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Qualification and Modeling of the Non-Linear Response of the First Large-Area DEPFET Pixel Sensors with Internal Signal Compression

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+ acknowledments to many people at XFEL and DSSC Consortium

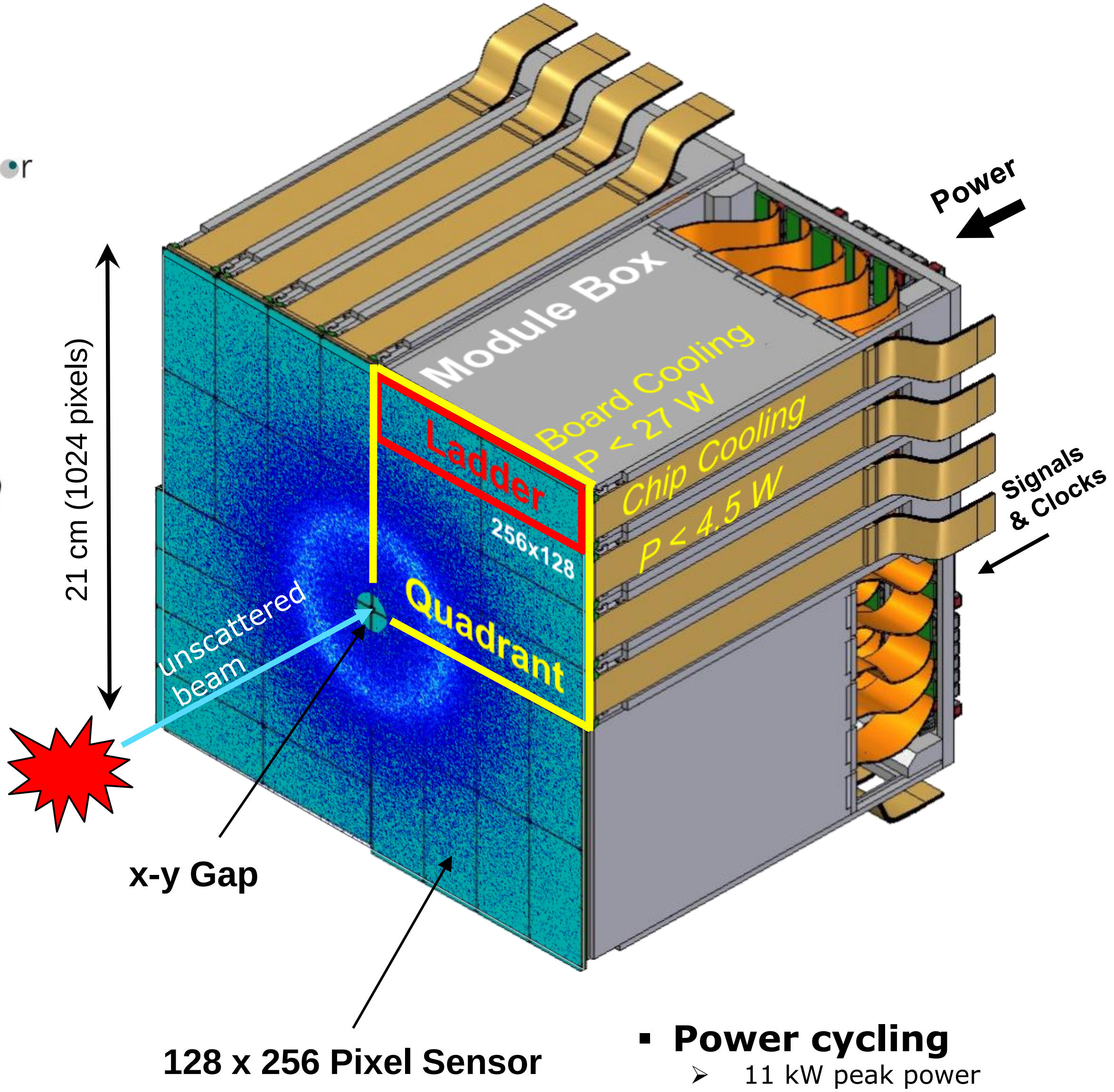
DEPFET Sensor with Signal Compression (DSSC) 1 Mpix camera

❑ 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 10,000 ph**
- **frame rate 0.9 – 4.5 MHz**
- digitization/storage during bunch train
- ~800 stored frames/macrobunch

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

↳ of particular importance is the qualification of the NL system response over the full dynamic range

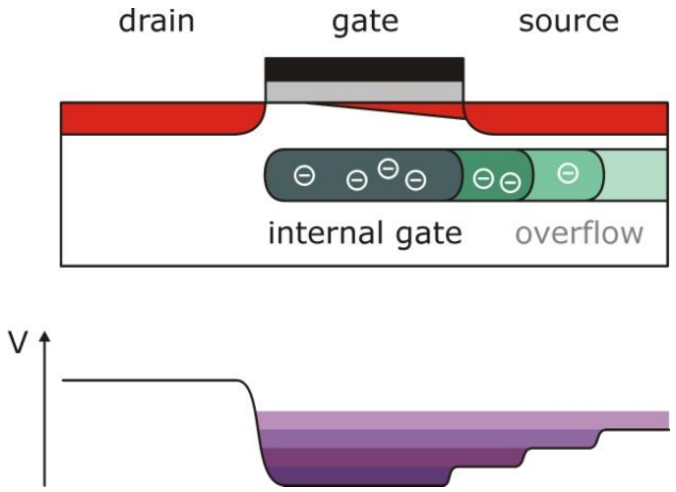


- **Power cycling**
  - 11 kW peak power
  - 240 W average power

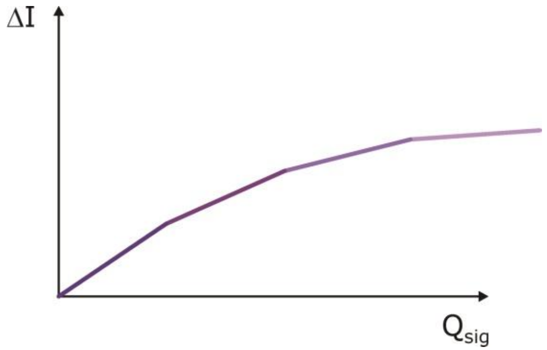
Signal compression at sensor level

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

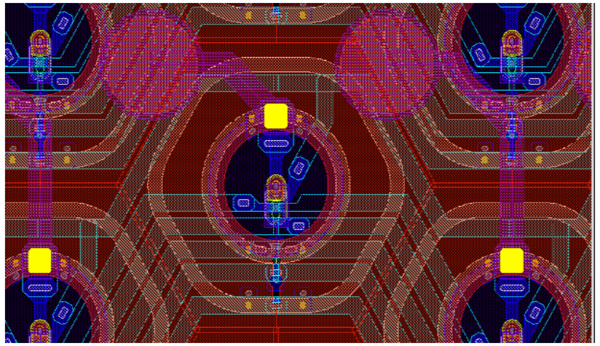


CMOS-foundry DEPFET technology (PNSensor GmbH)
Aschauer, et al. JINST (2017)

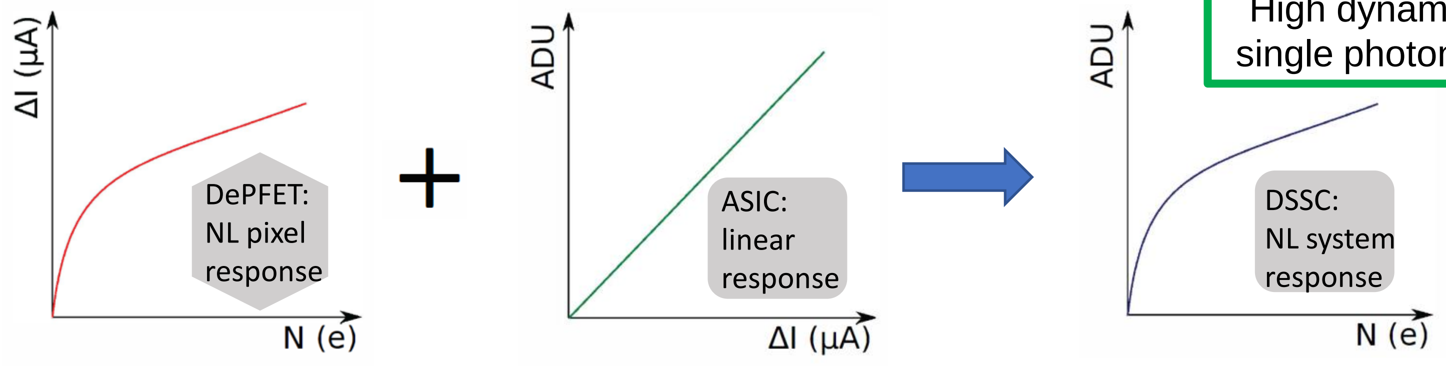


- ➢ Low noise (low capacitance)
- ➢ Fast collection
- ➢ Signal compression

(but internal gate not accessible from ASIC)

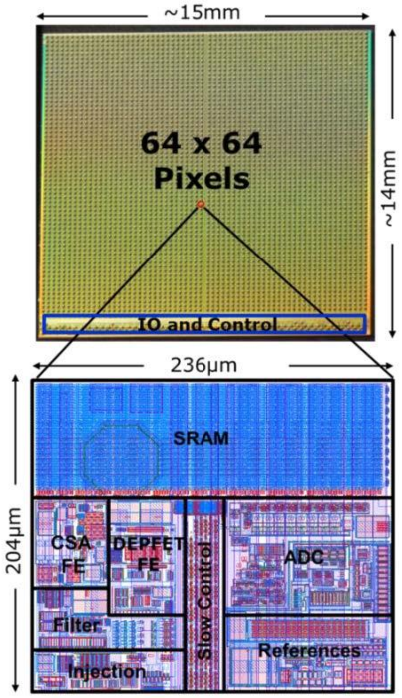


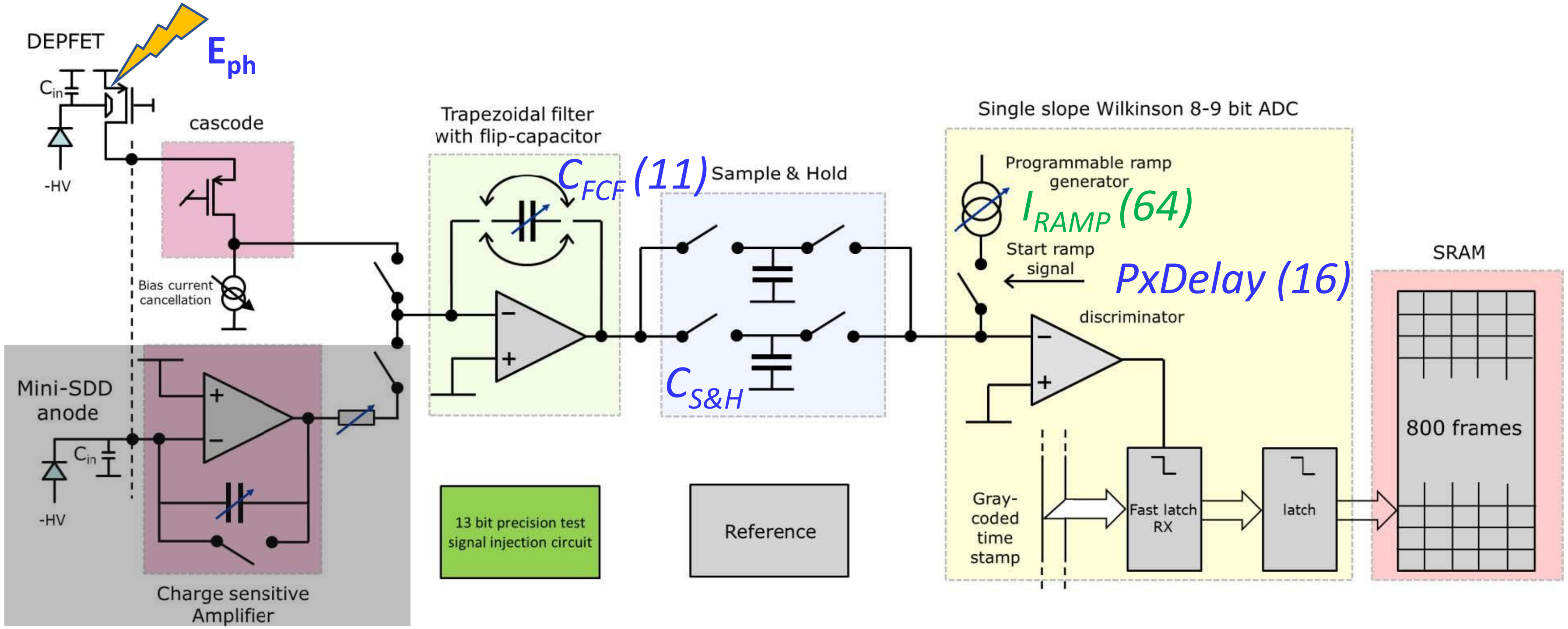
DEPFET Active Pixel



High dynamic range & single photon sensitivity

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

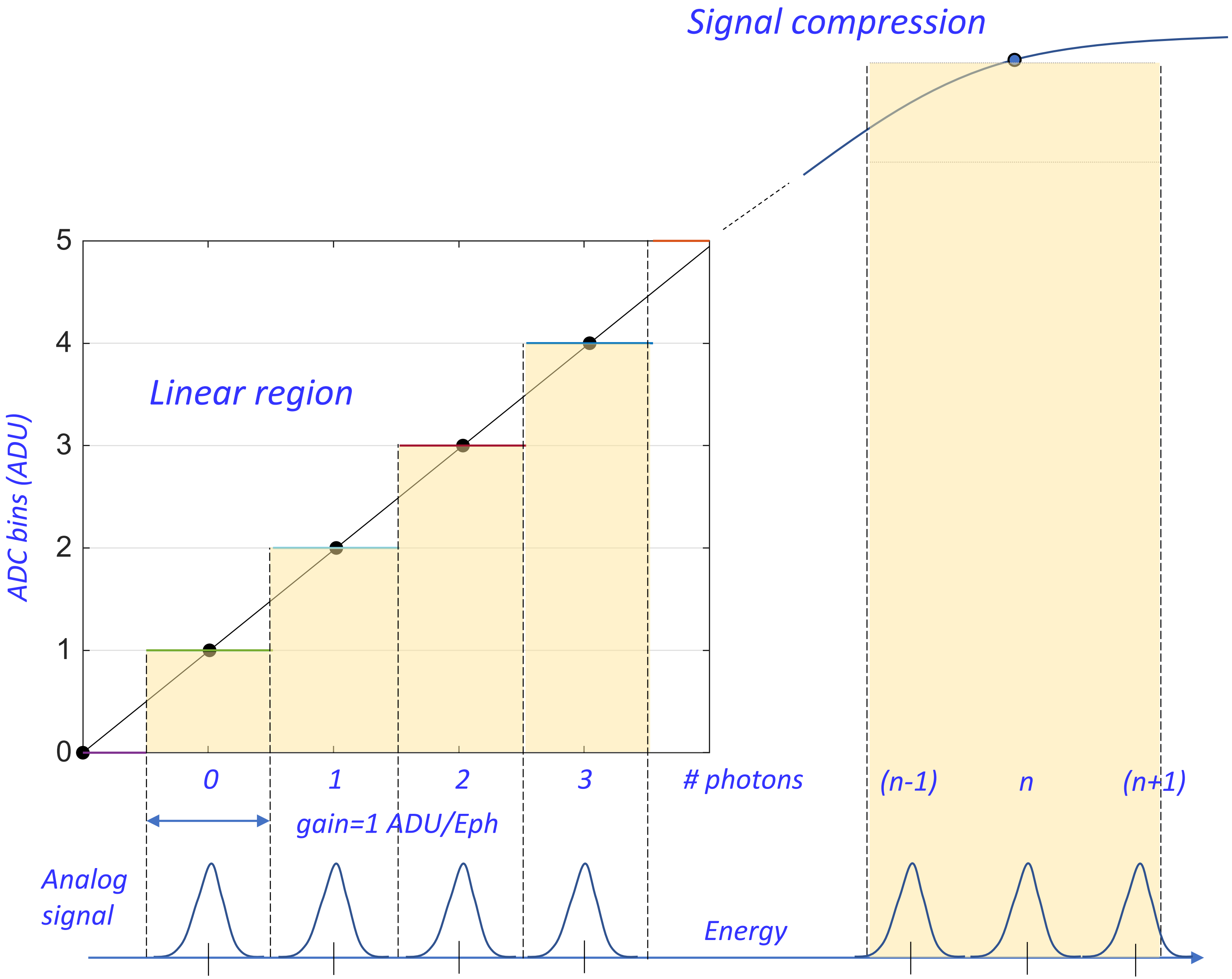
- 11 settings of Cfcf (coarse gain) for photon energy/dyn. range selection
- 6 bits of ADC gain fine trimming (nominal accuracy 2%)
- 4 bits for offset trimming (1.5 LSB range with 8% granularity)

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

↳ possibility of fine gain trimming @pixel level

Single photon sensitivity & high dynamic range

- 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
- **offset and gain** in the read-out ASIC must be set for the correct incident photon energy before a scientific experiment is performed
  - not possible 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)**



Two-step procedure:

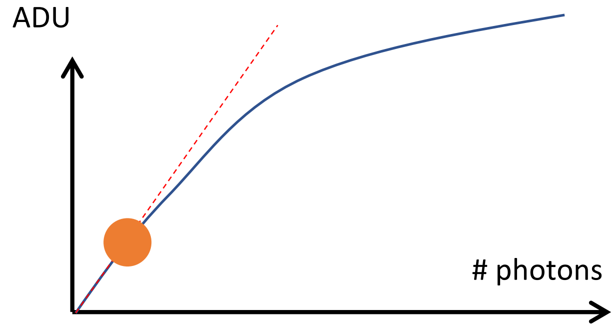
i. calibration of gain/offset in the linear region for all settings

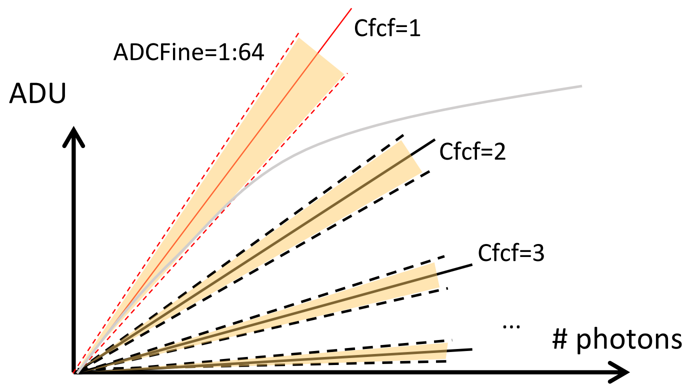
ii. qualification of the shape of non-linear (NL) DePFET response.

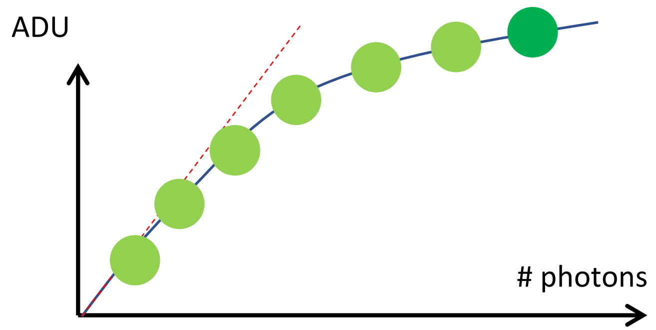
Detailed tasks:

- **hard X-ray spectra, high-gain mode setting (Cfcf=1)**
  - ↳ DSSC-PulXar setup
- **LookUpTable of ASIC gain values (gain ratios)**
  - ↳ charge-injection circuit (13bit)
  - ↳ Cfcf=11 settings, ADC fine gain (2x64 settings)
- **qualification of the NL response**
  - ↳ few options: optical (LED/laser), leakage current, XFEL beam
  - ↳ only 1 gain setting

↳ validation of the calibration procedure at ladder level

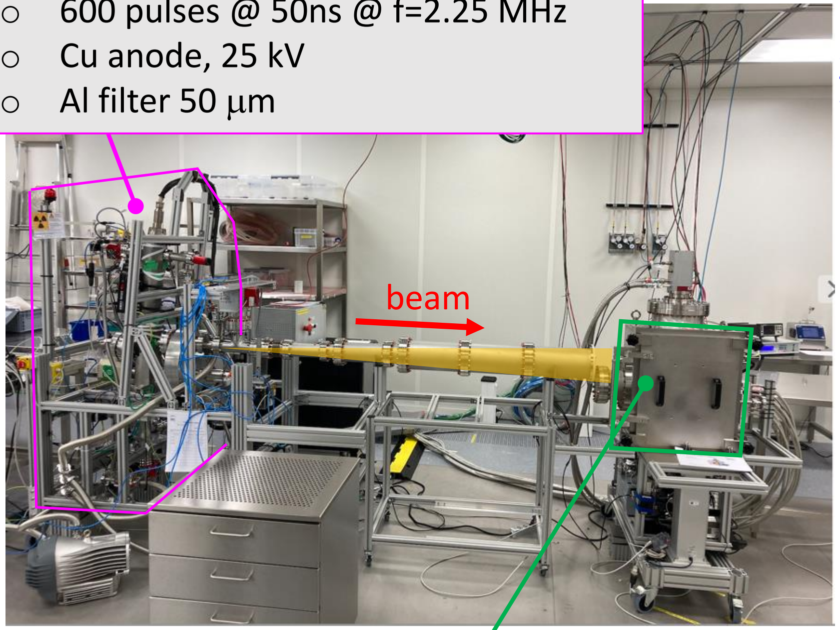




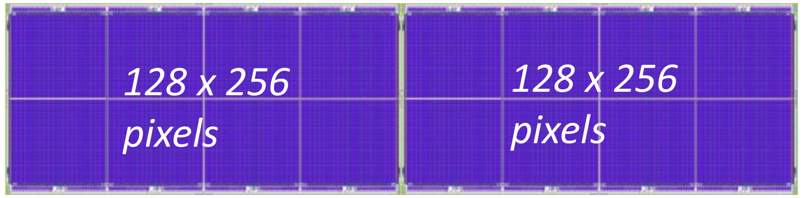


Calibration campaign of the 1st DEPFET ladder with X-rays

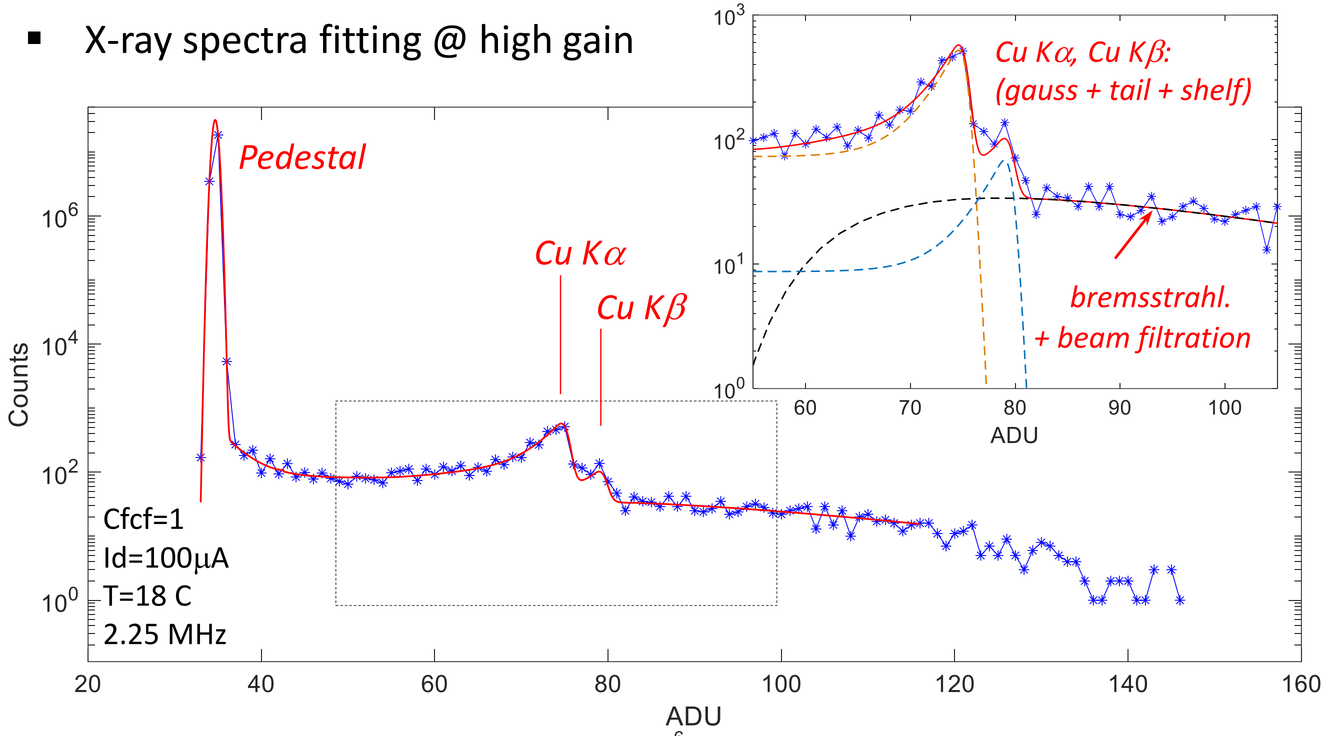
- PulXar source @XFEL DET Group
  - 600 pulses @ 50ns @ f=2.25 MHz
  - Cu anode, 25 kV
  - Al filter 50 µm



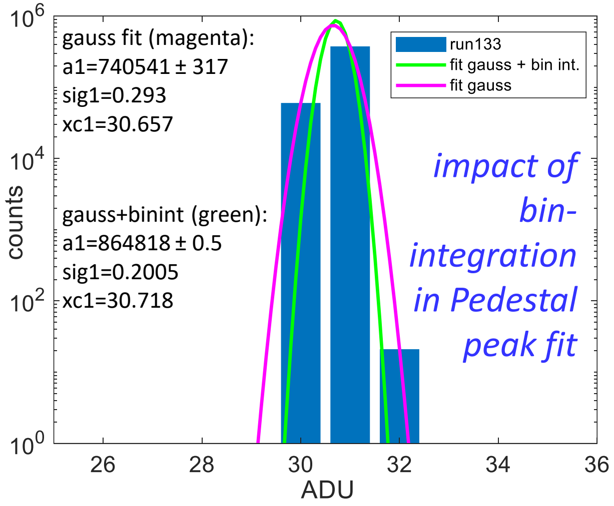
- DEPFET ladder (128 x 512)



- X-ray spectra fitting @ high gain

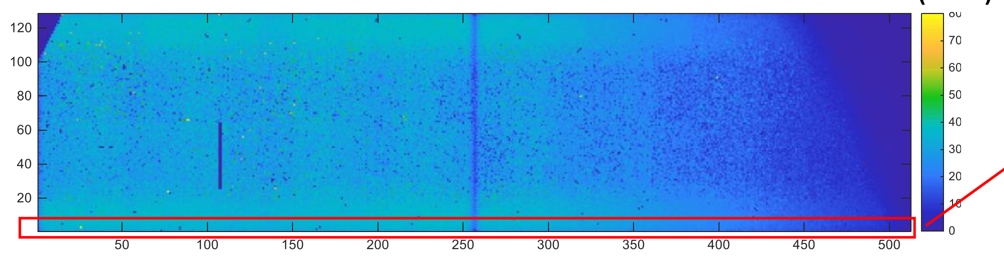


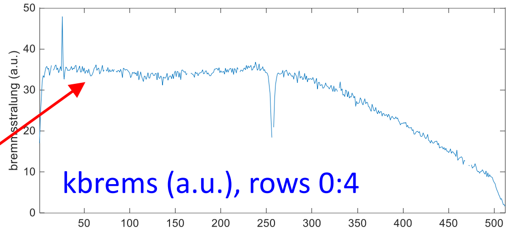
- 8-bit resolution impacts on accuracy of gain/offset determination
- characterization/modeling of DEPFET spectral response (high-res 14-bit test bench)
  - charge-sharing (i.e. low-energy peak tail)
  - bremsstrahlung
  - bin integration



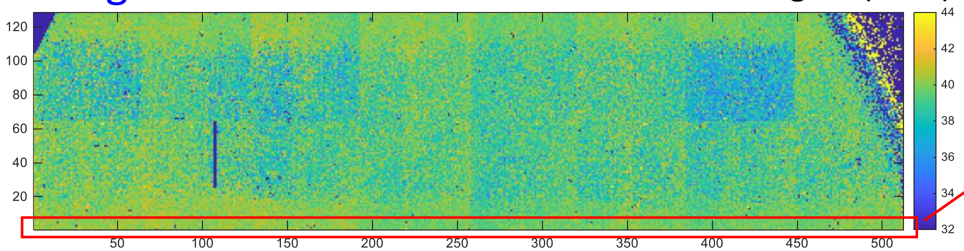
Gain / noise on DEPFET ladder @ high gain (PulXar spectra)

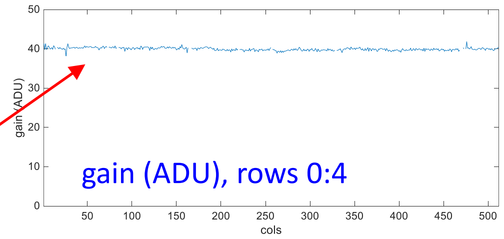
- bremsstrahlung (pixel intensity)

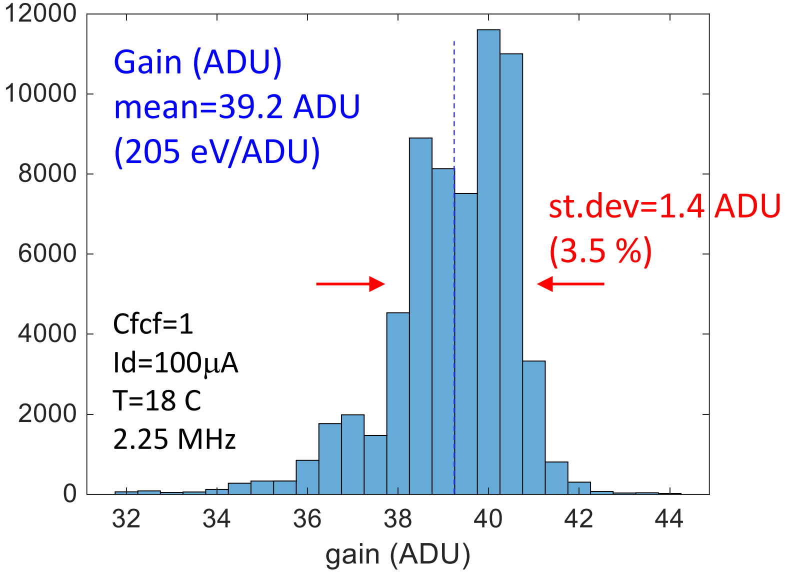




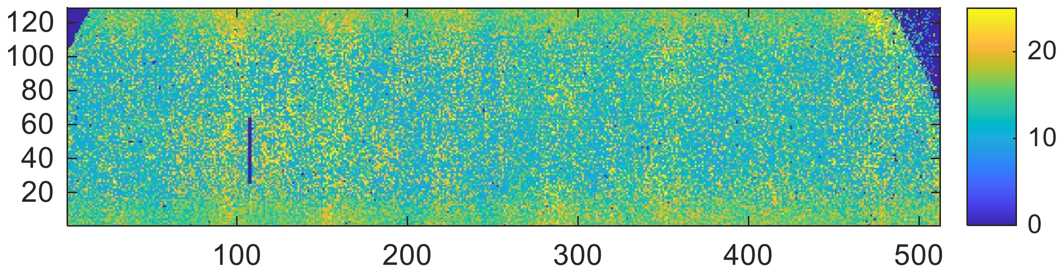
- gain

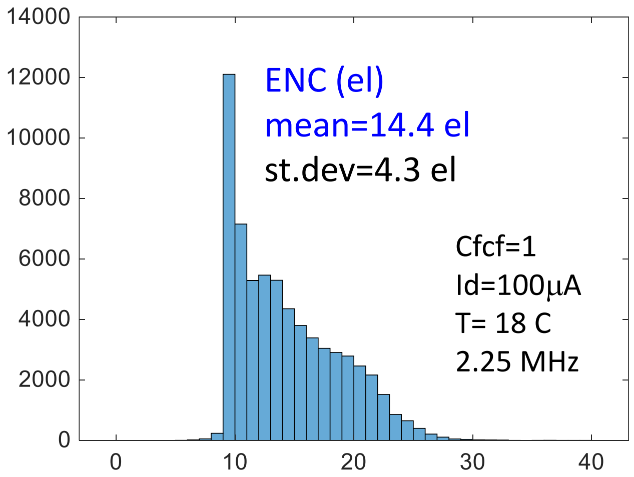






- noise





Gain (untrimmed)

- small gain spread (3.5%)
- std_error(gain) <1%

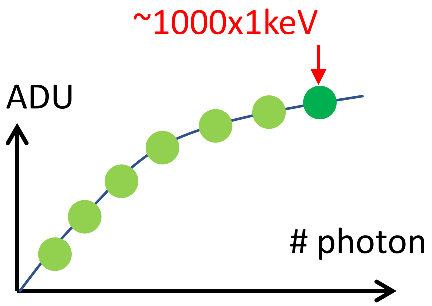
Noise

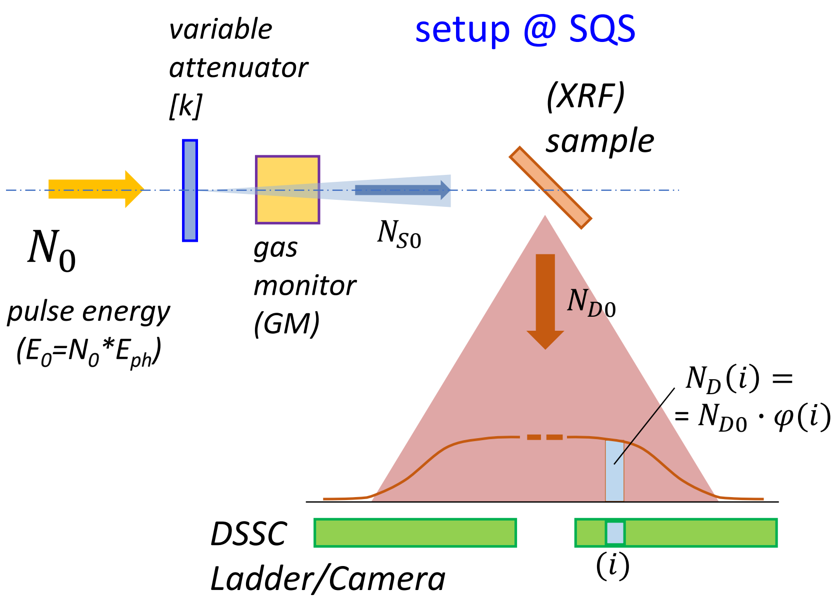
- ENC 14 ± 4 el rms @2.25 MHz

Qualification of the Non Linear DEPFET response - technique

- Constraints
  - 150nm Al layer on entrance window (optical block)
  - technique applicable to 1 Mpix camera

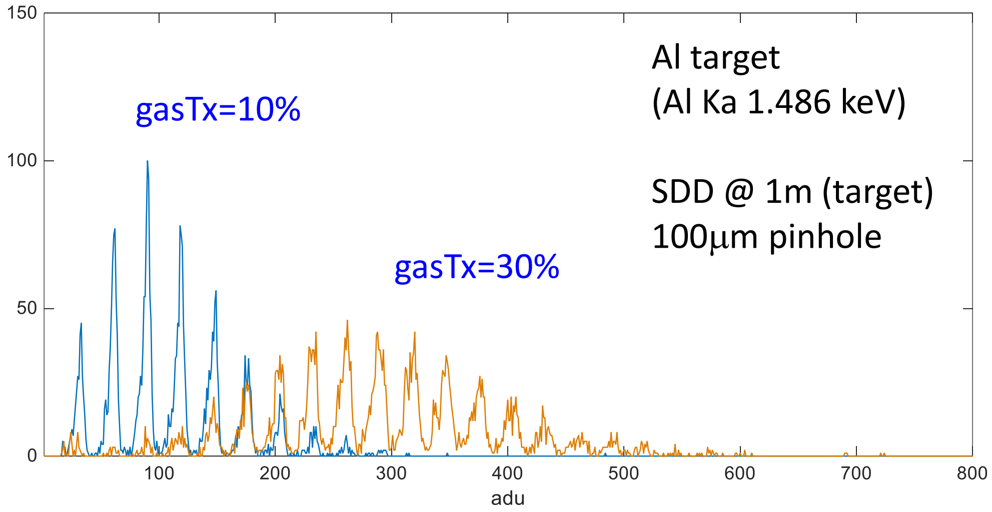
- XFEL beam on target: rationale
  - XRF emission proportional to beam intensity
  - pulse of N low-energy XRF photons (e.g. 1 keV) produce a "reference line"
  - to scan the NL curve we change beam attenuation (i.e. gas transmission)
  - irradiation of one full quadrant





- Feasibility tests @ XFEL SQS beamline
  - SDD + pinhole to define photon flux
  - high spectroscopy resolution allows accurate intensity calibration (photon# peaks)
  - verified linearity range of (XRF counts vs. beam intensity)

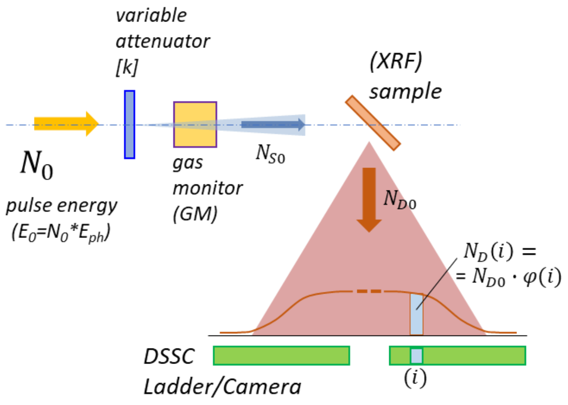
SDD spectra at different beam intensity

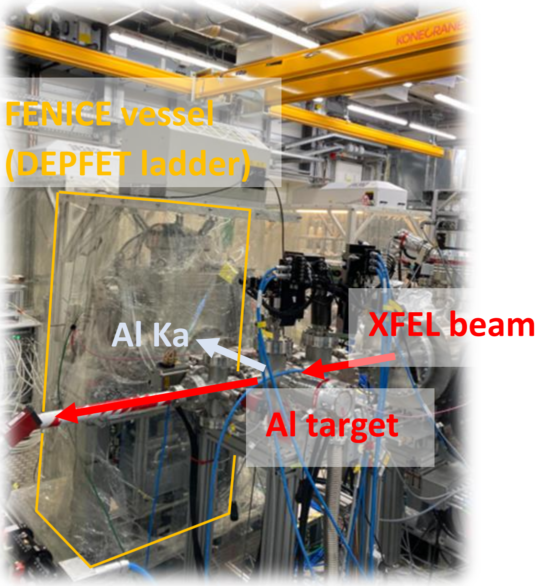


Beam time @ SQS beam line (Oct. 2021)

❑ Goal: verification of NL response measurement technique

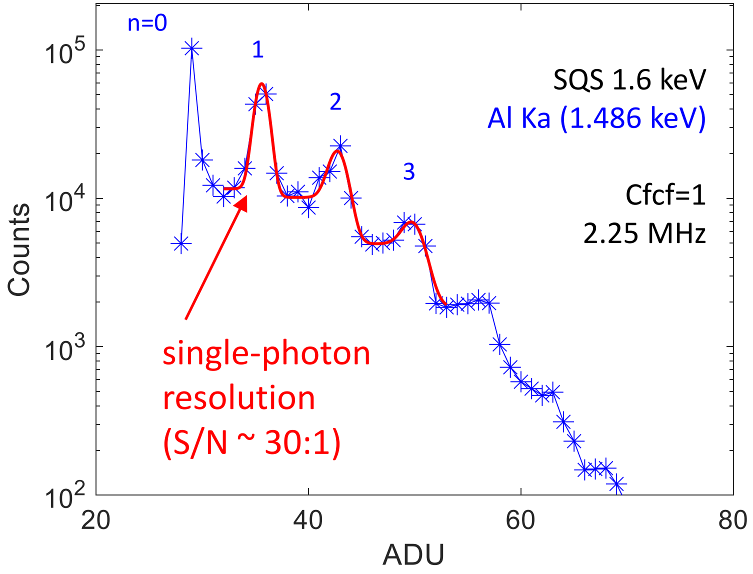
- DSSC mounted @ 40cm from Al target to maximize photon rate
- SQS instrument must provide a stable beam
- reference monitor of beam intensity (x-ray gas monitor)



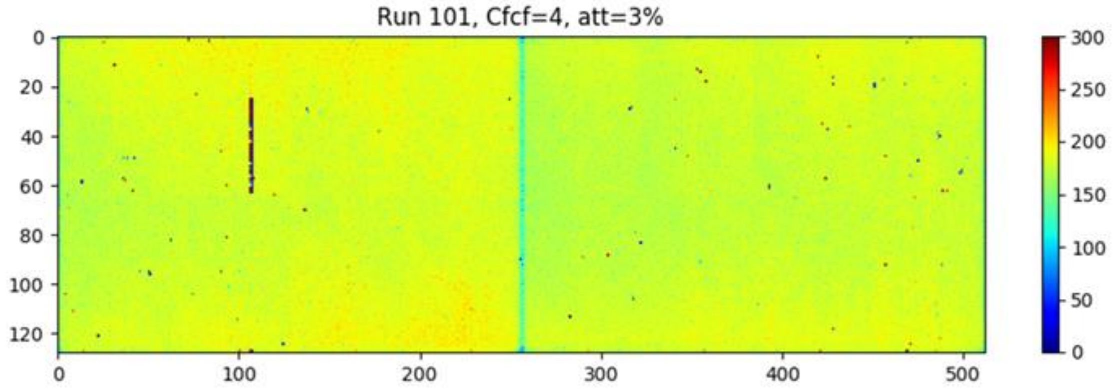


❑ Tests at low intensity & high gain setting (linear region)

- Energy spectrum Al Ka photons



- irradiation profile of Al Ka photons



nice flat profile

→ possible irradiation of 1 quadrant (=4 ladders)

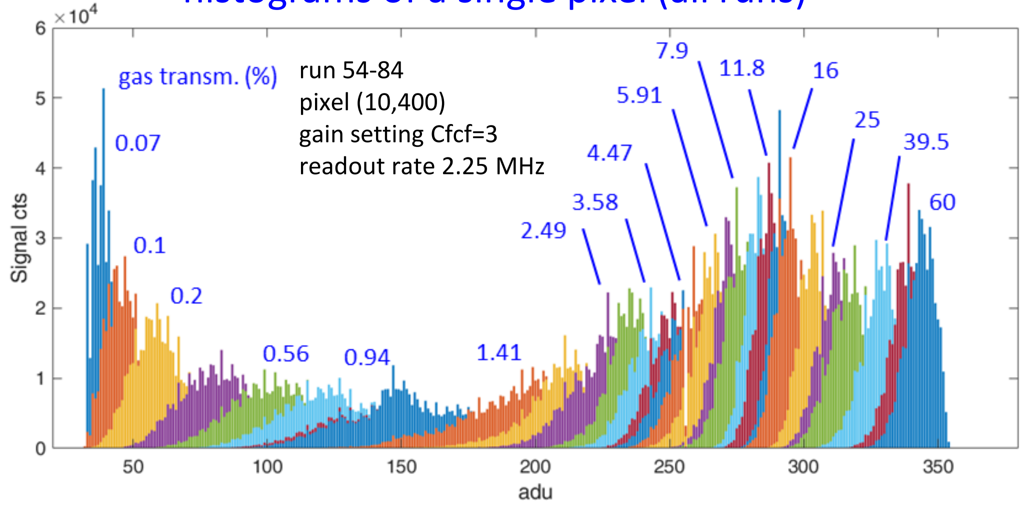
- single-photon resolution: Al Ka photon peaks well separated (signal/noise ~30:1)
- ENC from SQS spectra (14.1 el.) confirm values obtained from PulXar (14.4 el.)

Non linear response of DEPFET pixel

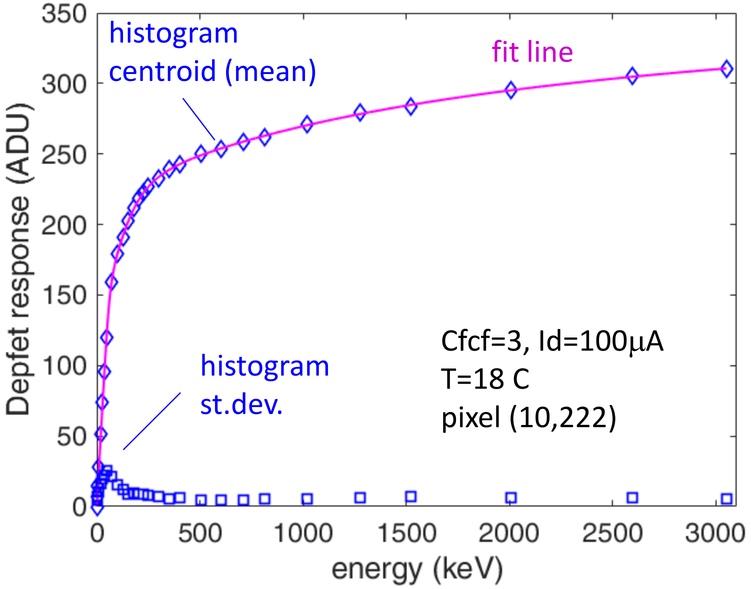
Intensity "scan"

- acquisition of flat-field images of Al Ka photons vs. gasTx
- X-ray Gas Monitor tracks beam intensity incident on the target
  - XGM data (electron-based): fast (single-frame)
  - XGM data (ion-based): slow (20s), accurate (down to few keV/pixel)
  - non-negligible beam intensity variations ("blue" weeks @ XFEL)
- energy calibration obtained by matching the response in the linear region with the measured DEPFET gain (from X-ray spectra)

• histograms of a single pixel (all runs)

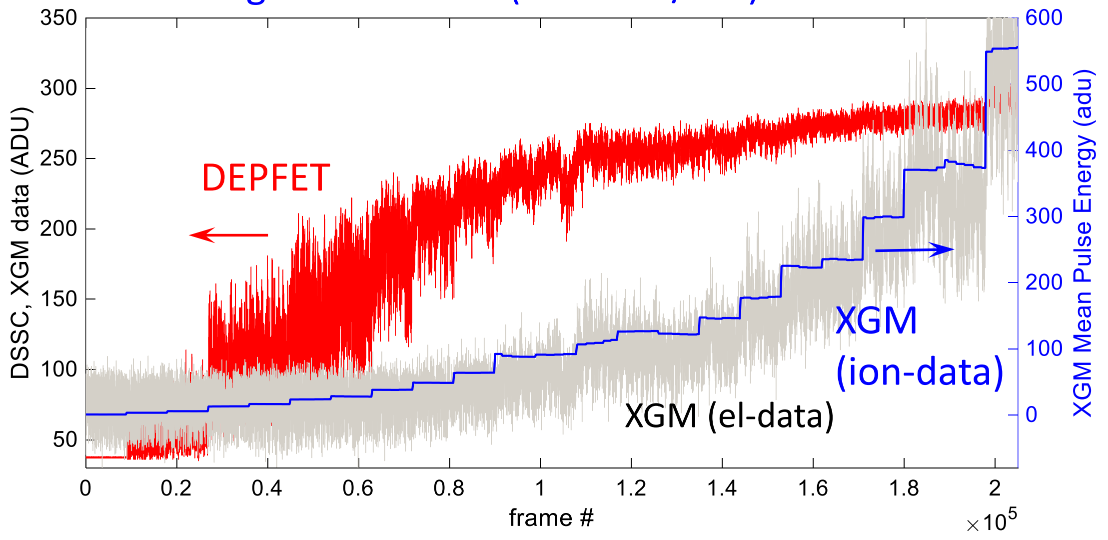


• NL response curve vs. deposited energy



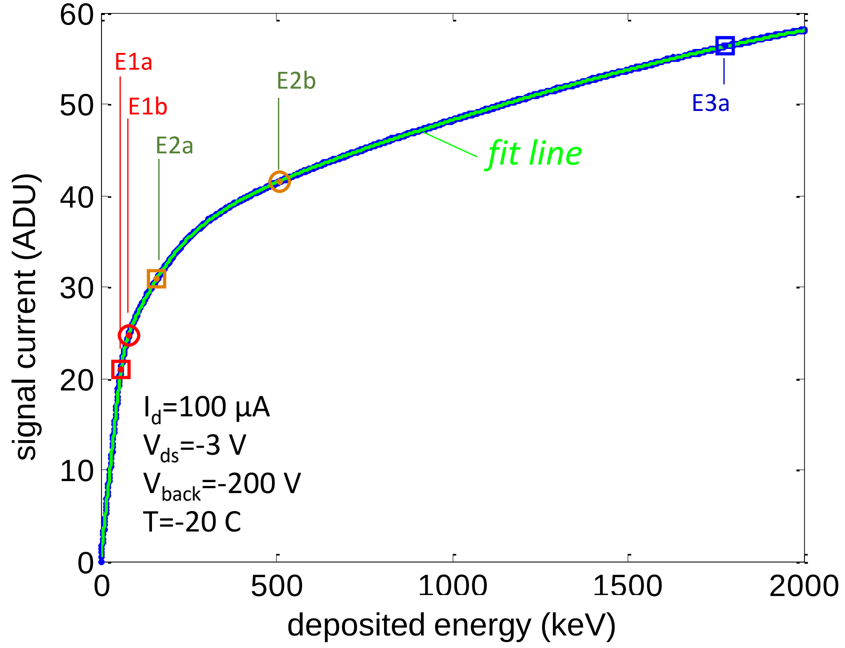
- successful qualification of the whole compression curve
- maximum deposited energy about 3 MeV (~2000 Al Ka/pixel)

• single-frame data (50 trains/run)

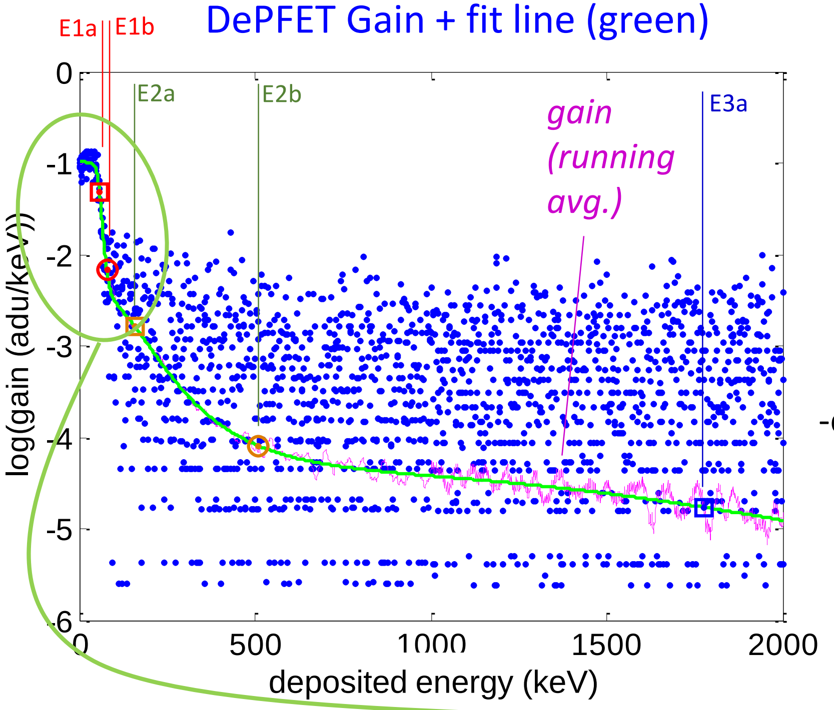


Fitting model of the NL response

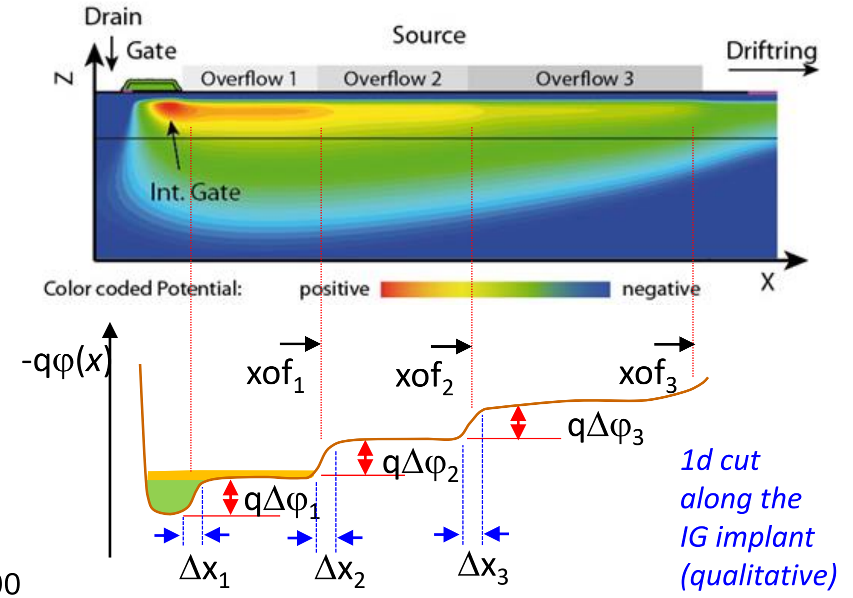
DePFET Signal + fit line (green)

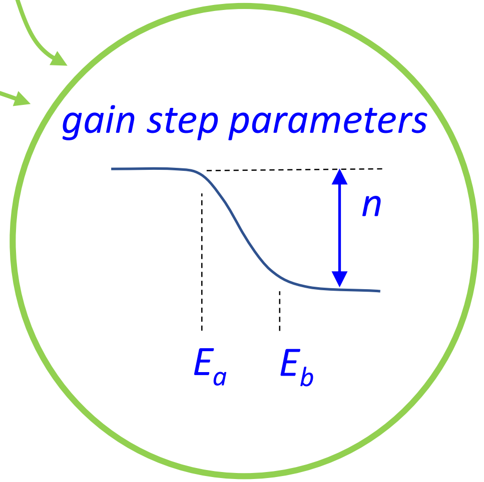


DePFET Gain + fit line (green)



CMOS-DEPFET technology

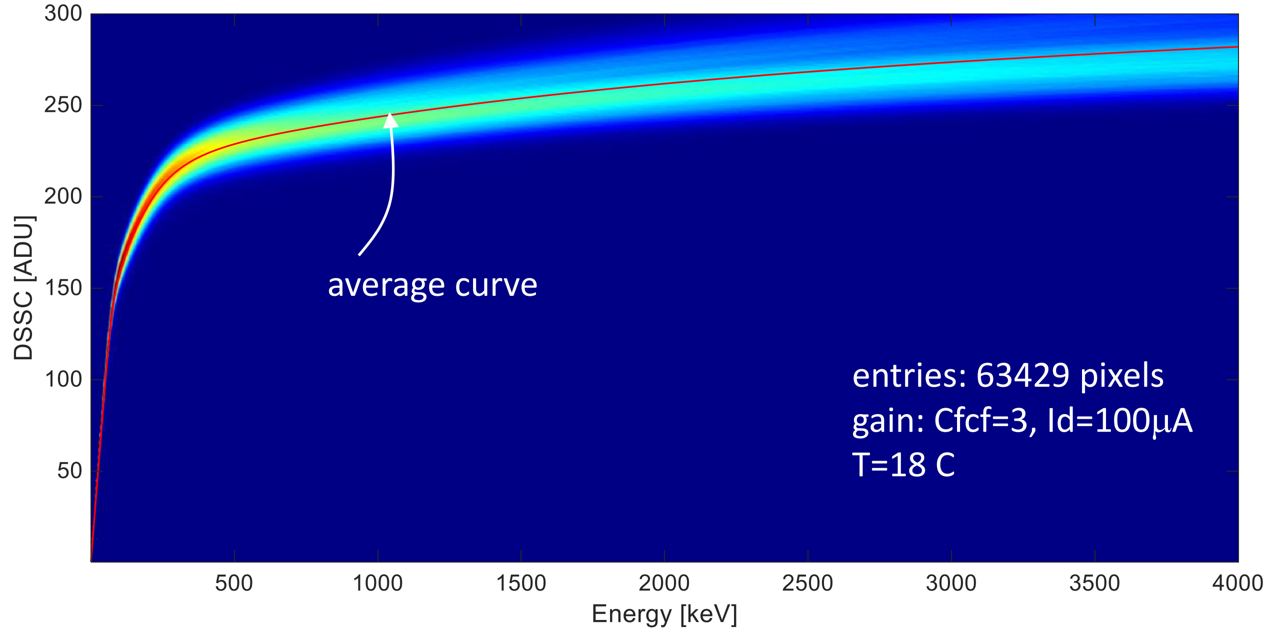




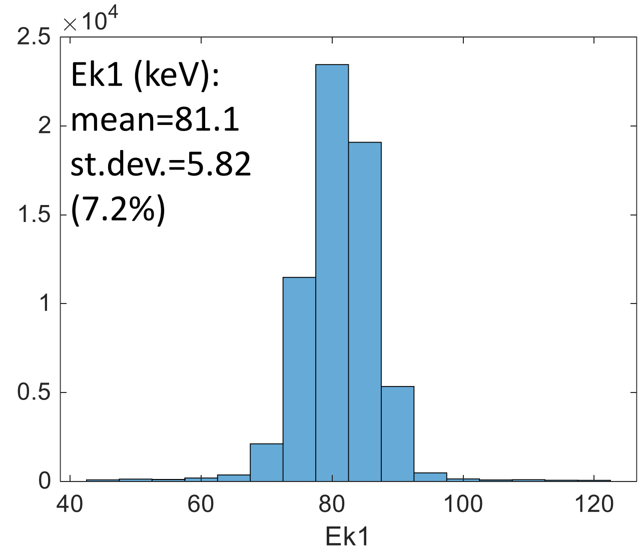
- A single gain step described by an elementary function with 3 fit variables (E_a, E_b, n), representing energy boundaries and amplitude of the gain step
- good-of-fitness: rmse <0.02 ADU, R2bar=1.0000, std error of fit variables <1%
- link from NL response model to DEPFET technology qualification

NL response – all DEPFET ladder

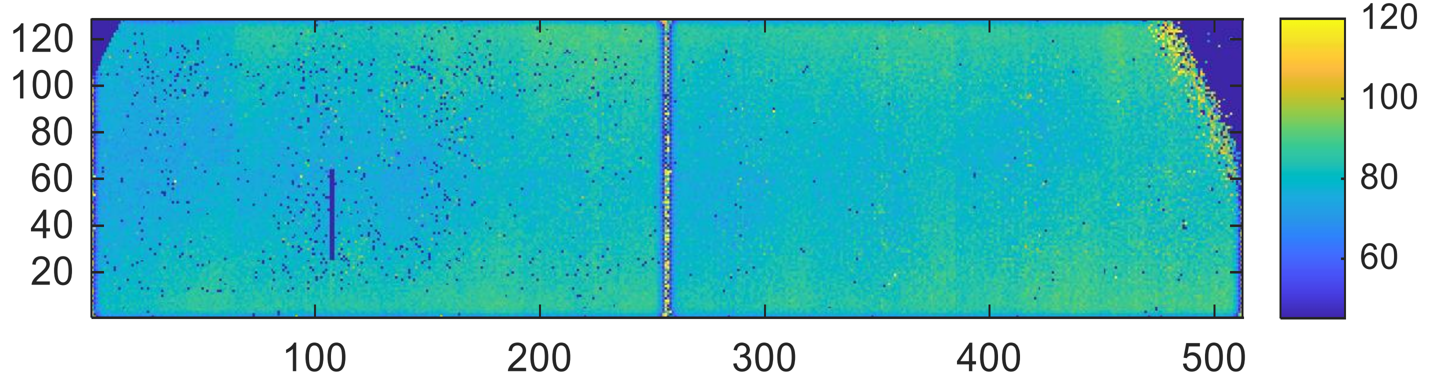
- NL response curves of all ladder



- data analysis/calibration over all pixels
- non-linear fit function
- extraction of all fit parameters pixel-wise



- first compression "kink" (E_{k1}) of the NL curve

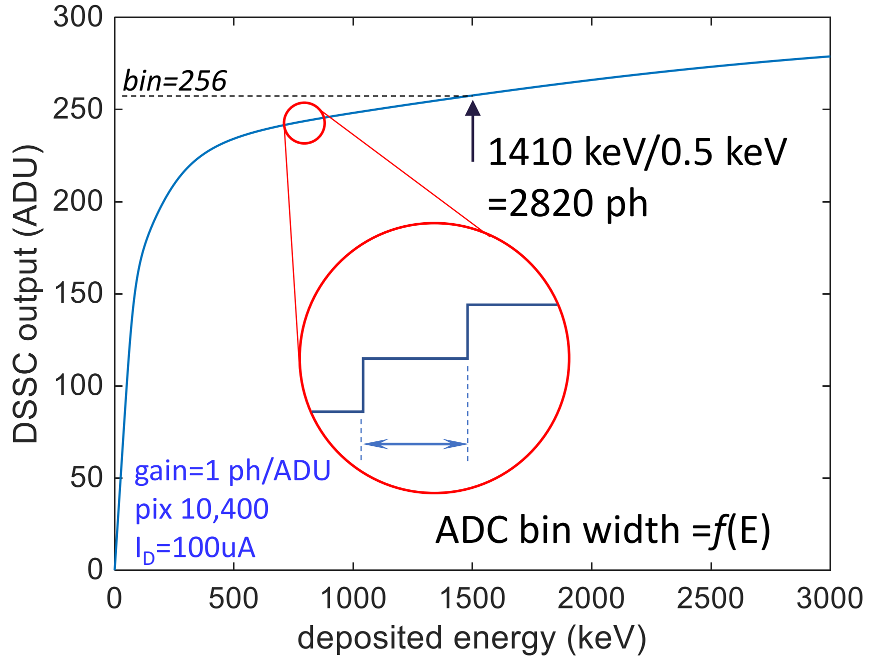


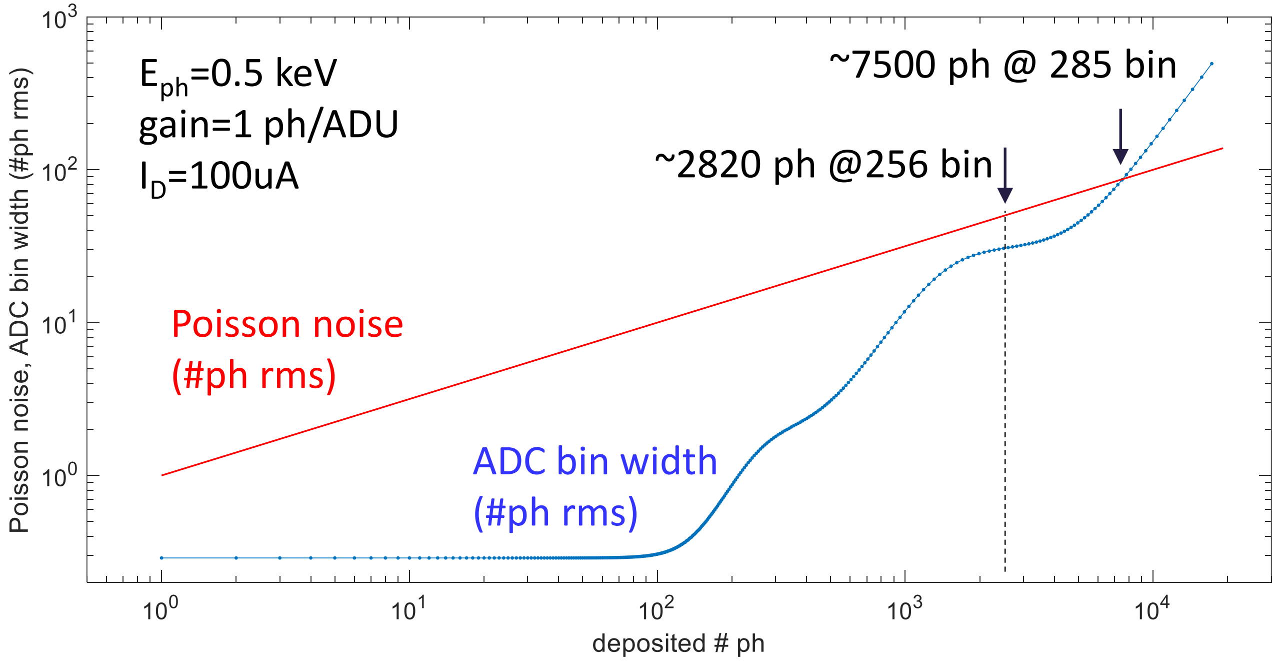
- mean value (81.1 keV) in line with lab tests
- nice uniformity: 7% spread over the ladder

Dynamic range

- maximum #photons at full scale of ADC, e.g. for 8 bit resolution @256ADU (or 512ADU if $f \leq 2.25$ MHz)
- maximum #photons for which ADC resolution equals Poisson noise

- **E.g. photon energy 0.5 keV**





- NL response more compressed than ideal shape (sqrt(x)), marginal increase of quantization noise
- single-photon counting -> gain = 1 photon/ADU (0.5 keV/ADU in the linear region)

↳ DR = 2820 photons @ 4.5 MHz (7500 photons @ 2.25 MHz)

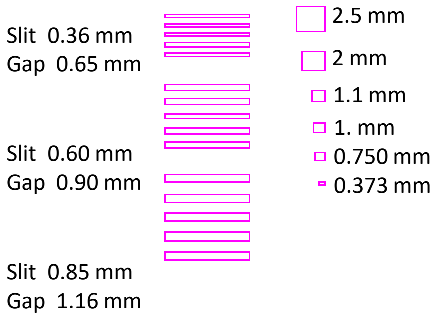
Conclusions and outlook

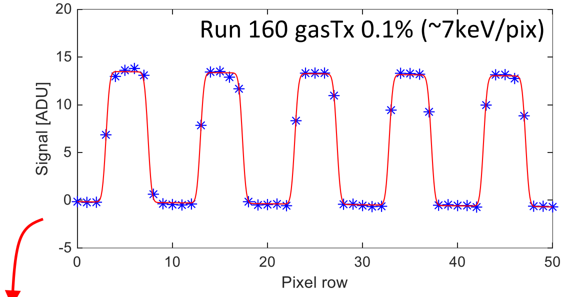
- combination of single-photon counting & high dynamic range with limited ADC resolution reflects in a significant challenge for calibration, directly linked to the performance of the DSSC detector
- the experimental qualification of first DEPFET ladder gave a very successful feedback:
  - noise level of 10-20 el rms
  - gain/noise accurate calibration from PulXar spectra @ Cu Ka (8 keV), confirmed at SQS @ Al Ka (1.48 keV)
- qualification technique of the NL response @ SQS (XFEL beam on Al target) successful
  - fulfilled required intensity (~3 MeV/pixel), quadrant-size field of illumination
  - DEPFET response qualified over the whole ladder
  - beam intensity variations observed (“blue week” not “user week”), XGM data and correction techniques under study to minimize impact
- dynamic range @ 0.5 keV photon energy: DR~3000 ph @ 4.5 MHz or ~8000 ph at 2.25 MHz.
- so far so good, but a lot to do next...
  - sensor response as a function of photon energy (< 1 keV), correction for ADC DNL, optimization of the compression shape vs. DEPFET operating conditions, imaging properties, etc.

spares

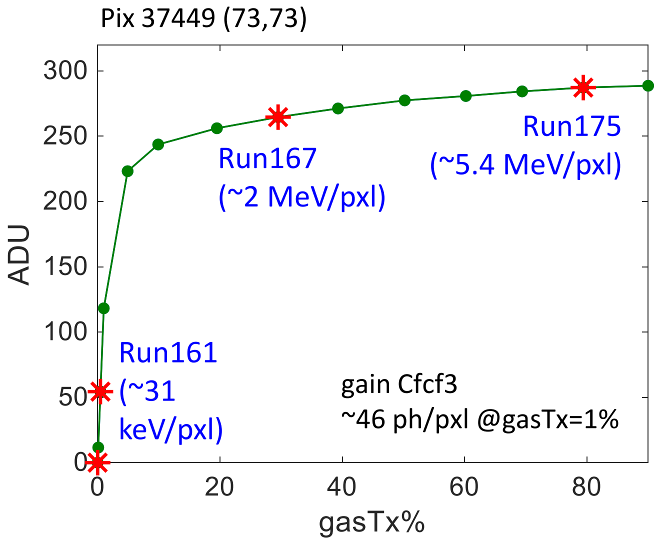
Imaging properties at 1.48 keV (Al Ka photons @ SQS) - preliminary

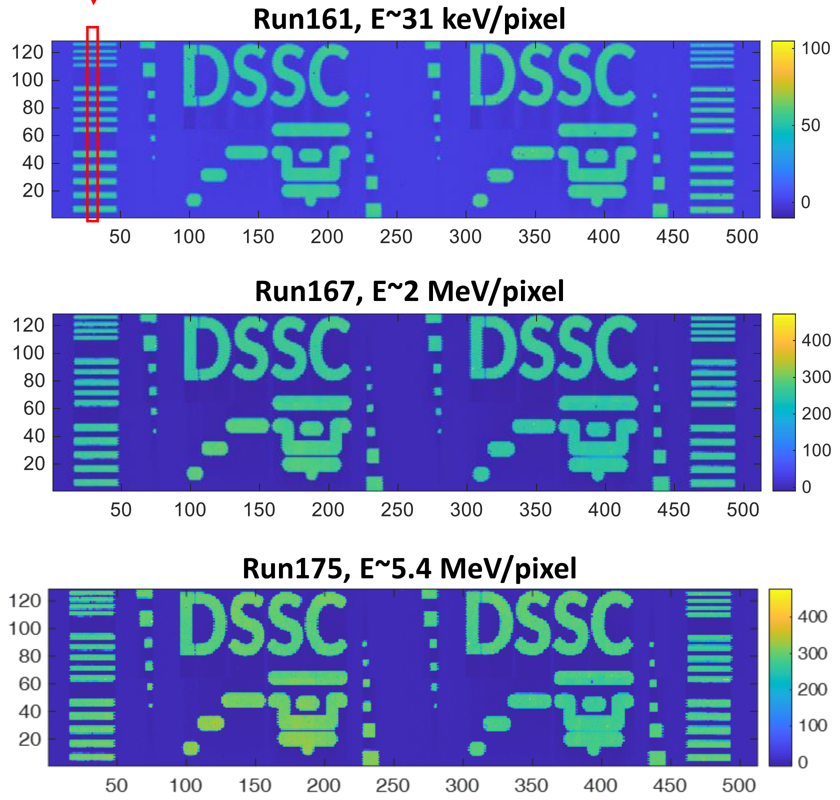
Steel, 0.5 mm

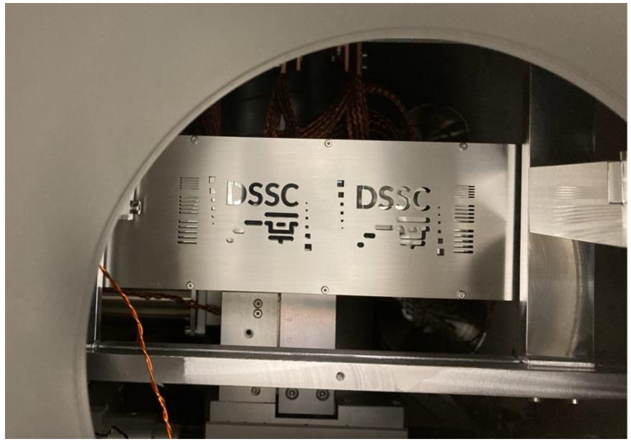




- average of 25 cols
- erf fit: σ=0.31 pix







- image details well resolved for all intensities up to 5.4 MeV (colormap rescaled)
- work in progress