X-ray Detectors

How do they work ?
How are they characterized ?
What will the future bring?

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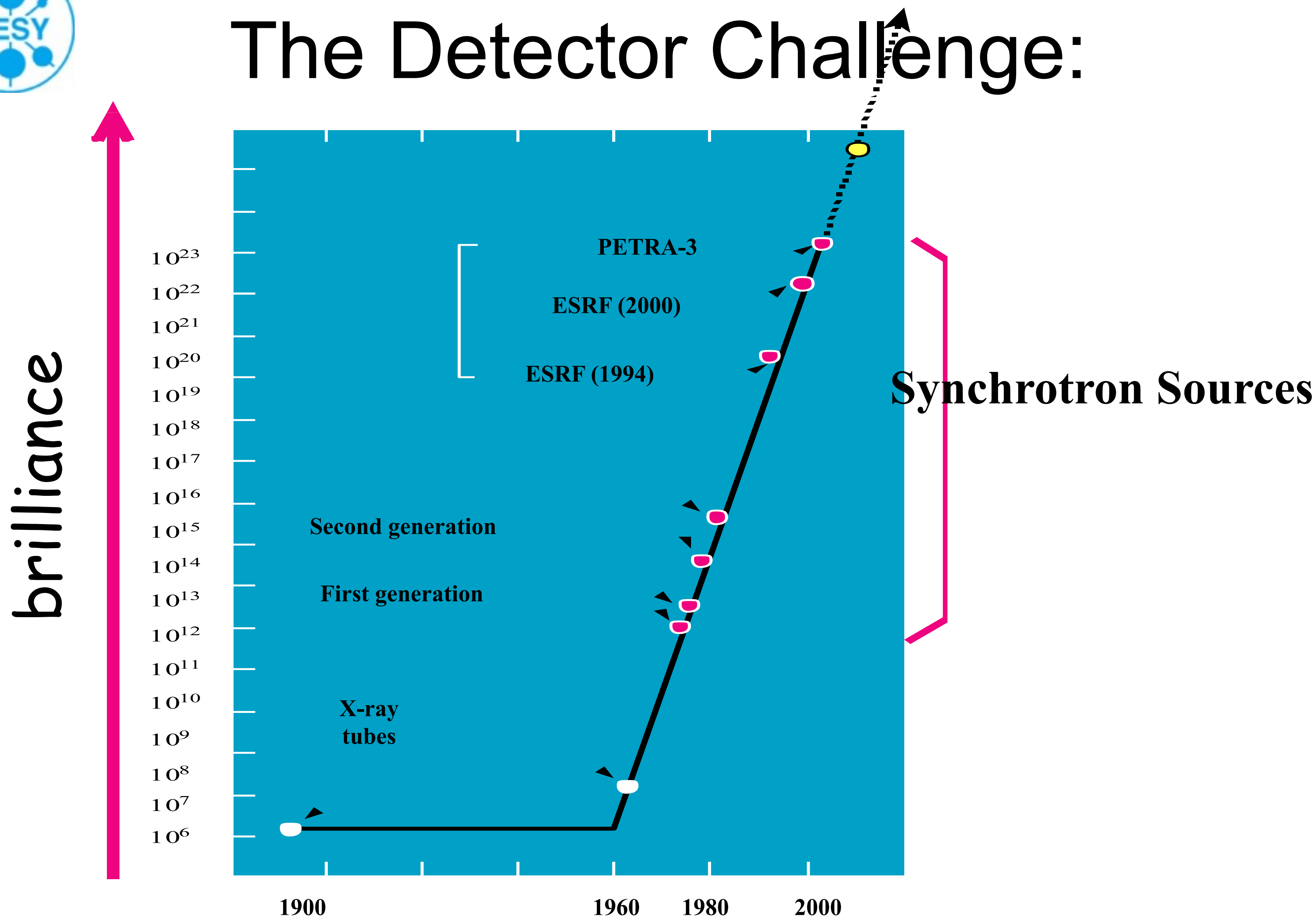
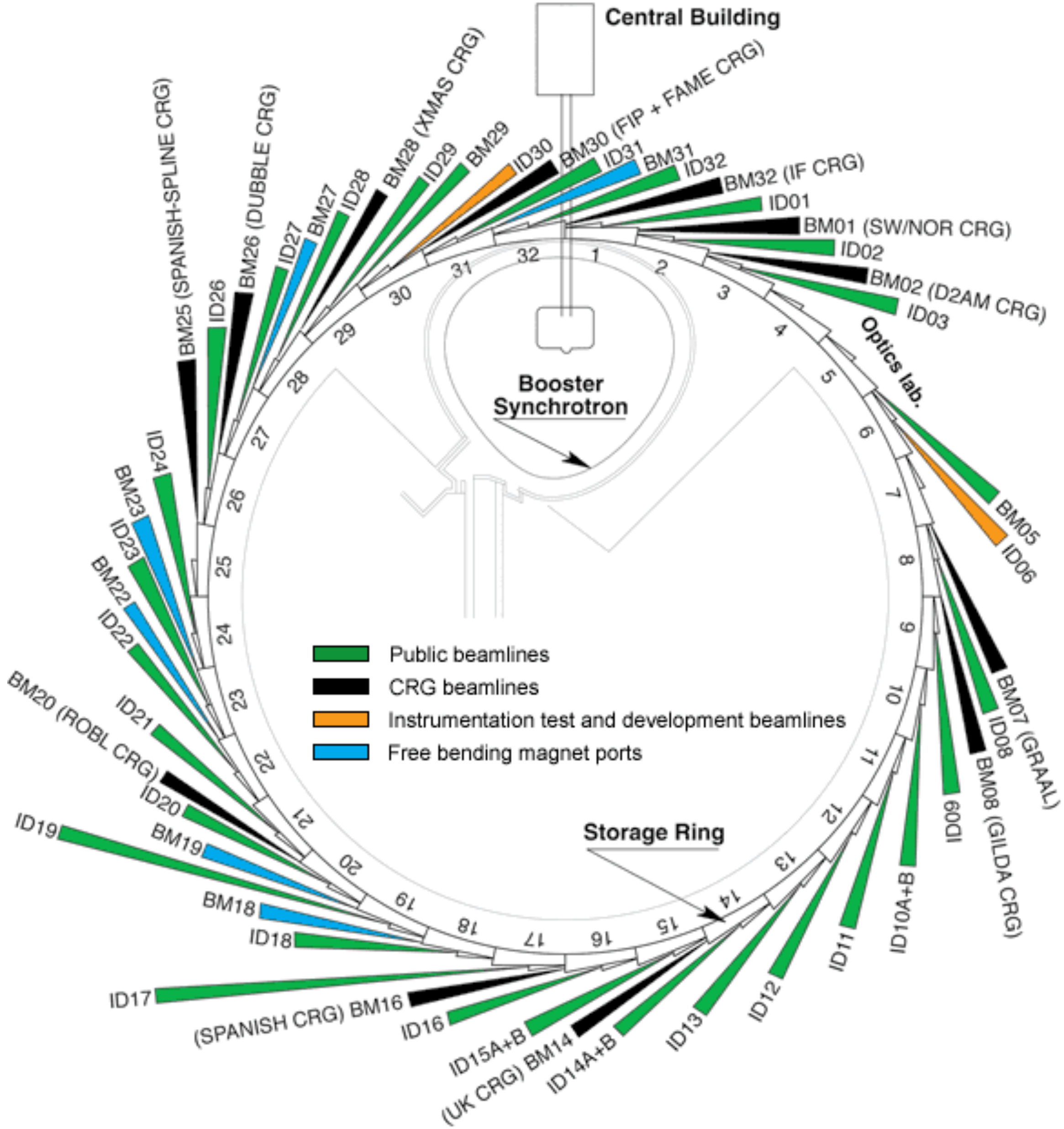
The Detector Challenge:



The Detector Challenge:



The Detector Challenge:

- **Spectroscopy** (determine energy of the X-rays):
  - meV – 1 keV resolution
  - time resolved (100 psec) – static
- **Imaging** (determine intensity distribution)
  - Micro-meter – millimeter resolution
  - Tomographic
  - Time resolved
- **Scattering** (determine intensity as function of momentum transfer = angle)
  - Small angel – protein crystallography
  - Diffuse – Bragg
  - Crystals - liquids

What are the basic principles ?

1. X-ray light is quantized (photons)
2. In order to detect you have to transfer energy from the particle to the detector
3. A photon is either fully absorbed or not seen at all (no track like for MIPs)
4. The energy absorbed is transferred into an electrical signal and then into a number (digitized).

Signal Generation → Needs transfer of Energy

Any form of elementary excitation can be used to detect the radiation signal:

Ionization (gas, liquids, solids)

Excitation of optical states (scintillators)

Excitation of lattice vibrations (phonons)

Breakup of Cooper pairs in superconductors

Typical excitation energies:

Ionization in semiconductors:	1 – 5 eV
Scintillation:	appr. 20 eV
Phonons:	meV
Breakup of Cooper pairs:	meV

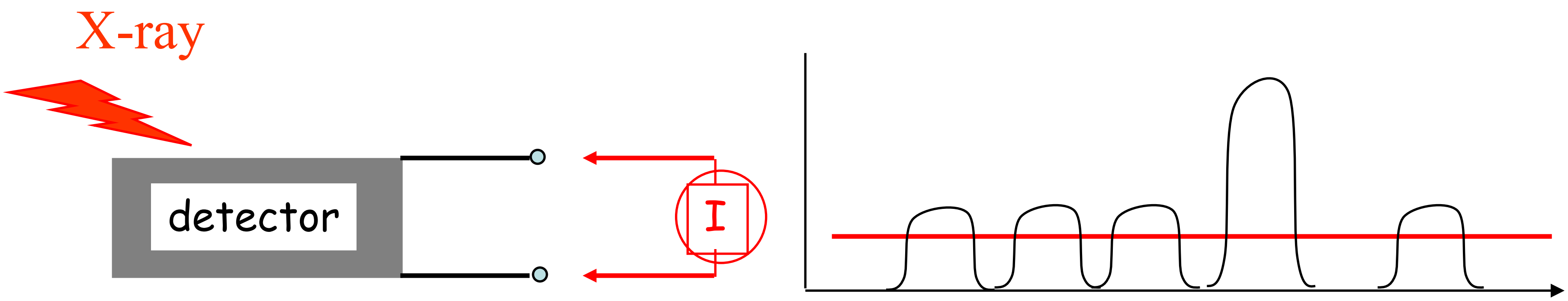
What would you like to know about your X-rays?

1. Intensity or flux (photons/sec)
2. Position (or often angles)
3. Energy (wavelength)
4. Arrival time (time resolved experiments)
5. Polarization

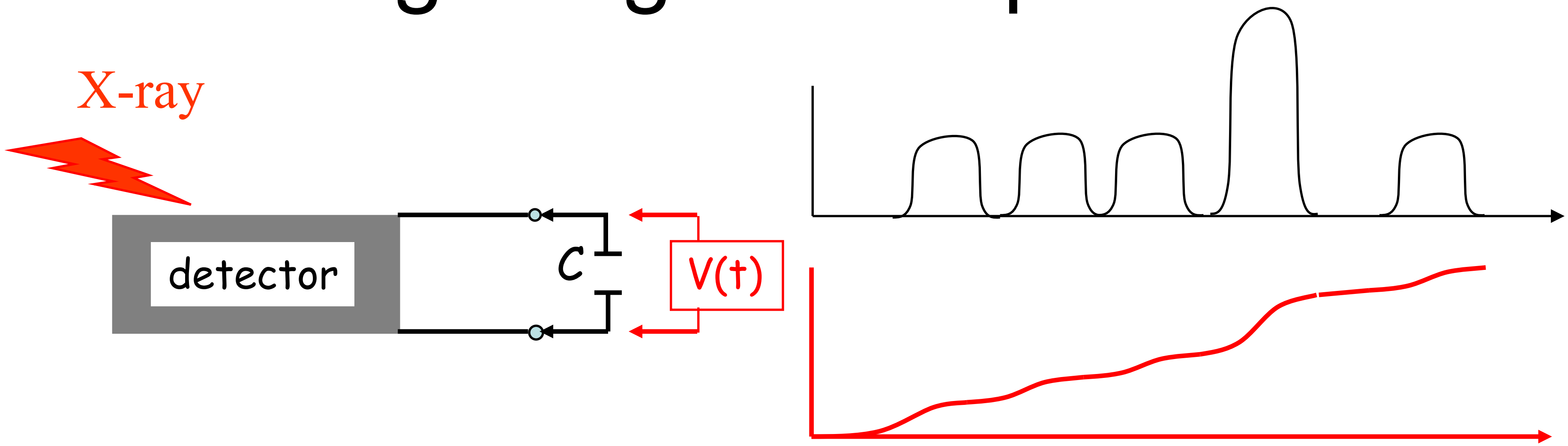
4 modes of detection

1. Current (=flux) mode operation
2. Integration mode operation
3. Photon counting mode operation
4. Energy dispersive mode operation

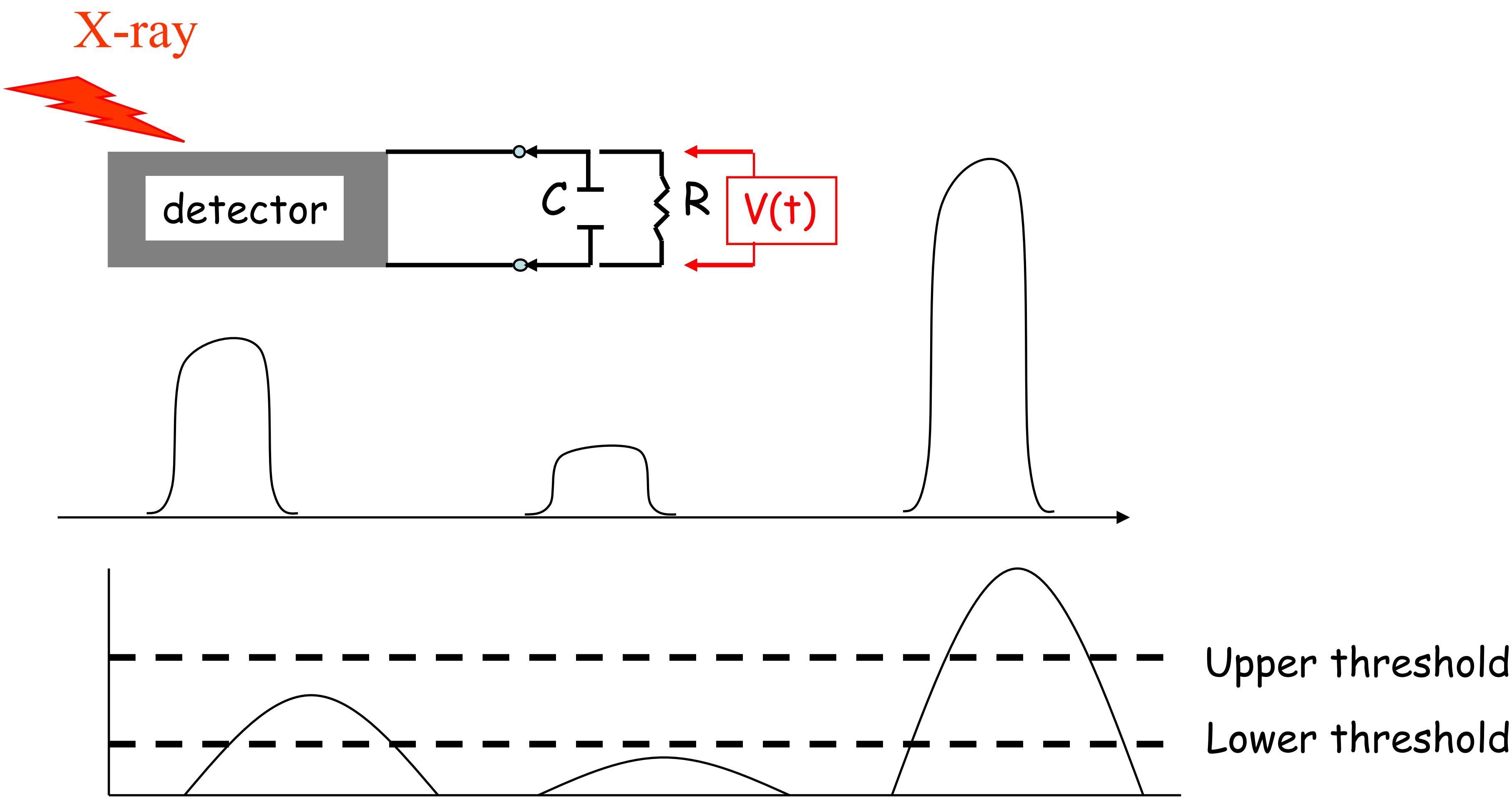
Current mode operation



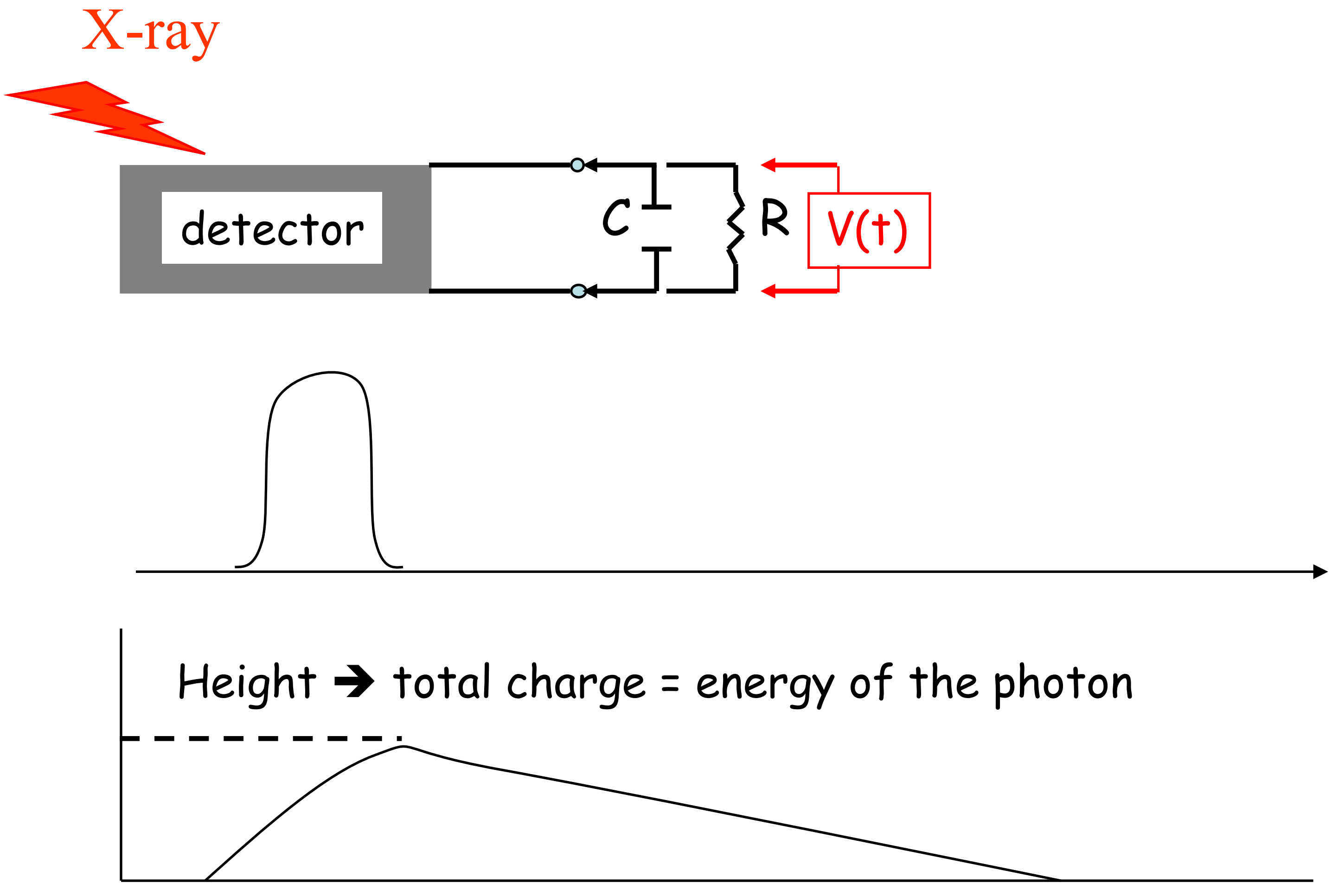
Integrating mode operation



Photon counting mode



Energy dispersive mode



Some general detector parameters

- **QE** = Quantum Efficiency = fraction of incoming photons detected (<1.0). You want this to be as high as possible.

- **Gain** = relation between your signal strength (V, A, ADU) and the number of photons.

Warning: when doing science analysis, make sure you converted your numbers back to photons!

2-Dimensional X-ray Detectors

- Workhorses at synchrotron sources → make the best use of the available photons.
- Counting or Integrating
- Direct detection or Indirect detections (Indirect = first convert X-rays to optical photons, then detect optical photons)

Some parameters for 2D systems

- **DQE** = Detective Quantum Efficiency =

$$\frac{(signal/noise)_{out}}{(signal/noise)_{in}} < 1.0$$

Detector can never increase signal, nor decrease noise!

So signal to noise will always degrade in the detector.

NB: **signal to noise is the most important parameter** when you measure something!

Some more parameters for 2D systems

- Point Spread Function (PSF) (Line spread function (LSF) or spatial resolution):

  A very small beam (smaller than the pixel size) will produce a spot with a certain size and shape. Very important are the FWHM; and the tails of the PSF.

  This is experimentally difficult ➔ use sharp edge and Edge Spread Function (ESF)

  Note: pixel size is not spatial resolution! (but should be close to it in an optimal design).

Some more parameters for 2D systems

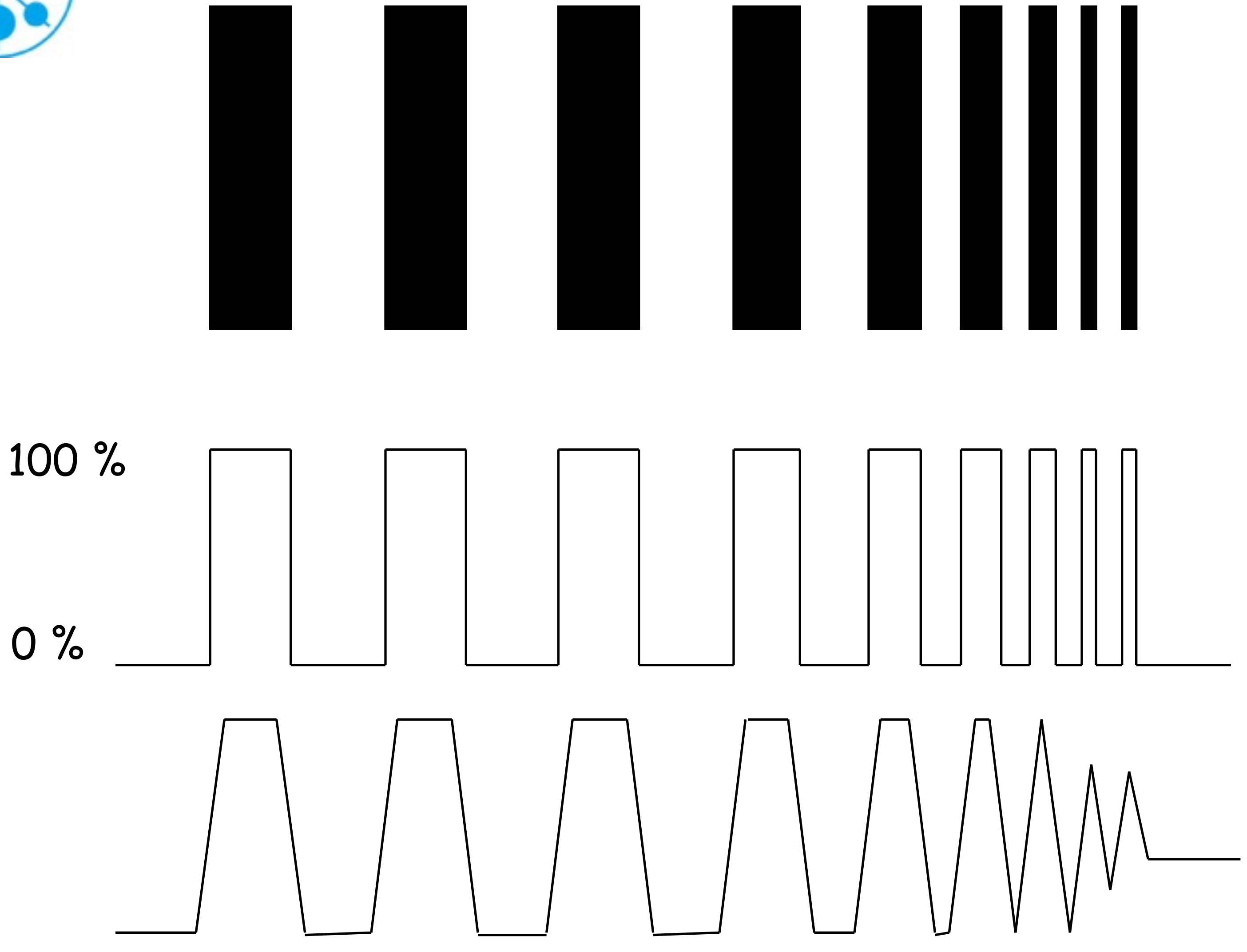
- Modulation Transfer Function (MTF):

  How is a spatially modulated signal (line pattern) recorded (transferred) by the detector?

$$Modulation = contrast = \frac{Max - Min}{Max + Min}$$

This depends on the frequency.

Is directly related to the LSF and the DQE


100 %
0 %

Some more parameters for 2D systems

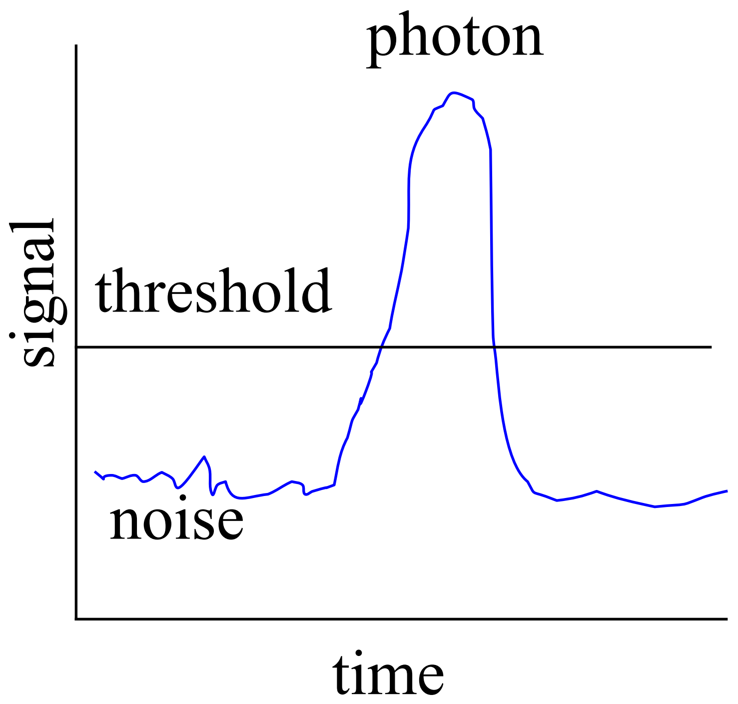
- Modulation Transfer Function (MTF) Example

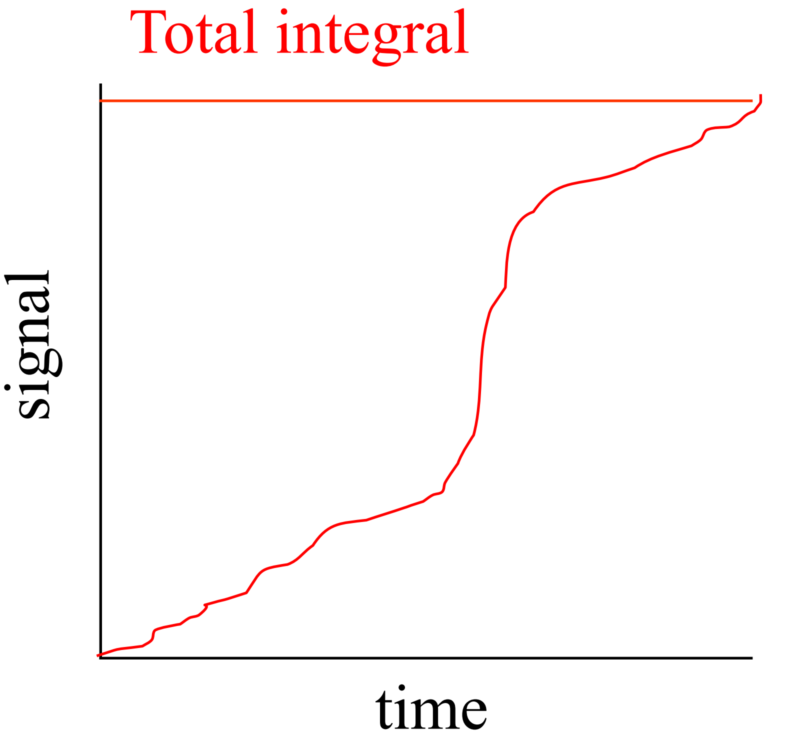
Ideal: $$contrast = \frac{100 - 0}{100 + 0} = 1.0$$

Effect of noise: $$contrast = \frac{150 - 50}{150 + 50} = 0.5$$

Effect of PSF: $$contrast = \frac{75 - 25}{75 + 25} = 0.5$$

Counting versus Integrating





Low noise **Fast**

Various 2D systems used at Synchrotrons:

- Charge Coupled Devices: CCD
- Hybrid Pixel Array Detectors: HPAD
- Monolithic Active Pixel Sensors: MAPs; CMOS imagers

The current generation 2D detectors: Hybrid Pixel Array Detectors

What are they?

and

why are they so good?

Hybrid Pixel Array Detector (HPAD)

Diode Detection Layer

- Fully depleted, high resistivity
- Direct x-ray conversion
- Silicon, GaAs, CdTe, etc.

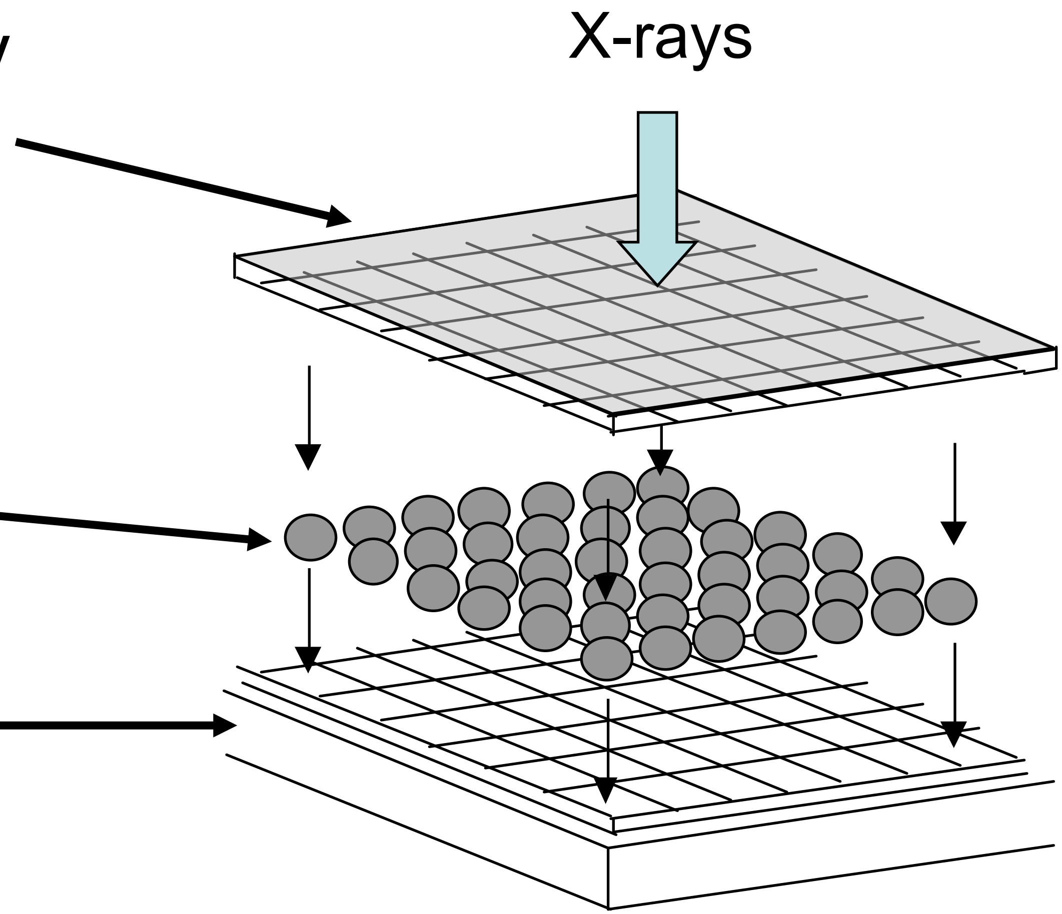
Connecting Bumps

- Solder or indium
- 1 per pixel

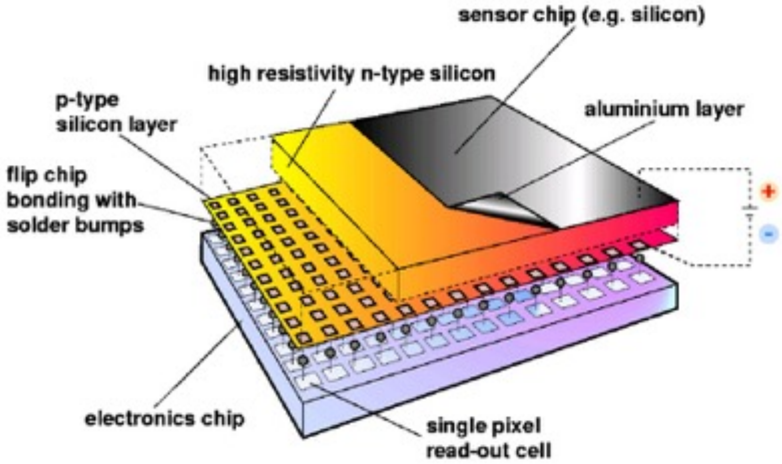
CMOS Layer

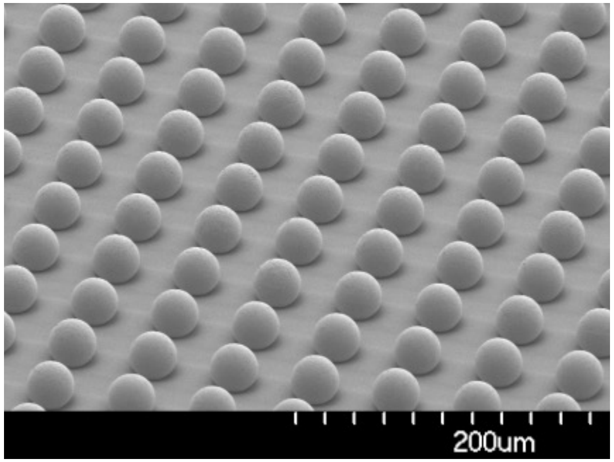
- Signal processing
- Signal storage & output

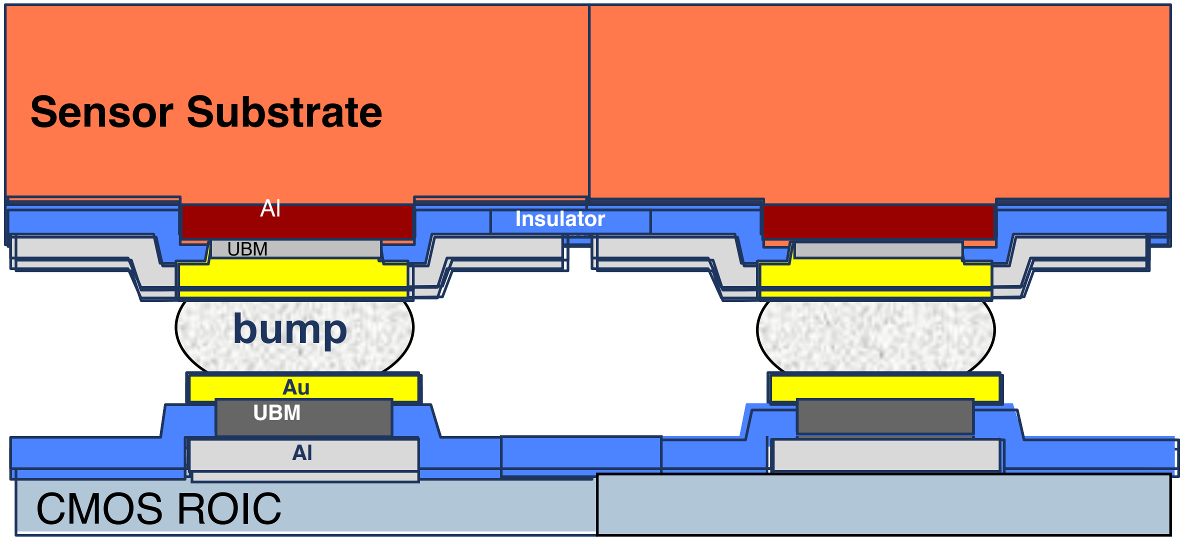
Gives enormous flexibility!



The new generation: Medipix et al.



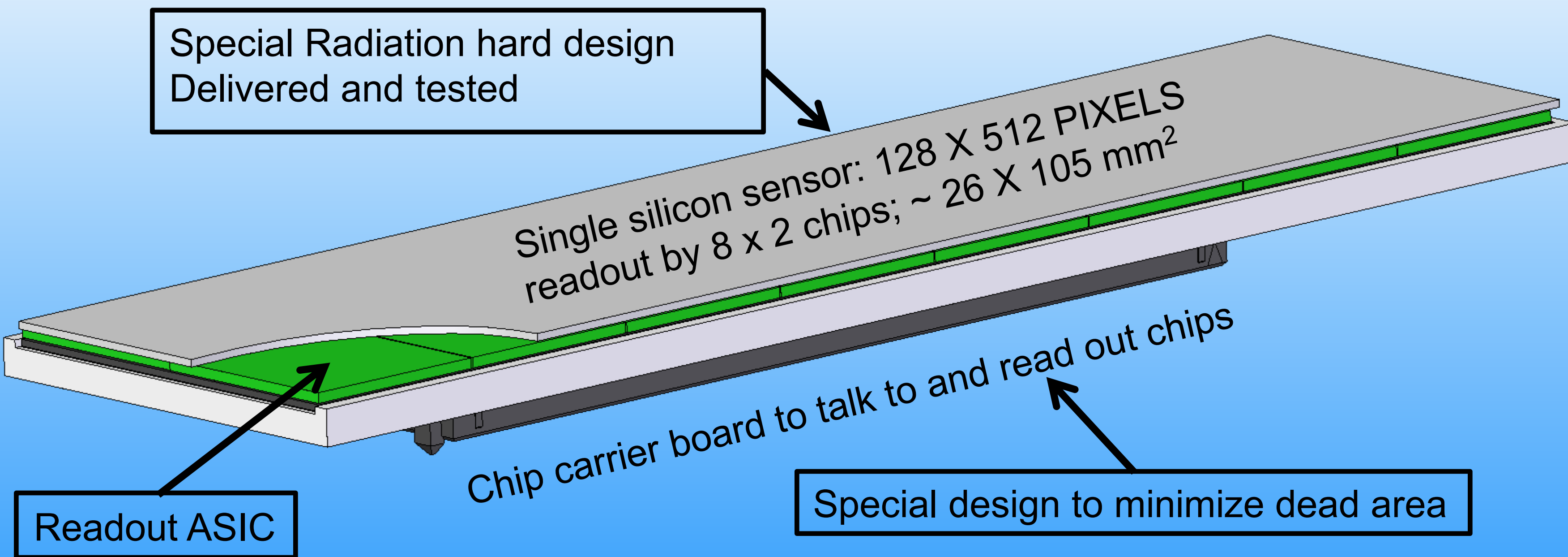




Why are HPADs so popular ?

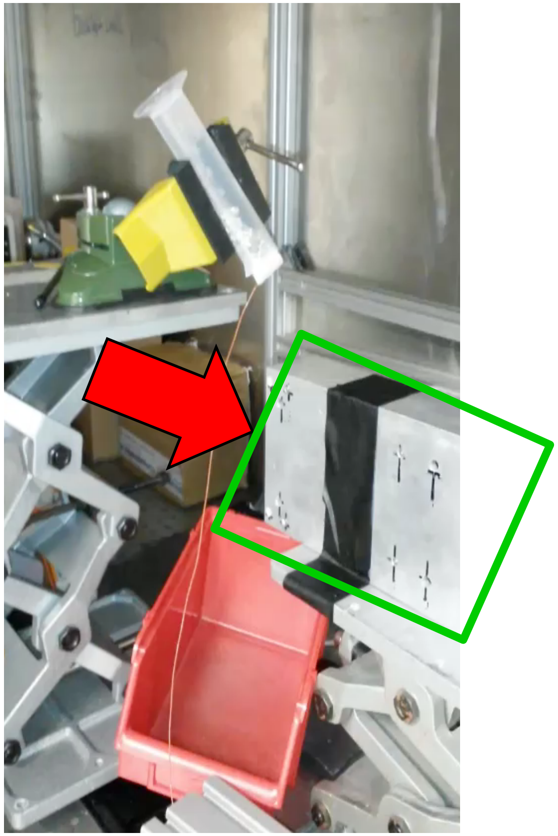
- Custom design of functionality: you design your readout chip specific for your application (unlike CCDs).
- Can do photon counting ➔ “no” noise.
- Can do photon integration ➔ fast
- Direct detection ➔ good spatial resolution
- Massive parallel detection ➔ high flux
- But: development takes long and is expensive.

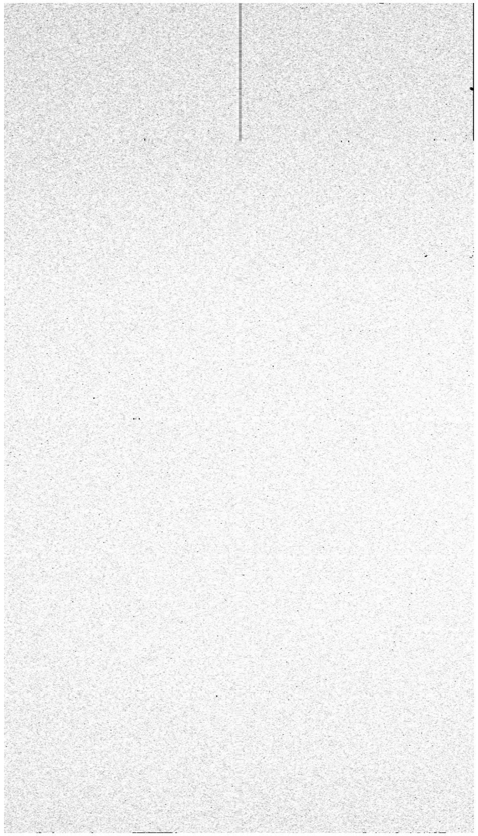
HPAD Front-end modules



Detector Modules

LAMBDA at 2000 fps





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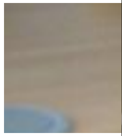
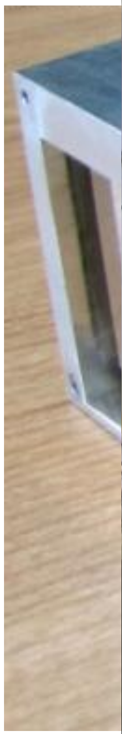
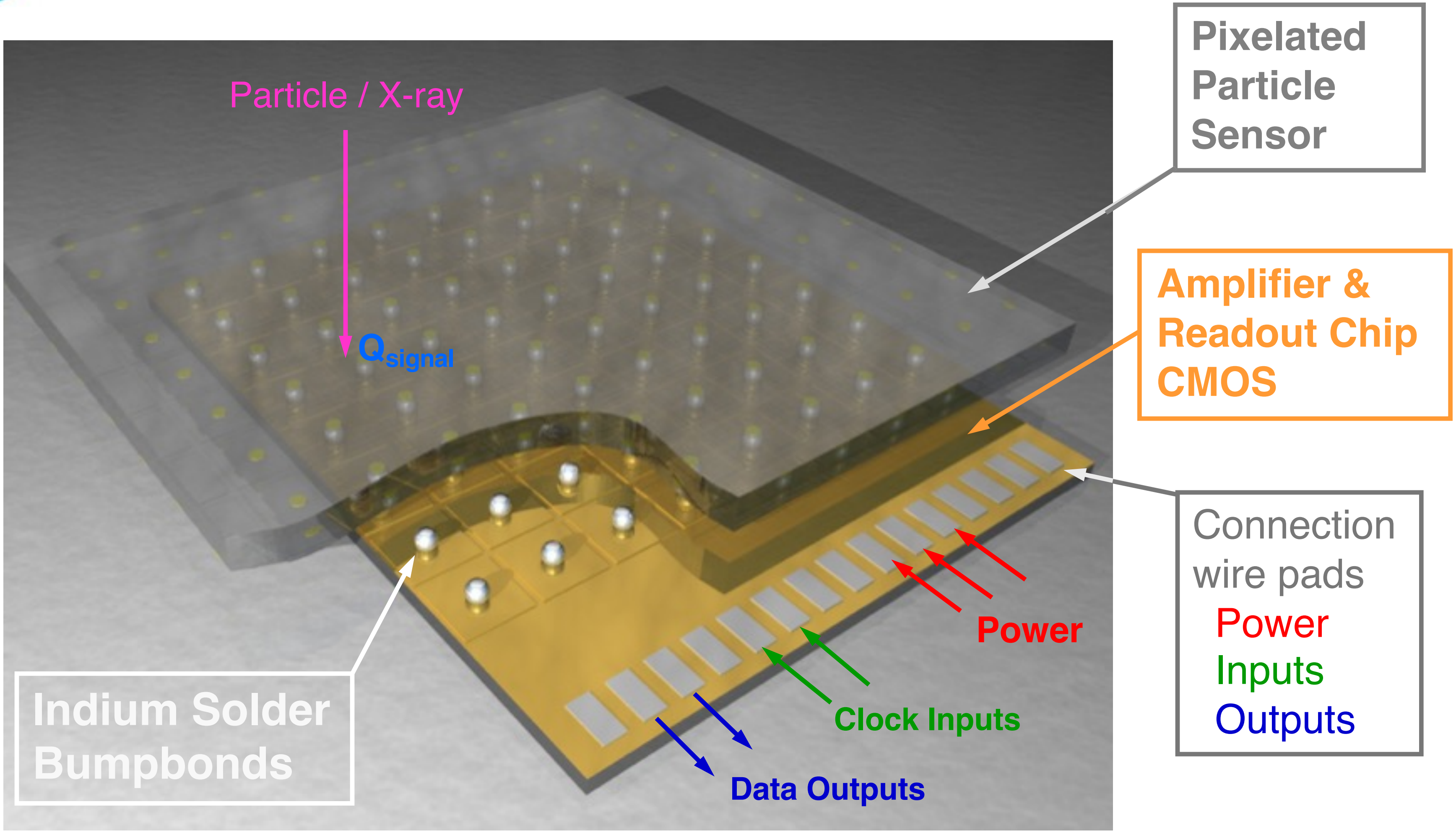


Det



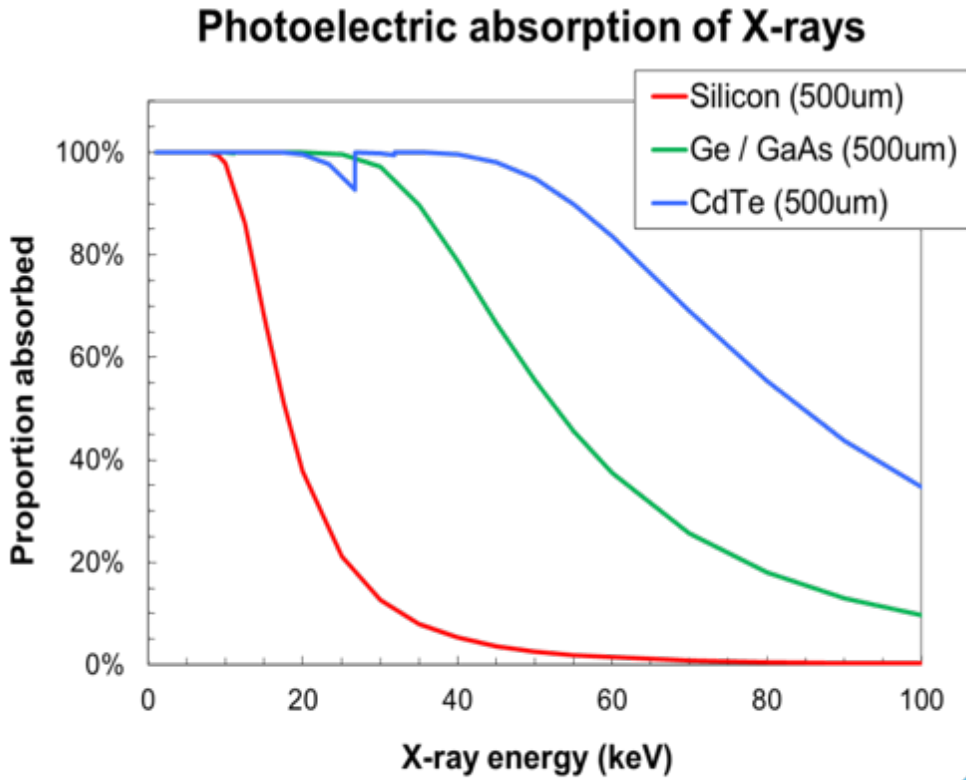
Hybrid Pixel Detectors

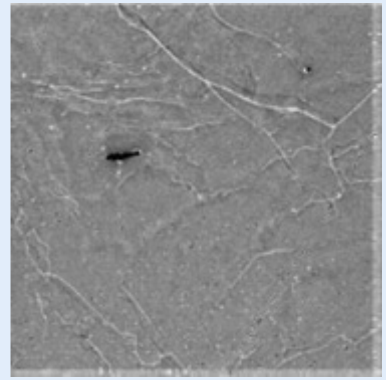
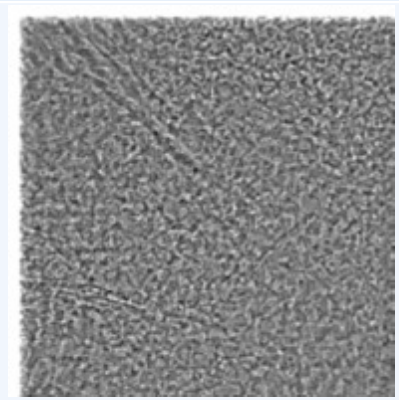
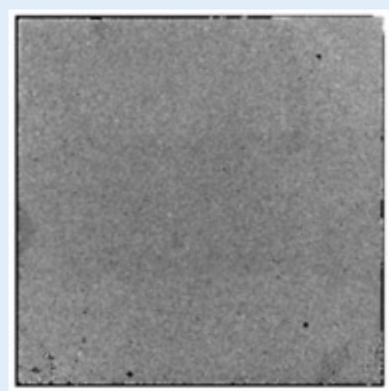


Particle / X-ray → Signal Charge → Electr. Amplifier → Readout → Digital Data

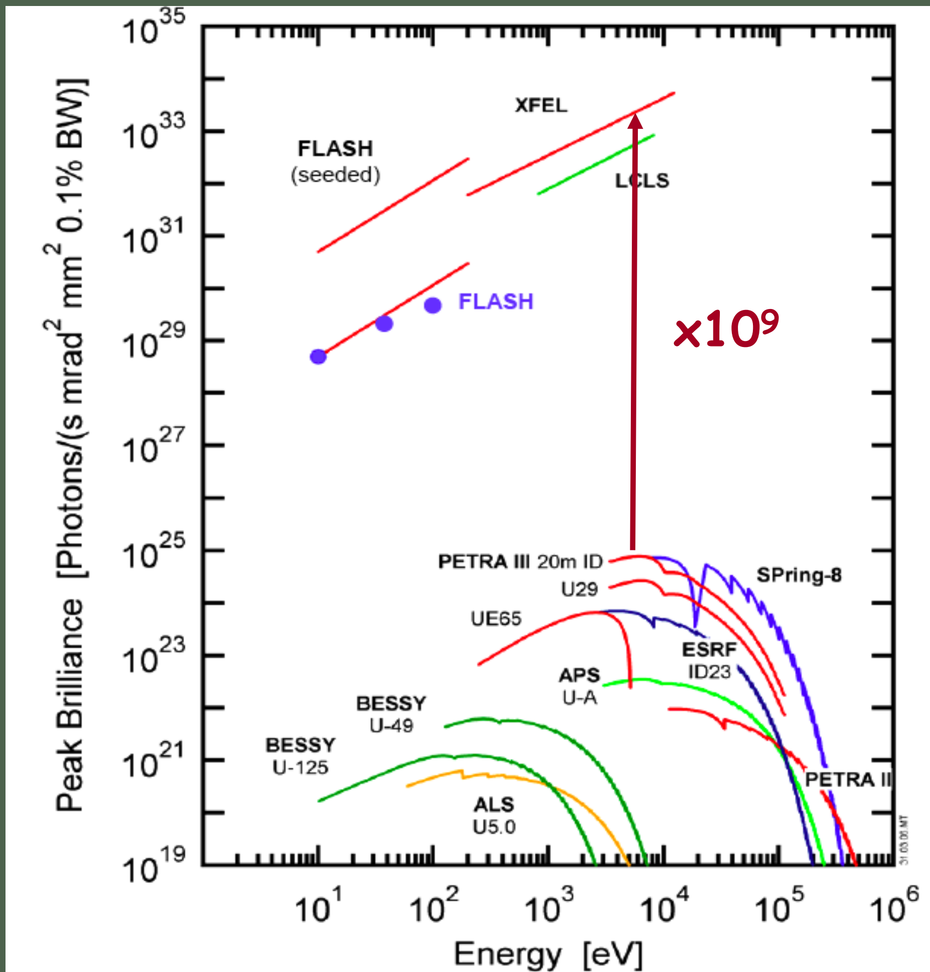
High-Z pixel detectors

- 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
  - Gallium arsenide
  - Cadmium telluride
  - Germanium



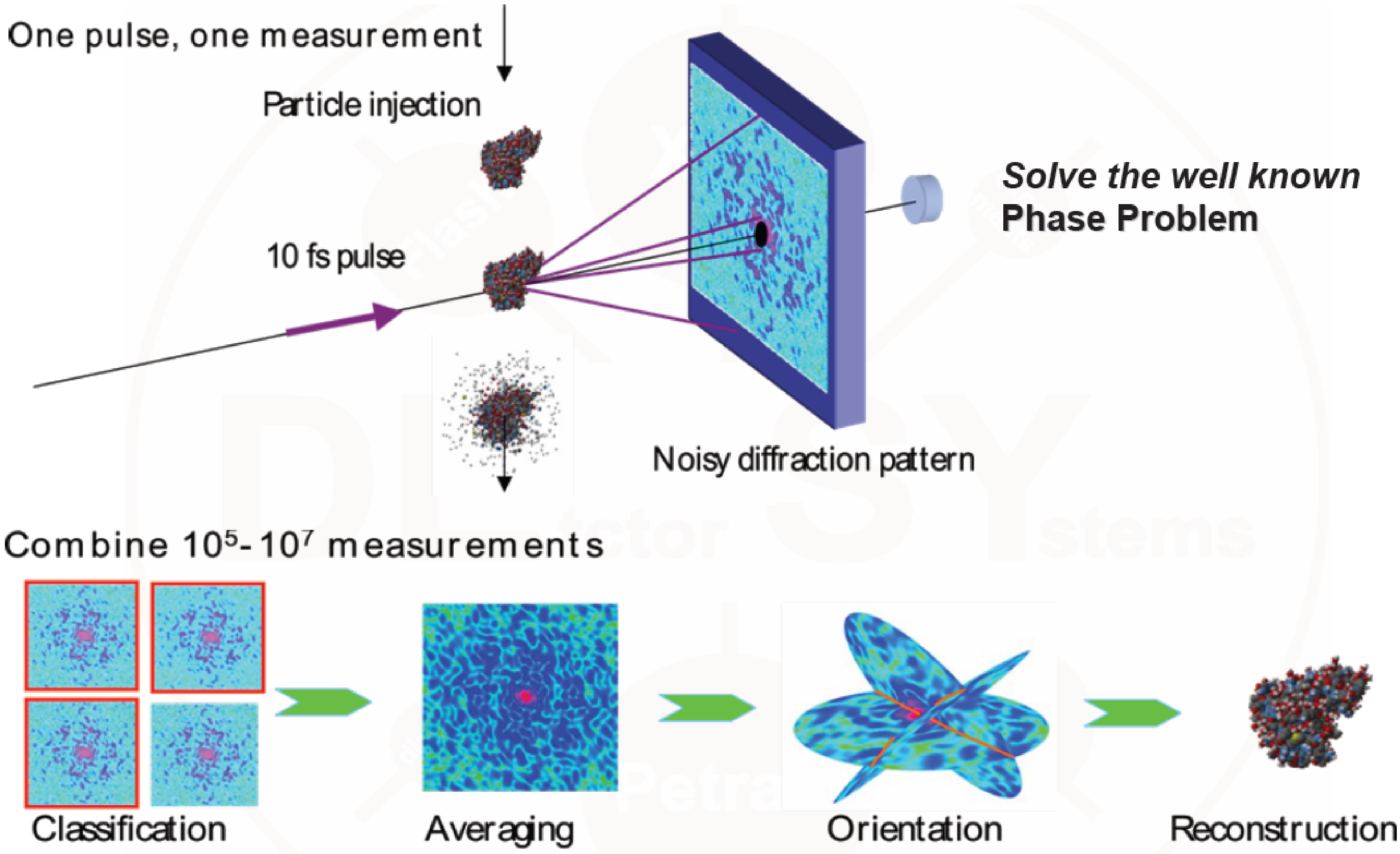
Material	Status	Raw image quality	Other pros/cons
Cadmium telluride	Established technology		Highest QE > 50keV Slow progress
Gallium arsenide	New production method, quick progress		Flatfield correction greatly improves images
Germanium	Newer development, still need to engineer system for beamline		High uniformity Cooling to -100 C required

The FEL-Challenge: Different Science



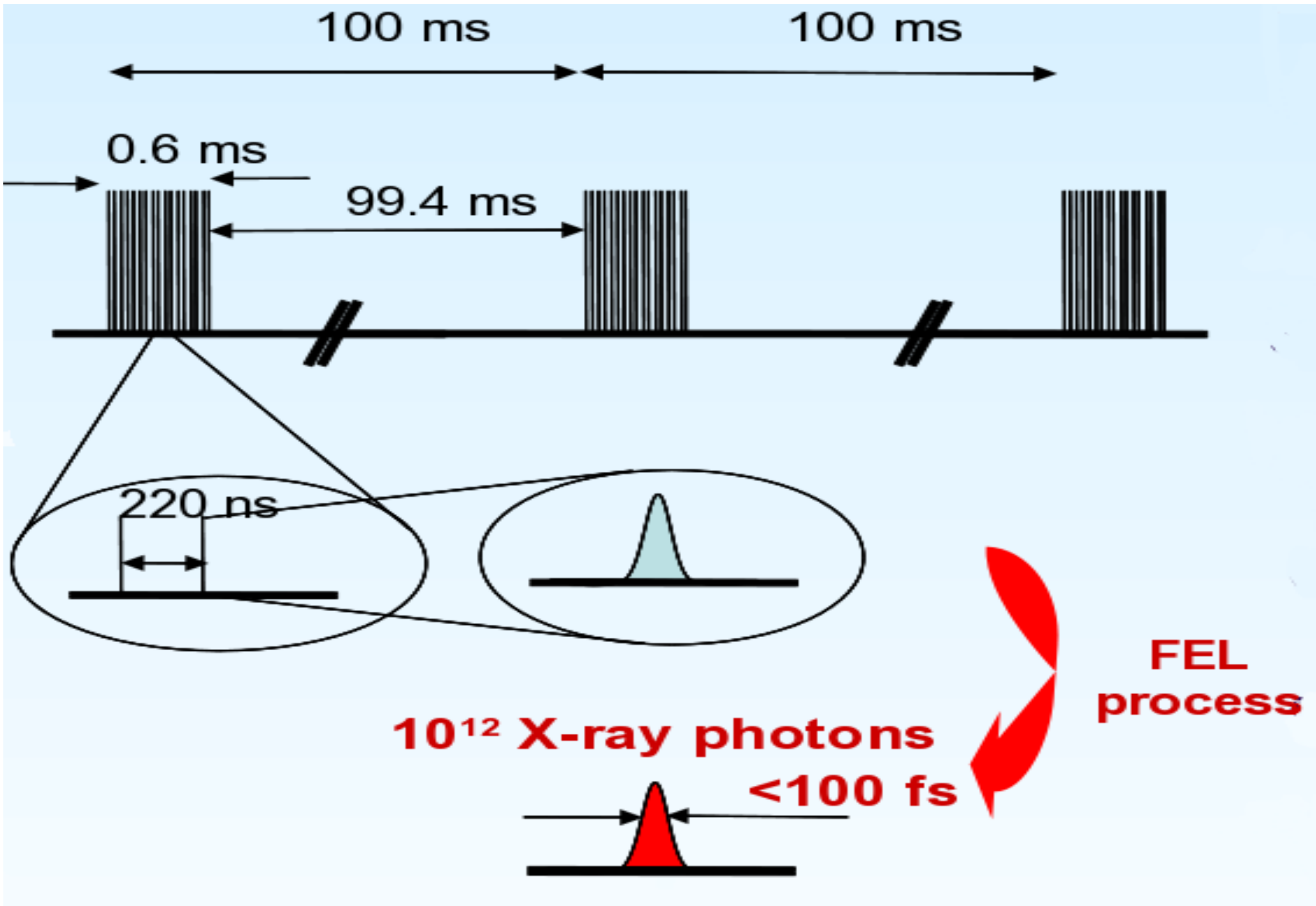
- Completely new science
- Fast science 100 fsec
- "Single shot" science

One of the Holy Grails

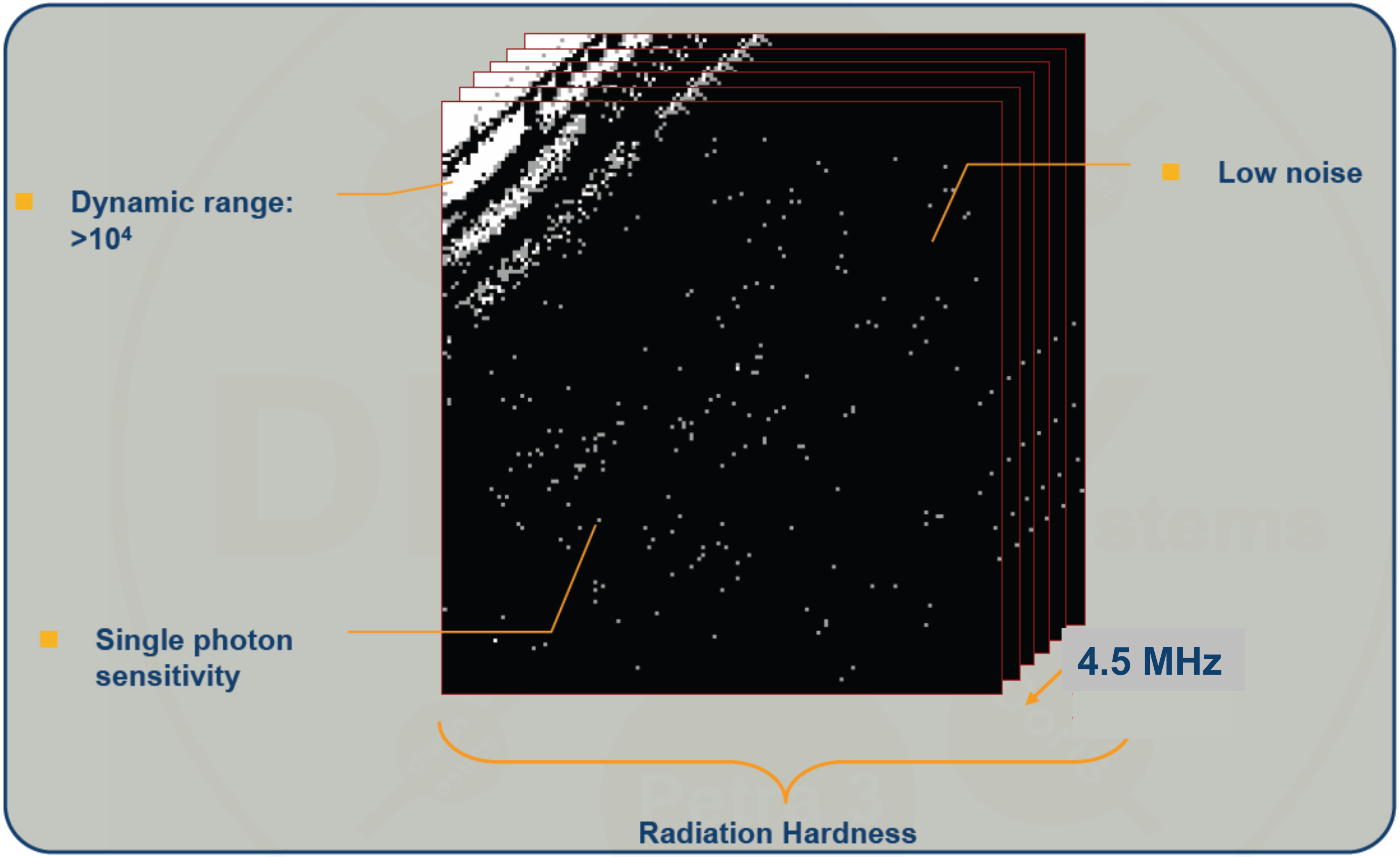


K. J. Gaffney and H. N. Chapman,
Science 8 June 2007

The European Free Electron Laser



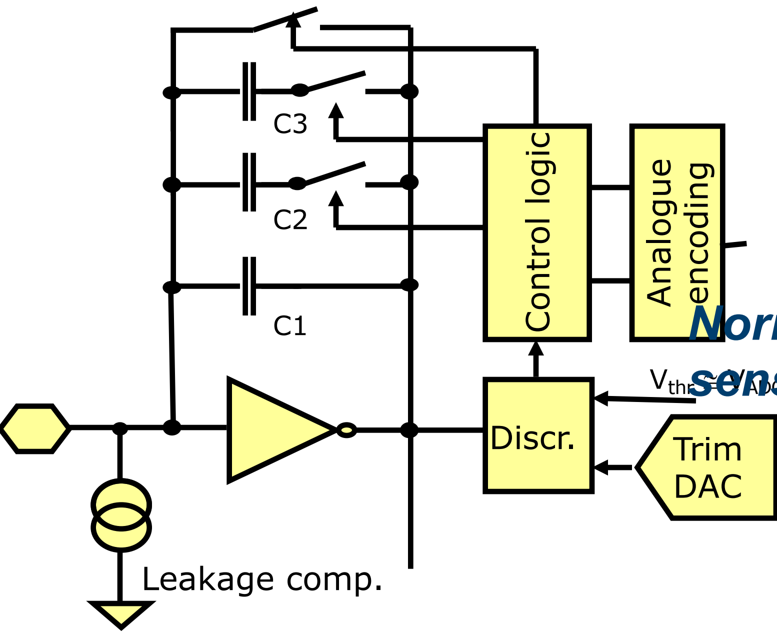
What are the Challenges ?



The Adaptive Gain Integrating Pixel Detector

High dynamic range:

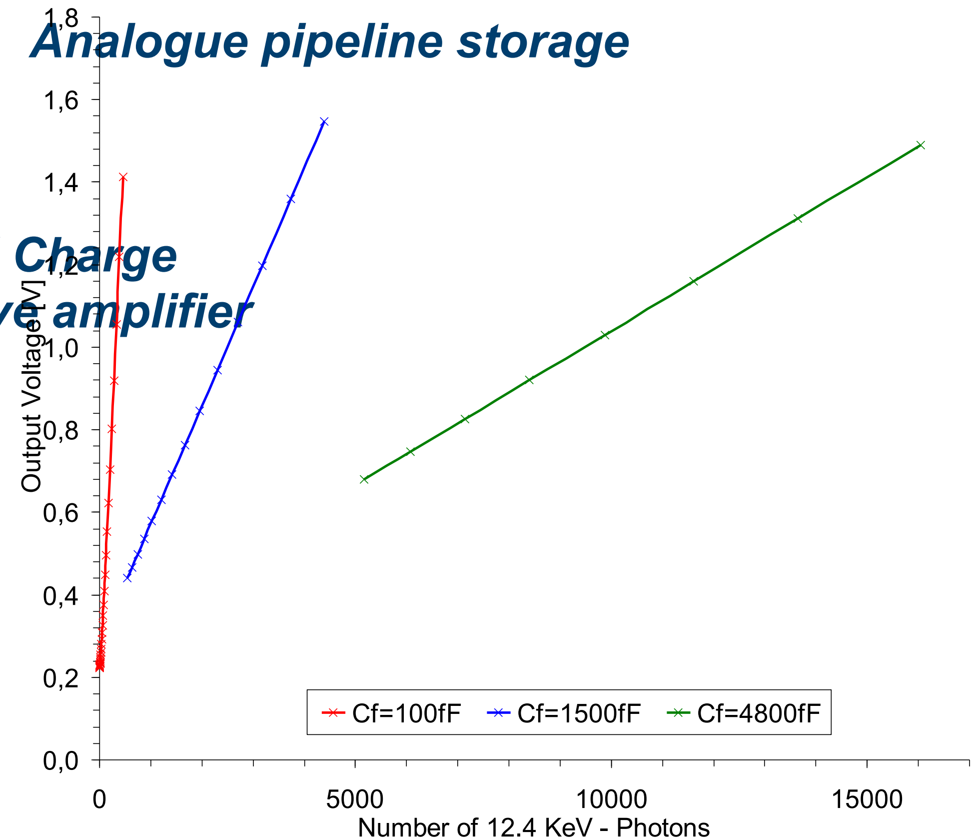
Dynamically gain switching system



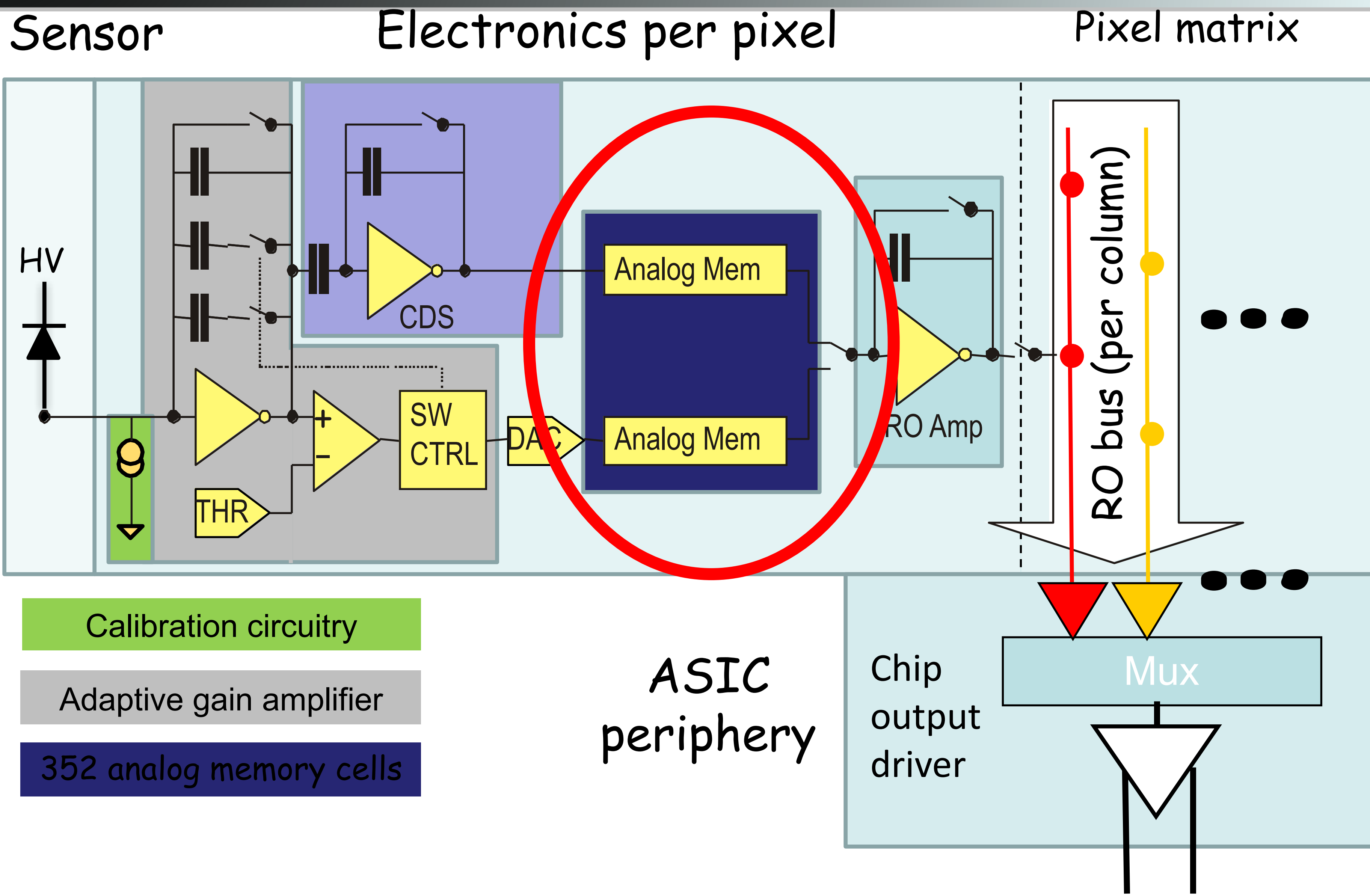
Normal Charge sensitive amplifier

Extremely fast readout (200ns):

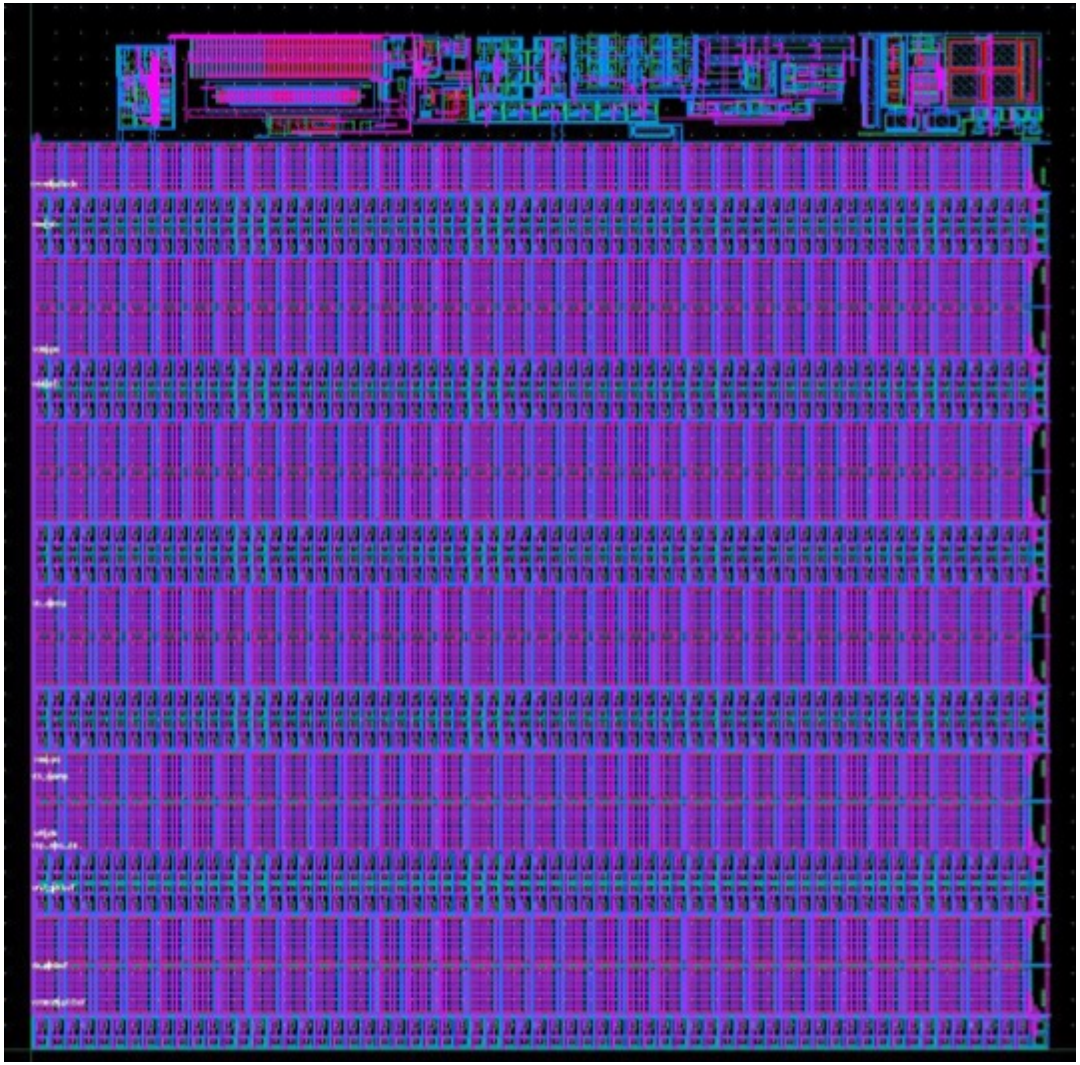
Analogue pipeline storage



The AGIPD RO-Principle

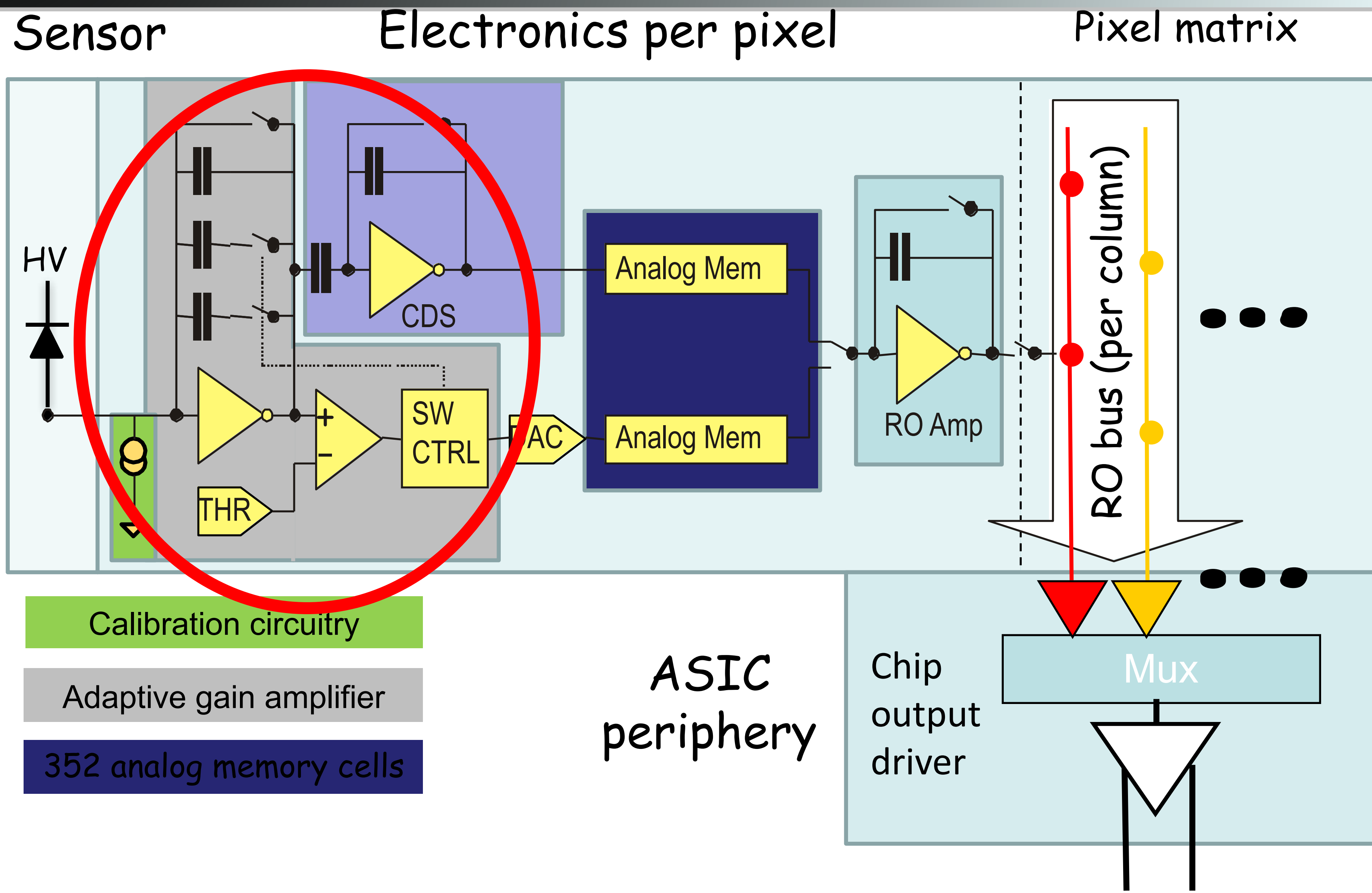


AGIPD 1.0 Pixel Electronics

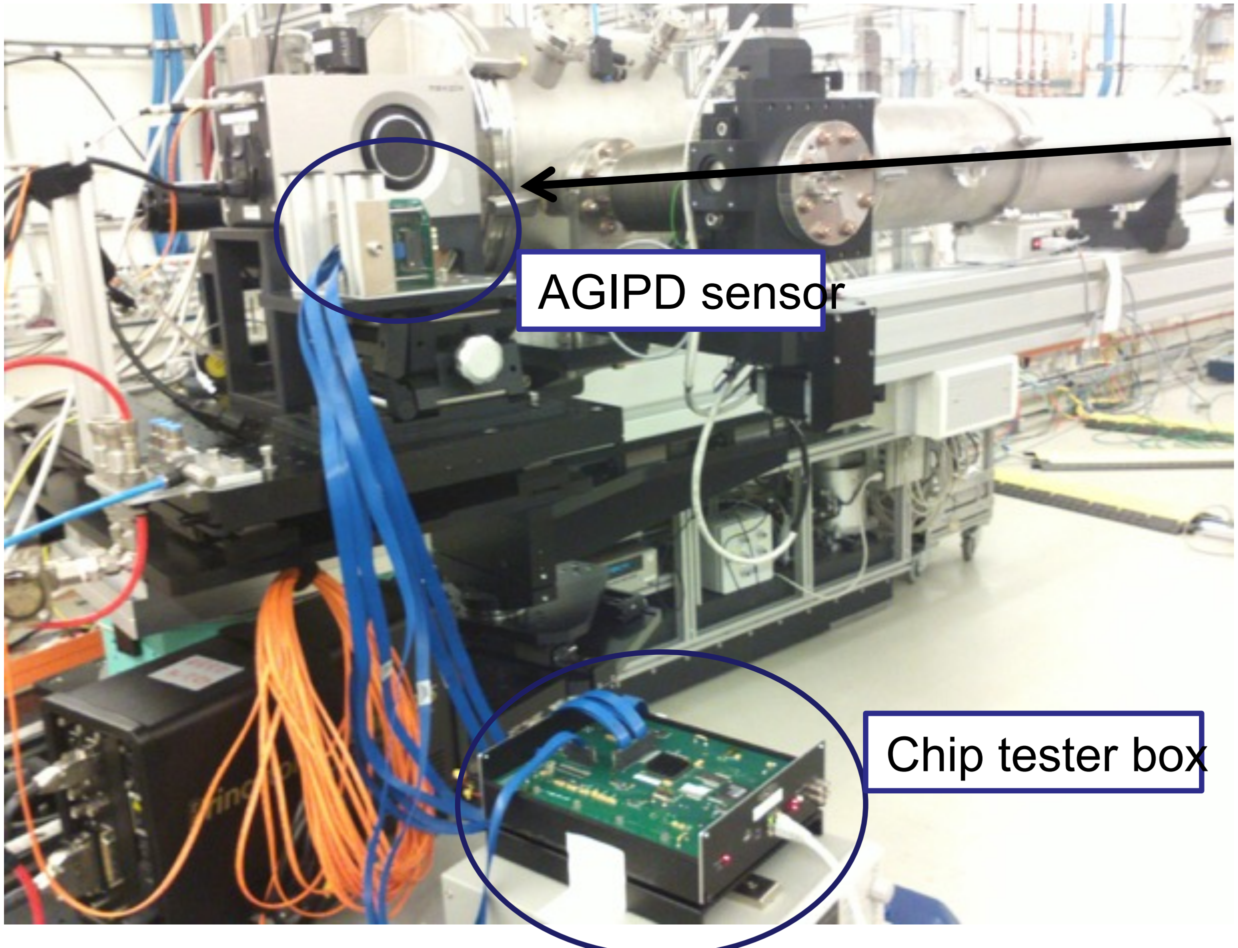


- 200 x 200 micron^2 pixels
- 352 storage cells + veto possibilities.
- Minumum signal ~ 300 e$^-$ =
  0.1 photon of 12.4keV
- Maximum signal ~ 33 10^6 e$^-$ =
  10^4 photons of 12.4keV
- 4.5 MHz frame rate
- 64 x 64 pixels per ASIC
- 2 x 8 ASICs per module (128x512 pixels, no dead area)
- 4 modules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

The AGIPD RO-Principle



At the P10 beamline

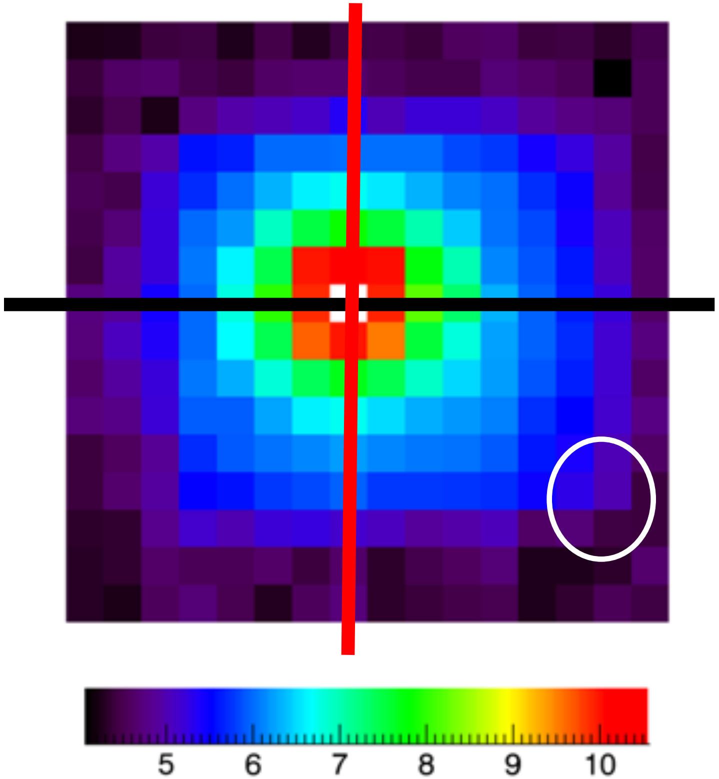


Beam direction (coming from sample)

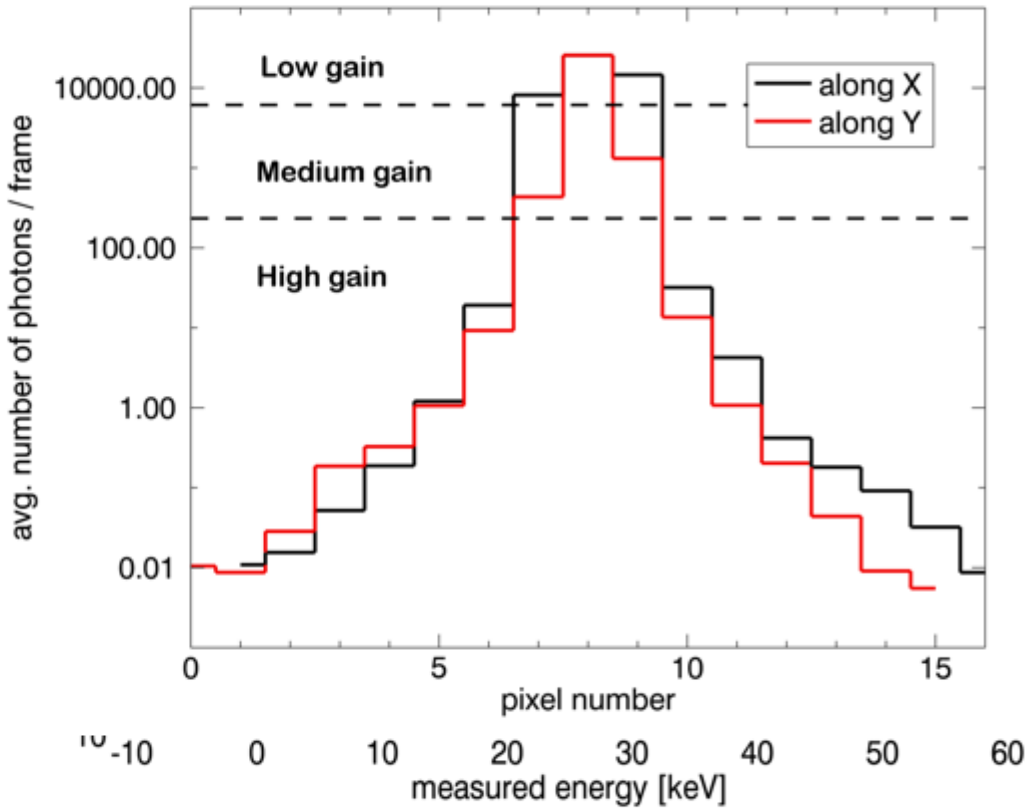
It took about 1 ½ hours to set up, after about 2 hours we saw the first image

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

Looking at the direct beam



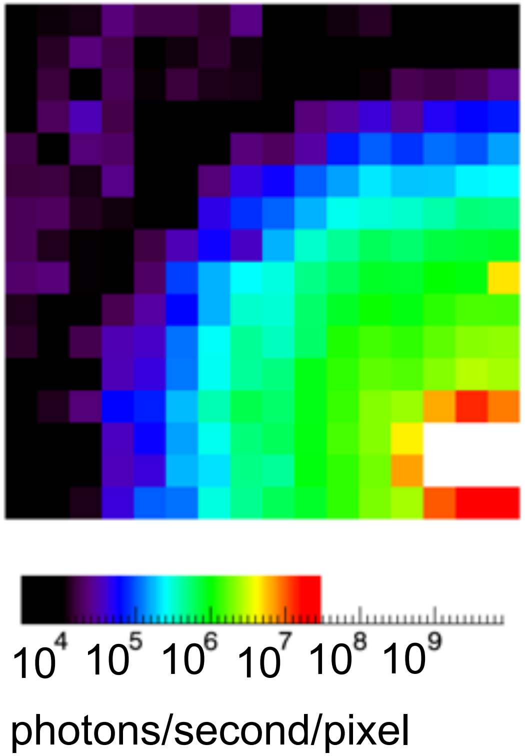
photons/second
Logarithmic color scale

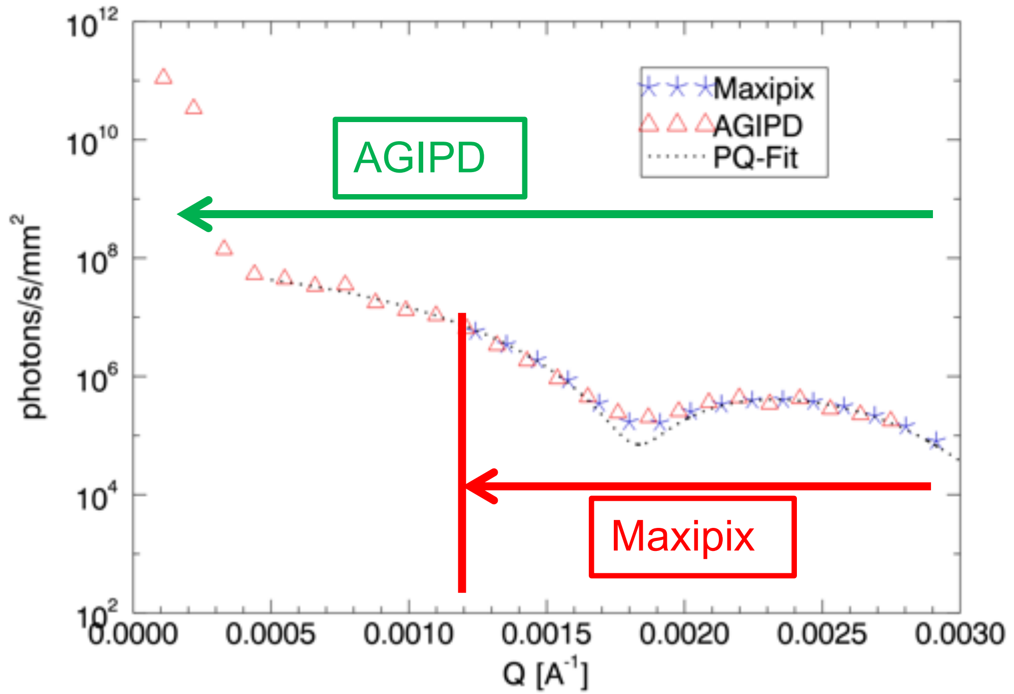


Gain switching experimentally proven

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

Some SAXS measurements





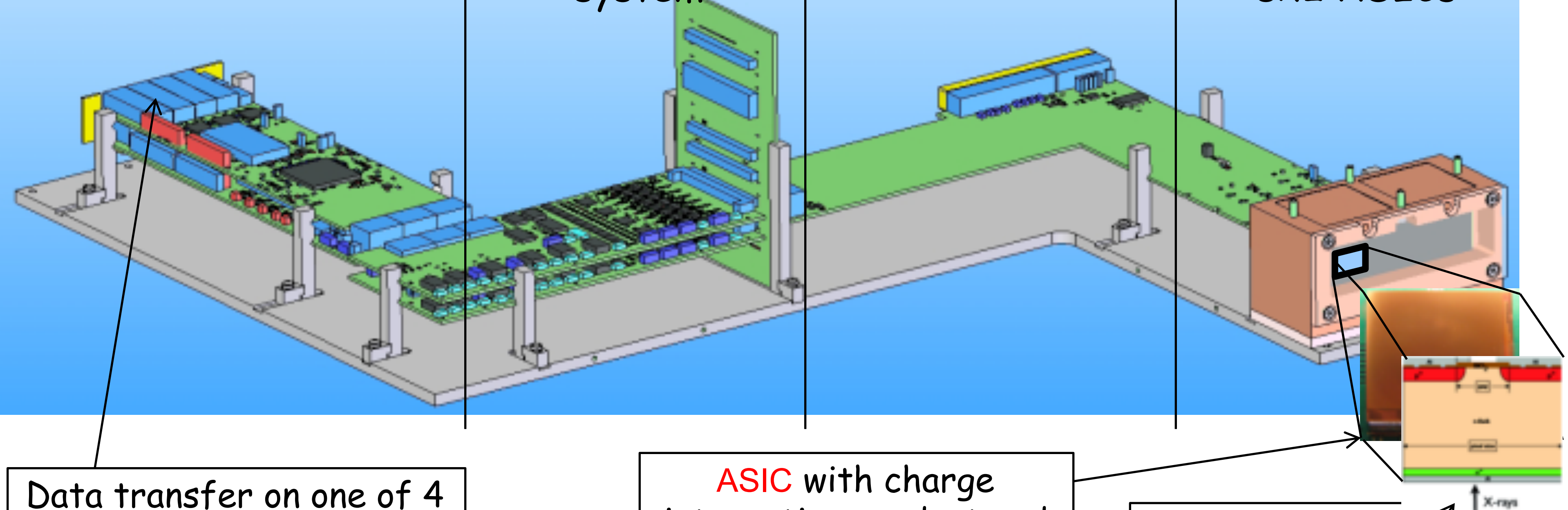
Scientific quality data obtained

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

Detector structure

AGIPD 1M consists of 16 detector modules:

Digital part: FPGA daughter board on carrier board	Analogue part: 64 ADC channels on a two board system	Vacuum board with a flexible connection	Detector head: 512x128 pixel sensor bump bonded to 8x2 ASICs



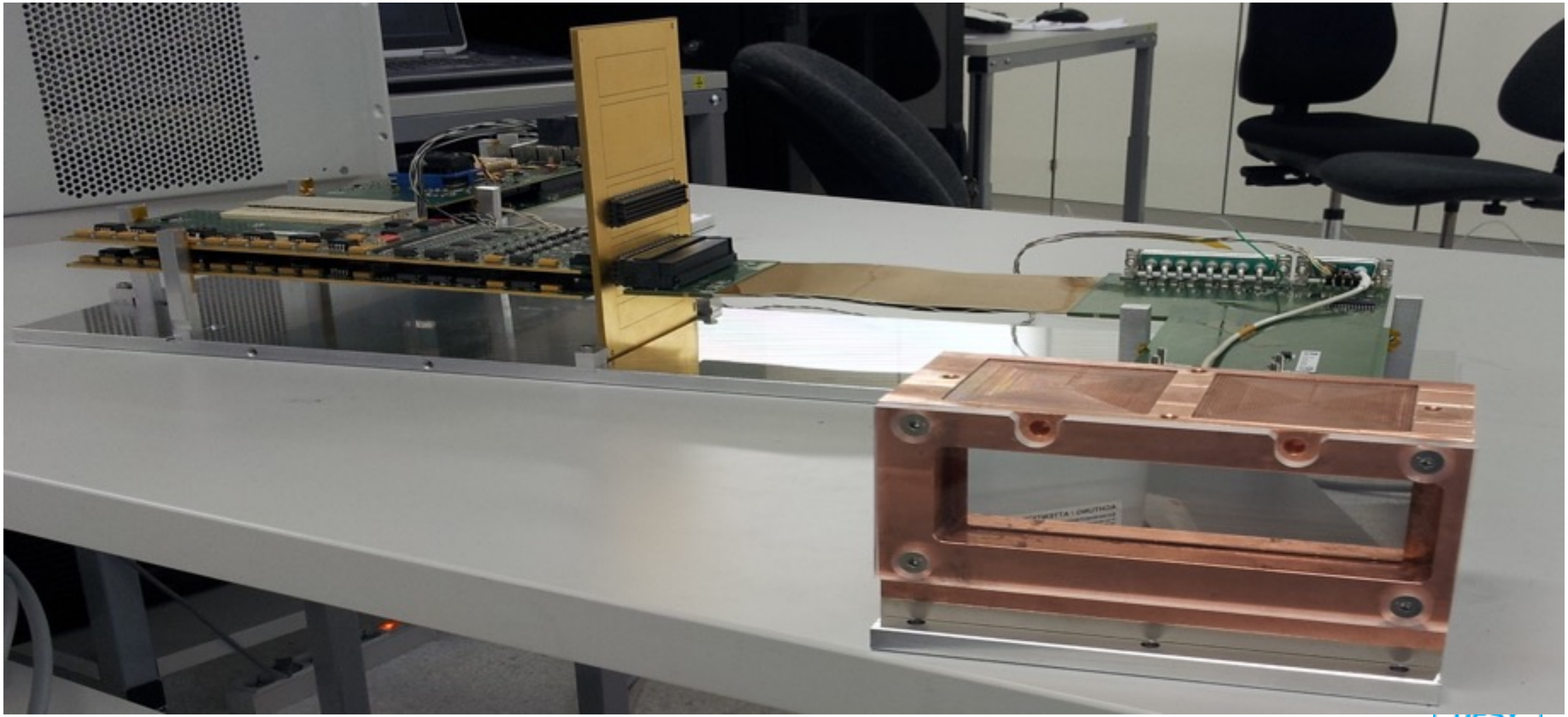
Data transfer on one of 4 10G compatible standard ethernet links via TCP/UDP

ASIC with charge integrating readout and analogue frame storage behind each pixel

Si-Sensor with $(200\mu m)^2$ pixels

Module construction

- 2 x 8 chips = 128 x 512 pixels
- 5 electronic boards per modules
- 16 modules per detector ➔ 80 (+ 4) electronic boards per detector



6.5Mhz frame rate at APS

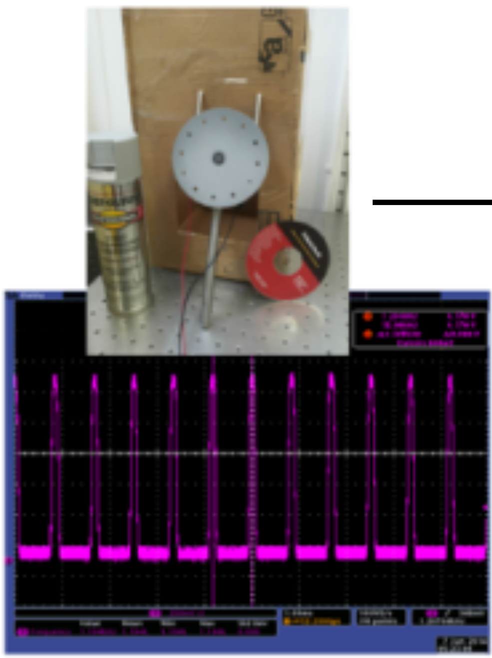
Single bunch imaging – a challenge to find processes fast enough

Experimental setup

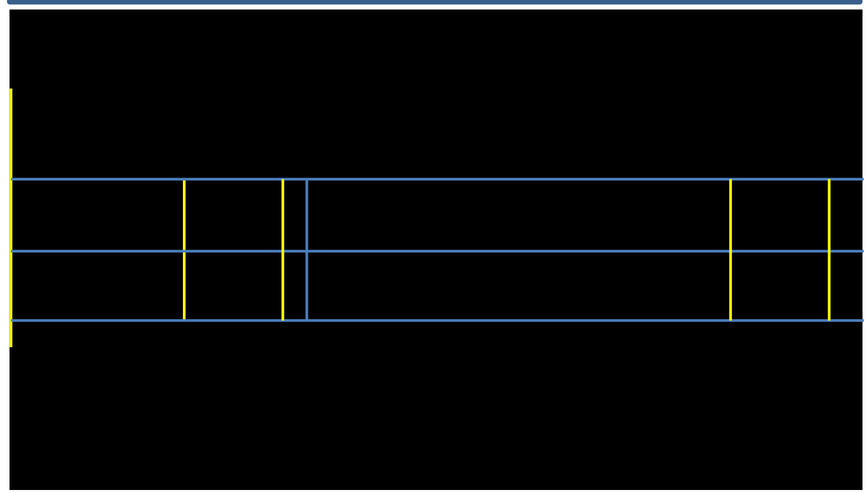
- Drilled equidistant holes into a DVD
- DVD painted with zinc to increase absorption
- Mounted DVD on a fast electric motor
- Measurement of hole to hole frequency with diode and oscilloscope: 1.208kHz

Calculation for burst imaging

- APS bunch spacing: t = 154ns
- Number of pixels crossed during burst of 352 images: ≈ 8
- Pixel size: 200µm

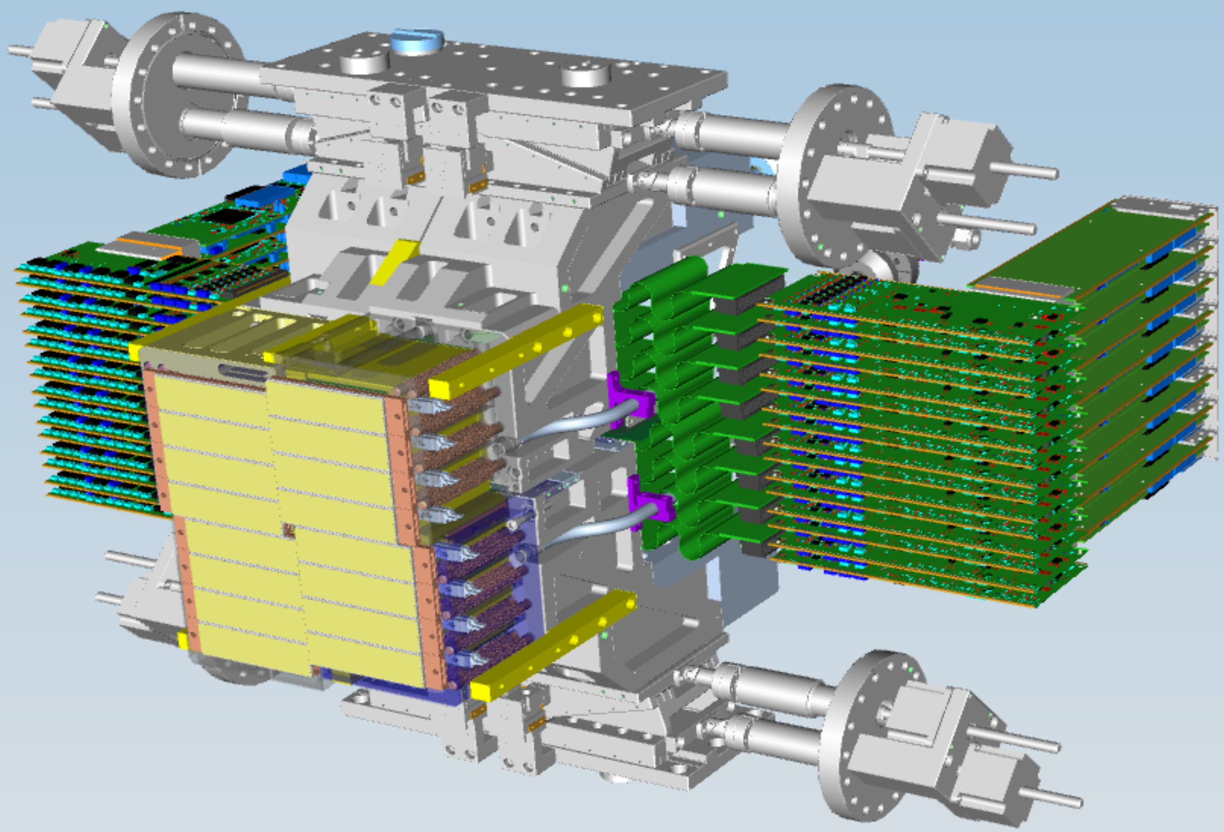


V_{disc}, AGIPD = 29.51m/s
≈ V_{disc}, Laser = 29.83m/s

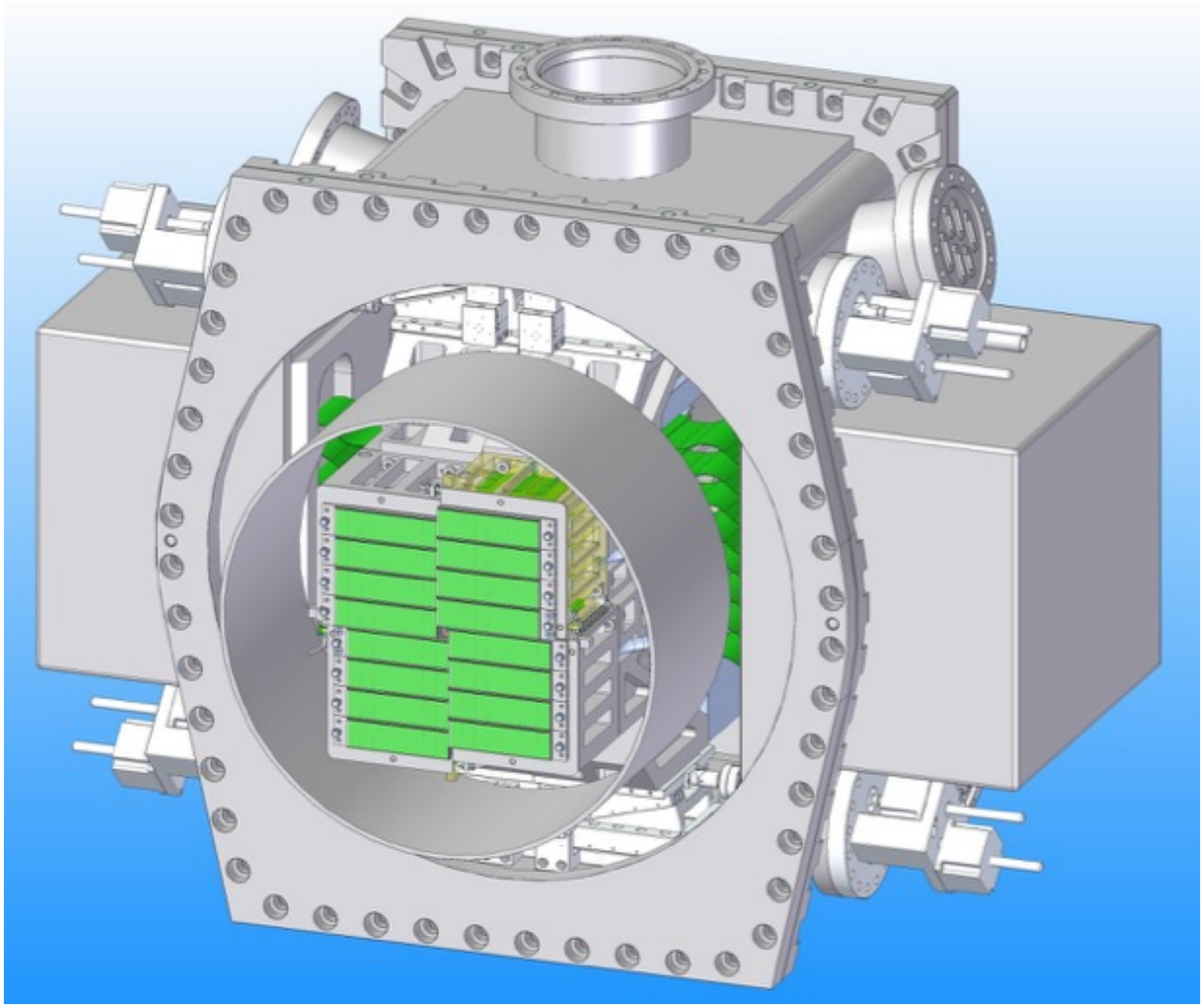


Single bunch imaging is possible even at a repetition rate of 6.5MHz!!

The final detector consists of 4 quadrants.
Each quadrant is independently movable via a motion system to shape the central hole



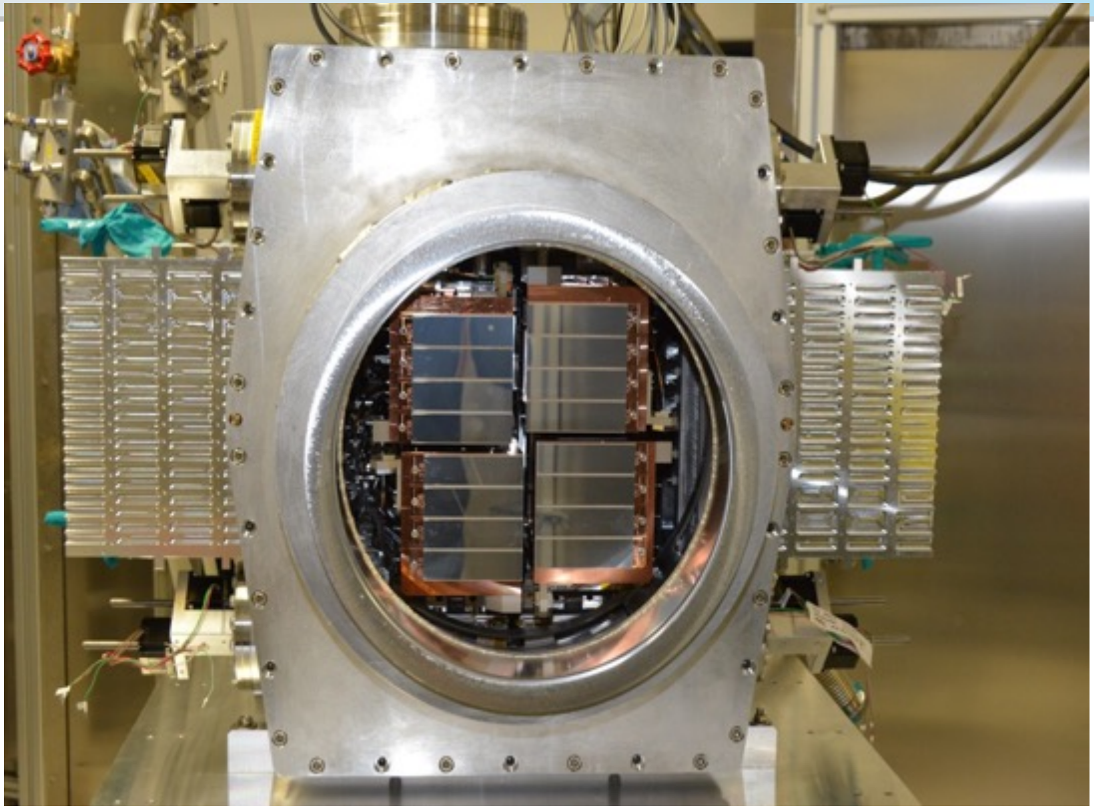
The final system

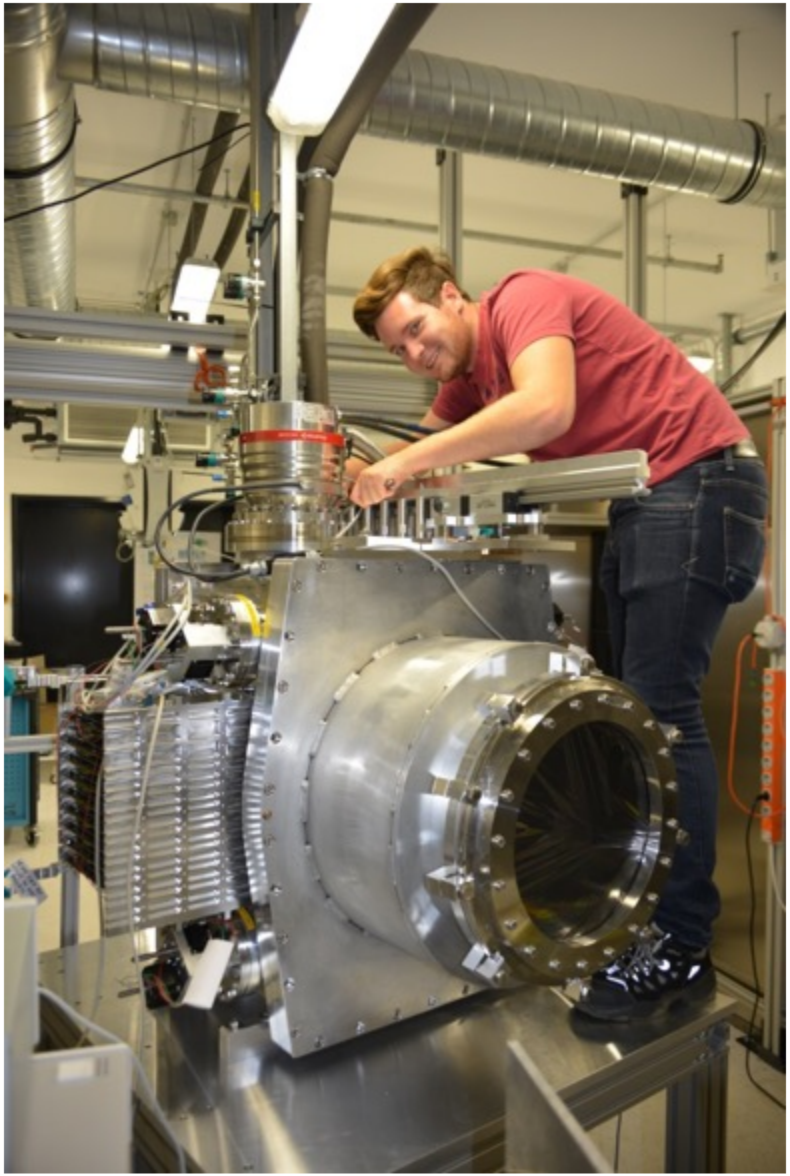


- 1 Million pixels
- 4 movable quadrants
- Central hole
- In vacuum
- -20 C
- ~300 kg

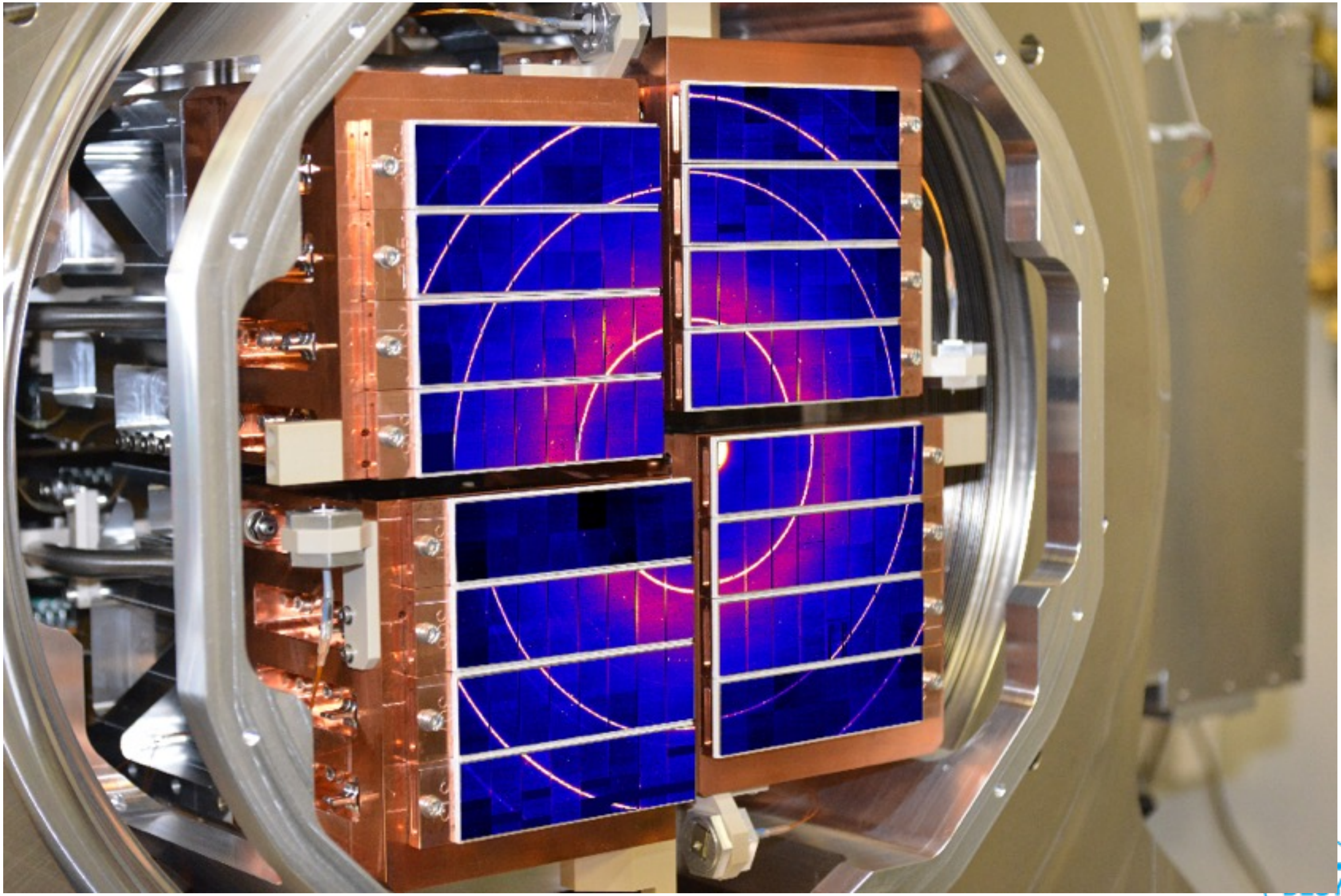
The real thing

AGIPD





AGIPD during the inauguration XFEL



The first experiment at XFEL SPB/SFX was an open collaboration

SPB/SFX Instrument Scientists
Adrian Mancuso
Richard Bean
Klaus Giewekemeyer
Marjan Hadian
Yoonhee Kim
Romain Letrun
Marc Messerschmidt
Grant Mills
Adam Round
Tokushi Sato
Marcin Sikorski
Stephan Stern
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Britta Weinhausen

XFEL Detector
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Alexander Kaukher
Astrid Münnich
Jolanta Sztuk-Dambietz

AGIPD
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Aschkan Allahgholi
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Alexander Klyuev
Manuela Kuhn
Torsten Laurus
Davide Mezza
Jennifer Poehlsen
Ulrich Trunk

Samples
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Carolin Seuring
Imrich Barak
Sadia Bari
Christian Betzel
Matthew Coleman
Chelsie Conrad
Connie Darmanin
XY Fang
Petra Fromme
Raimund Fromme
S. Holmes
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Iosifina Sarrou
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Miriam Barthelmess
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Ilme Schlichting
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John Spence
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Kartik Ayyer
Wolfgang Brehm
Aaron Brewster
Henry Chapman
Florian Flachsenberg
Yaroslav Gevorkov
Helen Ginn
Rick Kirian
Filipe Maia
Valerio Mariani
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Keith Nugent
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Marvin Seibert
Natasha Stander
Pablo Villanueva-Perez
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Nadia Zatsepin

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Katerina Dörner
Rita Graceffa
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Kimon Filippakopoulos
Manfred Knaack
Siriyala Kujala
Luis Maia
Maurizio Manetti
Bartosz Poljancewicz
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Nasser Al-Qudami
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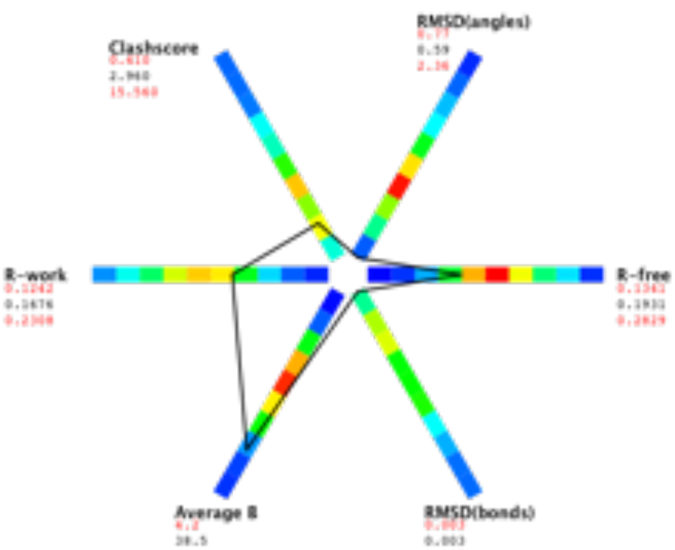
Andreas Beckmann
Valerii Bondar
Cyril Danilevski
Wajid Ehsan
Sergey Esenov
Hans Fangohr
Gero Flucke
Gabriele Giovanetti
Dennis Goeries
Burkhard Heisen
David Hickin
Anna Klimovskaia
Leonce Mekinda

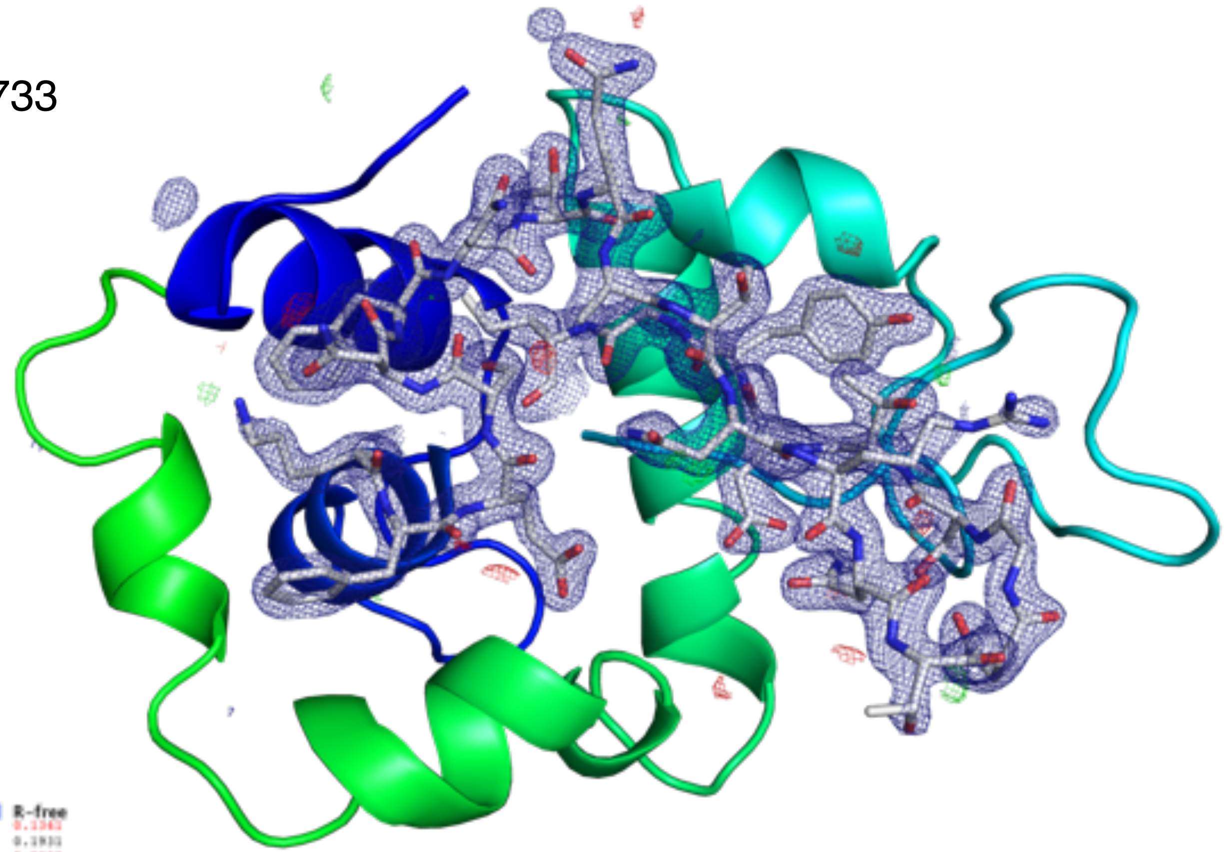
The initial analysis of the European XFEL data gives excellent densities

Number of frames: 44,699
Number of indexed frames: 24,733
Number of crystals: 26,755

Rsplit to 1.8 A: 12.0%
R_{work}/R_{free}: 0.168 / 0.193
Average B_{ISO}: 34.9 Å^2
RMSD bonds: 0.003 Å
RMSD angles: 0.592°



Comparison to other structures with same resolution



2mFo-DFc map (1.5σ) and mFo-DFc map (3σ) over residues 33-55 of lysozyme

Dominik Oberthur: Structure refinement
17 Nov 2017

Various 2D systems used at Synchrotrons:

- **Charge Coupled Devices: CCD**
- **Hybrid Pixel Array Detectors: HPAD**
- **Monolithic Active Pixel Sensors: MAPs; CMOS imagers**

Soft X-ray Imagers: Soft is Hard

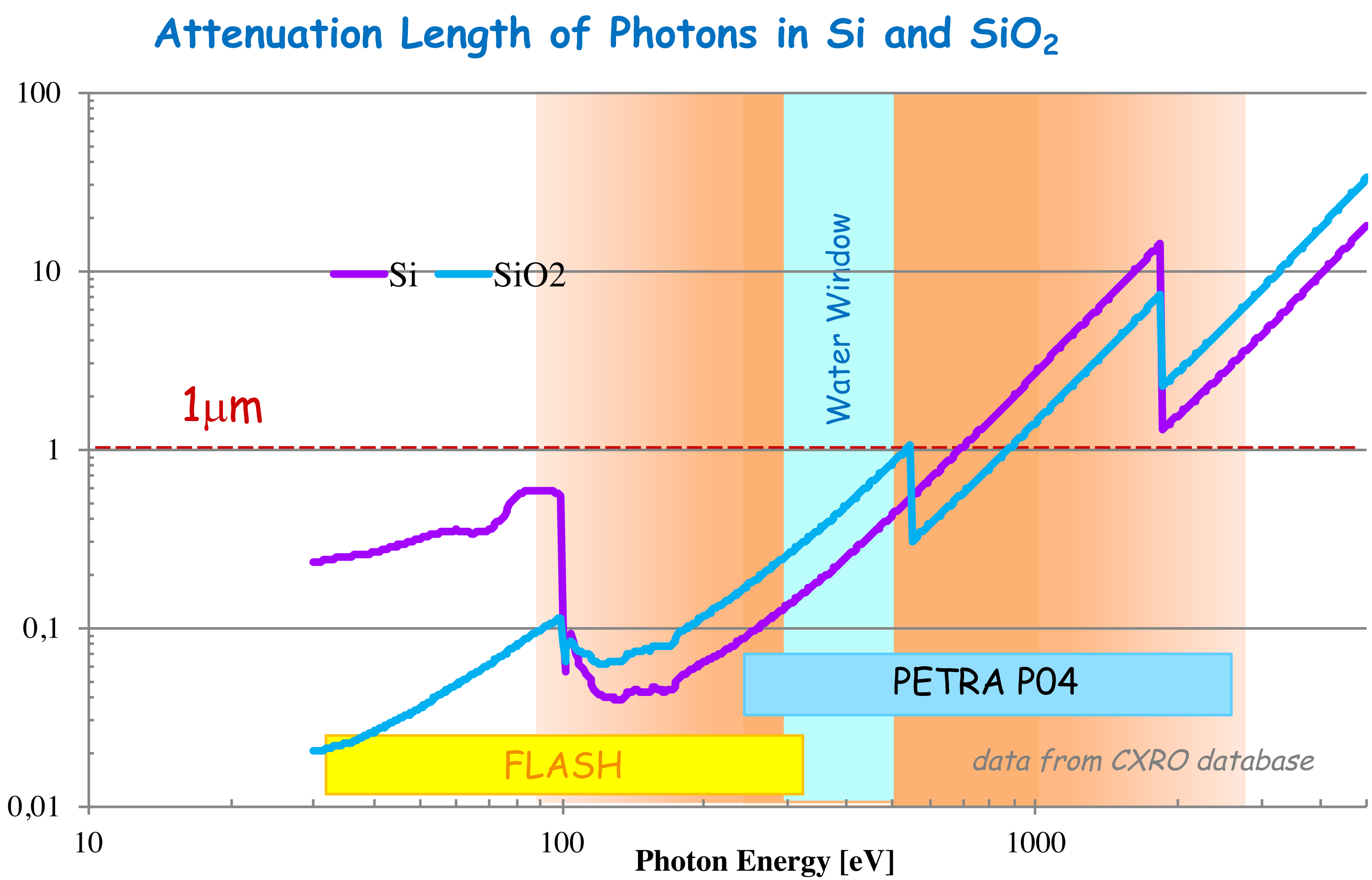
Soft X-ray Imaging is very important for:

- FEL science (soft X-ray FELs are cheaper than hard X-ray FELS)
- Biology
- Magnetism
- Atomic physics
- …
- …

But Soft X-ray Imaging is a neglected corner:

1. only few beamlines at large facilities
2. detecting soft X-rays is hard
    - It is difficult to get the photons in the detector
    - Photons don't create a strong signal

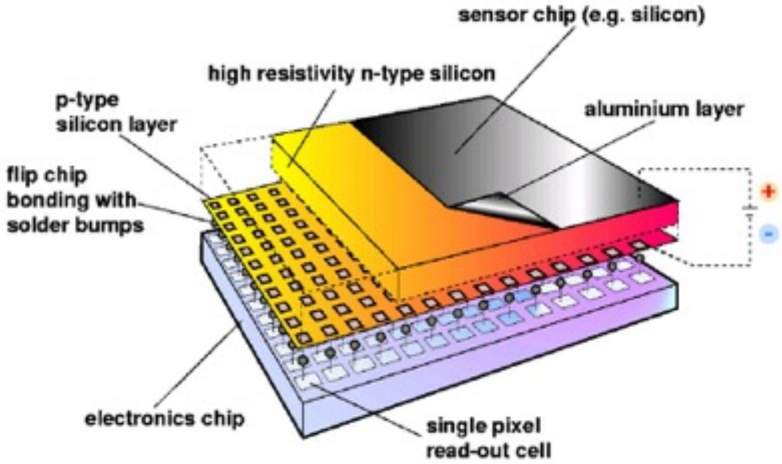
Soft X-ray Challenges – reaching the sensor

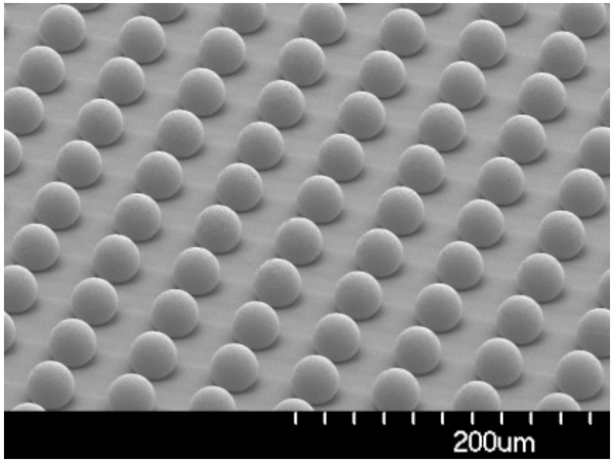


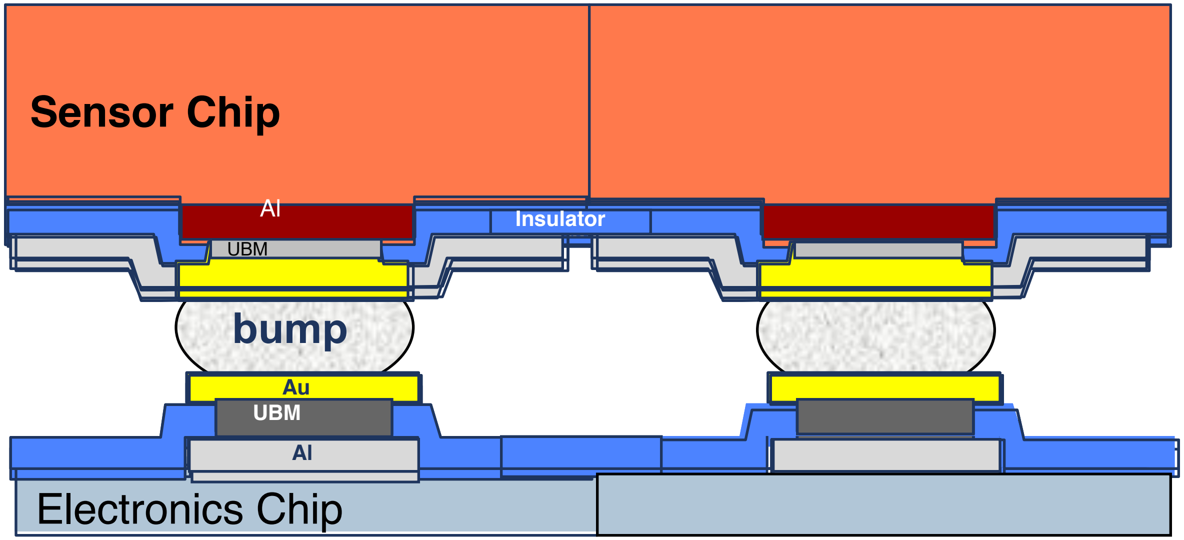
At (very) soft X-ray energies, QE is limited by passive window thickness!

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

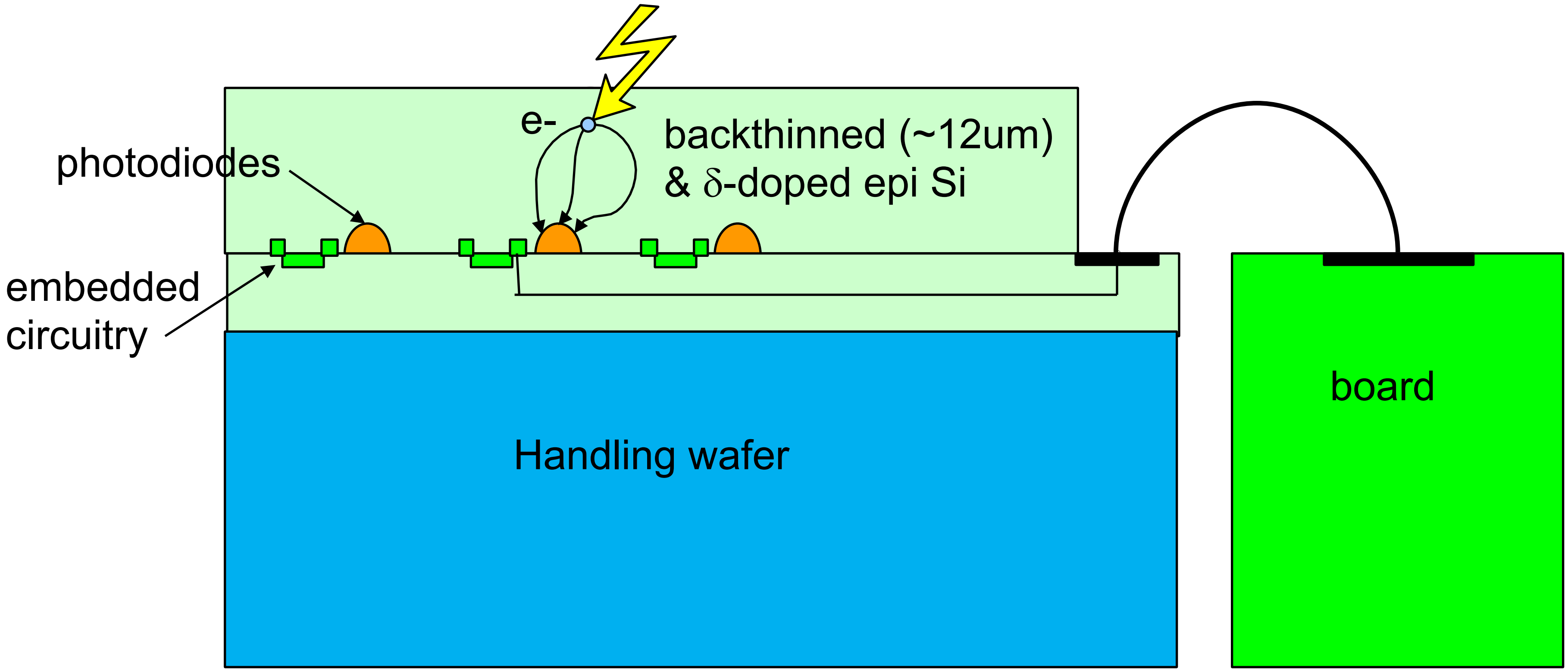
Hybrid Pixel Array Detectors in some detail.







Monolithic Active Pixel Sensor (aka CMOS imagers (CIS))

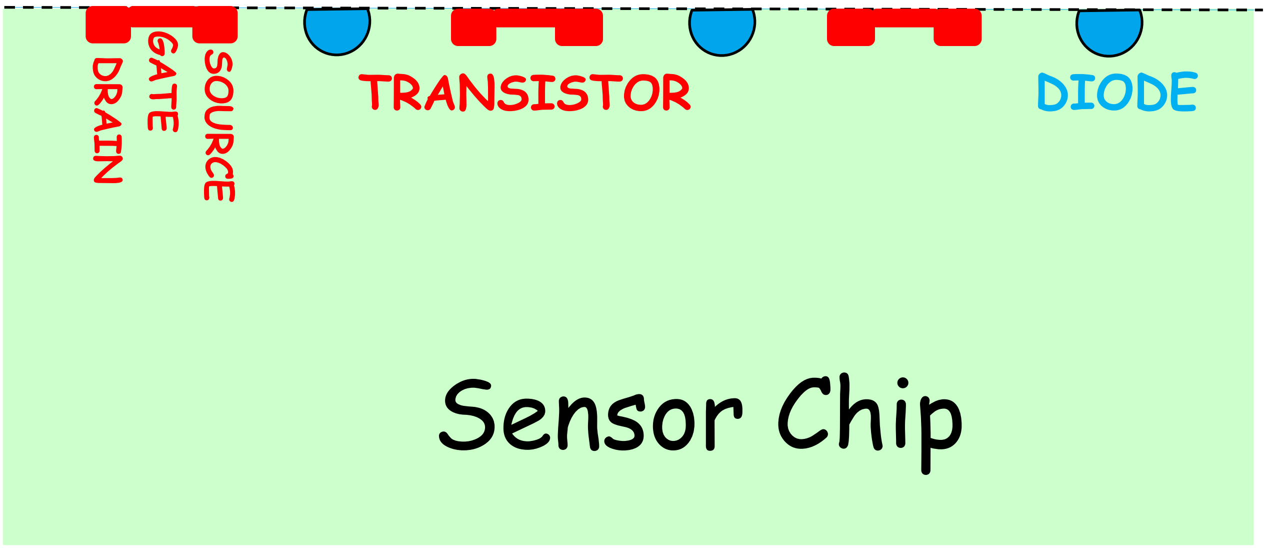


Monolithic: Collecting diodes & readout circuitry share the same substrate

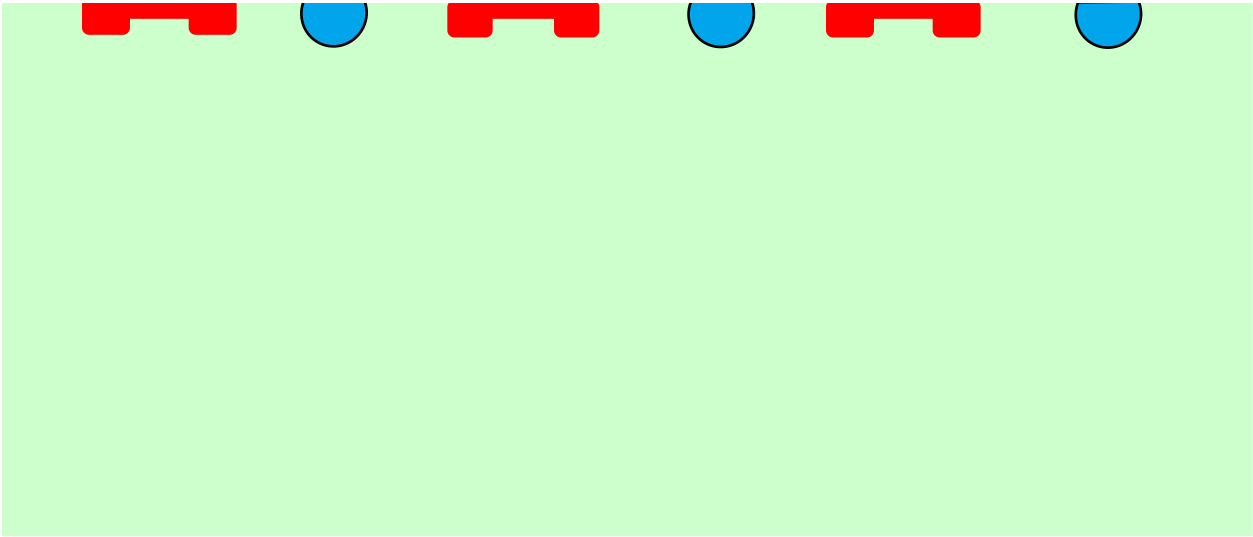
Coupled to handling wafer, back-thinned, back-illuminated: 100% fill factor

Back surface delta-doped, post-processed: almost no entrance window

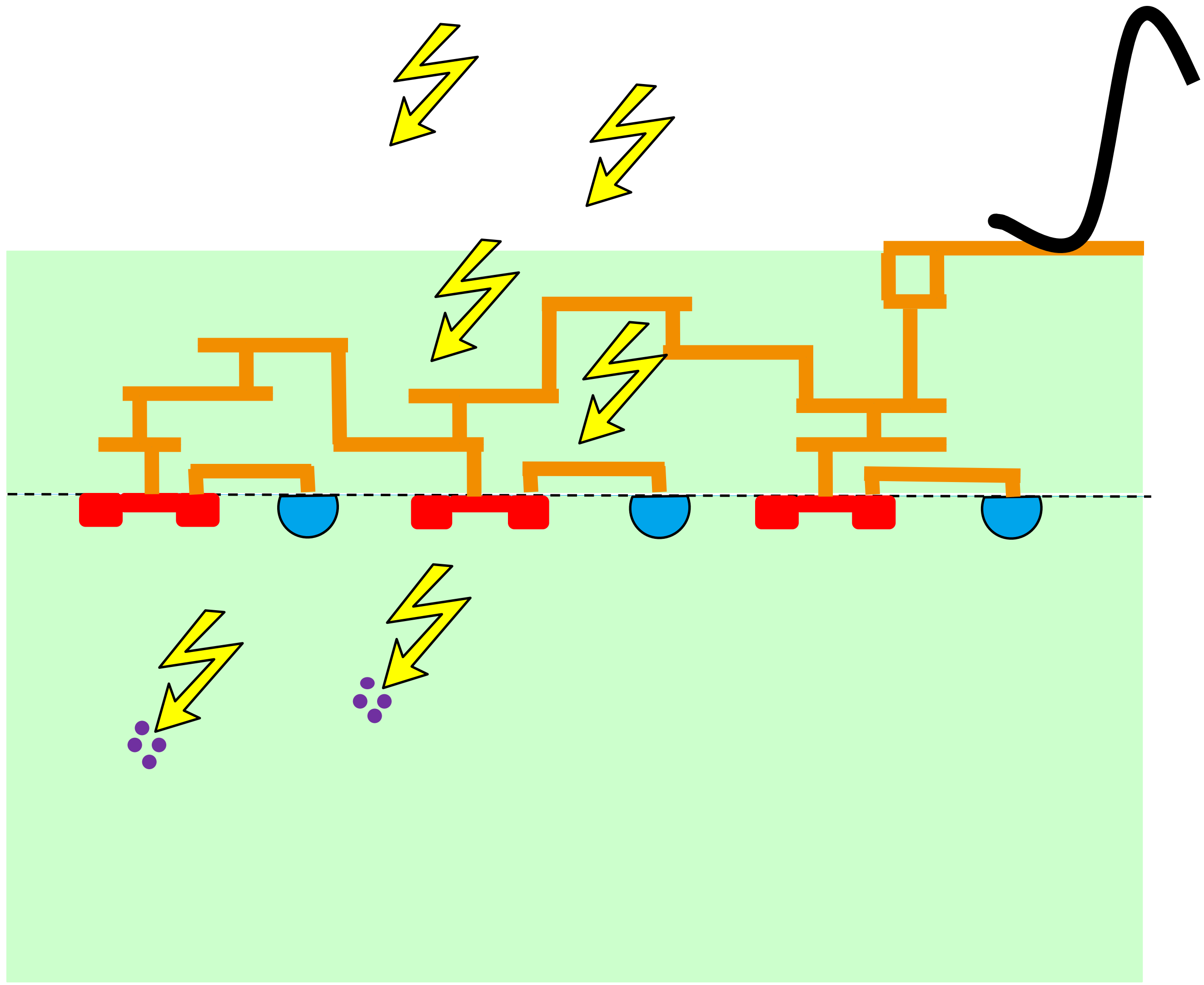
Monolithic Active Pixels Sensor (MAPS / CMOS)

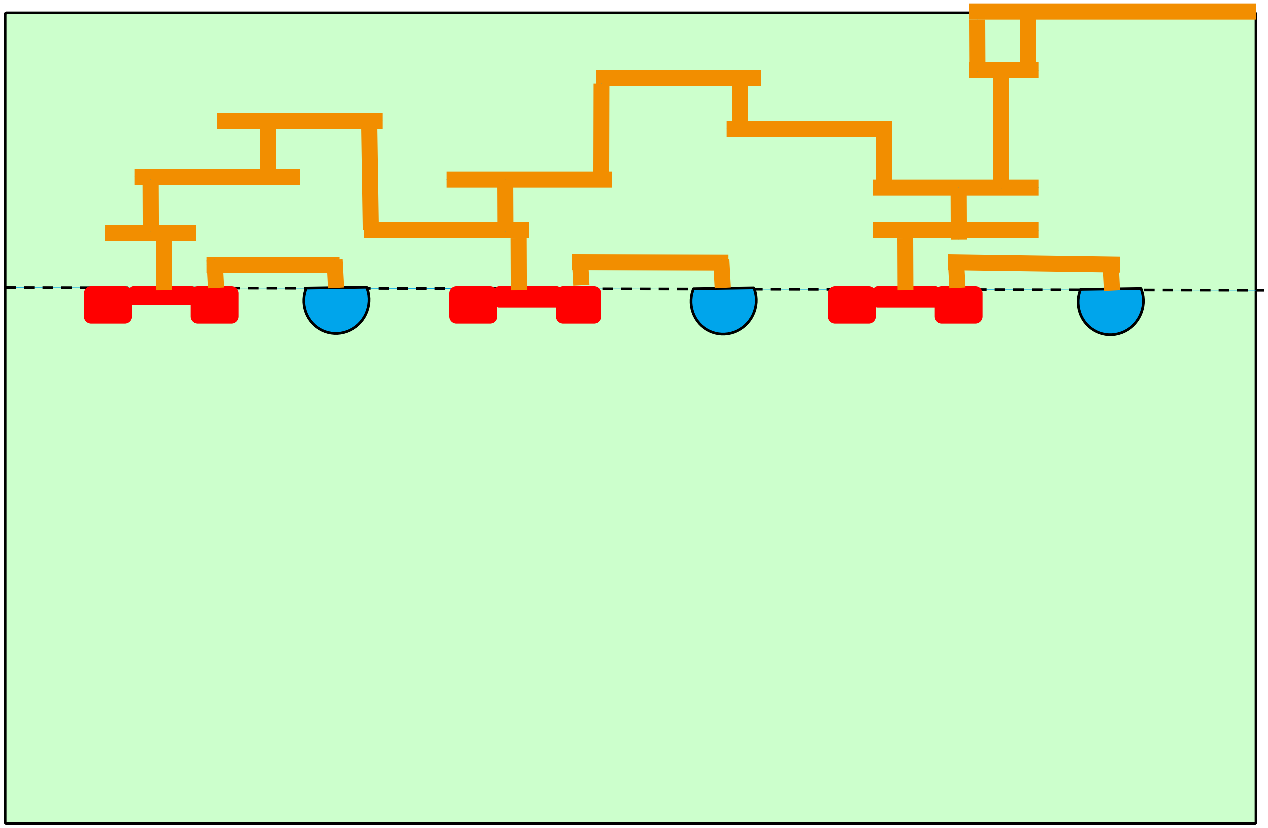


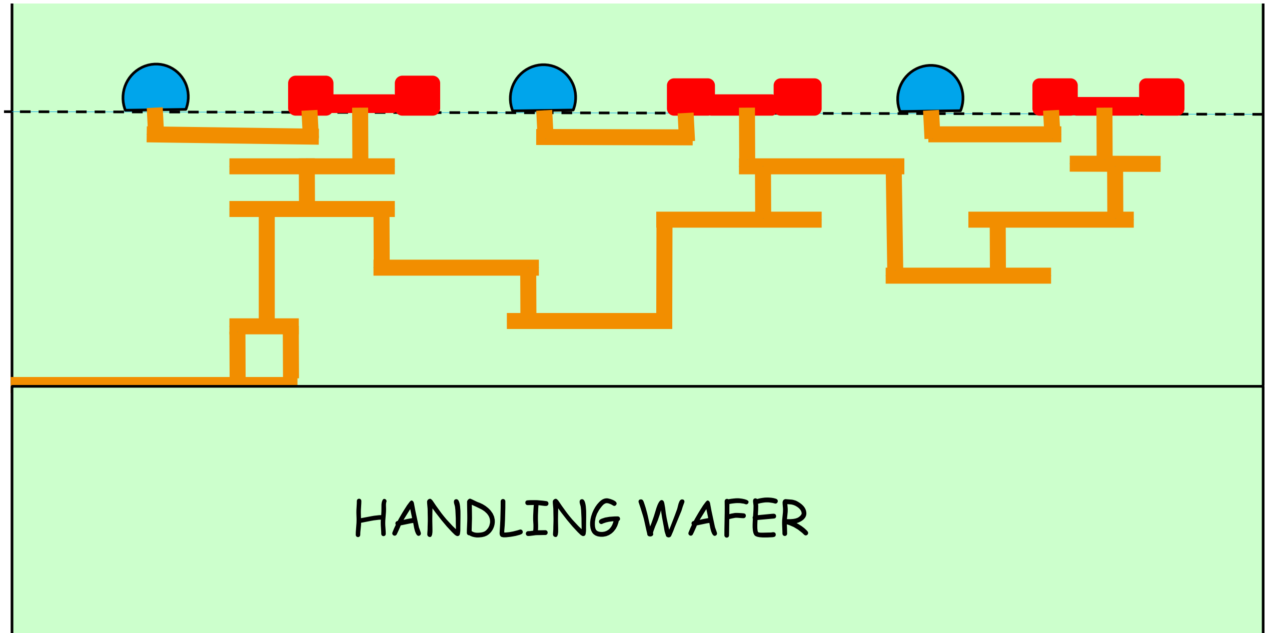
Monolithic Active Pixels Sensor (MAPS / CMOS)



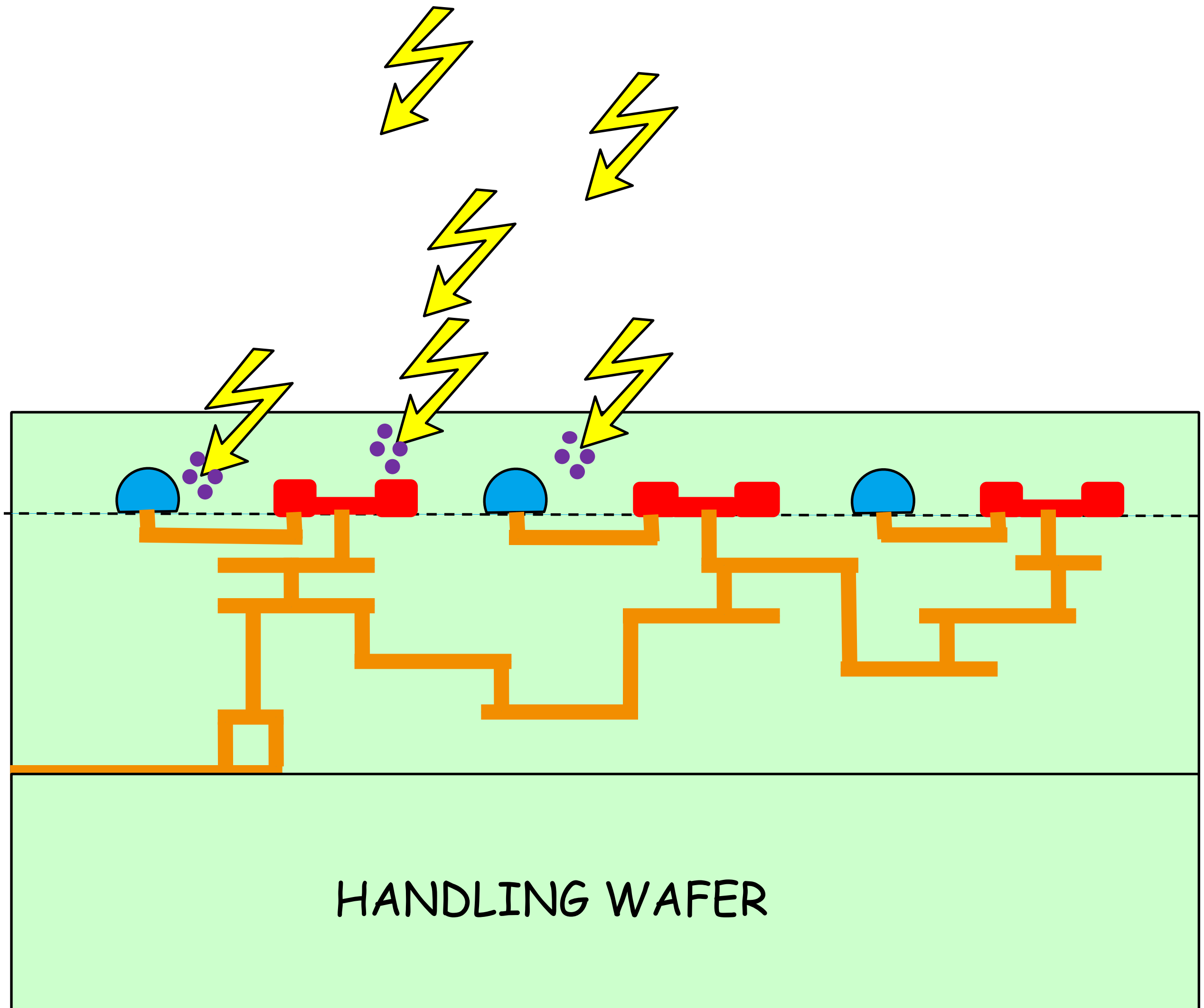
A Front-Side illuminated CMOS imager



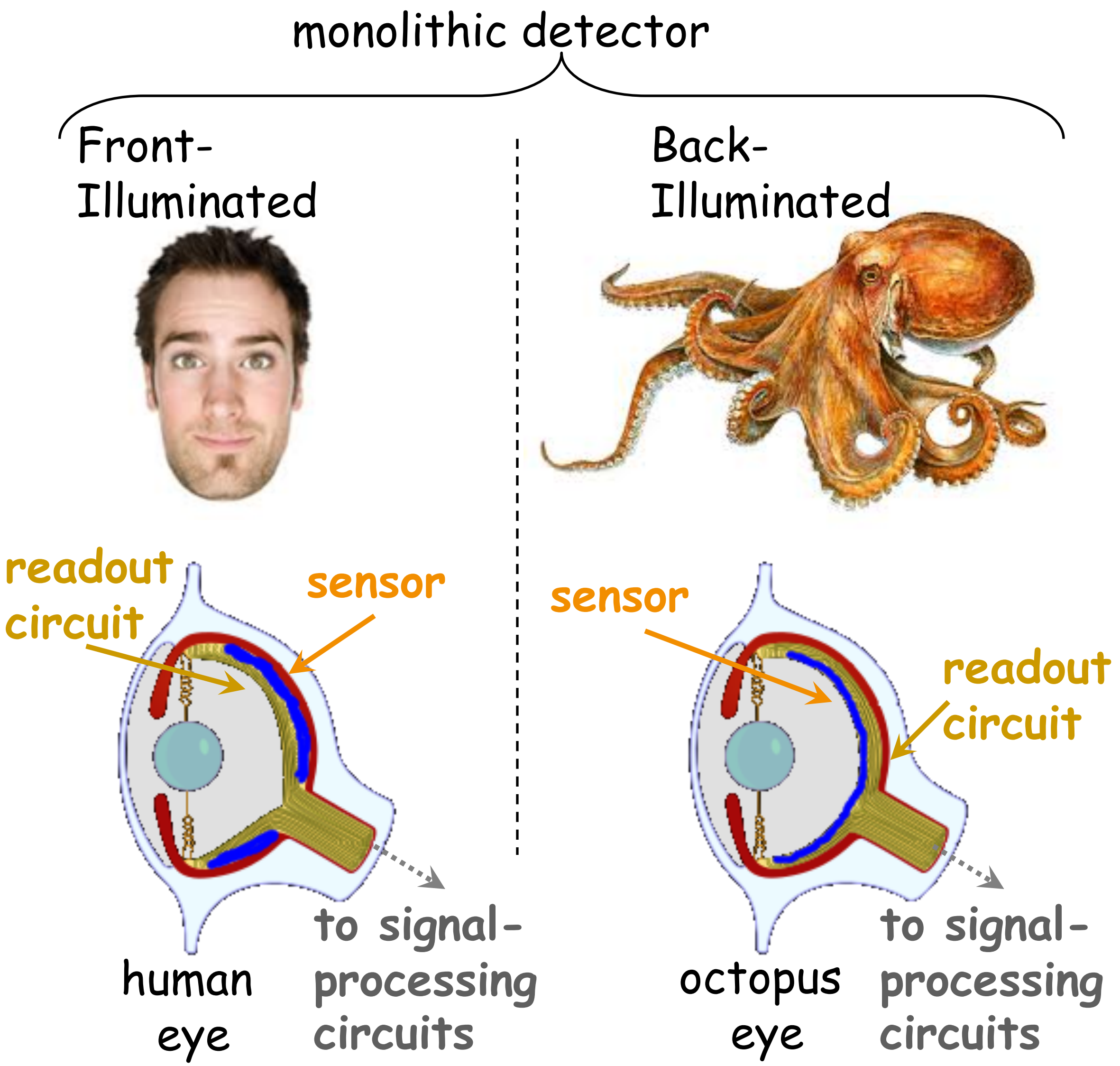



HANDLING WAFER

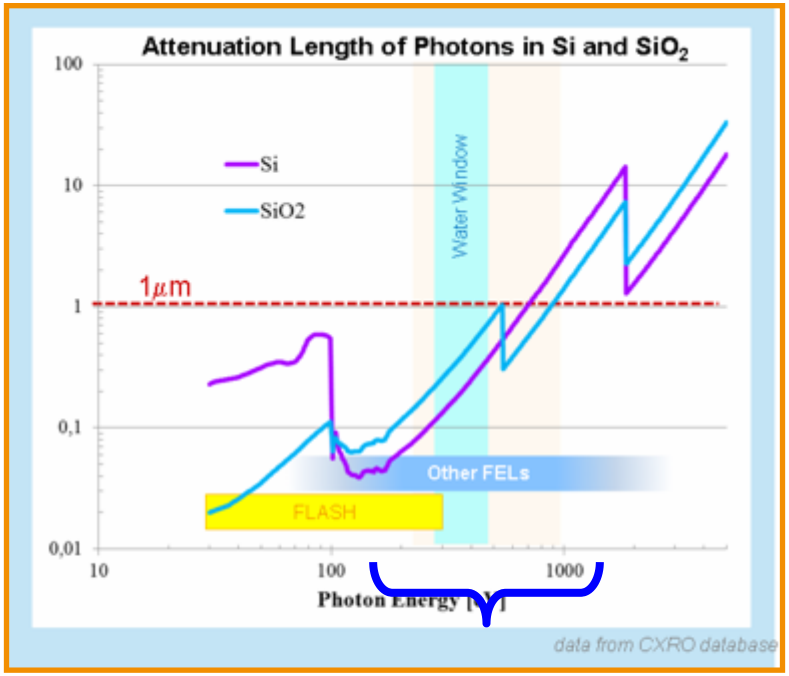
A Back-Side Illuminated CMOS Imager

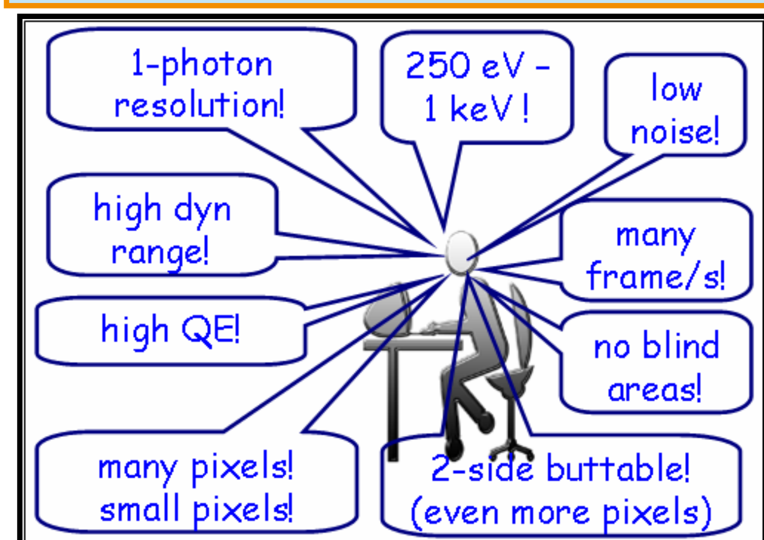


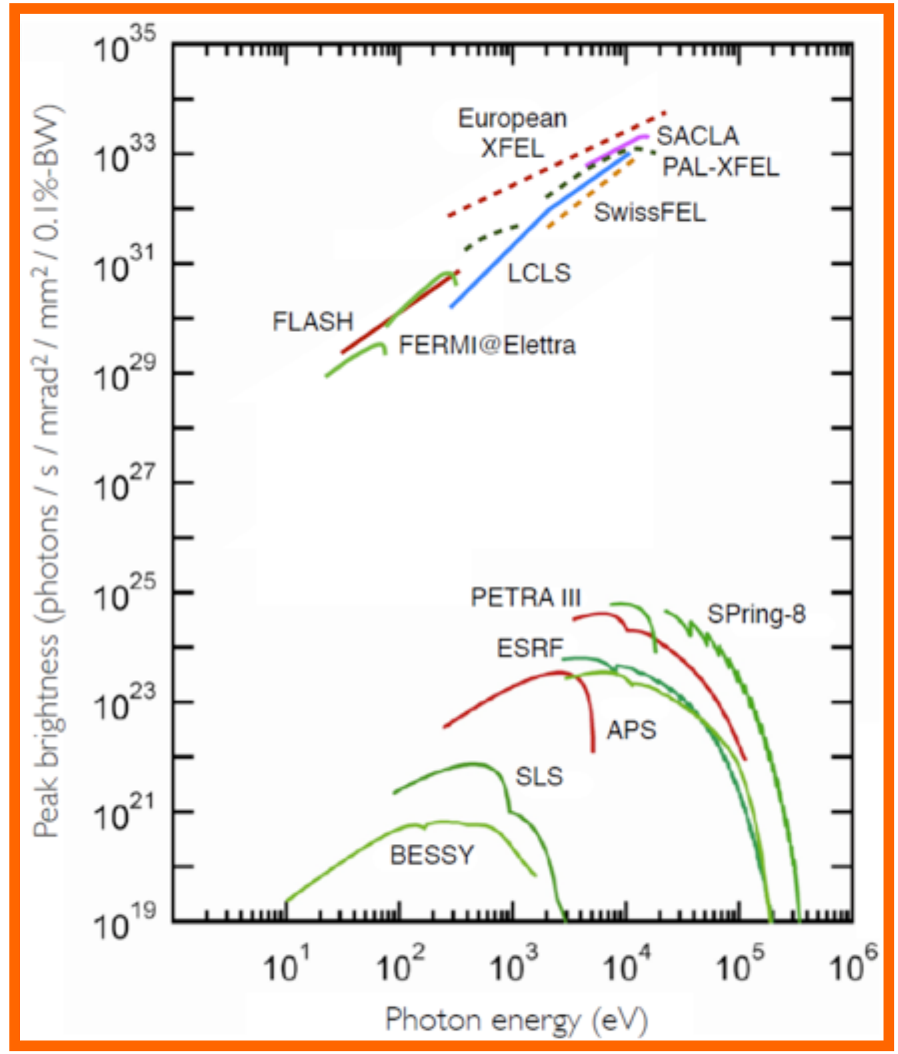
The Octopus had it already figured out...



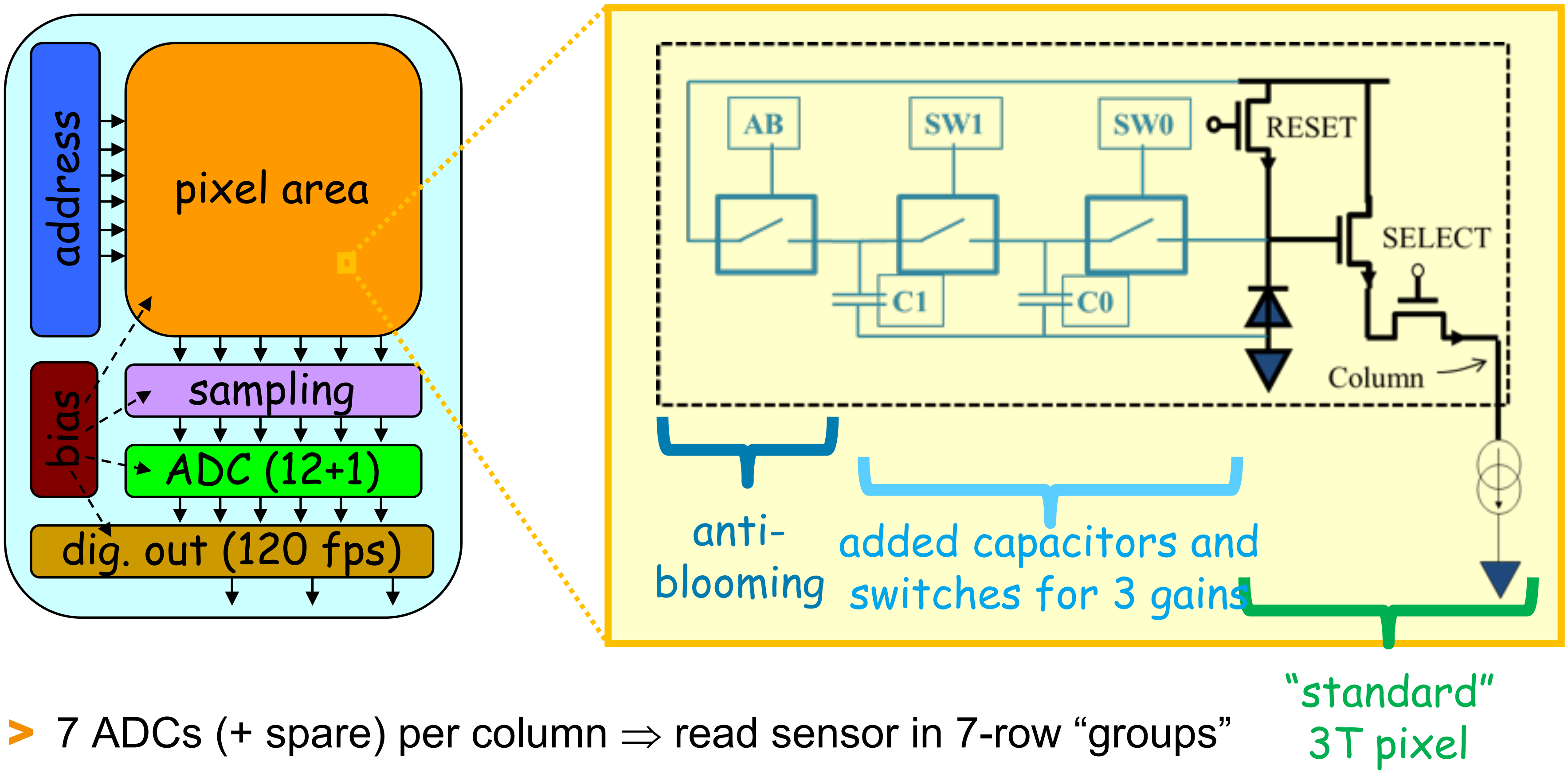
PERCIVAL for FLASH and other low-E sources





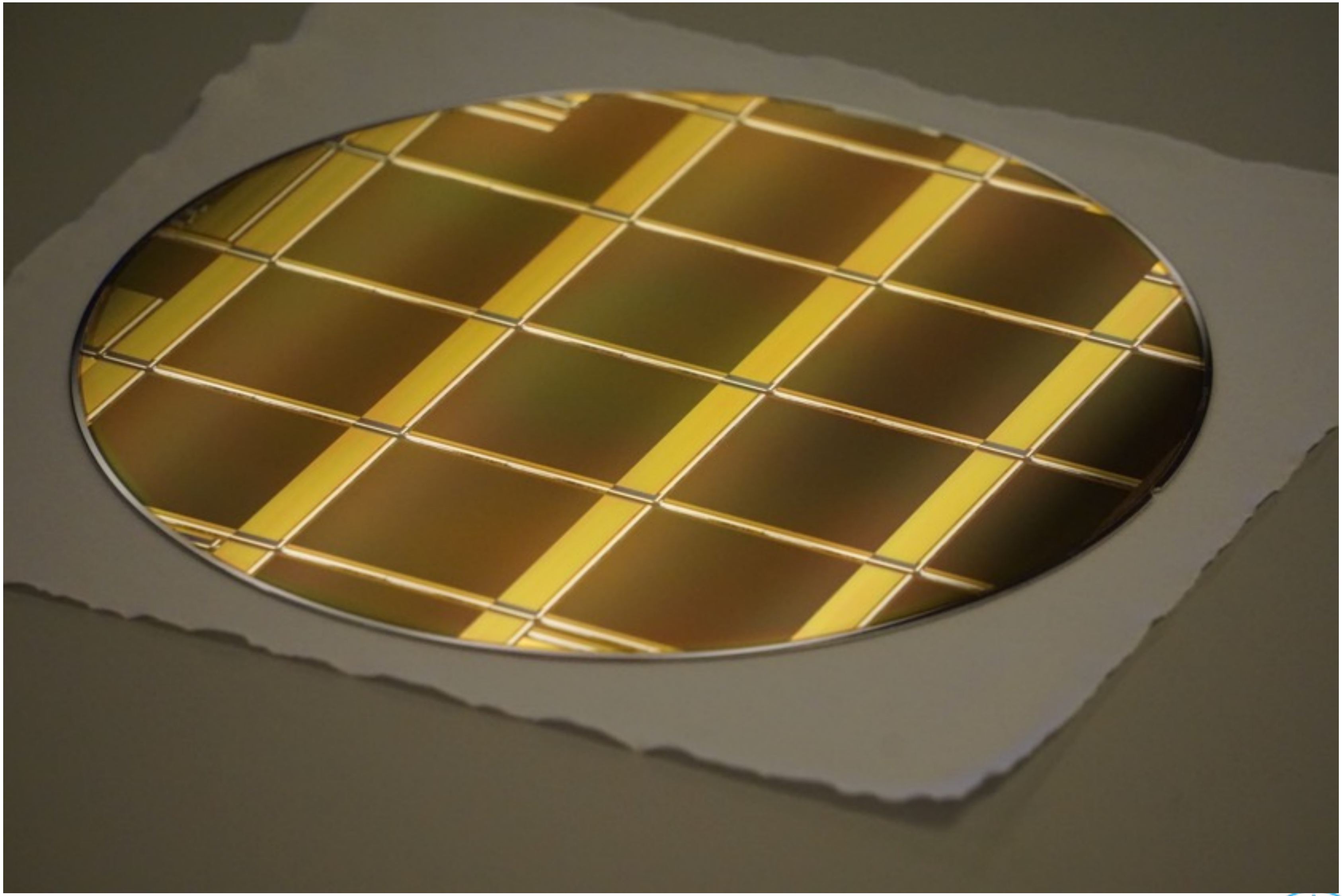


The Percival Sensor

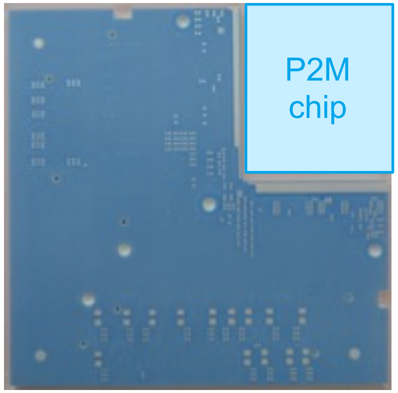


- 7 ADCs (+ spare) per column ⇒ read sensor in 7-row "groups"
- 1408 columns + 32 dark ⇒ 11.5k ADCs in a 2M chip
- 12+1(over-range)+2 (gain) bits ⇒ 15 (x2 for CDS) bits/pixel/frame
- 45 LVDS output lines at 480MHz data rate for one 2M chip (20 Gbit/s)

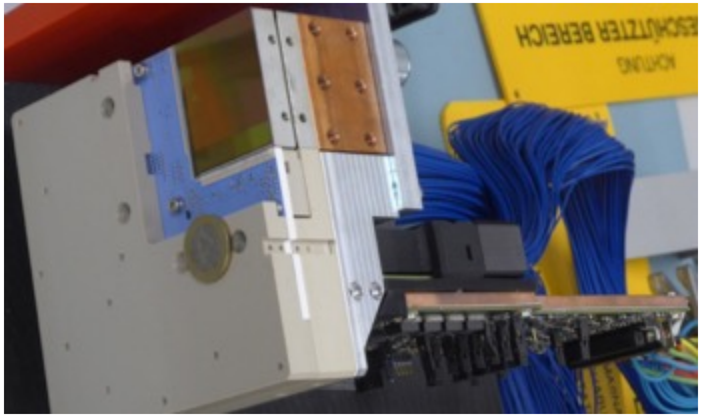
Wafers with 8 sensors with 2-million pixel

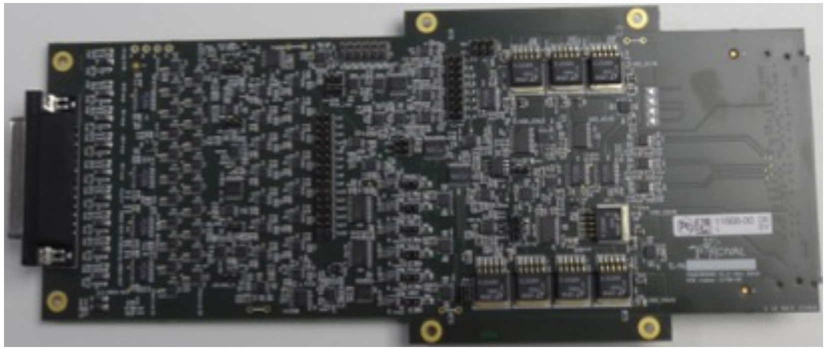


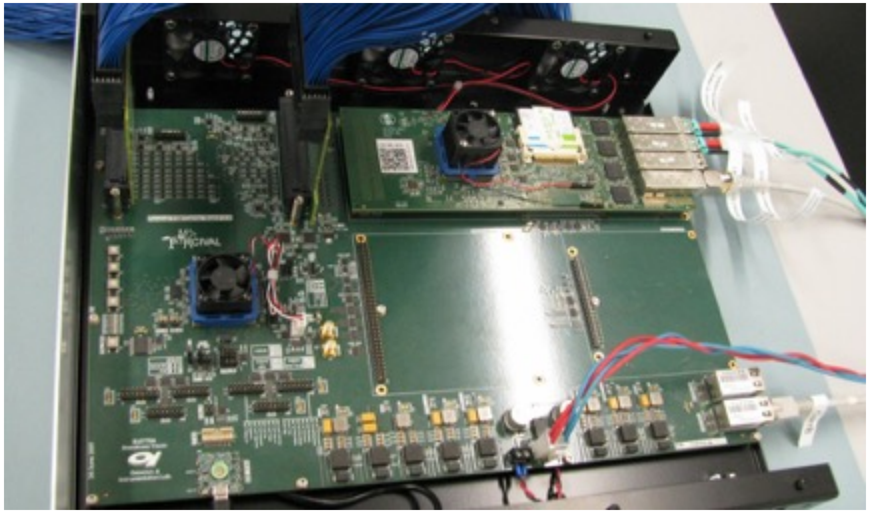
From wafer to system



LTCC board

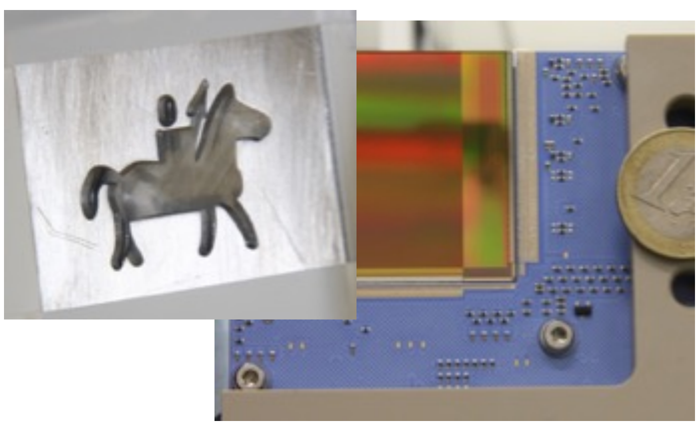

Mechanics and cooling

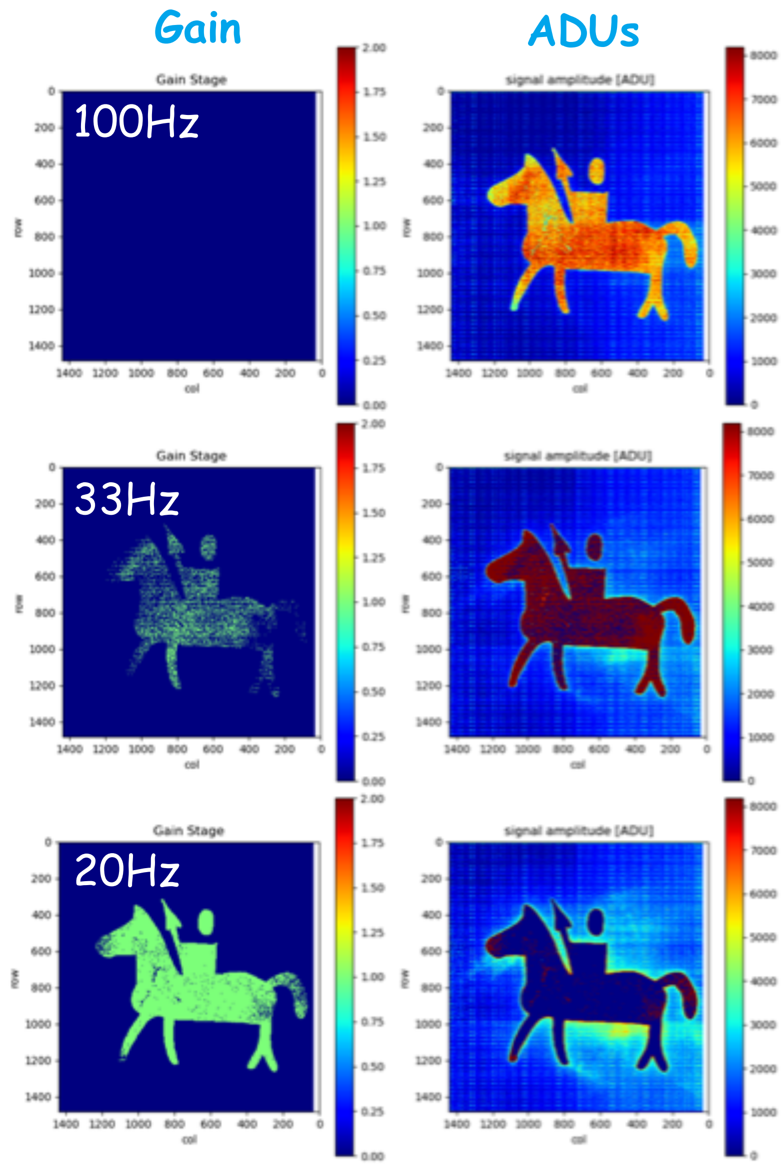

PowerBoard for sensor supply & biasing


Control and DAQ board

P2M Operation

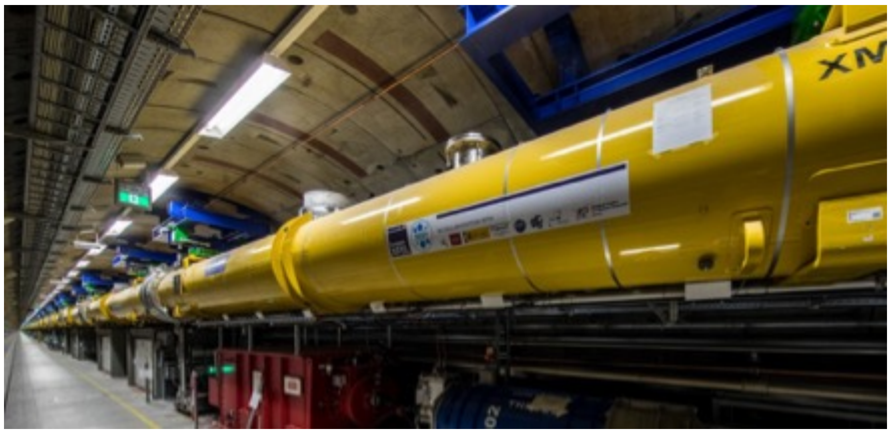
- First light November 2018!
- Visible light, room temperature
- 100Hz frame rate
- Automatic gain switching works
- First “real” system: fall 2019

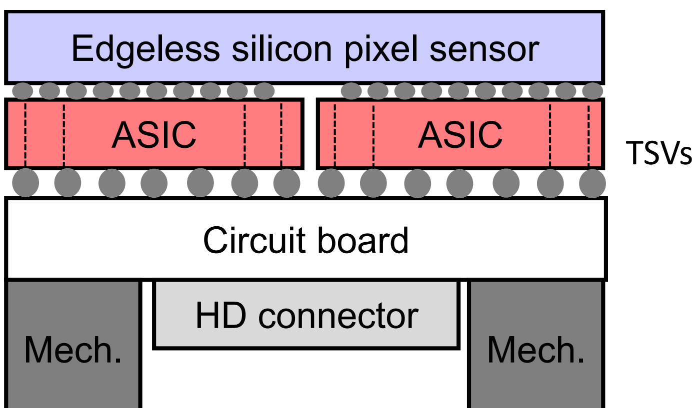


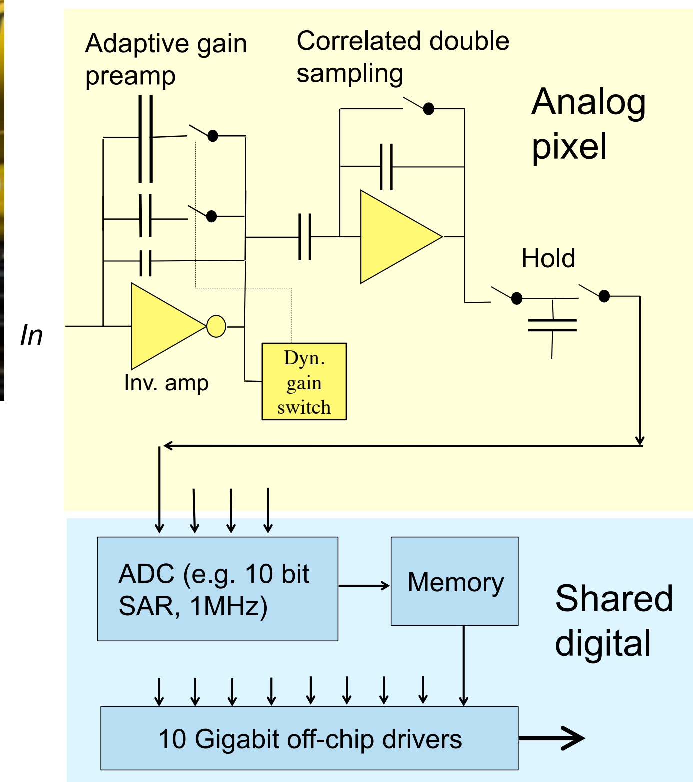


What comes next?

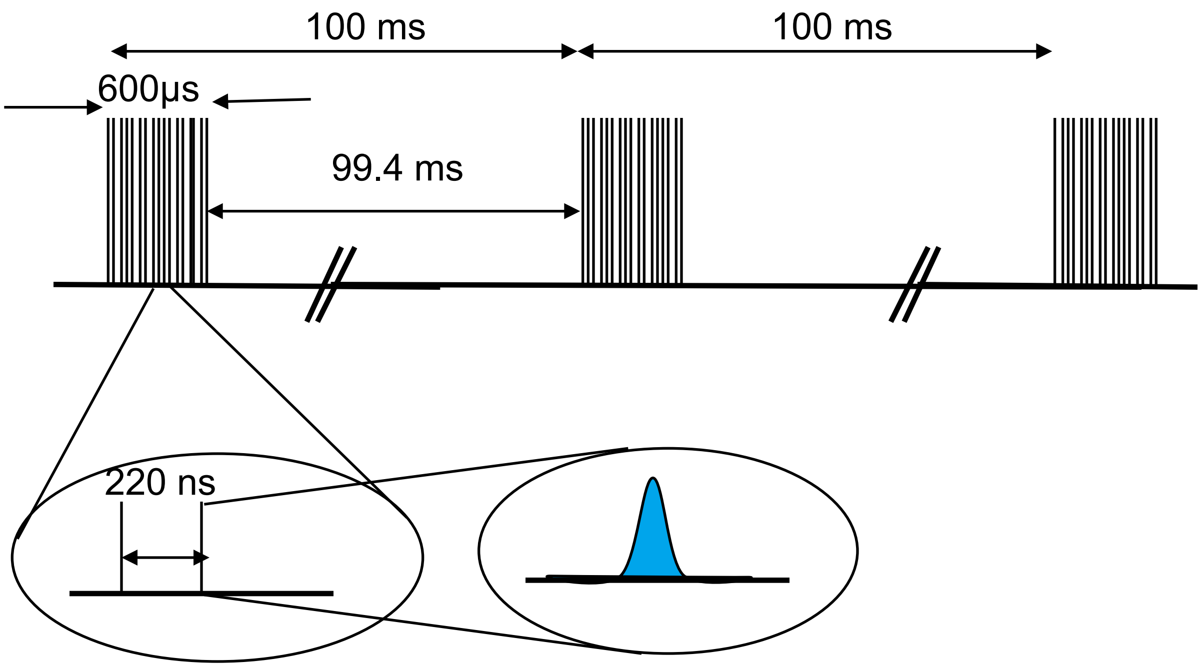
High Frame Rate X-ray Imager for Photon Science







Current European XFEL bunch structure



2700
bunches in
train

27 000 bunches/s
with
4.5 MHz
bursts

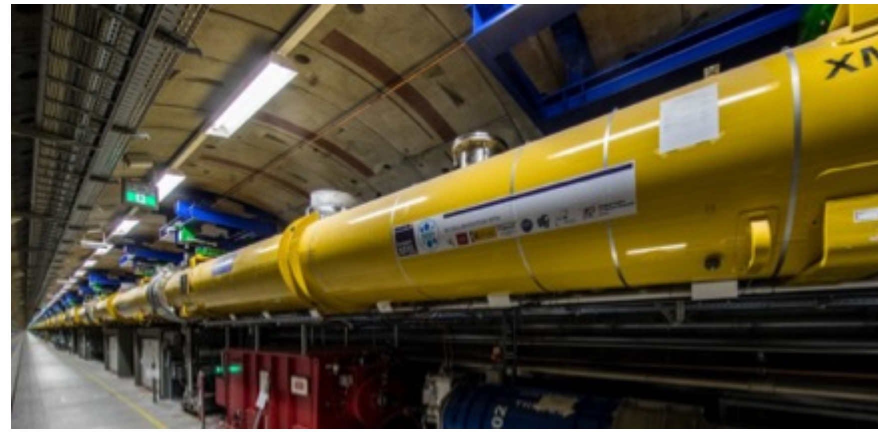
Duty cycle = 0.6%
99.4 % of the time it is dark!!

Requirements for future sources

PETRA-IV (~2027)

- Diffraction-Limited Storage Ring
- Approx continuous X-ray beams
- x 100 increase in X-ray brilliance
- Measurements from atomic to macroscopic scale, 10μs resolution

CW-XFEL (~2028)



- Free electron laser
- Extremely intense X-ray pulses
- 100 kHz to 1MHz continuous bunch rate (source)
- "Flash photography" on atomic scales

Detector wish list

- **≥ 100 kHz continuous frame rate**
- Multi-megapixel (>10 Mpixel)
  - Minimal dead area
- ≤ 100 μm pixel size
- Single photon sensitivity
- 10^5 photon upper range
  - Noise below Poisson statistics
- Compatible with different sensors for hard / soft X-rays
- Compatible with vacuum operation, radiation hard…

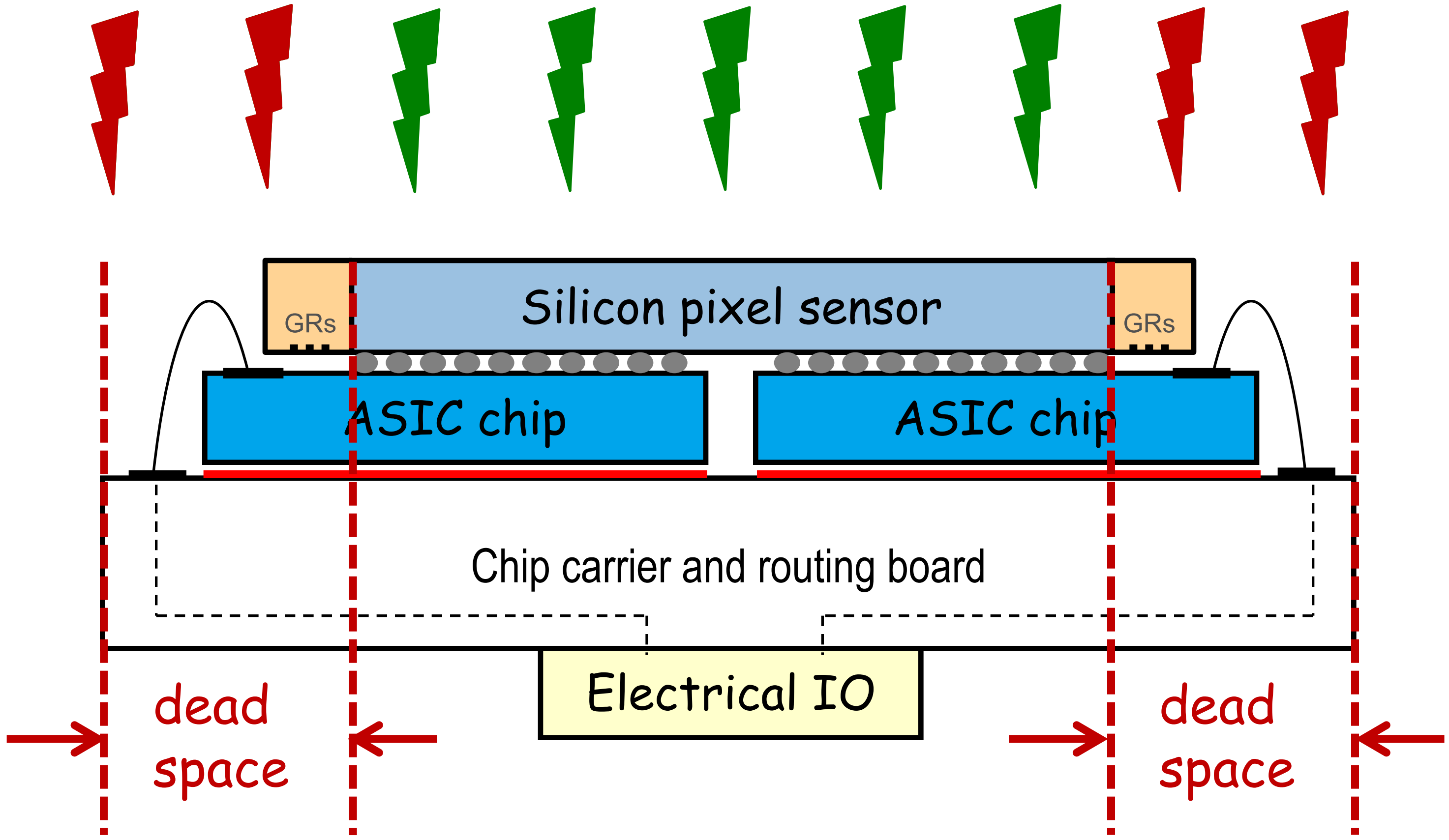
Data rates – what does this mean?

- 1 Megapixel * 100 kHz * 12 bits = 1.2 Tbit / second!
- Data throughput per module?
  - 100 µm pixel size means 1 Megapixel = 10 x 10 cm^2 area
  - So (for example) 4 modules of 10 cm x 2.5 cm at 300 Gbit/s each
  - This is *minimum* requirement!
- Multi-megapixel systems could have multi-terabit data throughput!

→ **This needs: “on-the-fly date selection / vetoing / triggering”**

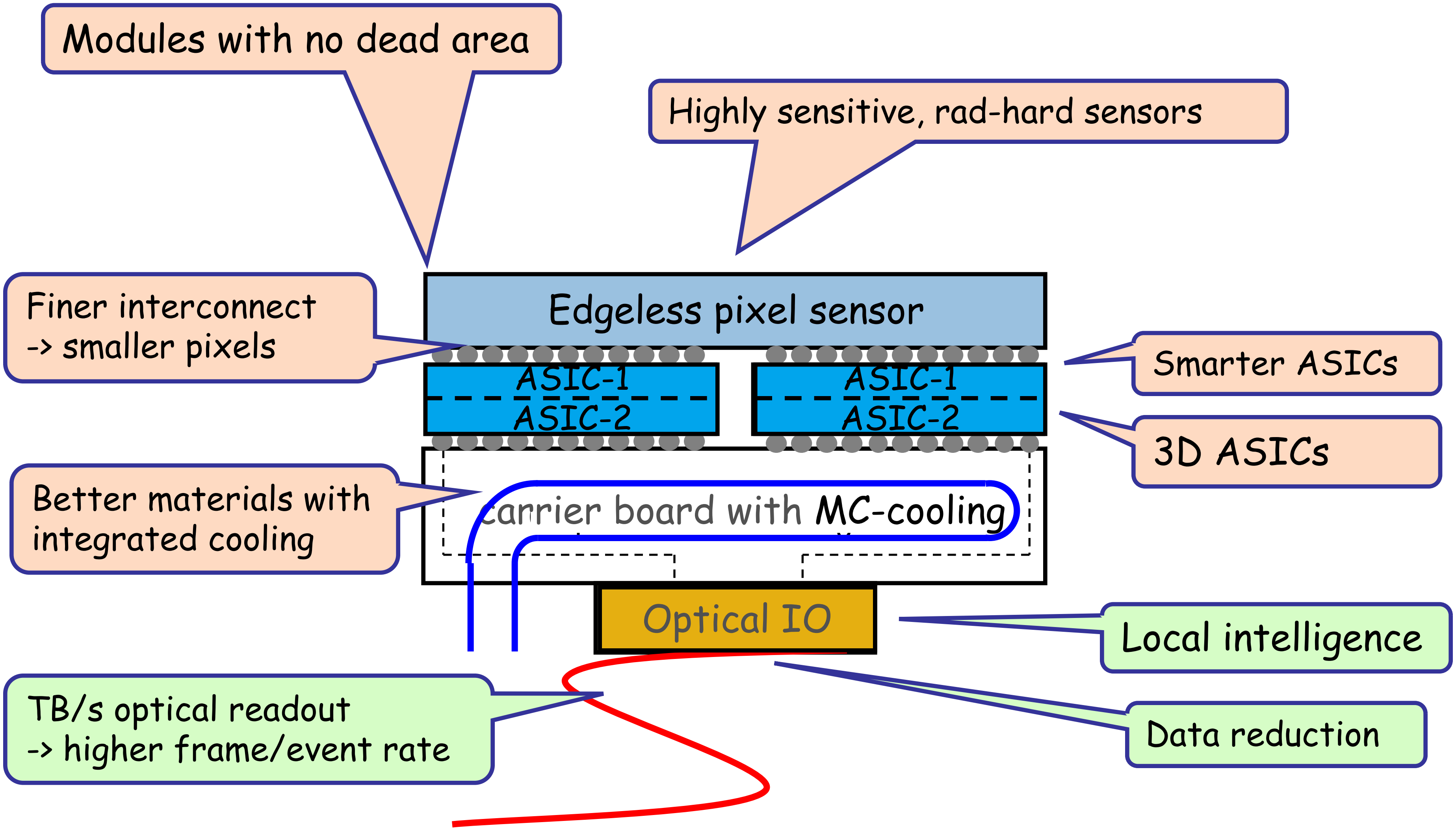
„Discrimination in Photon Science“

Hybrid pixel detectors for future experiments



Current hybrid pixel technology

Hybrid pixel detectors for future experiments



Future hybrid pixel technology

Summary Detectors

- Signal-to-noise ratio most fundamental parameter in measurements.
- A detector is always a compromise (ex. speed vs. noise). Application determines what you compromise.
- Never take a detector as a “perfect black box”, be aware of limitations.
- Understanding your detector is part of understanding your science.

Enjoy the rest of the course

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