16TH PISA MEETING ON ADVANCED DETECTORS
La Biodola, Isola d'Elba, May 26-June 1, 202

Calibration and Performance of the First Depfet Ladder of the DSSC X-ray Imager

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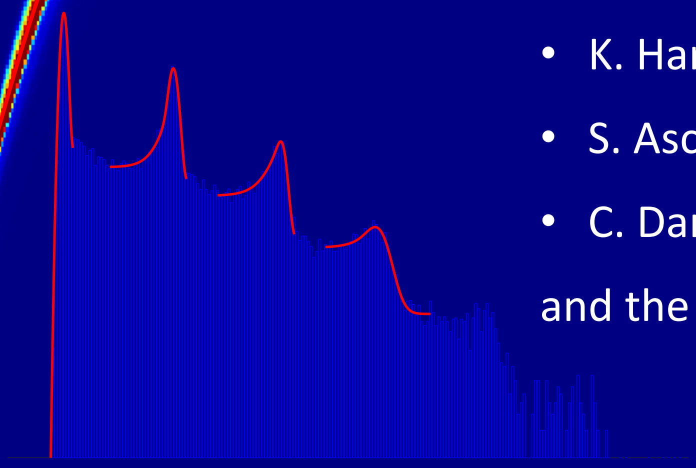
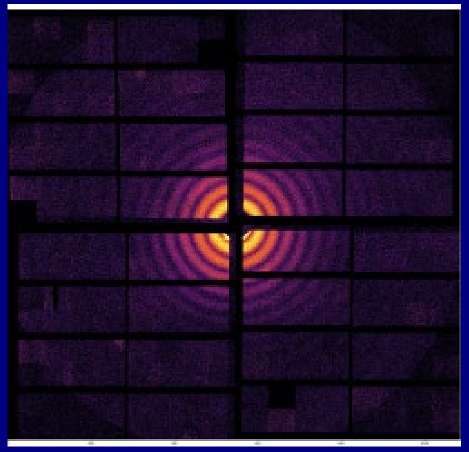
- S. Aschauer, L. Strüder, PNSensor GmbH
- C. Danilevski, M.Turcato, M. Porro, European XFEL GmbH

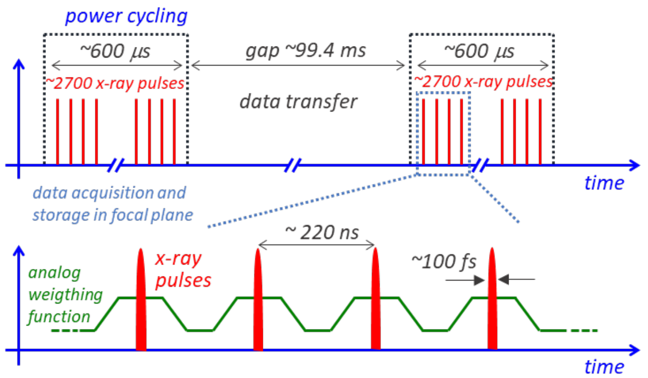
and the DSSC Consortium



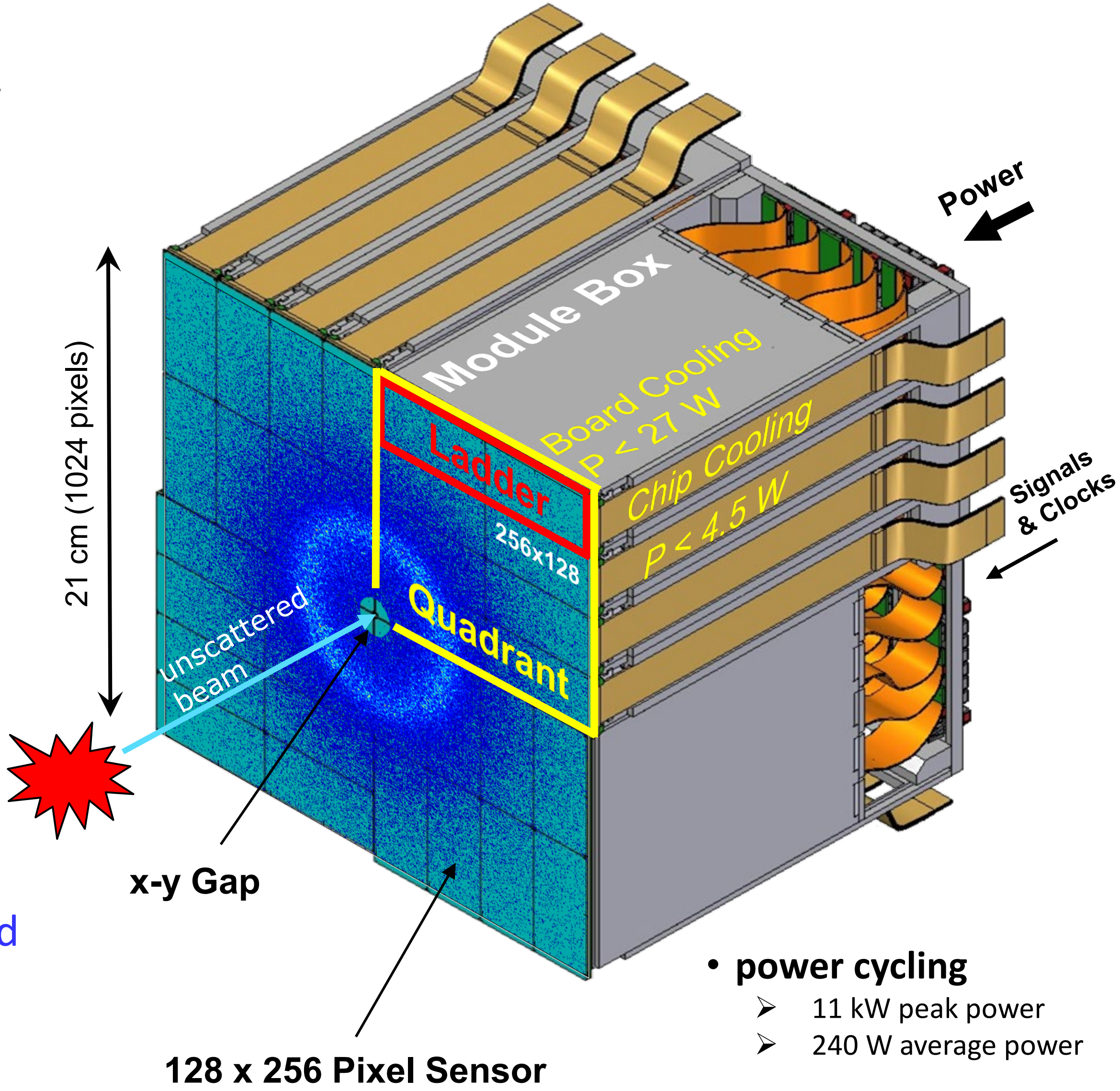


DEPFET Sensor with Signal Compression (DSSC) 1 Mpix X-ray camera

- ❑ Main features
  - based on **non-linear DEPFET** sensors
  - ~200 µm hex pixel (1024 x 1024)
  - **photon energy 0.5 - 6 keV**
  - **single-photon sensitivity**
  - **dynamic range 1:10,000 ph**
  - **frame rate 0.9 – 4.5 MHz**



4.5 MHz operation (burst mode) at the European XFEL

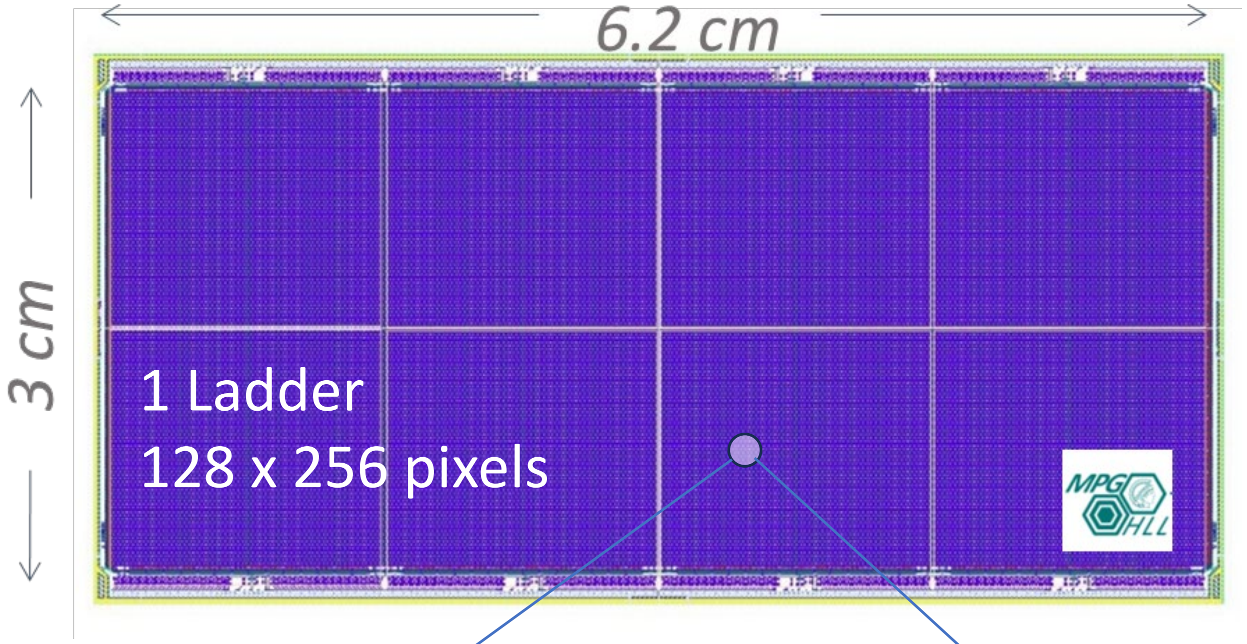


- **power cycling**
  - ➢ 11 kW peak power
  - ➢ 240 W average power

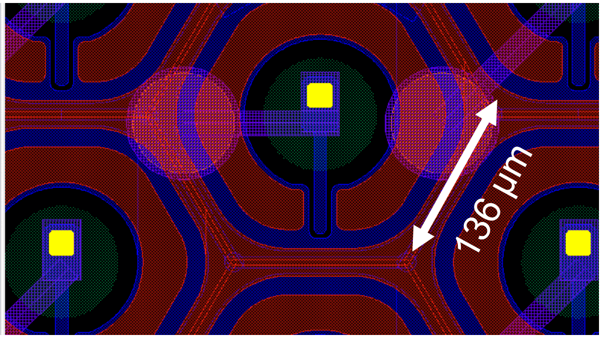
↳ accurate calibration of multiple DSSC properties is needed (gain, offset, noise, QE, charge-sharing, etc)

↳ performance qualification of the 1st DEPFET ladder

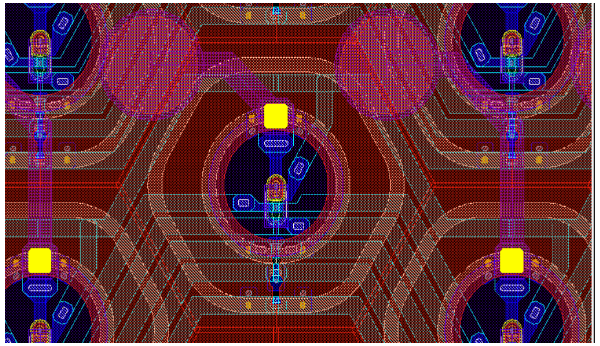
Sensors: Mini-SDD and DEPFET (w/ signal compression)



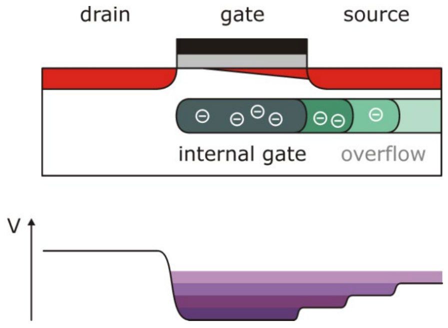
- **Passive anode („mini“-SDD) (1 Mpix delivered in 2019)**
- **DSSC adaptation of the DEPFET concept:**
  - ↳ internal gate extends under the source
  - ↳ at high levels, signal charges gradually spread under source
  - ↳ **non-linear $\Delta I/Q_{sig}$ curve**
  - ↳ gain curve engineering by dose & geometry of implantations



MiniSDD
Passive anode
450 µm thickness

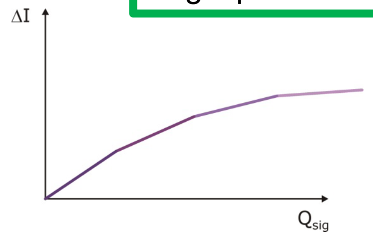


CMOS-DEPFET Active Pixel
(IMS, PNSensors)
8” Si wafer 750 µm thickness



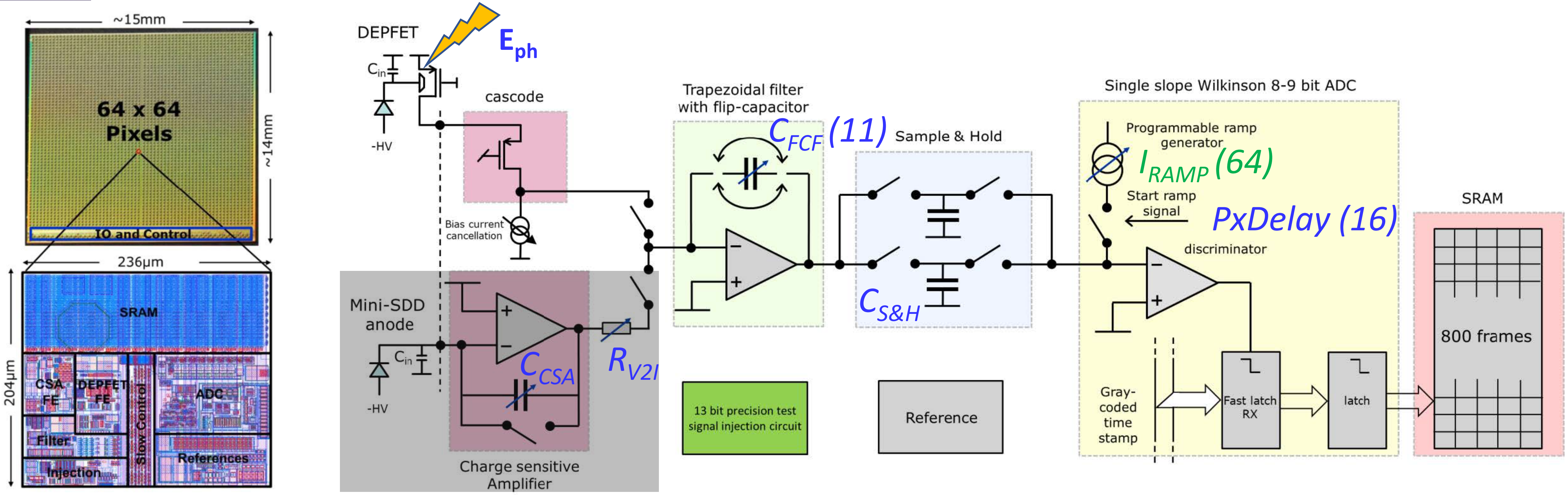
CMOS-foundry DEPFET technology
(PNSensor GmbH)
S. Aschauer, et al. JINST (2017)

High dynamic range &
single photon sensitivity



- ➢ Low noise
- ➢ Fast collection
- ➢ Signal compression

ASIC - Pixel readout channel



Readout concept

- Full-parallel readout
- Analog shaping
- In-pixel 8-bit digitization (9-bit @ f<4.5MHz)
- In-pixel SRAM (800 frames/burst)
- Data transmission during gaps

↳ limited ADC resolution

Gain and offset adjustable pixel-wise

- 11 settings of Cfcf (coarse gain) for photon energy/dyn. range selection
- 6 bits of ADC gain fine trimming (nominal accuracy ~1%)
- 4 bits for offset trimming (1.5 LSB range with 8% granularity)

$$Gain \propto g_Q \frac{1}{C_{FCF}} \frac{1}{I_{RAMP}} (t_{INT} \cdot C_{S\&H}) (2 \cdot f_{clock})$$

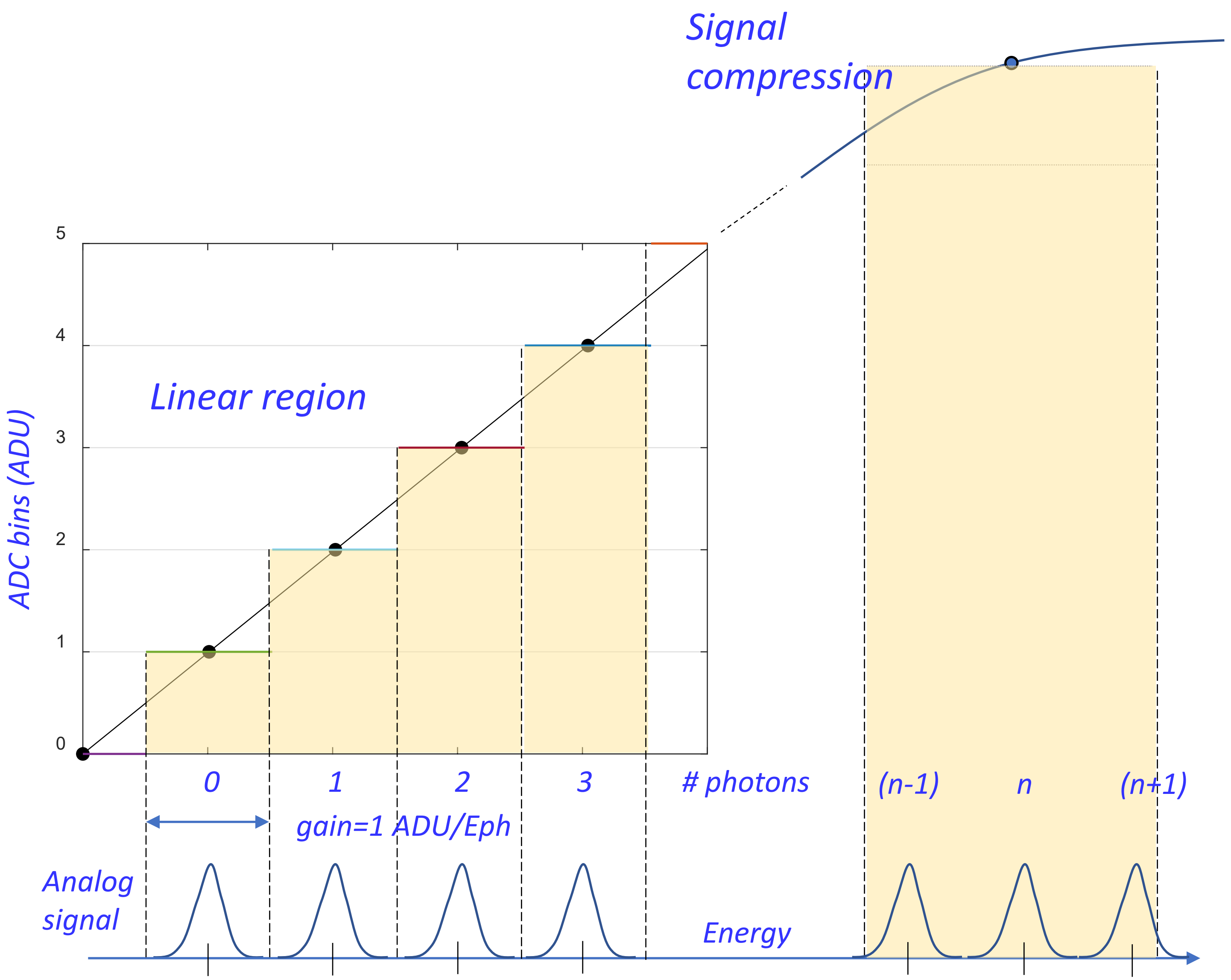
↳ fine gain/offset trimming @pixel level

Single photon sensitivity & high dynamic range & low ADC resolution

- Under the constraints of maximum **dynamic range** and **8-bit resolution,** single-photon counting is possible by setting DEPFET signal for 1 photon equal to 1 (or *n*) ADC bin
  - signal compression will extend the DR

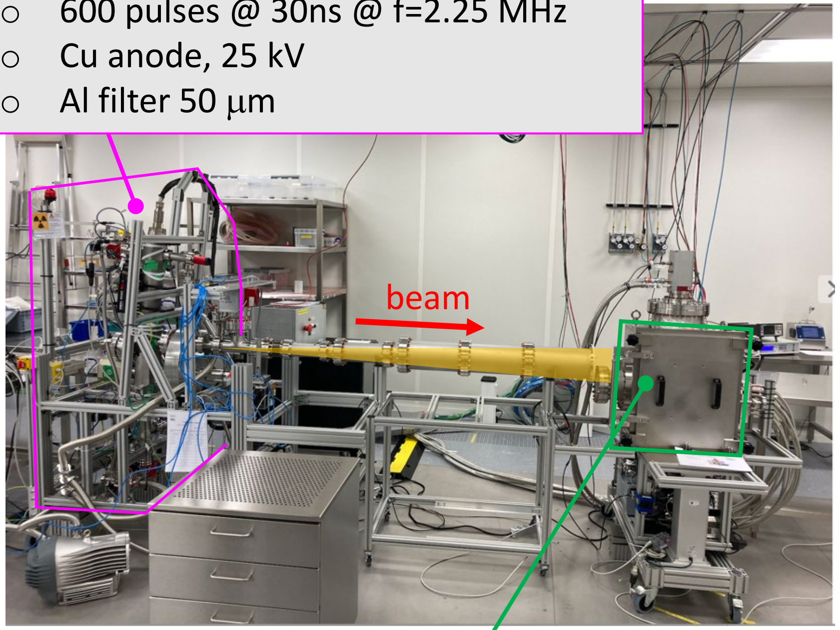
- **Gain and offset** in the read-out ASIC must be set for the chosen photon energy ***a priori*,** before the experiment is performed
  - difficult to re-gain single-photon counting by a re-calibration of the data

- inevitable **process variations** in the sensor as well as in the read-out ASIC
  - **each DSSC pixel** must be **calibrated individually (~1% accuracy)**



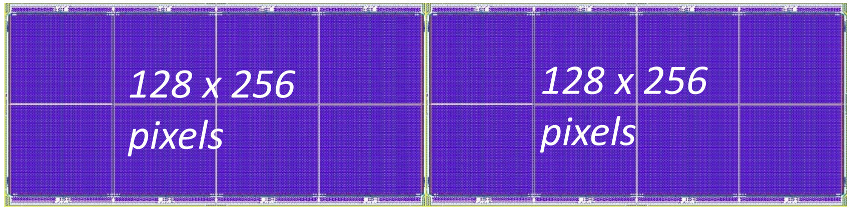
Calibration campaign with PulXar: DEPFET linear response

- PulXar source @XFEL DET Group
  - 600 pulses @ 30ns @ f=2.25 MHz
  - Cu anode, 25 kV
  - Al filter 50 μm

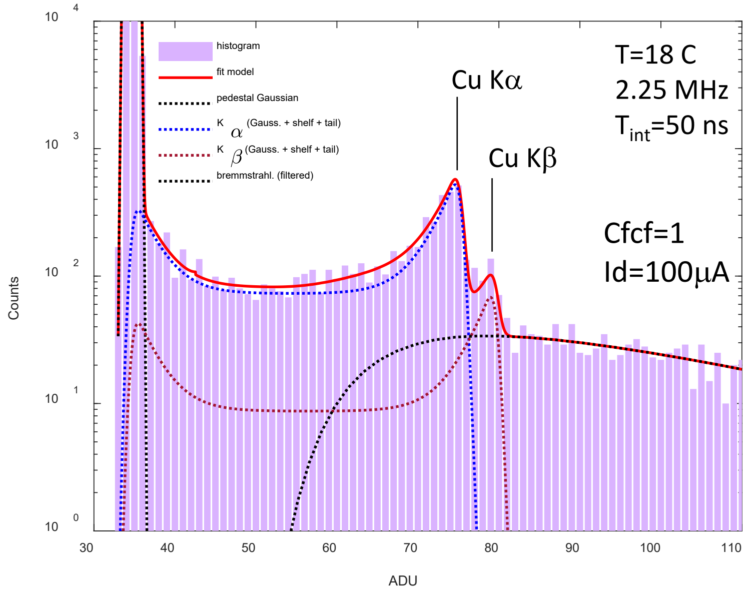


FENICE vessel/DEPFET ladder

- DEPFET ladder (128 x 512)

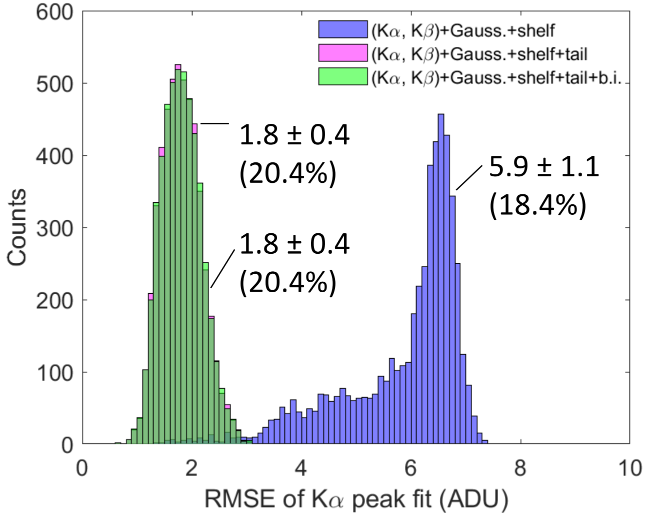


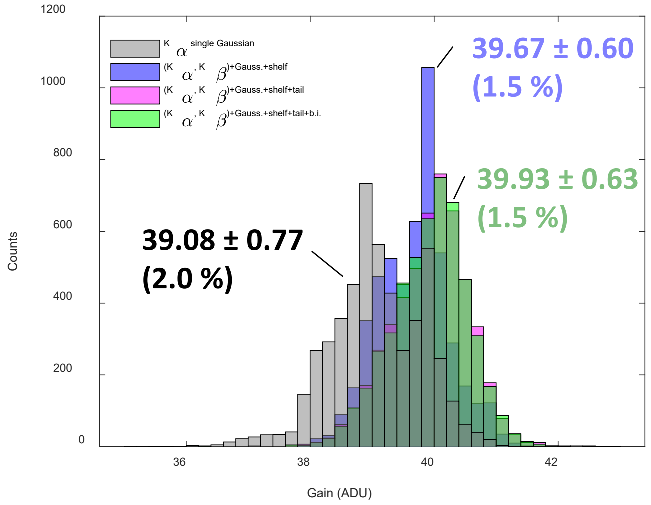
- X-ray spectra fitting @ high gain



- low ADC resolution impacts on accuracy of gain/offset determination
- characterization/modeling of DEPFET spectral response (14-bit test bench)
  - charge-sharing (i.e. low-energy tail)
  - bremsstrahlung
  - bin integration

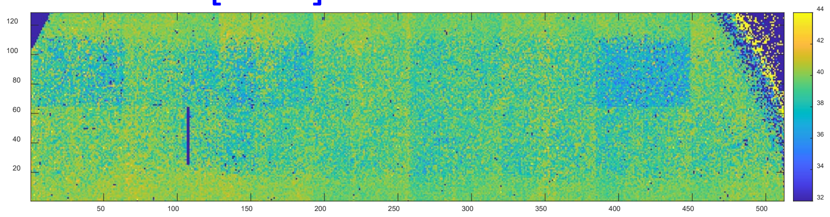
- "Trimming" X-ray spectra fit models



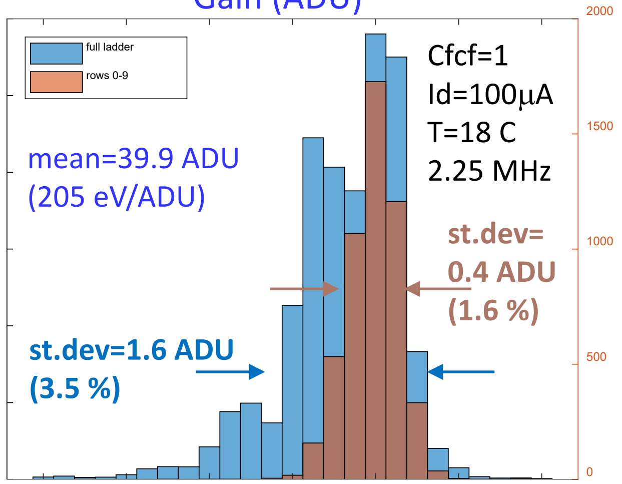


Gain / noise on DEPFET ladder from PulXar spectra (Cu Kα)

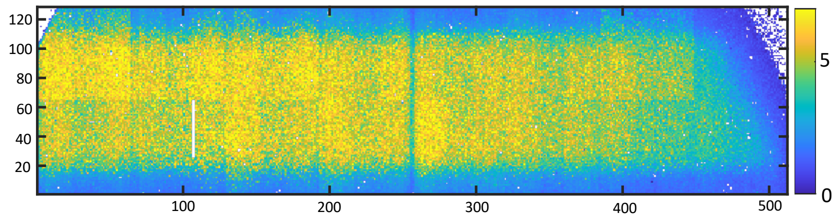
- Gain [ADU]



Gain (ADU)

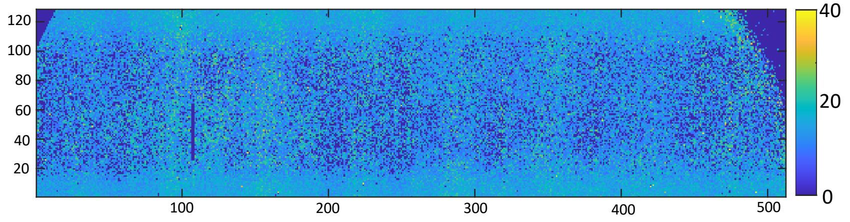


- Cu Kα fit RMSE [ADU]

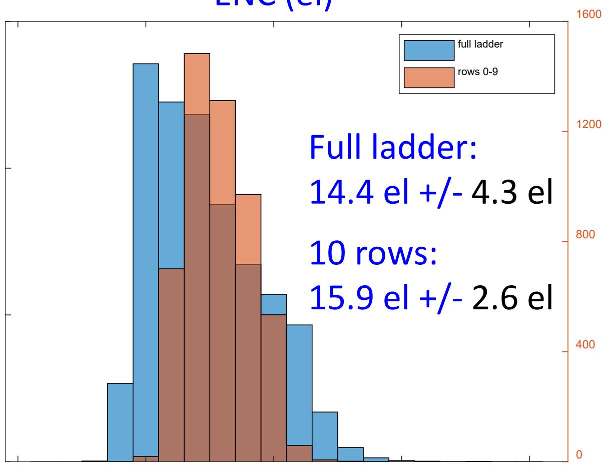


- Noise

ENC (el rms)



ENC (el)

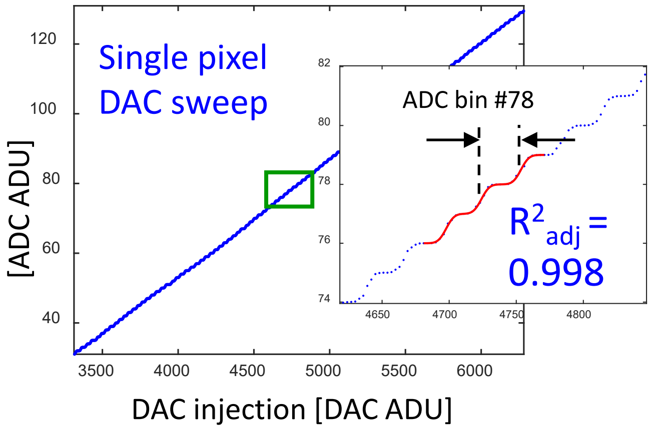


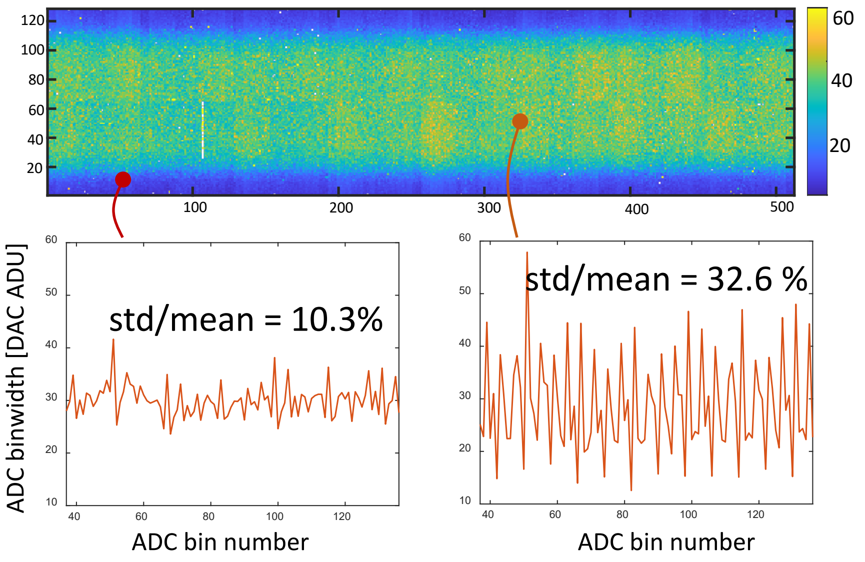
Gain
- small spread across ladder (gain untrimmed)
- “10-row” spatial pattern ?
  → related to ADC non linearity

Noise (@ T=18 C)
- ENC 16 el rms @2.25 MHz

Impact of ADC differential non-linearity errors

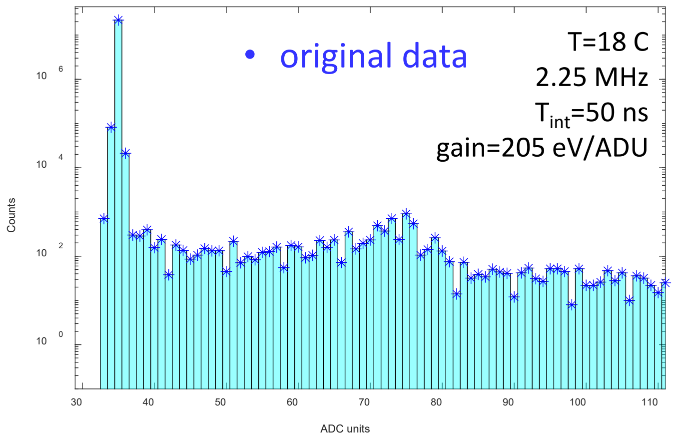
- Measured ADC differential non-linearity (DNL) %

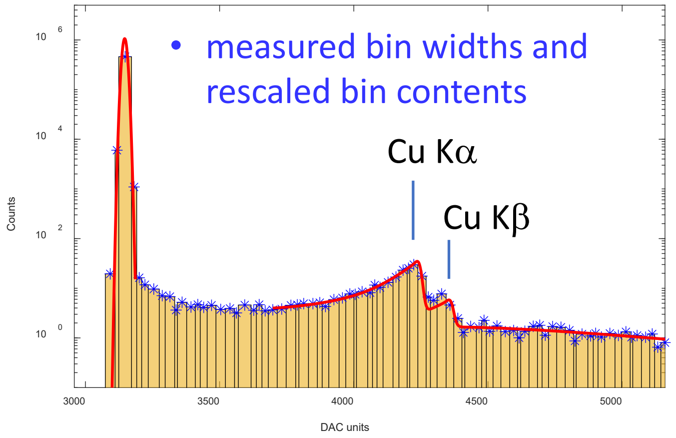




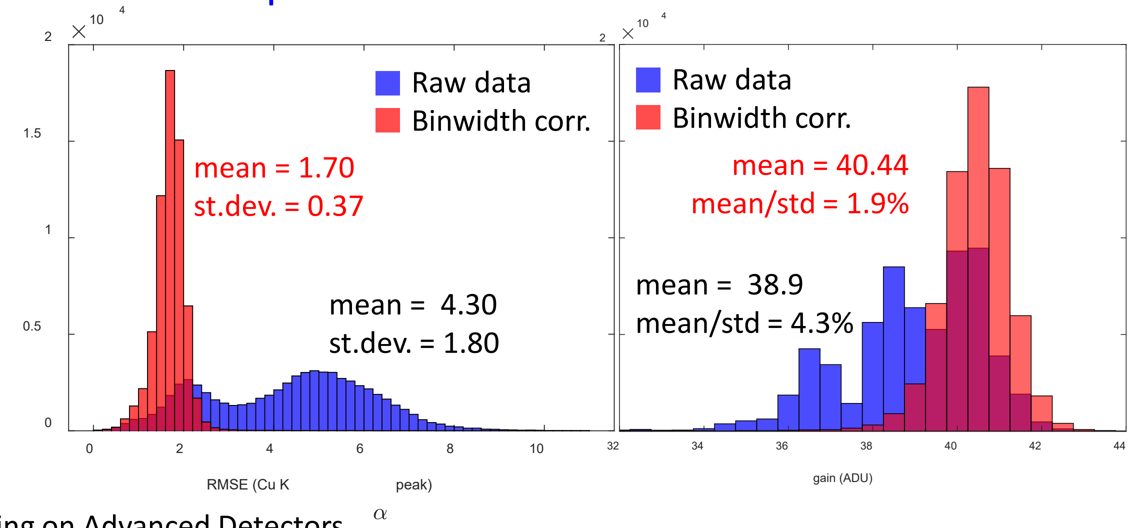
- ADC "staircase" measured on all pixels with 13-bit DAC
- Use of measured ADC binwidths shows clear improvement of all GOF indicators in peak fitting/spectral performance
  - gain accuracy ~ 1% over all ladder
- Automatic procedure, can be extended at camera level

- PulXar Cu Ka spectra/gain calibration



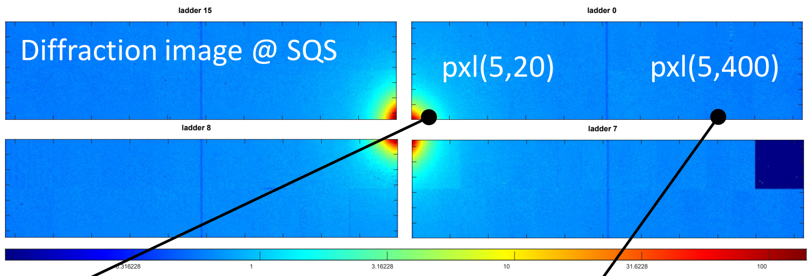


- Impact of DNL correction on ladder results

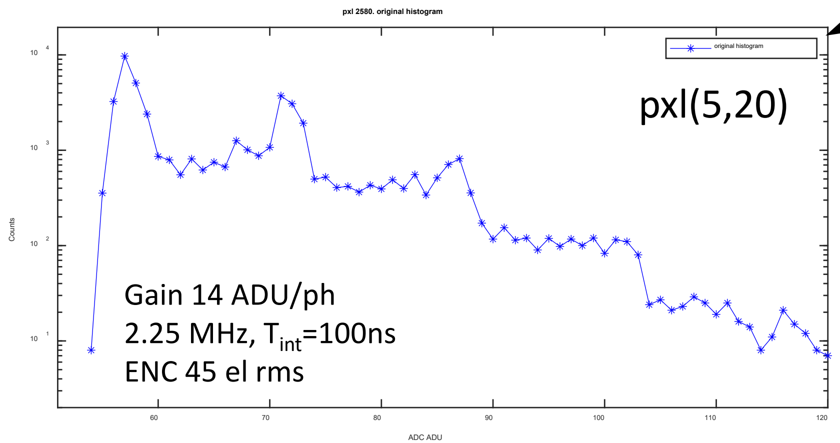


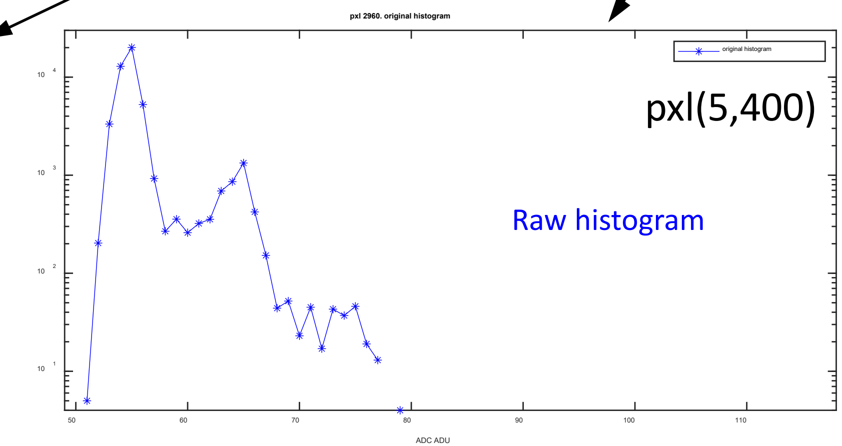
DNL correction on Mini-SDD commissioning runs (XFEL SQS, 2021)

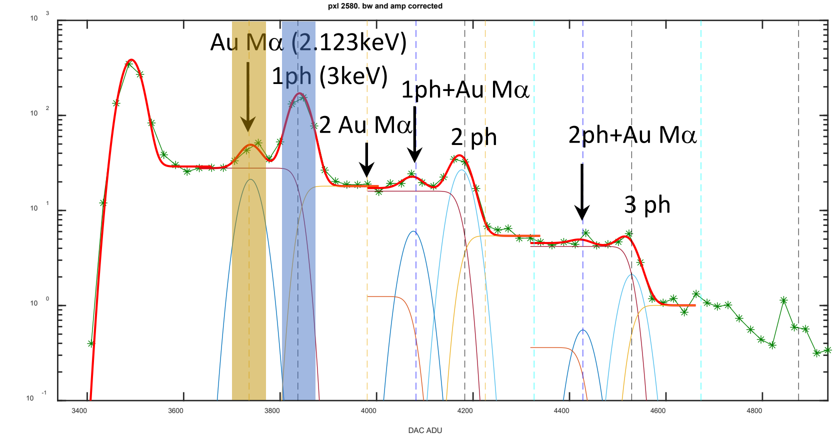
- Diffraction mask (pinhole array)
  - 30nm SiN
  - 5 nm Cr/250nm Au coating

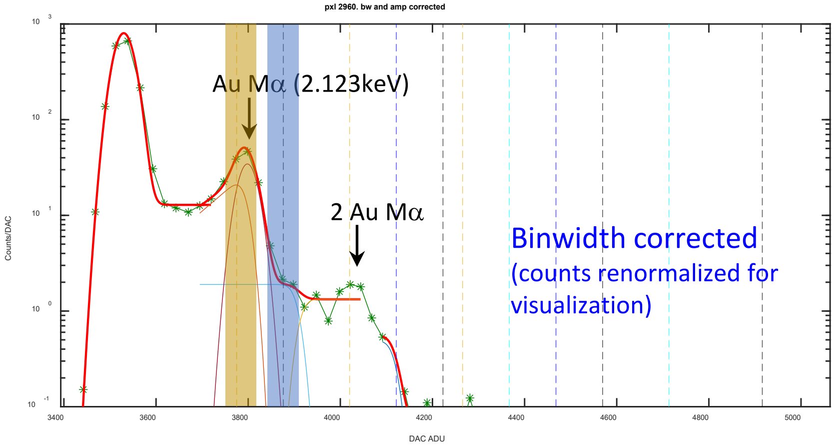


- Pixel spectra vs. primary/XRF intensity



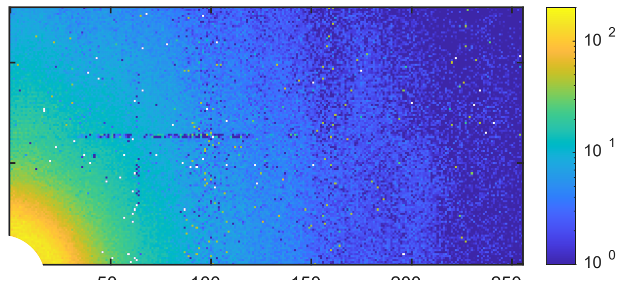




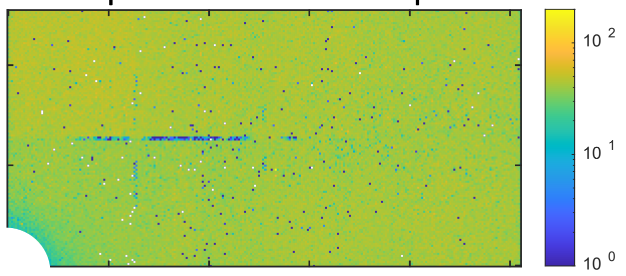


- ADC binwidth measured on 1 Mpix MiniSDD camera
- Preliminary extraction of «2-color» maps (3 keV and Au Mα 2.123 keV)

Amplitude of 3 keV peak



Amplitude of Au Mα peak

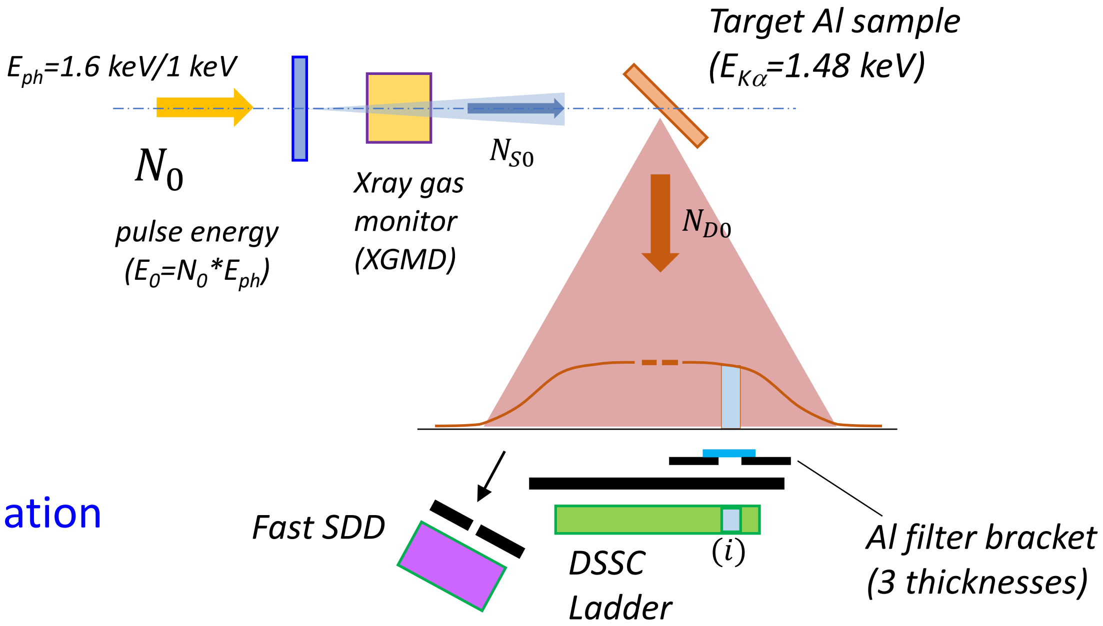


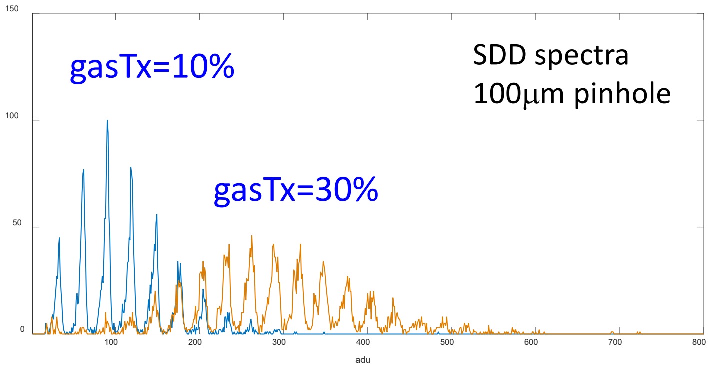
- ADC binwidths (meas. 2024) successfully applied to detector data nearly 3 years older (2021)

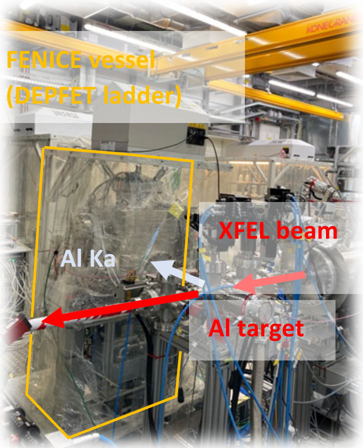
DEPFET ladder performance @ XFEL beam

- Dedicated beamtime at XFEL:
  - spectroscopic performance
  - qualification of the non-linear DEPFET response
- Setup @ SQS beamline
  - XFEL beam on Al target
  - DEPFET ladder perpendicular to the beam → uniform irradiation
- NL response
  - to scan the NL curve we change beam attenuation
  - 3 different intensity monitors (SDD, DEPFET + Al filters, X-ray gas detector)

setup @ SQS beamline

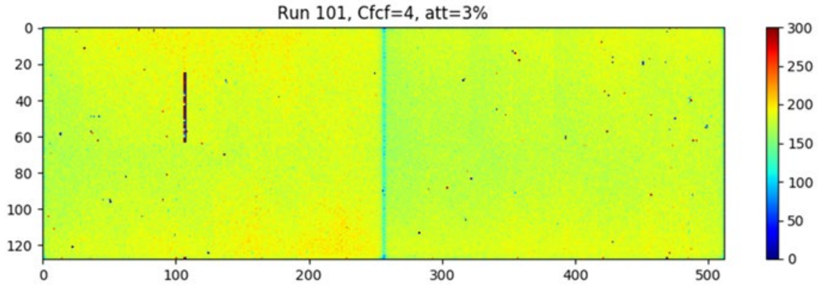






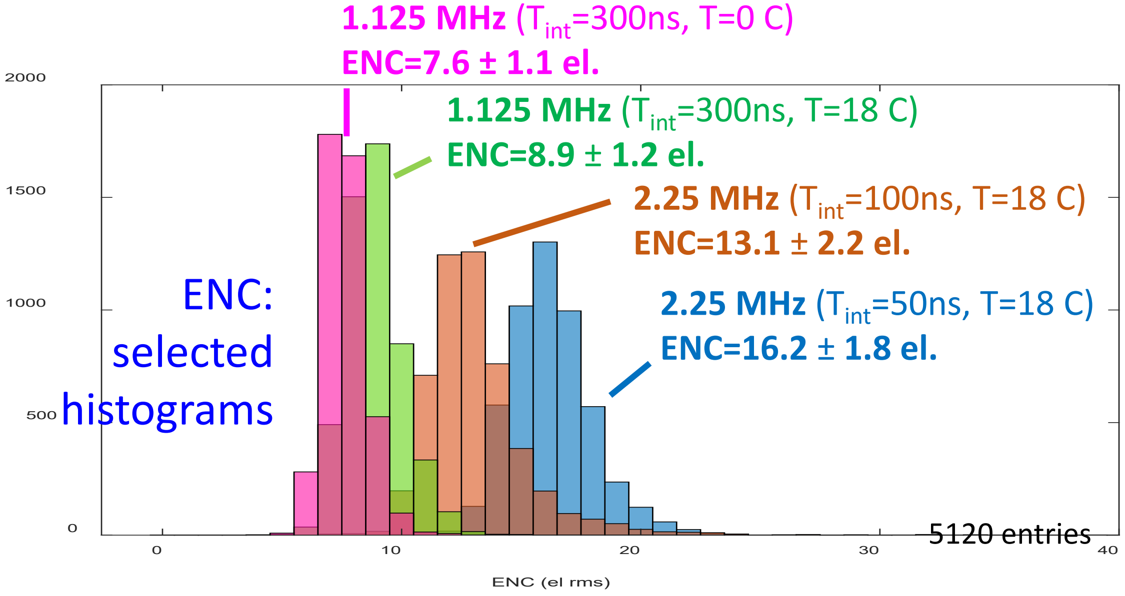
DEPFET noise study vs. frame frequency/integration time @ SQS beamline

- irradiation profile of Al Ka photons

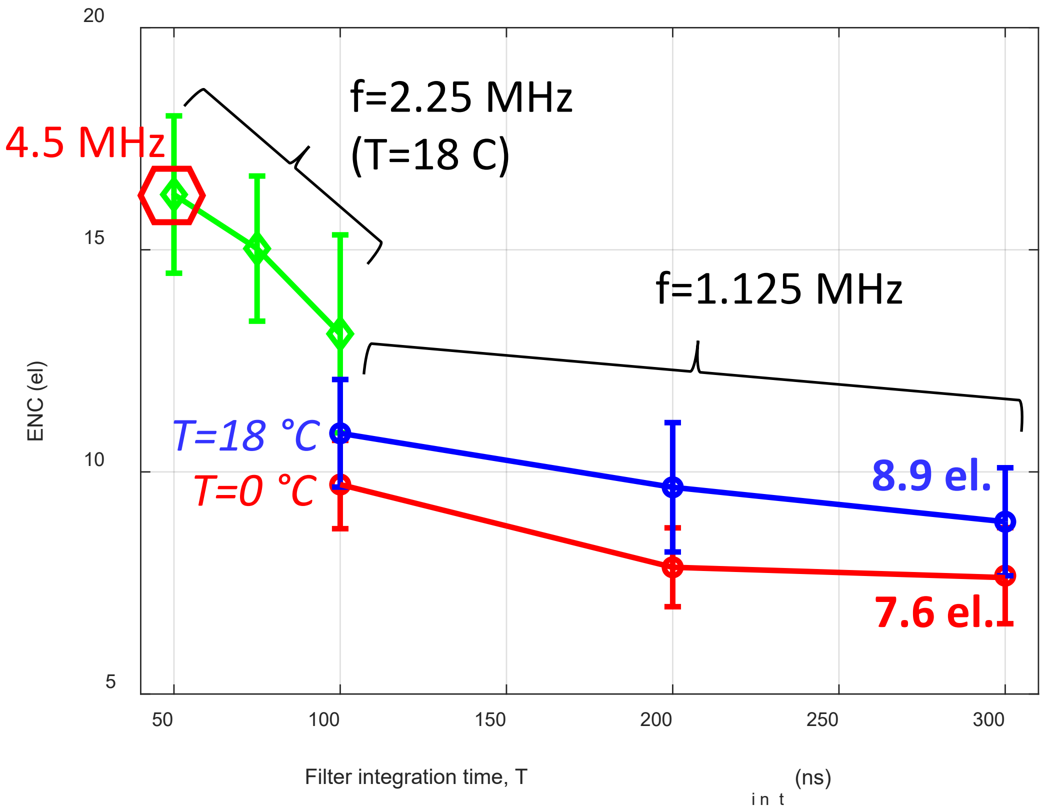


nice flat profile

→ irradiation of 1 quadrant (=4 ladders)



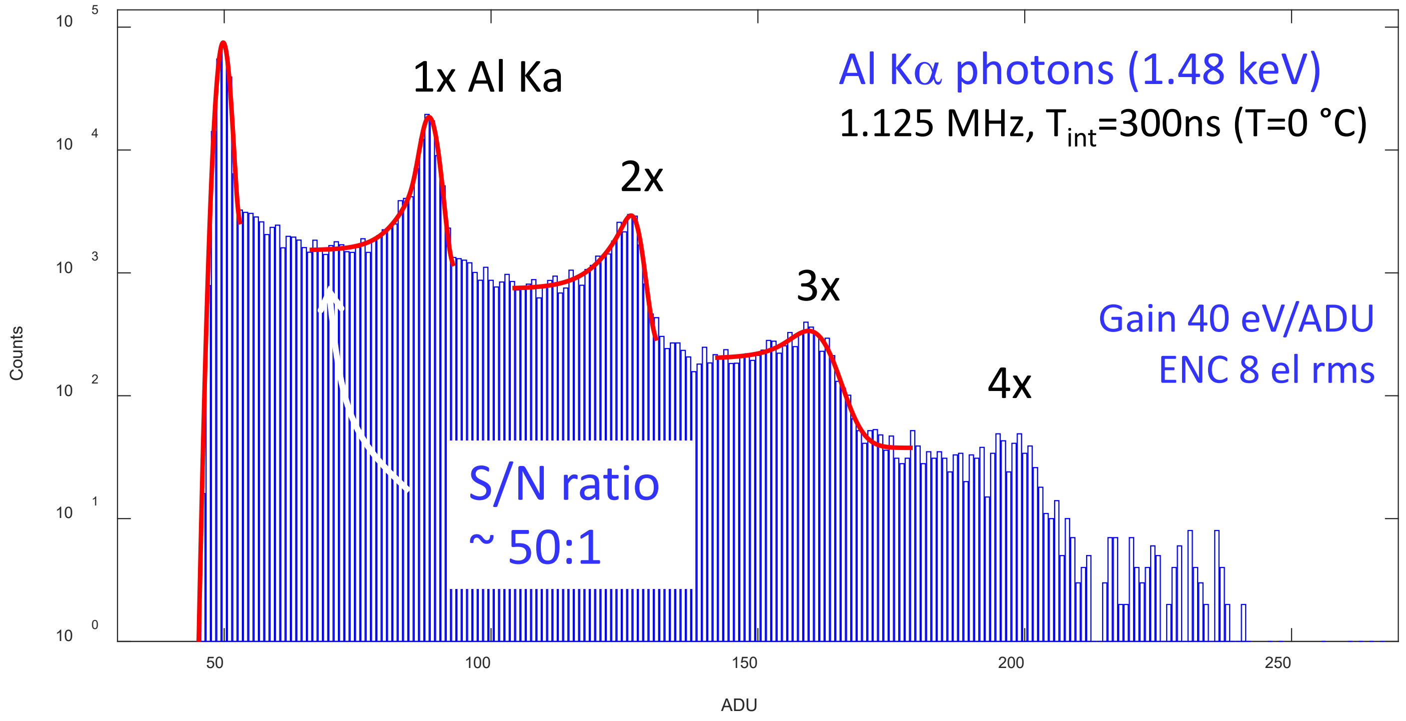
- ENC: dependence on integration time

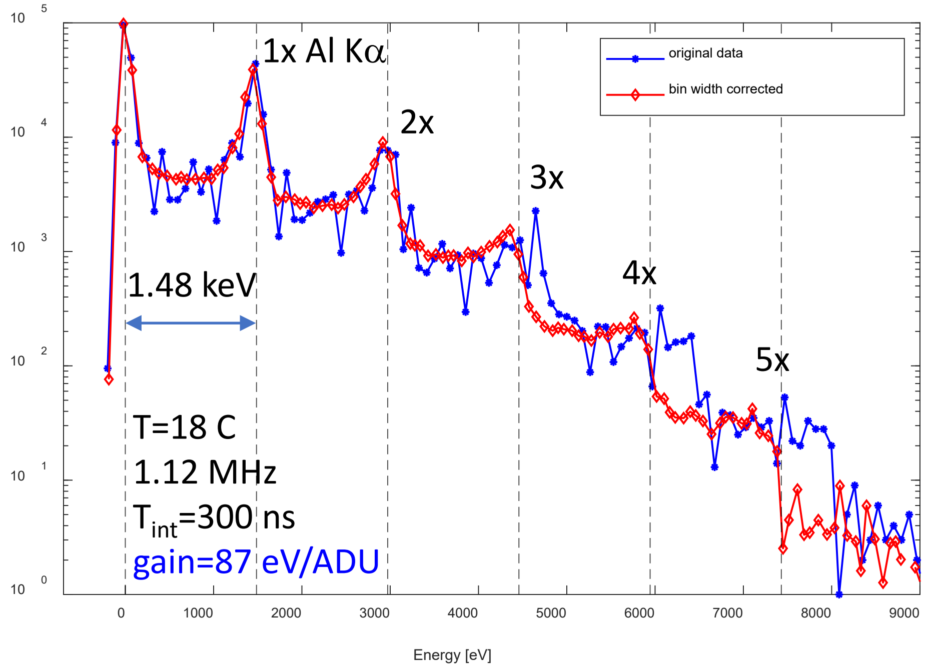


- ENC ~ 16 el @ T_{int}=50ns, compatible with PulXar results (f=4.5 MHz operation)
- ENC improves with int. time: ENC< 10 el rms @ T_{int} > 100ns

DSSC spectroscopic performance, single-photon resolution

- SQS beamline / Al target



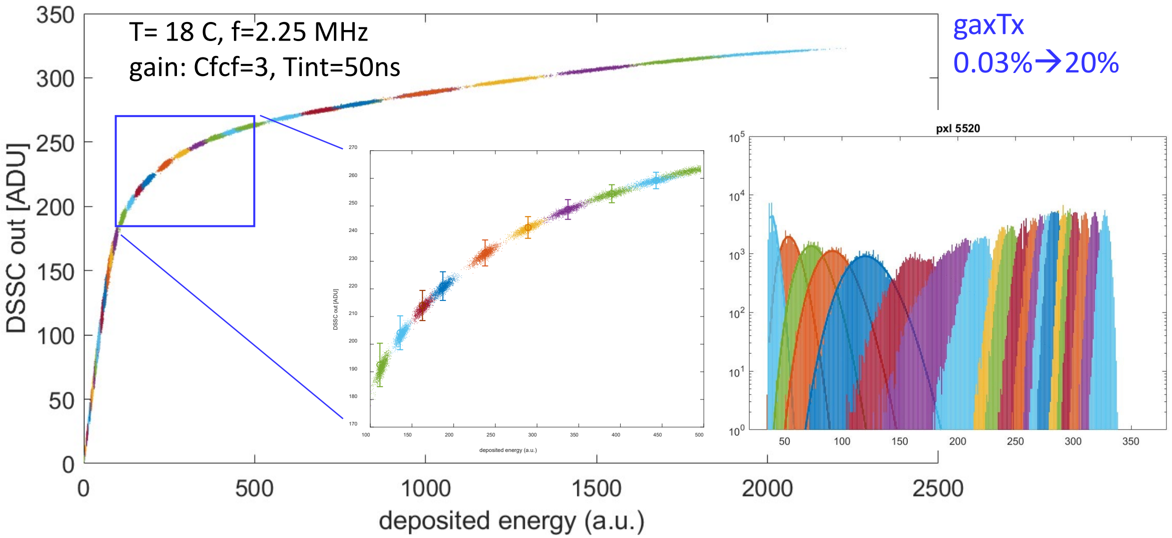


- high gain mode tested (40 eV/ADU), **single-photon resolution** of Al Ka photon peaks with **S/N~50:1**
- multi-peak spectrum shows INL errors, effectively improved by binwidth correction (INL ~10^{-3} ph)
  - better spectroscopic discrimination for soft X-rays

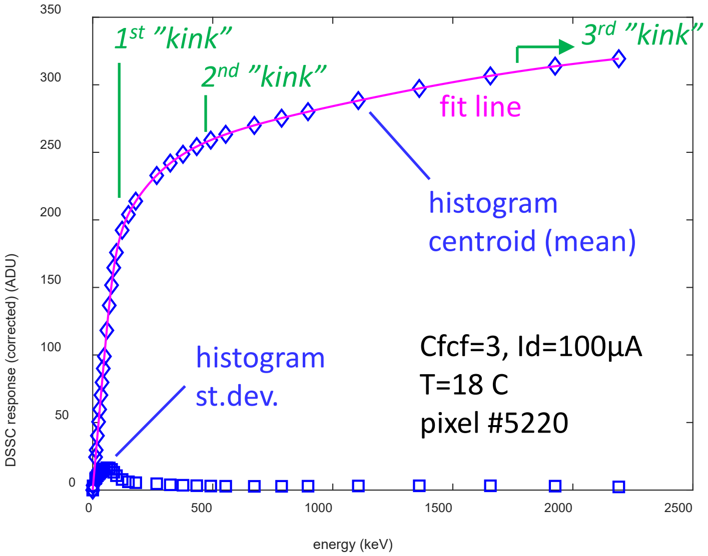
Non linear response of DEPFET: single pixel

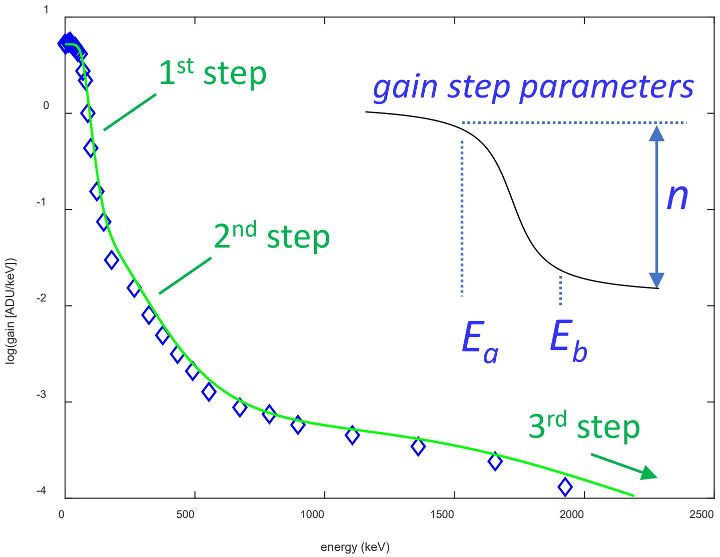
- Intensity ”scans”
  - acquisition of flat-field images of Al Ka photons vs. gasTx
  - successful qualification of the whole compression curve

- Raw data of a single pixel (train data)



- Single pixel NL response curve / gain vs. deposited energy
  - DEPFET response curve
  - DEPFET gain

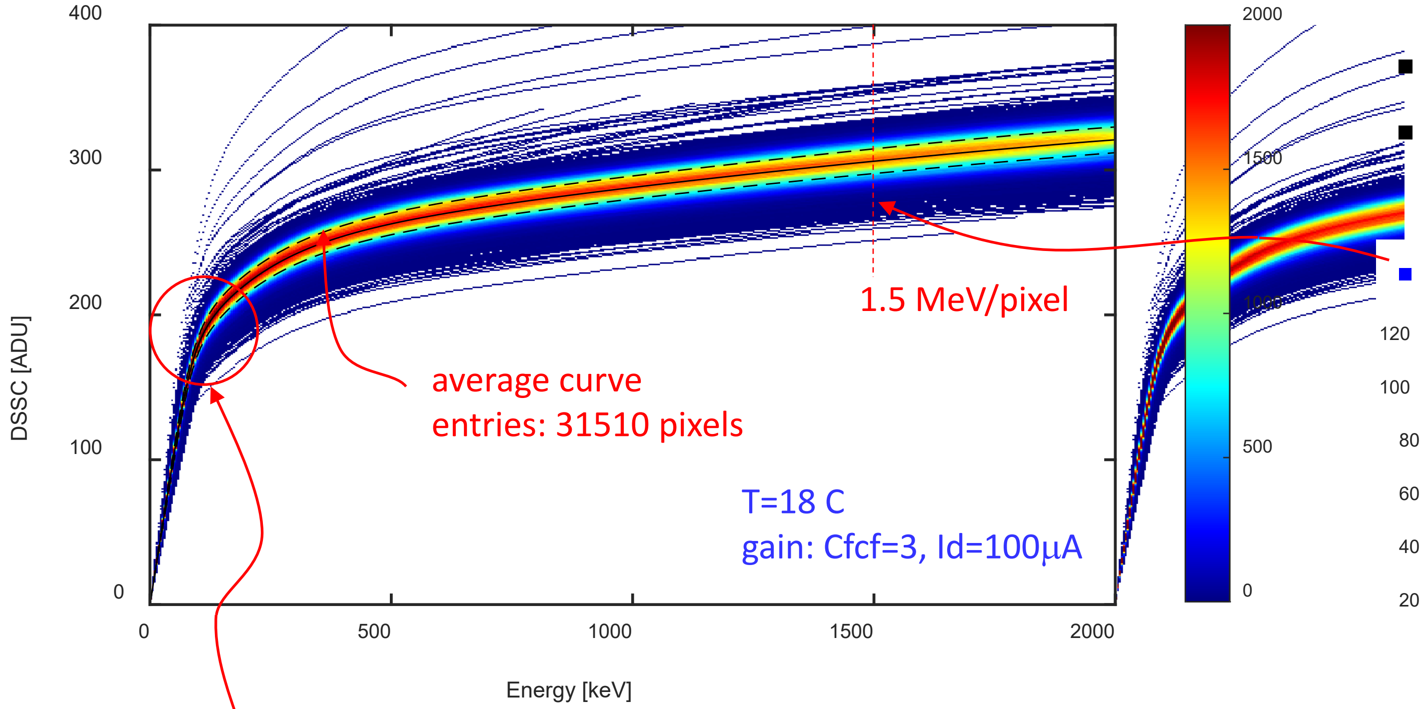




- maximum tested energy about 2 MeV (~1400 Al Ka/pixel)
- Custom fit model (3 fit var/kink)

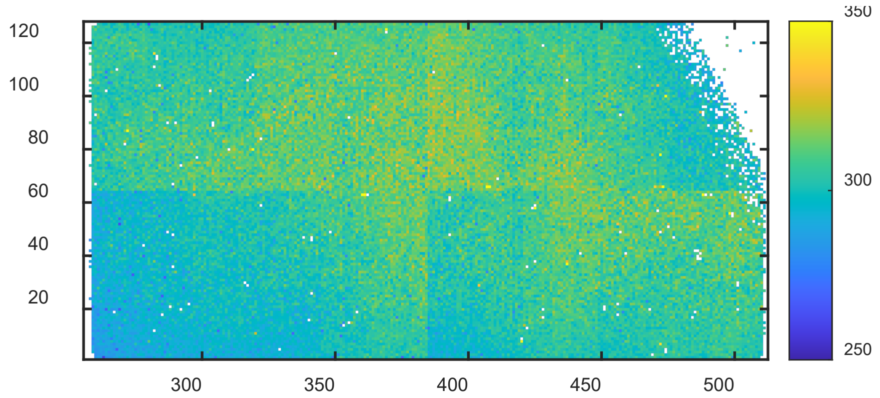
Non-linear response – full size DEPFET sensor

- NL response curves (right sensor) – persistence plot



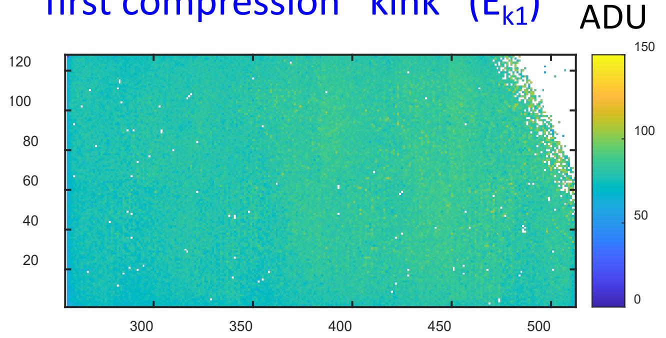
- data analysis/calibration over all pixels
- non-linear fit function, 9 fit parameters/pixel

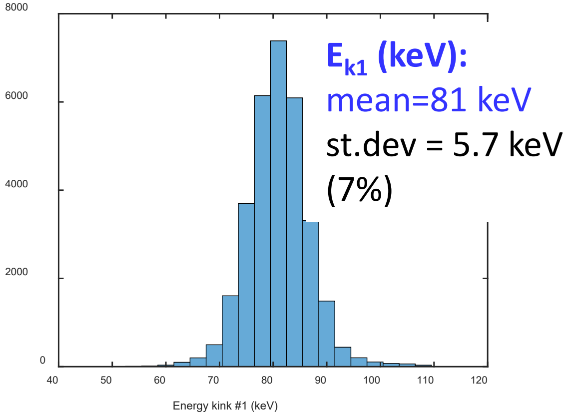
- DSSC output (ADU) @ E=1.5 MeV/pixel



spread over the sensor < 3%

- first compression "kink" (E_{k1})

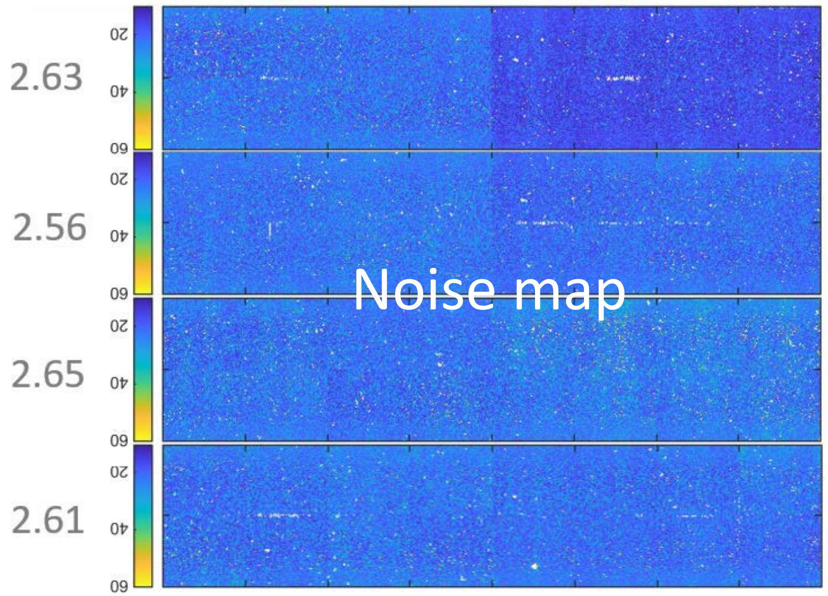


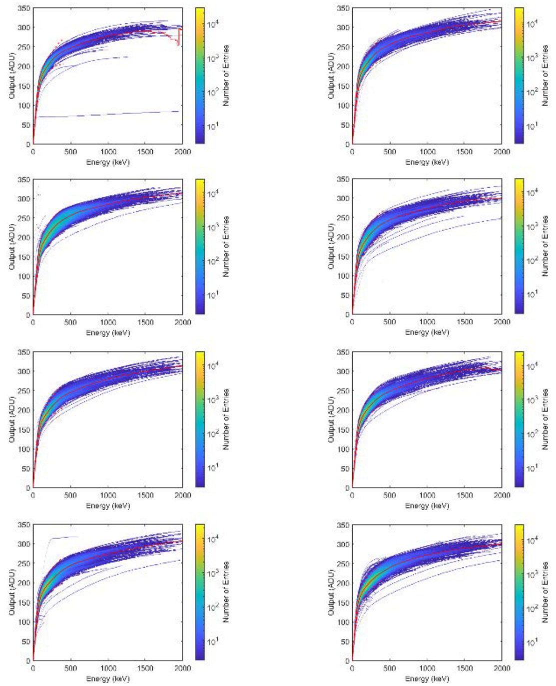


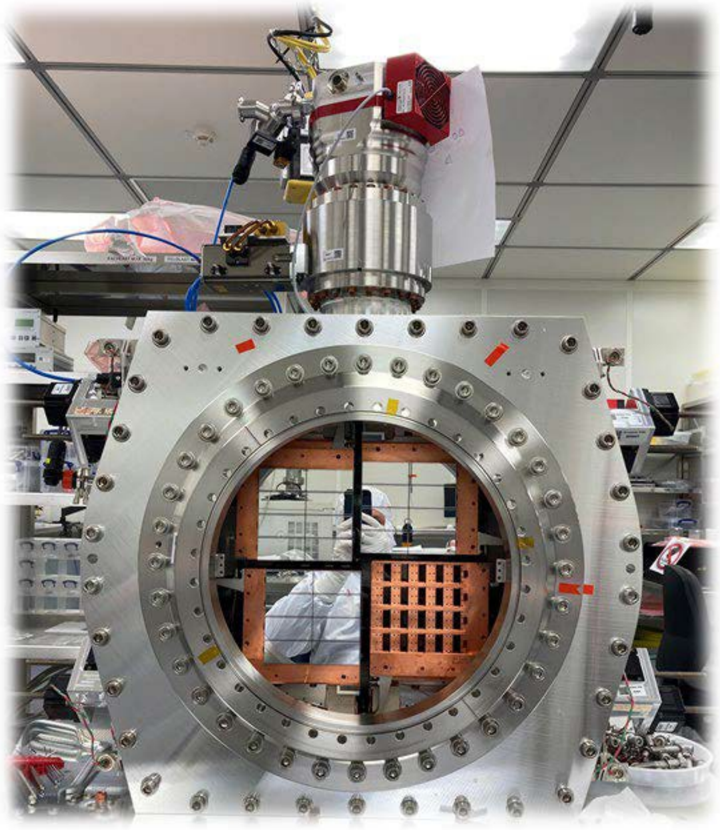
- first energy kink at ~81 keV with small spread (~7%) over the sensor
- at high intensity, very nice uniformity (< 3%)

1-Mpixel DEPFET Camera Assembly

- Functional tests at Quadrant level







- After quality control on submodules, 3 quadrants of the DEPFET camera have been assembled
- An additional DEPFET production is ongoing in order to complete the camera and provide spare parts
- First user experiments scheduled for the first half of 2025

Conclusions and outlook

- single-photon counting of soft X-rays & high dynamic range with limited ADC resolution turned to be a significant challenge for calibration of the DSSC detector
- experimental qualification of first DEPFET ladder confirmed improvements promised by the novel CMOS-DEPFET technology
  - noise 16 el rms @ T=18C @4.5 MHz, improved to 8 el rms @T=0 °C @1.1 MHz
  - ADC binwidth correction shows decisive improvement of spectroscopic discrimination capability and of calibration data accuracy
- qualification technique of the DEPFET NL response @ SQS beamline validated
  - quadrant-size illumination, accurate calibration of the deposited energy, dynamic range of several 1000s photons @ 1 keV
    - ➢ *potential of the DEPFET-based pixel to reach **single-photon imaging** down to the **lowest photon energy** (0.5 keV or lower) combined with **high dynamic range** at camera level*
- outlook
  - qualification of the response at soft X-ray energies (< 1keV). Beam time @ XFEL SCS foreseen in Q3 2024
  - Calibration of the assembled 1 Mpix DEPFET camera

Thank you for your attention !

DSSC@SQS beamline