



Detector Developments at DESY for Free Electron Lasers.

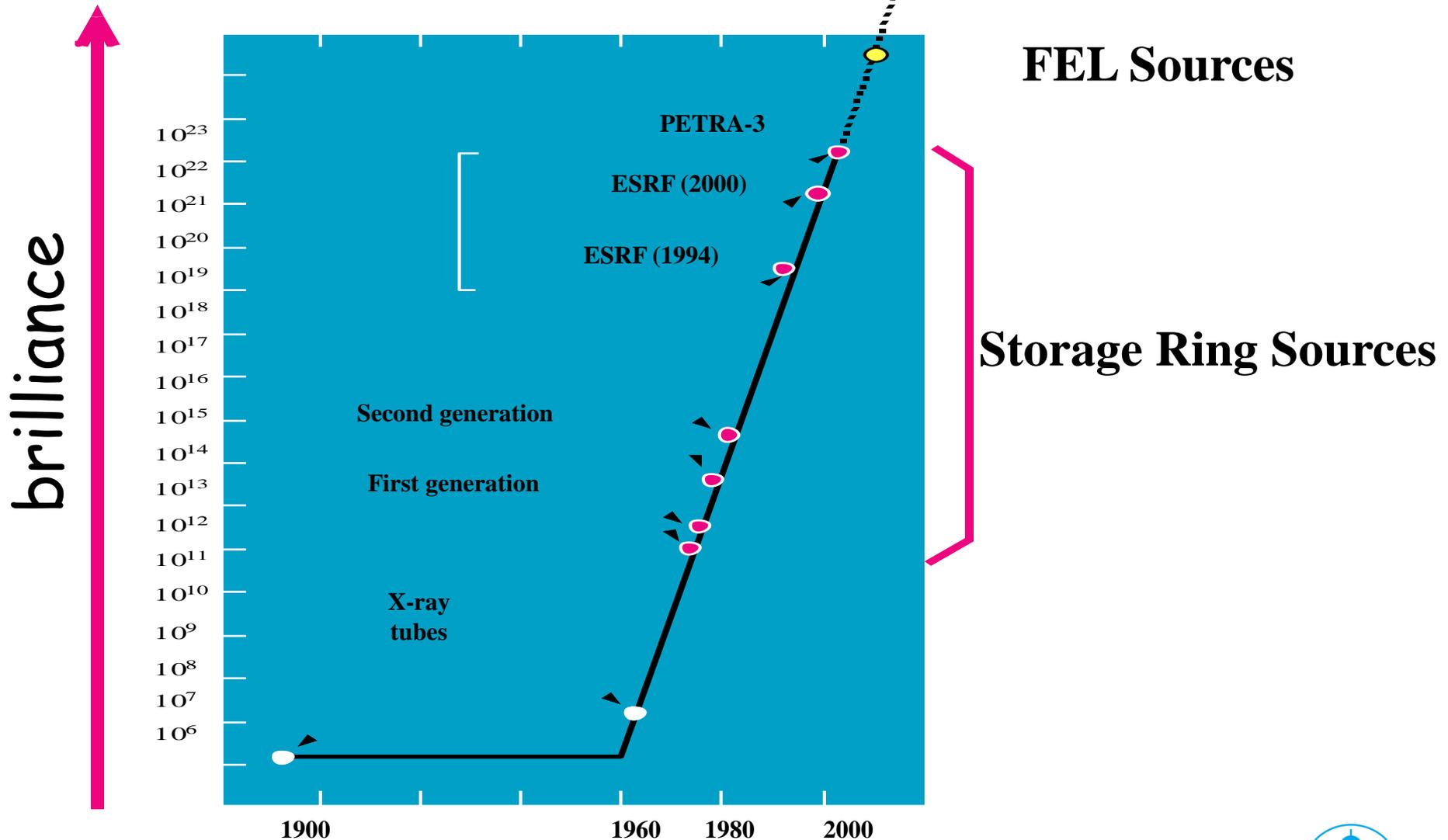
Heinz Graafsma,

*DESY-Hamburg Germany &
University of Mid-Sweden*

- Free-Electron Lasers and the challenges for imaging detectors
- Projects for the European FEL
- Imaging of low energy photons: the PERCIVAL project
- Future directions and needs

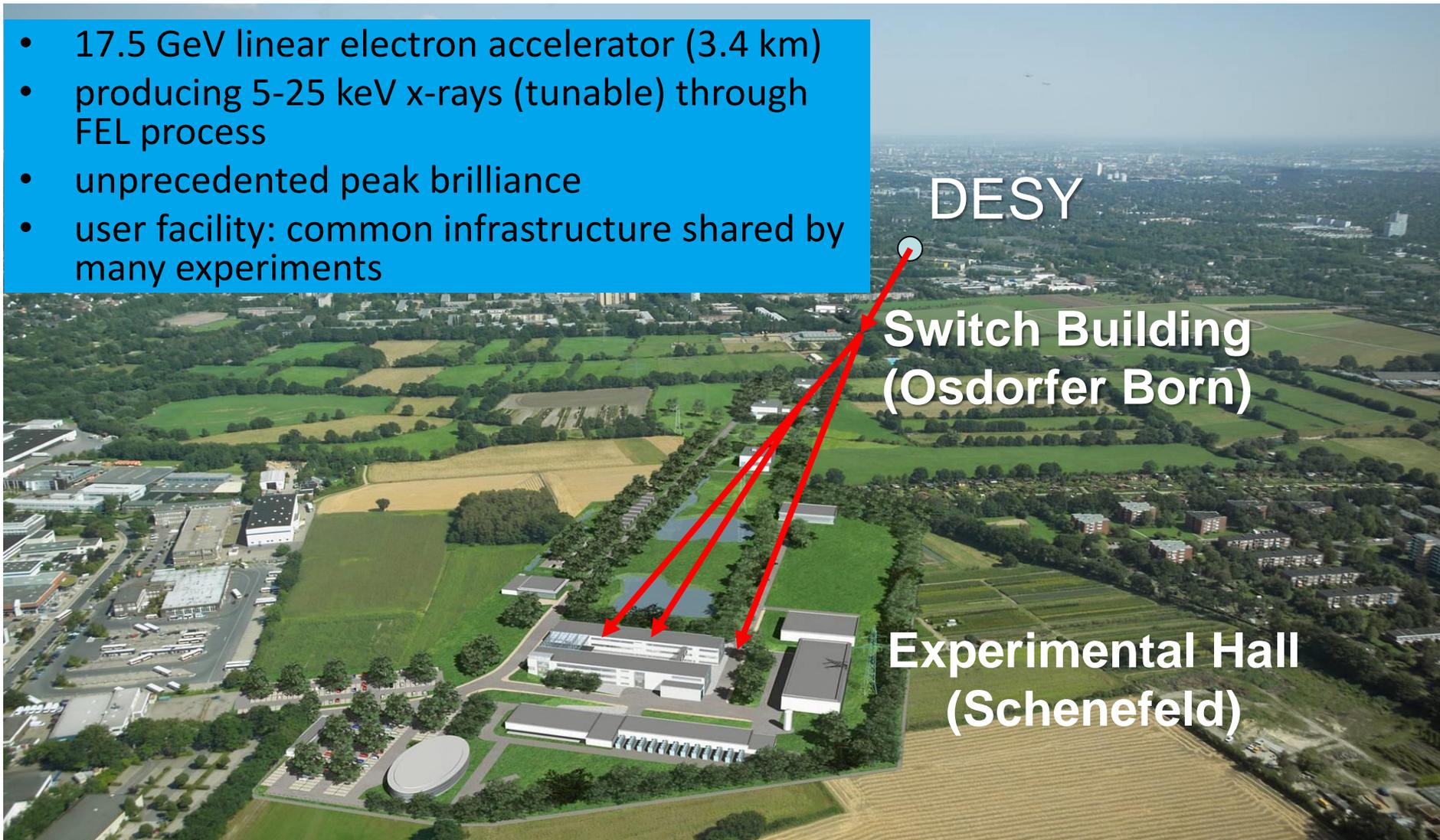


The Detector Challenge for Synchrotron Sources:



The European X-ray Free Electron Laser

- 17.5 GeV linear electron accelerator (3.4 km)
- producing 5-25 keV x-rays (tunable) through FEL process
- unprecedented peak brilliance
- user facility: common infrastructure shared by many experiments



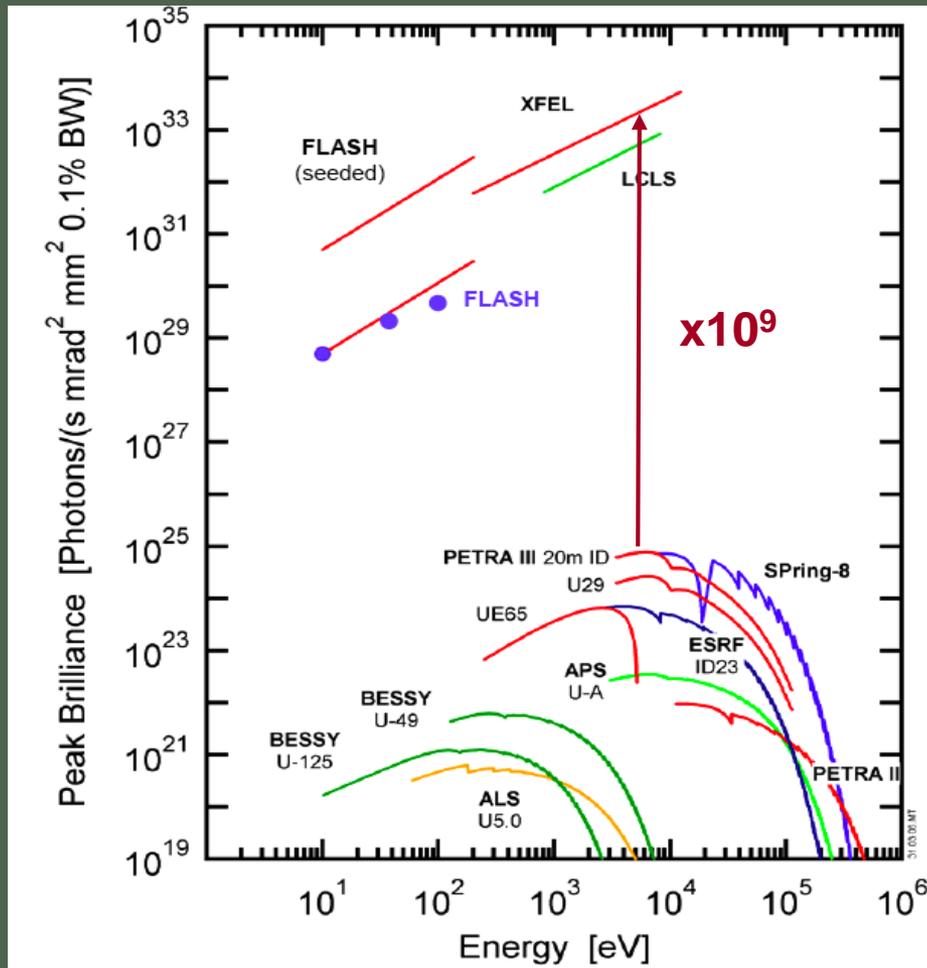
DESY

Switch Building
(Osdorfer Born)

Experimental Hall
(Schenefeld)

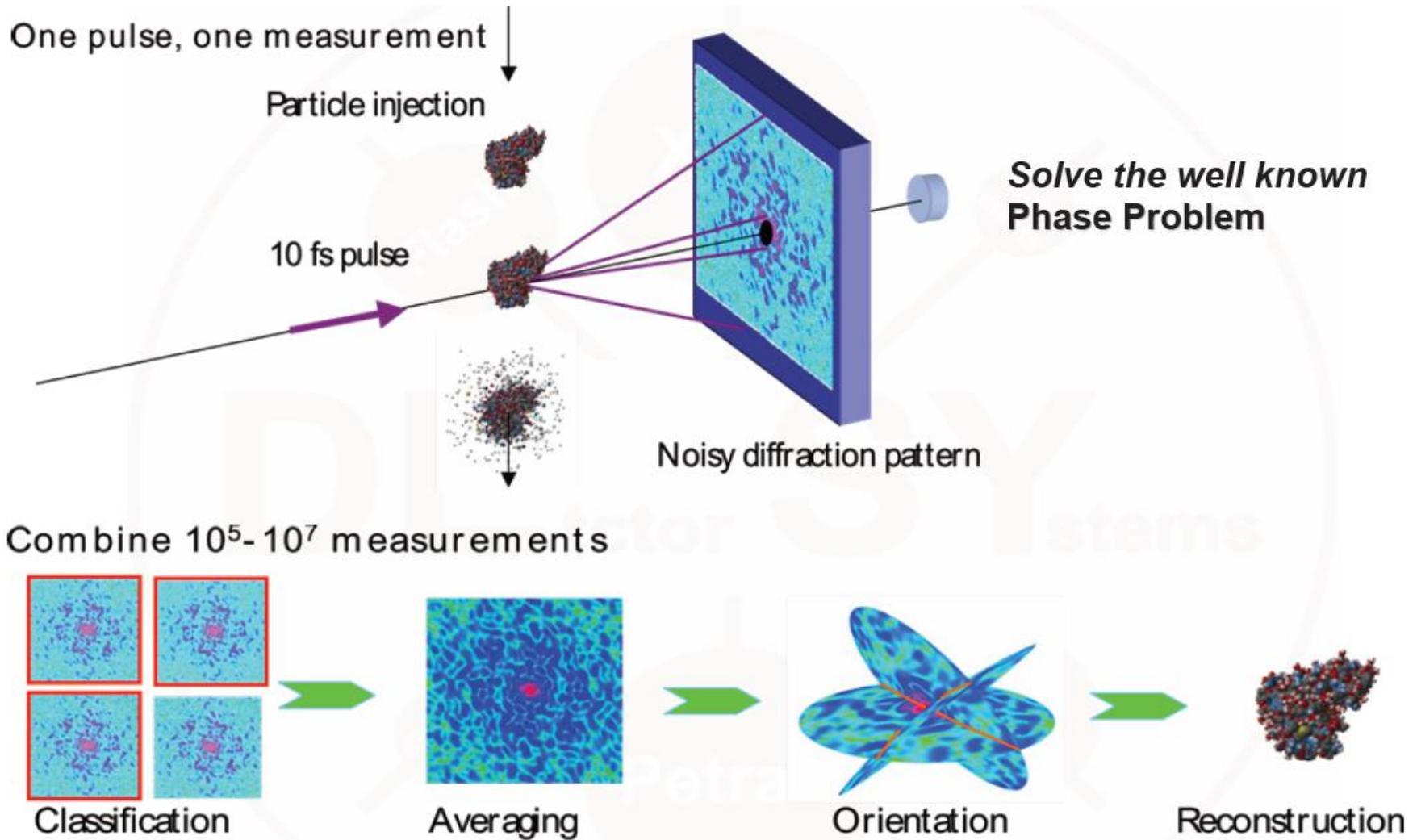


The XFEL-Challenge: Different Science



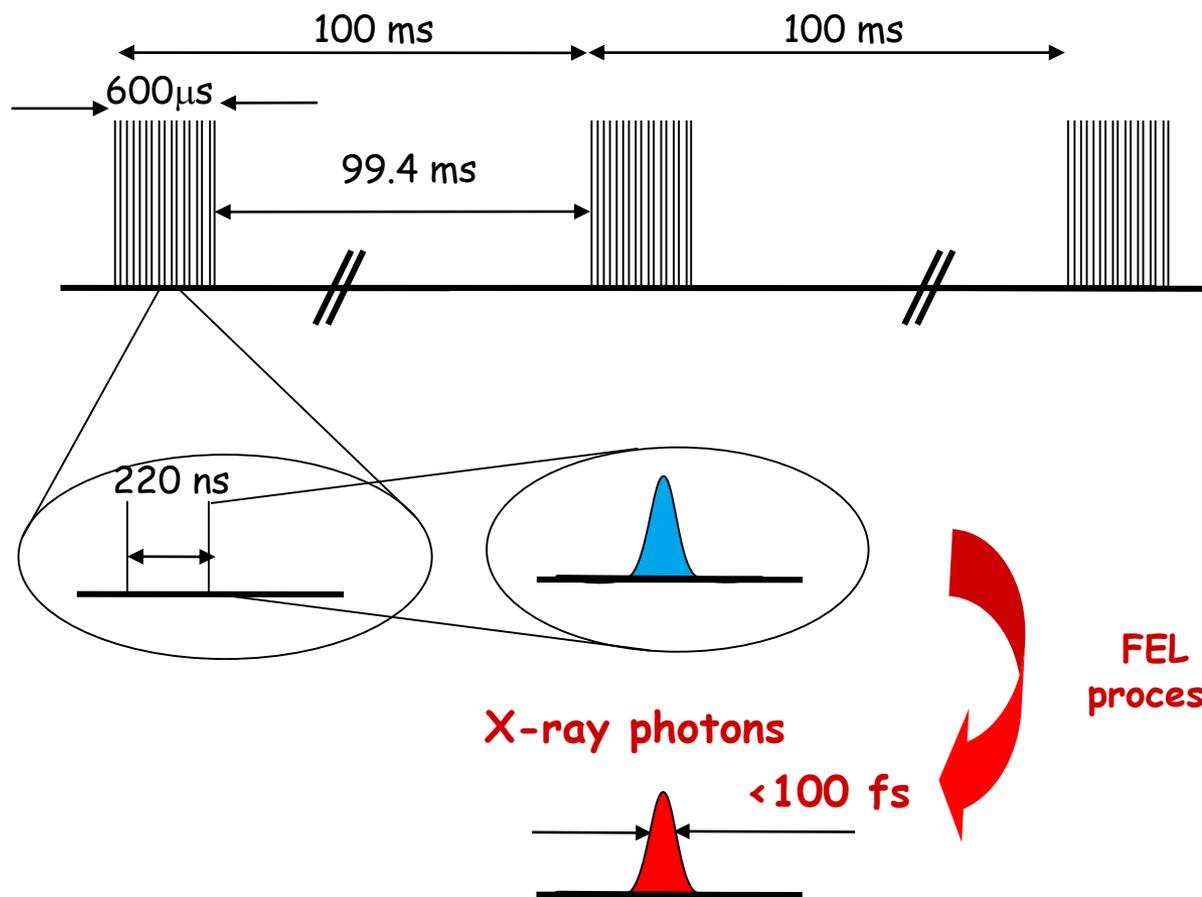
- Completely new science
- Fast science 100 fsec
- “Single shot” science

The Holy Grail ?



European XFEL Linac: Time Structure Challenge

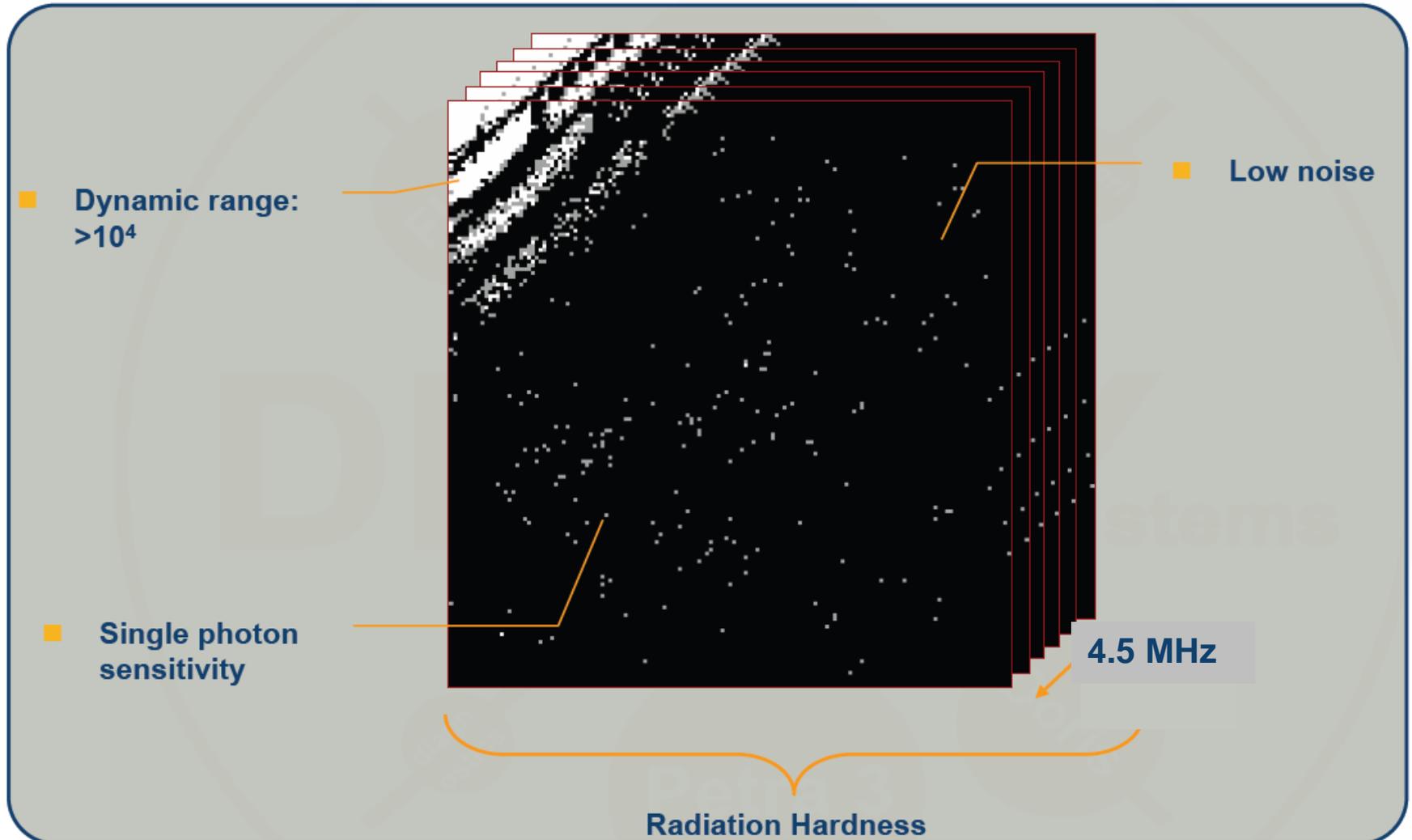
Electron bunch trains; up to 2700 bunches in 600 μsec , repeated 10 times per second.
Producing 100 fsec X-ray pulses (up to 27 000 bunches per second).



27 000 bunches/s
with
4.5 MHz
repetition rate

av. Rate:
27kHz XFEL
120Hz LCLS
60Hz SCSS

What are the Challenges ?



How to meet the challenge ?

Three dedicated Projects:

- **D**emos **S**ensor with **S**ignal **C**ompression
 - Non-linear gain, digital storage
- **A**daptive **G**ain **I**ntegrating **P**ixel **D**etector
 - Automatic adaptive gain, analogue storage
- **L**arge **P**ixel **D**etector
 - Three parallel gains, analogue storage



Hybrid Pixel Array Detectors (HPADs)

Pixel Array Detectors

X-ray Conversion Layer

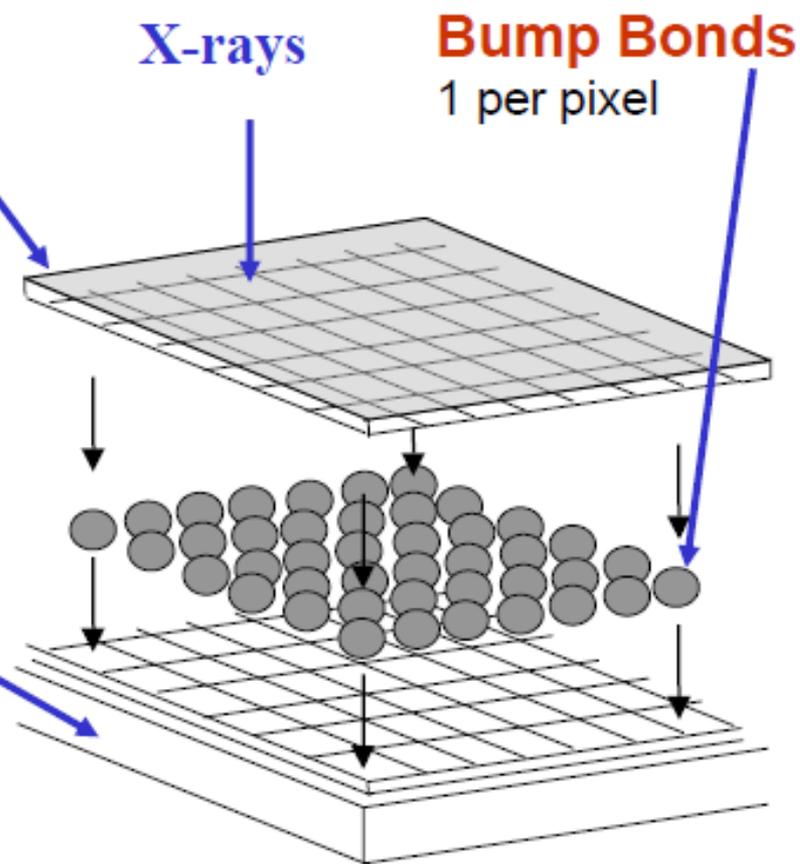
Si Diode - 0.3 - 1 mm thick

- **Large signal/x-ray**
Single photon sensitivity possible
 $2740 \pm 20 e^- / 10\text{keV x-ray}$
- **Excellent PSF**
Charge cloud ~ 15 micron spread
Signal $< 10^{-4}$ in next pixel
- **Prompt signal collection**
 \sim several ns collection

Signal Processing Layer

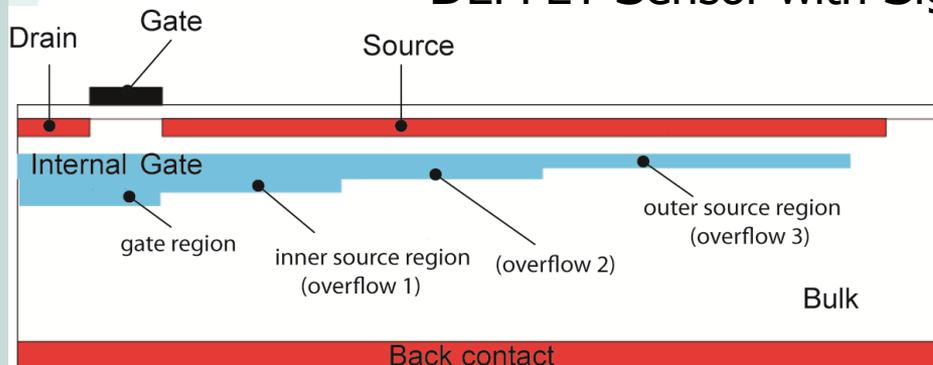
CMOS chip - application specific

- Electronic shuttering
- Photon counting
- High speed imaging
- In-pixel frame storage
- Phase-locked integration

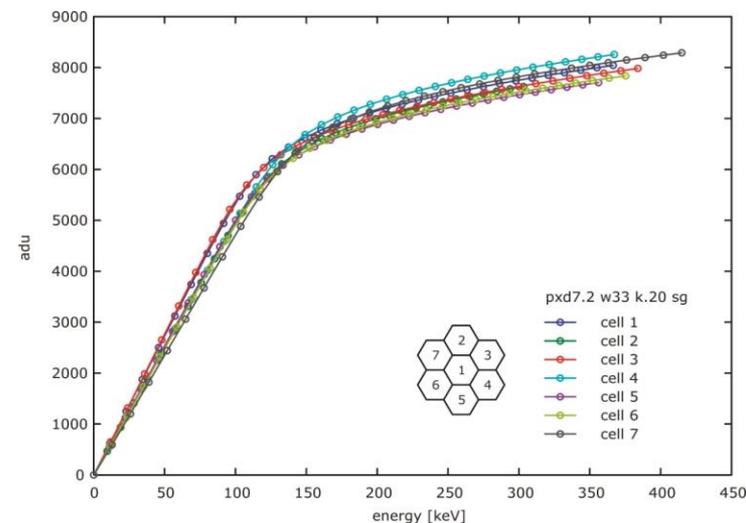
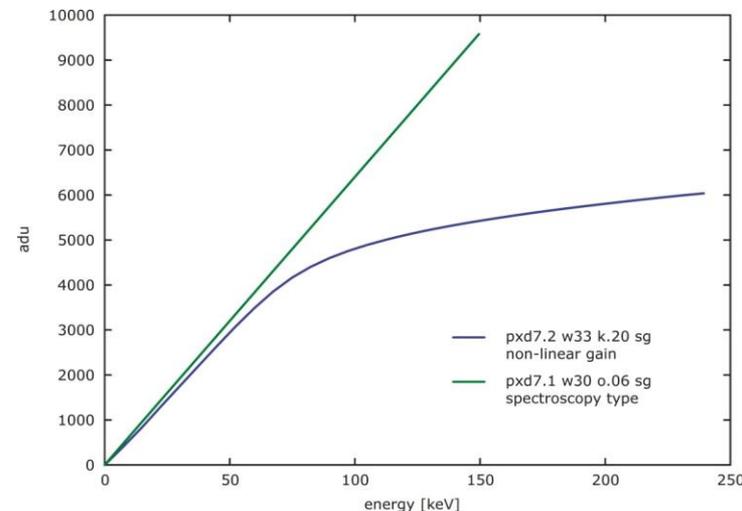
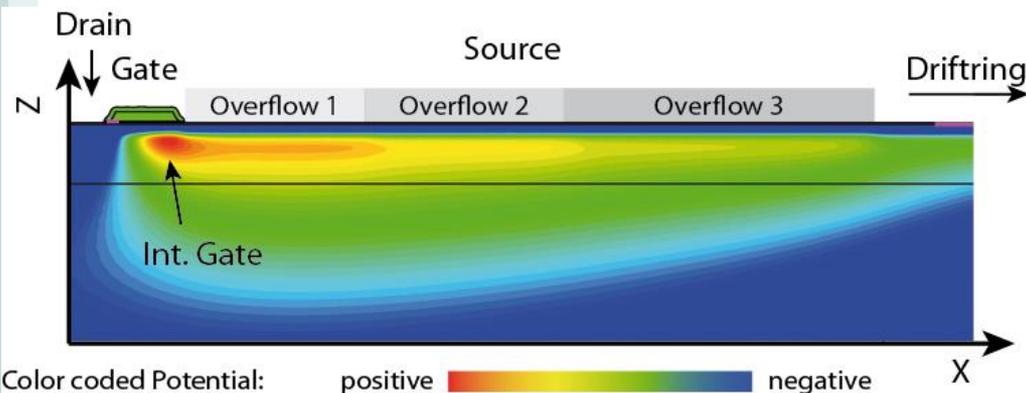


● Non linear DEPFETs

DEPFET Sensor with Signal Compression - DSSC



- The internal gate extends into the region below the source
- Small signals collected directly below the channel
 - ↳ Most effective, large signal
- Large signals spill over into the region below the source
 - ↳ Less effective, smaller signal
- staggered potential inside internal gate by varying impl. doses



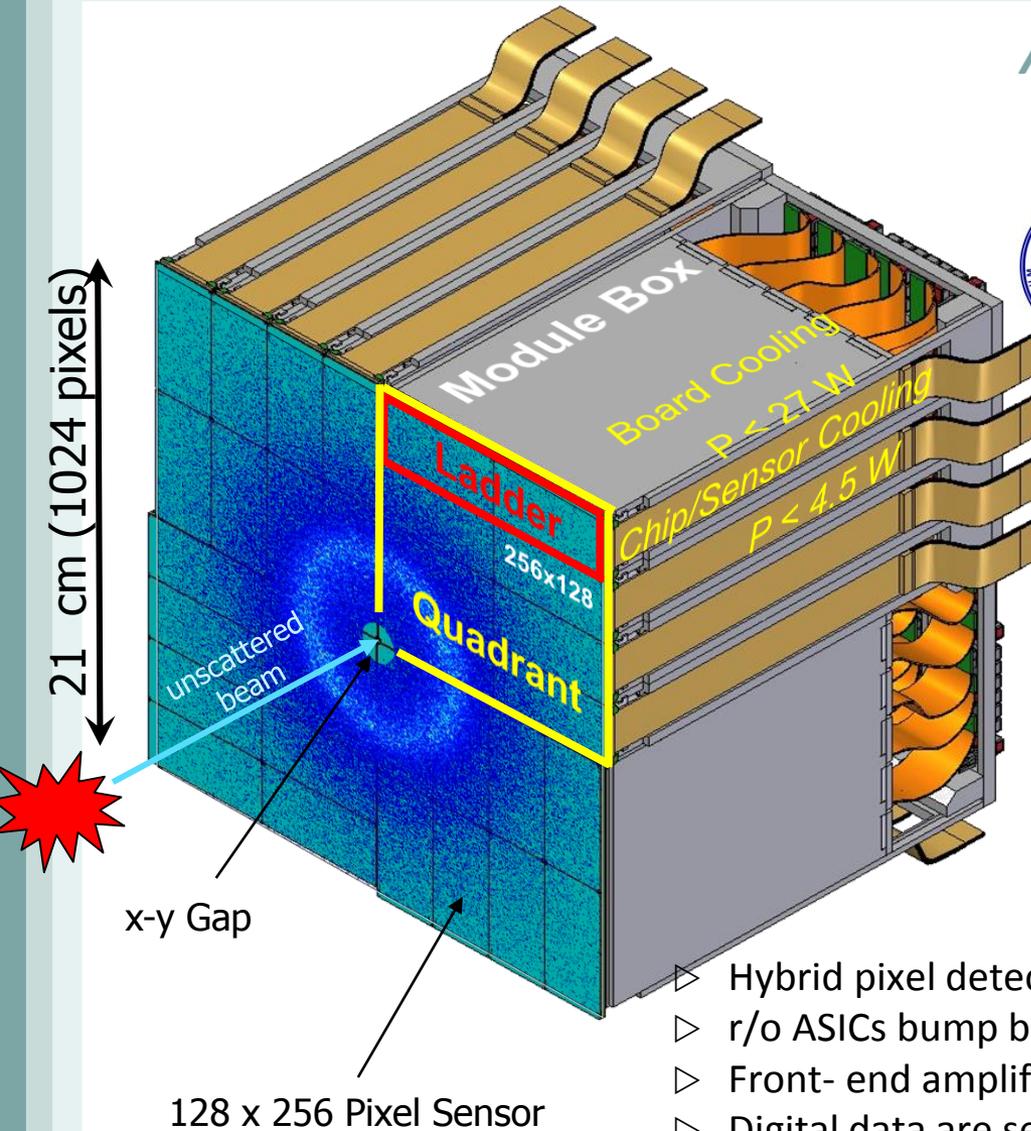
DSSC for XFEL



PNSensor



Universität
Gesamthochschule
Siegen



focal plane

- ▷ Sensitive area 21x21 cm²
- ▷ 4 quadrants
- ▷ dead area: 14.5 %
- ▷ central hole for beam dump

- ▷ Hybrid pixel detector with DEPFET active pixels
- ▷ r/o ASICs bump bonded, one bump per pixel
- ▷ Front- end amplifier, ADC, and SRAM per pixel
- ▷ Digital data are sent off the focal plane during the train gap (~100ms)
- ▷ Power cycling: sensors and analog f/e in stand-by during train gap

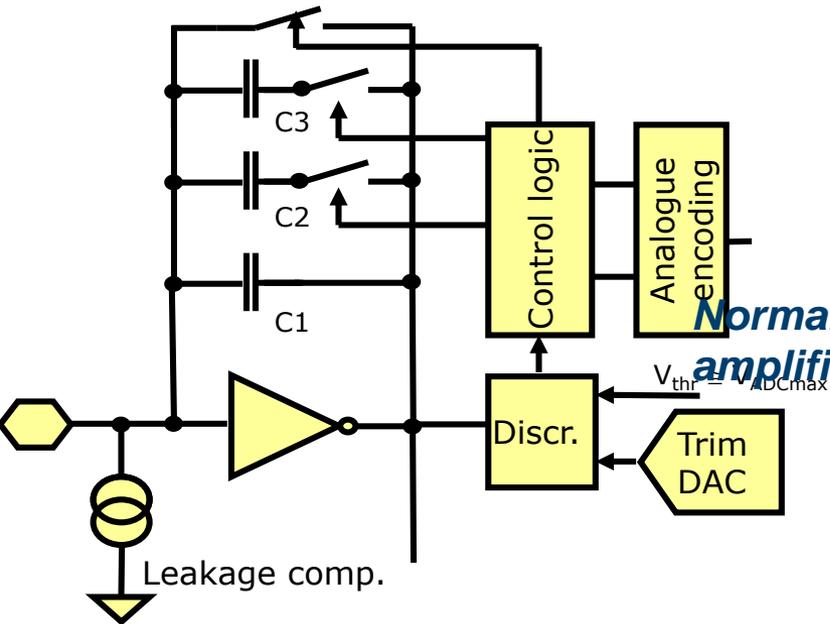
The Adaptive Gain Integrating Pixel Detector (AGIPD)



Adaptive Gain principle

High dynamic range:

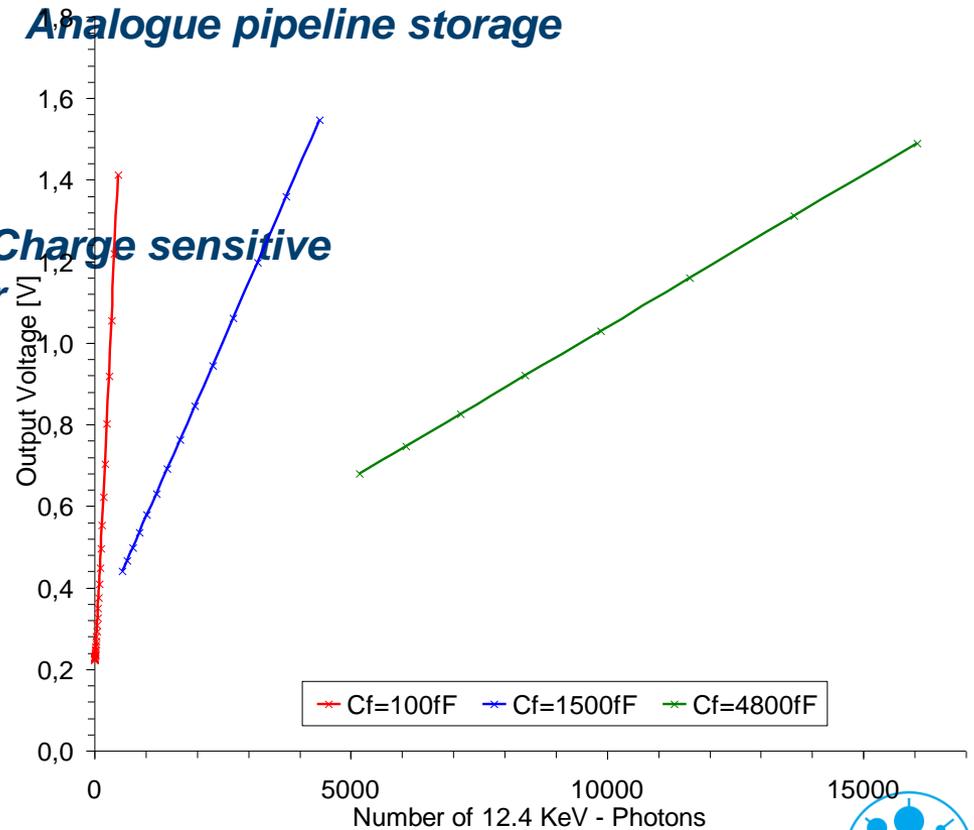
Dynamically gain switching system



Extremely fast readout (200ns):

Analogue pipeline storage

Normal Charge sensitive amplifier



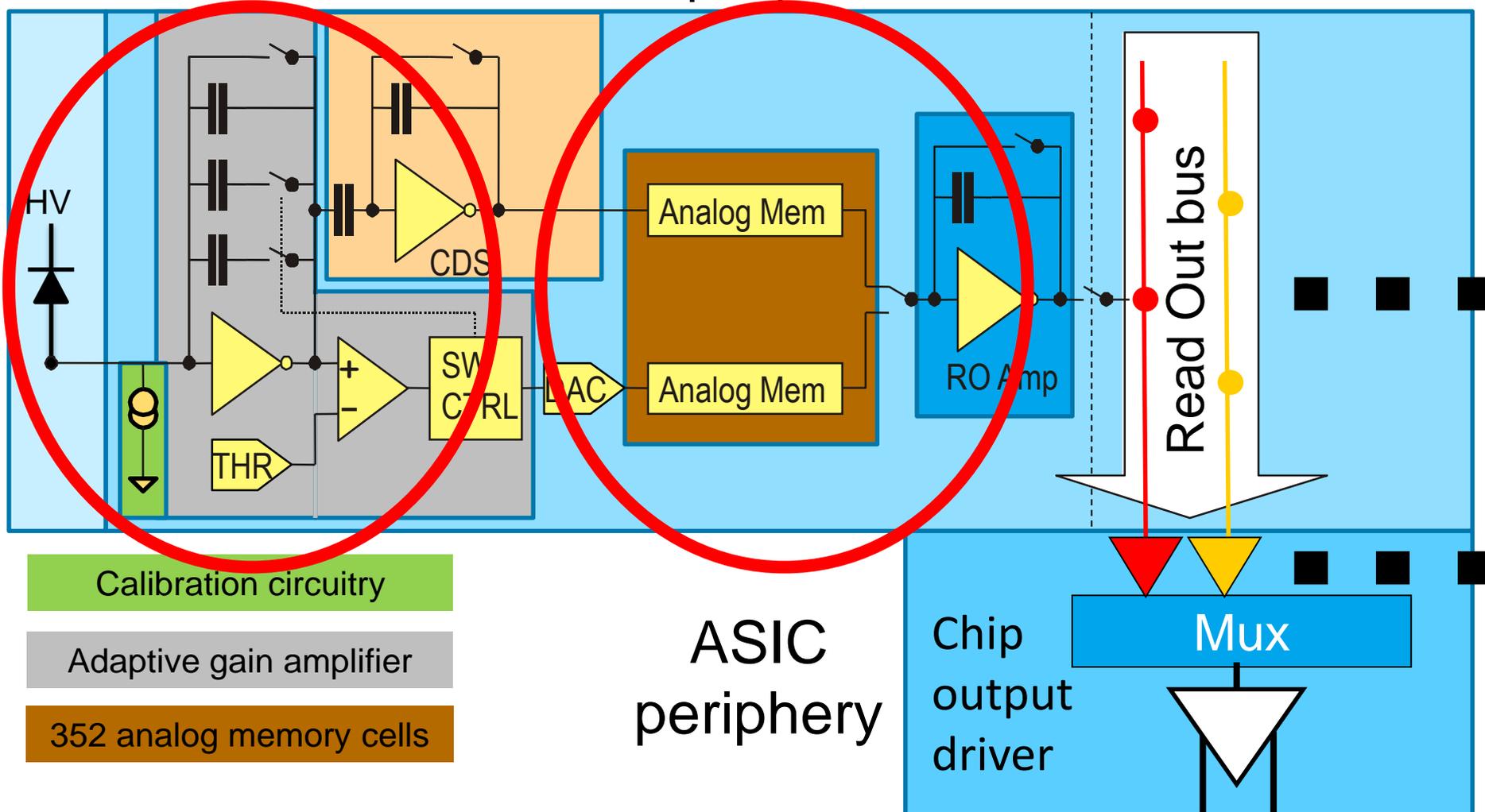
The AGIPD Read Out-Principle



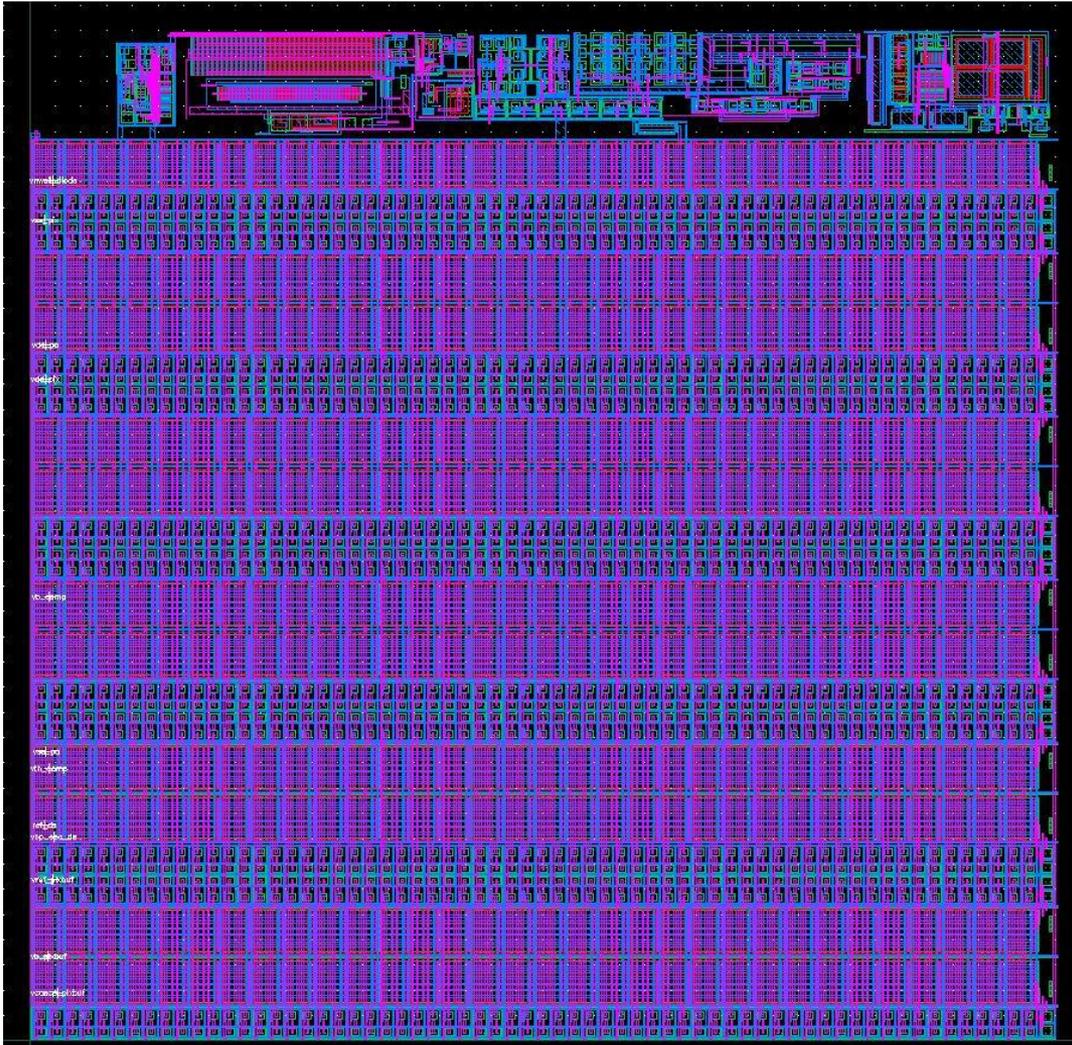
Sensor

Electronics per pixel

Pixel matrix



AGIPD 1.0 Pixel Electronics



- 200 x 200 micron² pixels
- 352 storage cells + veto possibilities.
- Minimum signal $\sim 300 e^- = 0.1$ photon of 12.4keV
- Maximum signal $\sim 33 \cdot 10^6 e^- = 10^4$ photons of 12.4keV
- 4.5 MHz frame rate
- 64 x 64 pixels per ASIC
- 2 x 8 ASICs per module (128x512 pixels, no dead area)
- 4 modules per quadrant



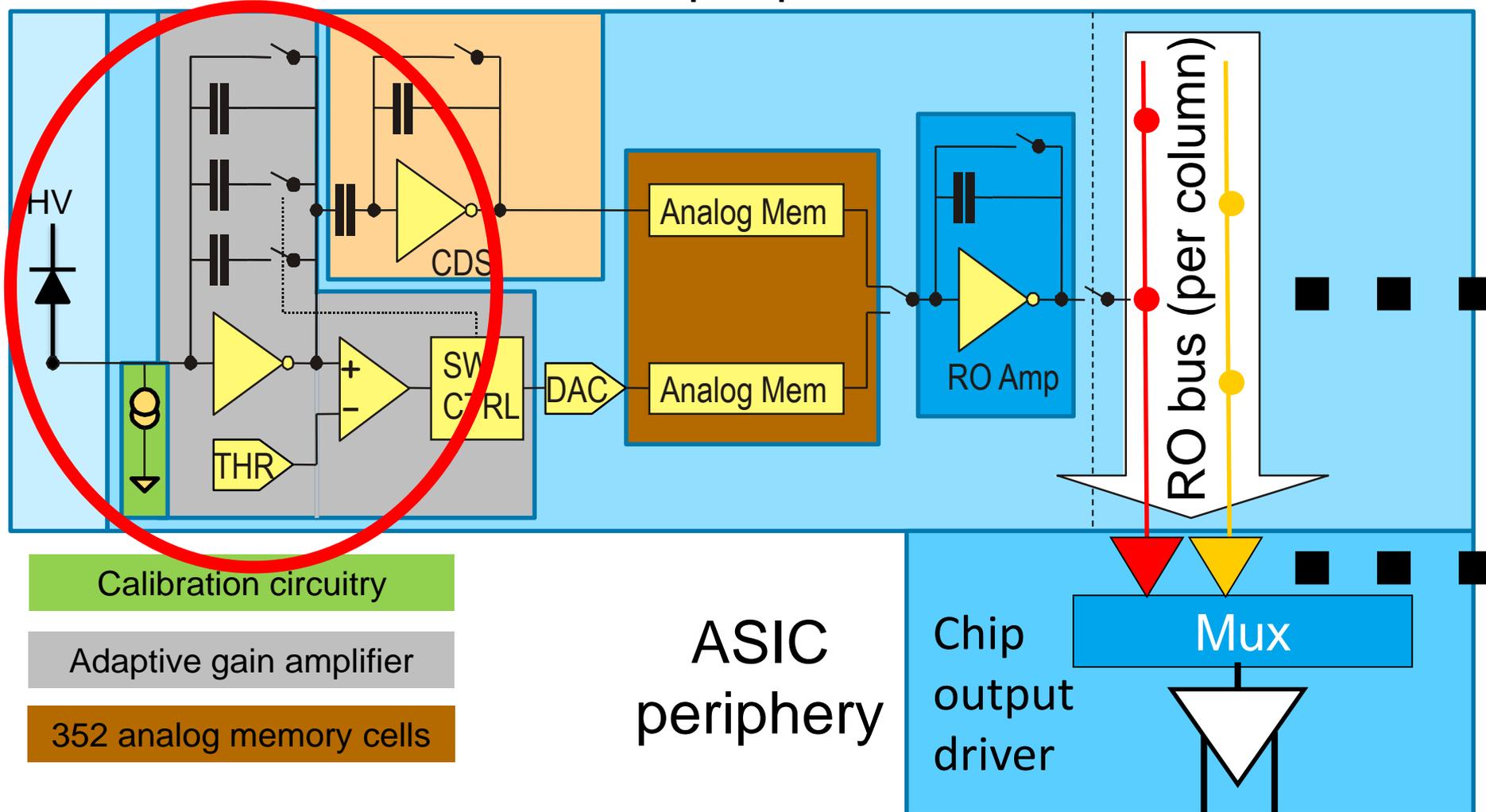
The AGIPD RO-Principle



Sensor

Electronics per pixel

Pixel matrix

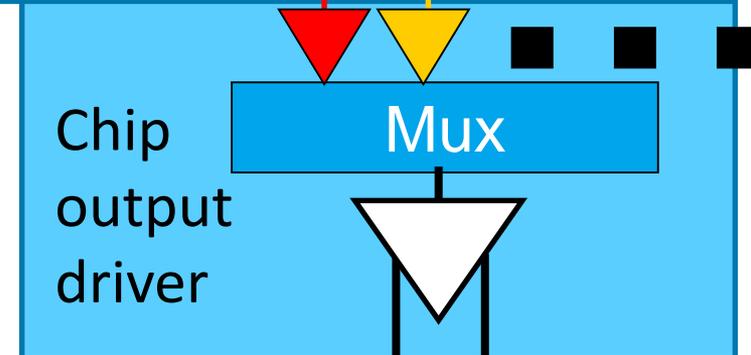


Calibration circuitry

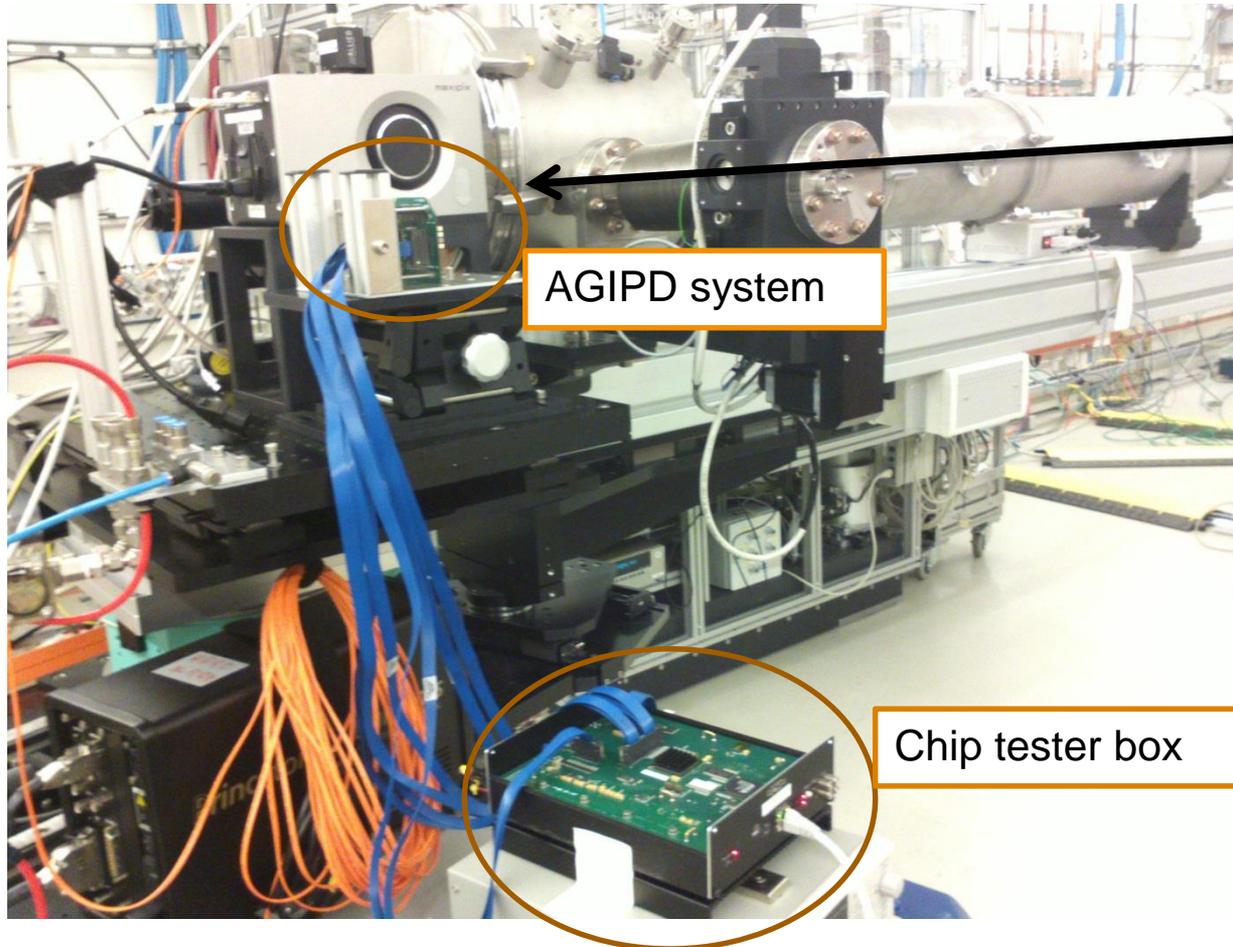
Adaptive gain amplifier

352 analog memory cells

ASIC periphery



At the P10 beamline



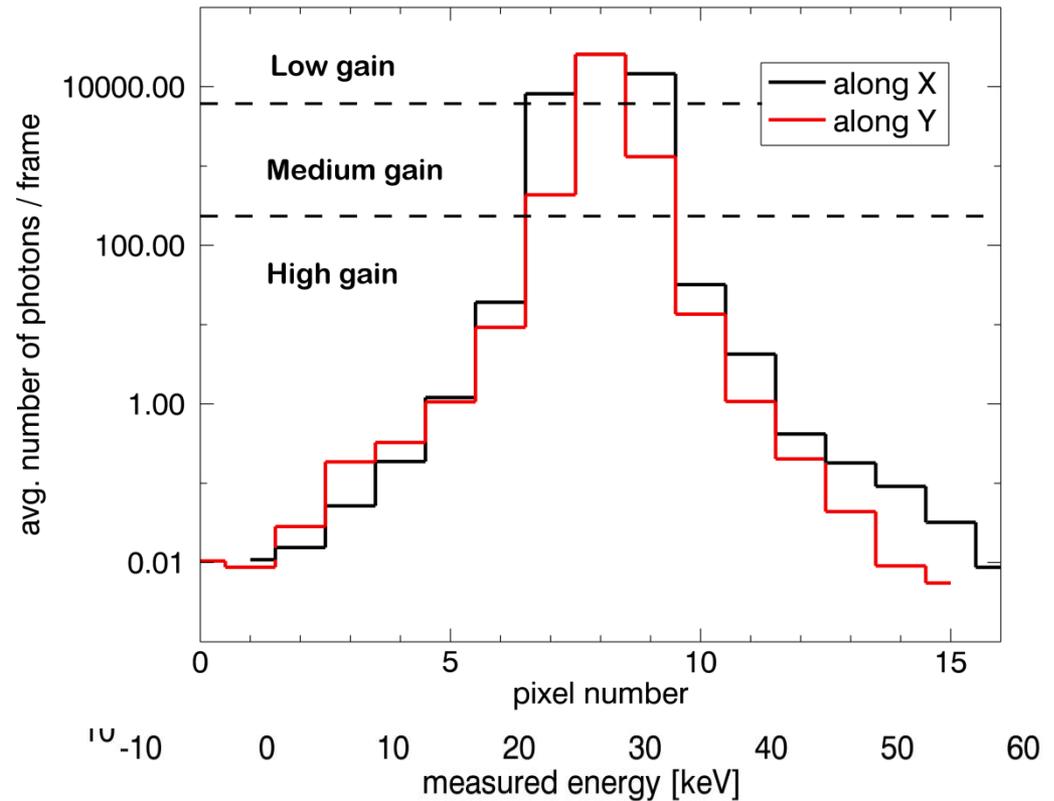
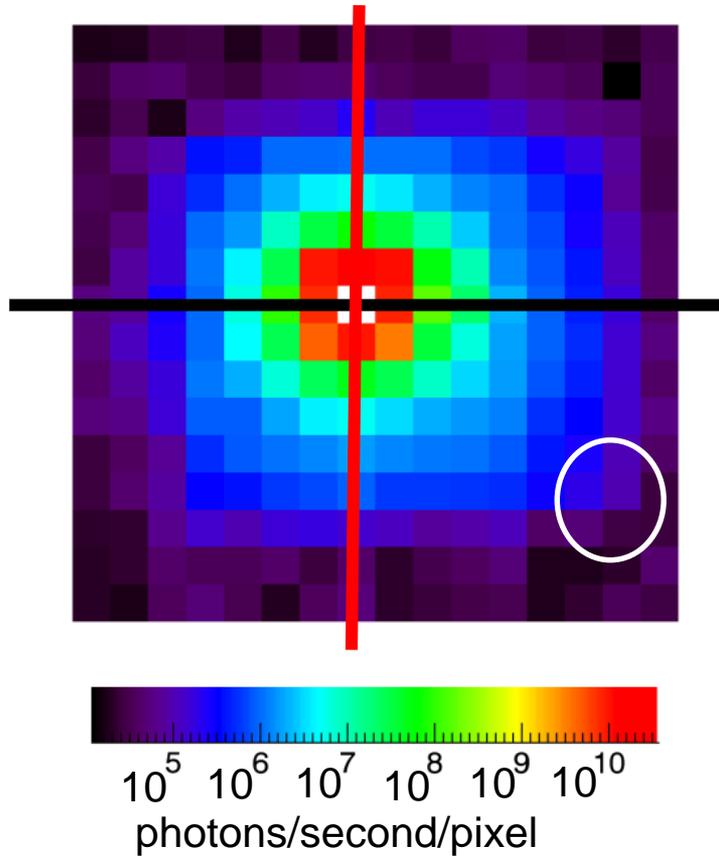
Beam direction (coming from sample)

It took about 1 ½ hours to set up, after about 2 hours we saw the first image

Not in the picture: Sample, Alexanders PC, people, ...



Looking at the direct beam

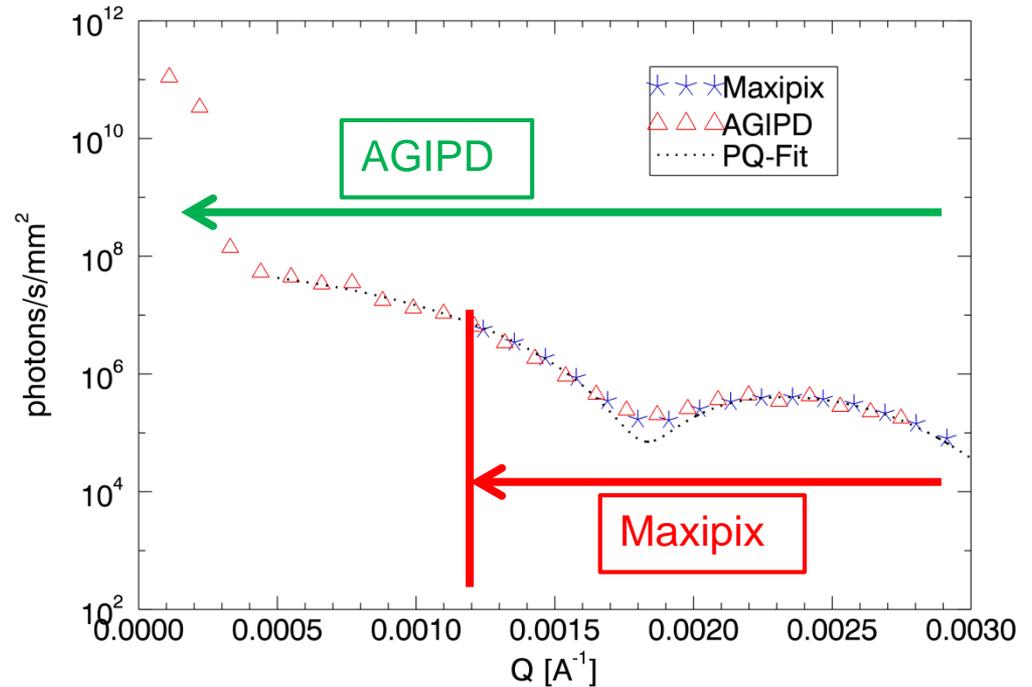
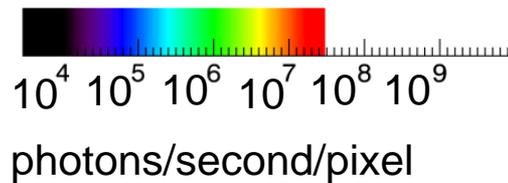
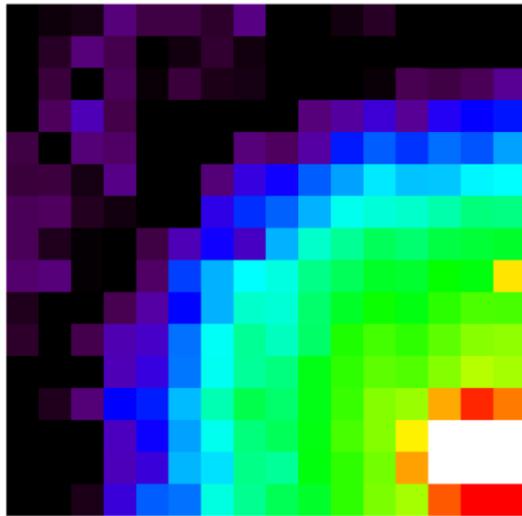


Gain switching experimentally proven

- 10^4 photons / pulse
- Single photon sensitivity
- 4.5 MHz frame rate



Some SAXS measurements

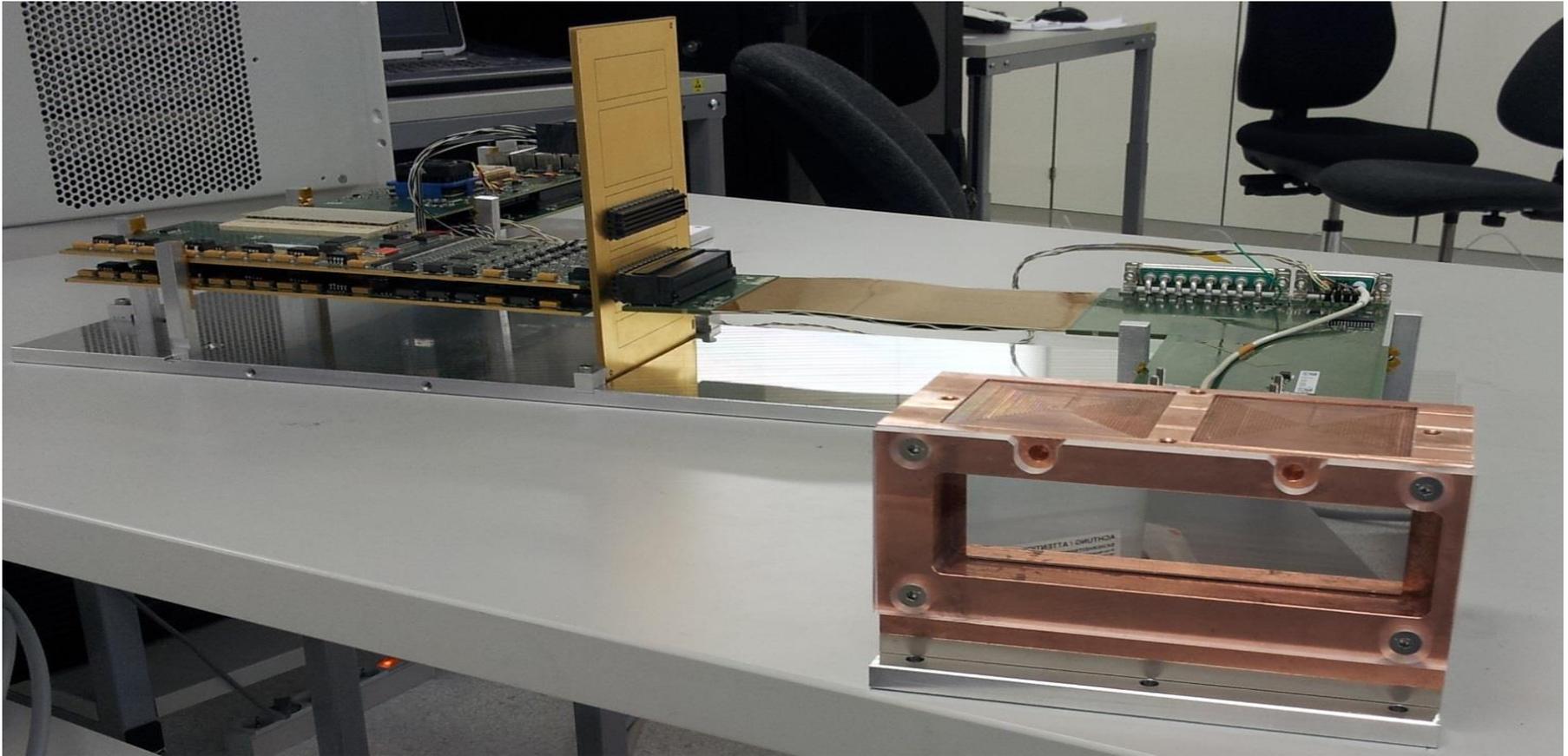


Scientific quality data obtained

- Complete system proven to work
- Calibration proven to be adequate

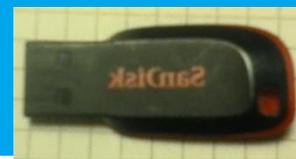


A single module

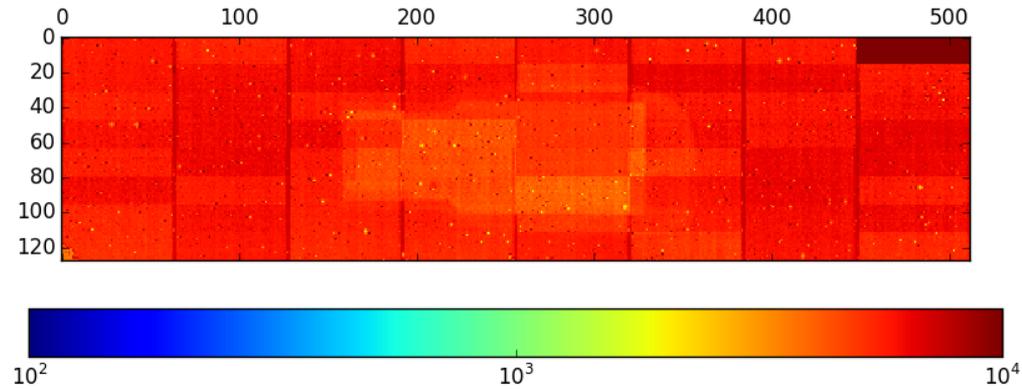


128 x 512 pixels

X-Ray Image of a pen drive



Mean of 30000 frames
50 μ s integration time per frame



Experiments: AGIPD module @APS

Single bunch imaging – a challenge to find processes fast enough

Experimental setup

- Drilled equidistant holes into a DVD
- DVD covered with zinc paint to increase absorption
- Mounted DVD on a fast electric motor
- Measurement of hole to hole frequency
- with diode and oscilloscope:

1.208kHz

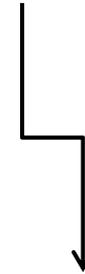


Experiments: AGIPD module @APS

Calculation for burst imaging

- APS bunch spacing: $t = 154\text{ns}$
- Number of pixels crossed during burst of 352 images: ~ 8
- Pixel size: $200\mu\text{m}$

Result from laser measurement



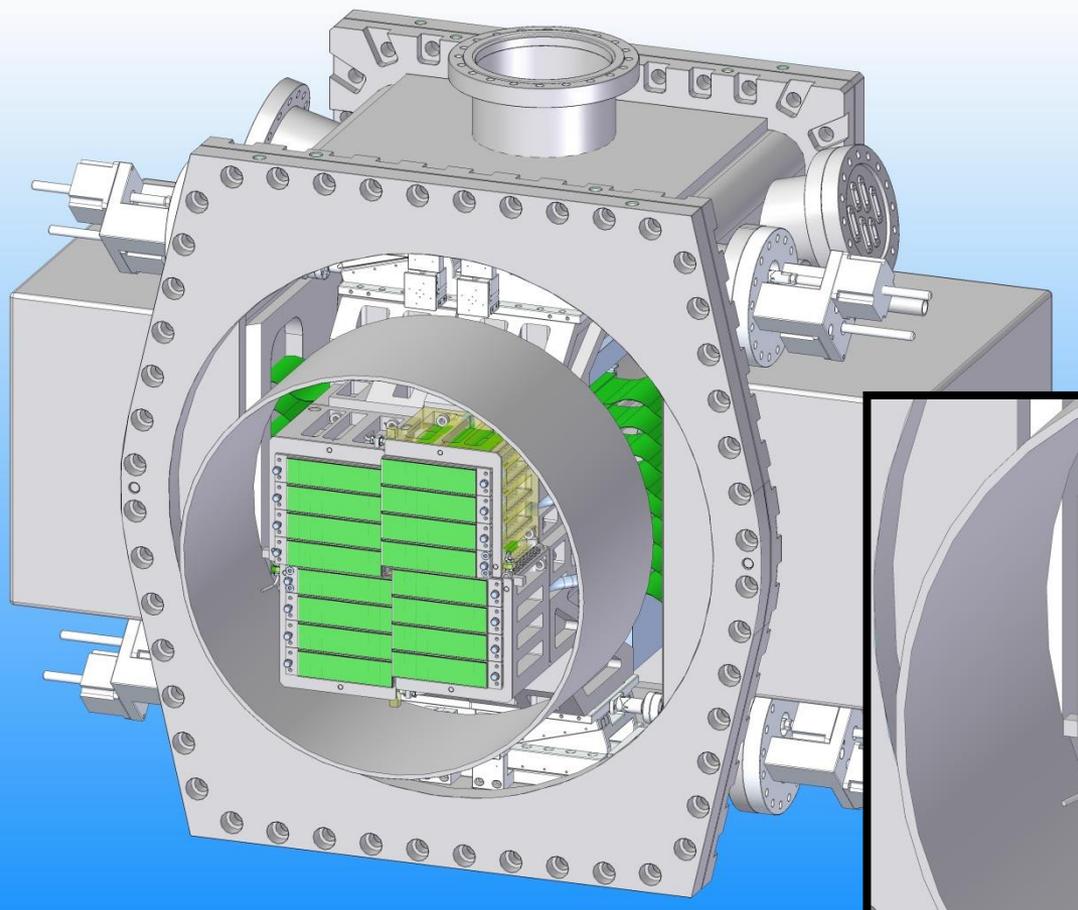
Vdisc, AGIPD = 29.51m/s	≈	Vdisc, Laser = 29.83m/s
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Single bunch imaging is possible even at a repetition rate of 6.5MHz!!



A 1M pixel camera with a variable hole



- Protruding out of detector vessel to minimize sample to detector distance
- Independently movable quadrants
- Angled electronics to minimize footprint along beam axis





an answer for soft X-rays:



(Pixelated Energy Resolving CMOS Imager, Versatile And Large)

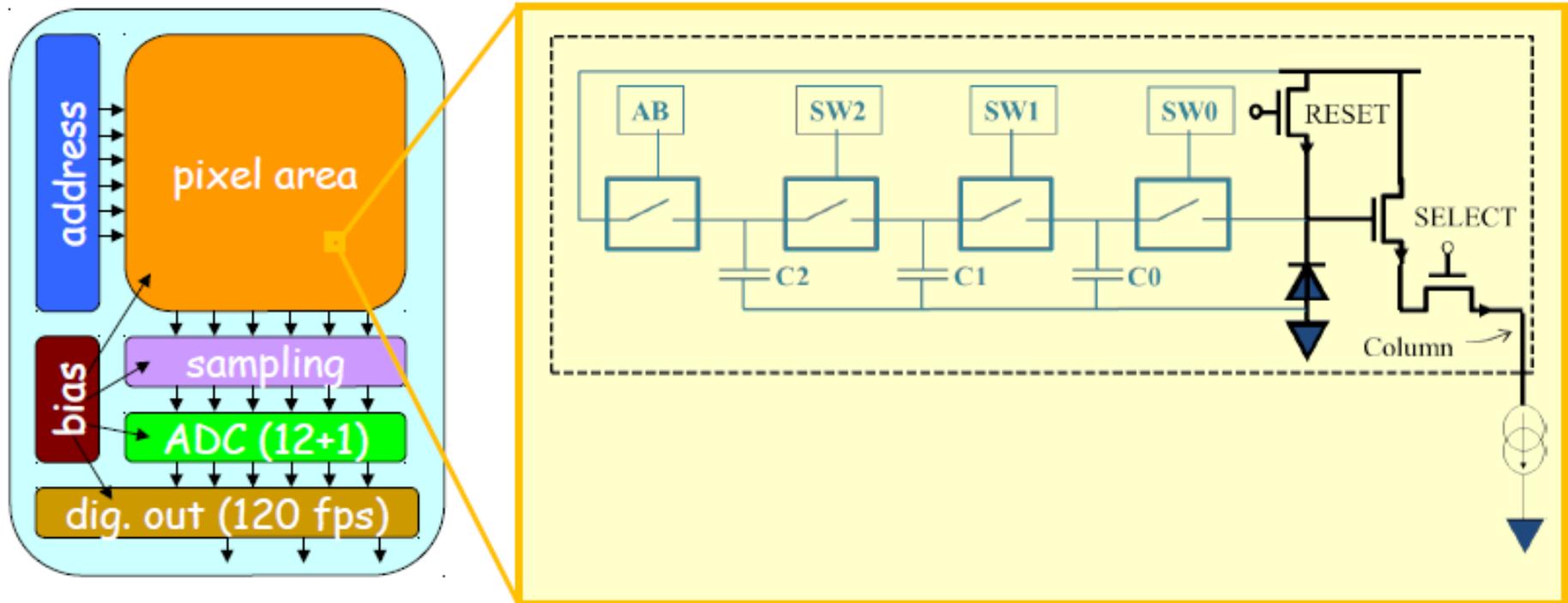


Percival design goals :

Energy range	(<) 0.25 – 1+ [keV]
QE over full energy range	>0.85, uniform over pixel
Frame rate	(1 -) 120 [Hz]
Pixel size	27 (prototypes: 25) [μm]
Sensor size	<ul style="list-style-type: none">• 2 M 1408×1484 pixels, 4×4 cm²• 13 M 3520×3710 pixels, 10×10 cm²
Noise rms	< 15 [e-]
“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	<ul style="list-style-type: none">* FEL (all photons in < 300 fs)* Synchrotron (quasi-continuous)

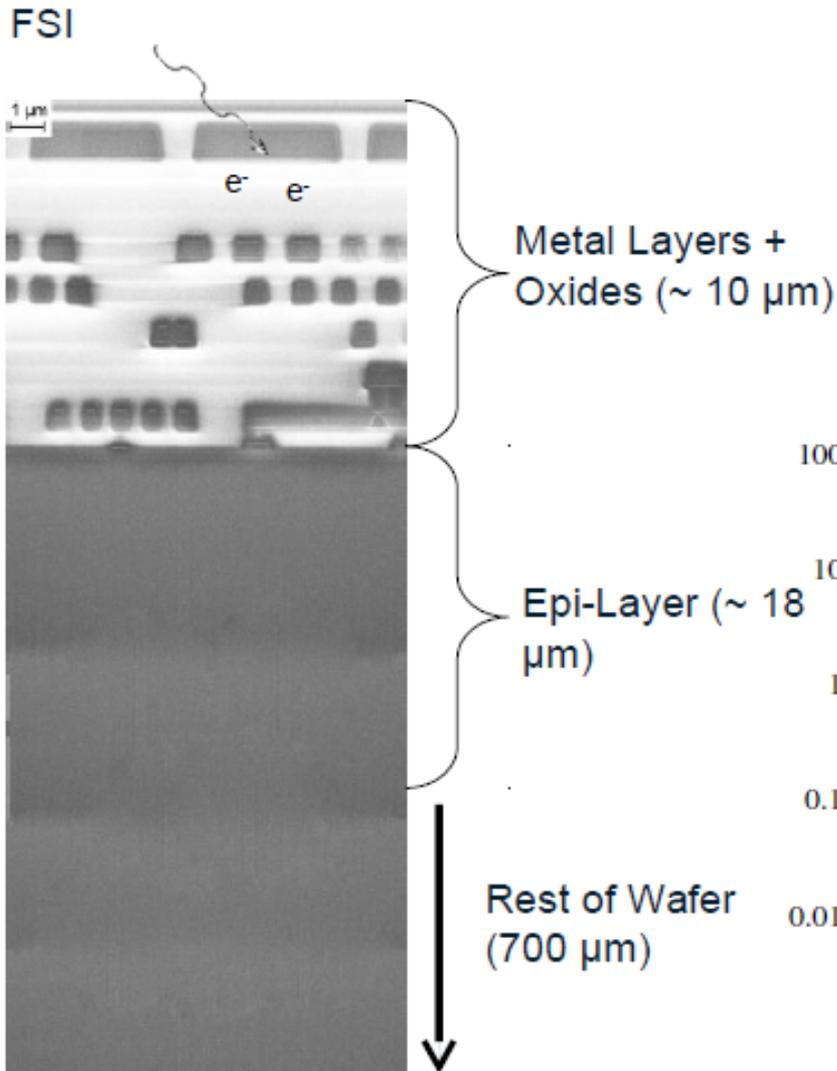


Multiple gain structure

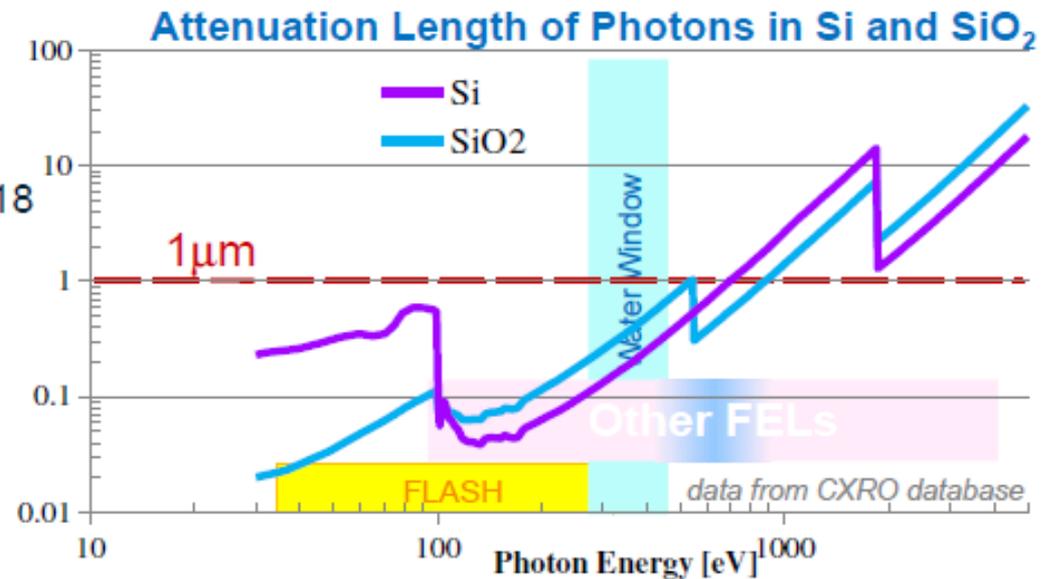


- 7 ADCs (+ spare) per column -> read sensor in 7-row “groups”.
- 3520 columns -> 28k ADCs in a 13M chip.
- 12+1(overrange)+2 (gain) bits -> 15 (x2 for CDS) bits/pixel/frame.
- 111 LVDS output lines at 480MHz data rate for 13M chip (50 Gbit/s).

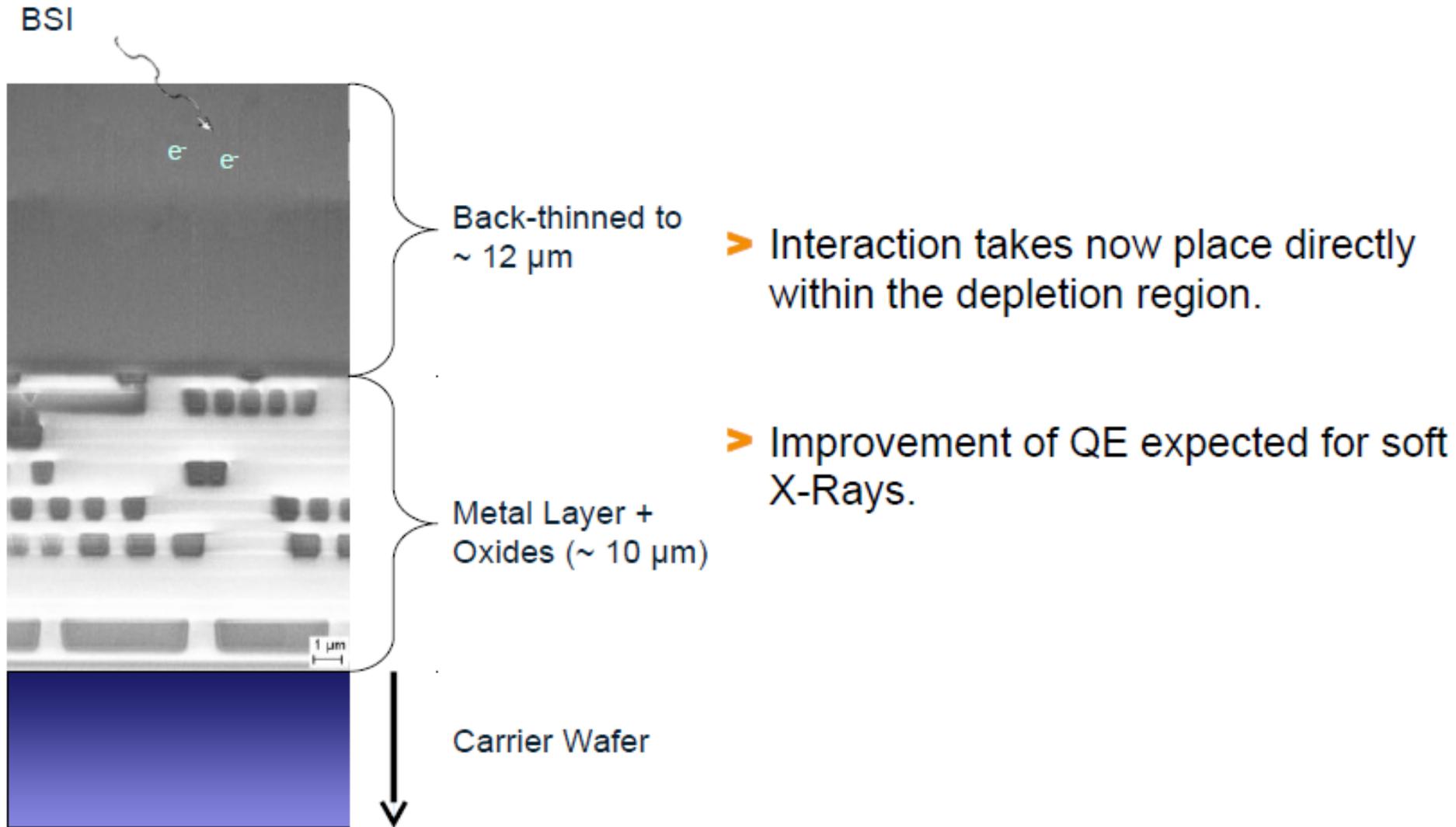
Front side Illumination:



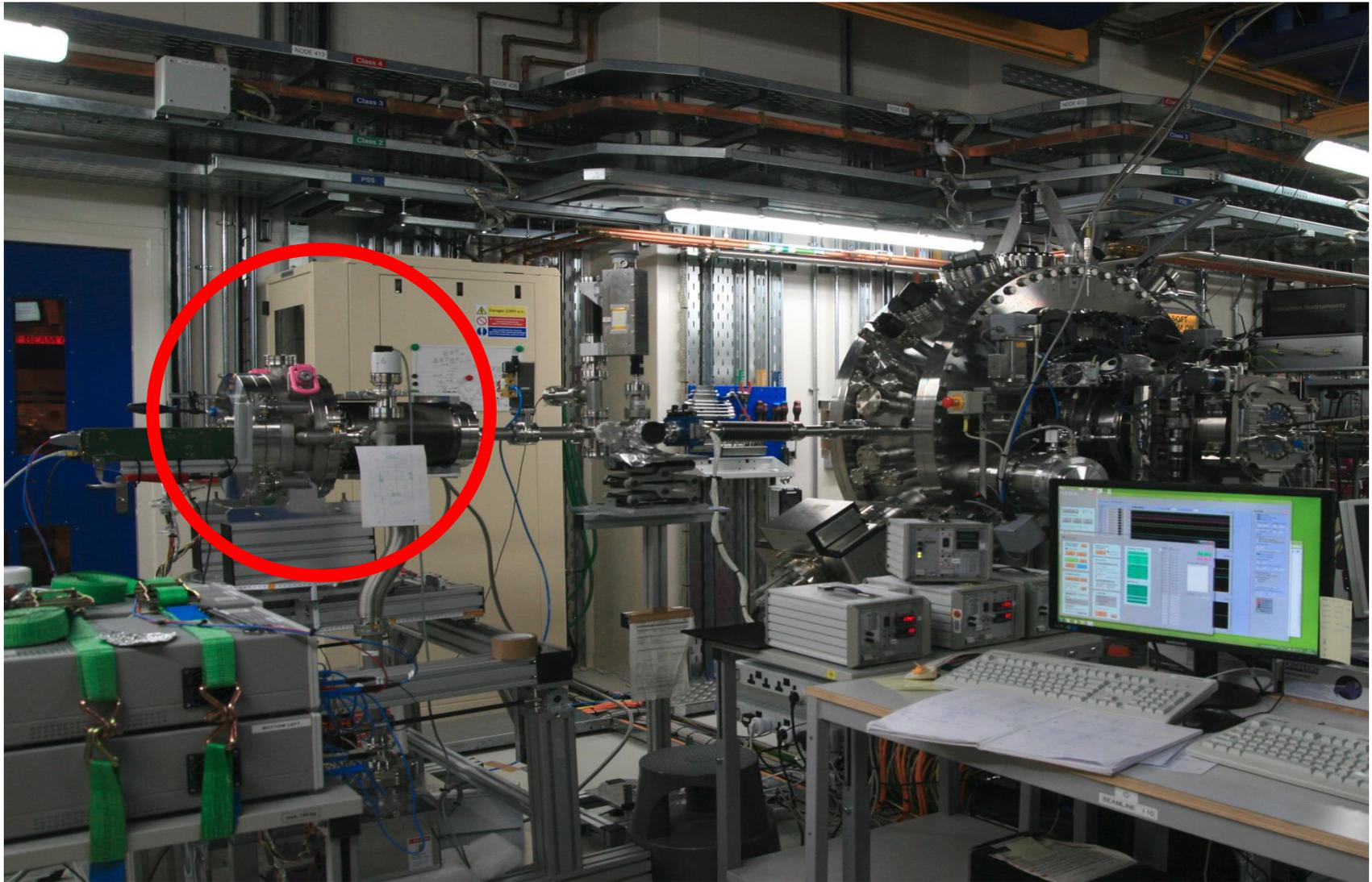
- > Photons have to travel through metal and oxide layers.
- > Absorption lengths is between 100 nm and 2.7 μm (250eV-1keV).



Back side Illumination



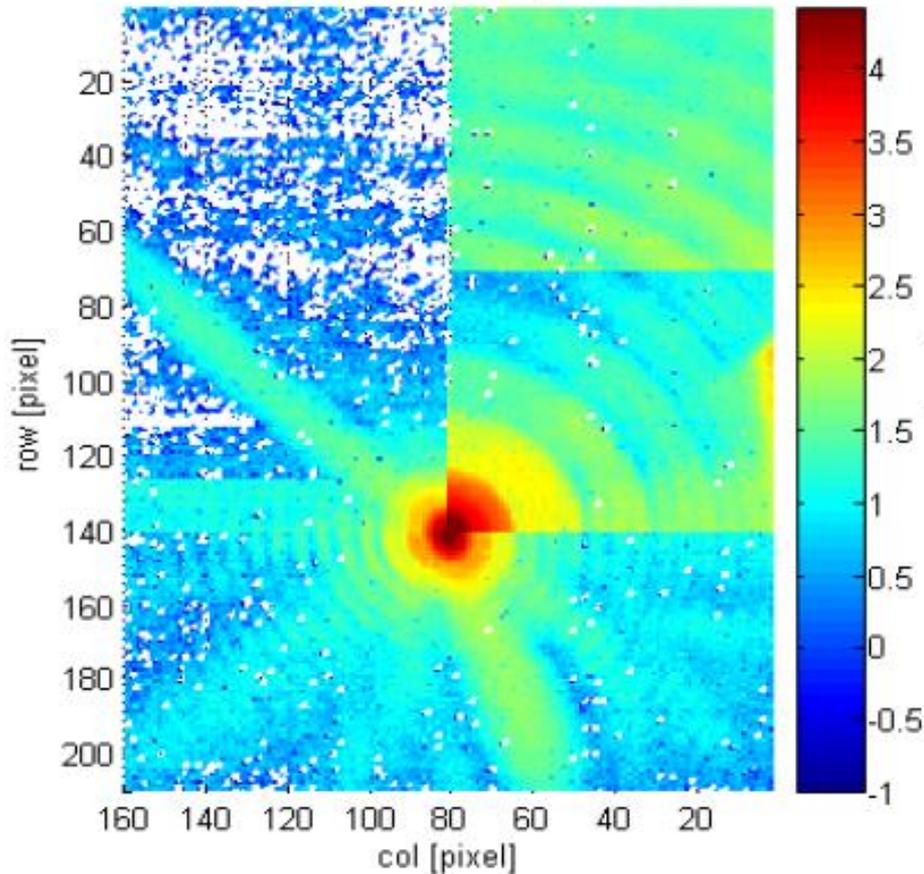
Percival at Diamond Light Source



Experimental Results

- Twin-Mic (350eV + higher Harmonics).

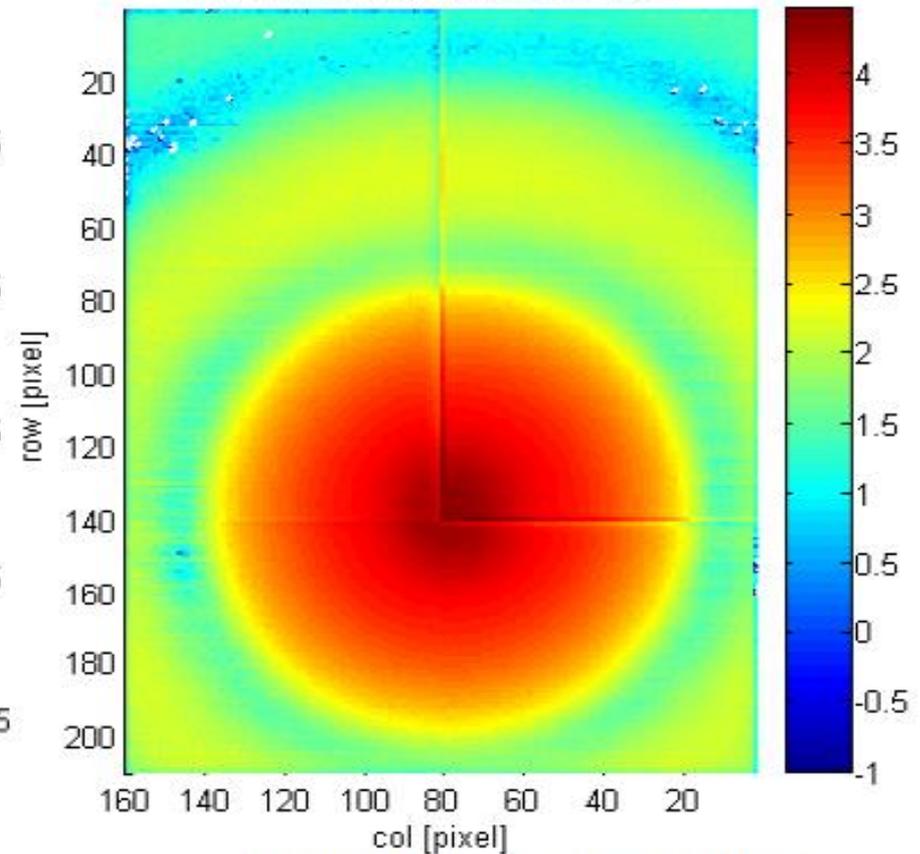
W14-22-TS1BSI, 350eV, 10^x scale



- *Acknowledgment to A. Gianoncelli @ TwinMic*

- I-10 (400eV).

W22-33-TS1BSI, 400eV, 10^x scale



- *Acknowledgment to P. Steadman & M. Sussmuth, R. Fan @ I-10*

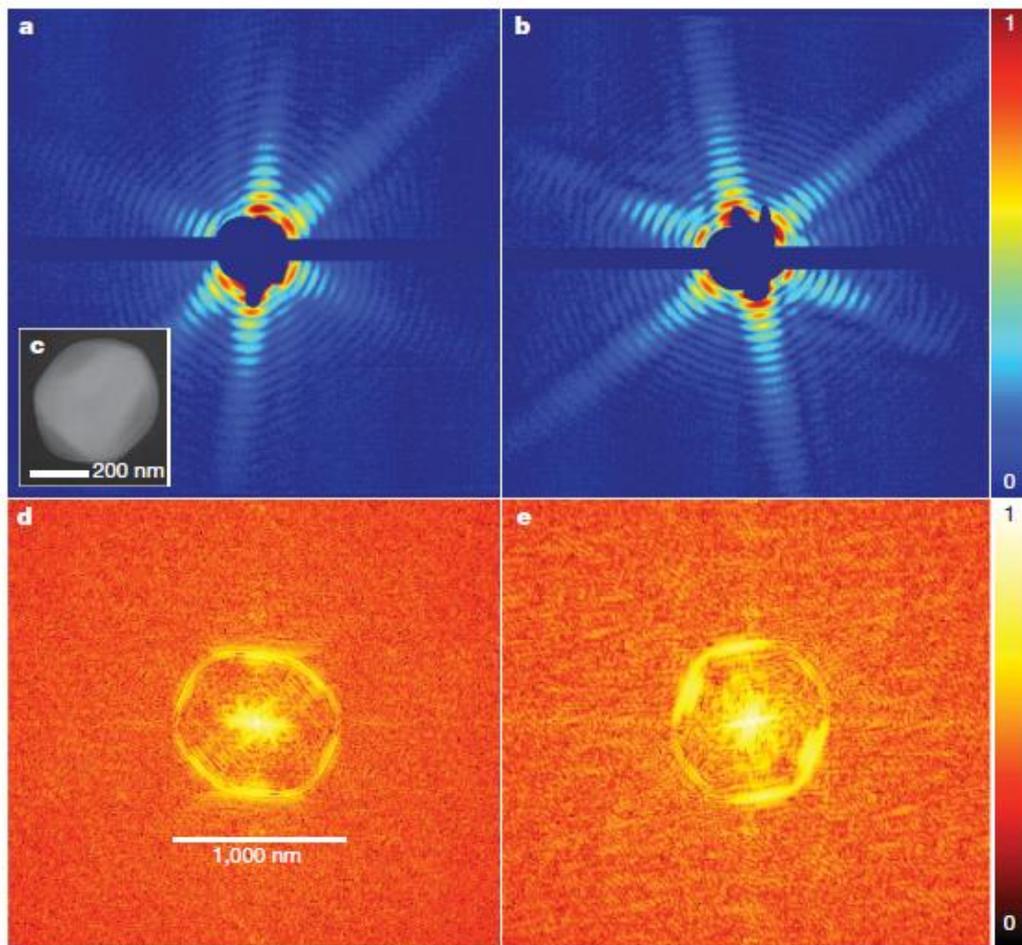
Future Developments



“Edgeless” units

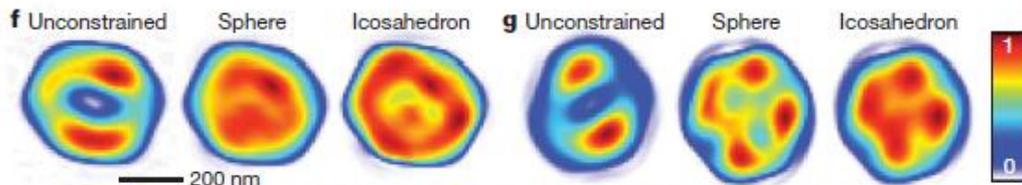
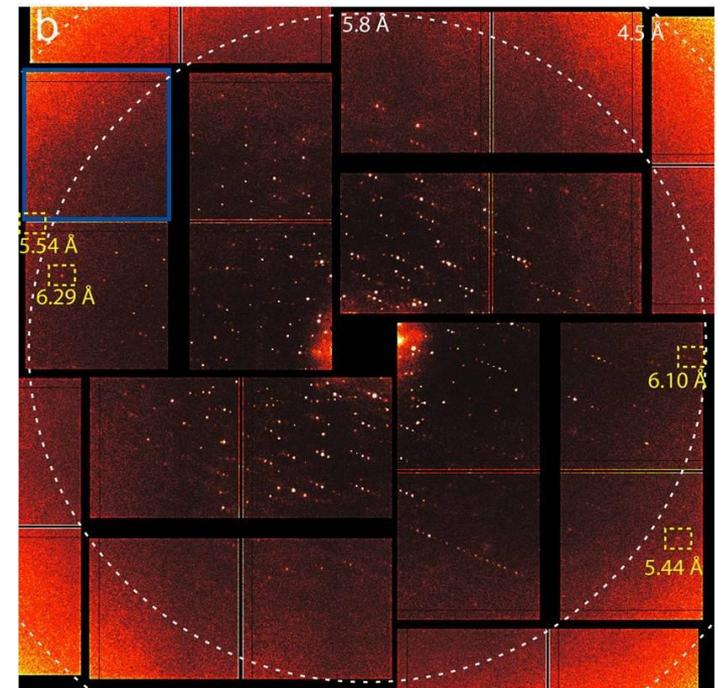


The problem of missing data, an example:



What happens, if central speckle (or more) is not measured?

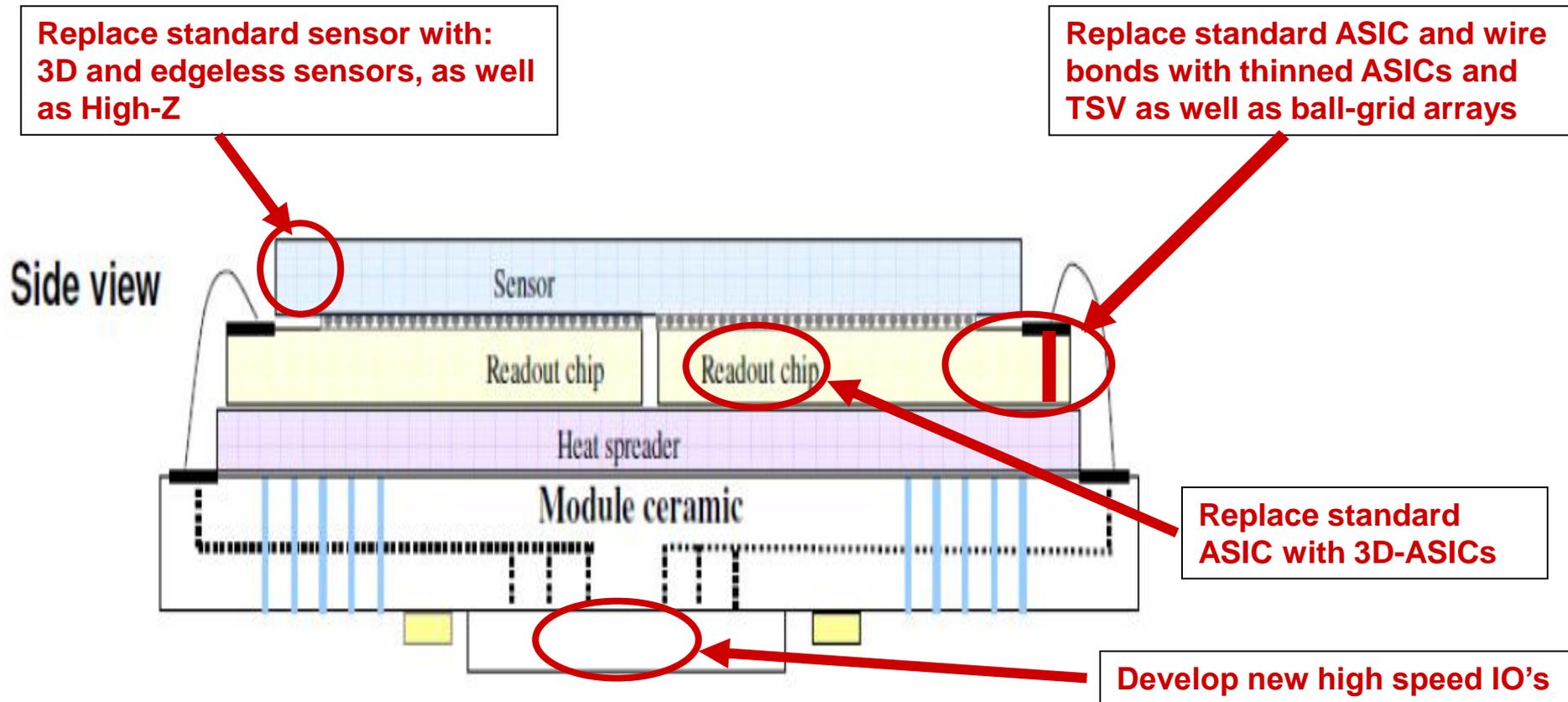
- The reconstruction becomes ambiguous ...
- Quantitative character of the method is lost
- High resolution diffraction signal does NOT help here



Nature 470, 78 (2011)

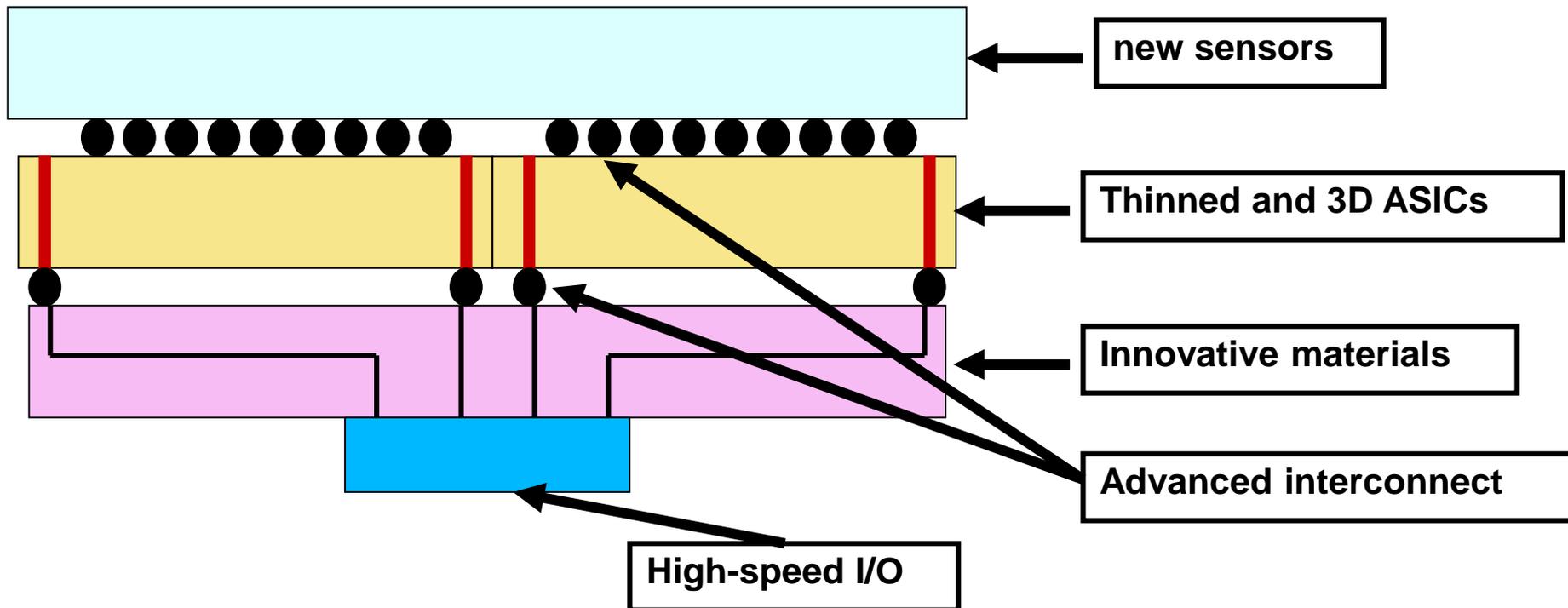
Vertically Integrated Detector Technology

Current state-of-the-art



Vertically Integrated Detector Technology

What we will have “tomorrow”

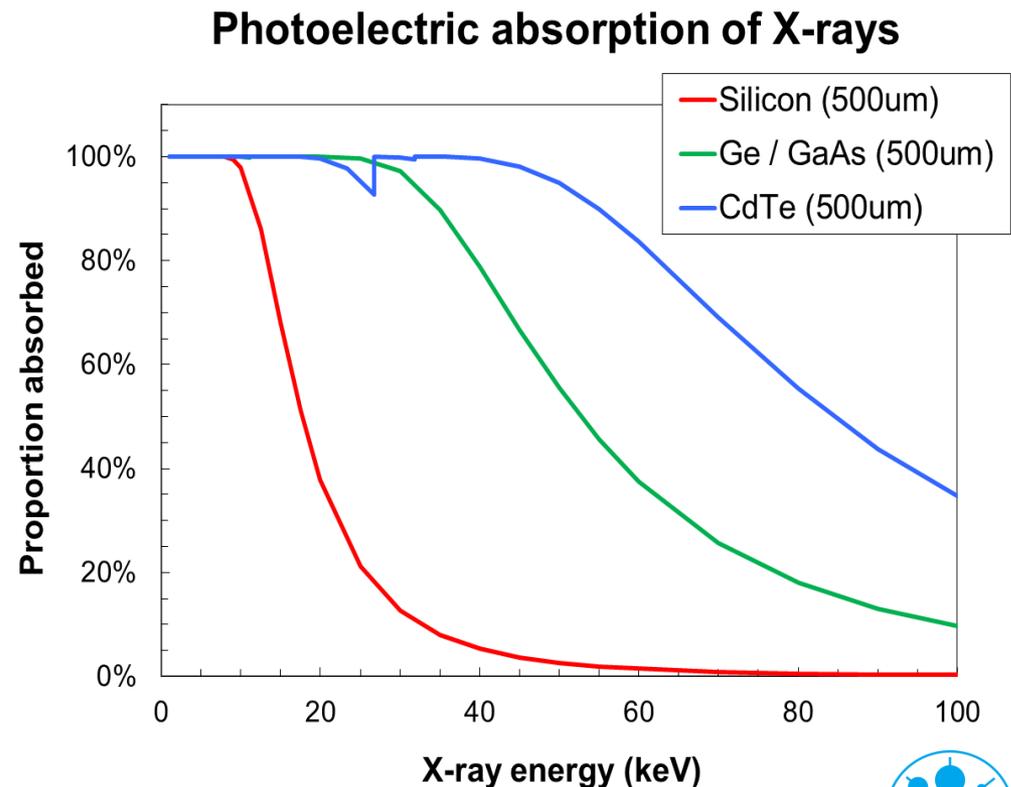


Sensors for higher photon energies



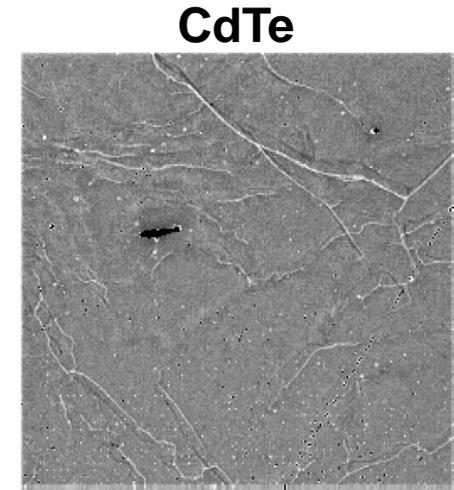
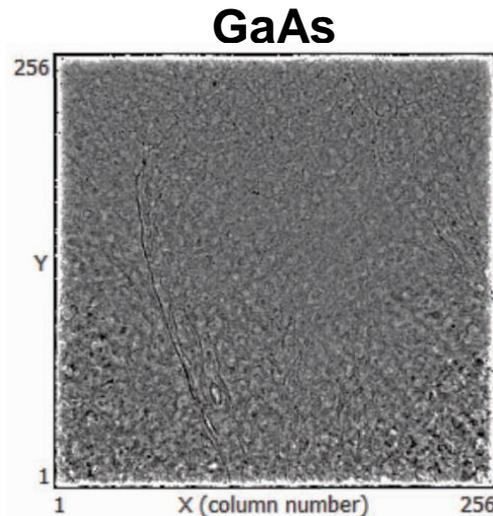
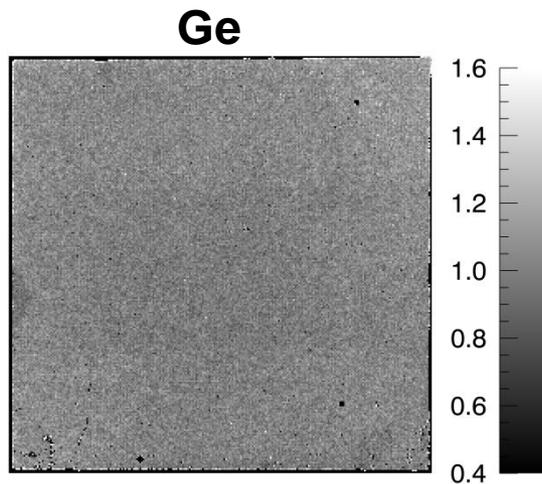
High-Z pixel detectors for high(er) X-ray energies

- Aim: replace silicon sensor in LAMBDA with high-Z semiconductor
 - Combine high QE with hard X-rays, high frame rate, high signal-to-noise
- Investigating different materials in collaboration with other institutes and industry
 - Germanium
 - Gallium arsenide
 - Cadmium telluride



High-Z sensors

- > Ge, GaAs and CdTe could be used for experiments
- > Each material has strengths and weaknesses
 - Germanium technology now works – but high cooling power for large systems
 - GaAs – widespread but correctable nonuniformity – very limited supply
 - CdTe – most well-established, still some problems with uniformity and stability



Multi-tier or 3D ASICS



Technology enablers:

TSV processing during CMOS process

- **Technology:**

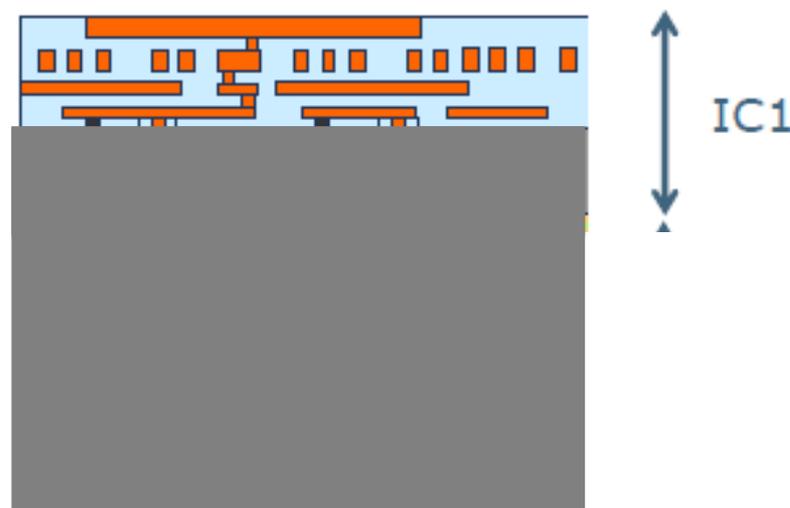
- fabrication at device level, i.e. as a part of (CMOS) flow
- after FEOL, before BEOL
- will become established in advanced CMOS foundries (core partners, e.g. TSMC, Matsushita, Intel, Micron, ...) participate in 3D IC work at IMEC

- **Specifications:**

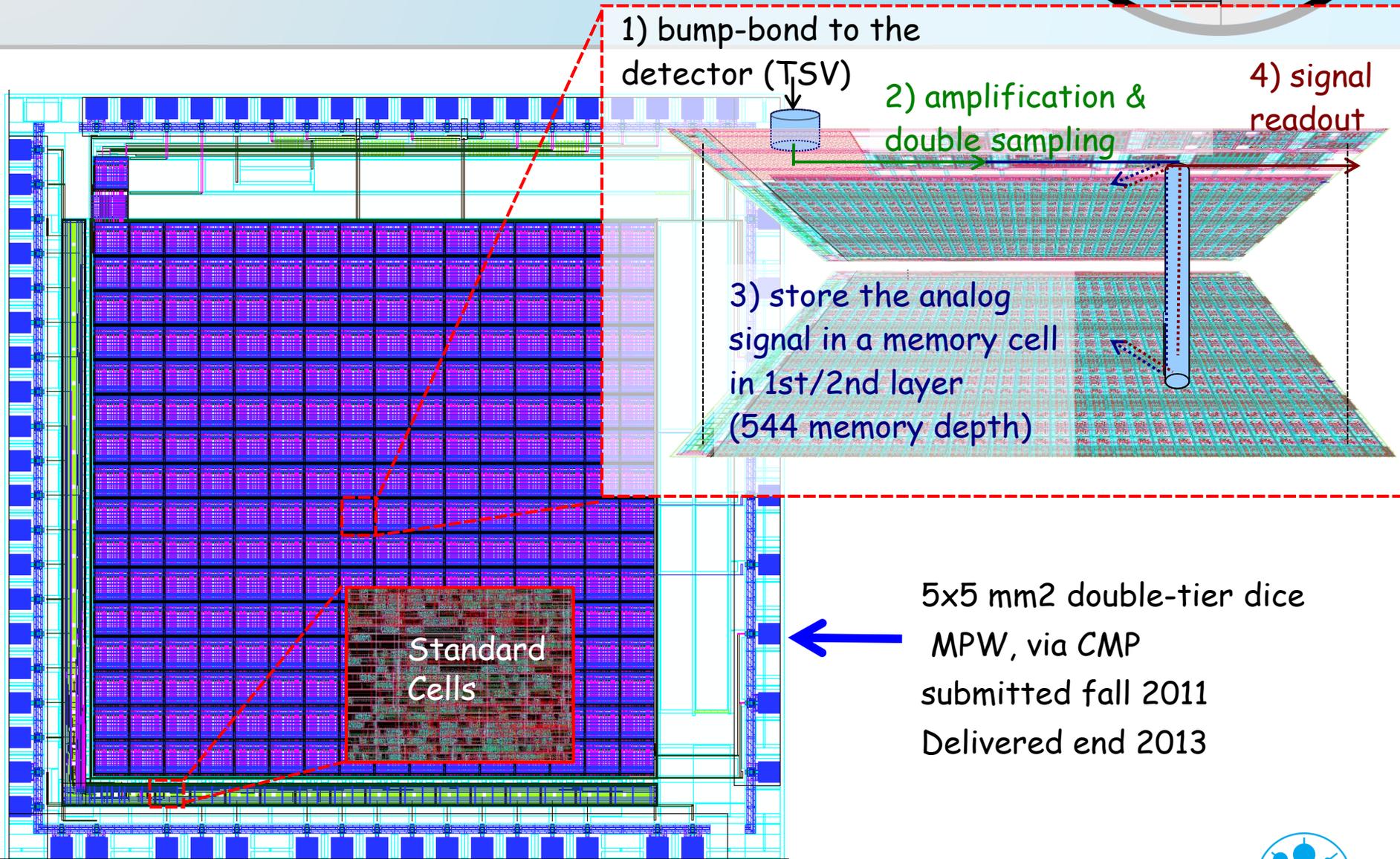
- Si thickness: 10 – 20 μm
- via diameter: 3 – 5 μm
- via pitch: 10 μm

- **Applications:**

- Pixel level interconnect
- imager/processor/logic/memory stacking



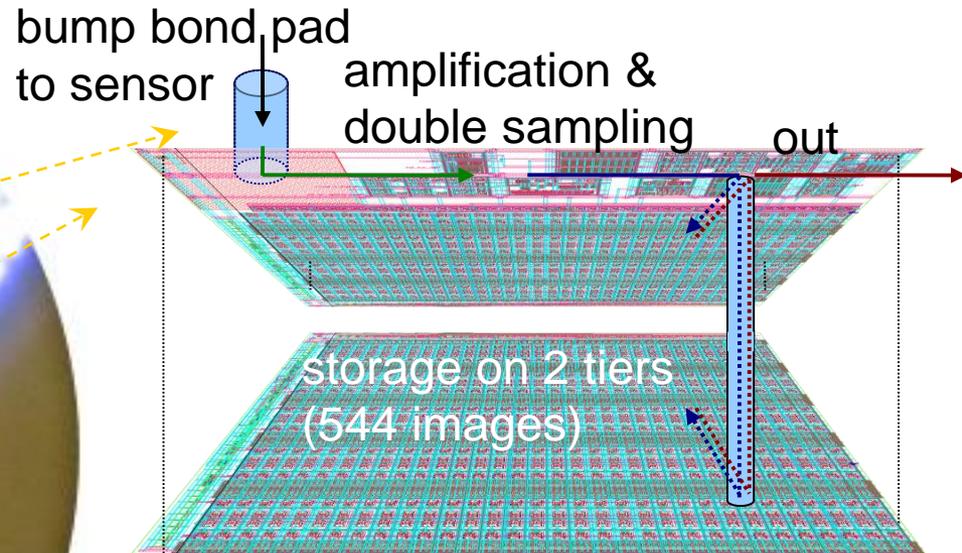
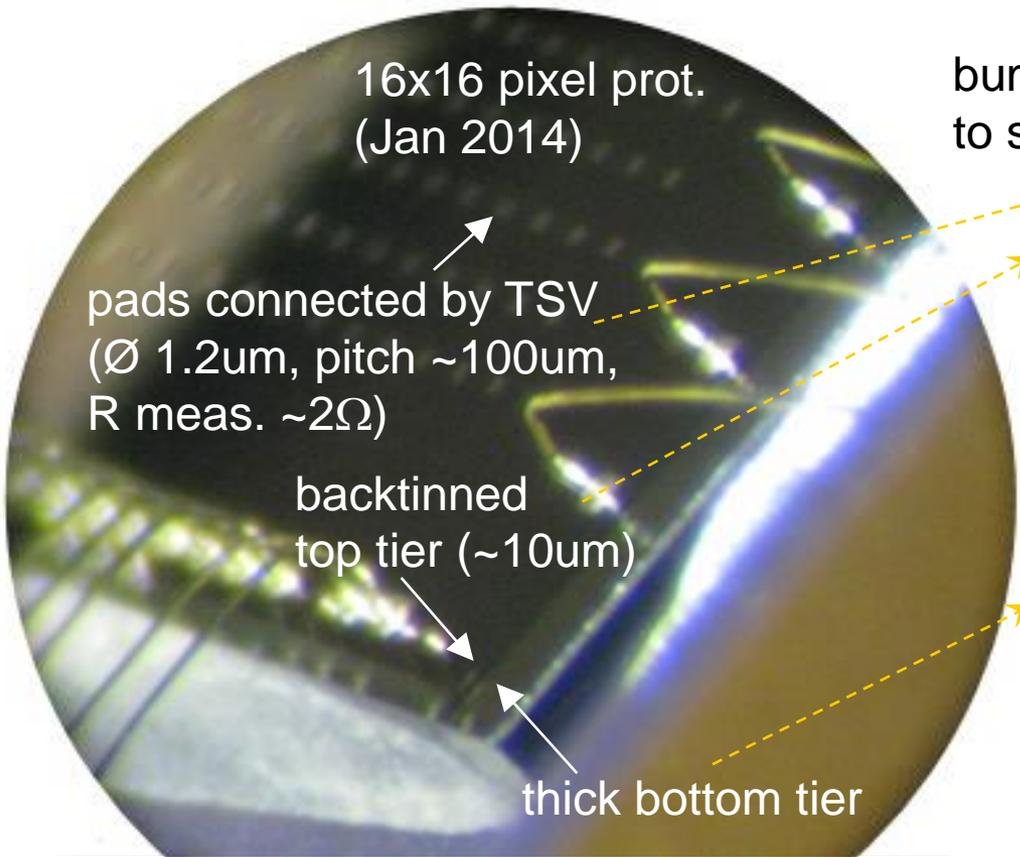
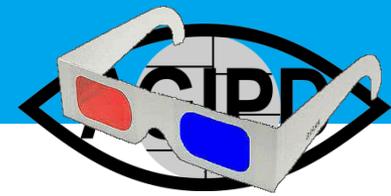
3D-CMOS: a 2-tier AGIPD



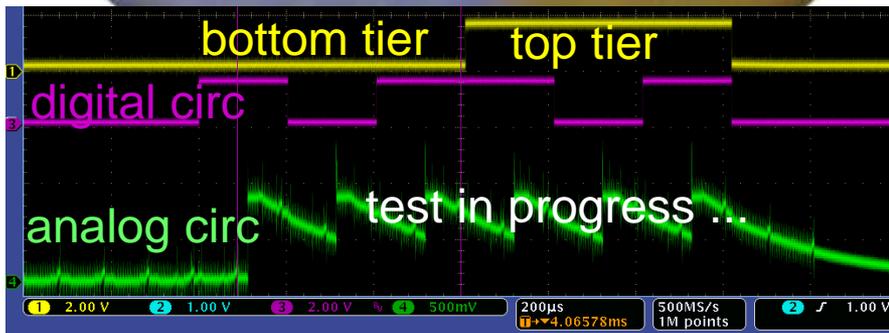
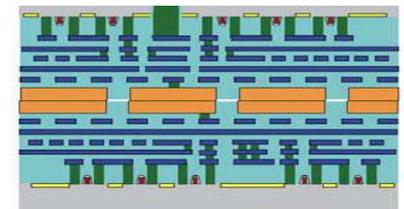
5x5 mm² double-tier dice
MPW, via CMP
submitted fall 2011
Delivered end 2013



3D Evolution of the AGIPD detector

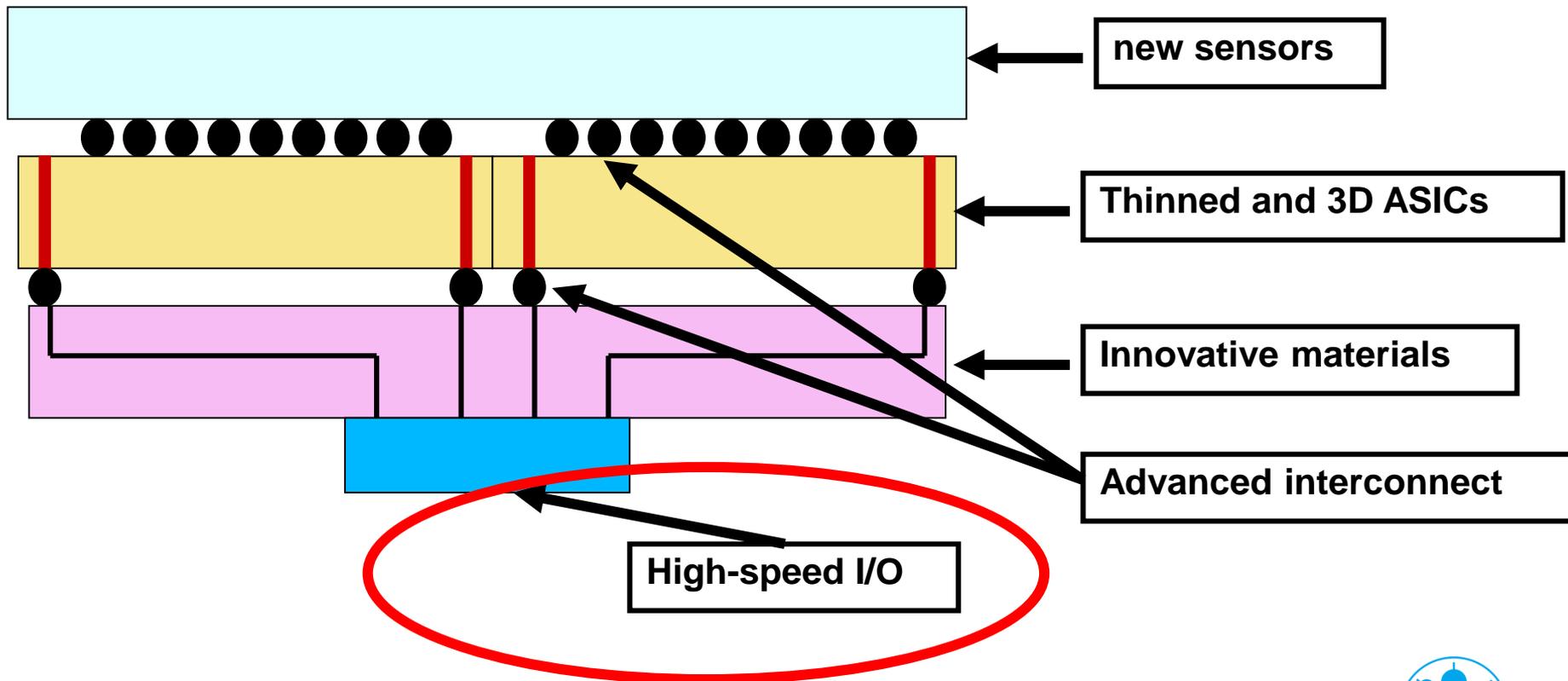


face-to-face conn.
using top metal
(pitch \sim 5 μ m,
R meas. \sim 0.3 Ω)



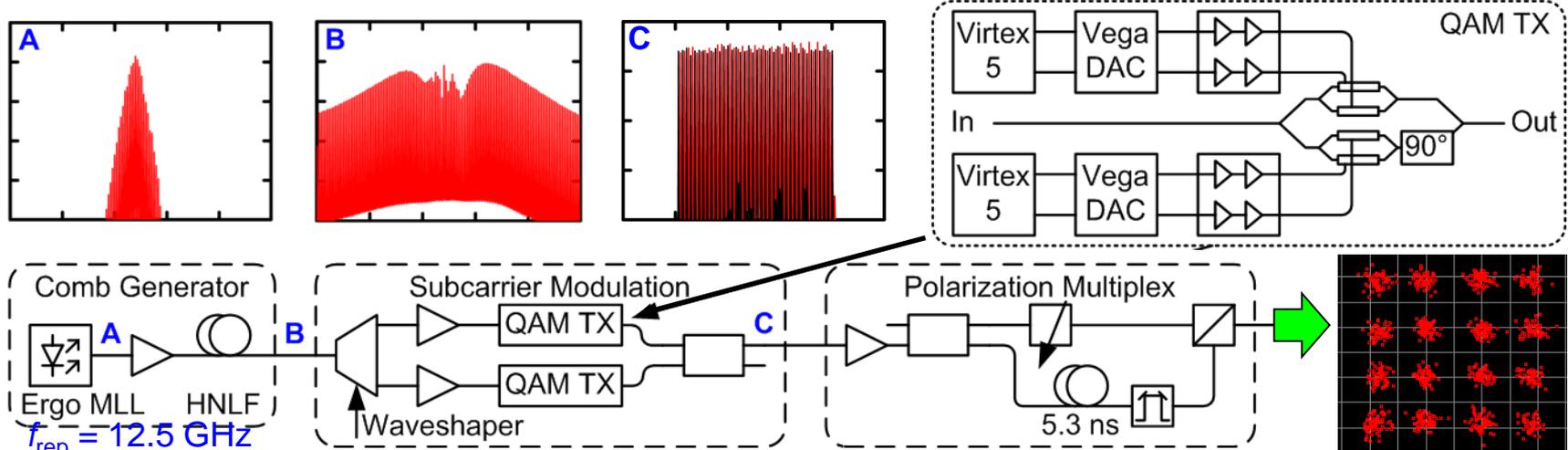
Vertically Integrated Detector Technology

What we will have “tomorrow”



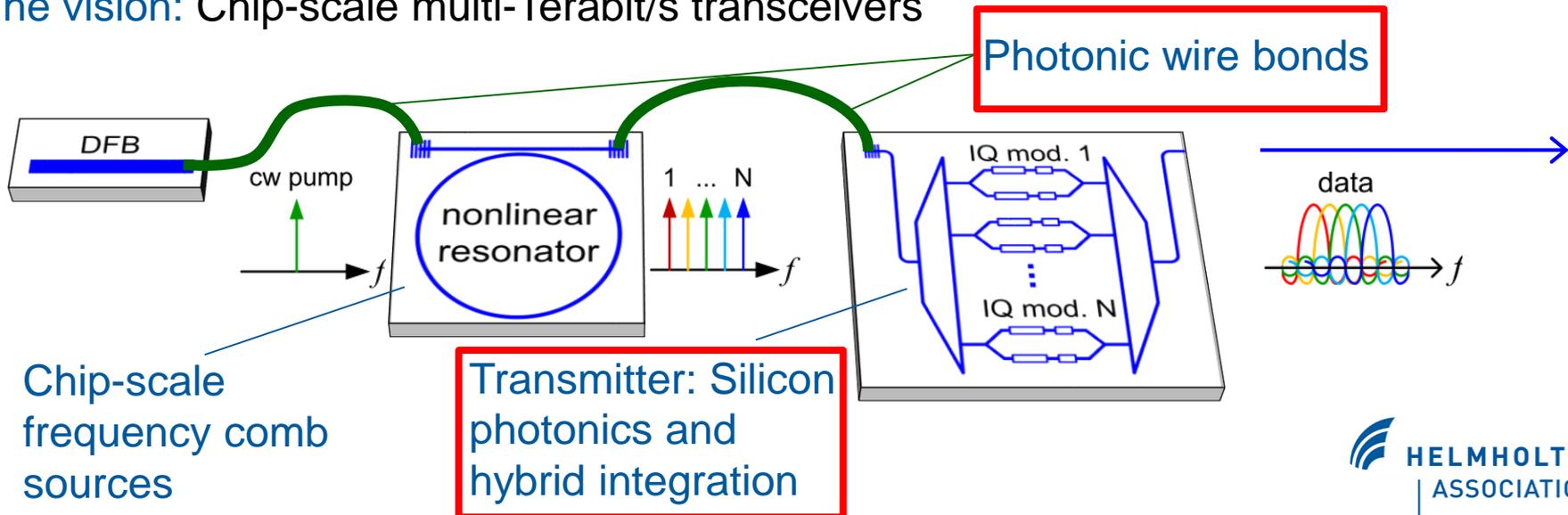
Terabit communications: Proof-of-principle

Frequency comb source: 325 channels, 12.5 GBd, 16 QAM, PoIMUX => **32.5 Tbit/s**



Hillerkuss et al., Nature Photonics 5, 364–371 (2011)

The vision: Chip-scale multi-Terabit/s transceivers



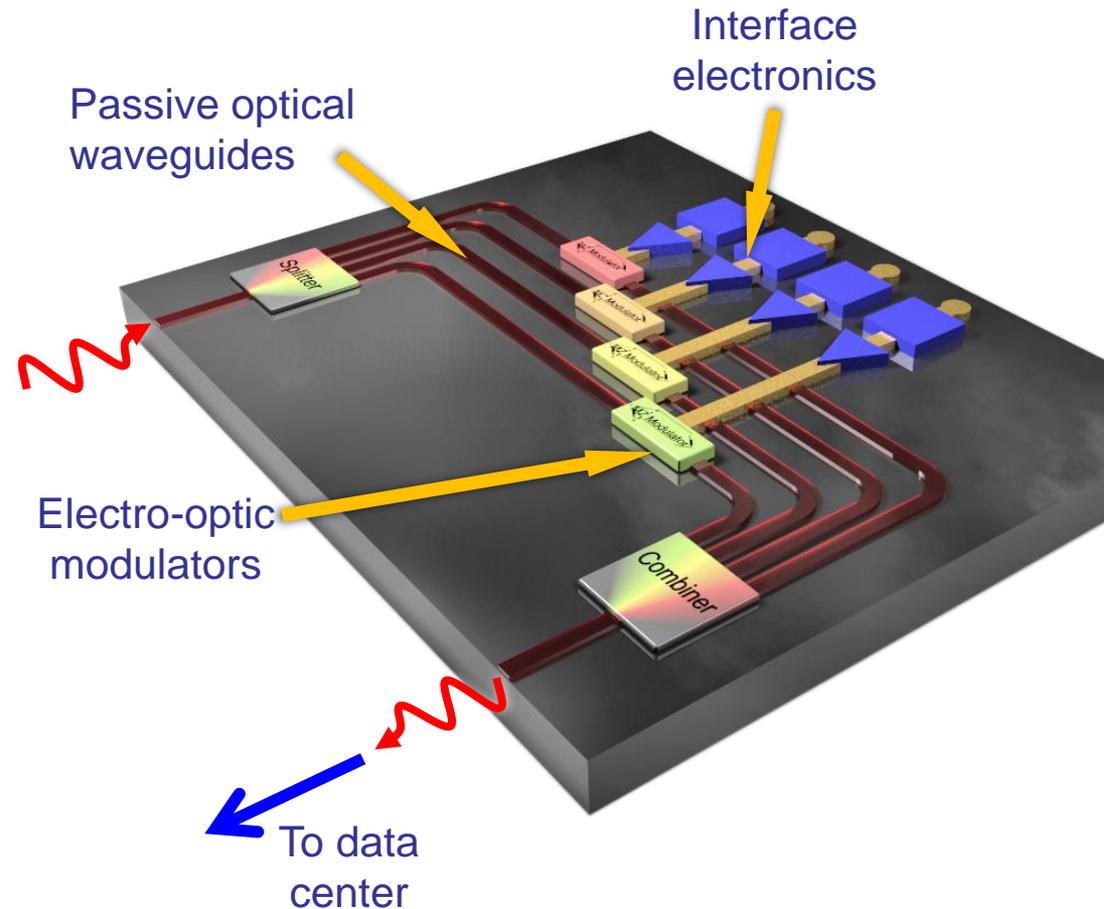
Chip-scale frequency comb sources

Transmitter: Silicon photonics and hybrid integration

Photonic wire bonds

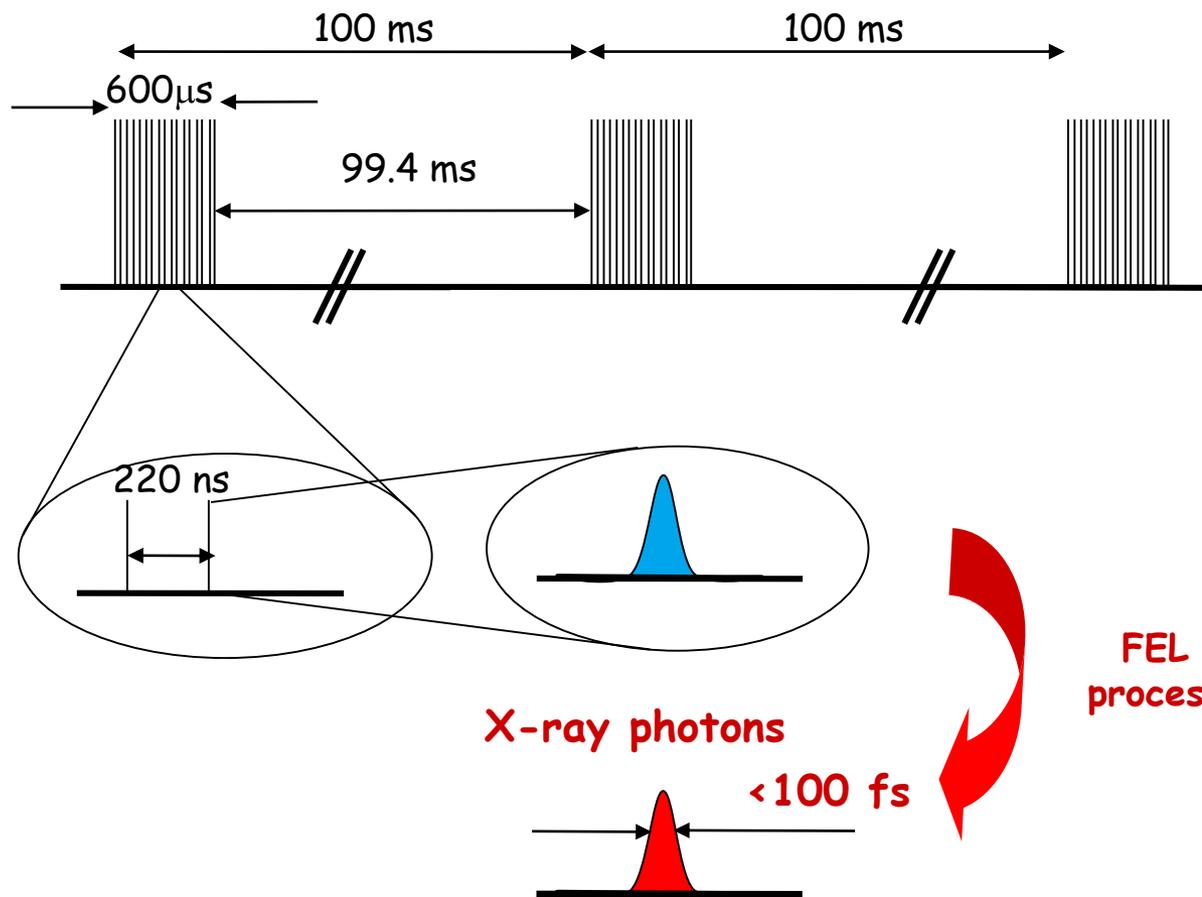
The Vision: Terabit/s communications in particle detectors

- Intimate co-integration of photonics and electronics for terabit communications
- Fast readout of full detector: Get raw data out for “offline processing” in data center
- Less electronics and more detectors in detector volume
- Less mass in detector for higher accuracy



European XFEL Linac: Time Structure Challenge

Electron bunch trains; up to 2700 bunches in 600 μ sec, repeated 10 times per second.
Producing 100 fsec X-ray pulses (up to 27 000 bunches per second).



27 000 bunches/s
with
4.5 MHz
repetition rate

av. Rate:
27kHz XFEL
120Hz LCLS
60Hz SCSS

FEL
process



Can we handle a high rep-rate/ DC / CW Machine ?

- > What is the time structure ?
- > What is the photon energy (noise) ?
- > What is the intensity per pulse per pixel in the image (dynamic range) ?
- > When will the machine be ready ?
- >many, many more questions.....

- > There certainly are possibilities !!



Conclusions

- Photon detectors for FELs are challenging, but,
- First systems allowed for new science
- European XFEL will have appropriate detectors (with limiting # frames)
- Detectors can be build to handle DC/CW/high rep-rate machines. But we have to know what the machine will look like.

