITION → END DATA RECORD → RUN POST-SCAN HOOKS

DATA ACQUISITION → SYNCHRONIZATION

Contrast based acquisition system



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