Fast Soft X-ray Detectors

Soft X-ray Detector Challenges

Percival

(selected) other developments (Jungfrau0.4, DSSC, epix100)

Summary / Outlook

Cornelia Wunderer

DESY – Photon Science Detector Systems & CFEL

cornelia.wunderer@desy.de

HELMHOLTZ ASSOCIATION

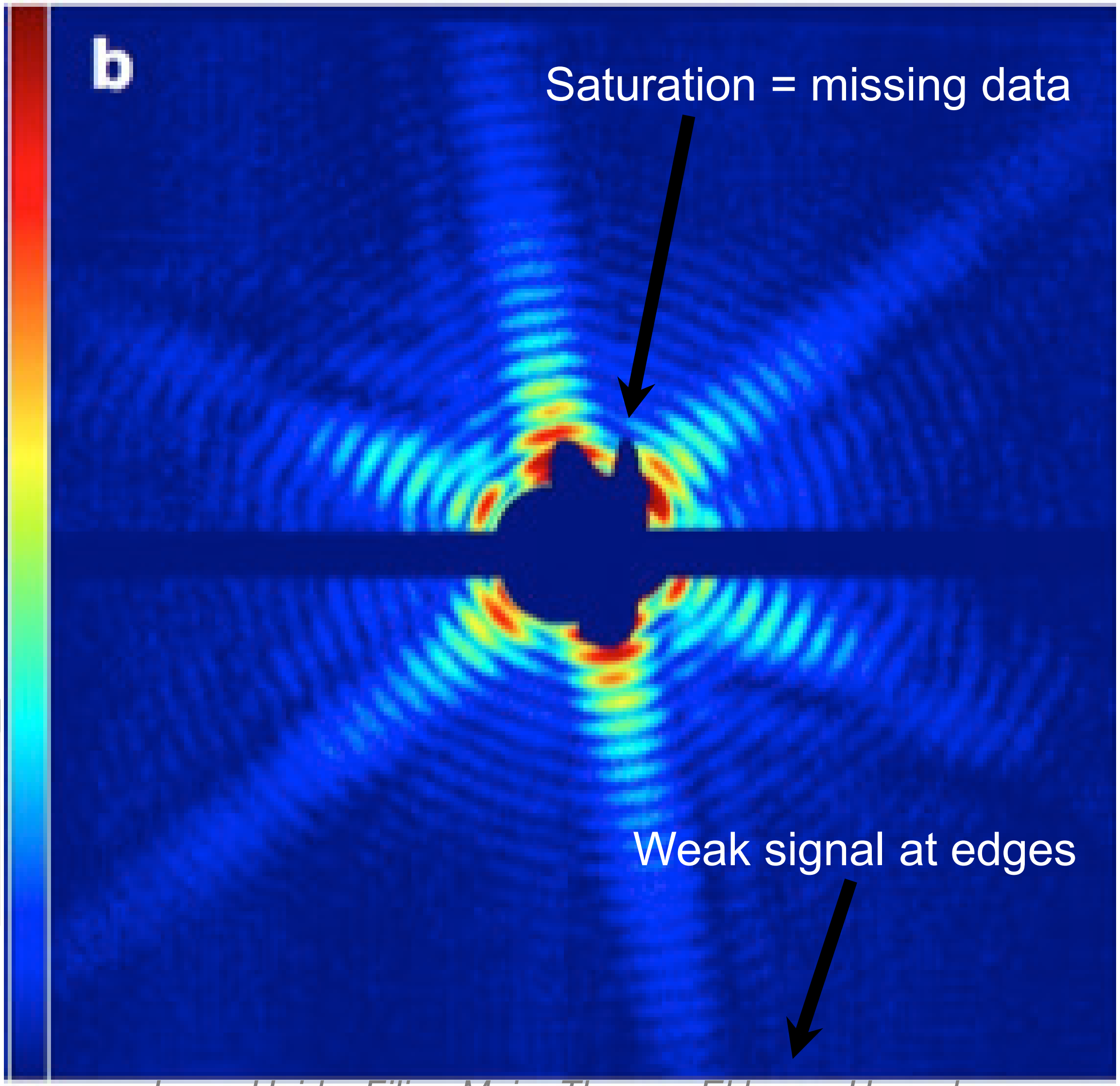
CFEL SCIENCE

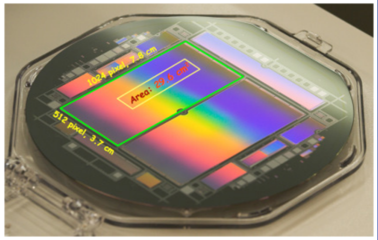
AXSIS

European Research Council
Established by the European Commission

Soft X-ray Detector Challenges

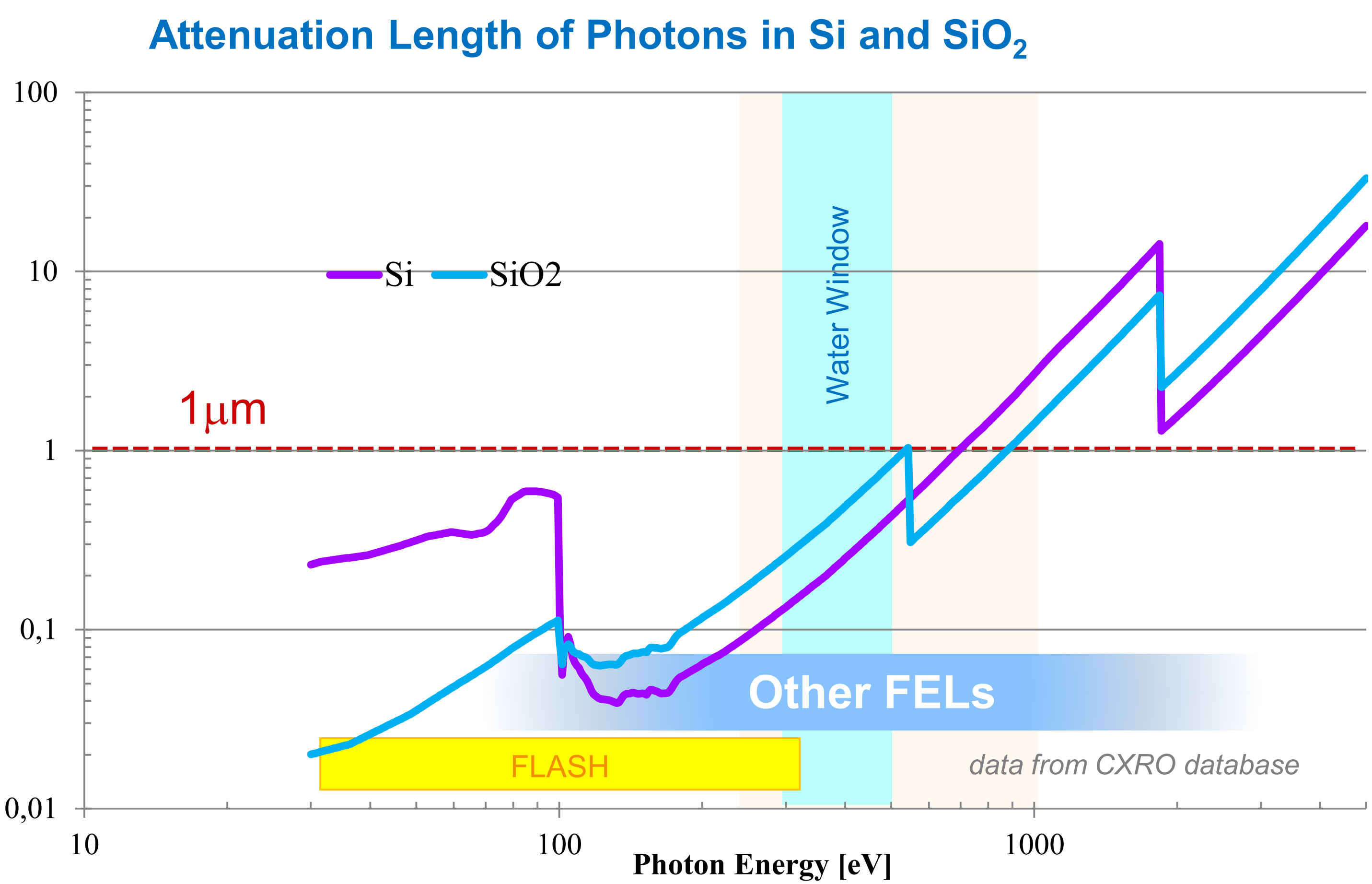
Challenges in the details to be recorded





Janos Hajdu, Filipe Maia, Thomas Ekberg - Uppsala

Soft X-ray Challenges – Can the X-ray reach the sensor?



At (very) soft X-ray energies, QE is limited by passive window thickness!

e.g. 50 nm of SiO_2: loss of 25% of 250 eV photons

Soft X-ray Challenges – can we detect a single X-ray?

Goal: reliable single-photon discrimination

- At 1 keV (250eV), a single photon generates ~ 275 e- (69 e-)
  - Charge collection even in a very good detector is never 100% (80-90%)
  - Interactions at pixel boundaries will result in shared charge
- In order to achieve
  - single photon detection with an
  - acceptably low number of false positives
  - in a ~ Megapixel detector system
- detection levels must be on the order of 5 σ
- and consequently noise levels must be better than 55 e- (14 e-)

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(Pixelated Energy Resolving CMOS Imager, Versatile And Large)

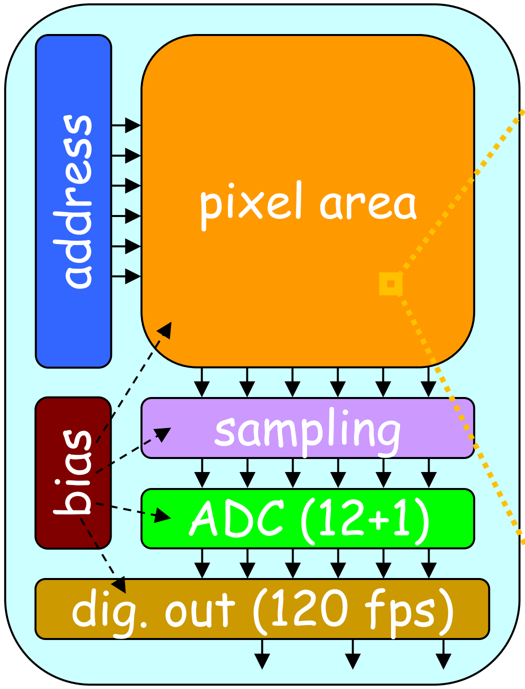
DESY

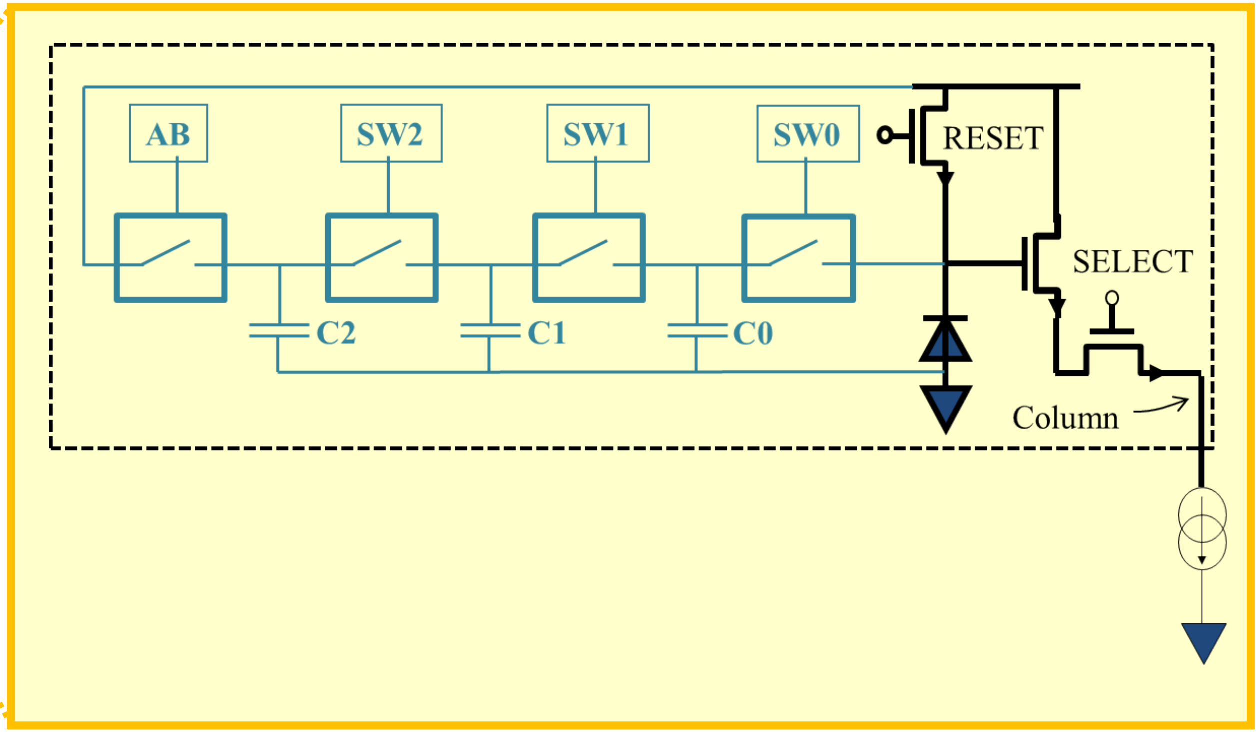
CFEL SCIENCE

Percival System Aims

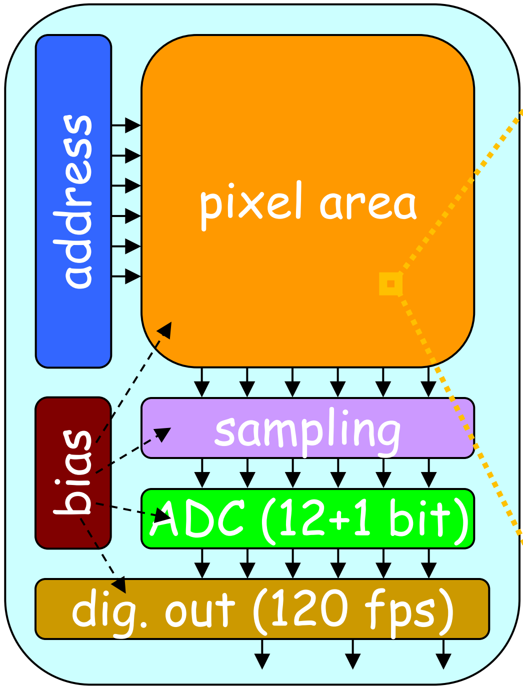
Energy range	0.05 …. **0.25 – 1 keV** … few keV
QE over full energy range	>0.85, uniform over pixel
Pixel size	**27 µm** (prototypes: 25µm)
Sensor size	"13M": 3520×3710 pixels, **10×10 cm²** "2M": 1408×1484 pixels, 4×4 cm²
Frame rate	**(1 -) 120 Hz** **(300Hz for 2M)**
Noise in e- rms	**< 15**
"Full Well"	10 Me-
Resulting dynamic range	**10^5 photons** (250eV)
ADC conversion	On-chip/ per column/12b
Sensor output	Digital, LVDS
Buttability	2-side (adjacent edges)
Exposure modes	* FEL (all photons in < 300 fs) * Synchr. (quasi-continuous)

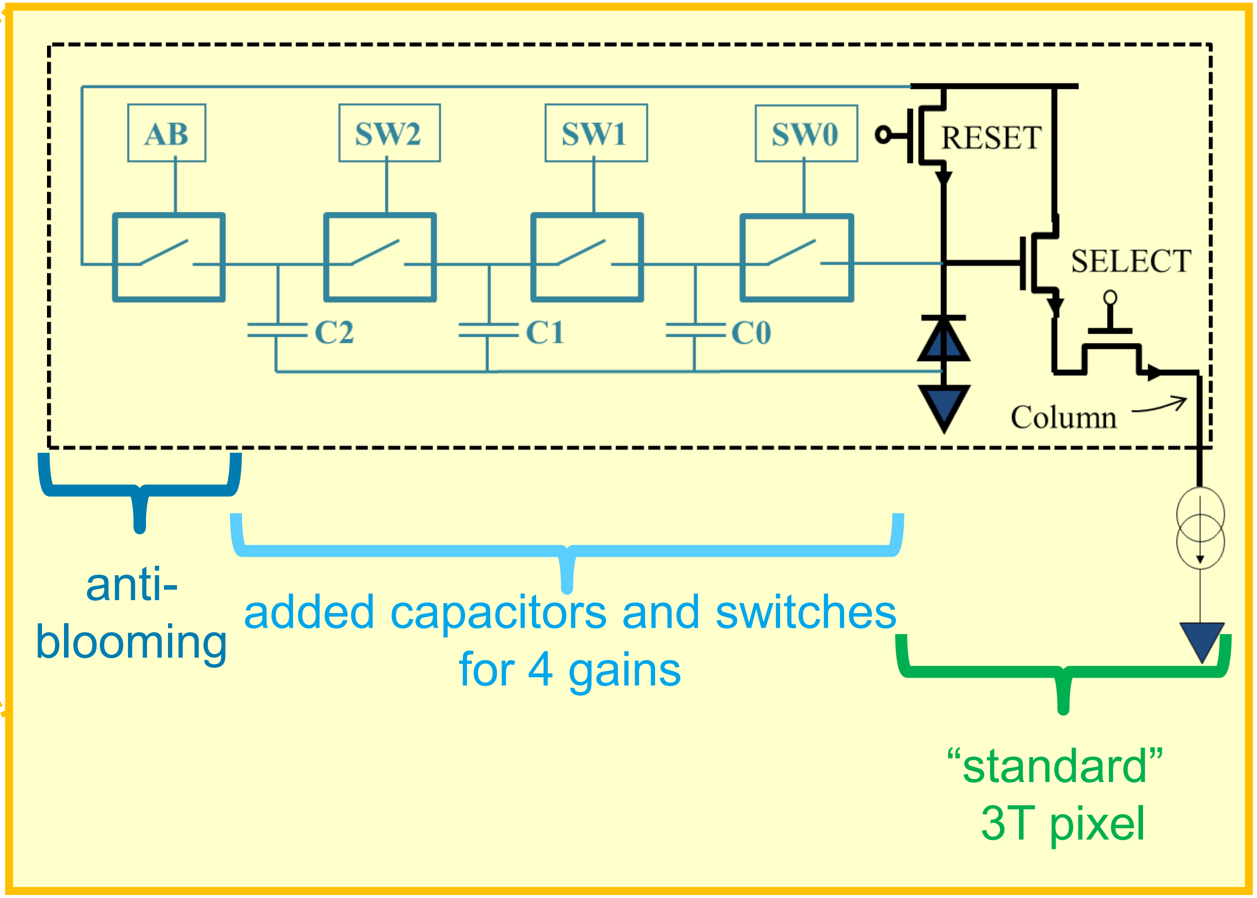
The Percival Sensor



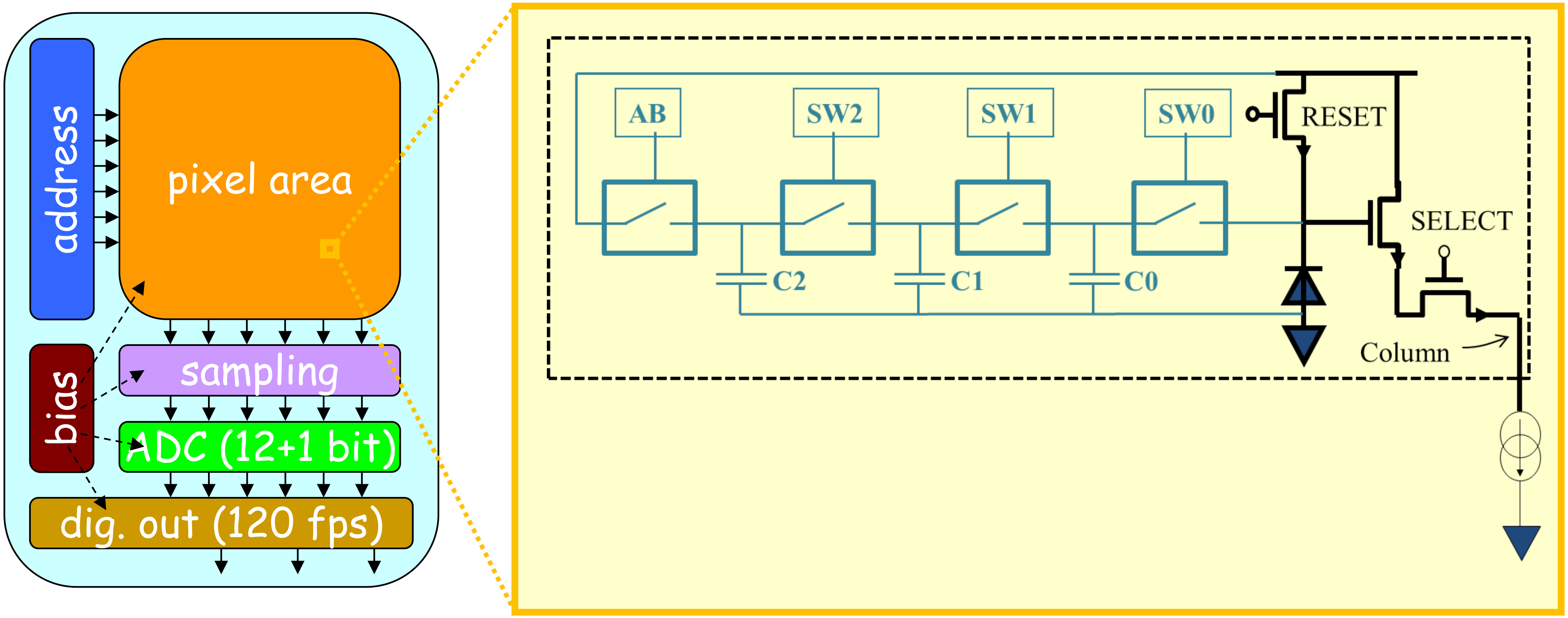


The Percival Sensor



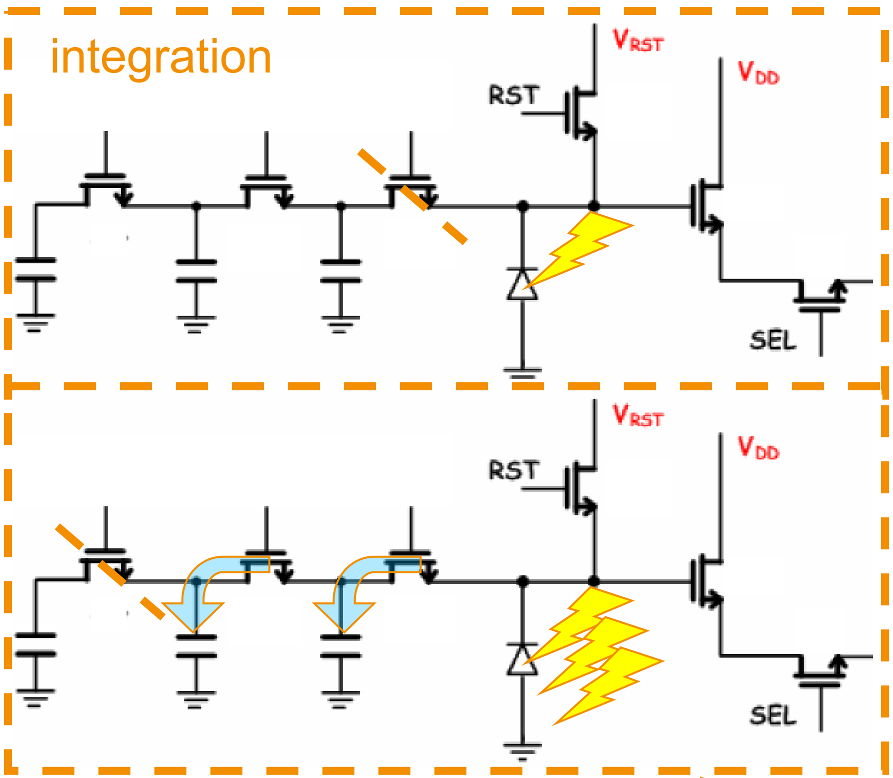


The Percival Sensor

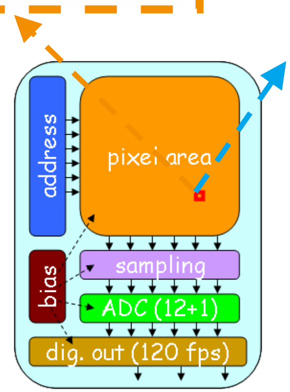


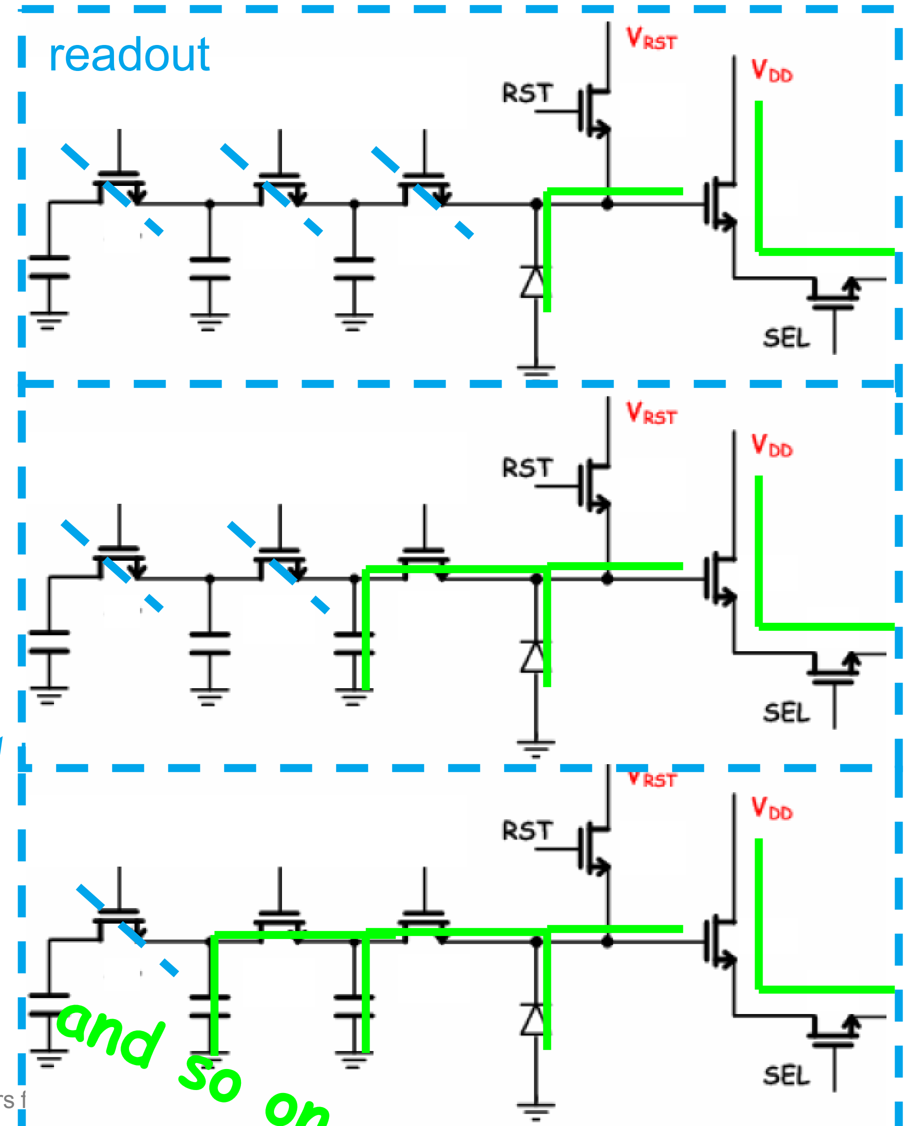
- 7 ADCs (+ spare) per column ⇒ read sensor in 7-row "groups"
- 3520 columns ⇒ 28k ADCs in a 13M chip
- 12+1(overrange)+2 (gain) bits ⇒ 15 (x2 for CDS) bits/pixel/frame
- 111 LVDS output lines at 480MHz data rate for 13M chip (50 Gbit/s)

Sensor: multiple gains



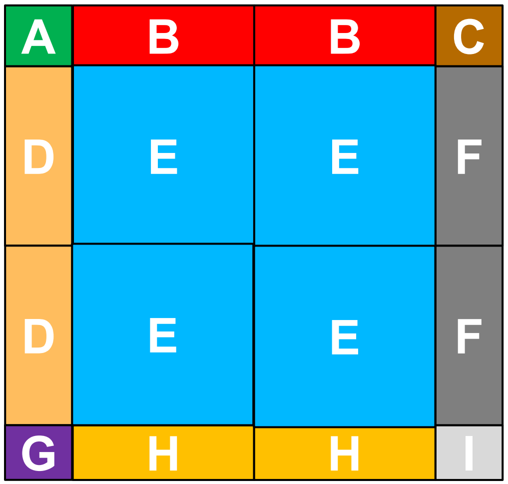
- Modified 3T pixel architecture
- High dynamic range achieved with multiple readings and lateral overflow



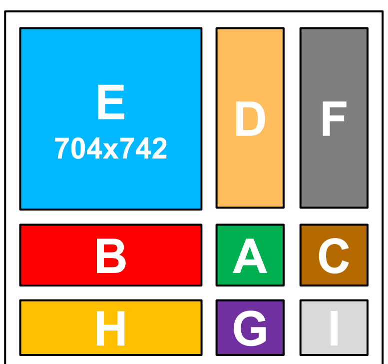


2 sensor sizes planned

1408 x 1484 pixel variant,
~4x4cm² "intermediate step"

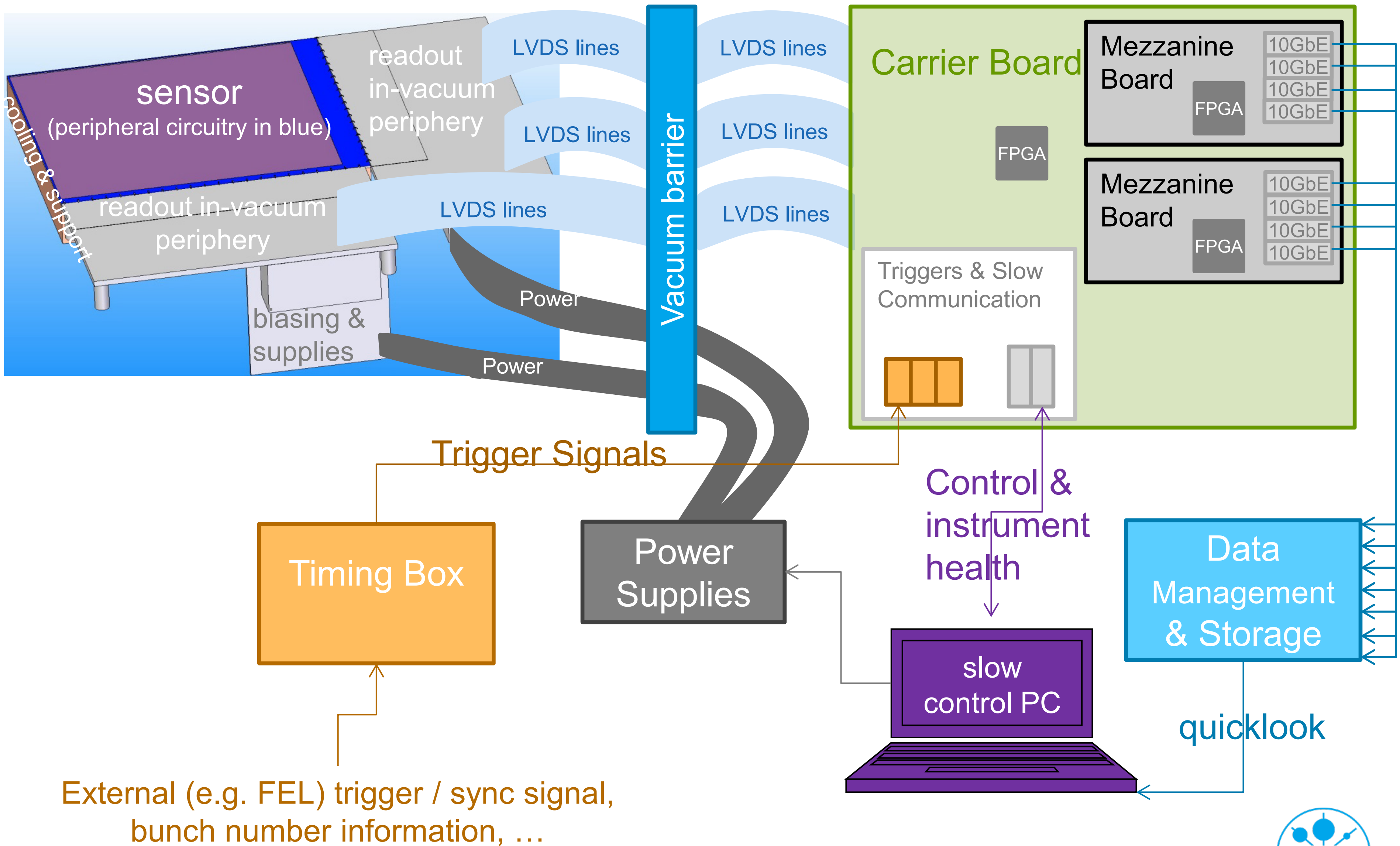


stitching blocks

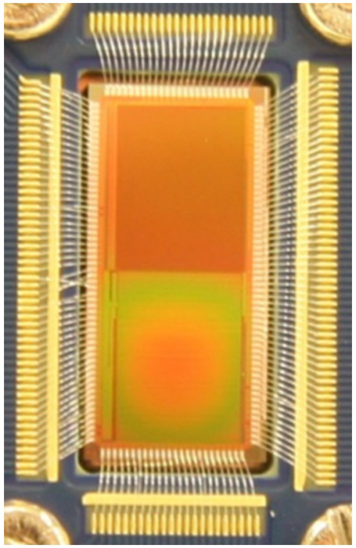


3520 x 3710 pixel variant, ~ 10x10cm²

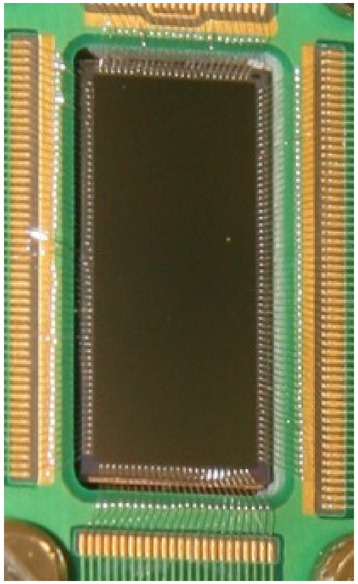
System


sensor
(peripheral circuitry in blue)
cooling & support
readout in-vacuum periphery
readout in-vacuum periphery
biasing & supplies
LVDS lines
LVDS lines
LVDS lines
LVDS lines
LVDS lines
LVDS lines
Power
Power
Vacuum barrier
Carrier Board
FPGA
Mezzanine Board
FPGA
10GbE
10GbE
10GbE
10GbE
Mezzanine Board
FPGA
10GbE
10GbE
10GbE
10GbE
Triggers & Slow Communication
Trigger Signals
Control & instrument health
Timing Box
Power Supplies
slow control PC
Data Management & Storage
quicklook
External (e.g. FEL) trigger / sync signal, bunch number information, …

Prototype Sensors



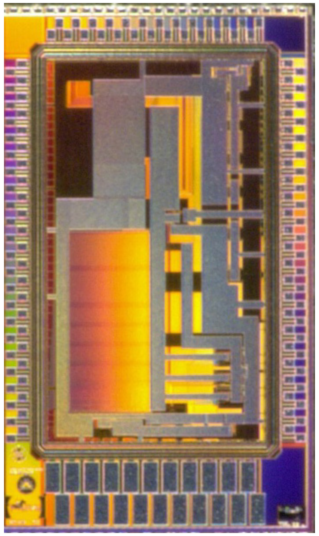
FSI (top), BSI (bottom)



> TS1 & TS2

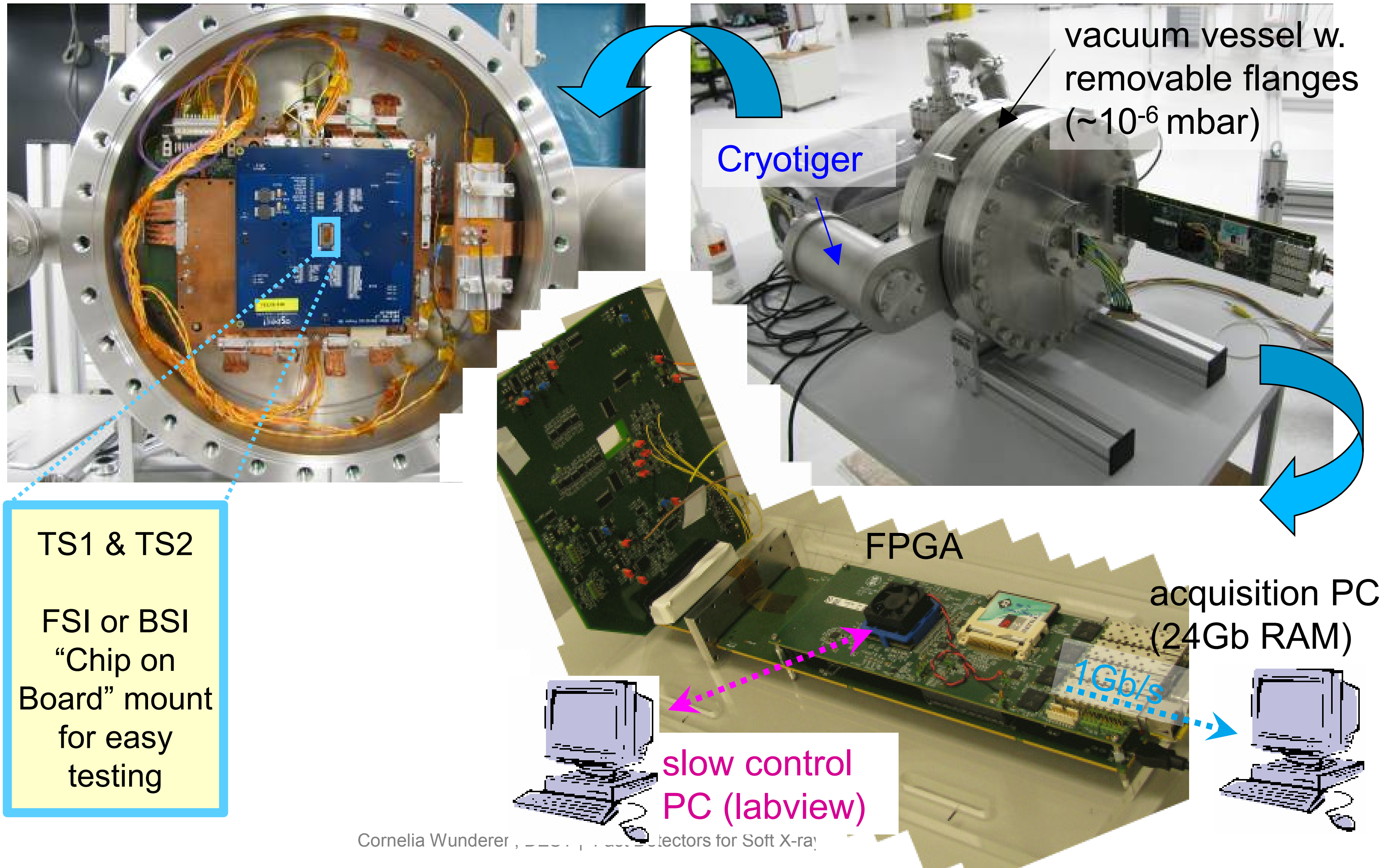
- 25 μm pixels
- 160x210 pixels
- 6 pixel flavors/chip
- TS1: annular partially-pinned photodiodes
- TS2: Nwell/P-epi diodes

> TS3
> fast digital readout

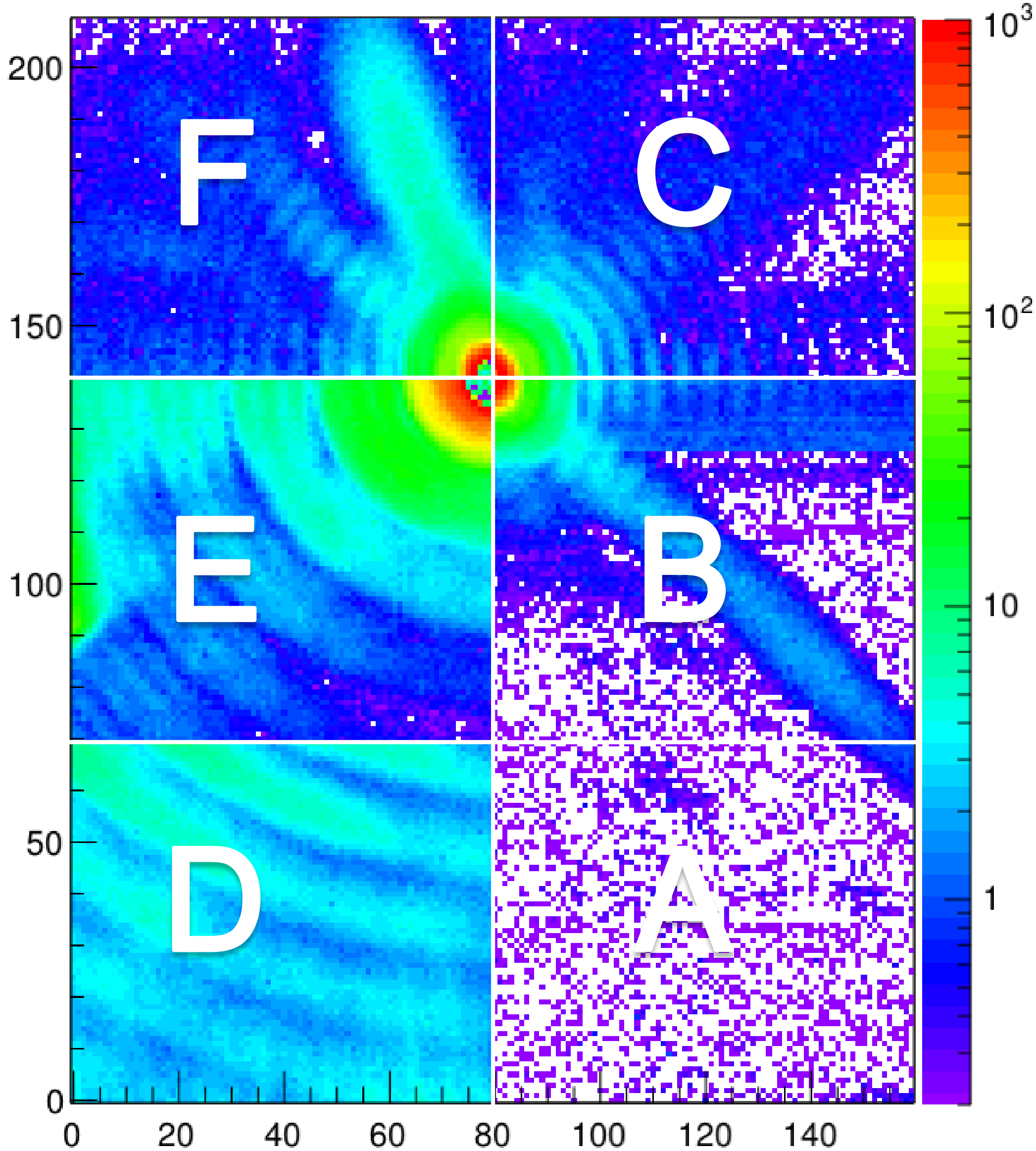


- 1120 ADCs/chip, running @ speed required for 120Hz operation of 13M sensor
- 8 CMOS output lines running at 20 MHz
- Capability to multiplex out analogue data

The Prototype Test System

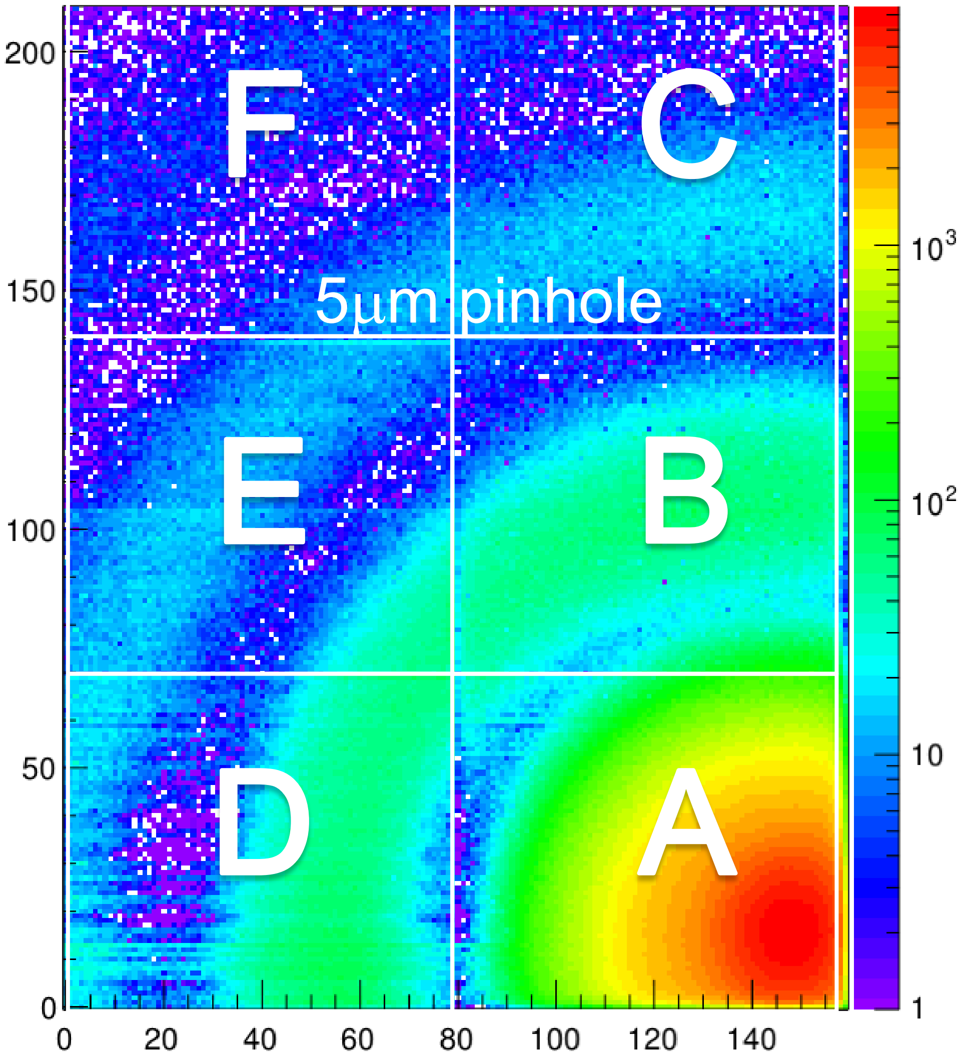


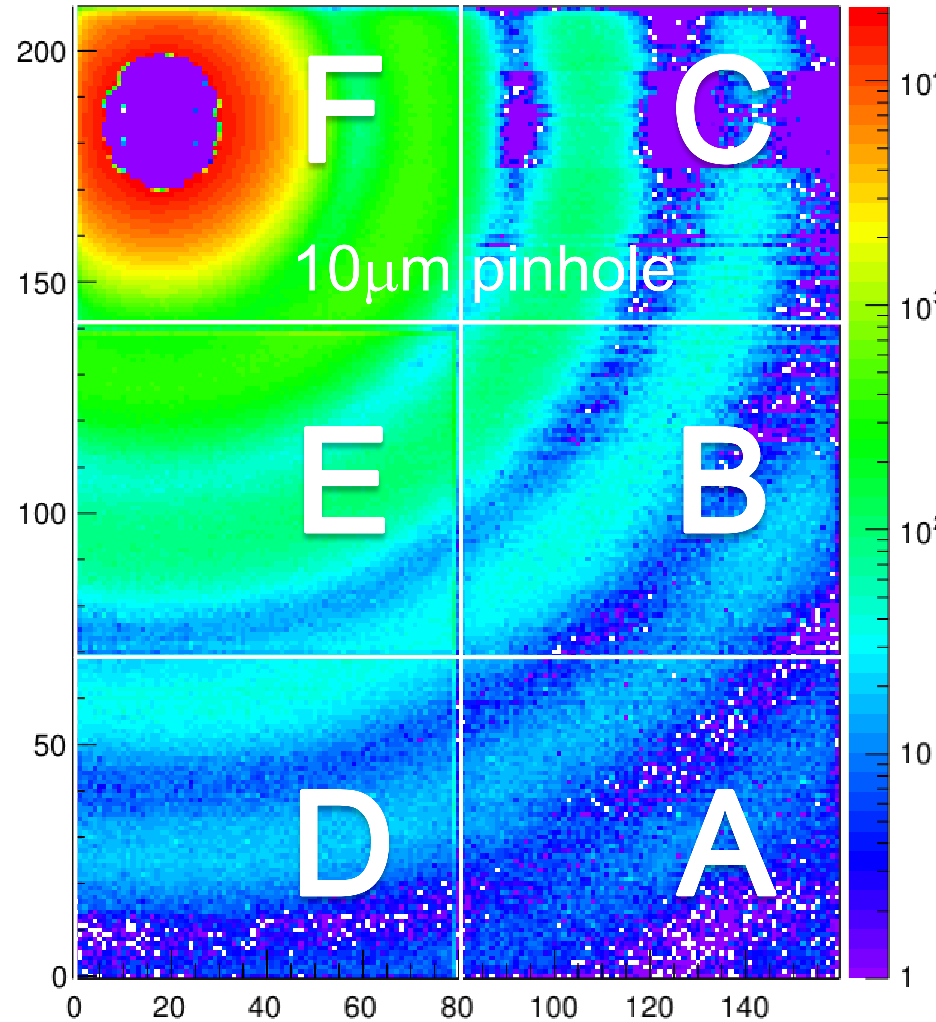
2014: 350eV Airy Ring Pattern on 1st BSI chip



- Harmonics dominate
- Primary discernible only in 1-2 pixel types (D & E)
- Response from different pixel types varies vastly
- Overall too few photons seen
- Showing average of CDSed and dark-subtracted images
- @ Elettra's TwinMic Beamline in March 2014

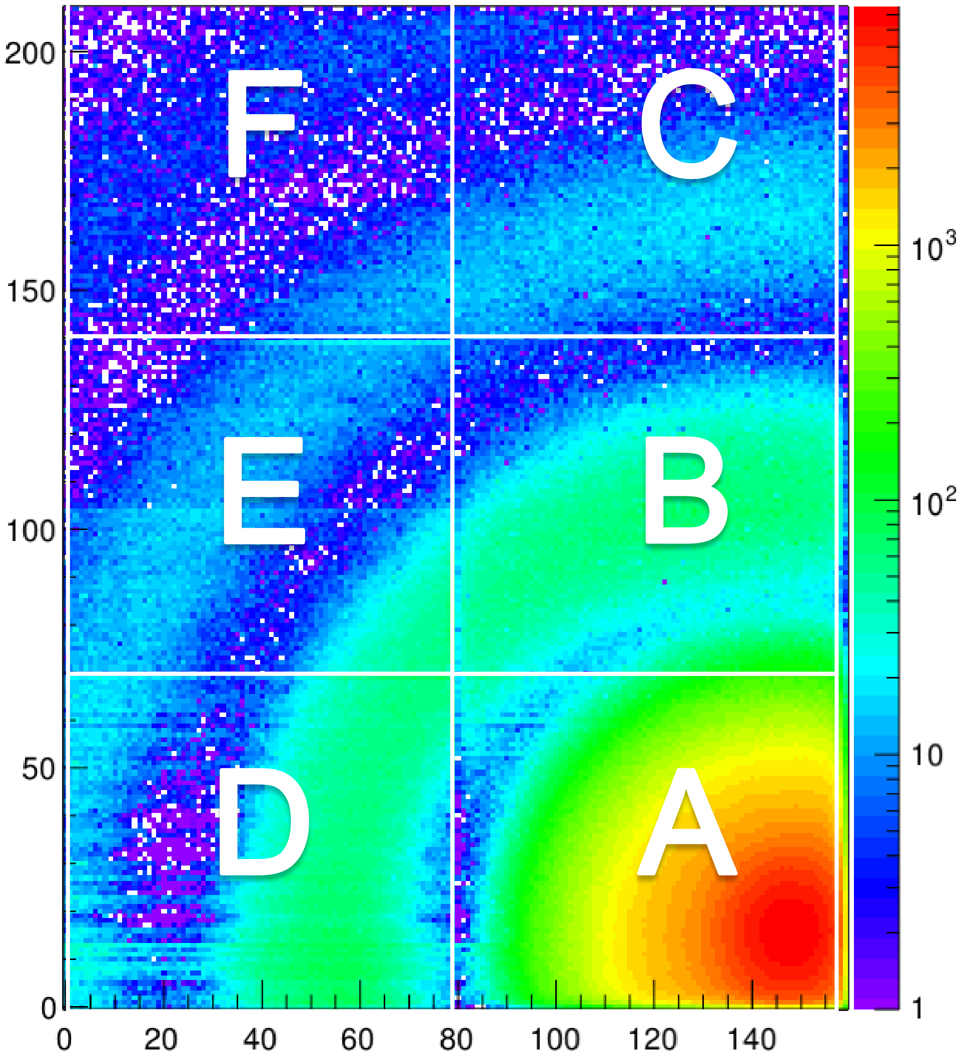
2015: 400eV Airy Ring Patterns on new BSI chip





@ DLS's I10 beamline in march 2015

2015: 400eV Airy Ring Patterns on new BSI chip



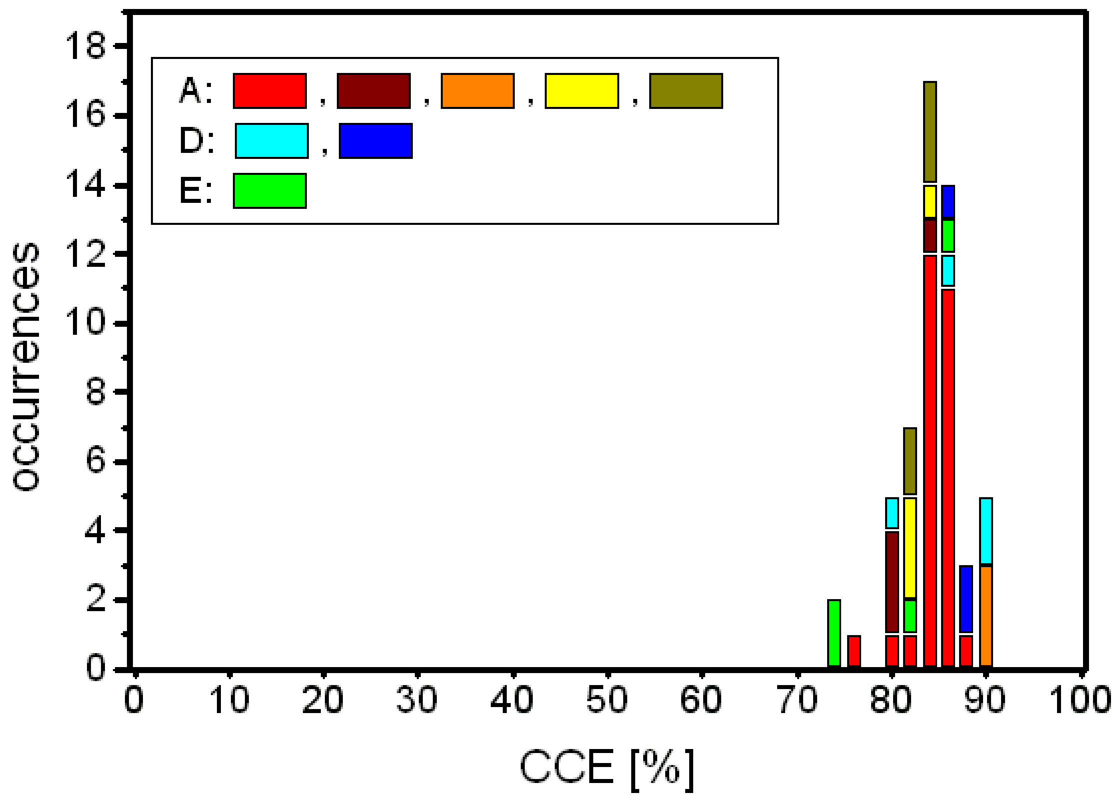
@ DLS's I10 beamline in March 2015

Still very preliminary:

> Primary dominates (no clear evidence of harmonics found to date)
> Response of all 6 quadrants comparable
> Overall roughly expected amount of charge observed
> Detailed analysis ongoing!

Charge Collection Efficiency at 400eV

- Images taken in highest gain
- CCE between 70% and 90%
- This constitutes a lower limit to the QE



… snapshots of other fast soft X-ray imaging systems …

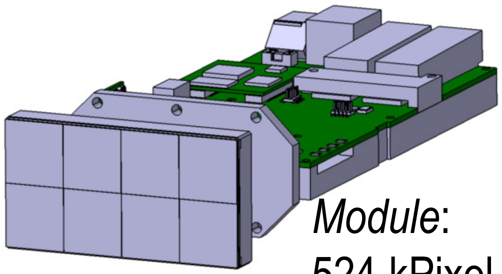
JUNGFRAU: Geometry & Readout

Final JUNGFRAU chip:

- *Pixel:* 75 µm × 75 µm
- *Chip:* 256 × 256 pixels, each with storage for 16 frames
- *Module:* 2 × 4 chips are tiled > 4 cm × 8 cm
- 320 µm or 450 µm silicon sensors (EIGER)
- Systems up to 16 Mpixel for two end stations at SwissFEL

→ Chip: Learn & copy from GOTTHARD (+ AGIPD)

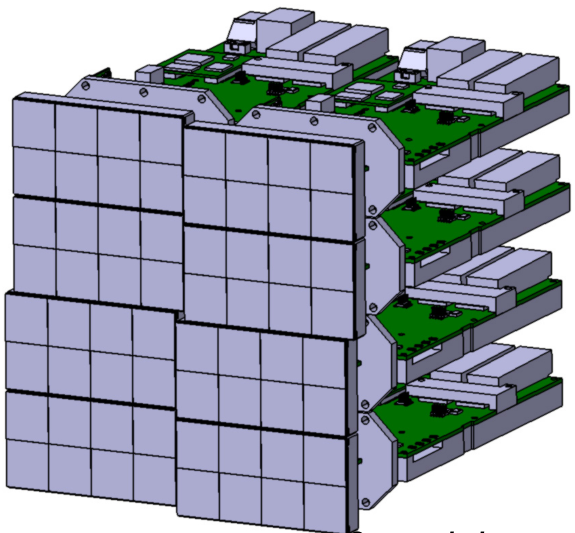
Single chip: 65 kPixel



Module:
524 kPixel

Readout:

- Readout rate > 2 kHz
- Linear count rate capability @ synchrotron:
  25 MHz/pixel
  → Learn & copy from GOTTHARD

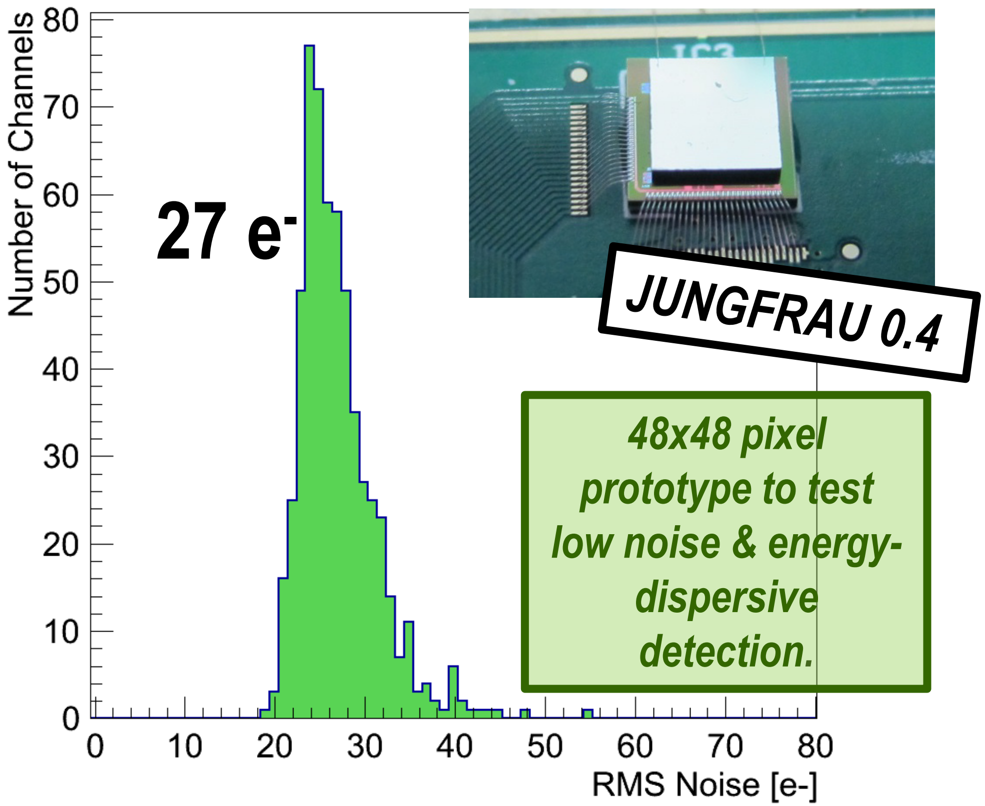


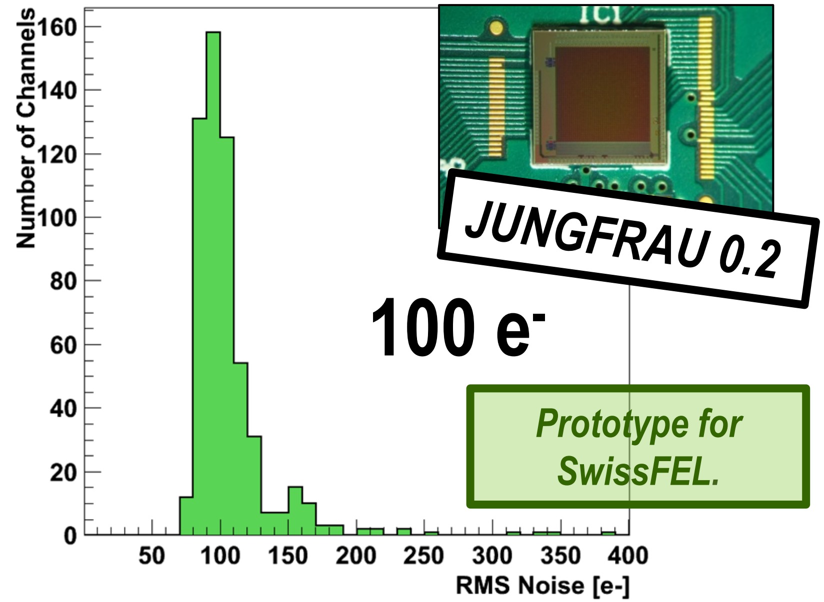
8 modules:
4 MPixel

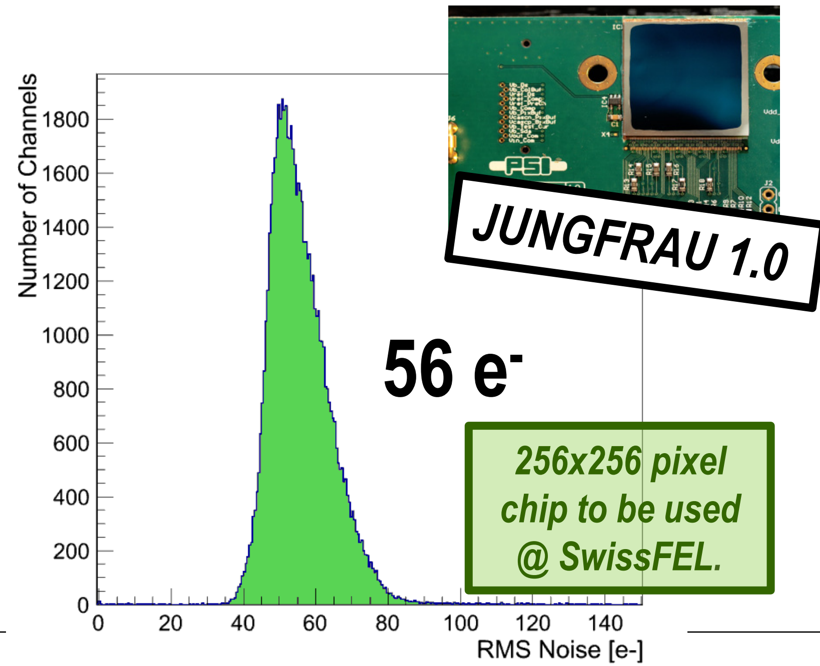
JUNGFRAU: A. Mozzanica et al., JINST, 9, C05010, 2014

(curtesy of Aldo Mozzanica, PSI)

NOISE of the JUNGFRAU Chips







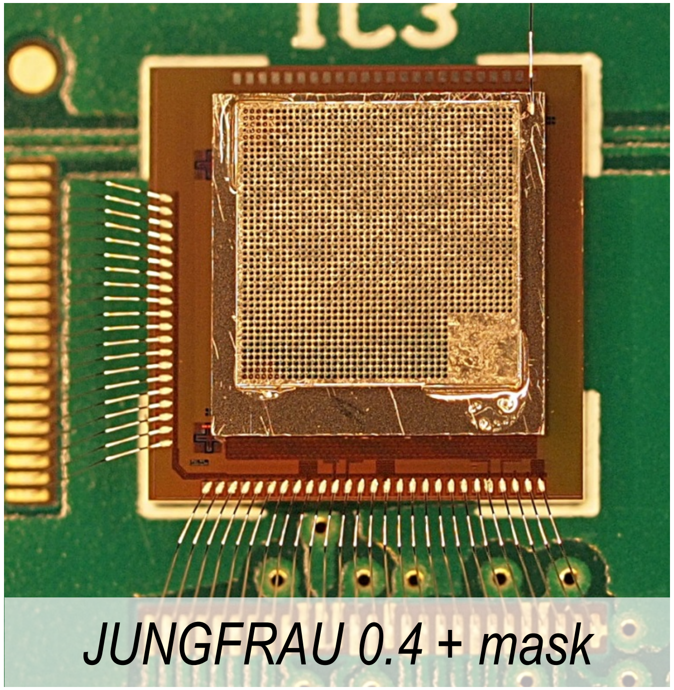
	JUNGFRAU 0.2	JUNGFRAU 0.4	JUNGFRAU 1.0
RMS Noise [e-]	100	27	56
RMS Noise [eV]	< 400	< 100	< 210
5σ RMS Noise [eV]	< 1800	< 500	< 1050

(curtesy of Julia Smith, PSI)

JUNGFRAU 0.4: Charge Sharing Suppression

PHOENIX Beamline: 1.2 keV Photons

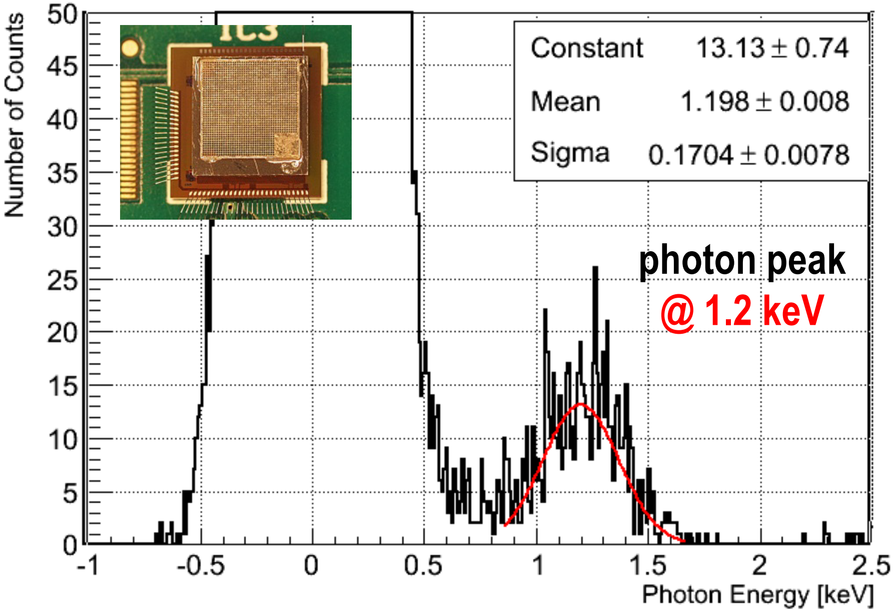
Single pixel spectra.

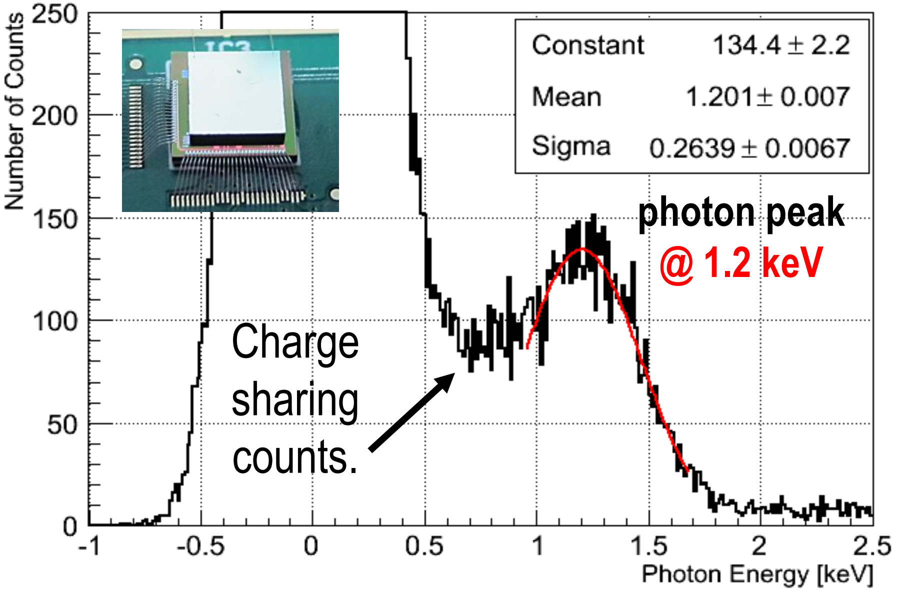


Mask: *"Cut out" Charge Sharing.*

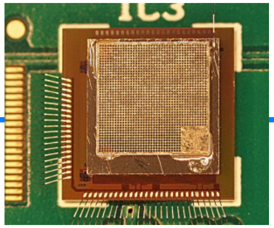
- 150 μm tungsten foil.
- 30 μm laser-drilled "holes".
- 75 μm pitch.
- Holes aligned with pixels.

(curtesy of Julia Smith, PSI)



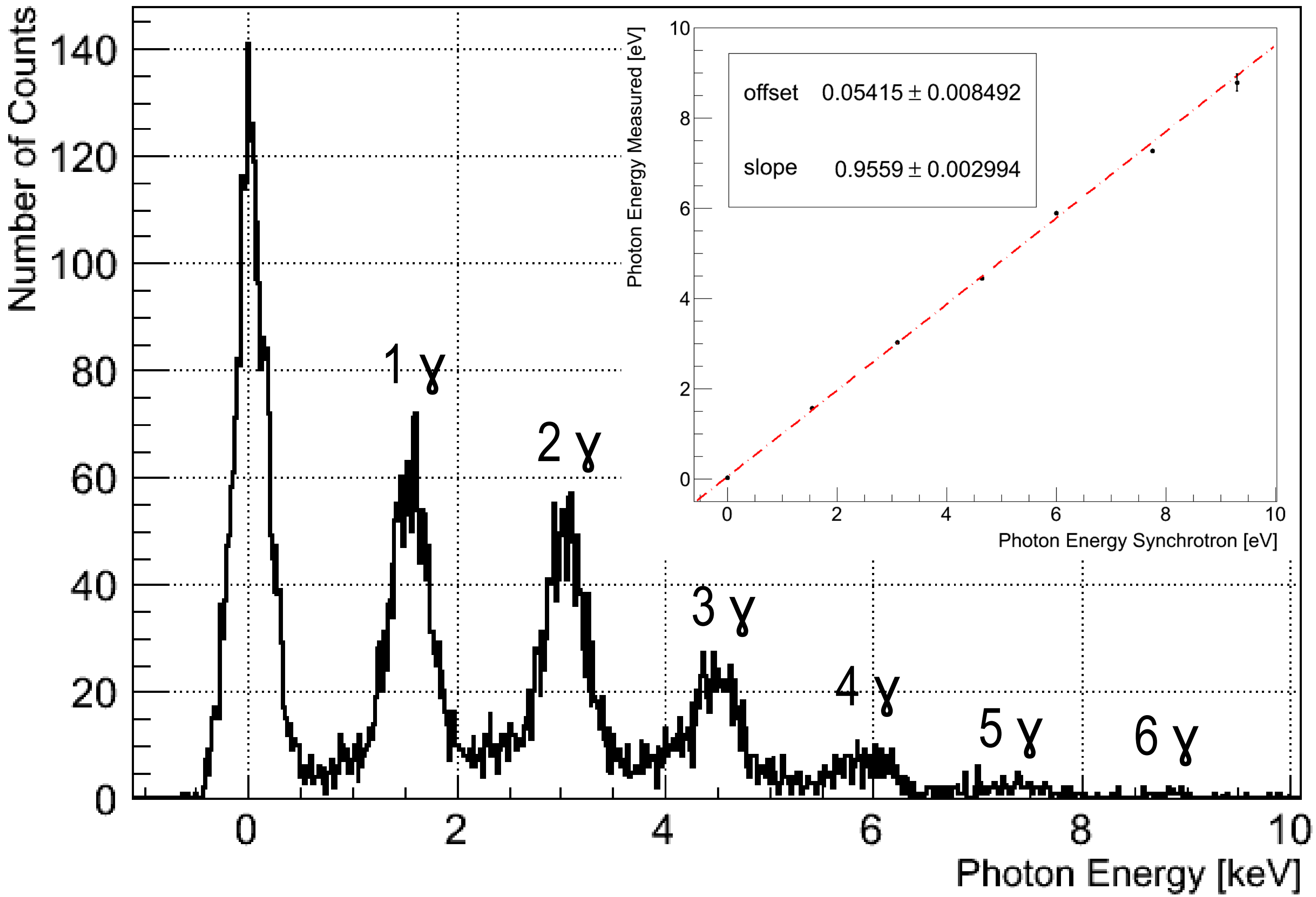


JUNGFRAU 0.4: “Low Energy” Measurements



PHOENIX Beamline: 1.55 keV Photons

Single pixel spectrum, acquisition time 5 µs.



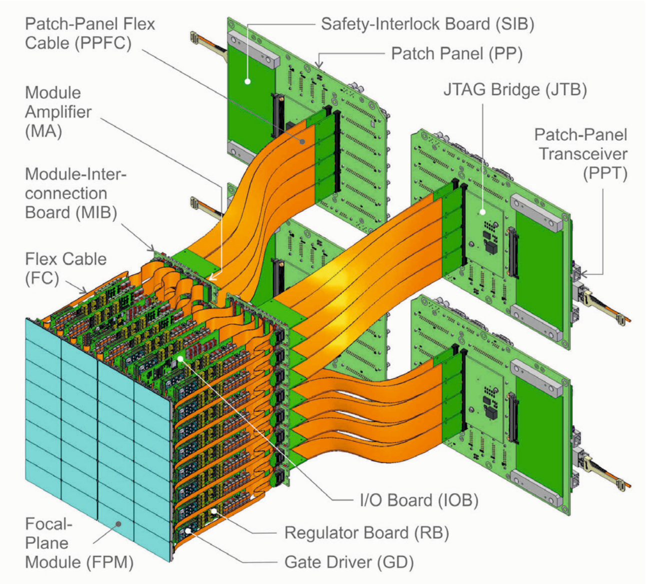
(curtesy of Julia Smith, PSI)

DSSC – System Parameters

Parameter	
Energy range	optimized for 0.5 … 6 keV
Number of pixels	1024 x 1024
Sensor Pixel Shape	Hexagonal
Sensor Pixel pitch	~ 204 x 236 µm^2
Dynamic range / pixel / pulse	~5000 ph @ 0.5 keV > 10000 ph @ E≥1 keV
Resolution	Single photon detection also @ 0.25 keV
Frame rate	0.9-4.5 MHz
Stored frames per Macro bunch	800
Operating temperature	-20˚C optimum, RT possible

1 Mpixel camera with:

- Single photon sensitivity event at 0.25 keV
- high-dynamic range (>10000 ph/pixel)
- Frame rate up to 4.5 MHz (1 image every 220 ns)

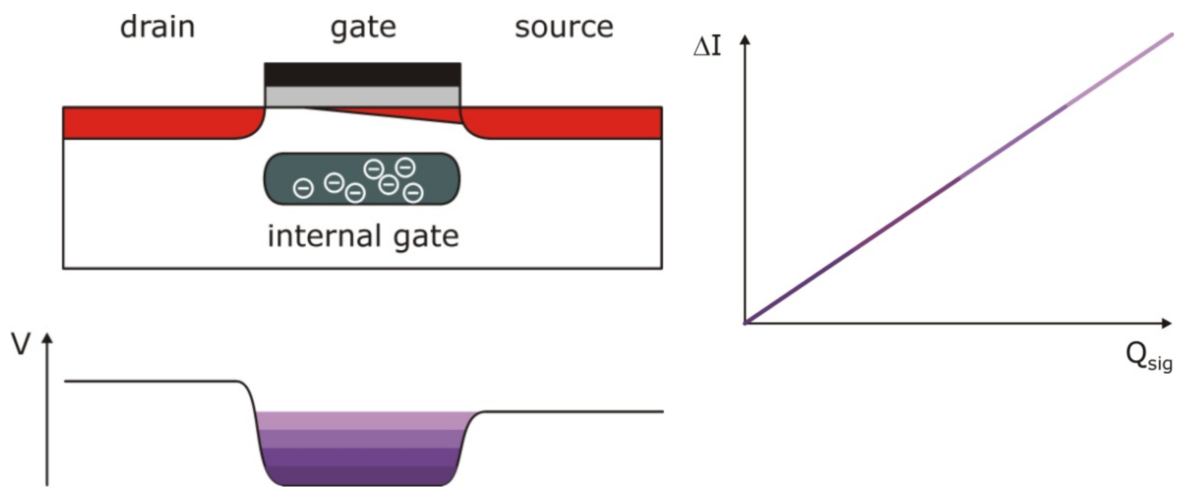


DSSC DEPFET Principle

J. Kemmer and G. Lutz, "New semiconductor concept," *NIM. A, 1987*

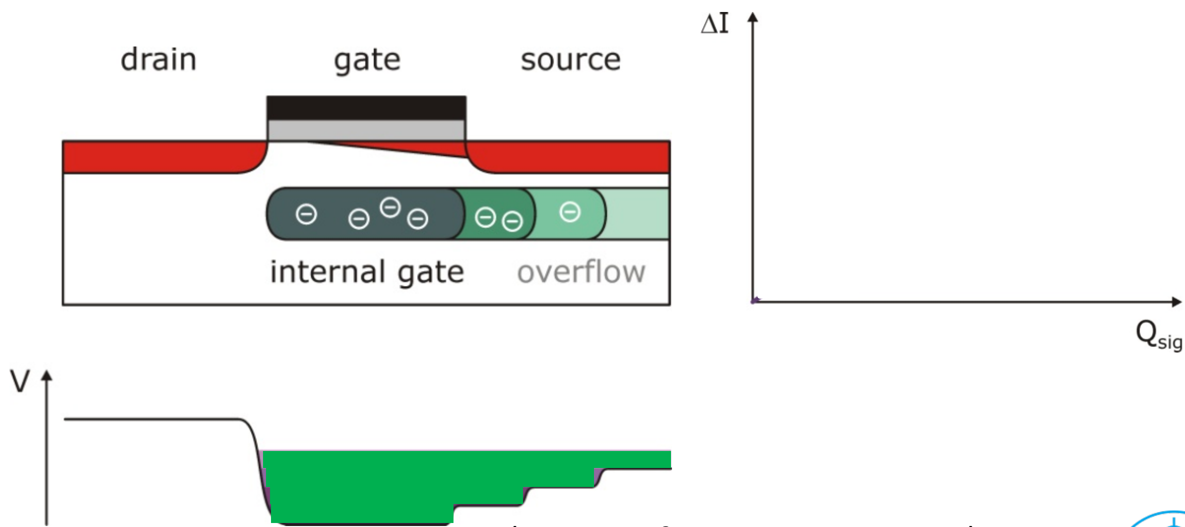
Standard DEPFET principle

- p-FET on depleted n-bulk
  - ↳ All signal charge collected in potential minimum below FET channel **"internal gate"**
  - ↳ all signal charges cause an equal effect on the FET current
  - ↳ **linear $\Delta I/Q_{sig}$ characteristics**
- reset via ClearFET
- low capacitance & noise



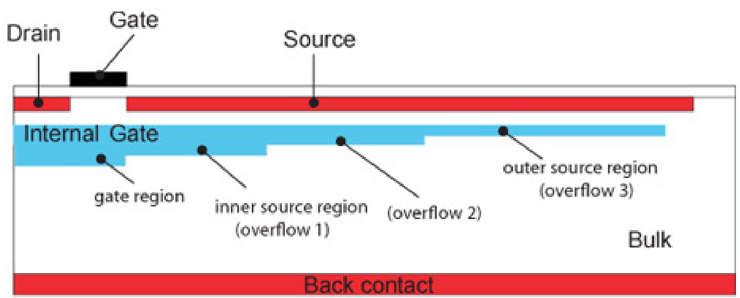
DSSC adaptation

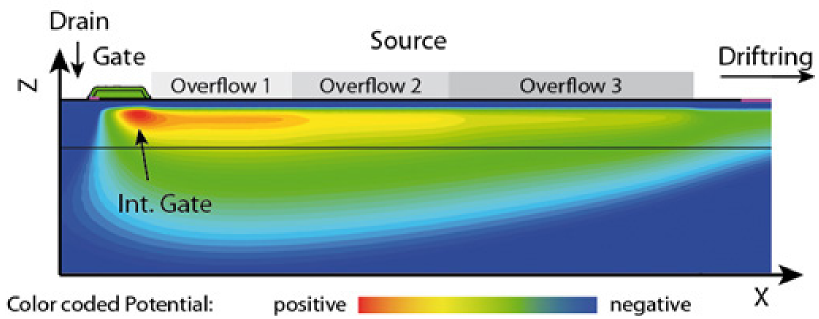
- ↳ signal charges at high levels also stored under source
- ↳ less/no effect on FET current
- ↳ **non-linear $\Delta I/Q_{sig}$ characteristics**
- ↳ gain curve engineering by dose & geometry of implantations

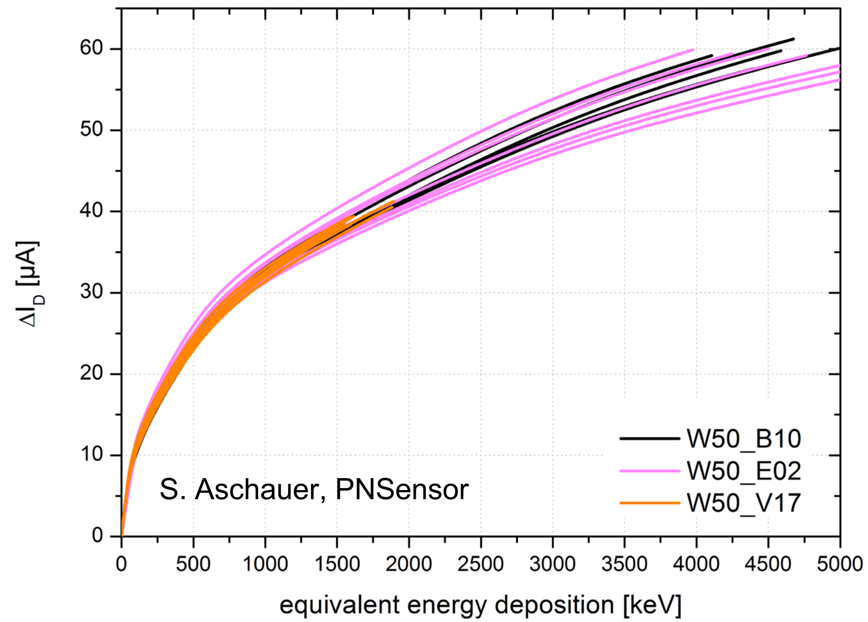


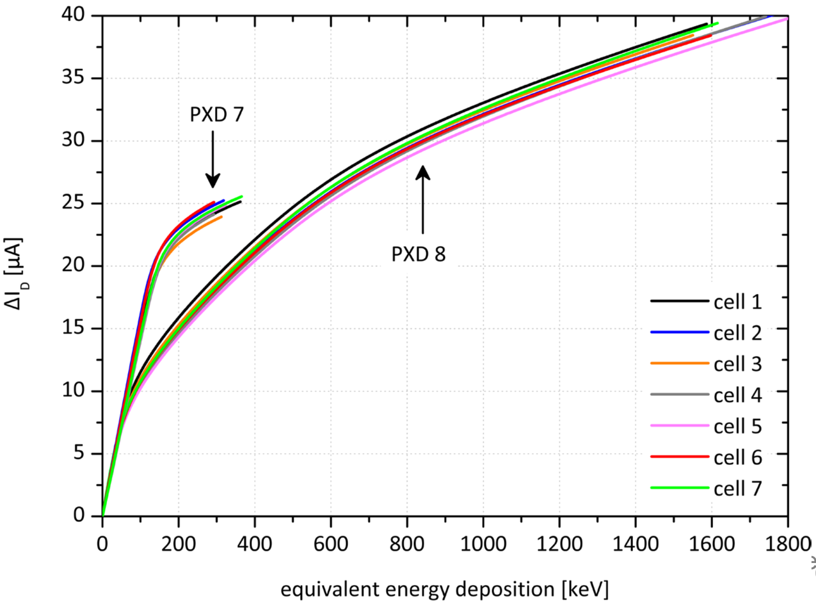
(curtesy of Matteo Porro, MPE)

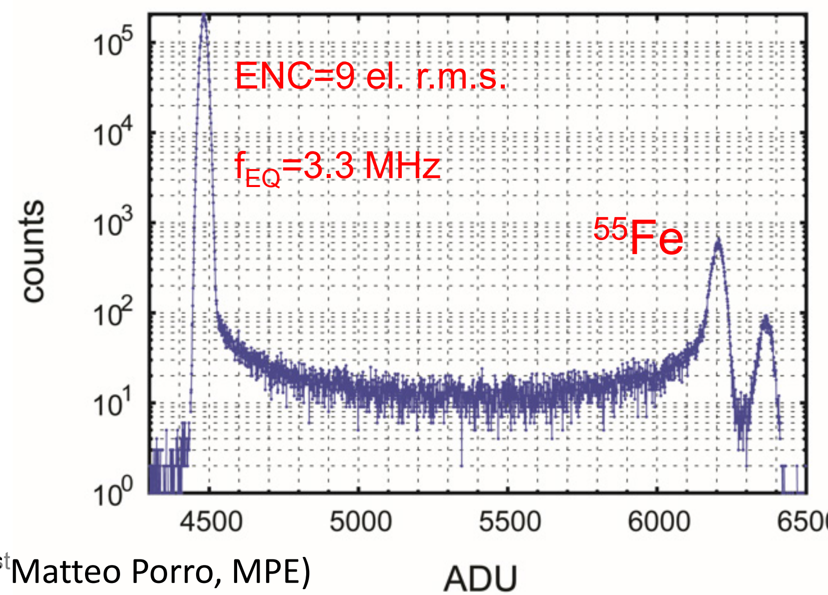
DSSC – DEPFET Sensor Prototype Measurements





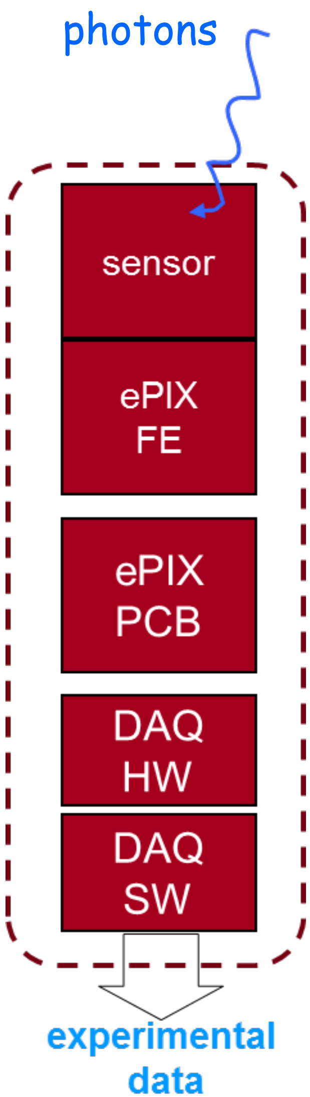






(curtesy of Matteo Porro, MPE)

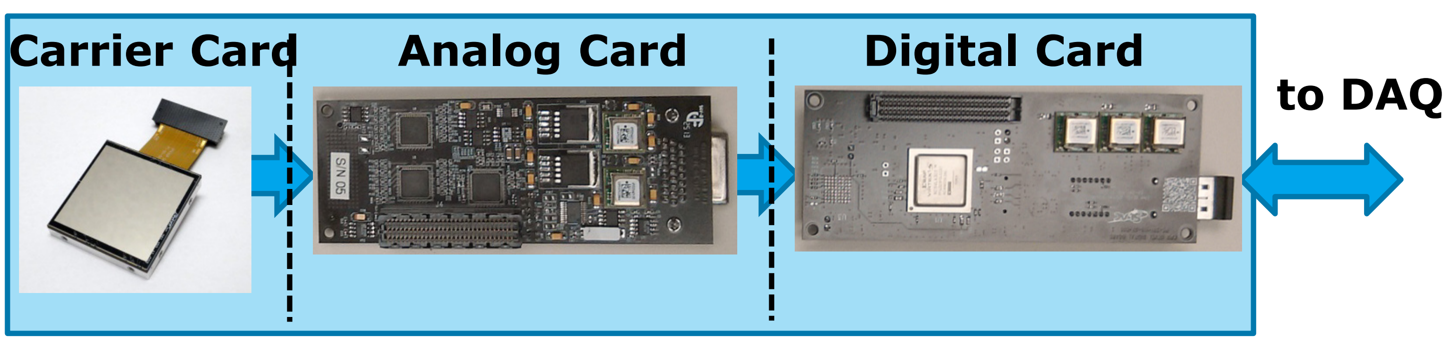
2nd generation for LCLS: ePix100



low noise, high spatial resolution applications:

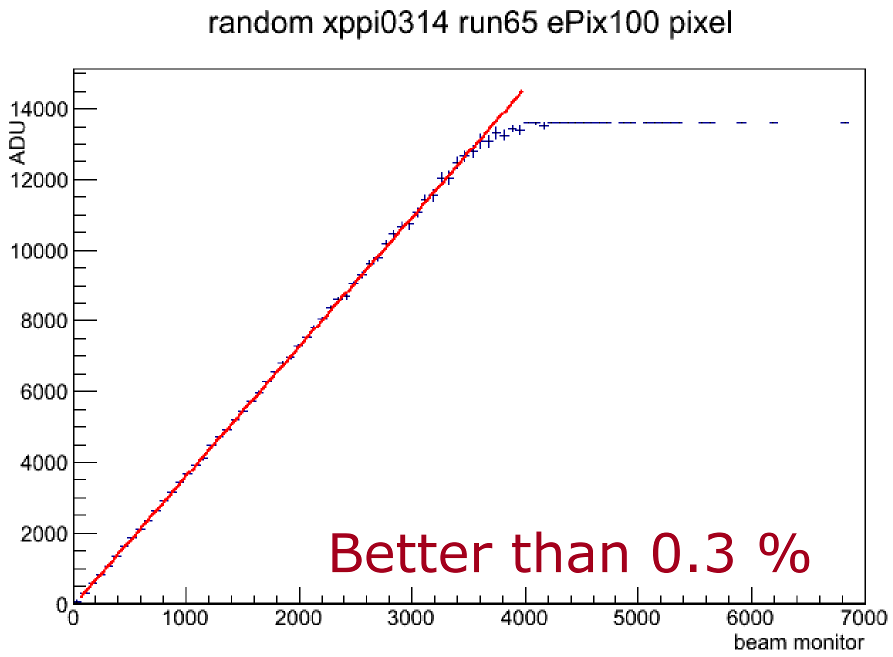
ePix 100	
Pixels per ASIC	384 x 352
Pixel Size (µm)	50
Noise r.m.s. (eV)	250
Maximum signal (8 keV equivalent)	100
Frame rate (Hz)	120, up to 240

Camera Module



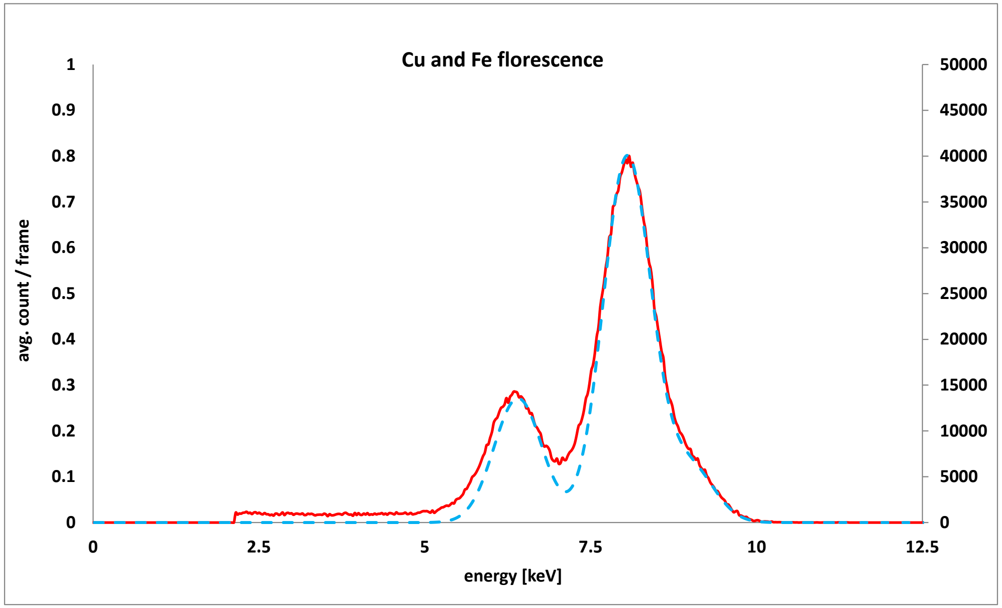
(curtesy of Gabriella Carini & Sven Herrmann, SLAC)

ePix Developments – epix100 performance



Scattering 9.5 keV

Linearity measurements at LCLS at fixed integration time



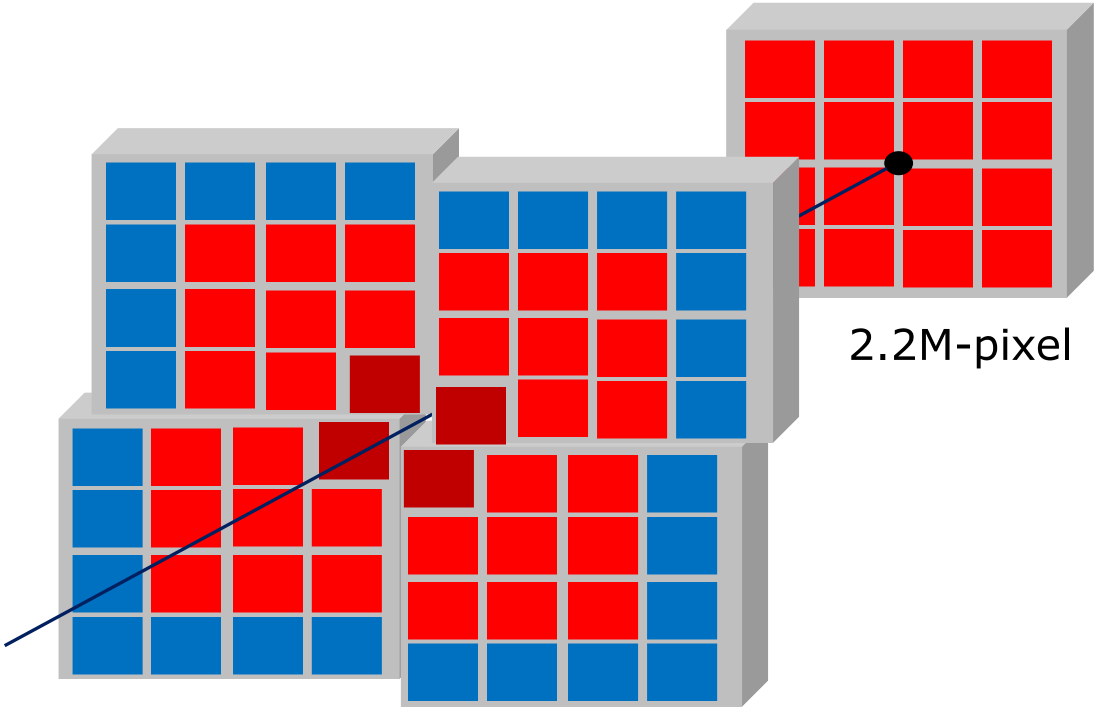
Cu & Fe Fluorescence Spectral Performance

(curtesy of Gabriella Carini & Sven Herrmann, SLAC)

ePix Developments & Possibilities

SLAC

one idea for a future configuration:



4.9M-pixel inner ePIX10k region
20M-pixel total (40cm width)

ePIX10k module: 135k-pixel (currently prototype stage)
ePIX100 module: 540k-pixel

(curtesy of Gabriella Carini & Sven Herrmann, SLAC)

Summary

(an attempt at an incomplete) Overview

	ePix100	Jungfrau	Jungfrau 0.4	DSSC (DEPFET)	Percival
Pixel Size [μm]	50	75	75	204 ⬡	27
System size	>1M	-16M	~16M	1M	up to 4x13M
Energy range [keV]	2-20	~3-20	~1.5-few	0.5-6	0.05 - 0.25-1 - few
Frame rate	120 Hz (240Hz)	>2 kHz	>2 kHz	4.5 MHz burst, ~ kHz contin.	120 Hz
Noise [ENC]	70	56	27	19-26	below 15
peak signal [Me-]	0.3	40	0.02	0.1-10	10
gains	1	3	1	non-lin.	4
Frame Storage	-	16	16	800	-

Note not all numbers are equivalent, e.g. aims & measured side by side

Getting to 1 kHz – 10 kHz frame rates

- **Percival:** max frame rate for the 13M is 120 Hz
  max frame rate for the 2M is 300 Hz
  max frame rate for a 742x1404/... chip) would be 600 Hz
  in ROI mode over ~ 450 rows could be 1 kHz,
  (as-is in ROI mode over ~42 rows could be ~10 kHz)

- **Jungfrau** as-is max frame rate 2 kHz

- **DSSC** max 800 frames every 100 ms => 8 kHz

- **Epix100** max frame rate as-is 240 Hz,
  in ROI mode over ¼ chip (e.g. 190x175 pixels)
  ~ 1kHz could be reached
  developments of faster systems in LCLS-II context coming

Summary

- Detectors for soft X-ray FEL applications face challenges
  - high frame rates, many pixels, dynamic range, …
  - single photon counting requires low noise
  - Thin entrance windows mandatory (more so below 1keV)
- Several options at different stages of development, with very promising results
  - Percival: ambitious development of multi-megapixel monolithic devices, prototypes under study
  - Jungfrau: small low-noise 0.4 prototype with promising results
  - plus other developments ongoing worldwide
- Soft X-ray detectors for FEL science are making great strides

Acknowledgments

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PERCIVAL

- **DESY**

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- **Diamond**

  Julien Marchal, Ulrik Pedersen, Nick Rees, Nicola Tartoni, Hazem Yousef

- **Elettra**

  Giuseppe Cautero, Dario Giuressi, Anastasiya Khromova, Ralf Menk, Giovanni Pinaroli, Luigi Stebel,

- **Pohang Light Source**

  HyoJung Hyun, KyungSook Kim, Seungyu Rah

- **RAL / STFC**

  Dipayan Das, Nicola Guerrini, Ben Marsh, Iain Sedgwick, Renato Turchetta