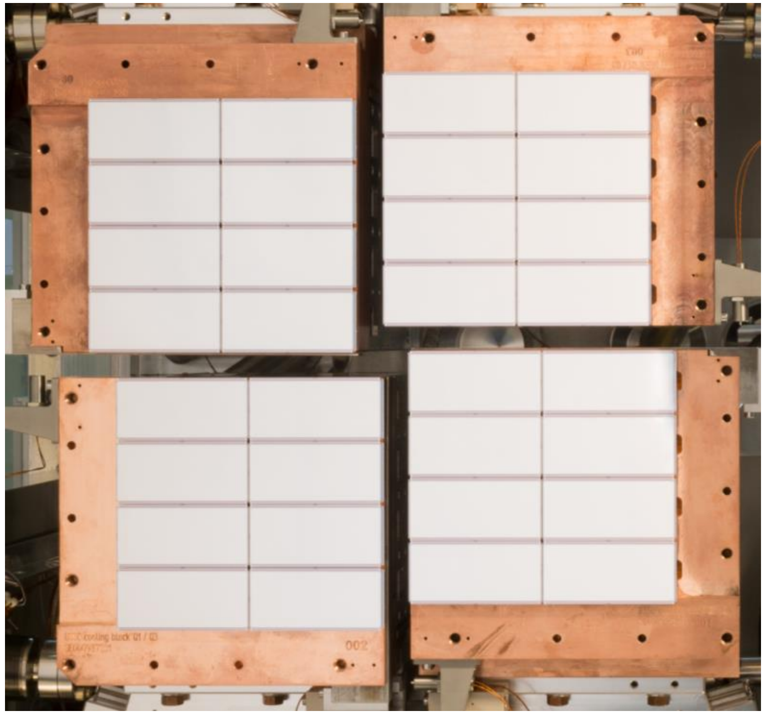
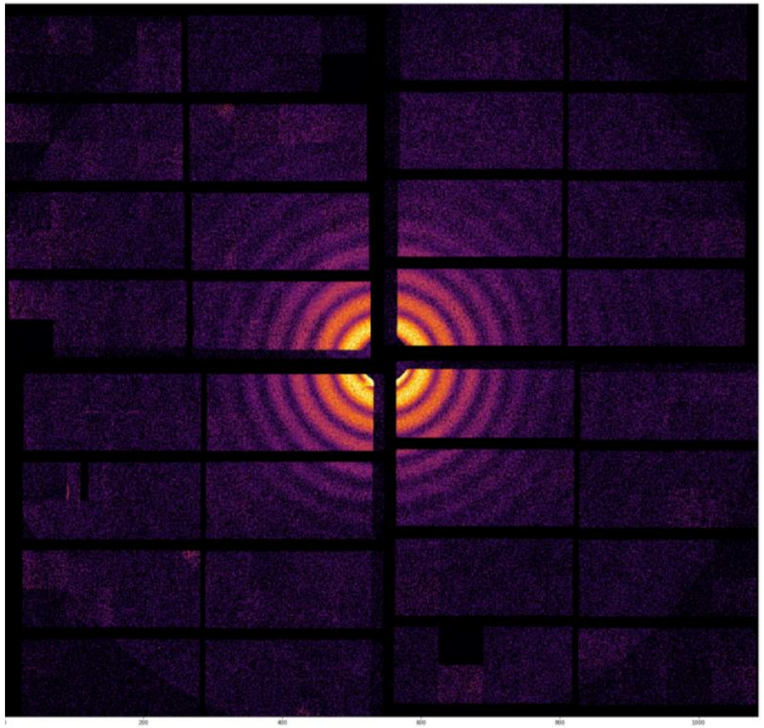
The DSSC soft X-ray Detectors with Mega-frame Readout Capability for the European XFEL

Stefano Maffessanti on behalf of the DSSC Collaboration





15th Pisa Meeting on Advanced Detectors

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Photo Detectors and Particle ID

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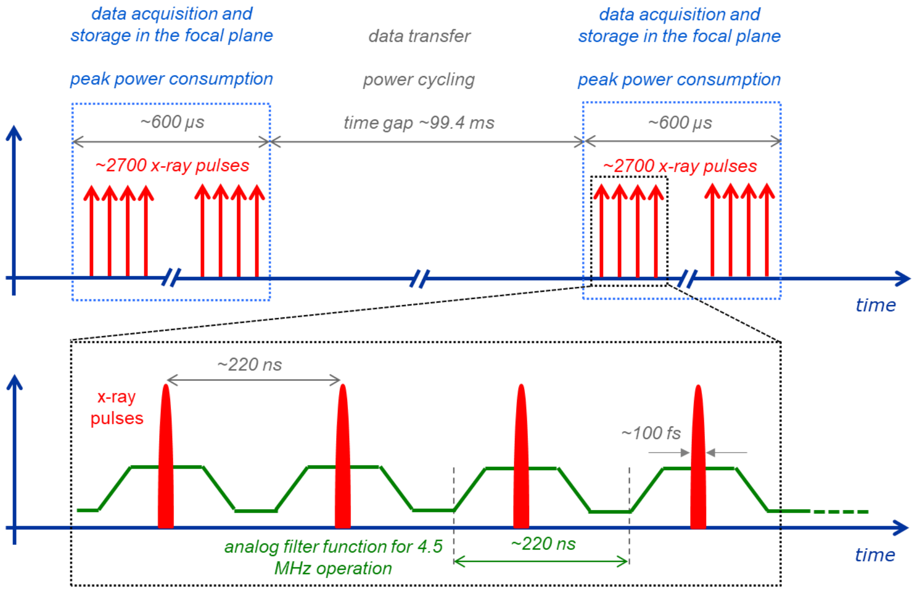
P.I.: M. Porro, European XFEL

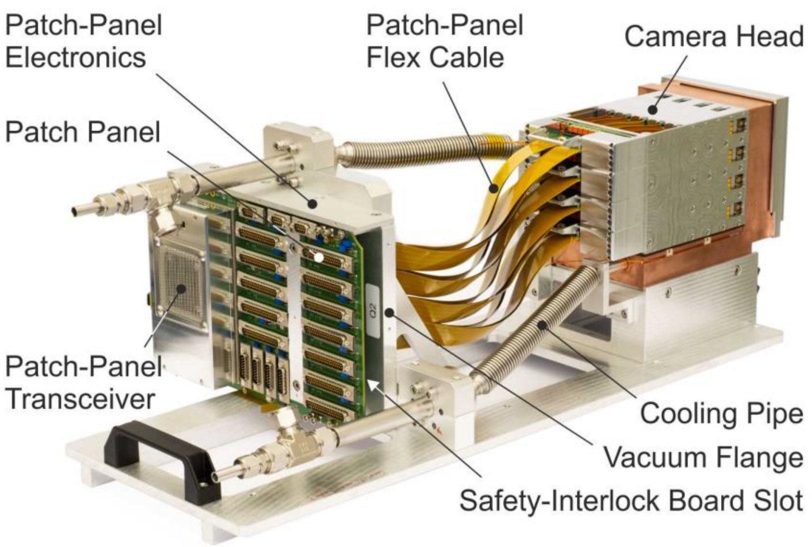
DSSC Detector System Overview 1/2

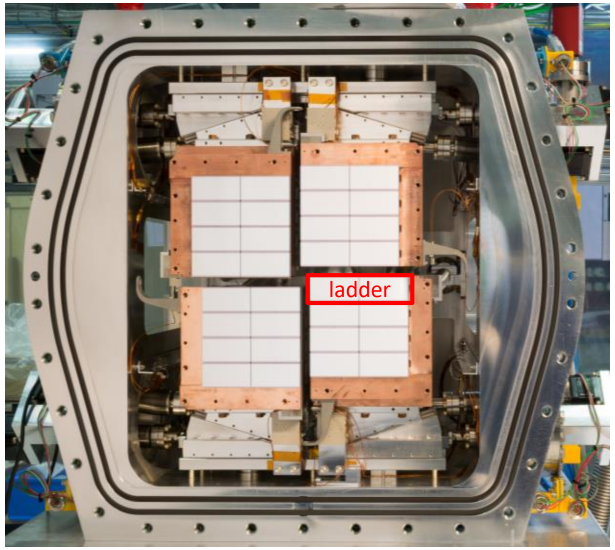


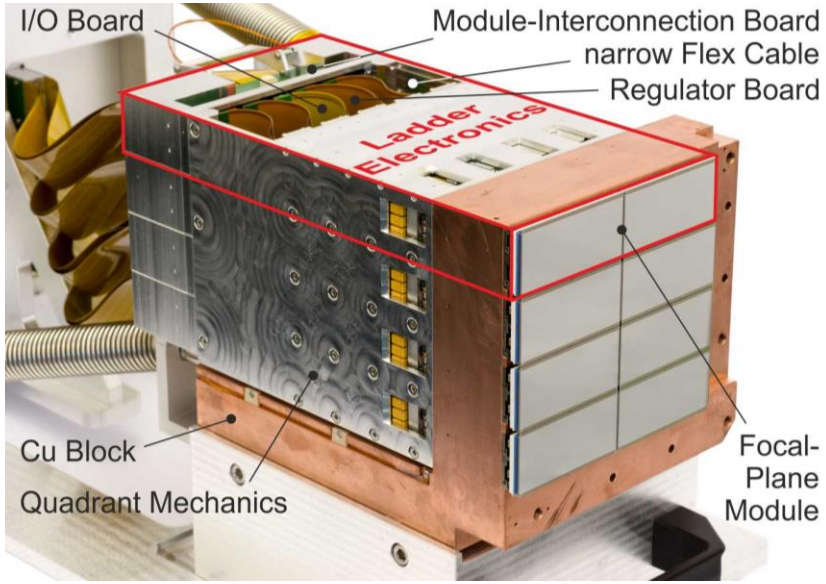
Parameter		Value
Target energy range		0.25 keV – 6 keV
Pixel count		1024 × 1024
Pixel shape		hexagonal
Sensor pixel pitch		~204 µm × 236 µm
Active area		~ 21 cm × 21 cm
Input photon range / pixel / pulse (*)	MiniSDD	2^n × N -1
	DEPFET	*>10^4*
Achievable noise	MiniSDD	~ 60 e- r.m.s.
	DEPFET	*~ 10 e- r.m.s.*
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

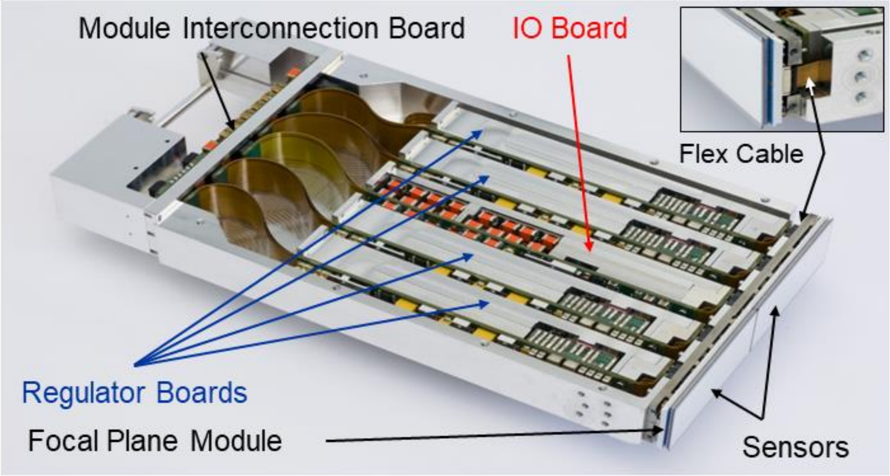
- 1 Megapixel camera **4.5 MHz peak frame rate**
  - 4 quadrants (512 x 512)
  - **16 ladders (512 x 128)**
  - 32 monolithic sensors 128x256
  - 256 Readout ASICs 64 x64
- Sensors:
  - **MiniSDD arrays 1st camera**
  - DEPFET arrays 2nd camera
- Readout concept
  - **Full parallel readout**
  - In pixel 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**

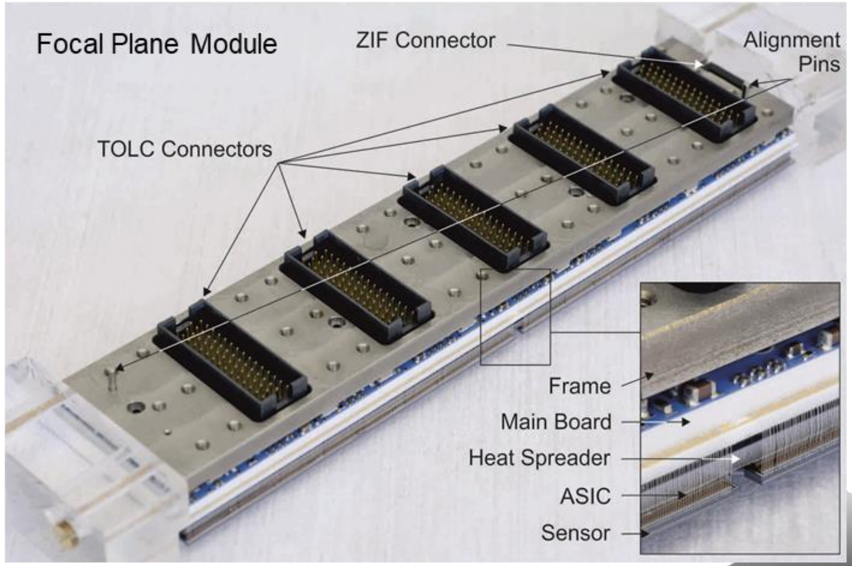
DSSC Detector System Overview 2/2



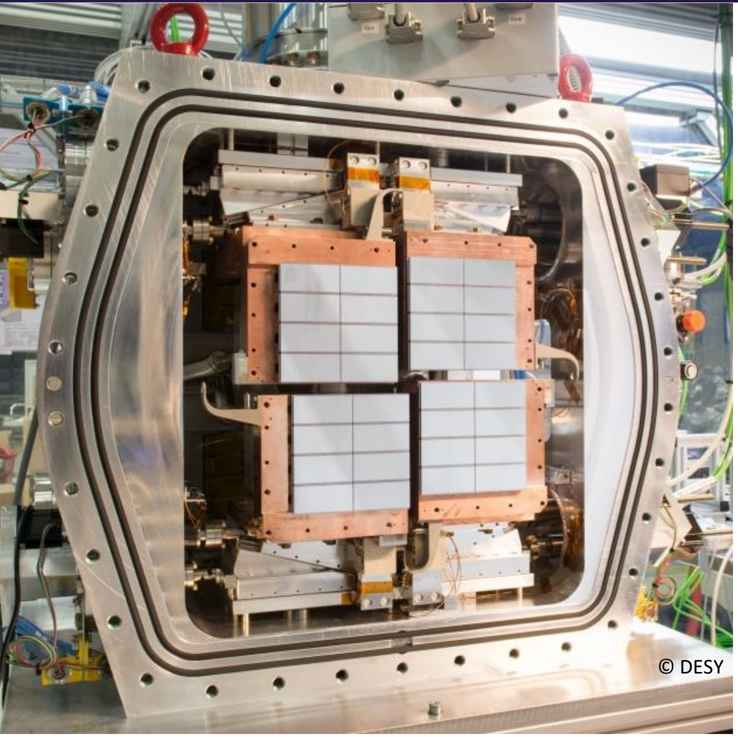








Camera Performance: *Power Consumption*

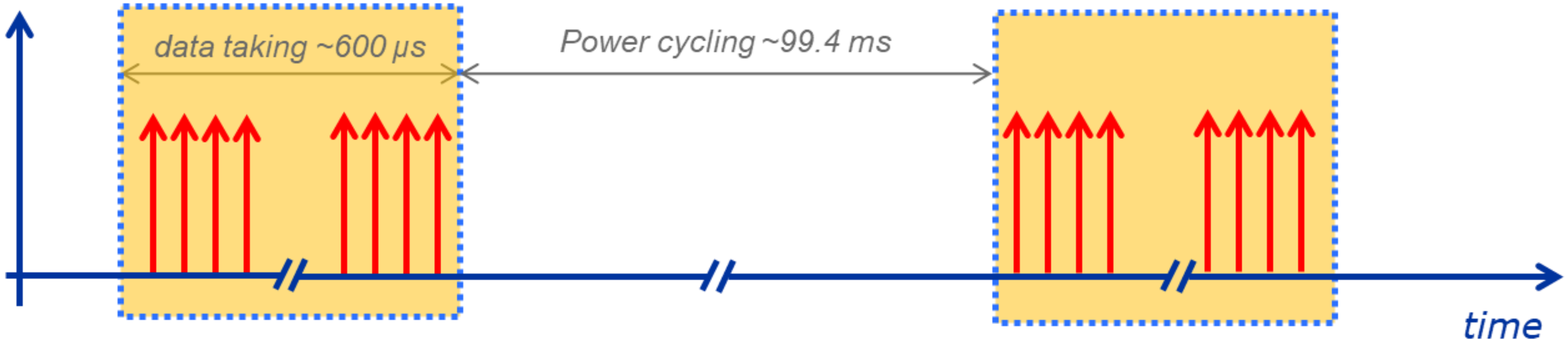


			Q1	Q2	Q3	Q4	Camera
Quadrant	IOB		12,42	12,44	12,38	12,21	**49,45**
	RB		9,42	9,05	9,21	8,99	**36,66**
	FPM	MB	10,09	10,07	10,07	10,07	**40,31**
		ASIC	5,30	4,98	5,12	4,84	**20,25**
		Sensor	0,60	0,61	0,61	0,52	**2,35**
Periphery	PP		2,65	2,54	2,61	2,56	**10,36**
	PPT		24,71	24,42	24,36	24,34	**97,82**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

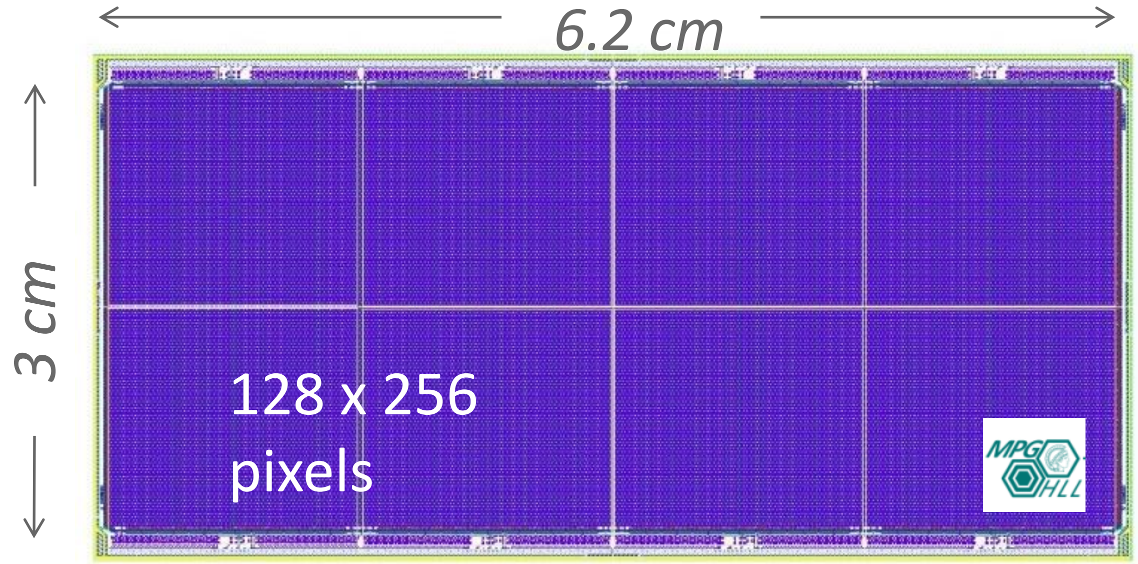
Focal Plane: 63 W (24%)

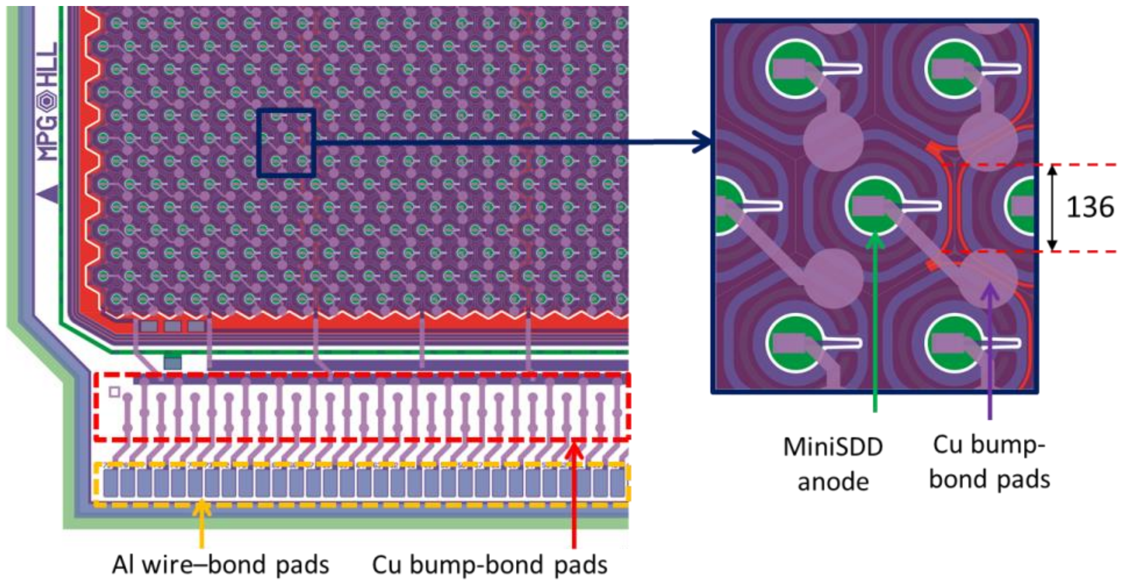
Periphery: 114 W (43%)



- 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

MiniSDD Sensor

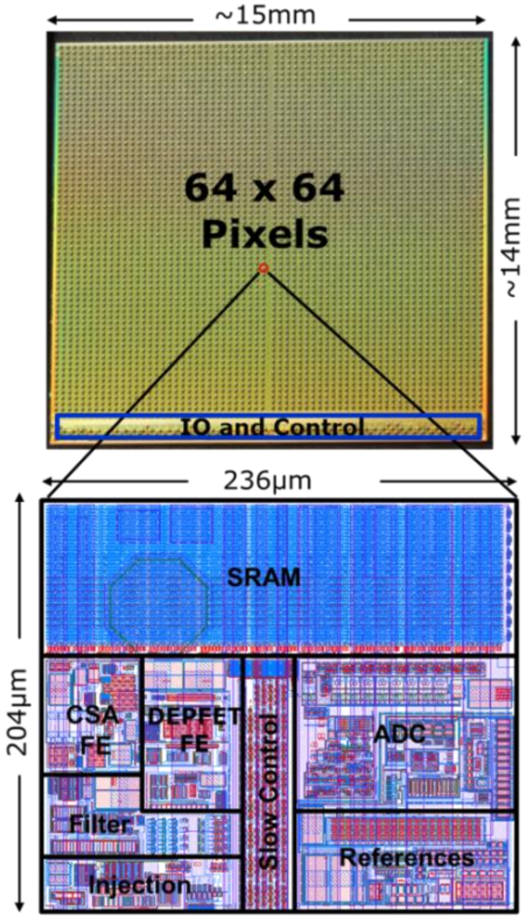




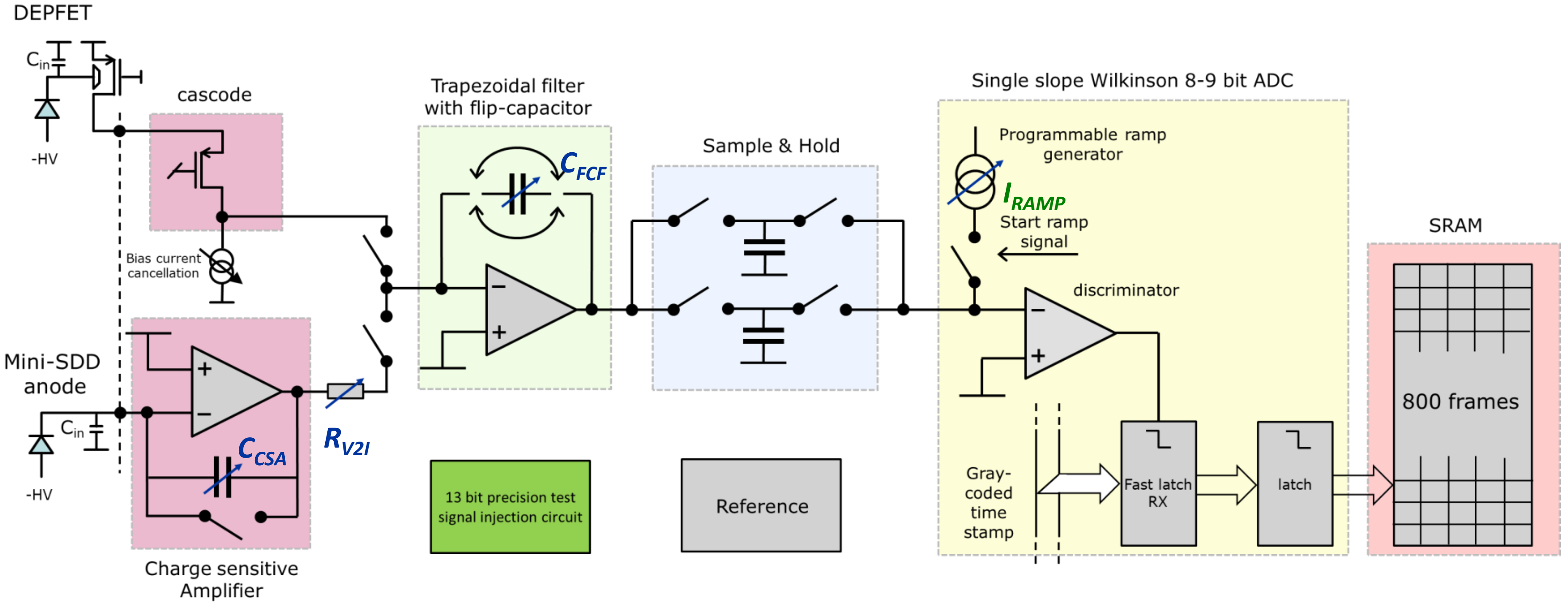
- Large area monolithic **Mini Silicon Drift Detector** Arrays produced at the Semiconductor Laboratory of the Max Planck Society
  - 128 x 256 hexagonal pixels; hexagon side 136 µm; pixel pitches 204 x 236 µm
  - passive collecting anode
  - 1 Alu layer, Cu layer

- 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 bit)

Full Format Readout ASIC



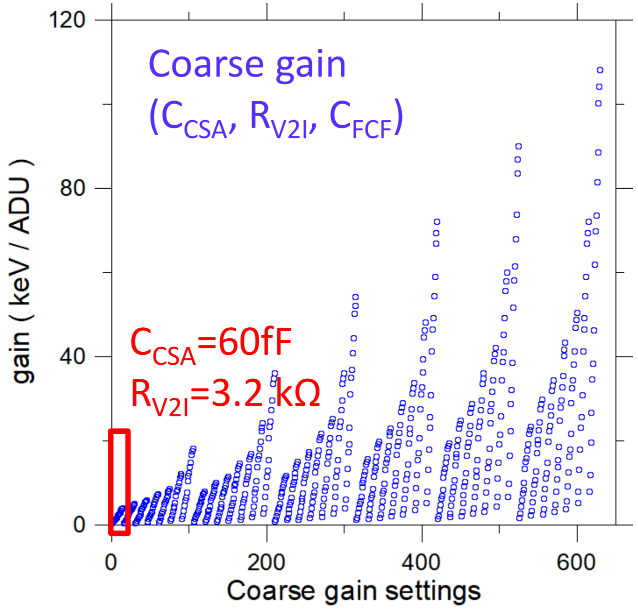
130 nm CMOS Process with C4 bumps

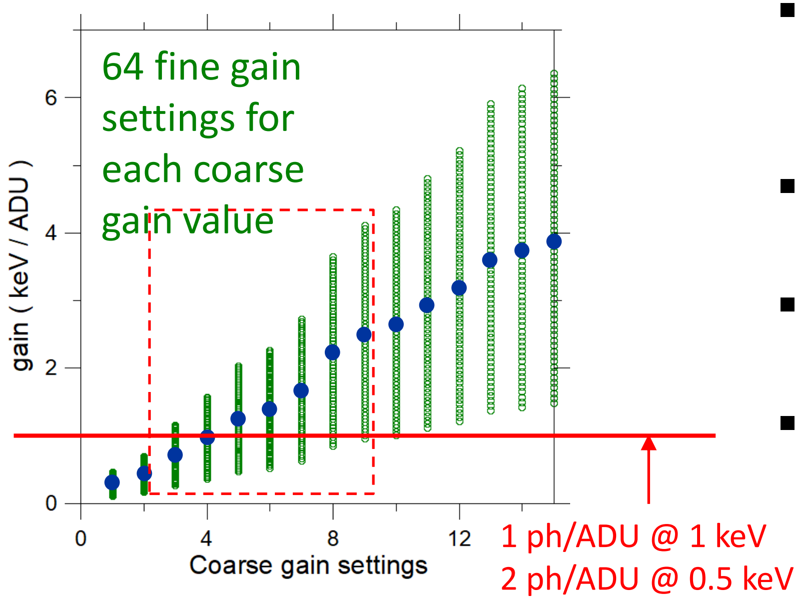


- Gain and offset can be adjusted pixel-wise:
  - **11 bits of coarse gain setting** for ph. energy and input range selection
  - **6 bits of gain fine trimming** (nominal accuracy 2%)
  - 4 bits for offset trimming (1.5 LSB range with 8% of granularity)

$$\frac{keV}{ADU} \propto \overbrace{C_{CSA} \cdot R_{V2I} \cdot C_{FCF}}^{\text{Pixel-wise coarse gain parameters}} \cdot \frac{1}{t_{filt}} \cdot \frac{1}{C_{S\&H}} \cdot \overbrace{I_{ramp}}^{\text{Pixel-wise fine gain trimming}} \cdot \frac{1}{2 \cdot f_{clock}}$$

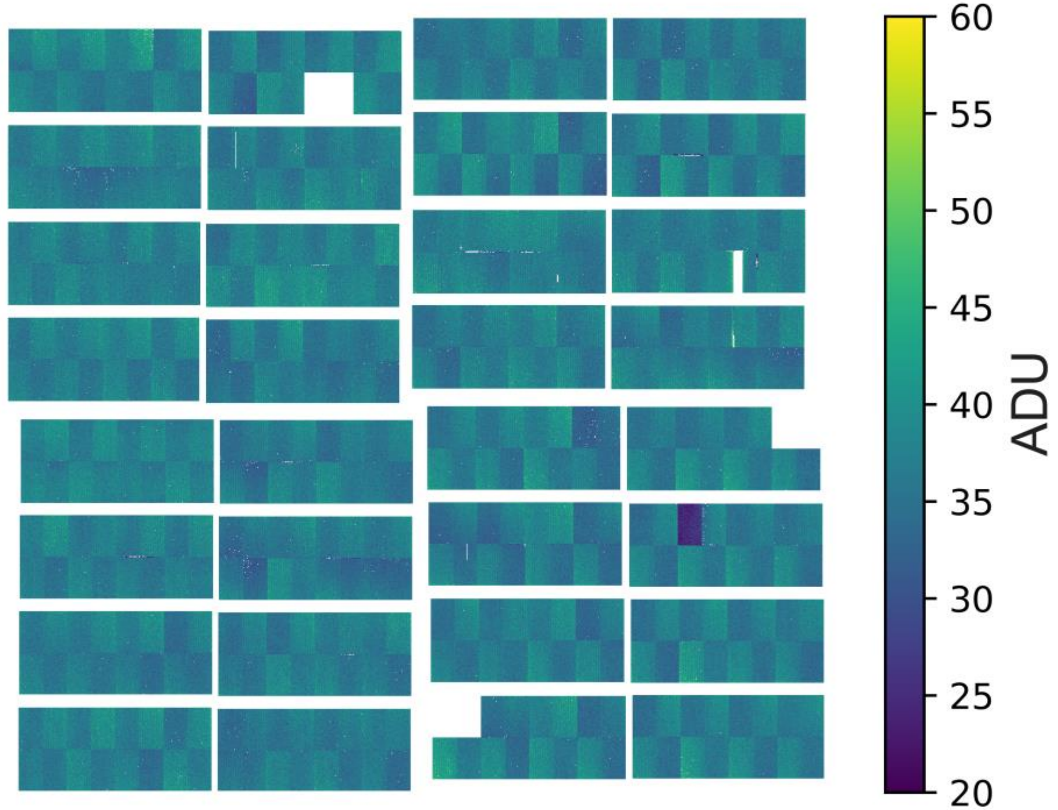
Fine Gain Trimming and Energy Range

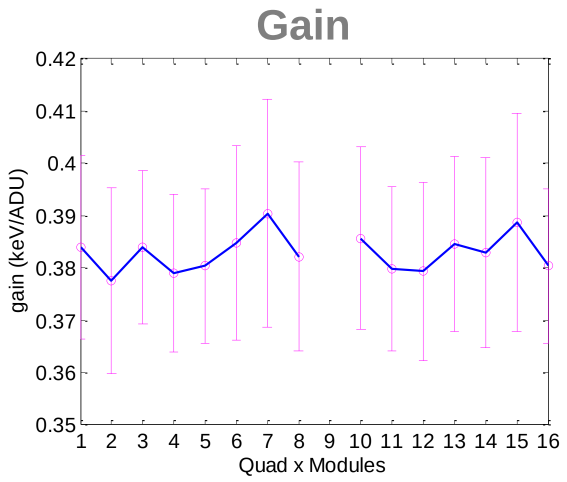




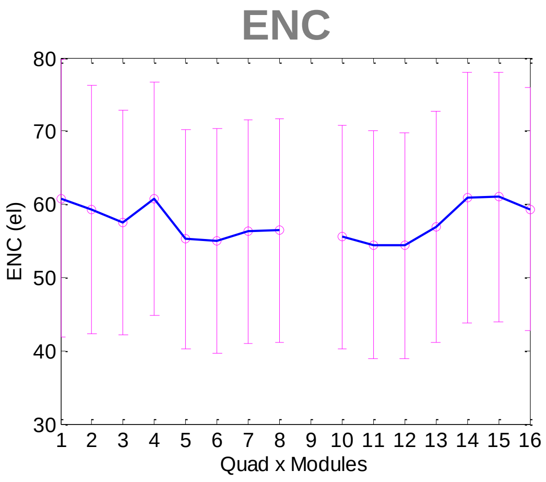
- pixel-wise **coarse gain settings** make it possible
  - to operate with photons of **different energies**
  - to **define the input dynamic range**, associating a defined number of photons to a single ADU
- Pixel wise **fine-gain trimming** is needed
  - To equalize the gain dispersion over the pixels 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)
- It is possible to set **different gains in different regions** of the detector
- The overall gain settings are **overlapping and have a granularity <1%**
- Possible to define precisely the gain **for any arbitrary energy** for **$0.5\ keV \leq E_{ph} \leq 10\ keV$**

DSSC 1 Megapixel Camera



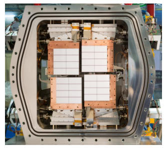


average: 382.9 ± 3.6 (1.0%)
average σ: 17.3 (4.5%)



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

- 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

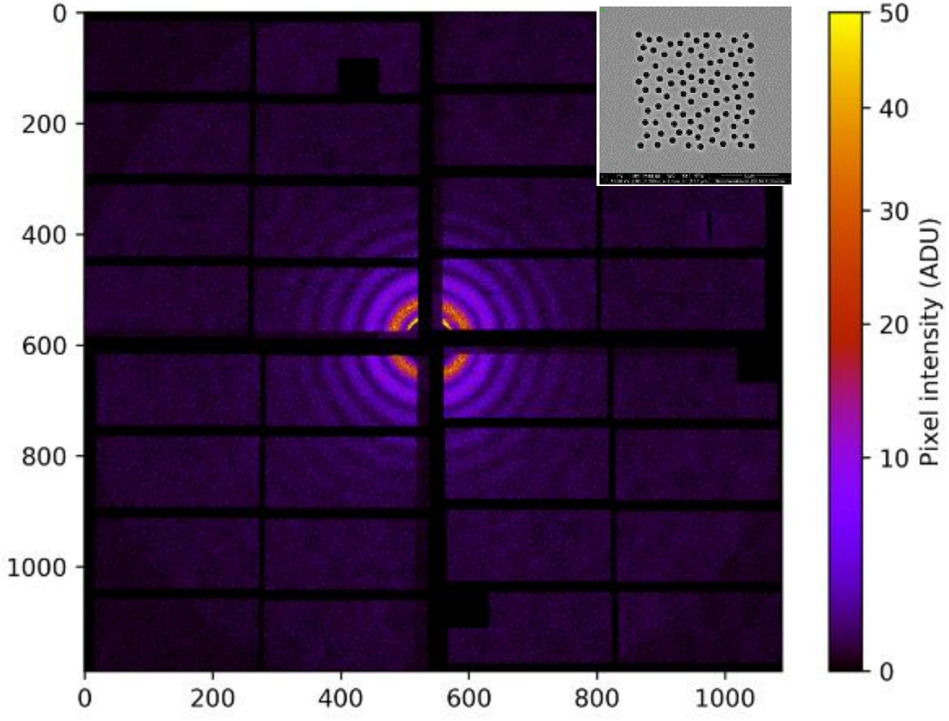


Dark-Image Test
- **w/o active Cooling at RT**
- **default Gain/Offset Settings**

Commissioning & Users' Experiments

- Installation in May 2019 @ Spectroscopy and Coherent Scattering (SCS) Instrument
- First user experiment May 28, 2019
- Since installation (to Dec 2021):
  - ✓ **16** user experiments at SCS:
    - – 8 Time resolved scattering
    - – 7 Time resolved XAS
    - – 1 Time resolved Holography
  - ✓ DSSC commissioned and installed at Small Quantum Systems (SQS) Instrument

Diffraction image of pinholes with 707 eV photons
SCS commissioning



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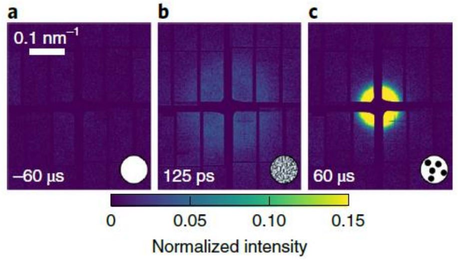

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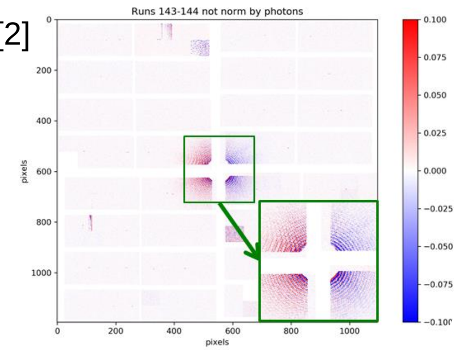

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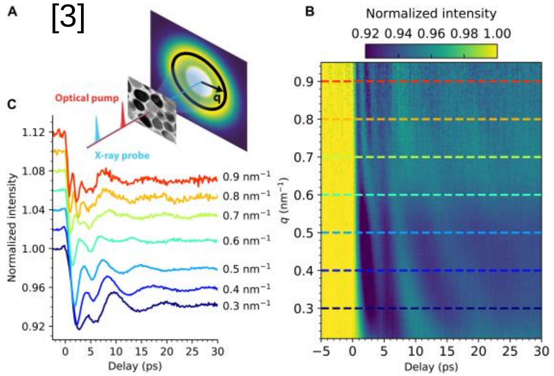


[1] Büttner, F; *et al.* Observation of fluctuation-mediated picosecond nucleation of a topological phase. *Nat. Mater.* **20,** 30–37 (2021). doi:10.1038/s41563-020-00807-1
[2] Hagström, N. Z.; *et al.* Megahertz-rate Ultrafast X-ray Scattering and Holographic Imaging at the European XFEL. *arXiv* (2022). 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

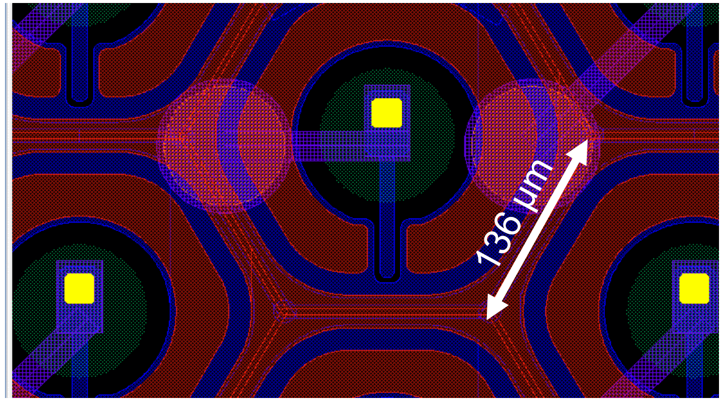
- In the second DSSC camera the MiniSDD sensors will be replaced by DEPFET arrays
  - Fully compatible ladder electronics, **additional components** installed for sensor operation
  - ASIC includes DEPFET FE
  - Produced by PNSensor

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

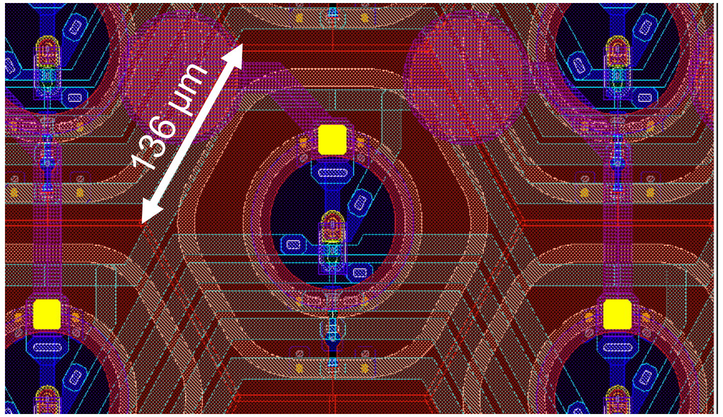
- The DEPFET arrays are **compatible with the existing DSSC system**

- **A maximum signal > 10^4 ph / pixel is achievable for E ≥ 800 eV,** assuming an **8-bit ADC** and single photon detection capability

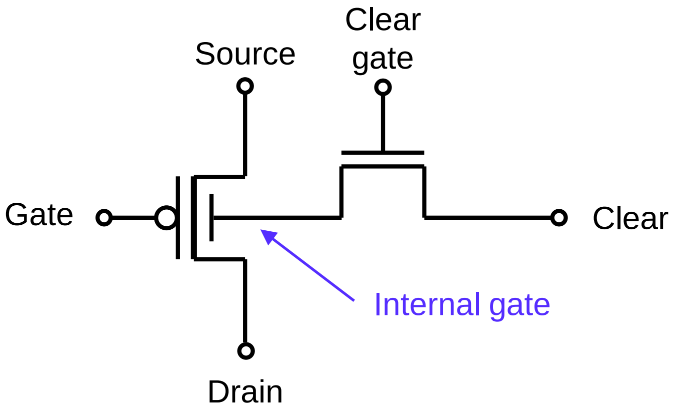
- Common-source configuration, I_{DRAIN} readout

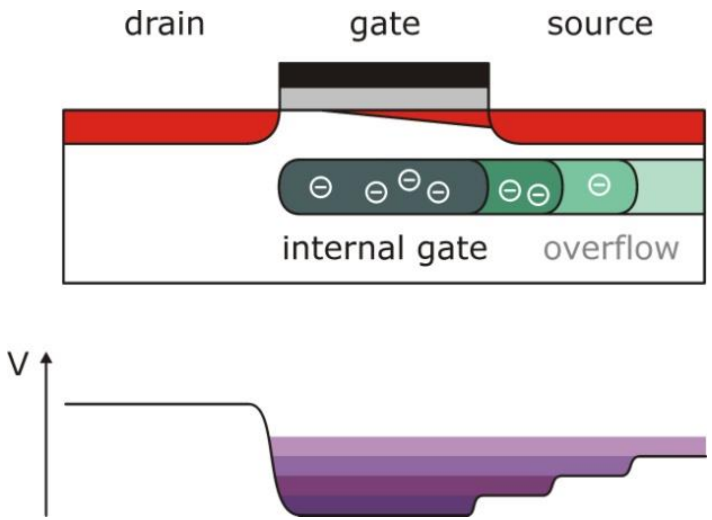


MiniSDD with passive collecting anode



DEPFET Active Pixel





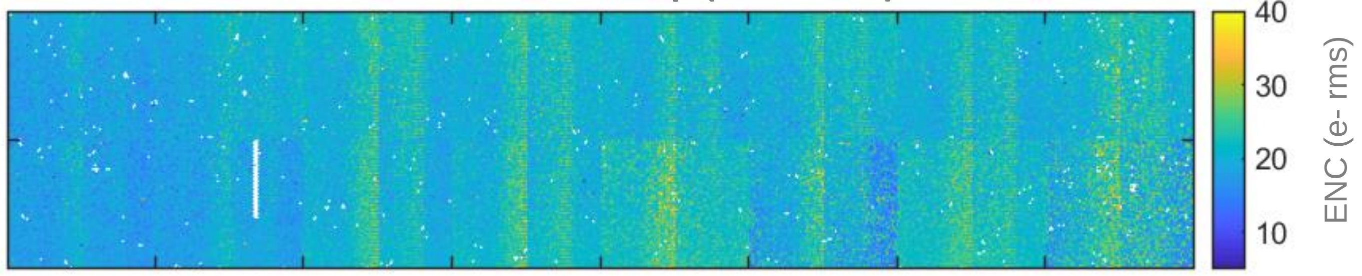
Lechner, P.; et al. DEPFET active pixel sensor with non-linear amplification, 2011 IEEE Nuclear Science Symposium Conference Record, 2011, pp. 563-568, doi:10.1109/NSSMIC.2011.6154112.
Aschauer, S.; et al. First Results on DEPFET Active Pixel Sensors Fabricated in a CMOS Foundry - a Promising Approach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

DEPFET-ladder prototype: *lab tests*

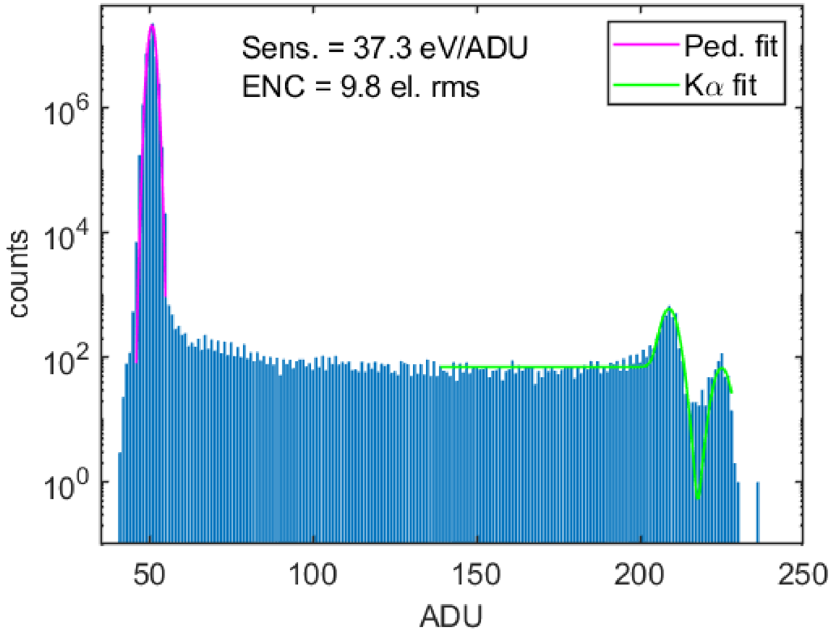
1st prototype characterization in the linear range

- 100 µA/pixel average DEPFET-bias current
- ENC 20.72 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

Ladder ENC map (2.25 MHz)



Calibration with ⁵⁵Fe (1.125 MHz)



DEPFET-ladder prototype: *NL curve*

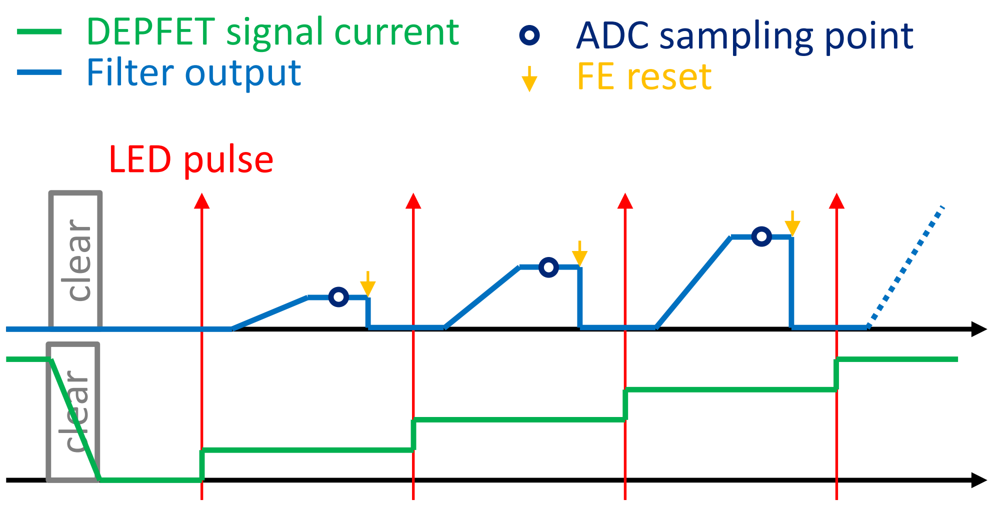
Non linear characteristics evaluation

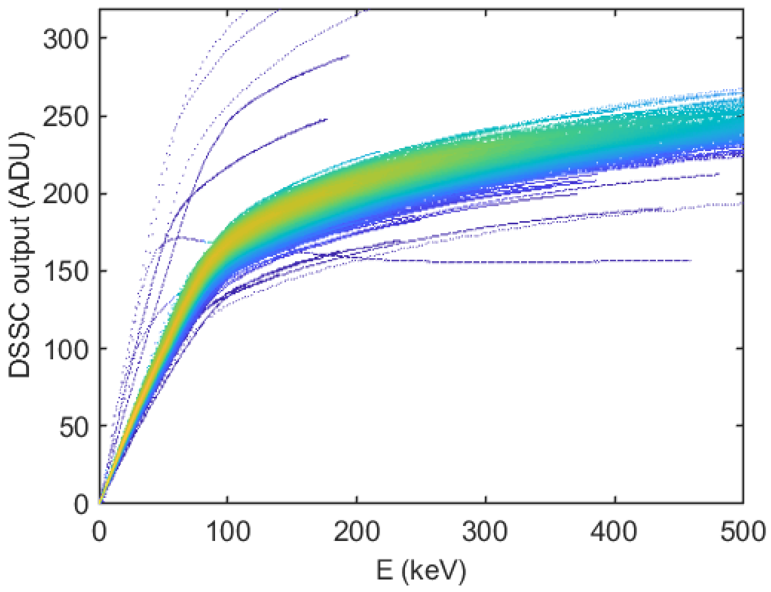
- 150 nm thick Al layer on entrance window
- laser pulser: 905 nm, 25 W
- Integrating charge into DEPFET internal gate, no clear between acquisition cycles
- Curve scan with 400 pulses in singe integration mode
- 50 ns integration time

✓ Estimated **dynamic range** with 8 bits:

~1000 ph @ 500 eV/ADU

~9000 ph @ 1000 eV/ADU





1[st] kink Energy: 80.6 ± 5.4 keV

Gain (linear): 473 eV/ADU

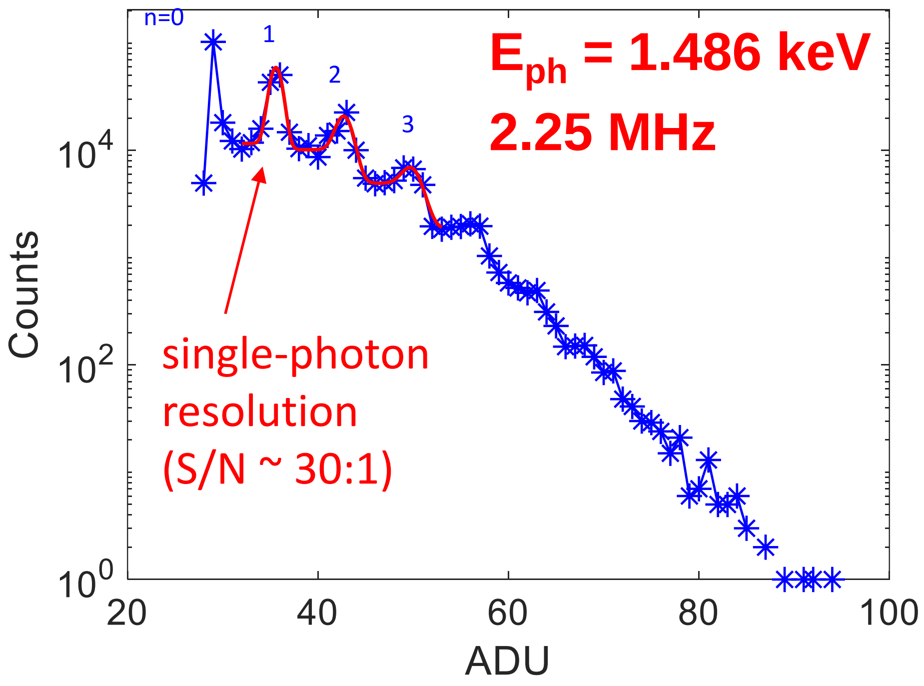
DR (@ 473eV ph): > 1000 ph

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

Al fluorescence



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) scientific instrument 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
- High number of exp. since 2019, with two paper published on high-ranking journals and others in preparation
- 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 at the end of this year (2022)
- First operation of a CMOS-DEPFET ladder in lab-test conditions confirms the excellent performances of the technology: three times better noise w.r.t. miniSDD and > 35 times better DR at 1 keV/photons while keeping single photon resolution
- ENC can be as low as to 9.8 e- rms at 1.1 MHz