Calibration Strategy and Experimental Qualification of the First DEPFET Pixel Sensors of the DSSC Camera

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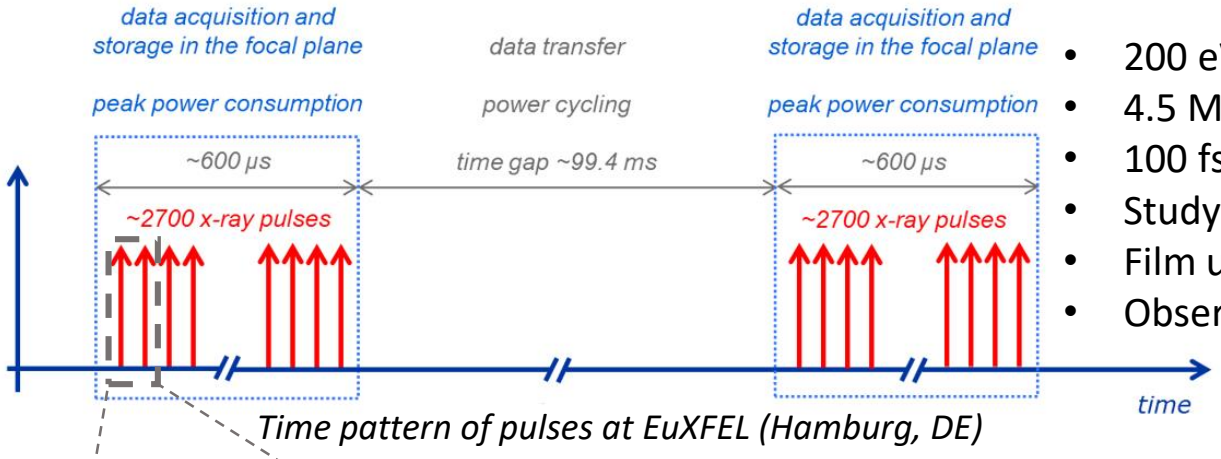
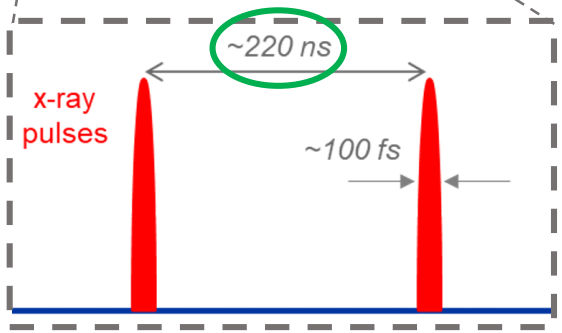
4: European XFEL GmbH, Schenefeld, Germany

Detectors for EuXFEL: a challenging detection system

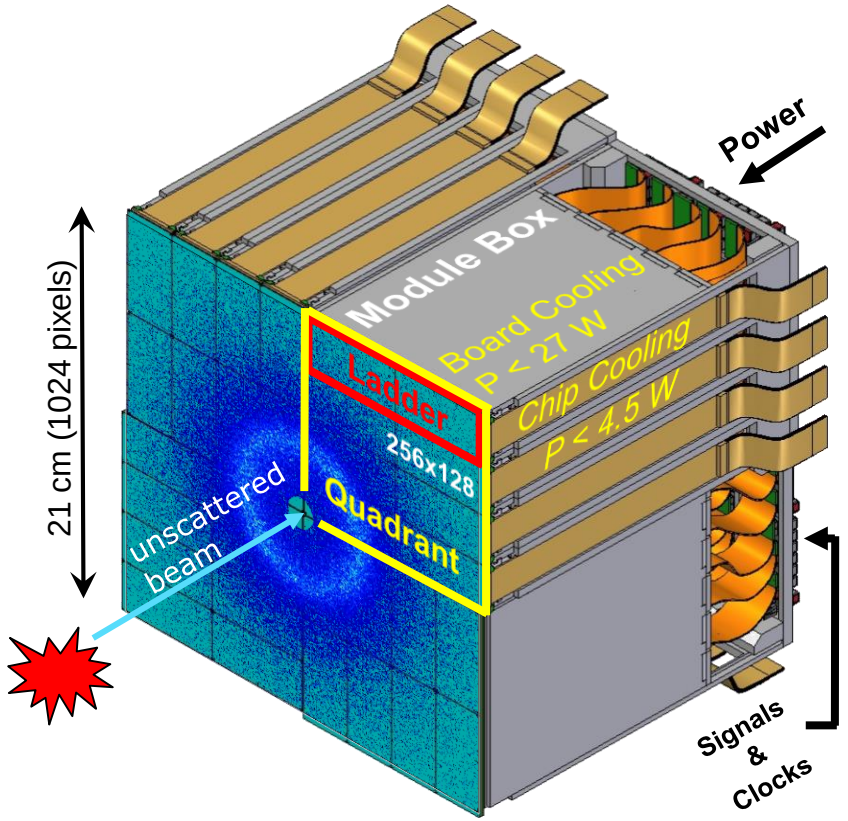
FEL: high brilliance X-ray source generating ultra-short X-ray pulses



Time pattern of pulses at EuXFEL (Hamburg, DE)



- 200 eV - 25 keV (0.05-4.7 nm)
- 4.5 MHz peak frequency
- 100 fs pulse width
- Study structure of molecules
- Film ultrafast phenomena
- Observe atoms in intense fields

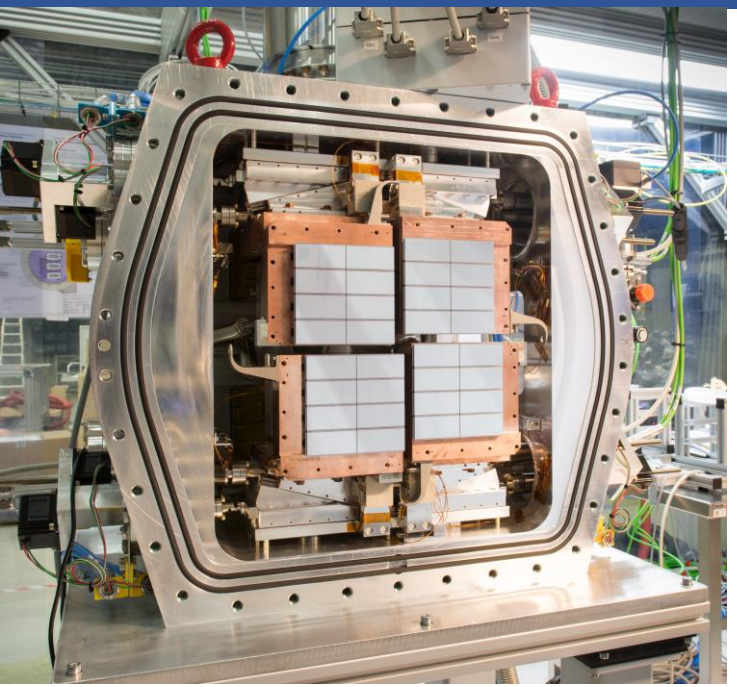


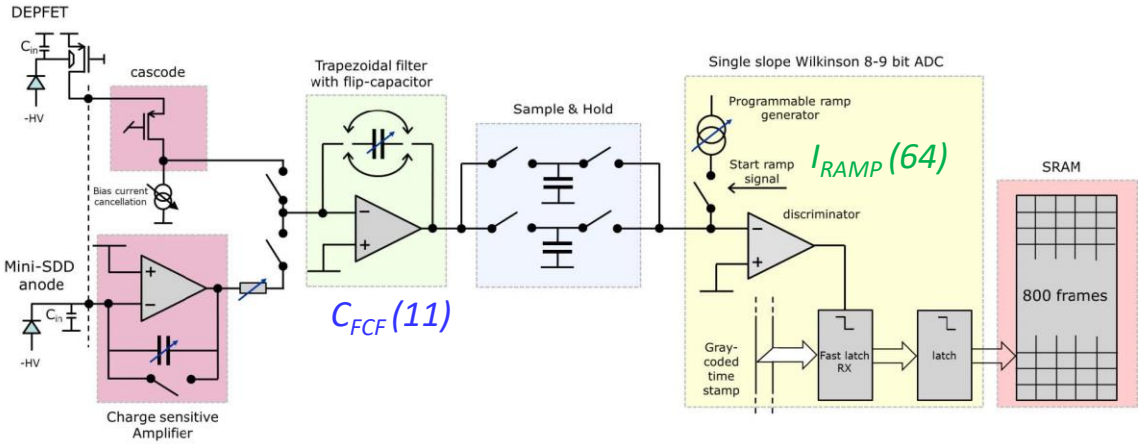
❑ DEPFET Sensor with Signal Compression (DSSC)

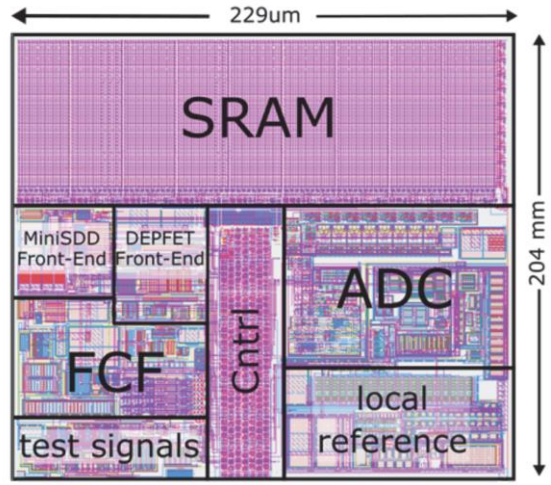
- **photon energy 0.5 – 6 keV (soft X-rays)**
- **frame rate 0.9 – 4.5 MHz**
- **single-photon sensitivity**
- **dynamic range 10,000 ph/pxl/pulse**
- 1 MPxl, 200 µm hex pixel
- digitization/storage during bunch train
- ~800 stored frames/macrobunch
- Average power dissipation 263W
- 2 versions developed: miniSDD based, DEPFET based

Geometry
4 quadrants (independently movable)
16 ladders (smallest functional unit)
32 monolithic sensors
256 readout ASIC (64x64 pxl)
Active area ~500 cm^2

DSSC camera 1st version: 1MPxl miniSDD





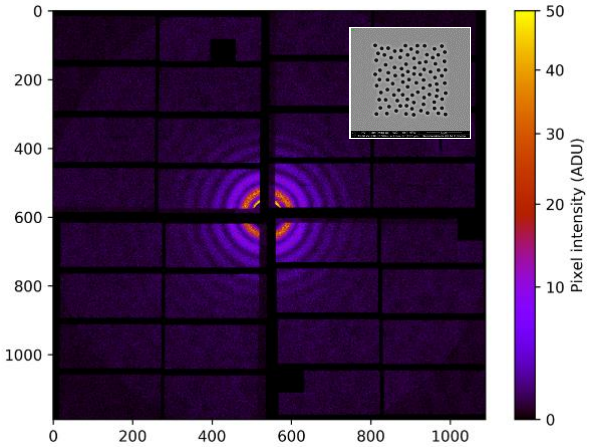


World's fastest soft X-ray imager

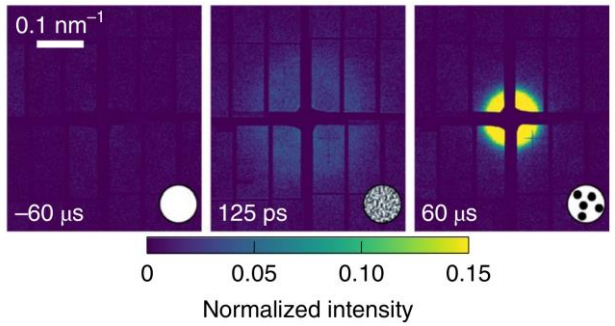
- Available for experiments since 05/2019
- Pixel based on Silicon Drift Detectors
- Noise level ~60 electrons @ 4.5MHz
  FWHM ~ 500 eV

- Full-parallel readout with analog shaping
- In-pixel **8-bit digitization** (9-bit @ f<4.5MHz)
- In-pixel SRAM (800 frames/burst) ↳ limited ADC resolution
- Data transmission during gaps
- 11 settings of Cfcf (coarse gain) for photon energy/dyn. range selection, 6 bits of ADC gain fine trimming
- 4 bits for offset trimming

BUT…
- ➢ Limited dynamic range (linear system)
- ➢ Limited SNR for the lowest energy range



Single-shot diffraction image of pinholes with **707 eV** photons @ **4.5 MHz**



Büttner, F; et al. Observation of fluctuation-mediated picosecond nucleation of a topological phase. **Nat. Mater**. 20, 30–37 (2021). doi:10.1038/s41563-020-00807-1

DSSC camera 2nd version: DEPFET signal compression

Second camera under developement is based on the same architecture as the first, but with another pixel sensor

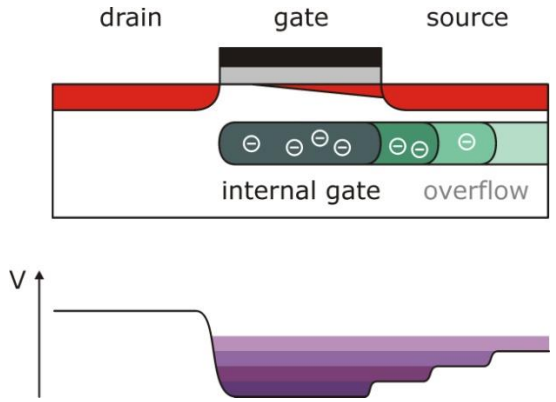
DEPFET Sensor with Signal Compression

DEPFET

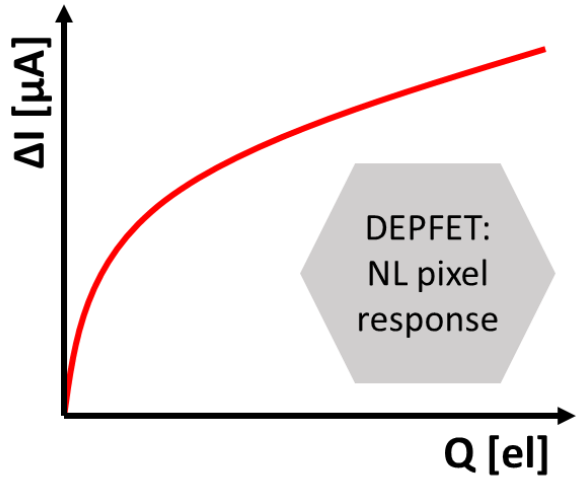
- ↳ **DE**pleted **P**-channel **F**ield **E**ffect **T**ransistor
- ↳ FET on fully depleted silicon substrate -> **active pixel**
- ↳ charge (electrons) generated by radiation gets collected in the internal gate (potential minimum)
- ↳ internal gate induces changes in the FET current -> signal

Compression

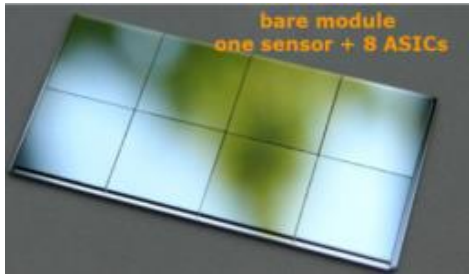
- ↳ internal gate extends under the source and charges gradually spread farther from FET channel, leading to lower inductive effect per-electron
- ↳ **non-linear $\Delta I/Q_{sig}$ curve**



CMOS-foundry DEPFET technology (PNSensor GmbH)
Aschauer, et al. JINST (2017)



Single photon sensitivity
High dynamic range



Camera module and ASICs

DEPFET pixel

- ↳ accurate calibration of multiple DSSC properties is requested (gain, offset, QE, charge-sharing, etc)
- ↳ particular importance to the qualification of the NL system response over the full dynamic range

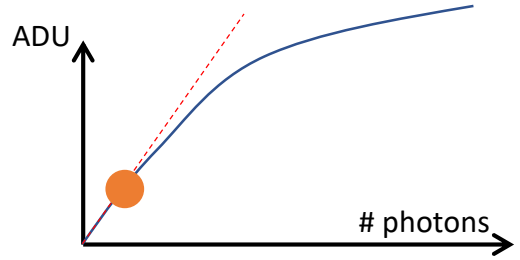
➢ calibration is a challenge by itself

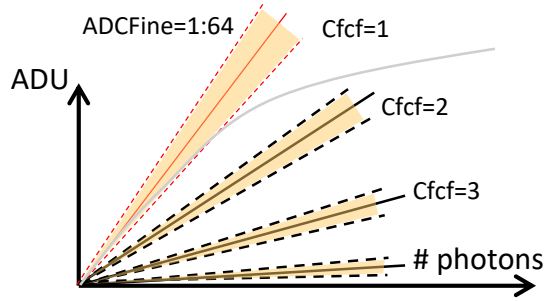
The challenge of calibration

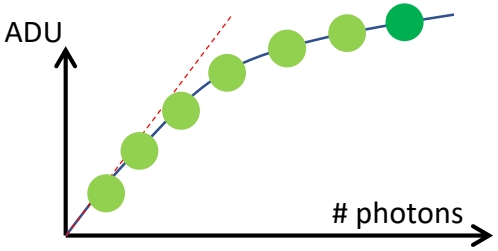
Two-step procedure:

1. Calibration of gain/offset in the linear region for all settings
   a) Acquisition of hard X-ray spectra with single high gain setting
      - low resolution 8 bit ADC makes difficult the assessment of the gain from acquired spectra with adequate accuracy
   b) In-ASIC charge injection circuit to probe all gain configurations and generate a LookUpTable of gain ratios

2. Qualification of the shape of non-linear (NL) DEPFET response by scanning the whole energy range up to few MeV/pixel
   - Few options: optical (LED/laser), leakage current, XFEL beam







high energy and uniformity on wide surface area needed, Al coating on entrance window (optical block) worsens efficiency, difficult integration in vacuum vessel

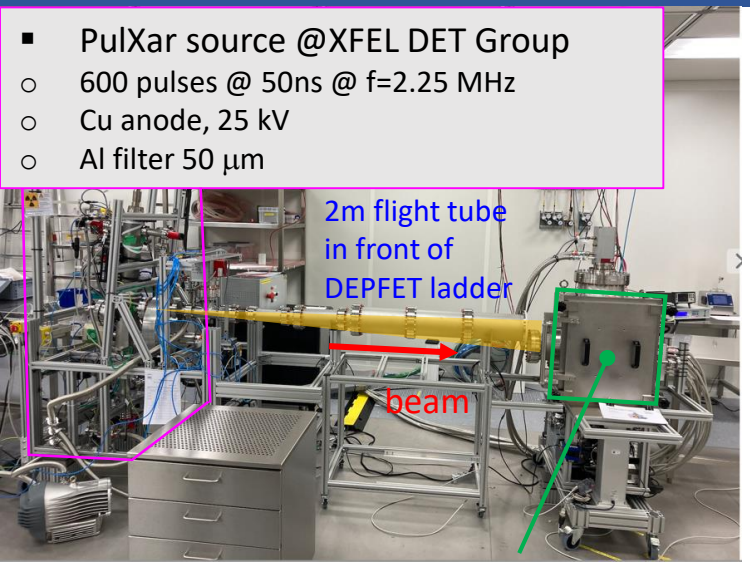
very low leakage per pixel, pixel to pixel variability, requires long integration time differently from ultra-fast experimental conditions

real experimental conditions: whole charge deposited in a pixel in one single frame, flat-field intensity on the whole sensor

➢ First calibration campaign on the first DEPFET ladder has been carried out

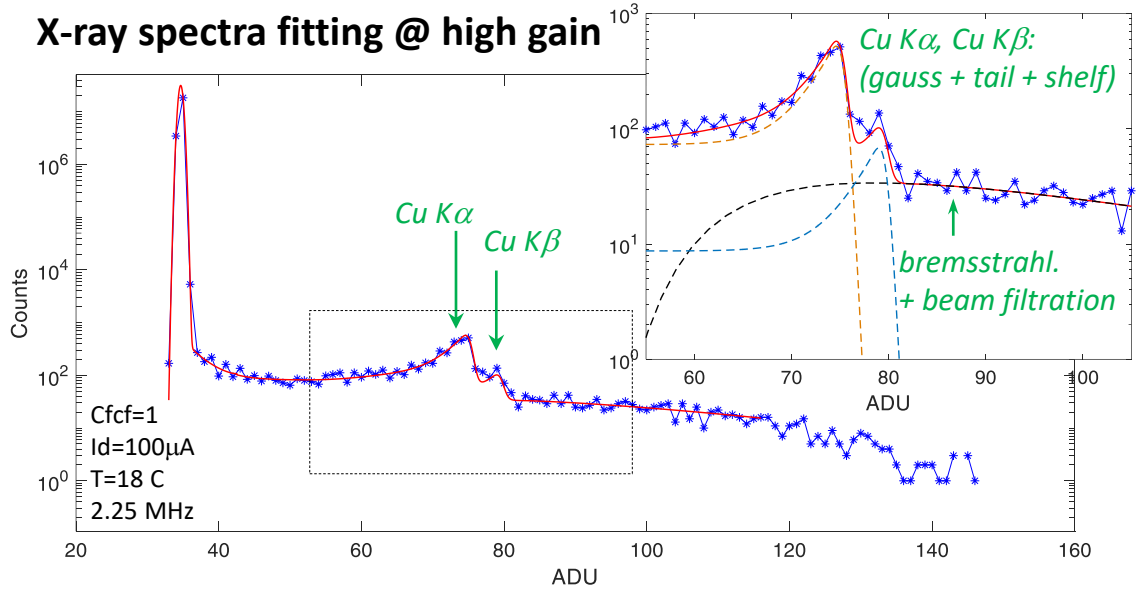
Linear gain calibration and noise

- PulXar source @XFEL DET Group
  - 600 pulses @ 50ns @ f=2.25 MHz
  - Cu anode, 25 kV
  - Al filter 50 μm



FENICE vessel/DEPFET ladder

X-ray spectra fitting @ high gain

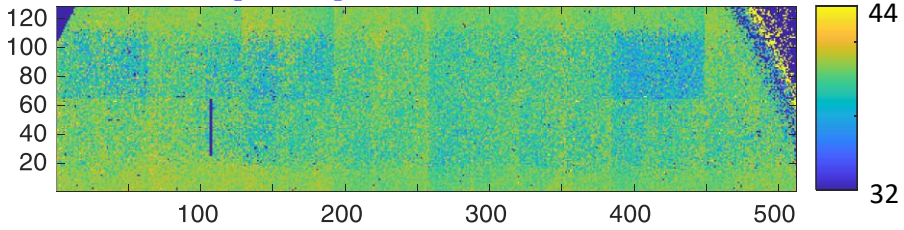


8-bit resolution impacts on accuracy of gain/offset determination

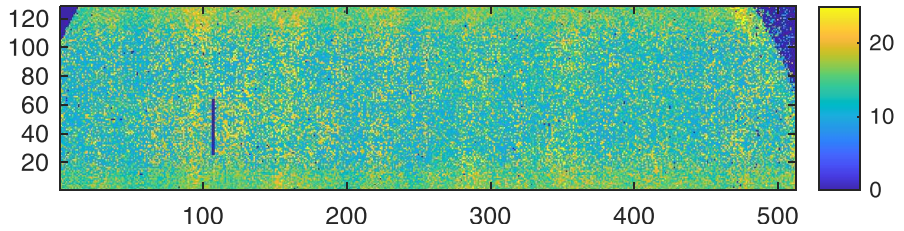
characterization/modeling of DEPFET spectral response (high-res 14-bit test bench)

- charge-sharing (i.e. low-energy peak tail)
- bremsstrahlung
- bin integration

- Gain [ADU]

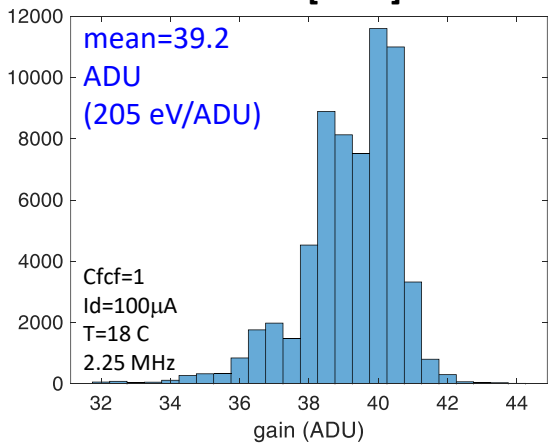


- Noise ENC



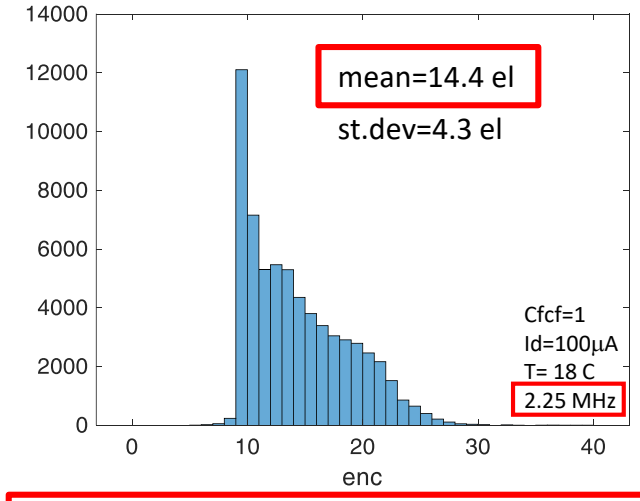
Good uniformity over the whole ladder

Gain [ADU]



gain st. dev. of fit around 1%

Noise [electrons]

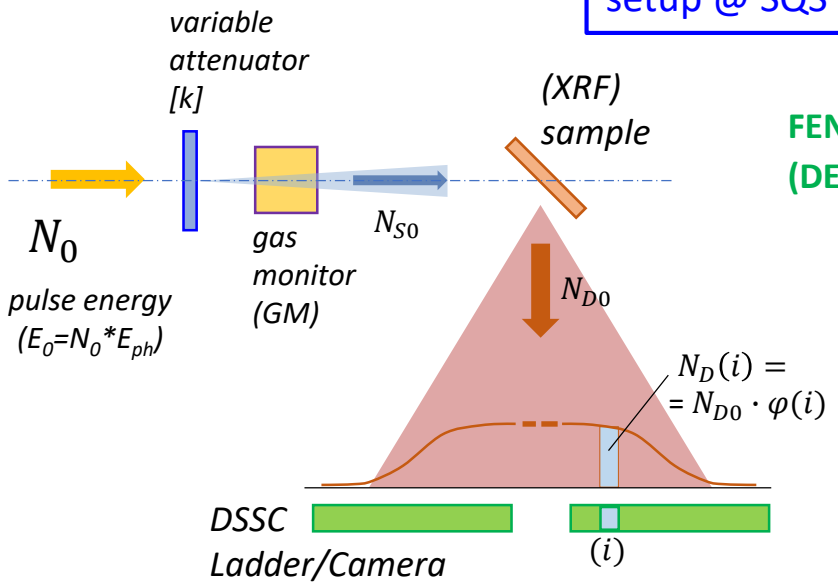


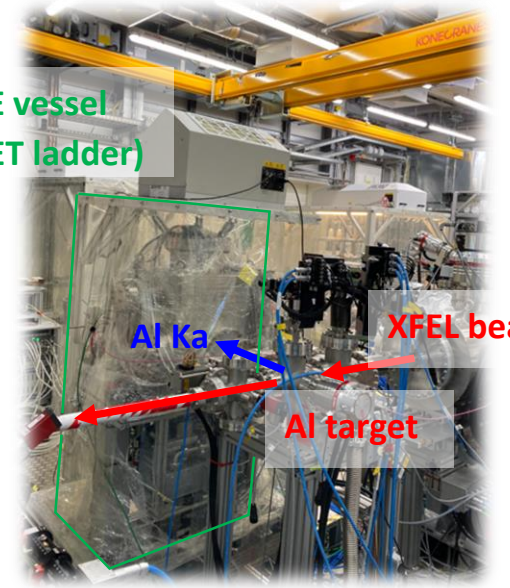
4 times better than the miniSDD!

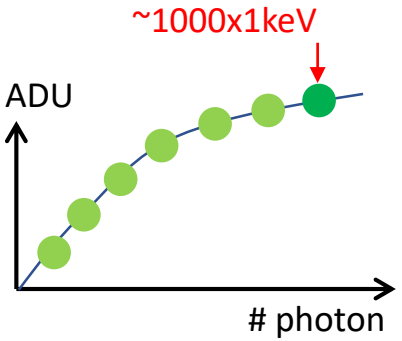
Non Linear response: qualification with XFEL beam

- Dedicated beamtime at SQS EuXFEL
- XFEL beam impacting on Al target, XRF emission proportional to beam intensity (E=1.486 KeV)
- To scan the NL curve we change beam attenuation (i.e. gas transmission)
  - ↳ gas monitor as reference for beam intensity
- First part of the response is matched with gain extracted from X-ray spectra to calibrate in energy
- Deposited energy up to few MeV/pixel

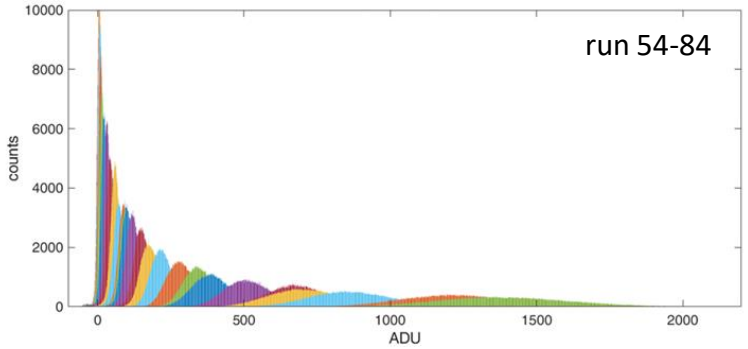
setup @ SQS



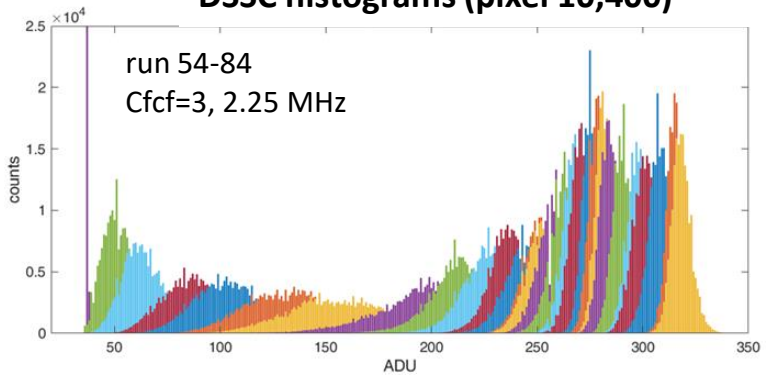




Gas monitor histograms

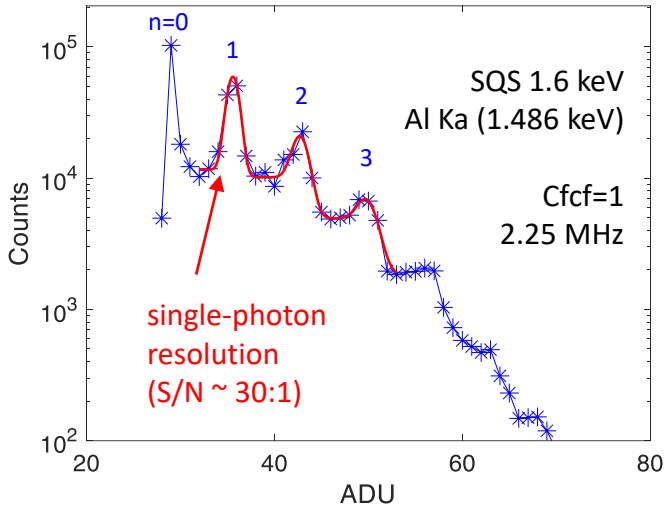


DSSC histograms (pixel 10,400)



Spectral performance and NL response of the ladder @ XFEL

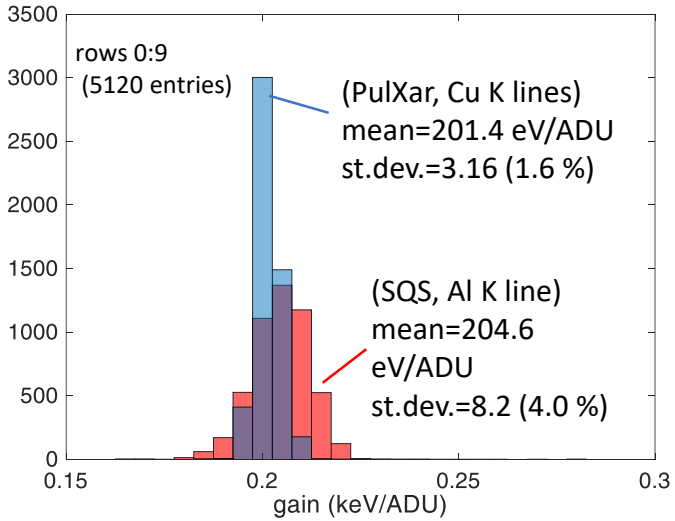
Energy spectrum Al Ka photons



Single photon resolution @1.486 keV

ENC from SQS spectra (14.1 el.) confirm values obtained from PulXar (14.4 el.)

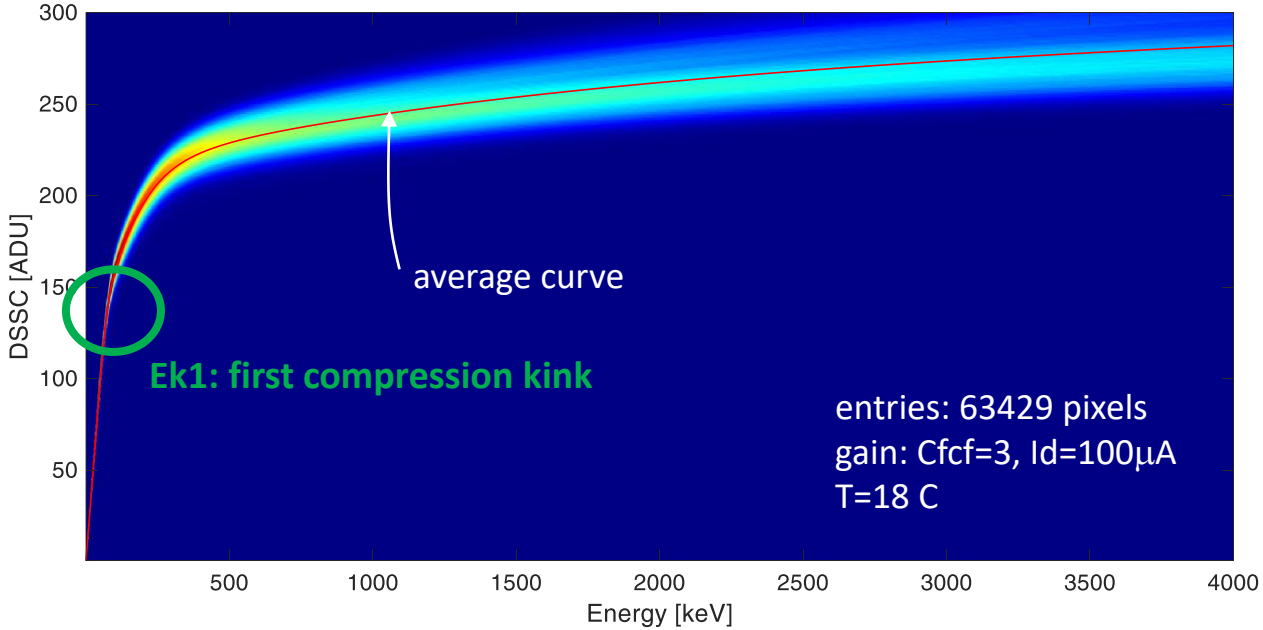
PulXar vs SQS gain

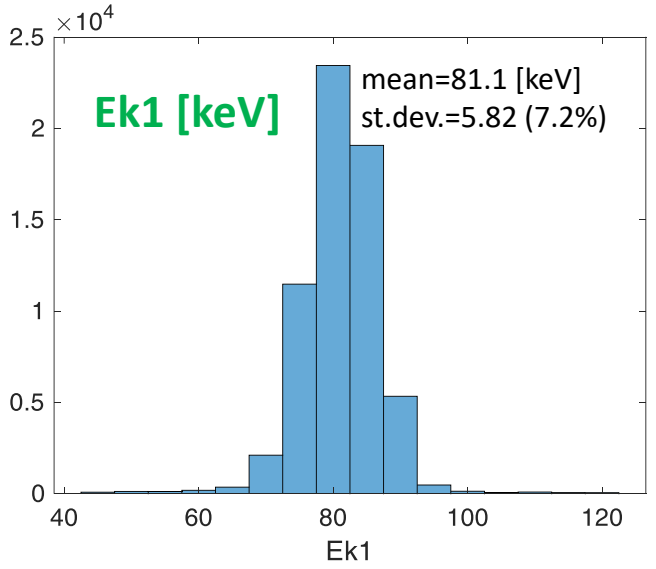


Avg value at SQS perfectly matched with PulXar results

Lower dispersion for higher energy X-ray line (expected)

NL response curves of whole ladder





Nice uniformity: 7% spread over the ladder

Linear range up to 60-70 keV

DEPFET compression allowed reaching signal level of MeV/pxl

Conclusions

- FEL facilities push for improvements in detector technologies. DSSC project aims at providing a camera with the desired performances in terms of frame-rate, noise and dynamic range for the soft X-ray spectrum band

- The first miniSDD camera is already available for user experiments, satisfying most of the requirements. Lower noise and much higher dynamic range can be reached by the second camera implementing DEPFET with signal compression

- Calibration of the system is a challenge by itself due to limited ADC resolution and high energy required to scan the whole range up to MeV/pxl/pulse in operating conditions

- The experimental qualification of first DEPFET ladder gave a very successful feedback
  - noise level below 15 el rms, 4 times better than the miniSDD camera and near pnCCD detectors, but at the much higher frame-rate of 4.5 MHz
  - gain/noise accurate calibration from PulXar spectra @ Cu Ka (8 keV), confirmed at SQS @ Al Ka (1.48 keV)
  - intensity scan up to 3 MeV/pixel over the whole ladder led to NL characterization of all pixels

- What's next? Optimization of the calibration procedure for the 1Mpxl DEPFET camera and preparation of the experimental campaign. Assembly of the full DEPFET camera expected by the end of 2022