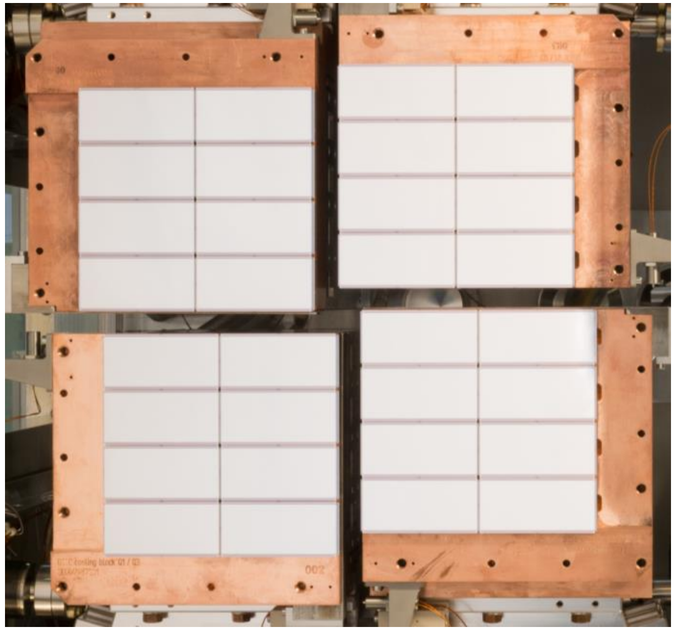
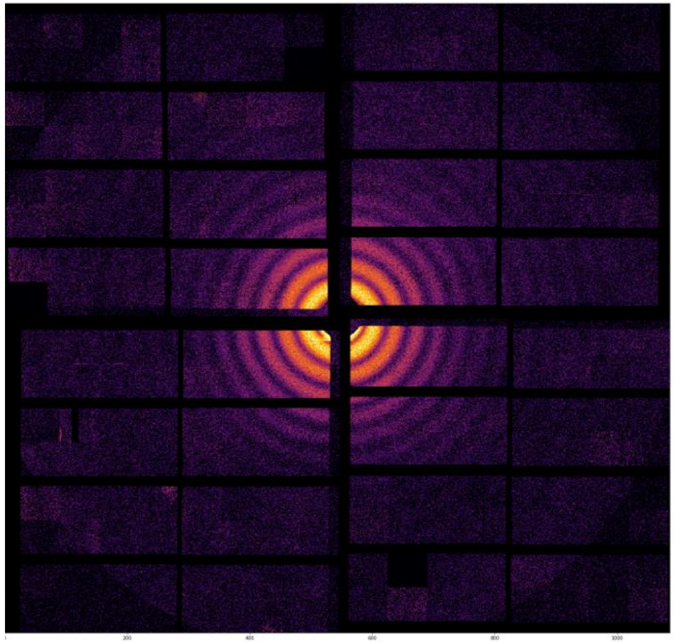
The DSSC soft X-ray Detectors with Mega-frame Readout Capability for the European XFEL

Matteo Porro on behalf of the DSSC Collaboration





23rd International Workshop on Radiation Imaging Detectors
Riva del Garda, Italy

Sensors I, 29.06.2022

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6) Dipartimento di ingegneria industriale, Università di Bergamo, Bergamo, Italy
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8) Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
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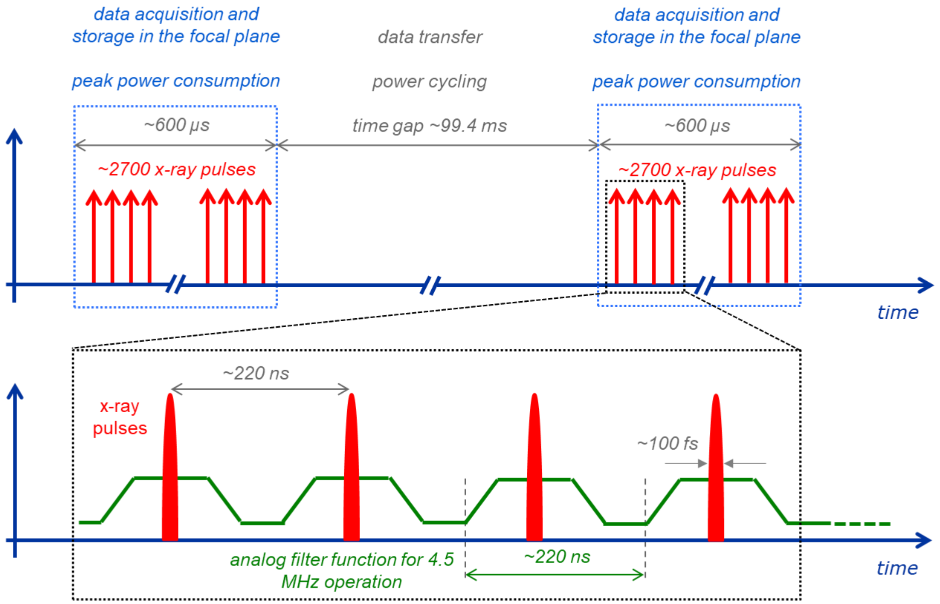
P.I.: M. Porro

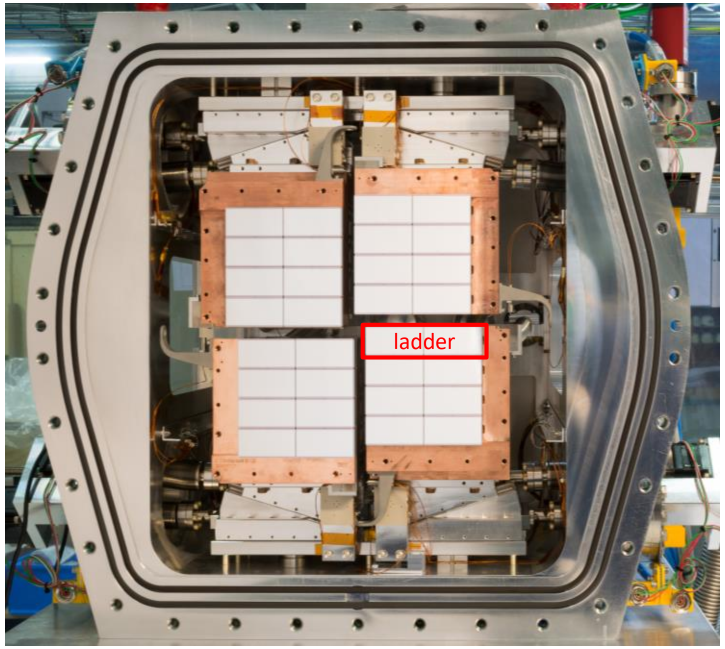
DSSC Detector System Overview 1/2

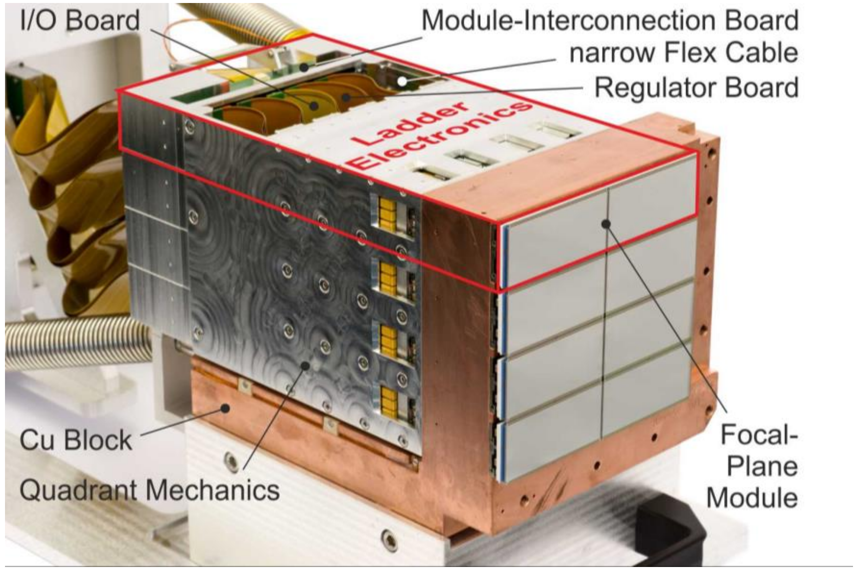


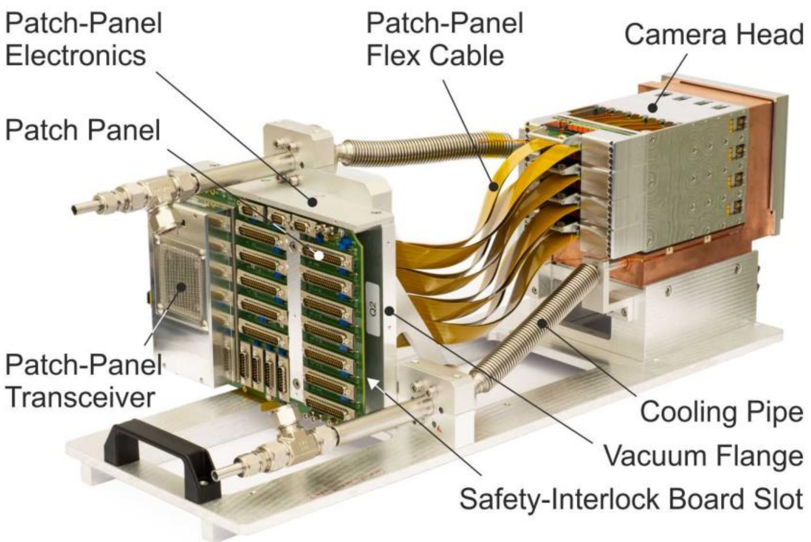
Parameter		Value
Target energy range		0.25 keV – 6 keV
Pixel count		1024 × 1024
Pixel shape		hexagonal
Sensor pixel pitch		~204 µm × 236 µm
Active area		~ 21 cm × 21 cm
Input photon range / pixel / pulse (*)	MiniSDD	$2^n \times N - 1$
	DEPFET	*>10⁴*
Achievable noise	MiniSDD	~ 60 e- r.m.s.
	DEPFET	*~ 10 e- r.m.s.*
Peak frame rate		4.5 MHz
Stored frames per X-ray train		800
Average / peak data rate		134/ 144 Gbit / s
Average power consumption		~ 260 W
Operating temperature		-20º C optimum, room T possible

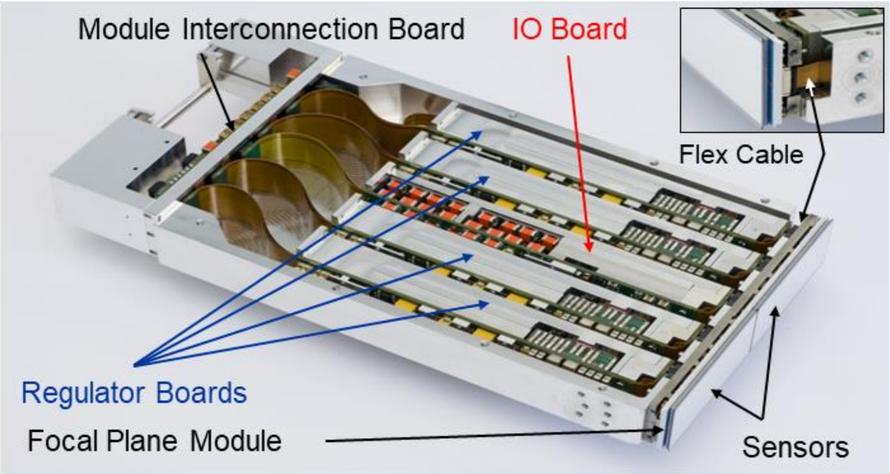
- 1 Megapixel camera **4.5 MHz peak frame rate**
  - 4 quadrants (512 x 512)
  - **16 ladders (512 x 128)**
  - 32 monolithic sensors 128x256
  - 256 Readout ASICs 64 x64
- Sensors:
  - **MiniSDD arrays 1st camera**
  - DEPFET arrays 2nd camera
- Readout concept
  - **Full parallel readout**
  - In pixel analog to digital conversion
  - **In pixel digital storage** (800 frames) with the possibility to overwrite non-valid frames (VETO)
  - Output average **data rate: 134.4 Gbit/s**
- Power cycling
  - The camera is **fully powered only during X-ray arrival**
  - total Power Dissipation **263 W** (250 µW per Pixel)
  - Coolant Load in Vacuum 149 W (142 µW per Pixel)

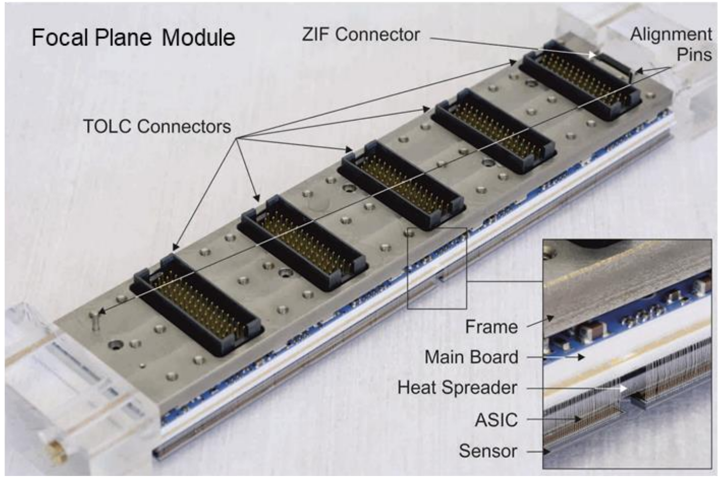
DSSC Detector System Overview 2/2

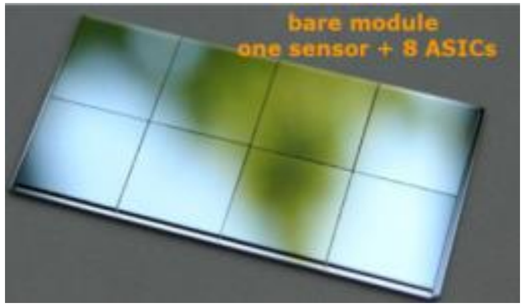






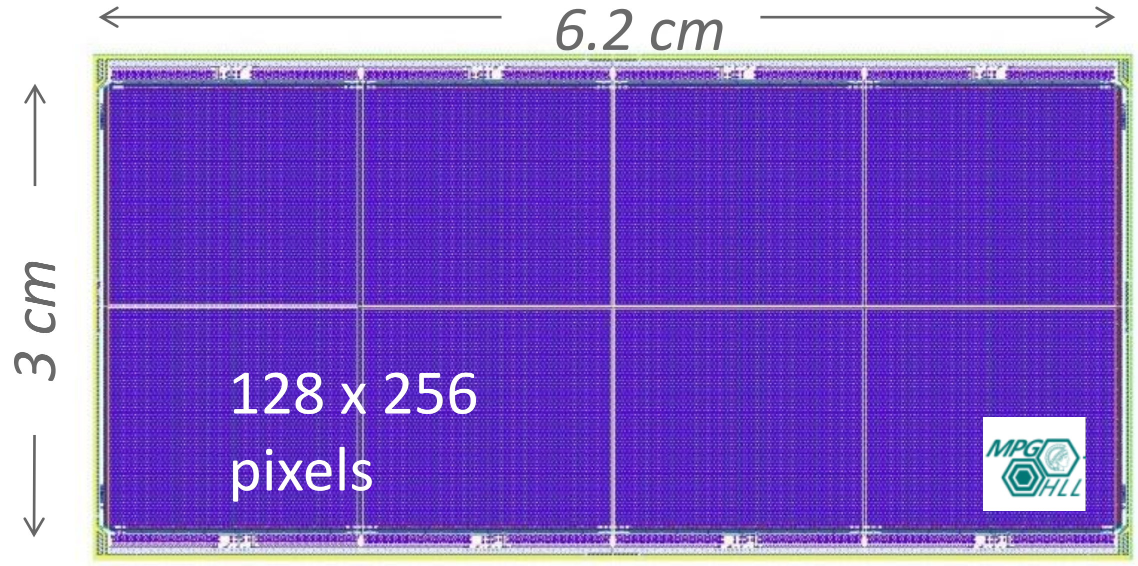


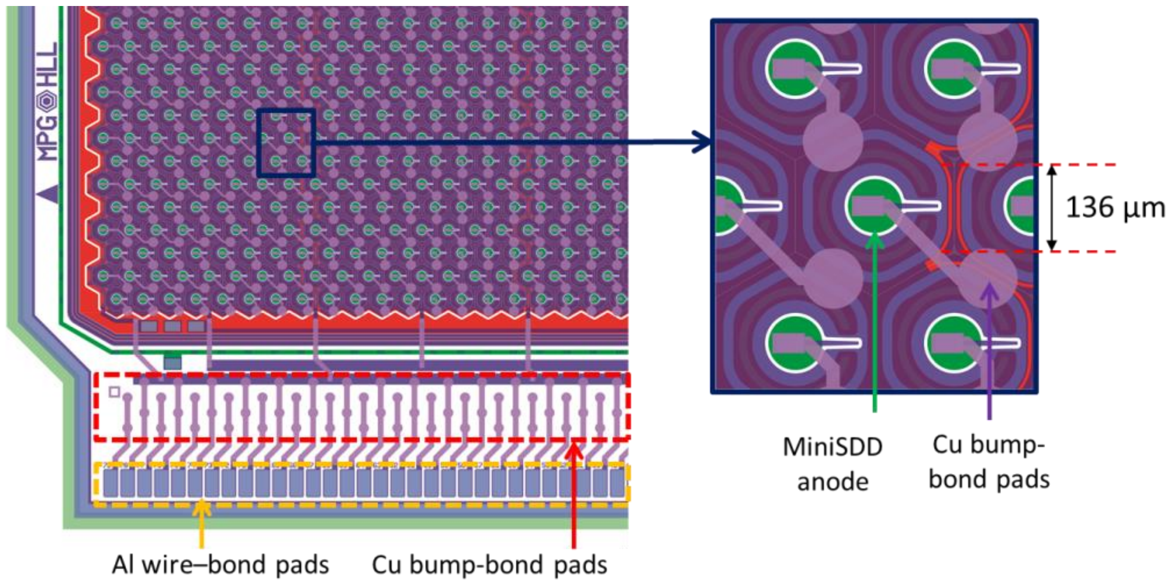




- Movable quadrants
- “service position’ in the pic
- Total active area ~ 505 cm^2
- Minimum insensitive area ~15%

MiniSDD Sensor

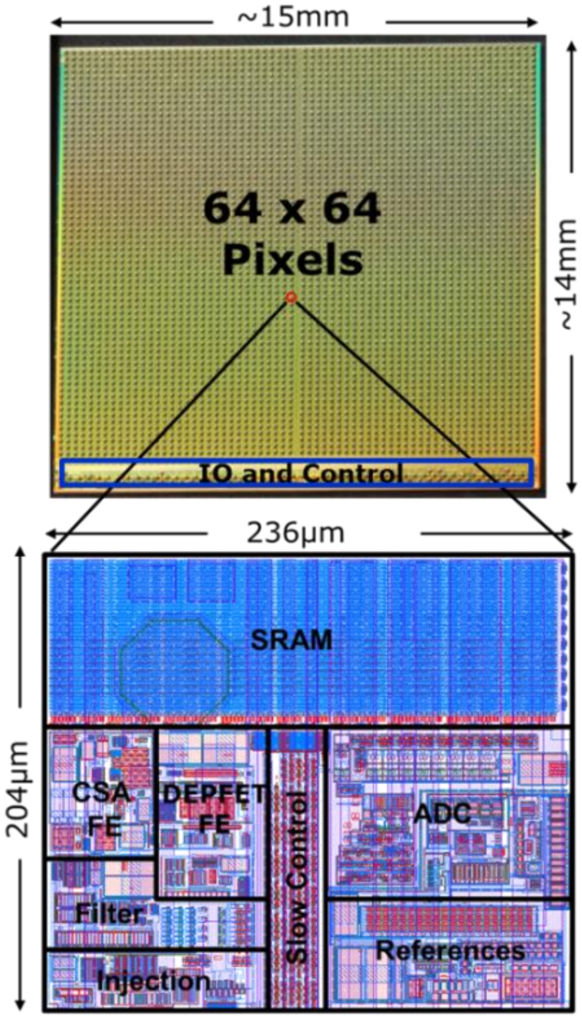




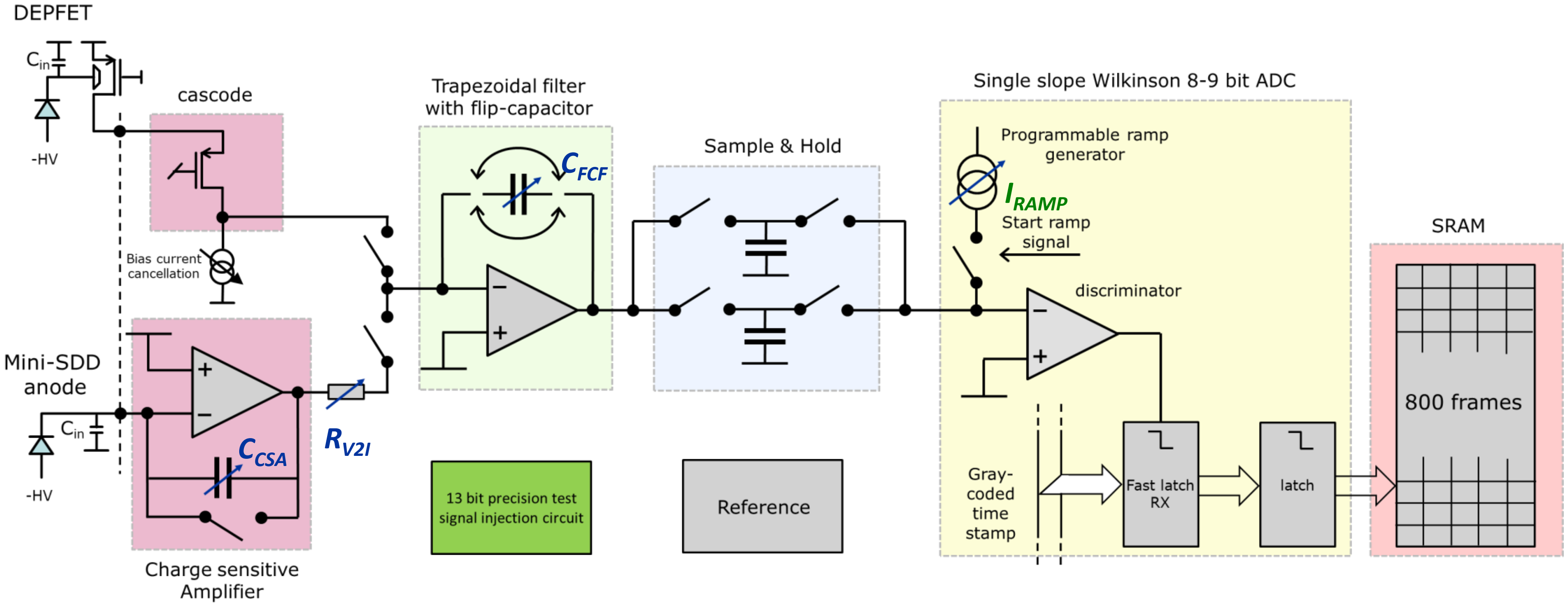
- Large area monolithic **Mini Silicon Drift Detector** Arrays produced at the Semiconductor Laboratory of the Max Planck Society (MPI-HLL)
  - 128 x 256 hexagonal pixels; hexagon side 136 µm; pixel pitches 204 x 236 µm
  - 450 µm thickness
  - passive collecting anode
  - 1 Alu layer, Cu layer

- Every pixel is bumped to the input of one CSA on the readout ASIC
  - **the system is linear**
  - Energy range and dynamic range are given by the gain of the ASIC and the ADC resolution (8/9 bit)

Full Format Readout ASIC



130 nm CMOS Process with C4 bumps



- Gain and offset can be adjusted pixel-wise:
  - **11 bits of coarse gain setting** for ph. energy and input range selection
  - **6 bits of gain fine trimming** (nominal accuracy 2%)
  - 4 bits for offset trimming (1.5 LSB range with 8% of granularity)

Pixel-wise coarse gain parameters — Pixel-wise fine gain trimming

$$\frac{keV}{ADU} \propto \overbrace{C_{CSA} \cdot R_{V2I} \cdot C_{FCF}} \cdot \frac{1}{t_{filt}} \cdot \frac{1}{C_{S\&H}} \cdot \overbrace{I_{ramp}} \cdot \frac{1}{2 \cdot f_{clock}}$$

Fine Gain Trimming and Energy Range

- pixel-wise **coarse gain settings** make it possible
  - to operate with photons of **different energies**
  - to **define the input dynamic range**, associating a defined number of photons to a single ADU

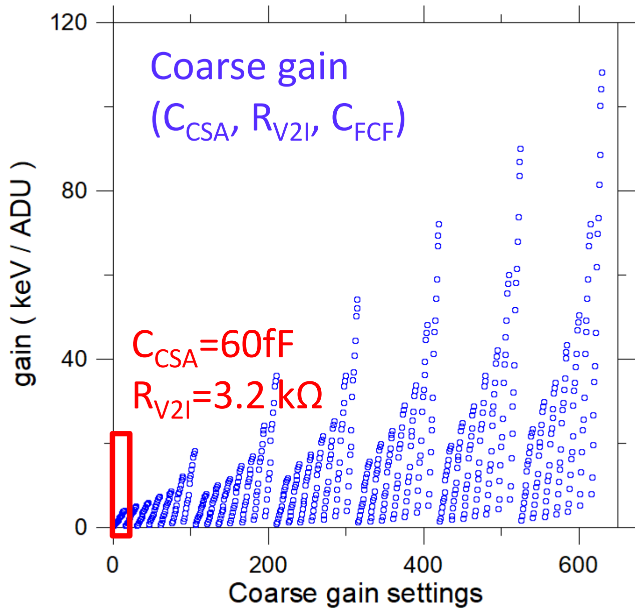
- Pixel wise **fine-gain trimming** is needed
  - **To equalize the gain dispersion over the pixels of the matrix**
  - To have a precise association of number of photons and ADUs

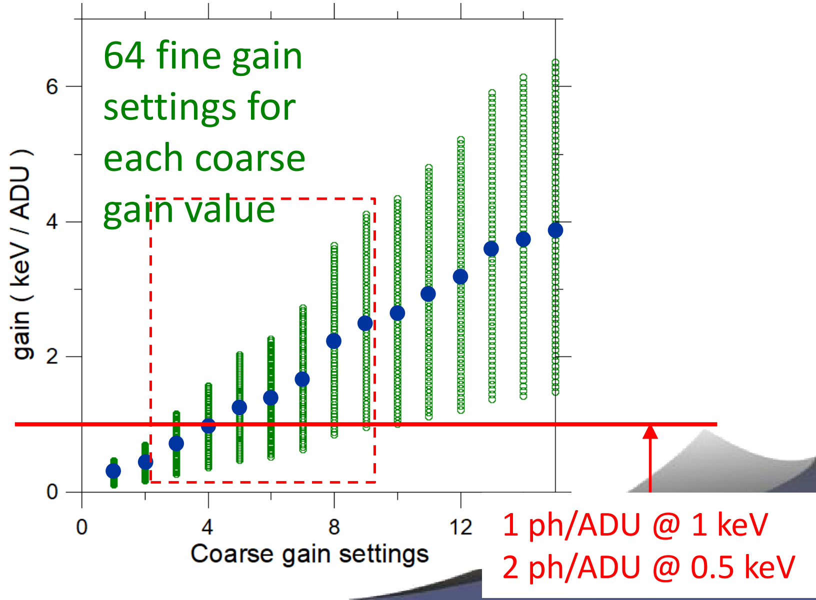
- Pixel-wise **offset trimming** is needed to place the signal produced by one photon in the middle of one ADU (minimization of error count rate)

- The overall gain settings are **overlapping and have a granularity <1%**

- Possible to define precisely the gain **for any arbitrary energy** for **$0.5\ \text{keV} \leq E_{ph} \leq 10\ \text{keV}$**

- It is possible to set **different gains in different regions** of the detector





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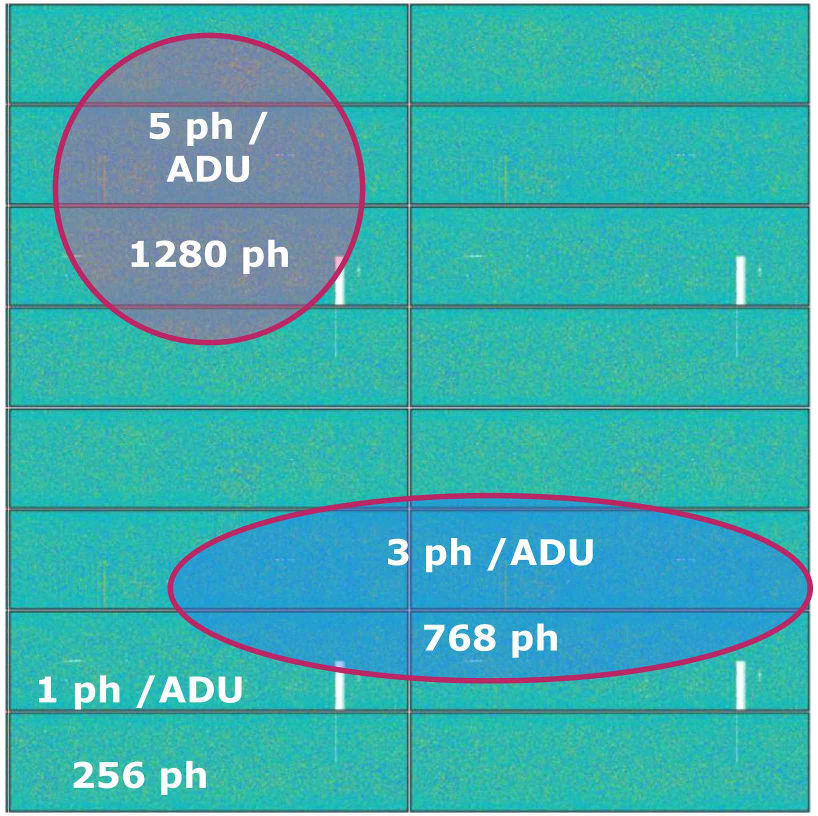
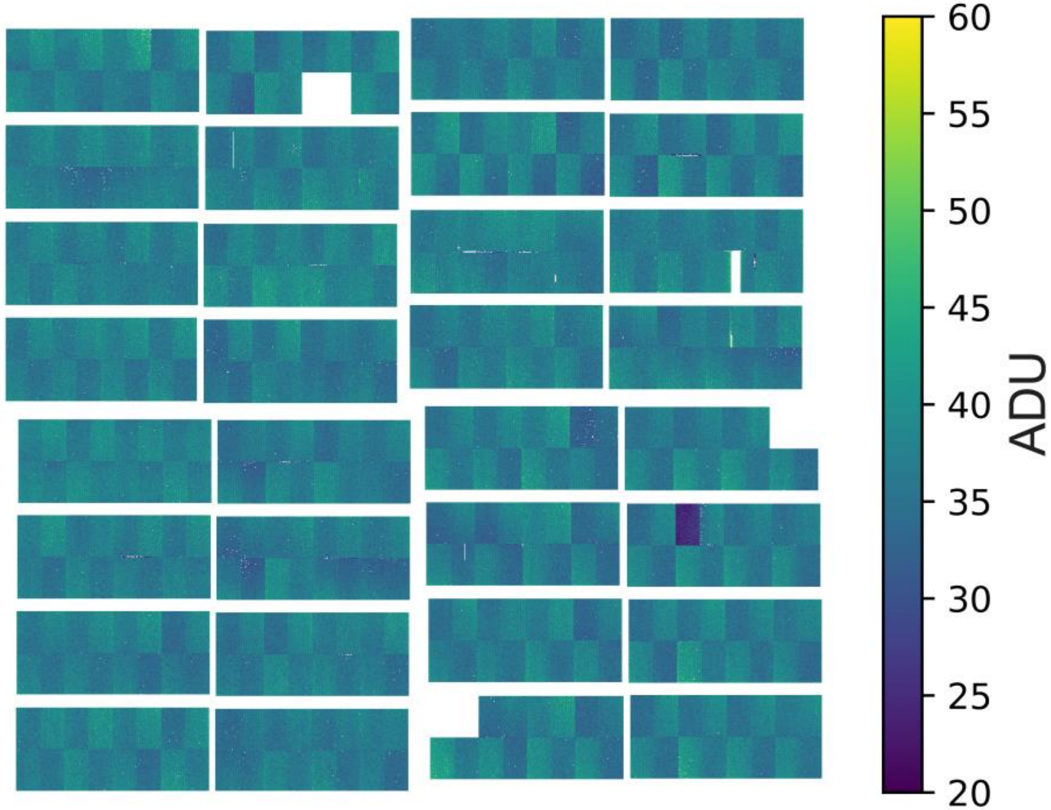
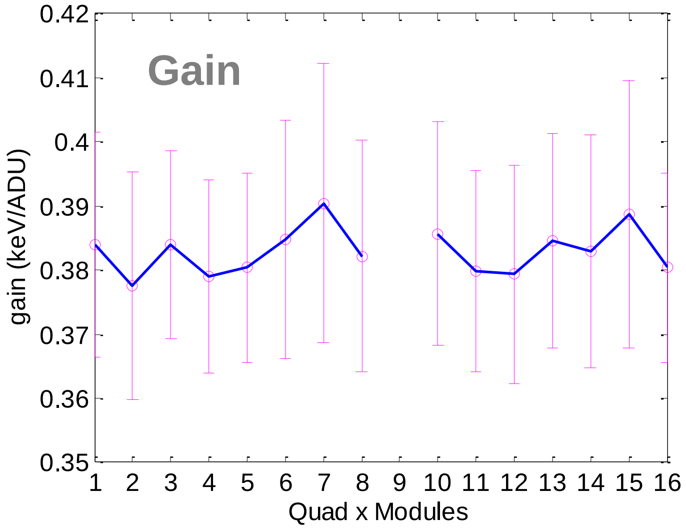
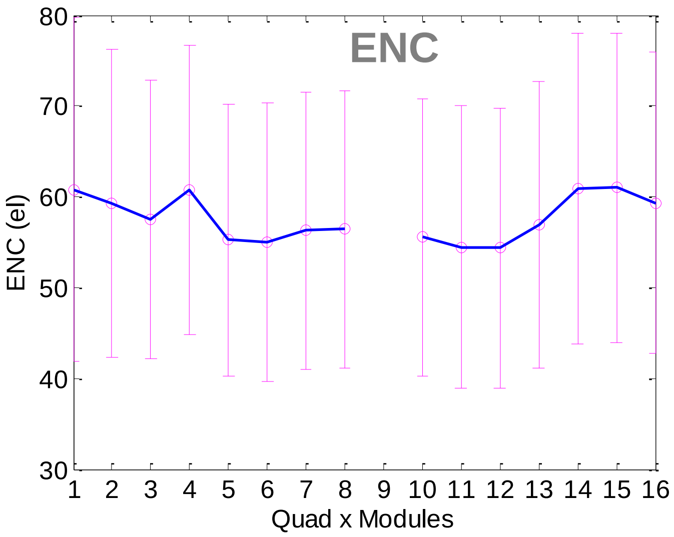


DSSC 1 Megapixel Camera

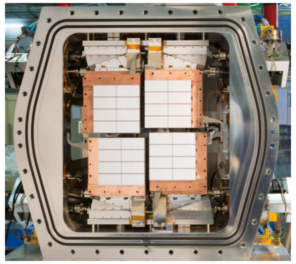




average: 382.9 ± 3.6 (1.0%)
average σ: 17.3 (4.5%)



average: 57.6 ± 2.5 (4.4%)
average σ: 16.1 (27.9%)



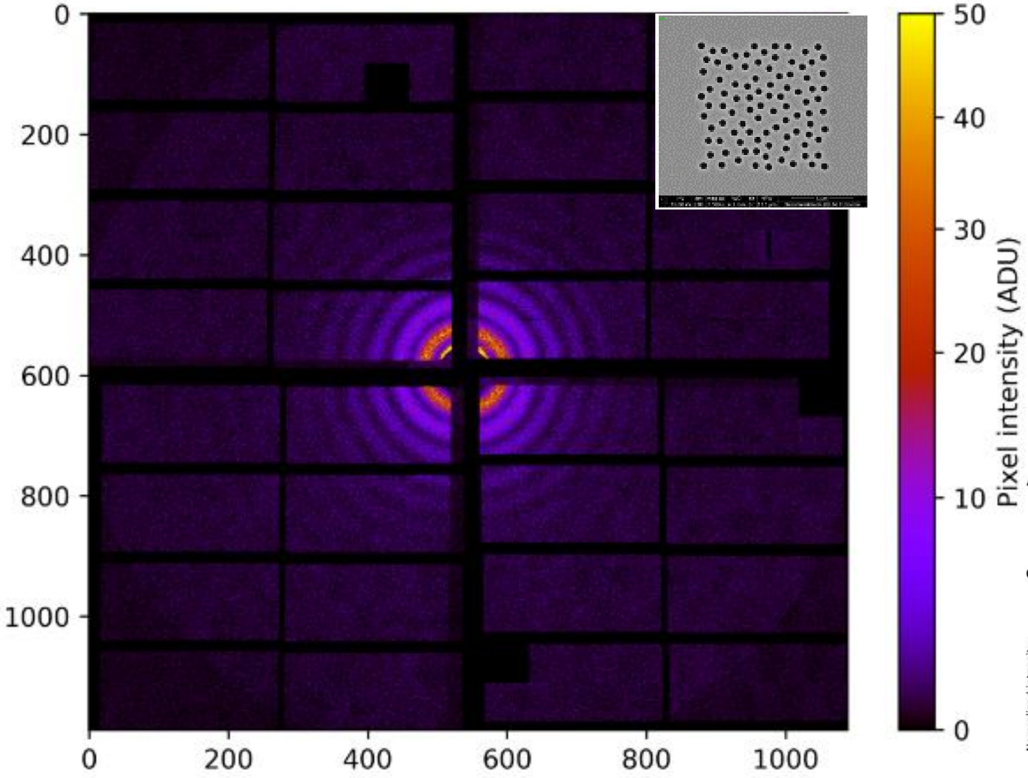
Dark-Image Test
- w/o active Cooling at RT
- default Gain/Offset Settings

- Failure Rate: 3 ASICs out of 256 are concerned (< 2 %)
- Camera calibration @XFEL with pulsed X-ray source PulXar
- Average gain ~400 eV/ADU (un-trimmed) and **ENC ~58 e- @ 4.5 MHz**
- Good uniformity for the 16 ladders

Commissioning & Users' Experiments

- Installation in May 2019 @ **Spectroscopy and Coherent Scattering (SCS)** Instrument
- First user experiment May 28, 2019
- Since installation (to Dec 2021):
  - ✓ **17** user experiments at SCS:
    - – 8 Time resolved scattering
    - – 7 Time resolved XAS
    - – 2 Time resolved Holography
- DSSC commissioned and installed at **Small Quantum Systems** (SQS) Instrument in 2021
  - ✓ First experiment performed: "High-repetition rate 3D X-ray imaging of single proteins‟, PI: F. Maia, August 2021

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



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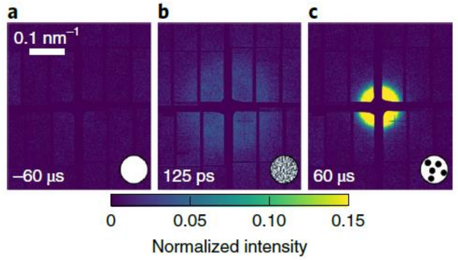
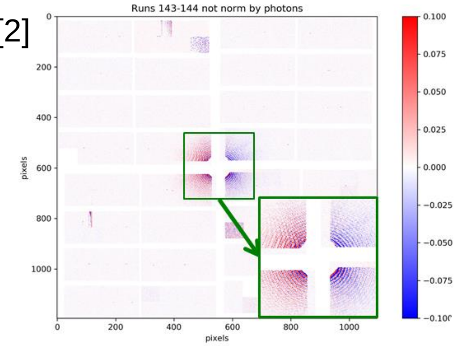


[2]



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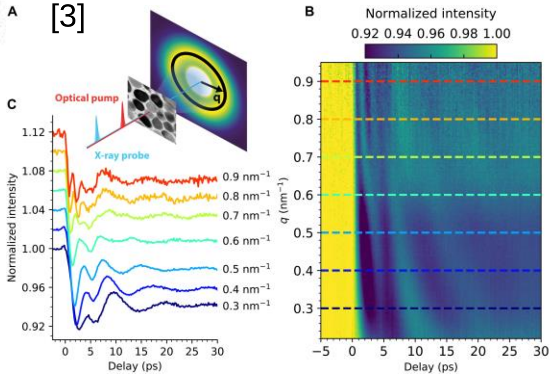


[1] Büttner, F; *et al.* Observation of fluctuation-mediated picosecond nucleation of a topological phase. *Nat. Mater.* **20,** 30–37 (2021). doi:10.1038/s41563-020-00807-1
[2] Hagström, N. Z.; *et al.* Megahertz-rate Ultrafast X-ray Scattering and Holographic Imaging at the European XFEL. *arXiv* (2022). doi:10.48550/arXiv.2201.06350
[3] Turenne, D.; et al. Nonequilibrium Sub–10 Nm Spin-Wave Soliton Formation in FePt Nanoparticles. *Sci. Adv*. 2022, 8, eabn0523. doi:10.1126/sciadv.abn0523

Towards the DEPFET 1 megapixel camera

DEPFET sensors

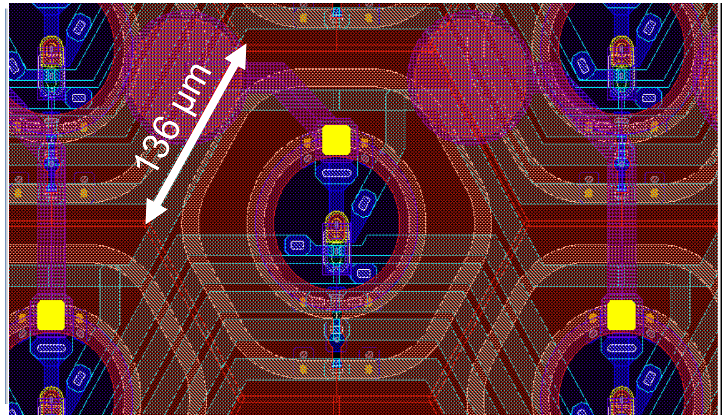
- In the second DSSC camera the MiniSDD sensors will be replaced by DEPFET arrays
  - Fully compatible ladder electronics, **additional components** installed for sensor operation
  - ASIC includes DEPFET FE

- Sensors are produced in a **CMOS foundry** (IMS) and at PNSensors
  - 8 inch wafers
  - 750 µm thickness
  - <400 V depletion voltage

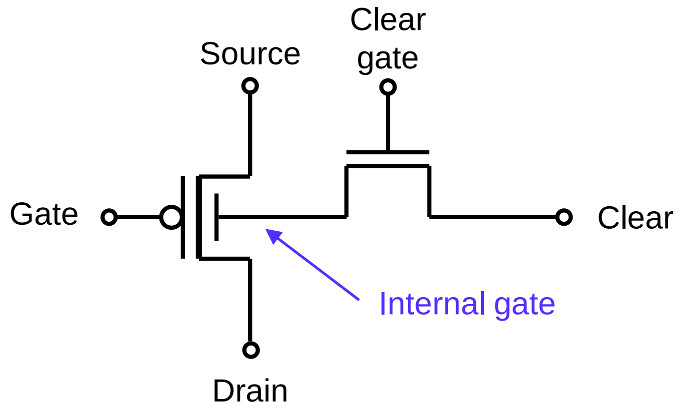
- **DEPFETs are active pixels that provide a non linear response**
  - Low noise for single photon detection
  - **High dynamic range**

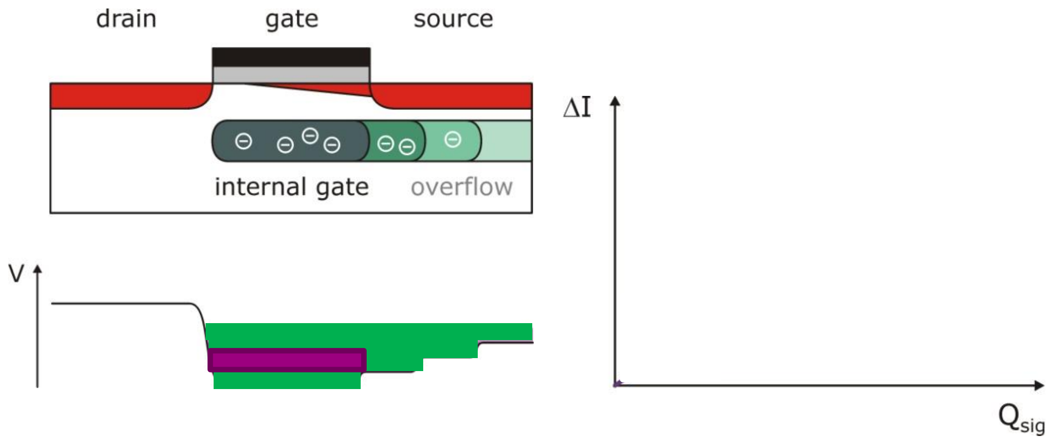
- The DEPFET arrays are **compatible with the existing DSSC system**

- Common-source configuration, I_{DRAIN} readout



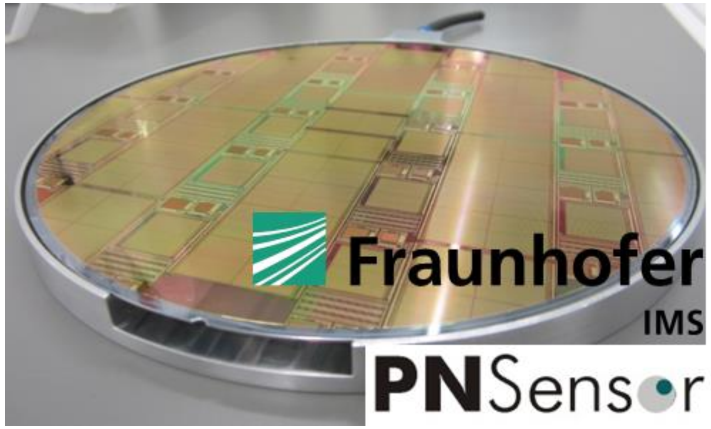
DEPFET Active Pixel

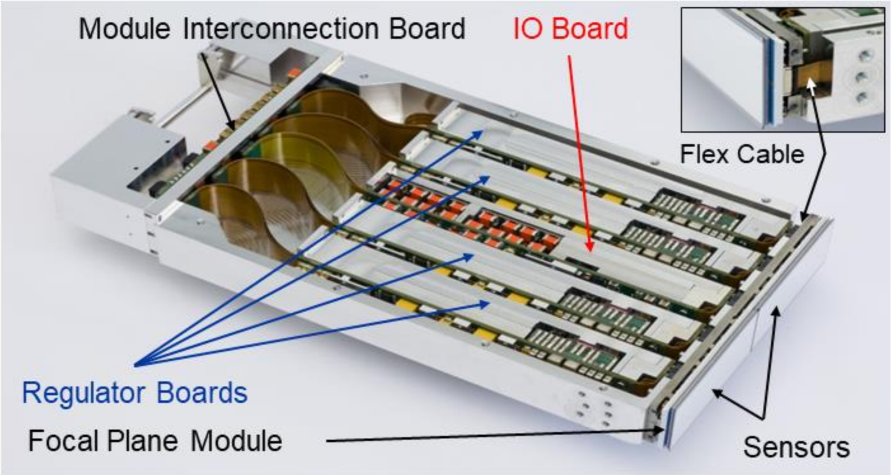


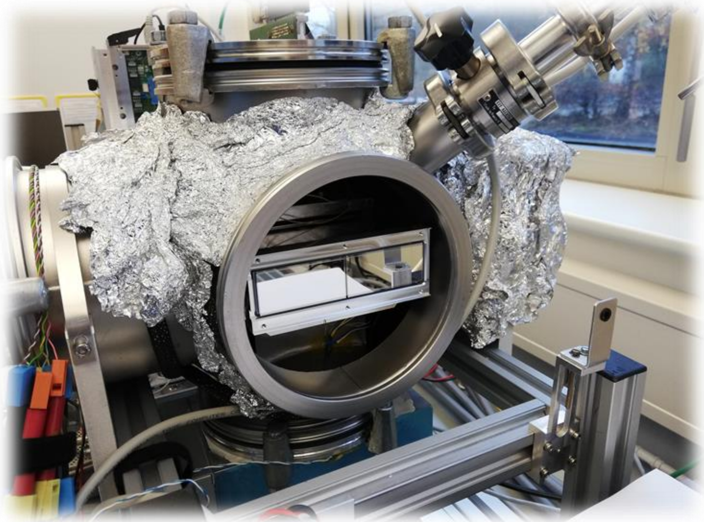


Lechner, P.; et al. DEPFET active pixel sensor with non-linear amplification, 2011 IEEE Nuclear Science Symposium Conference Record, 2011, pp. 563-568, doi:10.1109/NSSMIC.2011.6154112.
Aschauer, S.; et al. First Results on DEPFET Active Pixel Sensors Fabricated in a CMOS Foundry - a Promising Approach for New Detector Development and Scientific Instrumentation. *J. Inst.* 2017, 12, P11013–P11013. doi:10.1088/1748-0221/12/11/p11013

DEPFET-ladder prototype: *linear range*

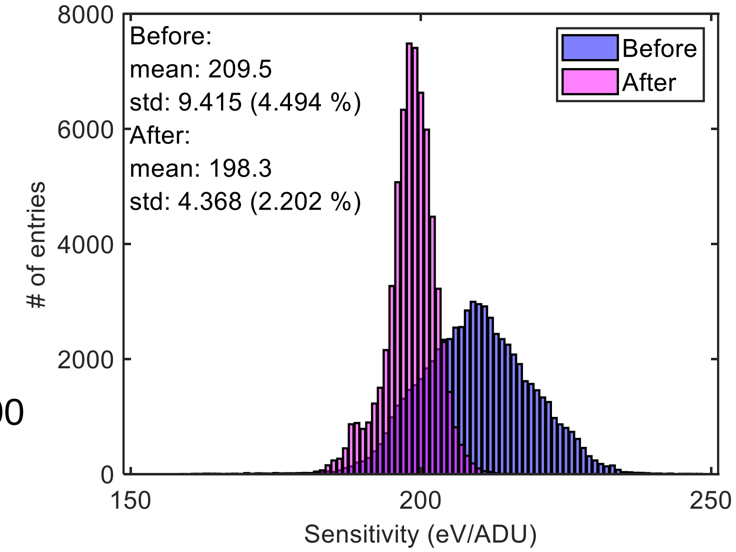


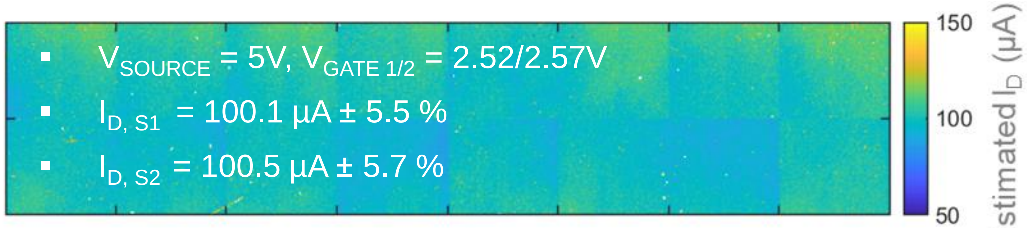




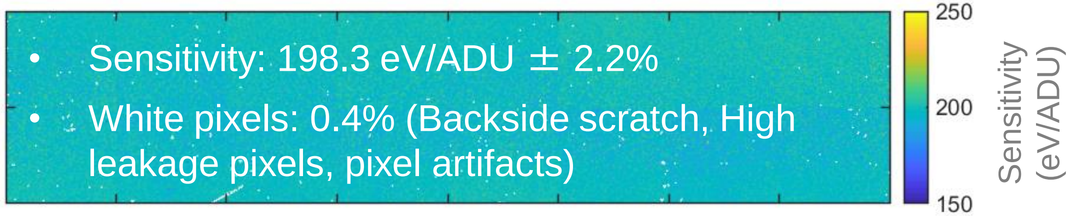
1st prototype characterization in the linear range with lab-setup at DESY

- 100 µA/pixel <u>average</u> DEPFET-bias current
- ***ENC 18 e- rms*** with T_{int} = 50 ns (2.25 MHz), 200 eV/ADU
- Down to **9.8 e- rms** with T_{int} = 300 ns (1.125 MHz operation), 37.3 eV/ADU
- Near room-temperature conditions



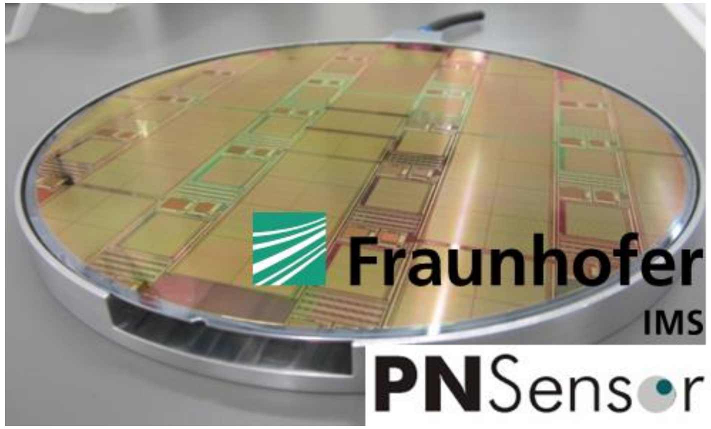


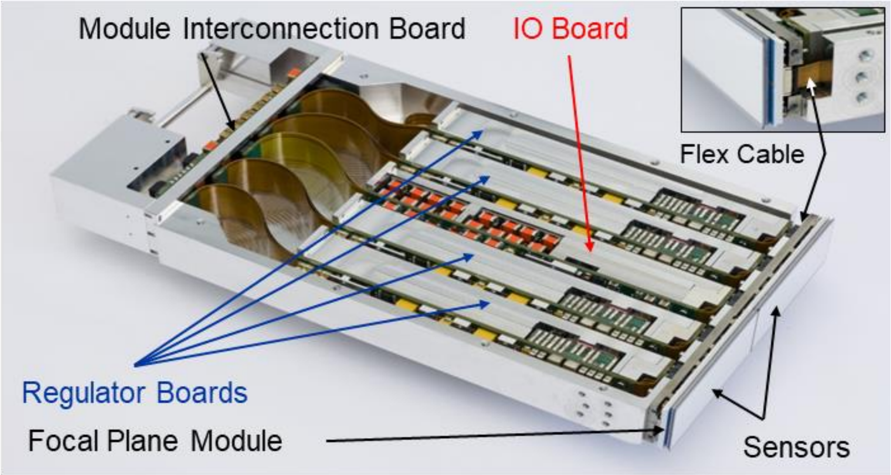
Sensor-wise DEPFET-drain current trimming capabilities, dispersion below 6%

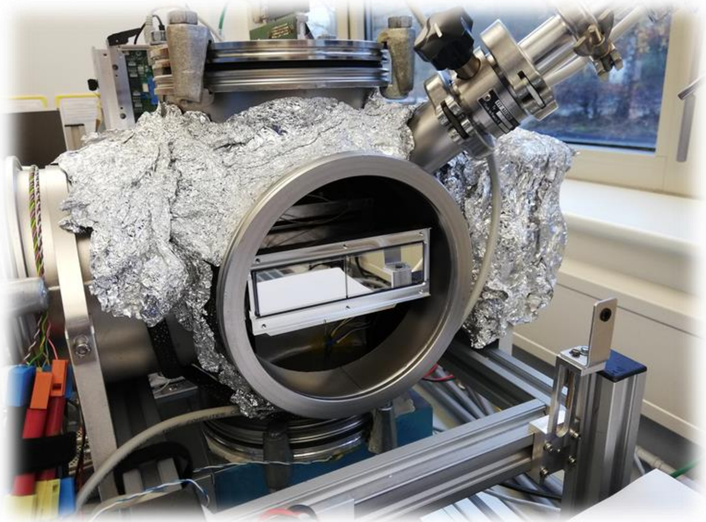


Pixel-wise gain trimming reduces dispersion below 2.2% on the full matrix

DEPFET-ladder prototype: *linear range*







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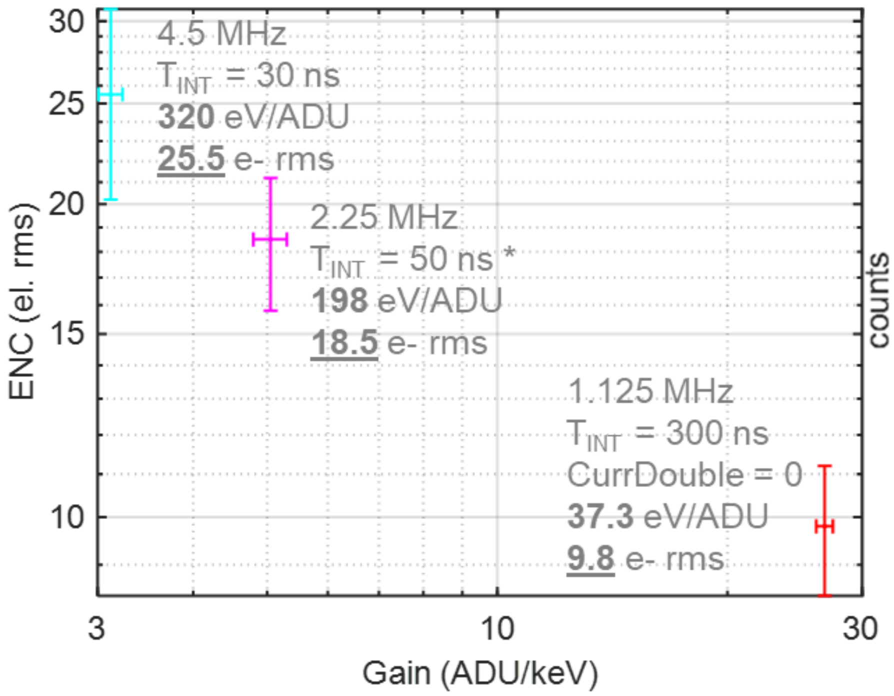
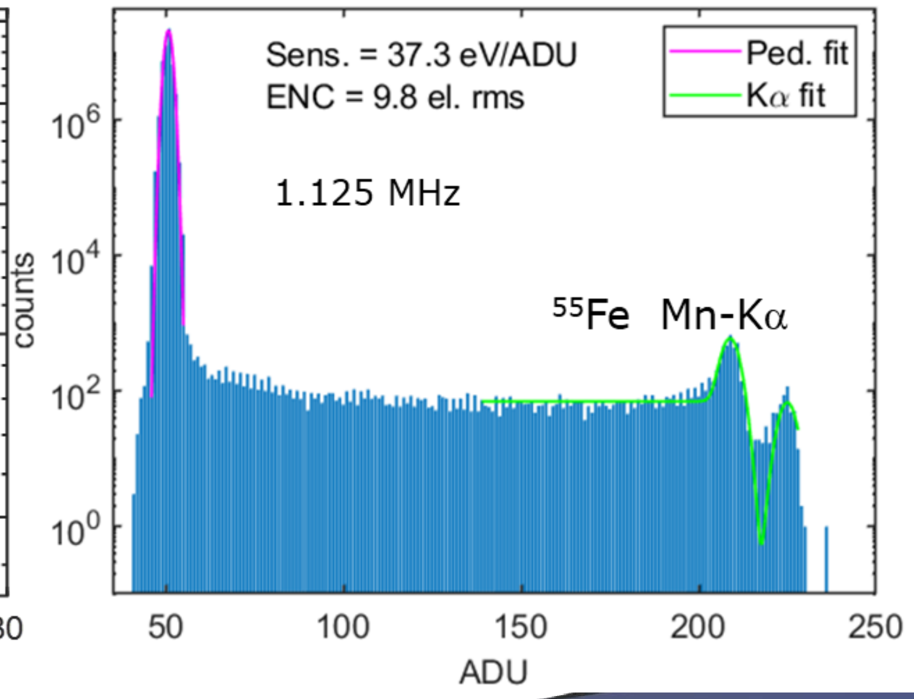


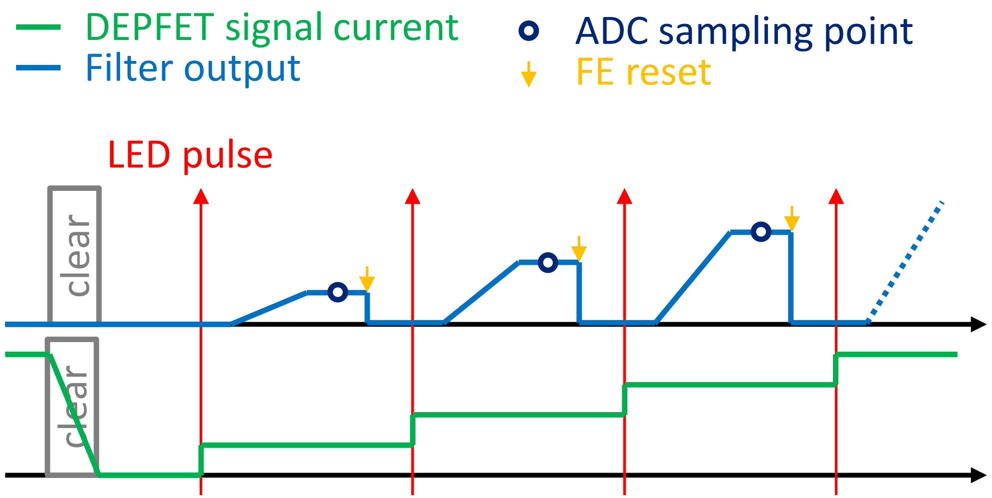


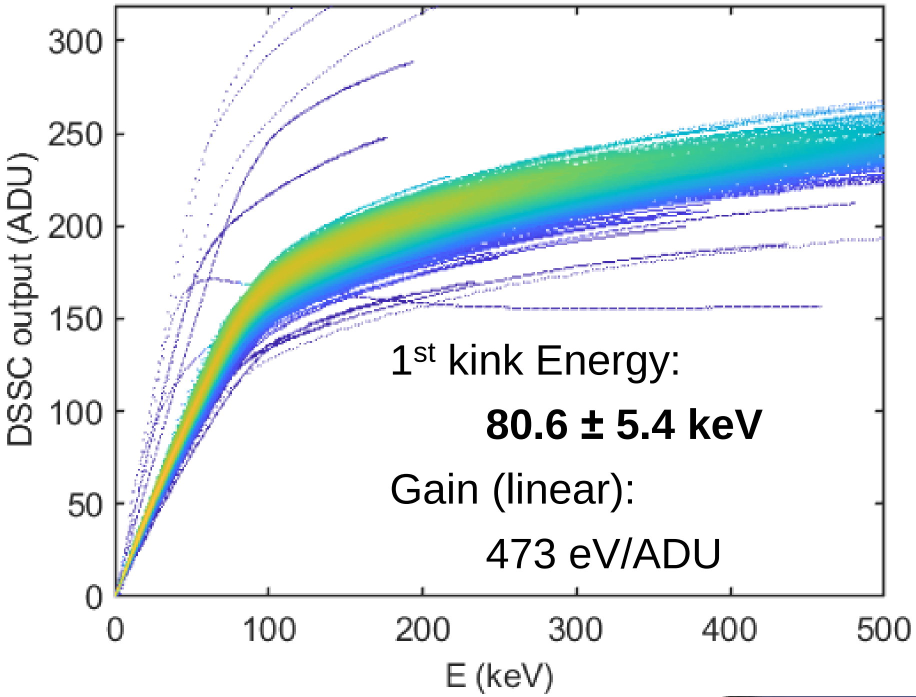
DEPFET-ladder prototype: *NL curve*

Non linear characteristics evaluation

- 150 nm thick Al layer on entrance window
- laser pulser: 905 nm, 25 W
- Integrating charge into DEPFET internal gate, no clear between acquisition cycles
- Curve scan with 400 pulses in singe integration mode
- 50 ns integration time

- Dynamic range of **several thousands 1 keV photons**

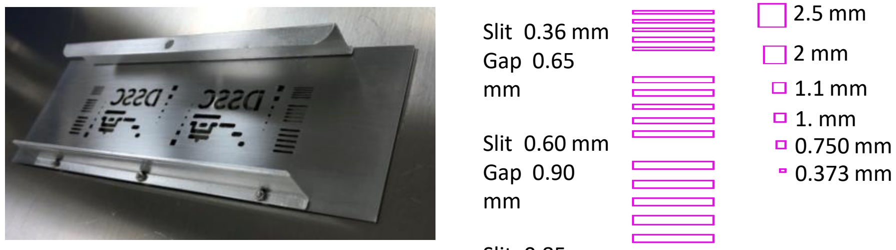




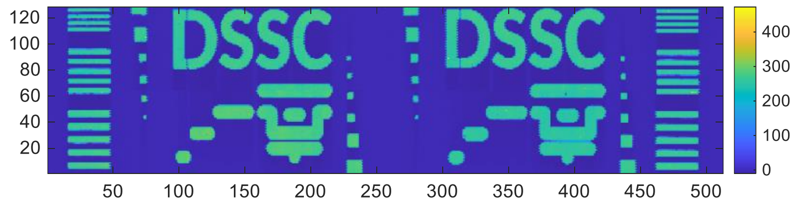
DEPFET-ladder prototype: *beamline tests*

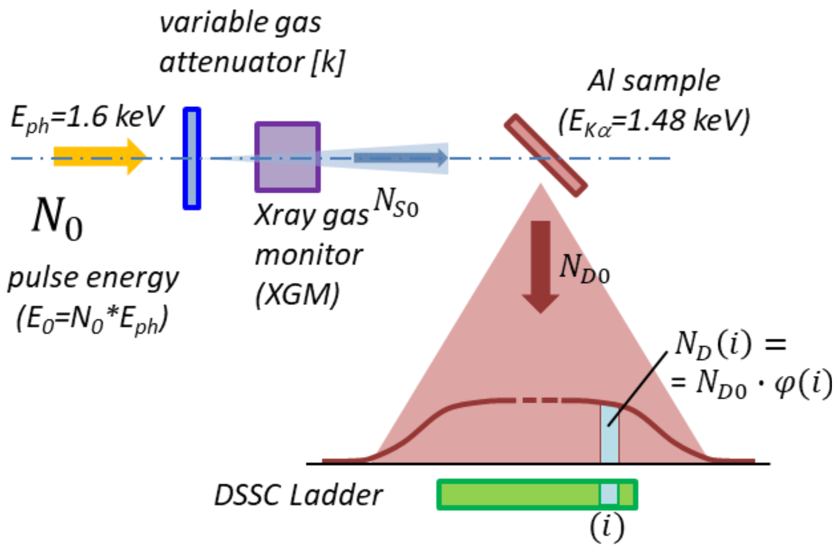
1st prototype characterization at Small Quantum System (SQS) Instrument @ EuXFEL

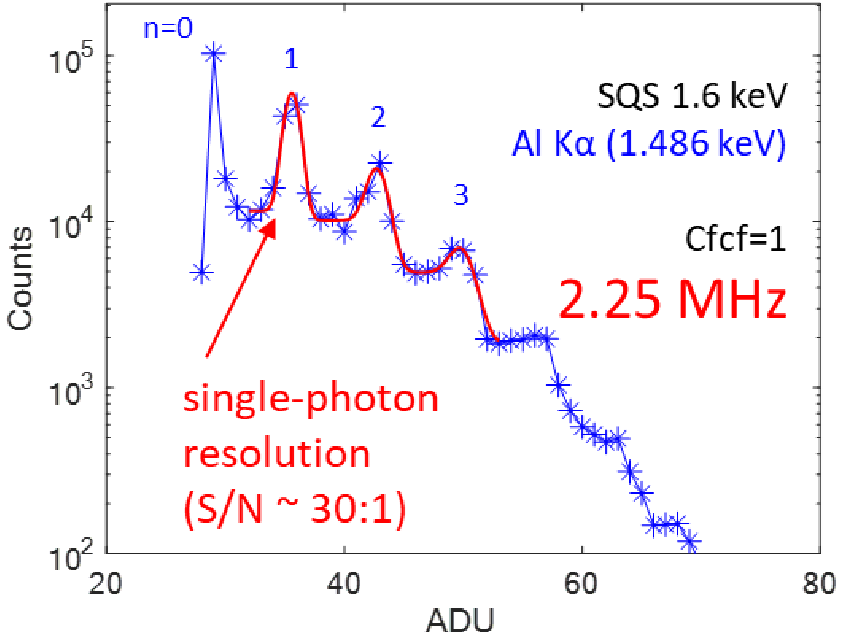
- 50 ns integration time, 2.25 MHz operation (beam at 1.1MHz)
- Al fluorescence (1.486 keV)
- Single photon resolution with S/N ~ 30
- Near room temperature operation



Steel, 0.5 mm







Details are given in the following talk:

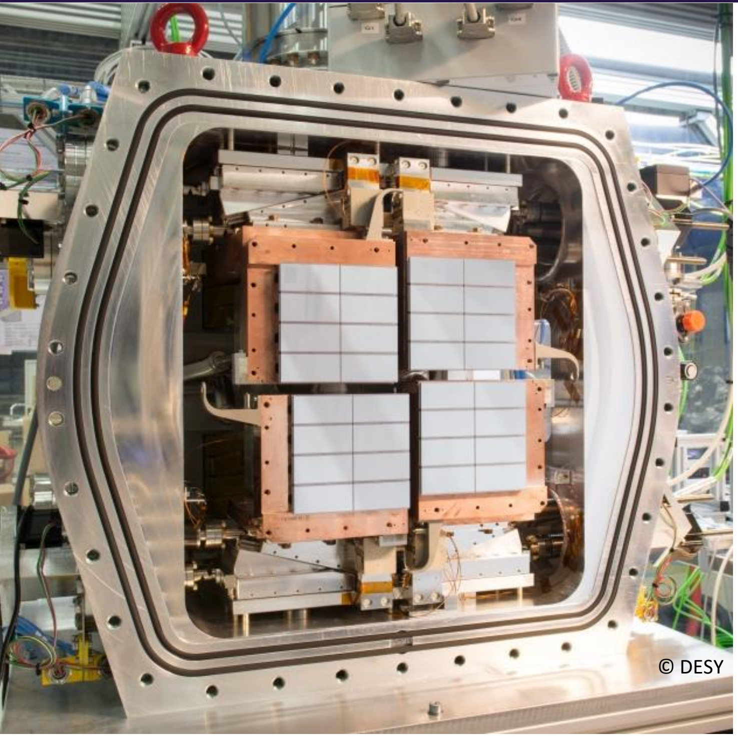
A. Castoldi, "Qualification and Modeling of the Non-Linear Response of the First Large-Area DEPFET Pixel Sensors with Internal Signal Compression"

Summary & Conclusions

- The first 4.5 MHz - 1 M-Pixel MiniSDD-based DSSC camera has been completed and successfully installed at the Spectroscopy and Coherent scattering (SCS) and the Small Quantum Systems (SQS) scientific instruments of the European XFEL
- The performance figures of the detector system are in excellent agreement with expectations and confirm the results obtained on the prototype module
- The second 1-Mpixel camera will be based on CMOS-DEPFET active pixel sensors that allow single photon detection and high dynamic range simultaneously. The camera will be available in the first half of 2023
- First operation of a CMOS-DEPFET ladder confirms the expected improvements given by the DEPFET technology
- ENC can be as low as to 9.8 e- rms at 1.1 MHz
- Dynamic range is of several thousands 1 keV photons

Thank you
for your attention

Camera Performance: *Power Consumption*

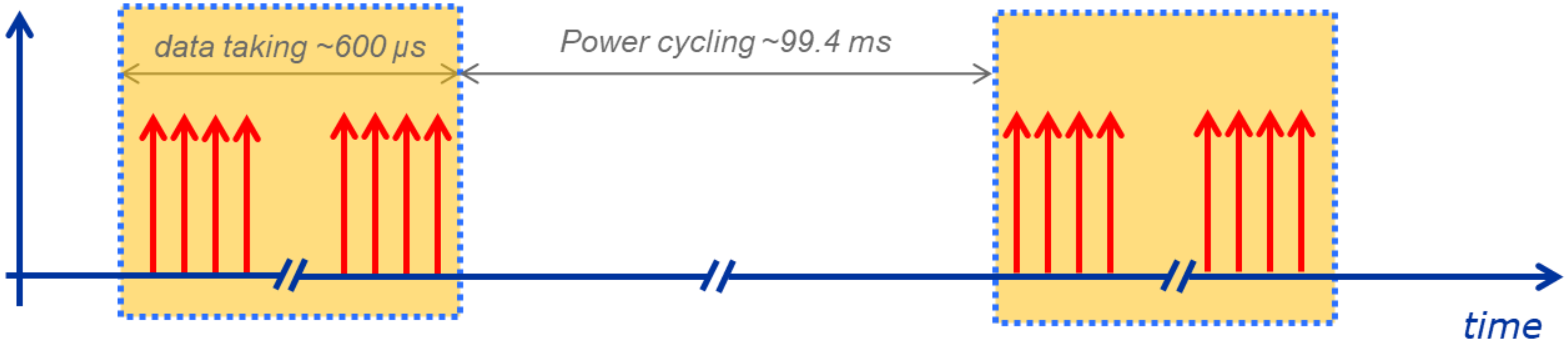


			Q1	Q2	Q3	Q4	Camera
Quadrant	IOB		12,42	12,44	12,38	12,21	**49,45**
	RB		9,42	9,05	9,21	8,99	**36,66**
	FPM	MB	10,09	10,07	10,07	10,07	**40,31**
		ASIC	5,30	4,98	5,12	4,84	**20,25**
		Sensor	0,60	0,61	0,61	0,52	**2,35**
Periphery	PP		2,65	2,54	2,61	2,56	**10,36**
	PPT		24,71	24,42	24,36	24,34	**97,82**
	SIB		1,41	1,35	1,34	1,37	**5,47**
		TOTAL	**66,62**	**65,45**	**65,69**	**64,90**	**262,66**

Ladder Electronics: 86 W (33%)

Focal Plane: 63 W (24%)

Periphery: 114 W (43%)



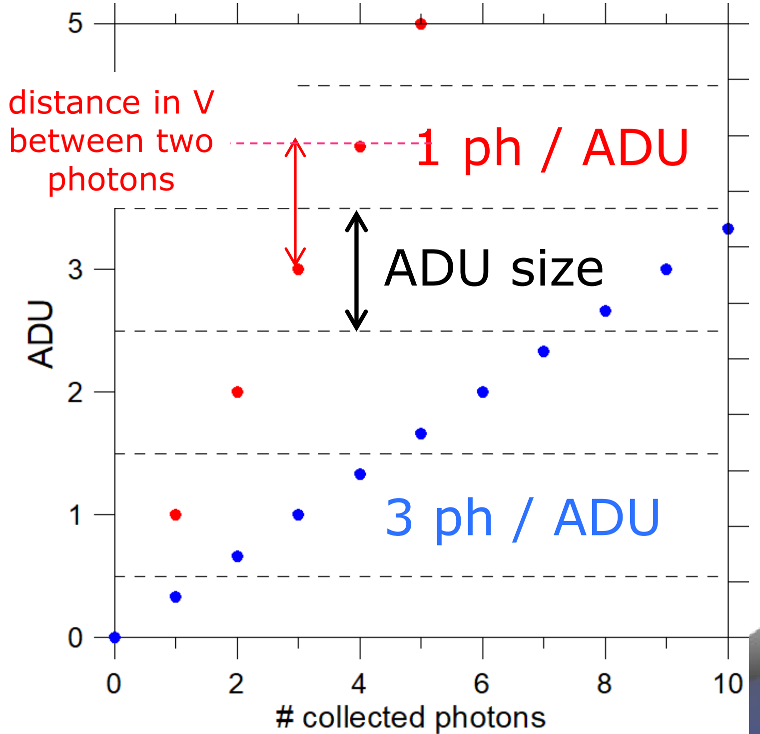
- Power Cycling: total Power Dissipation 263 W (250 µW per Pixel)
- Coolant Load in Vacuum 149 W (142 µW per Pixel)
- In Agreement with Calculations & Expectations

Gain Settings & Input Dynamic Range

- pixel-wise **coarse gain settings** make it possible
  - ➢ to operate with photons of **different energies**
  - ➢ to **define the input dynamic range**, associating a defined number of photons to a single ADU
- Pixel wise **fine-gain trimming** is needed
  - ➢ To equalize the gain dispersion over the pixels of the matrix
  - ➢ To have a precise association of number of photons and ADUs
- Pixel-wise **offset trimming** is needed to place the signal produced by one photon in the middle of one ADU (minimization of error count rate)

photons / ADU (minimum detectable input)	Maximum signal in photons (8 bit - 4.5 MHz)
10	2560
5	1280
3	768
1	256
0.5	128

single photon detection (rows 1 and 0.5)

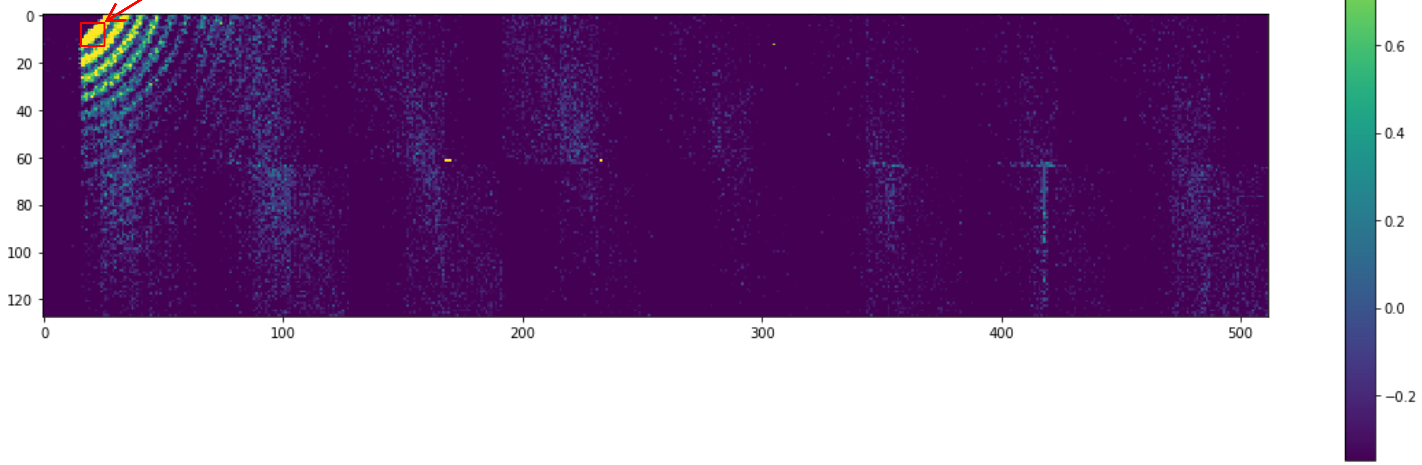


First Diffraction Patterns at SCS 2/2

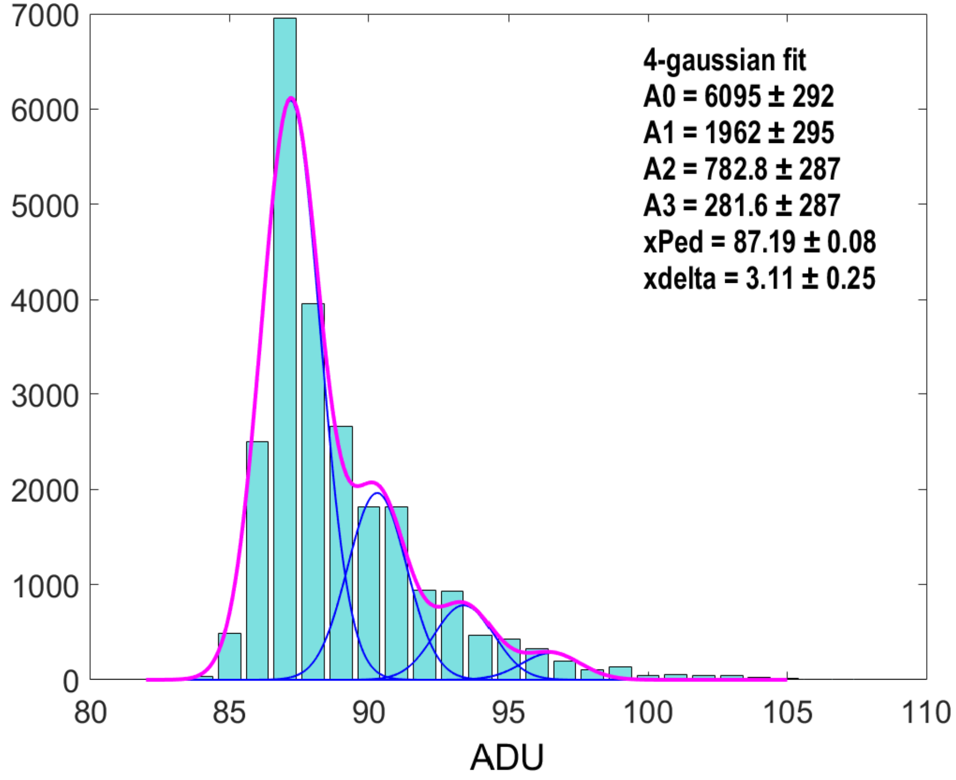
- Results are preliminary
- photon energy 707eV, 133 pulses/train
- low photon multiplicity on DSSC, acquisitions done at high gain 3 bin/ph (i.e. 0.236 keV/ADU)
- DSSC acquiring at 4.5MHz, 400 frames/train

single pixel spectra

run#32 – ladder#0



Spectrum of one pixel - 24000 frames



- 4-gaussian fit with free amplitudes (all sigma's fixed at Pedestal sigma)
- delta between centroids 3.11± 0.25 ADU, compatible with calibration (3 ADU)
- amplitudes nicely follow Poisson (λ=0.38)