Introduction to Synchrotron Radiation Detectors

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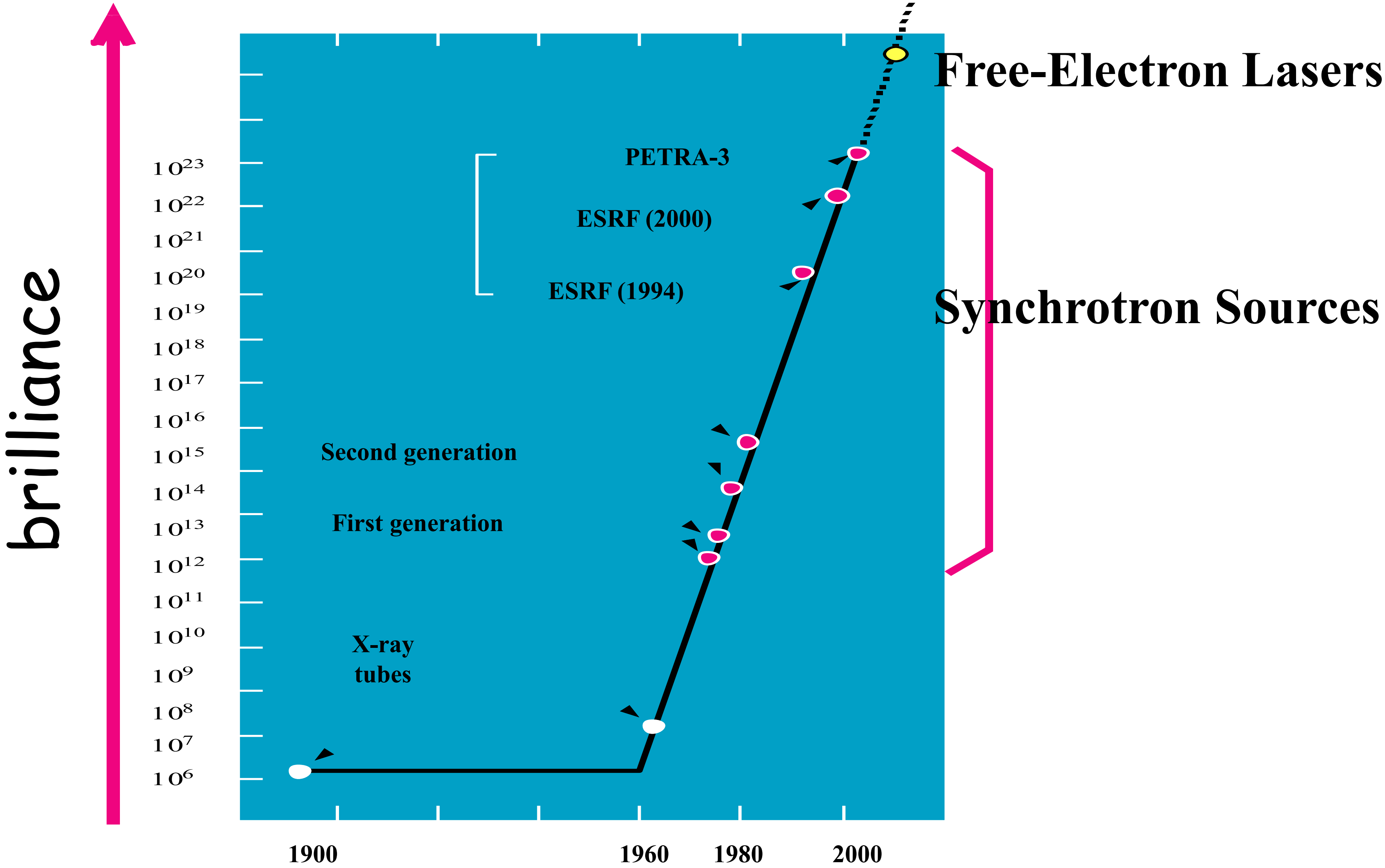
The Detector Challenge:



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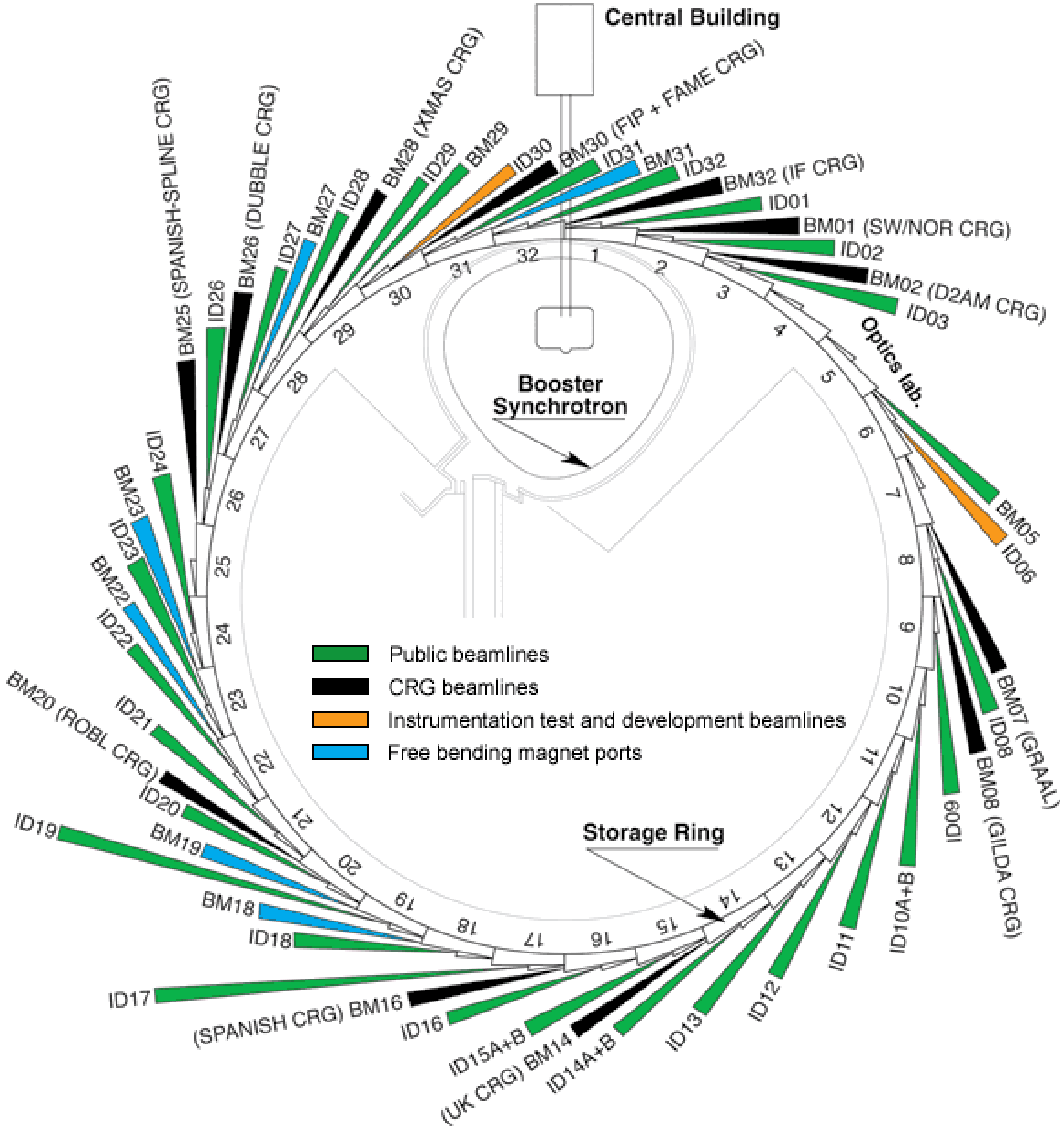
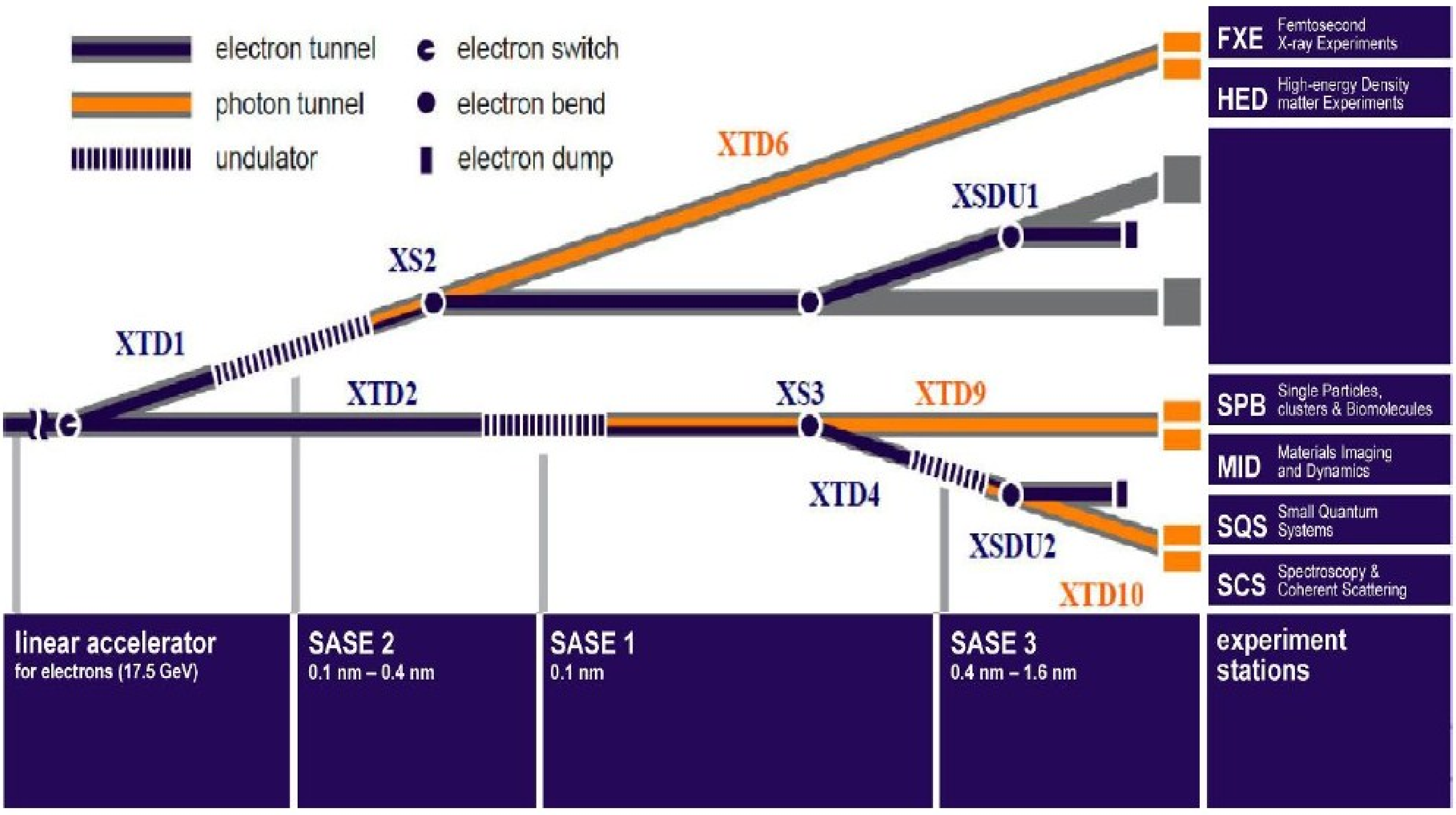


XFEL Beamline Layout



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 momentum transfer = angle)
  - Small angel – protein crystallography
  - Diffuse – Bragg
  - Crystals - liquids

What are the basic principles ?

1. In order to detect you have to transfer energy from the particle to the detector
2. X-ray light is quantized (photons)
3. A photon is either fully absorbed or not 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

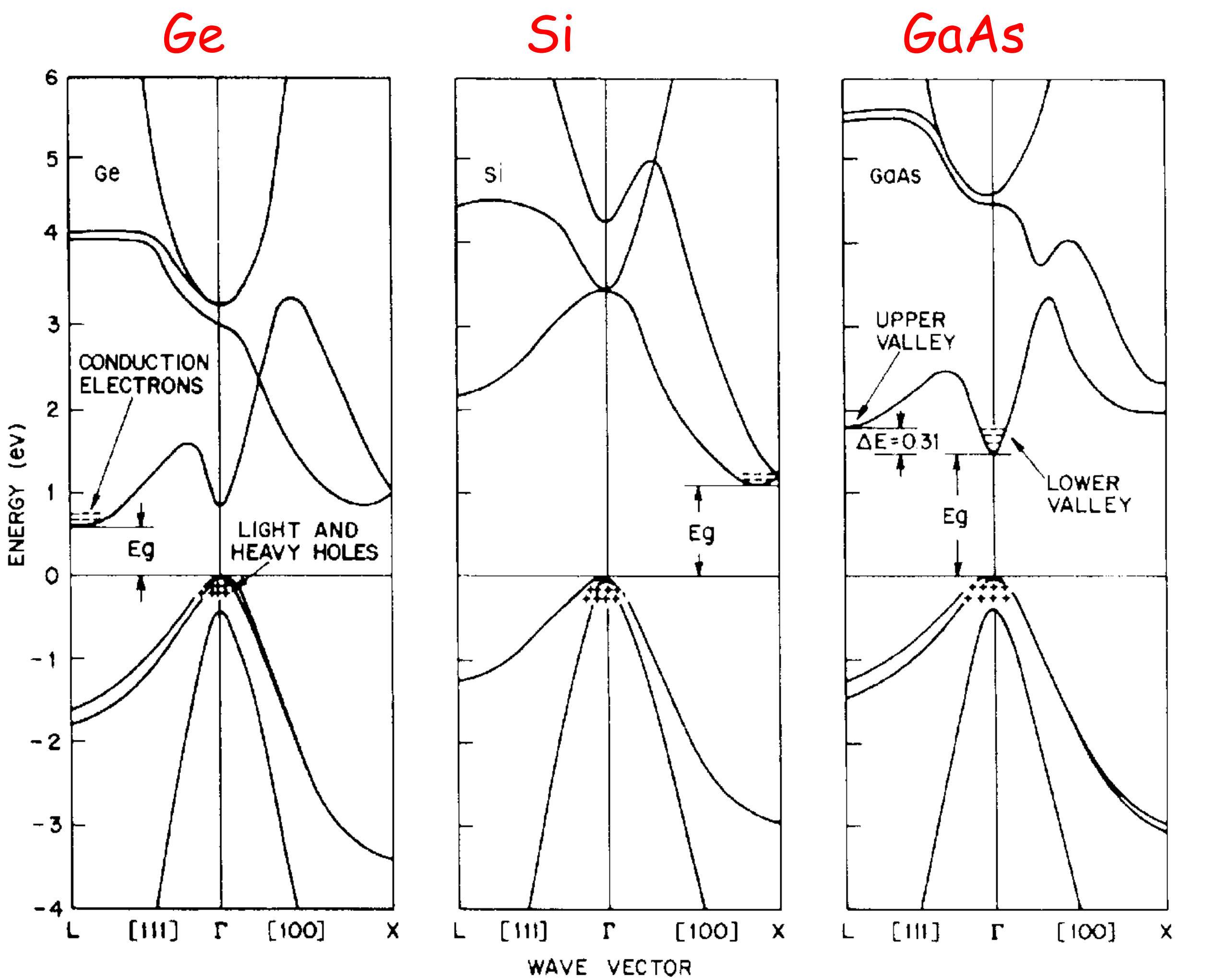
Any form of elementary excitation can be used to detect the radiation signal:

- 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

Band structure (3)



E_g = 0.7 eV　　E_g = 1.1 eV　　E_g = 1.4 eV

Indirect band gap　　Direct band gap

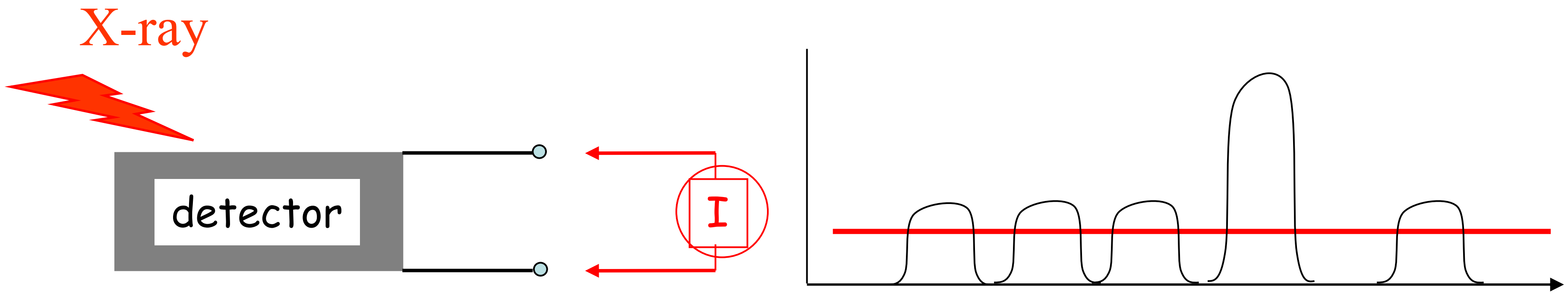
What would you like to know about your X-rays?

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

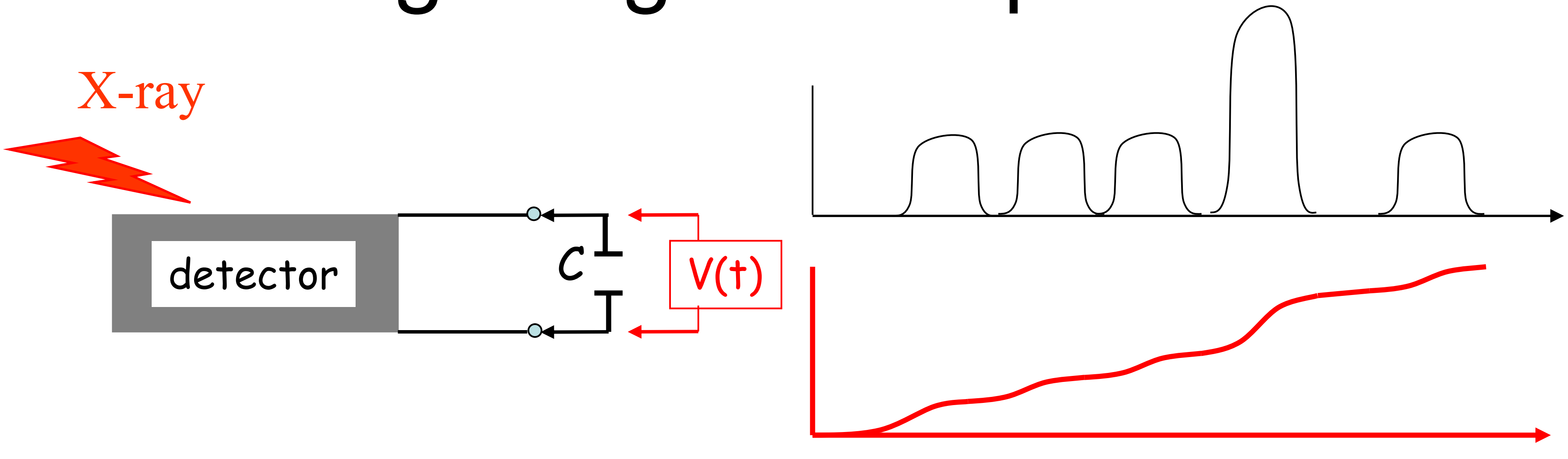
4 modes of detection

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

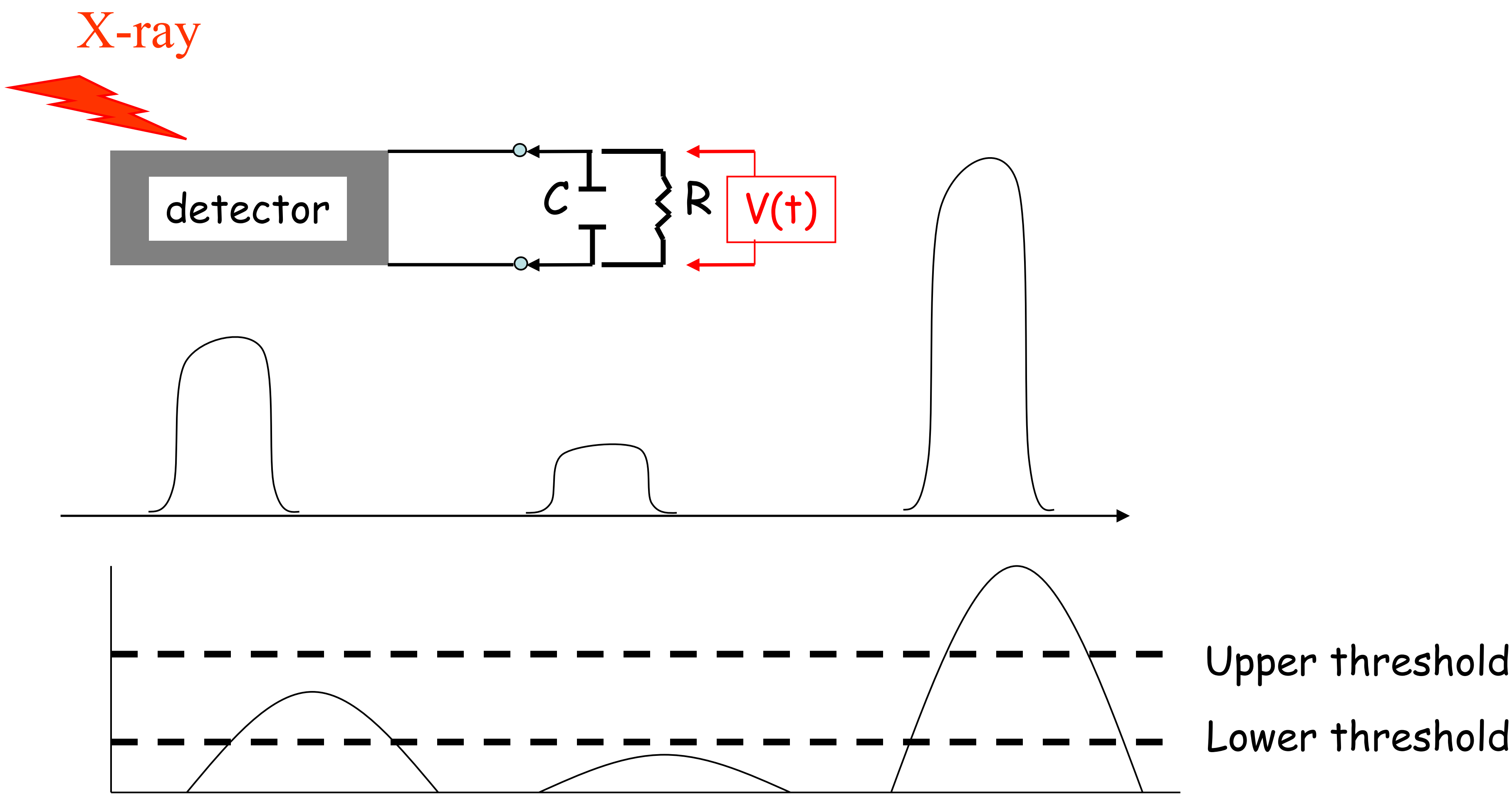
Current mode operation



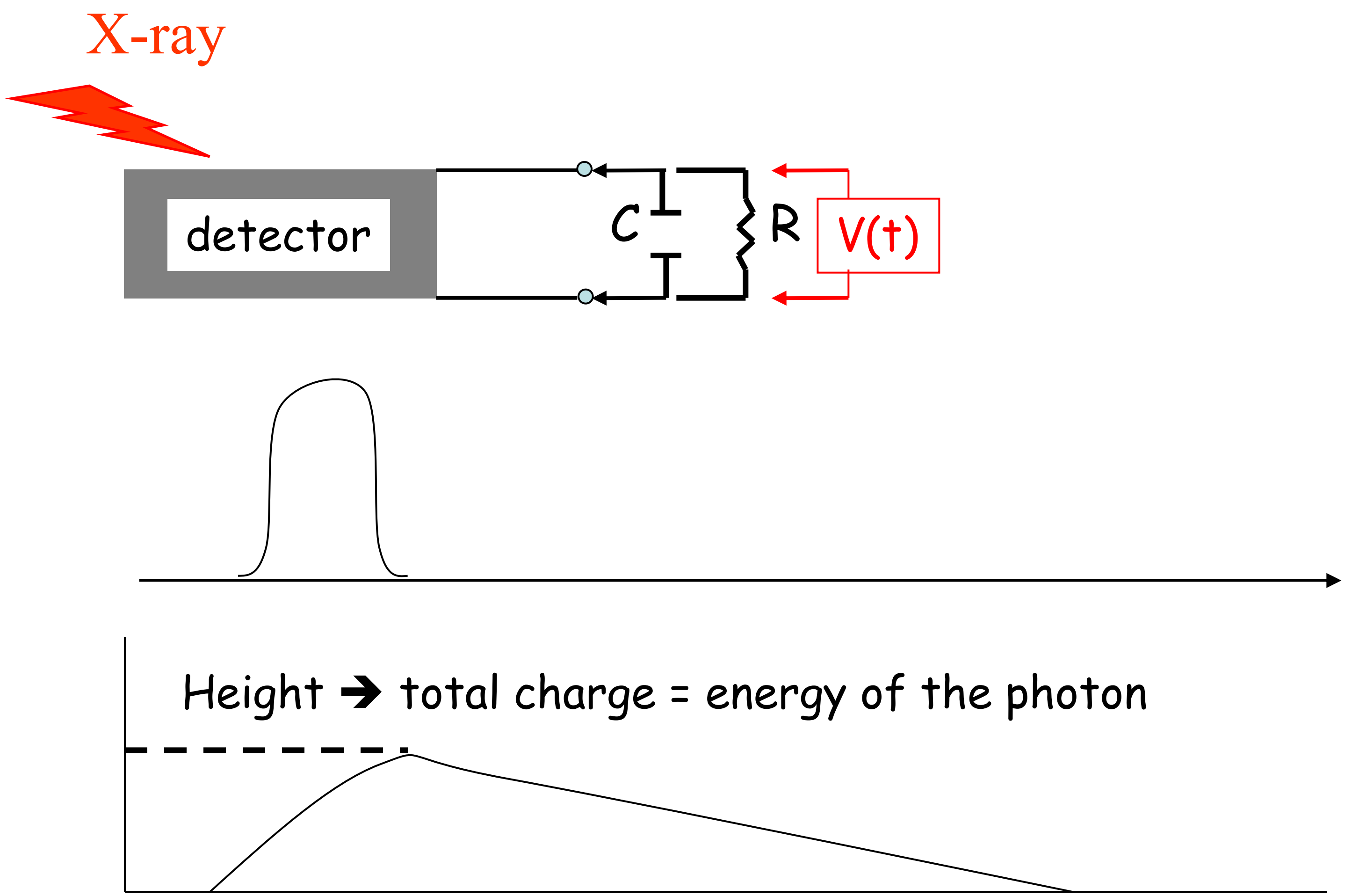
Integrating mode operation



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.
- **DQE** = detective quantum efficiency =

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

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

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 LSF

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

Some more parameters for 2D systems

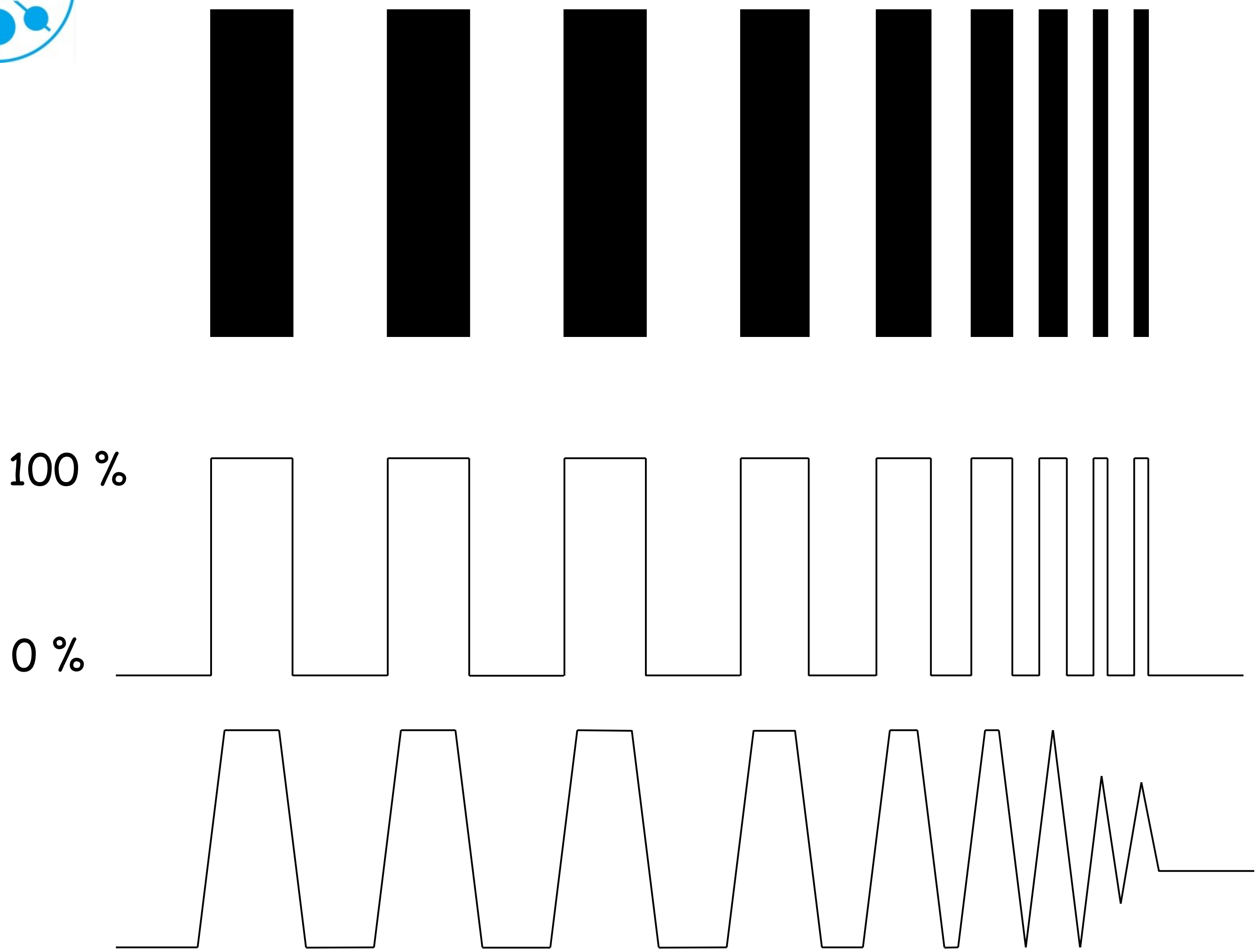
- Modulation Transfer Function (MTF):

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

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

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:

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

Effect of noise:

$$contrast \equiv \frac{150-50}{150+50} = 0.5$$

Effect of PSF:

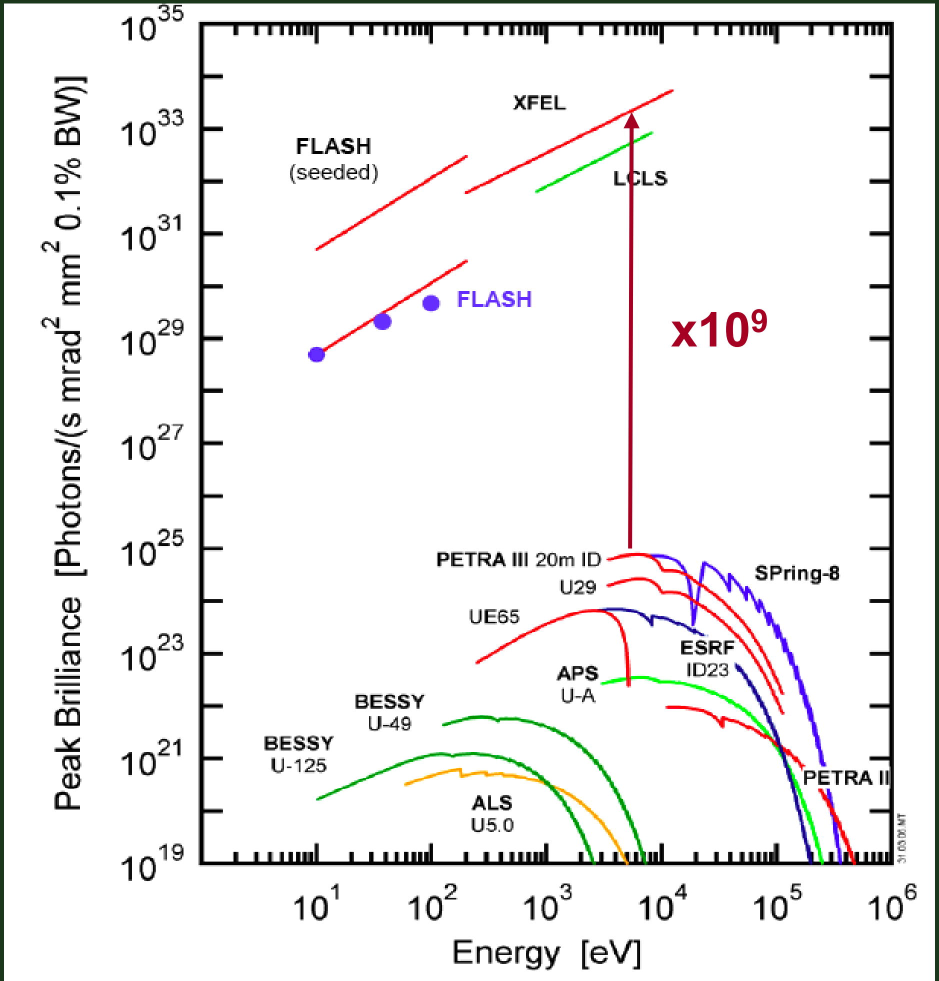
$$contrast \equiv \frac{75-25}{75+25} = 0.5$$

FEL Sources vs. Storage Rings

- Pulse length: 10^3 shorter (100 fsec vs 100 psec)
- Emmittance: 10^2 horizontal, 3 vertical lower
- Intensity per pulse: $3x10^2$ higher (10^{12} ph)
- Monochromaticity: 10 better

➔ Peak brilliance: 10^9 higher

FEL Challenge: Different Science



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

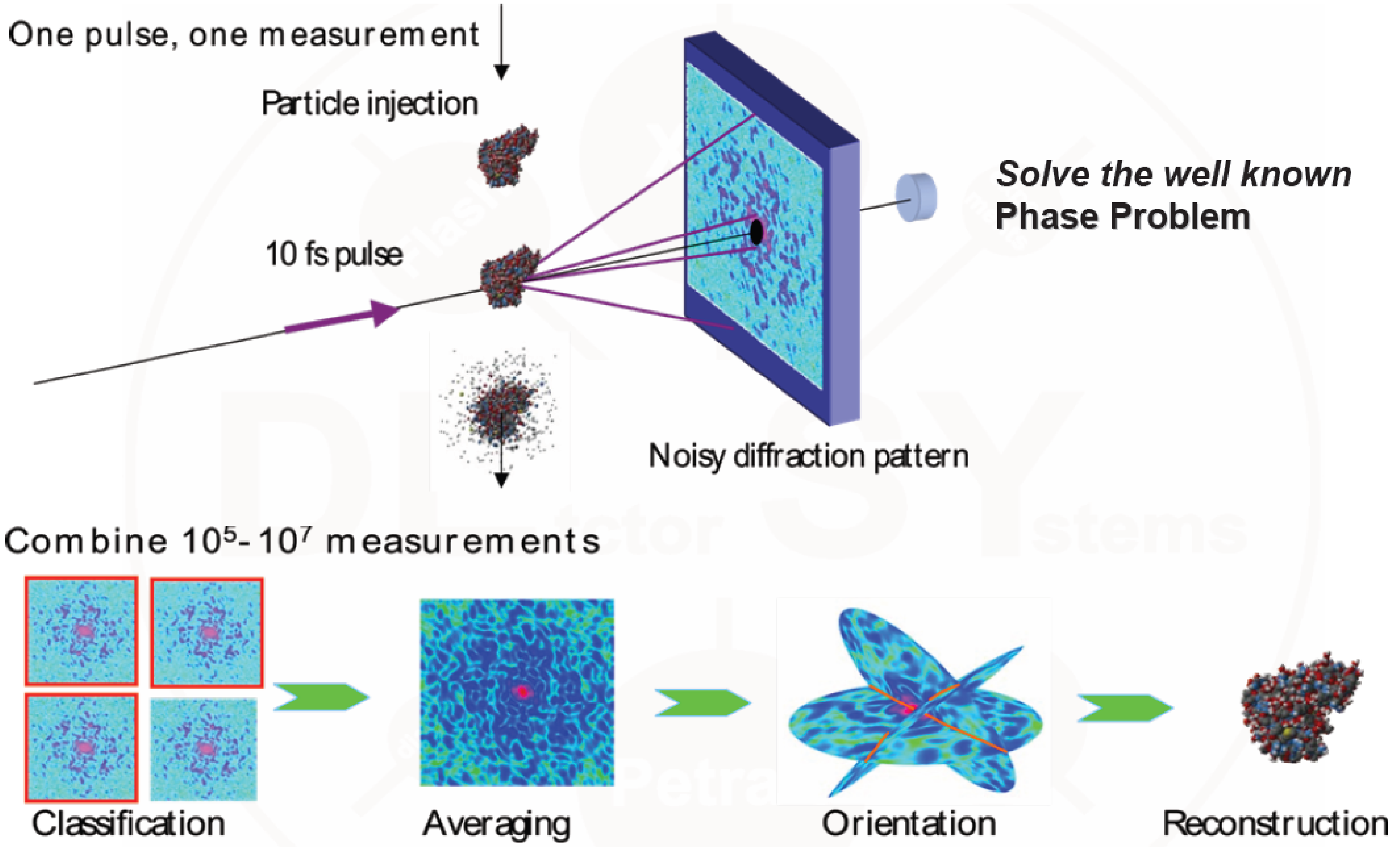
Consequences for the detector:

(H.Graafsma; Jinst, 4, P12011, (2009))

1. Single shot-science: 10^{12} ph in 100 fsec
   ➔ (complete) ionization of sample; followed by coulomb explosion.

- Fortunately scattering is faster: “diffract-and-destroy”. (<50 fsec) (*Nature* **406**, 752, (2000)).
- Crystal diffraction is “self-gating” (*Nature Photonics*, **6**, 35, (2012)).

Single shot imaging…



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

Consequences for the detector:

1. Single shot-science: 10^{12} ph in 100 fsec ➔ (complete) ionization of sample; followed by coulomb explosion.

- Fortunately scattering is faster: “diffract-and-destroy”. (<50 fsec) (*Nature* **406**, 752, (2000)).
- Crystal diffraction is “self-gating” (*Nature Photonics,* **6**, 35, (2012)).

2. Central hole in detector & no beamstop: 10^{12} ph @ 12 keV ➔ 1K rise in mm^3 Cu ➔ 3000 K per bunch train + huge background

Radiation doses: worst case (?)

- 5000 h User-operation per year
- Undulator shared between 2 experiments ➔ 2500 hrs/exp./year
- Date taking 50% (rest alignment etc.) ➔ 1250 hrs/year
- Each branch can take ½ of the load: 15000 pulses/sec

➔ $6.75\ 10^{10}$ pulses/year

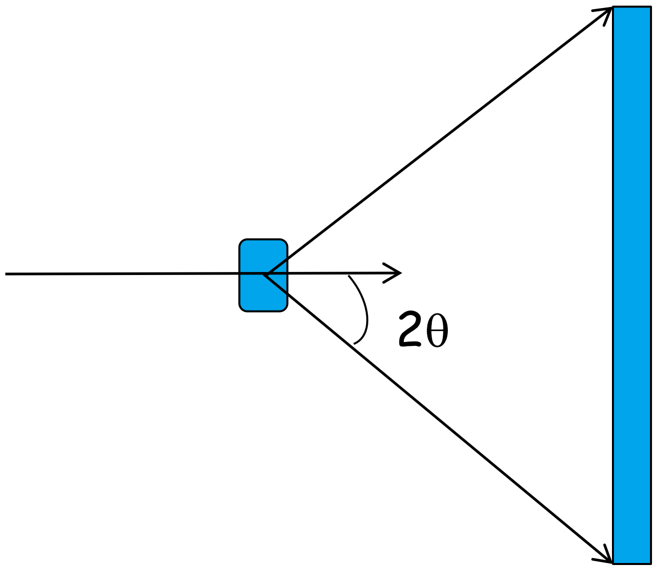
- Certain experiments expect $5\ x10^4$ photons per pixel (200 μm) per pulse. Small angle and liquid scattering always same place on detector

➔ $3.4\ 10^{15}$ photons/year = 10^{16} ph/3 years

(@ 12 keV ➔ silicon surface dose of 1 Giga Gray!!!)

Angular coverage / detector size:

- 12 keV = 0.1 nm in order to study features (d) to atomic resolution.
- Bragg's law ($2d\sin(\theta) = \lambda$) ➔ 2θ = 60 degrees ➔ 120 degrees total



Liquid scattering: momentum transfer 10 A^{-1} ➔ 200 degrees ➔ back scattering

Angular resolution 2 examples:

Coherent Diffractive Imaging (CDI):

- 0.1 nm spatial features: d_{min}
- 100 nm samples (e.g. virus): D

➔Nyquist ➔>2000 sampling points (pixels) ➔0.5 mrad

$$\Delta 2\theta = d_{min} \text{ x } \mathrm{asin}(\lambda/2d_{min}) / 2D$$

X-ray Photon Correlation Spectroscopy:

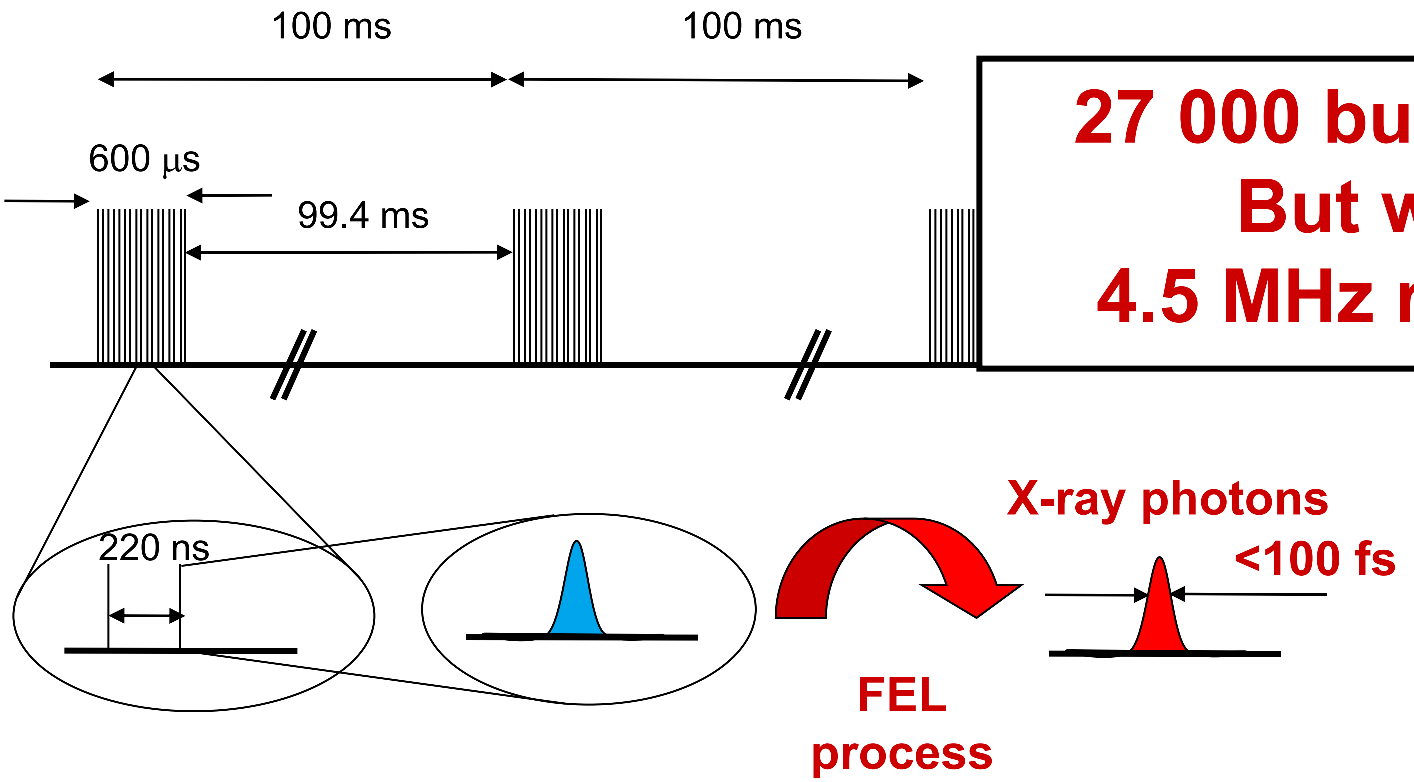
Speckle size: $\Theta_s = \lambda/D$, D is sample or beam size

Compromise between sample heating (large beam) and speckle size (small beam)

25 μm beam at λ=0.1 nm ➔ 4 μrad speckles (80 μm at 20 m)

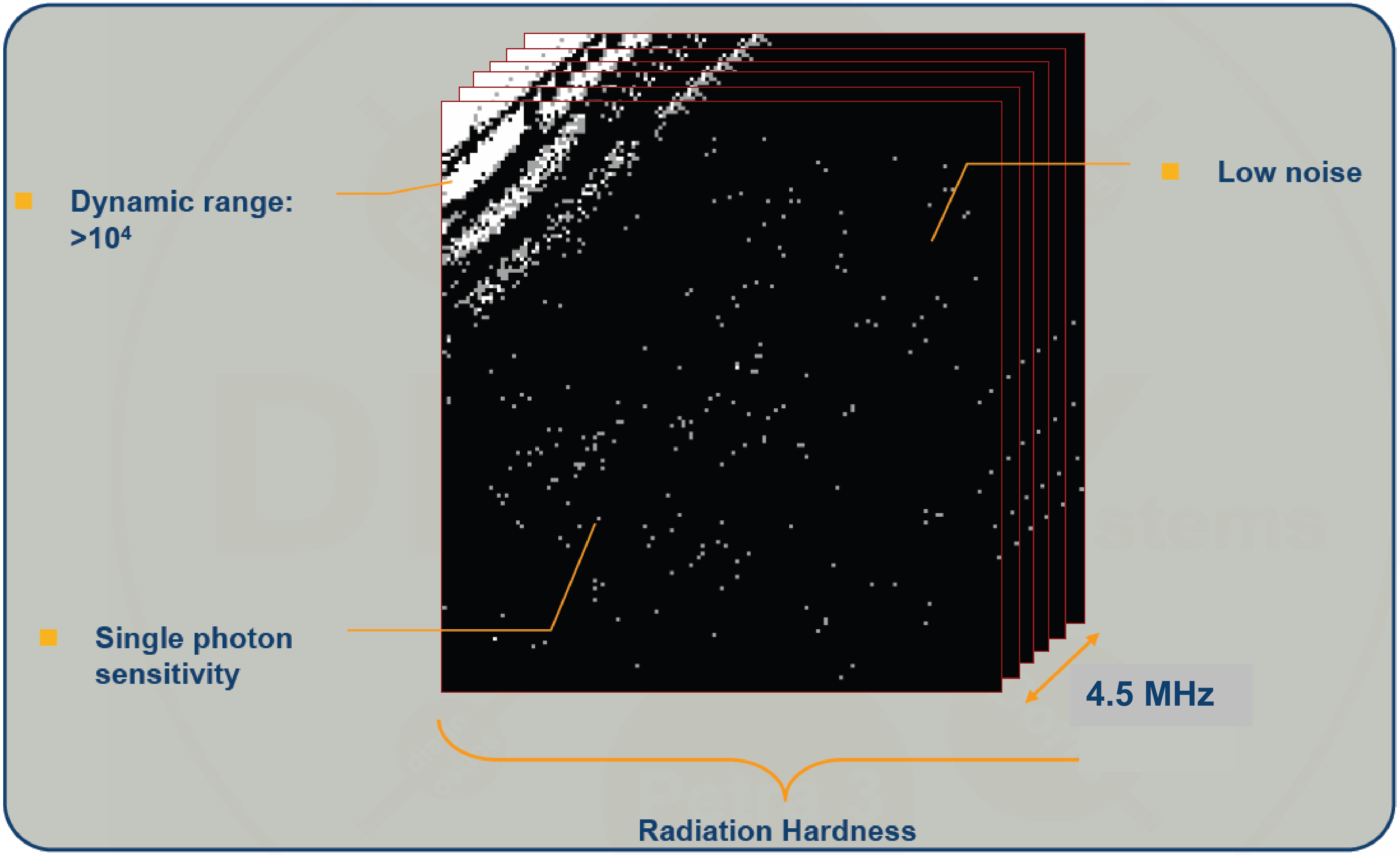
E-XFEL Challenge: Time structure = difference with “others”

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
But with
4.5 MHz rep rate

XFEL Detector requirements



The XFEL solutions:
Hybrid Pixel Array Detectors

Hybrid Pixel Array Detector (HPAD)

Diode Detection Layer

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

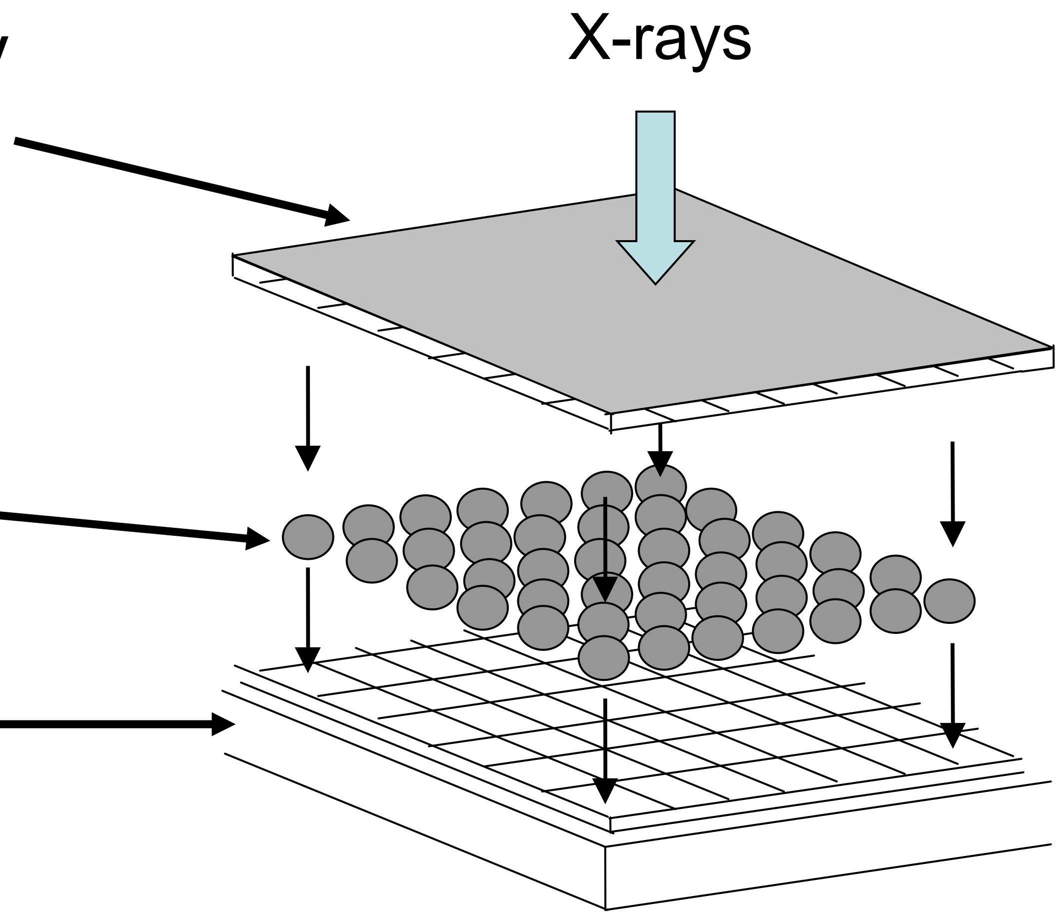
Connecting Bumps

- Solder or indium
- 1 per pixel

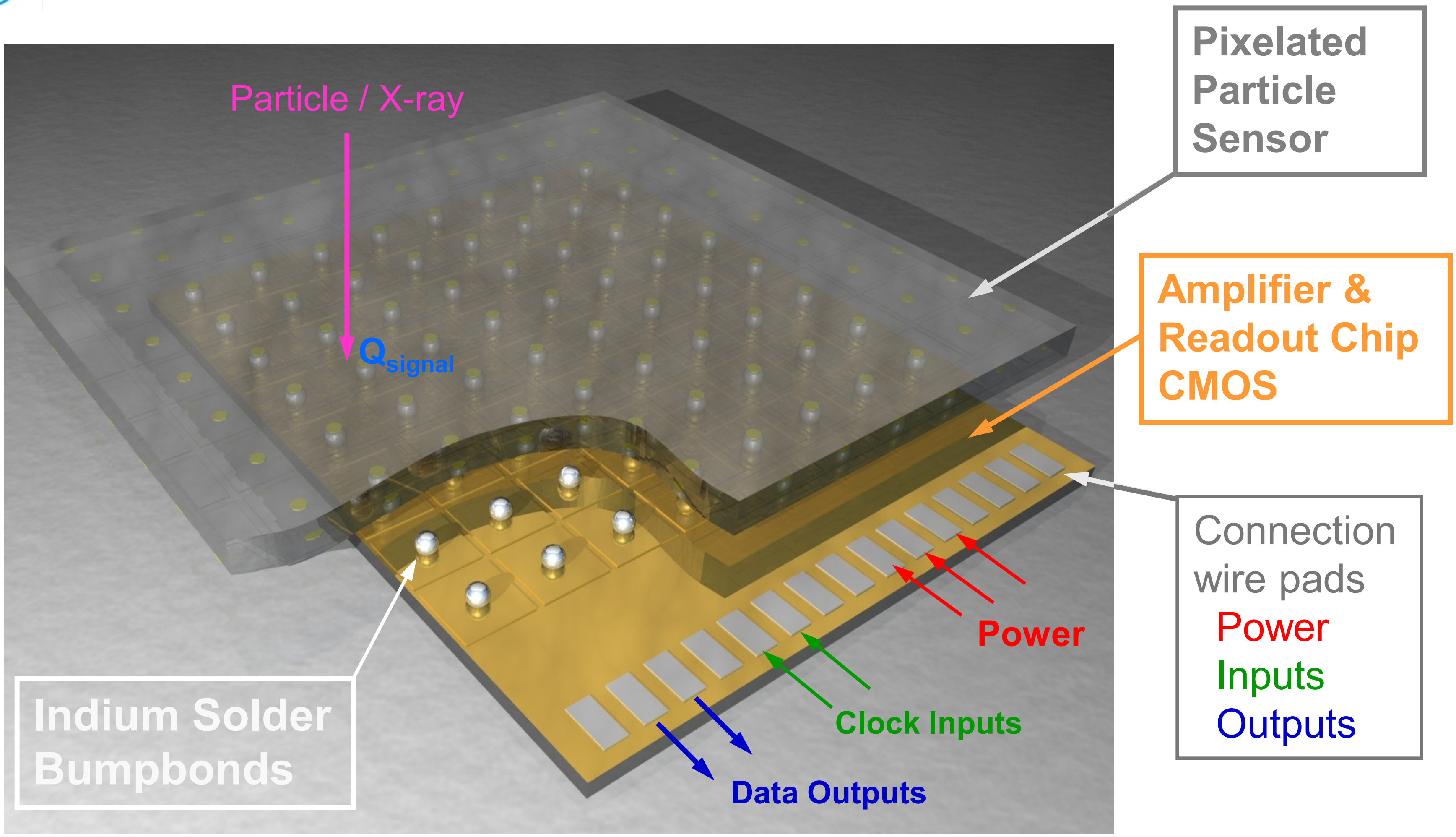
CMOS Layer

- Signal processing
- Signal storage & output

Gives enormous flexibility!

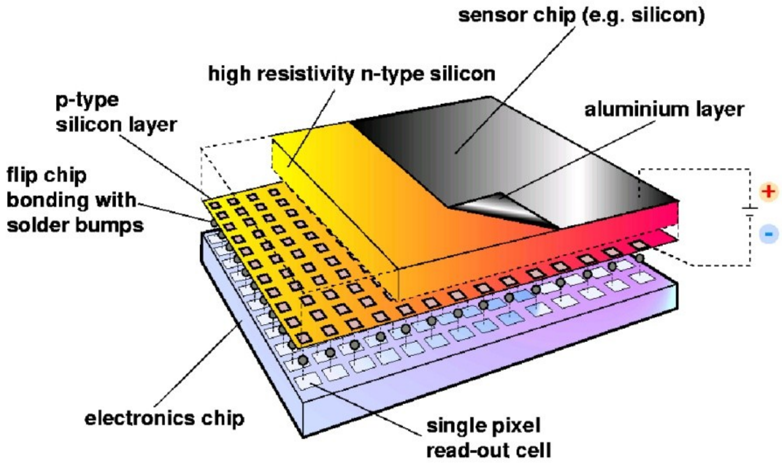


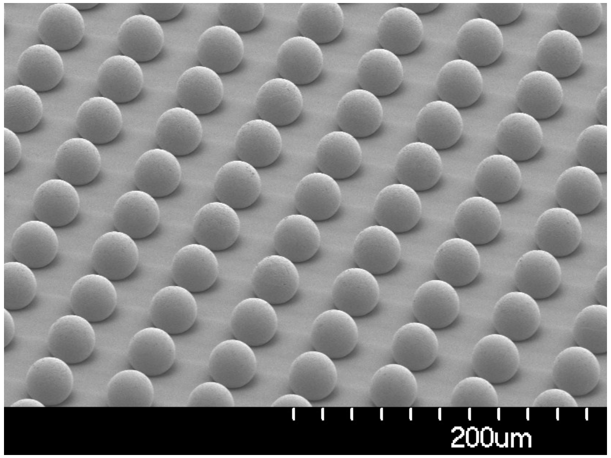
Hybrid Pixel Detectors

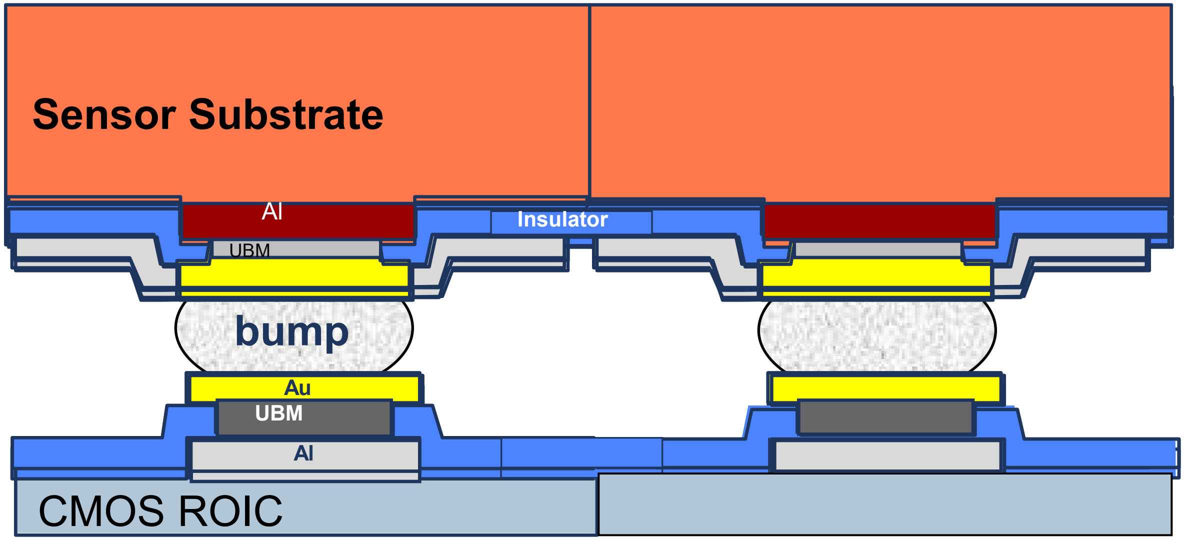


Particle / X-ray → Signal Charge → Electr. Amplifier → Readout → Digital Data

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).
- Direct detection ➔ good spatial resolution
- Massive parallel detection ➔ high flux
- But: development takes long and is expensive.

The Adaptive Gain Integrating Pixel Detector

The AGIPD consortium:

PSI/SLS -Villingen: **chip design; interconnect and module assembly**

Universität Bonn: **chip design**

Universität Hamburg: **radiation damage tests, “charge explosion” studies; and sensor design**

DESY: **chip design, interface and control electronics, mechanics, cooling; overall coordination**

Some Facts

6 years development

~ 20 people

Some Milestones

First 16x16 pixels prototype	End 2010
Definition of final design	Summer 2011
Production, assembly and test	>2013

The Adaptive Gain Integrating Pixel Detector

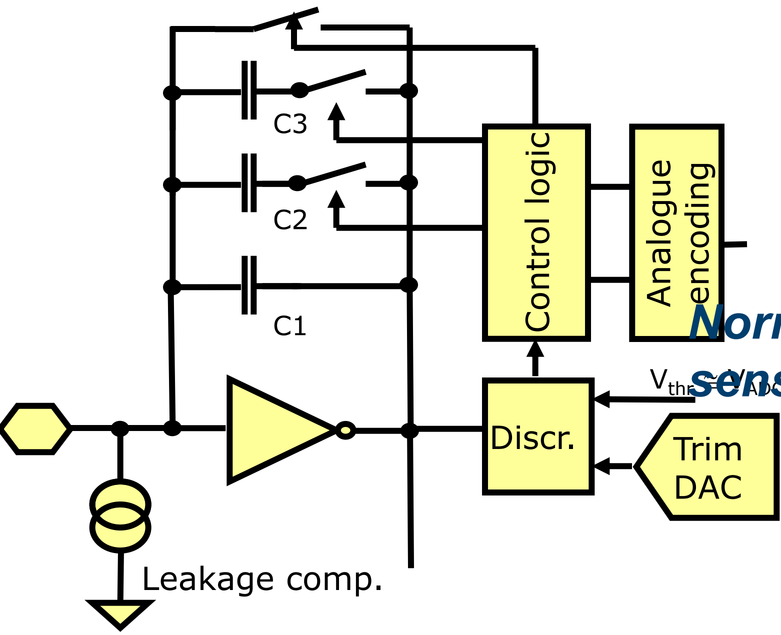
High dynamic range:

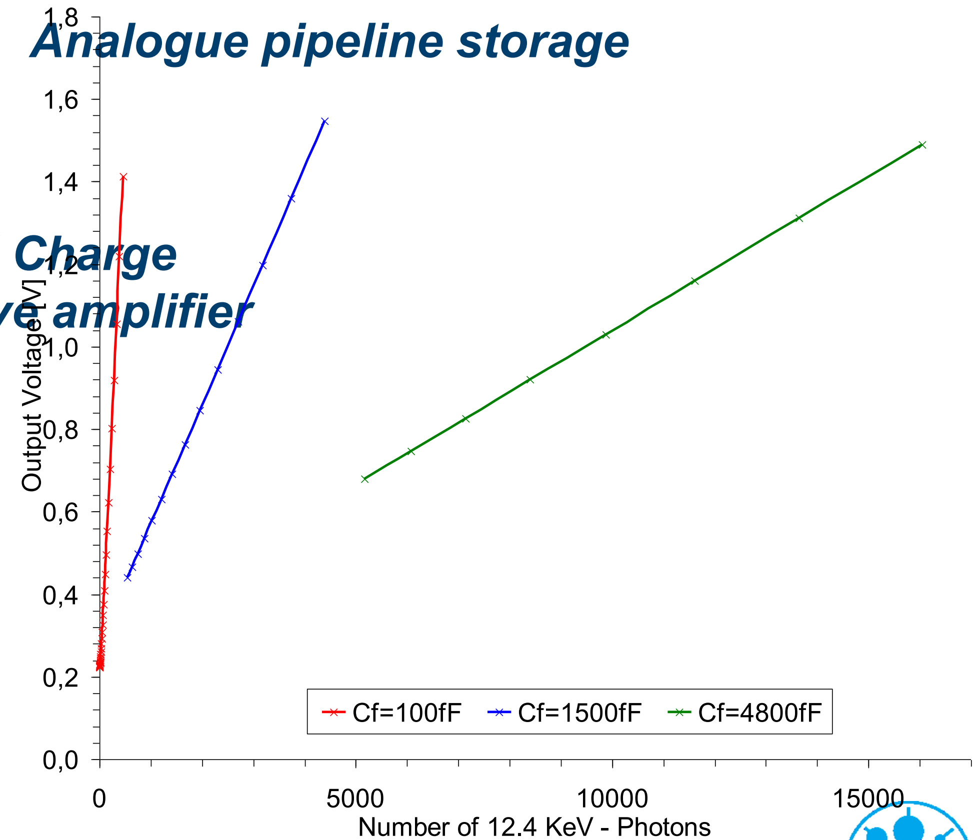
Dynamically gain switching system

Extremely fast readout (200ns):

Analogue pipeline storage

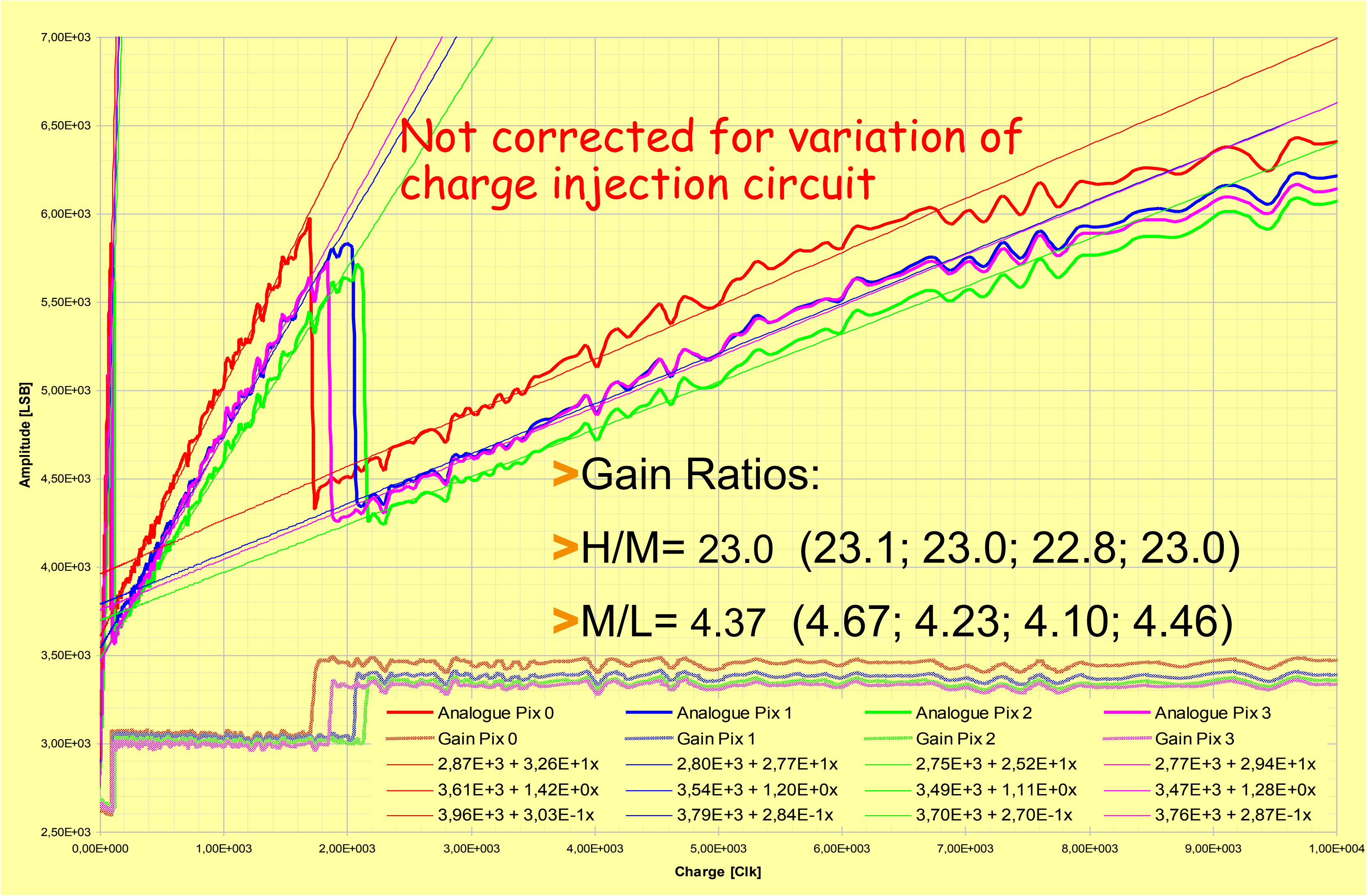
Normal Charge sensitive amplifier





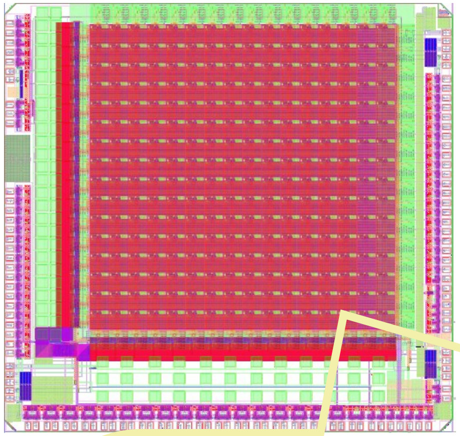
AGIPD03 Gains

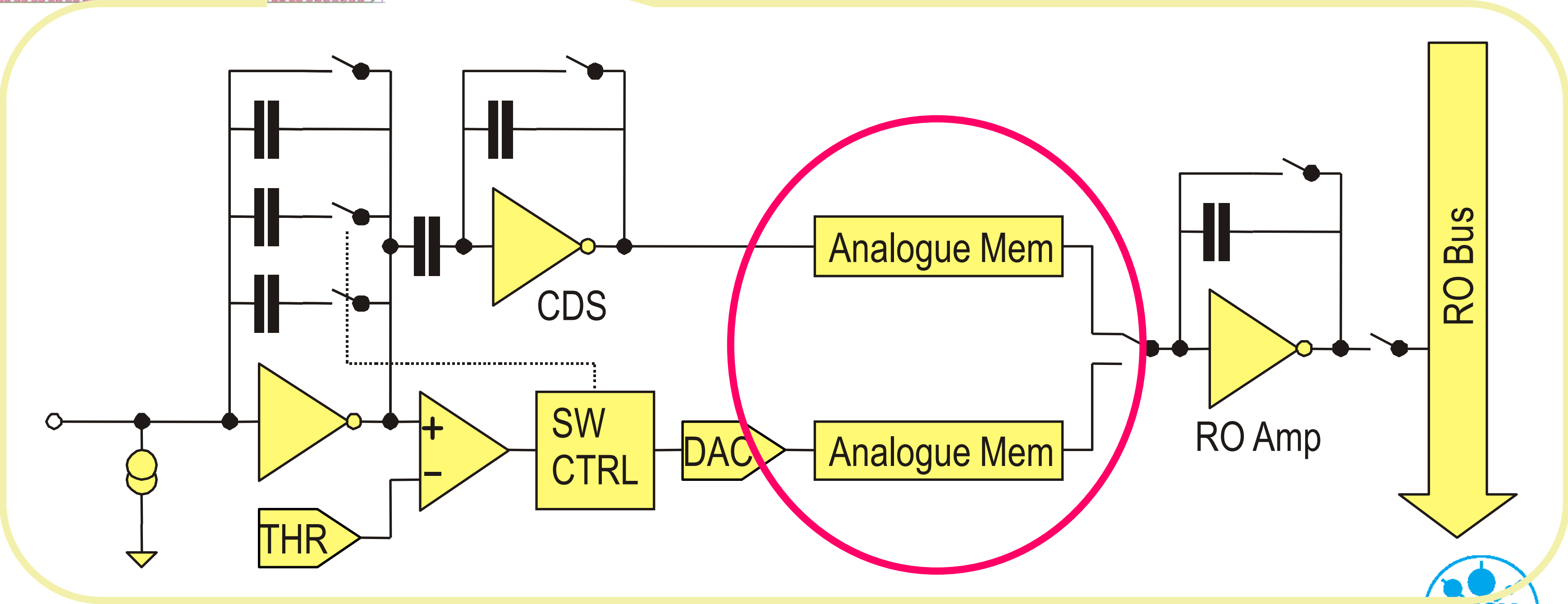
0 Gy



AGIPD – Analogue Memory & Radiation Hardness

- Droop (loss of signal)
  - Time
  - Radiation dose





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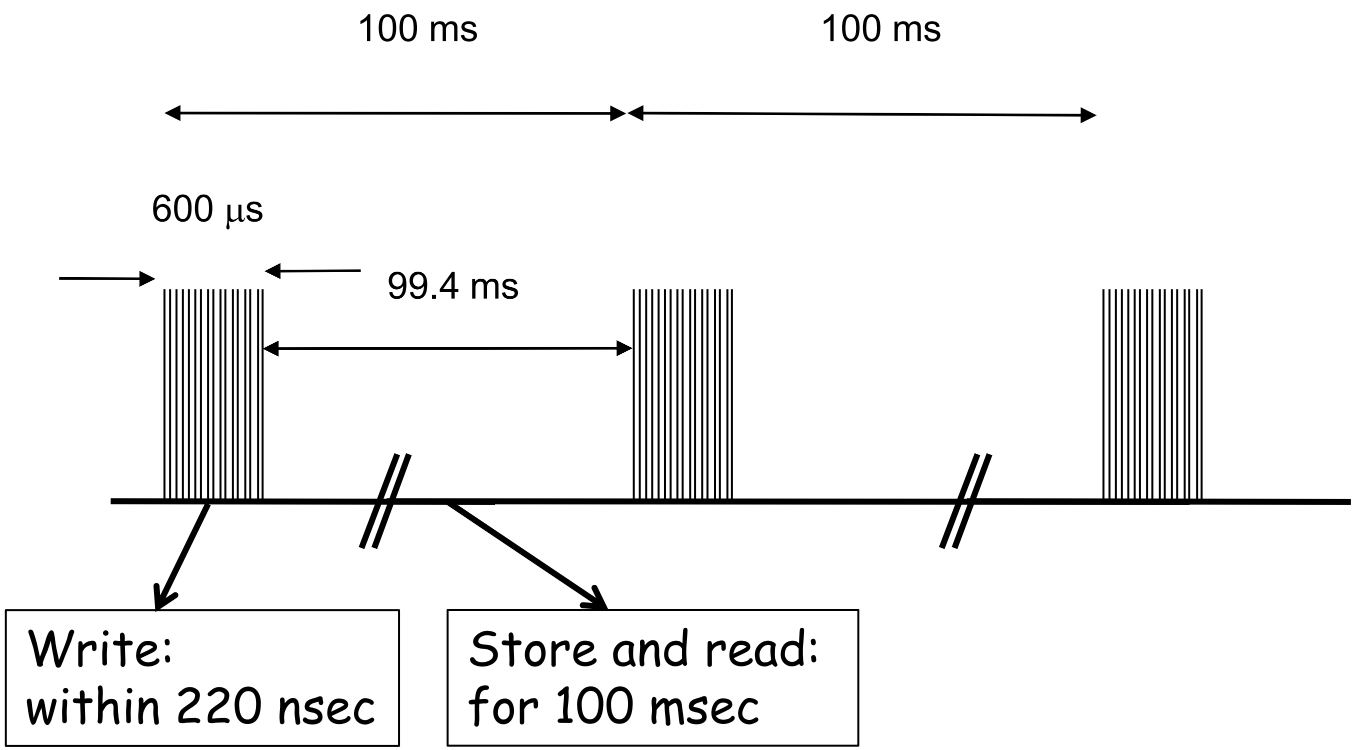
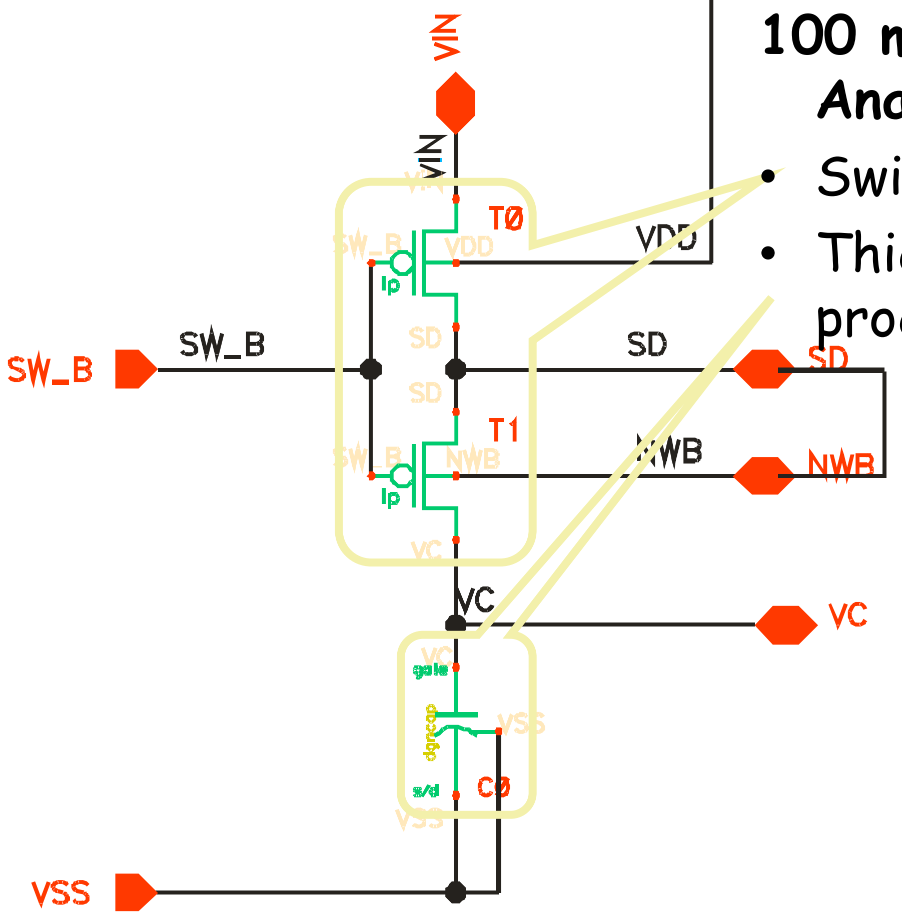


AGIPD - Analogue Memory



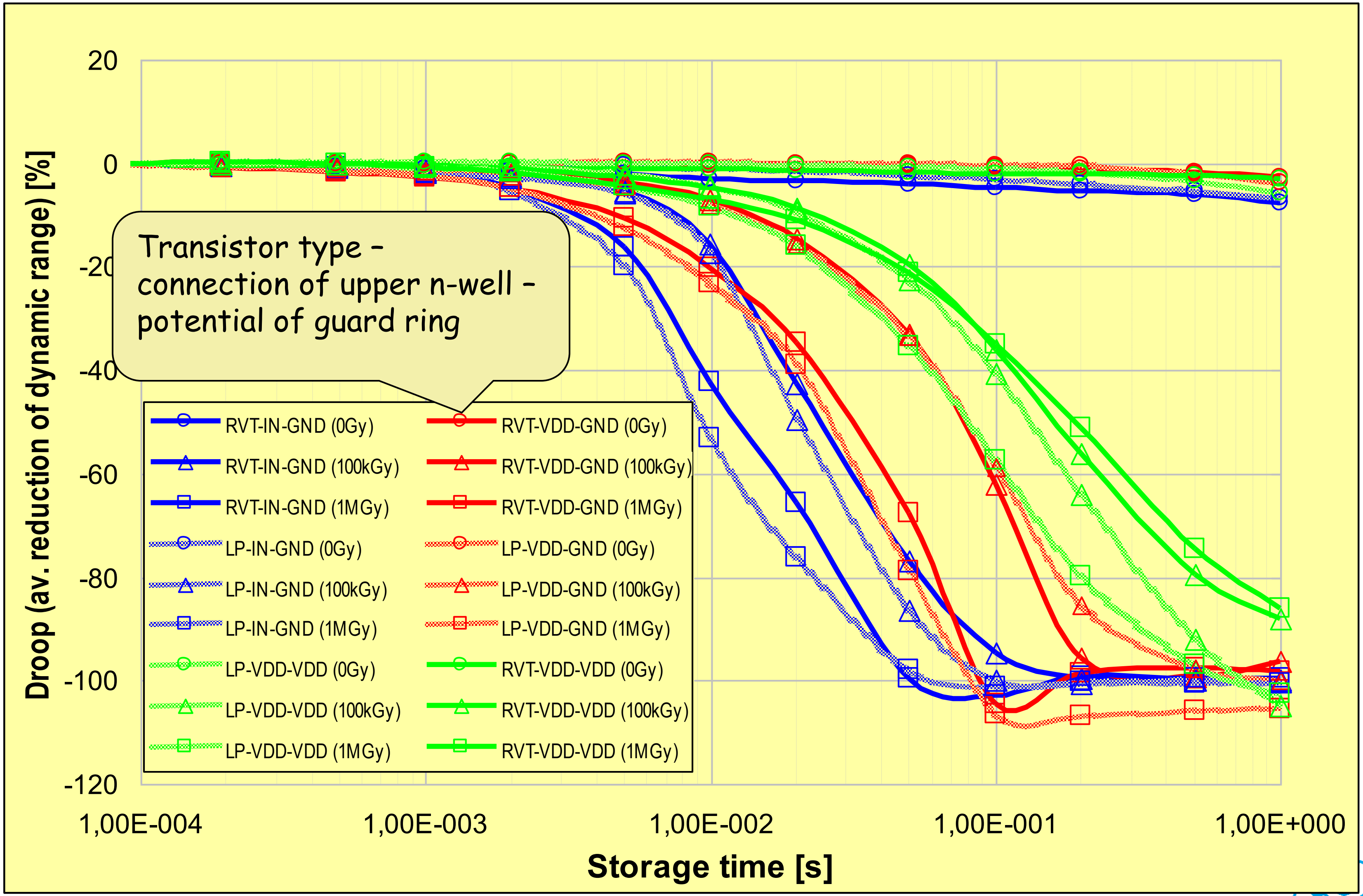
100 msec "loss free" Charge Storage in Analogue Pipeline

- Switch design is the challenge
- Thick oxide & MIM caps in IBM process are OK

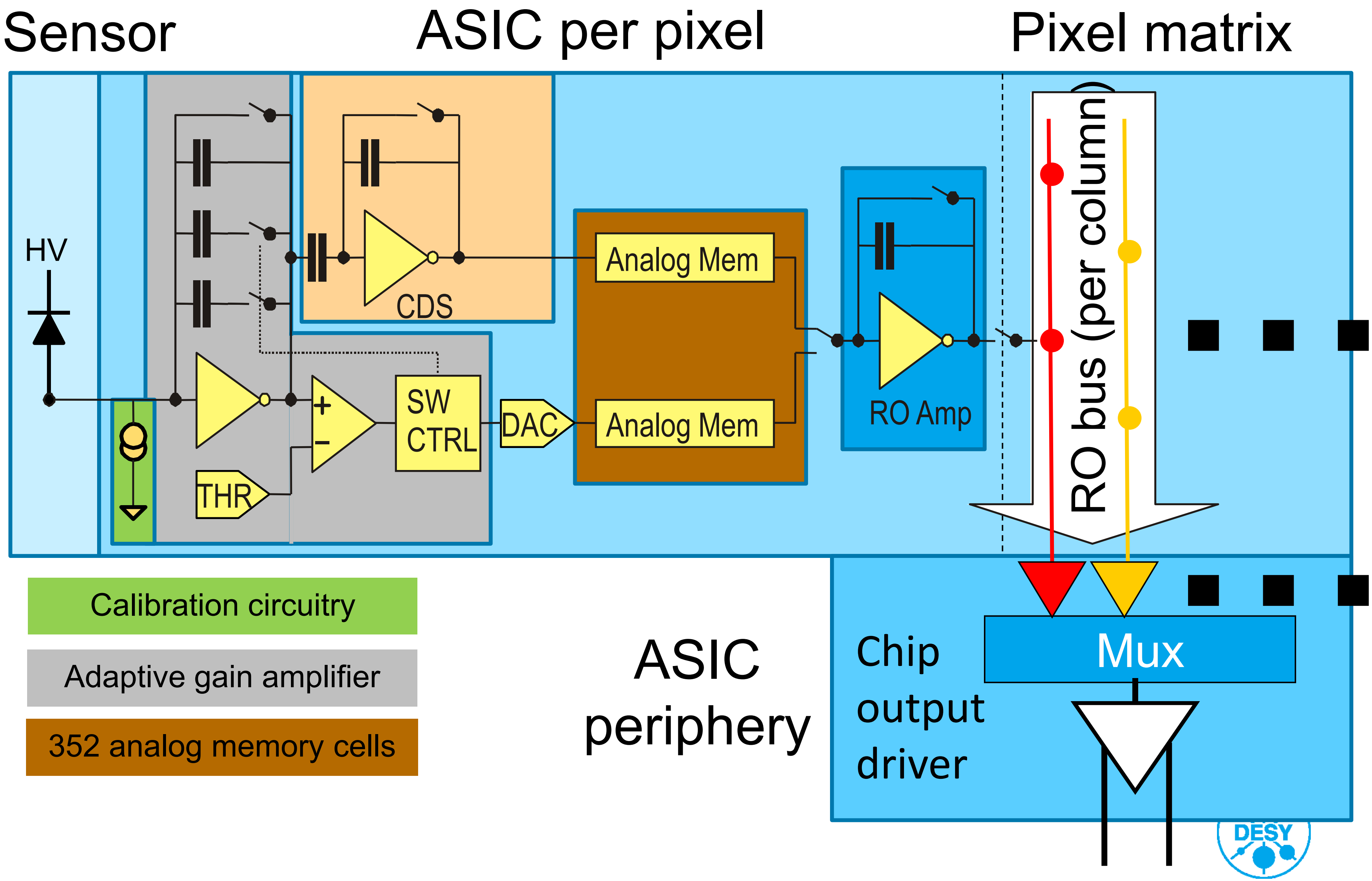
AGIPD analogue memory:

- DGNCAP (thick oxide n-FET in n-well) caps
- Minimise voltage drop across T1
  - Floating n-well
  - Special precautions for radiation hardness needed

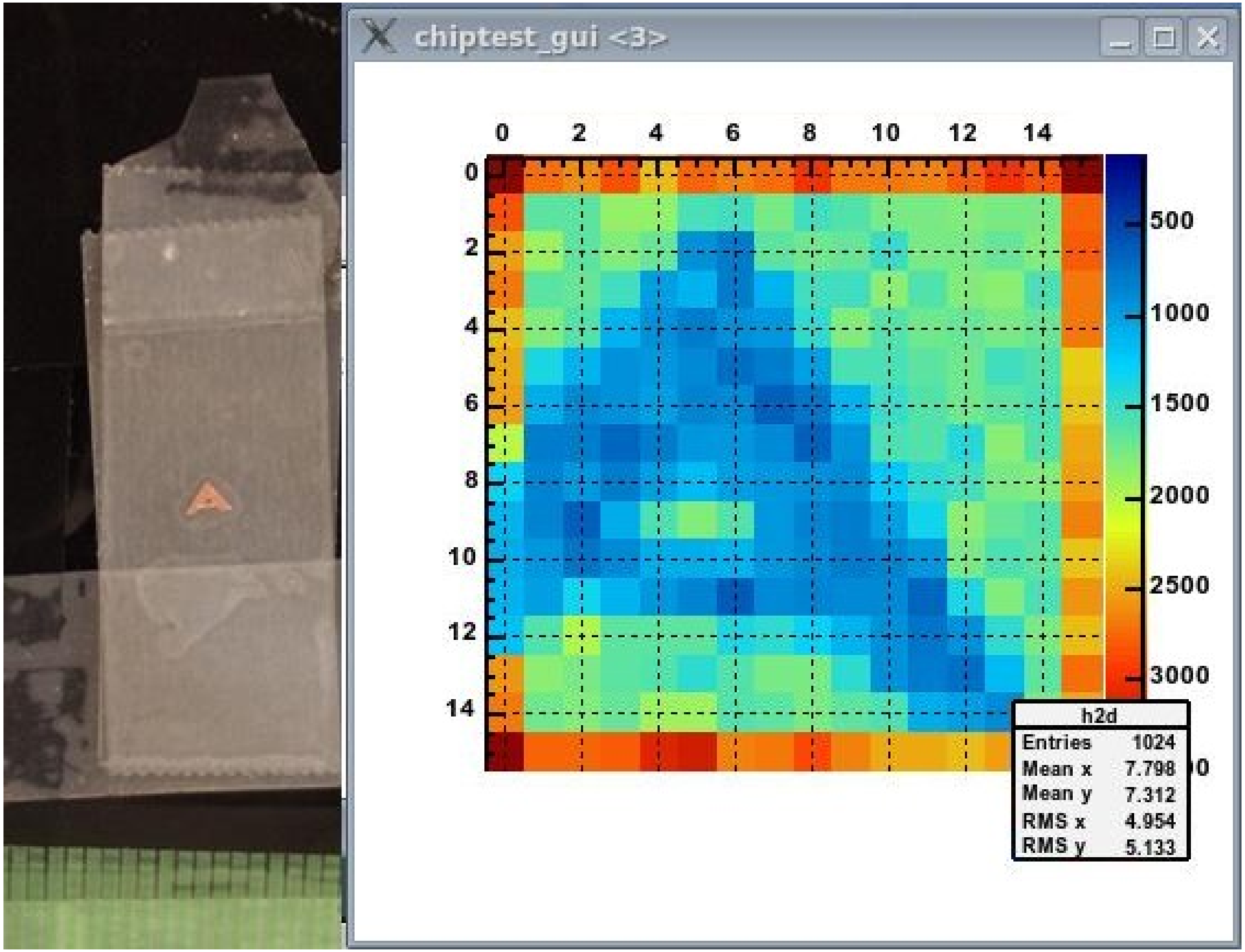
AGIPD03 Memory Leakage



AGIPD ASIC


Sensor
ASIC per pixel
Pixel matrix
HV
CDS
SW CTRL
DAC
THR
+
−
Analog Mem
Analog Mem
RO Amp
RO bus (per column)
Calibration circuitry
Adaptive gain amplifier
352 analog memory cells
ASIC periphery
Chip output driver
Mux

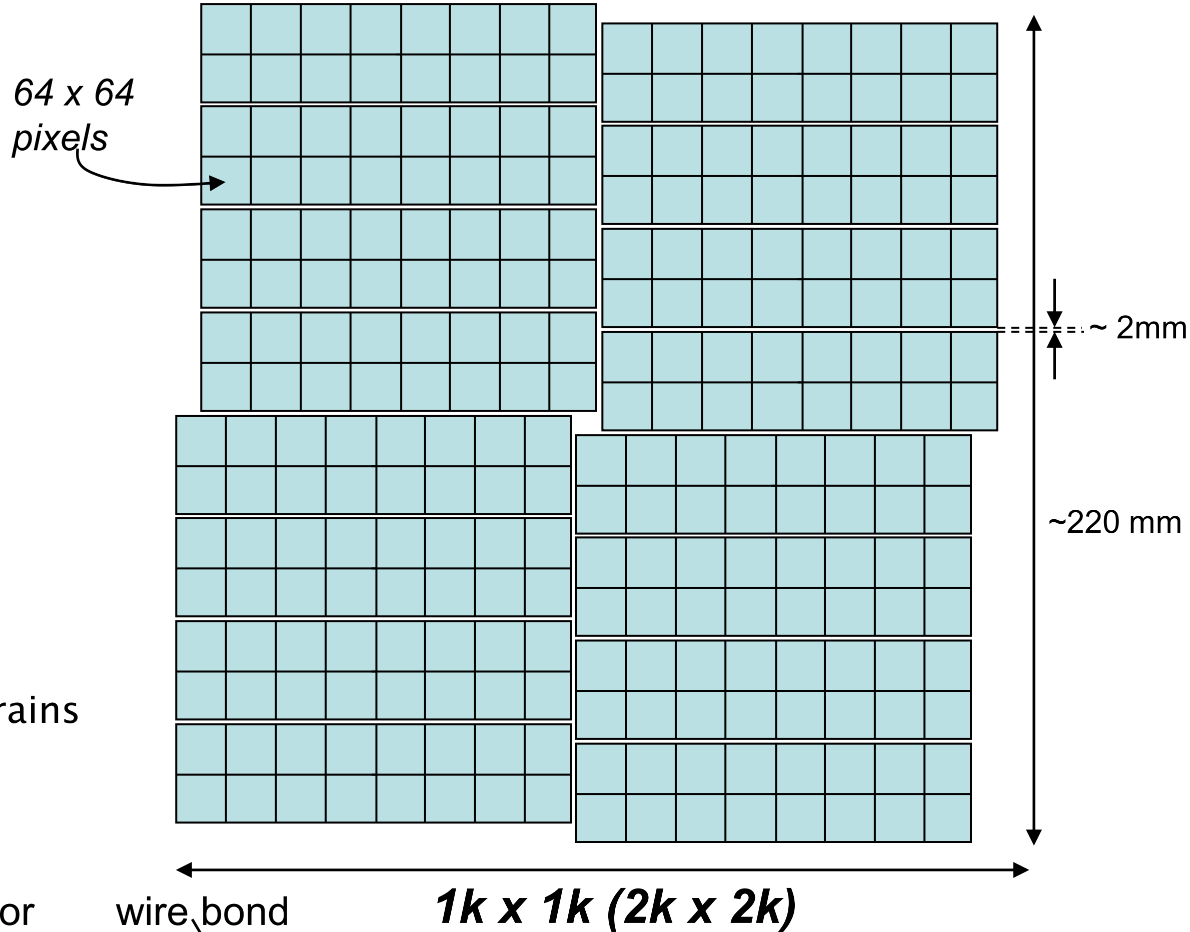
Imaging with AGIPD 0.2 prototype

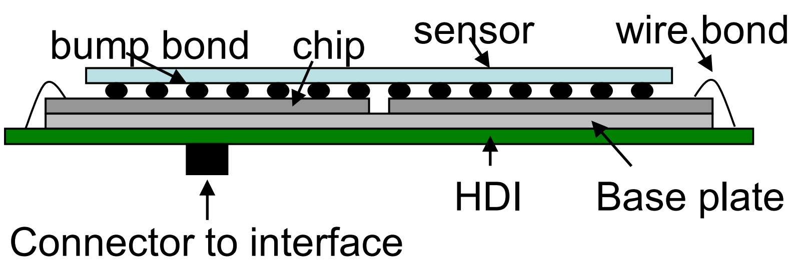


The Adaptive Gain Integrating Pixel Detector

<u>Basic parameters</u>

- 1 Megapixel detector (1k × 1k)
- 200μm × 200μm pixels
- Flat detector
- Sensor: Silicon 128 x 512 pixel tiles
- Single shot 2D-imaging
- 4.5 MHz frame rate
- 2 × 10^4 photons dynamic range
- Adaptive gain switching
- Single photon sensitivity at 12keV
- Noise ≤300e
- Storage depth ≥350 images
- Analogue readout between bunch-trains





Calibration challenges:

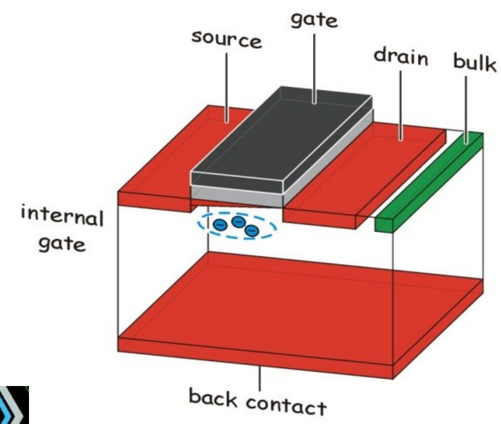
- 10^6 x 3 gains; with > 10 points per gain curve: $O(10^7)$
- 10^6 x 350 storage cells > 10 points per droop curve: $O(10^9)$
- How to store the calibration data and how to correct data?
- How often do we need to recalibrate
- On-chip calibration sources
- Cross calibration with physics (photons, alpha, …)
- How long does this all take?

Some reflections on the future

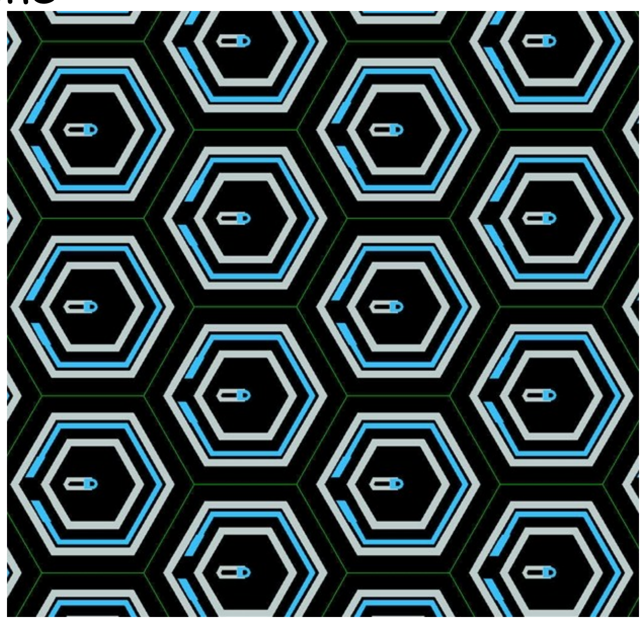
- Active Sensors (DSSC)

DSSC - DEPMOS Sensor with Signal Compression

- DEPFET per pixel
- Very low noise (good for soft X-rays)
- non linear gain (good for dynamic range)
- per pixel ADC
- digital storage pipeline



- **Hexagonal pixels 200µm pitch**

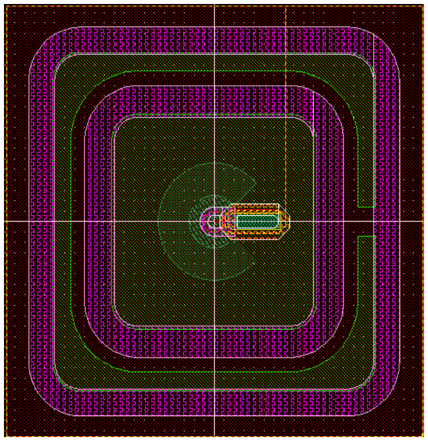


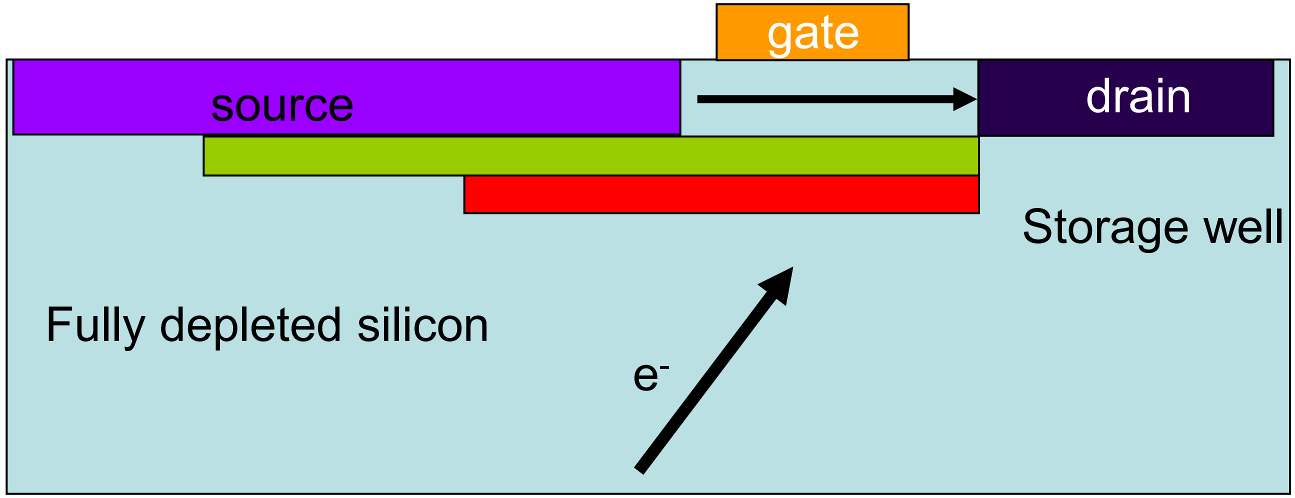
- combines DEPFET
- with small area drift detector (scaleable)

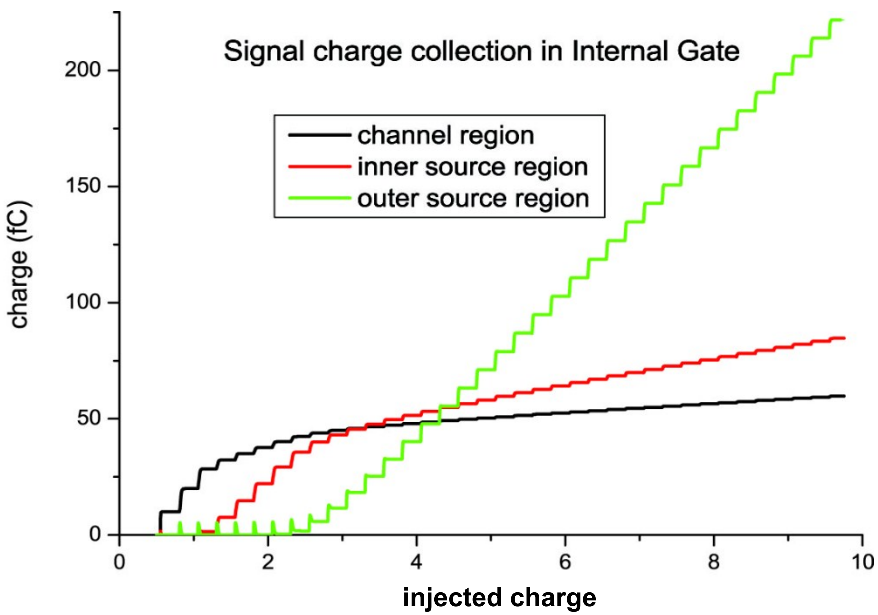
- MPI-HLL, Munich
- Universität Heidelberg
- Universität Siegen
- Politecnico di Milano
- Università di Bergamo
- DESY, Hamburg

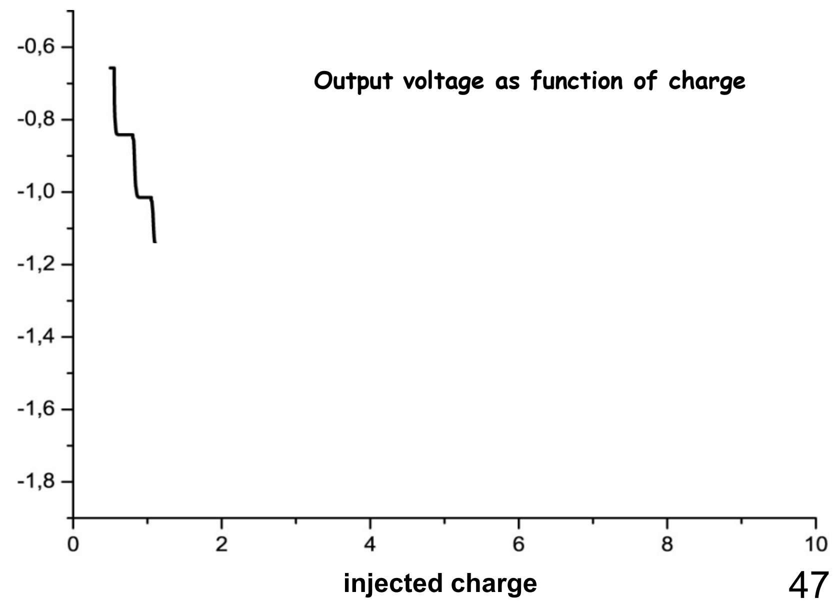
DEPFET: Electrons are collected in a storage well

⇒Influence current from source to drain









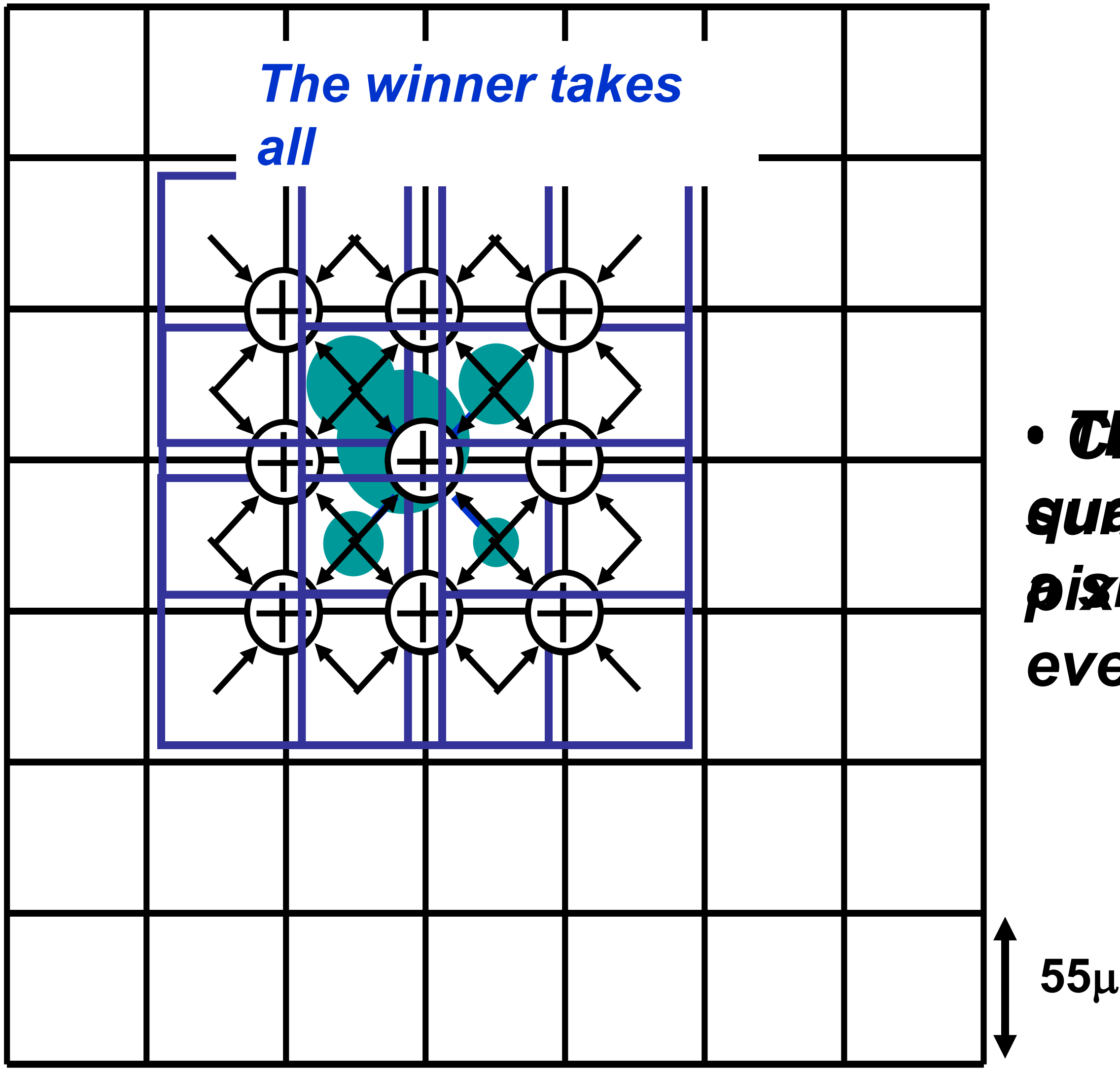
Some reflections on the future

- Active Sensors (DSSC)
- Built-in intelligence per pixel (AGIPD)

Some reflections on the future

- Active Sensors (DSSC)
- Built-in intelligence per pixel (AGIPD)
- Communication pixels (Medipix-3)

Medipix3 – charge summing concept

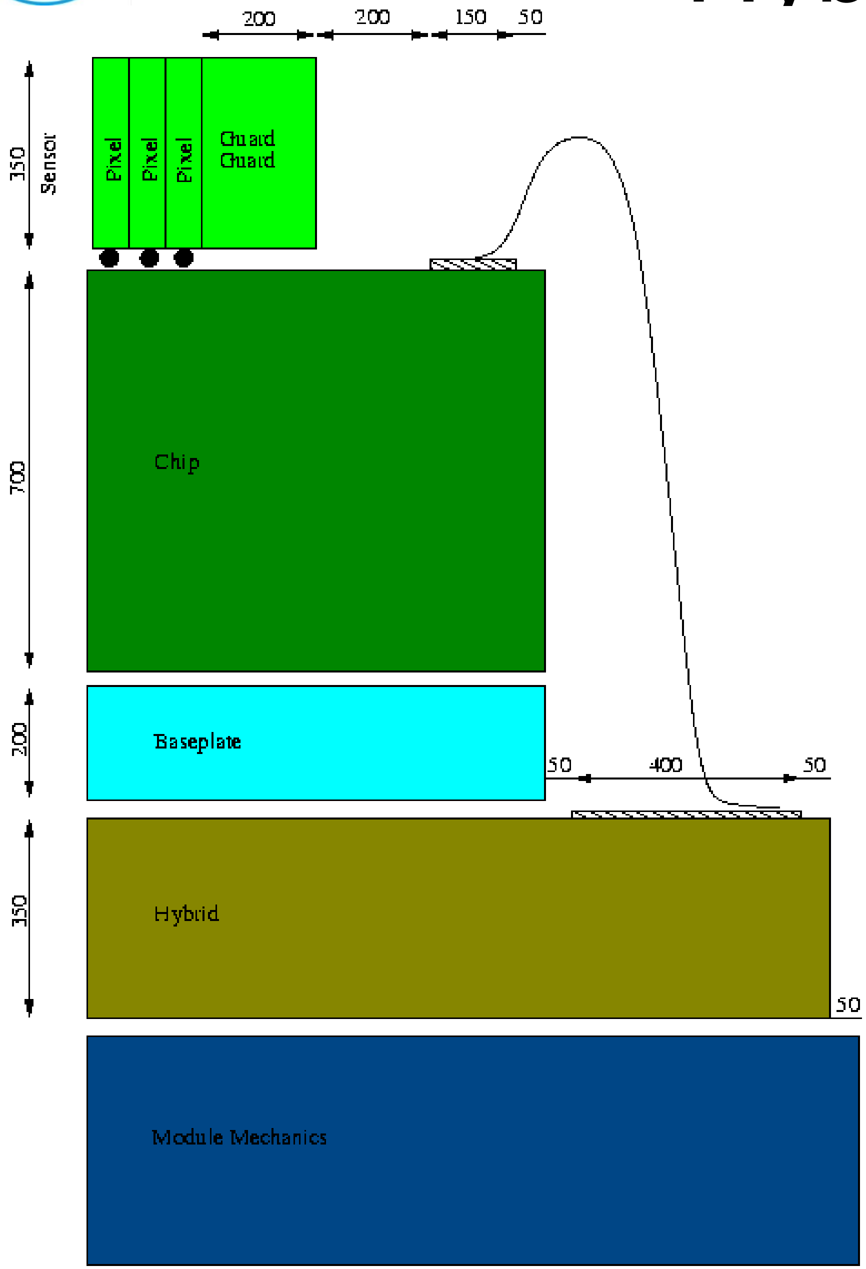


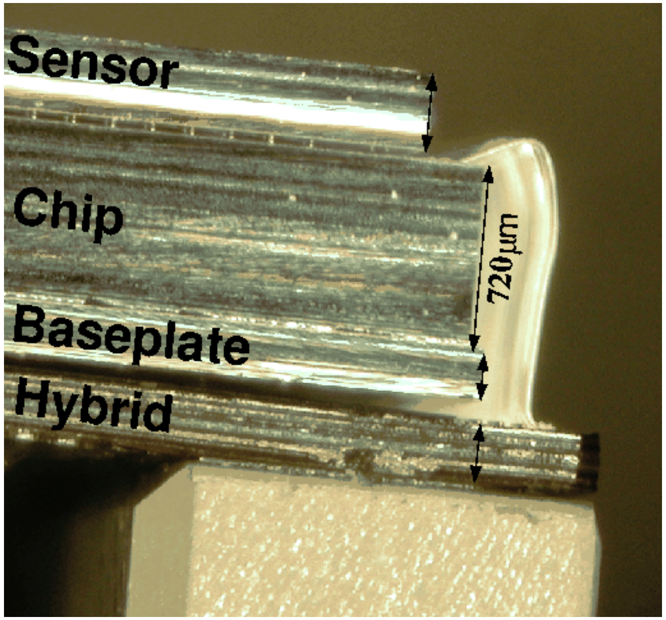
- *The incoming quantum is assigned as a single hit*
- *Charge processed is summed in every 4 pixel cluster on an event-by-event basis*

Some reflections on the future

- Active Sensors (DSSC)
- Built-in intelligence per pixel (AGIPD)
- Communication pixels (Medipix-3)
- More functionality per area/pixel: 3D-ASIC technology (Helmholtz Cube)

Hybridization

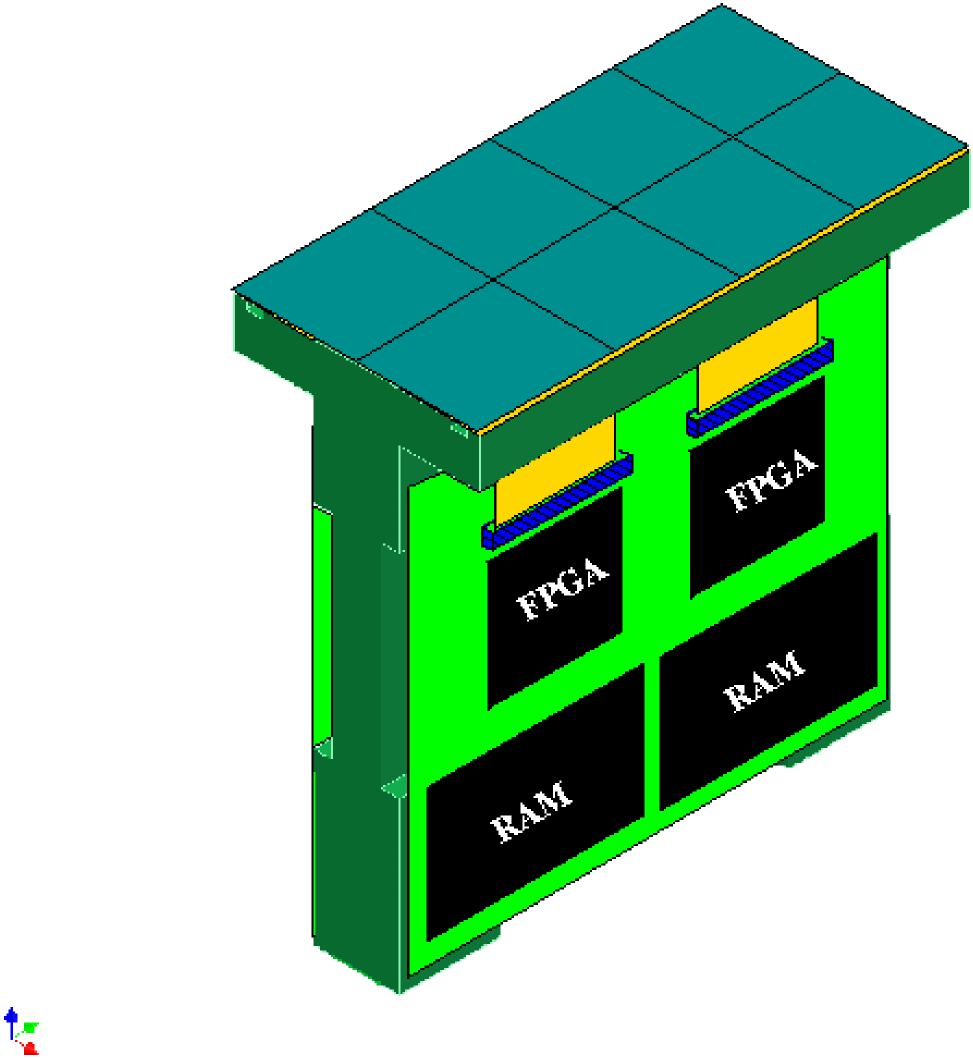


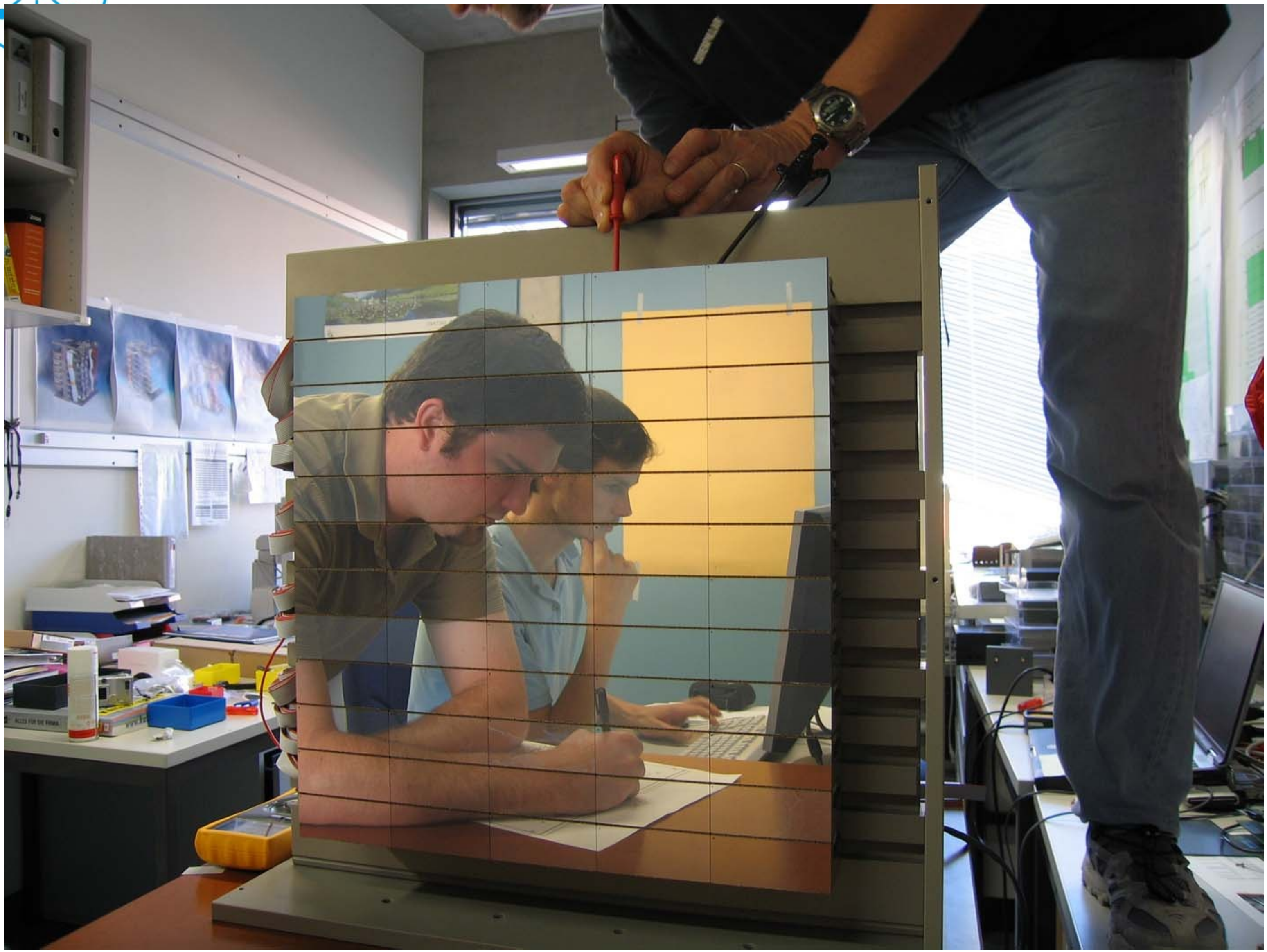


- Cut the sensor as close as possible
- Use thinned readout chips
- Stay within the exact n-fold pixel pitch

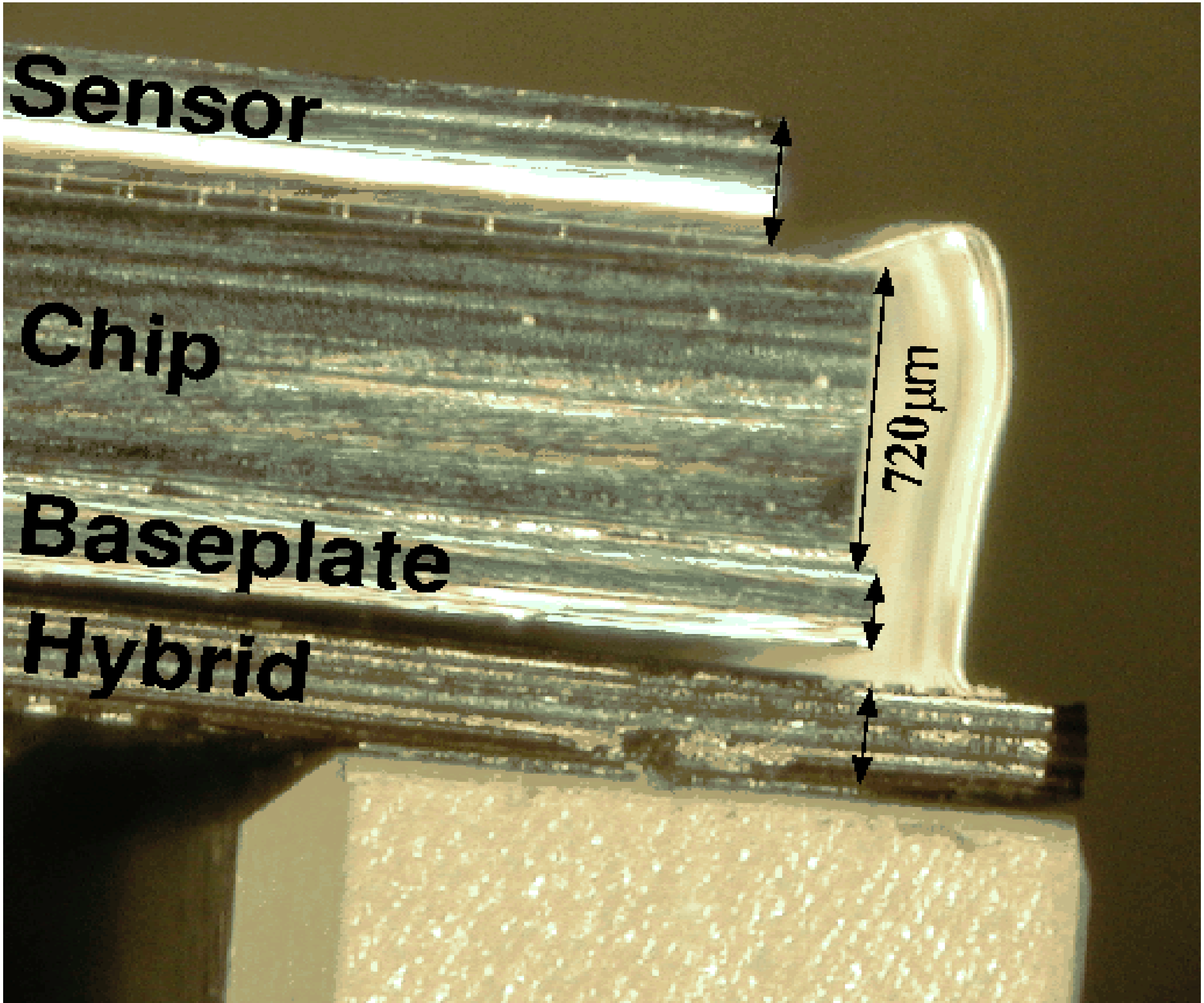
XFS Module Specification: PSI/SLS

Operate **2x4 (8)** Chips per Module. **~78 x 39 mm^2**

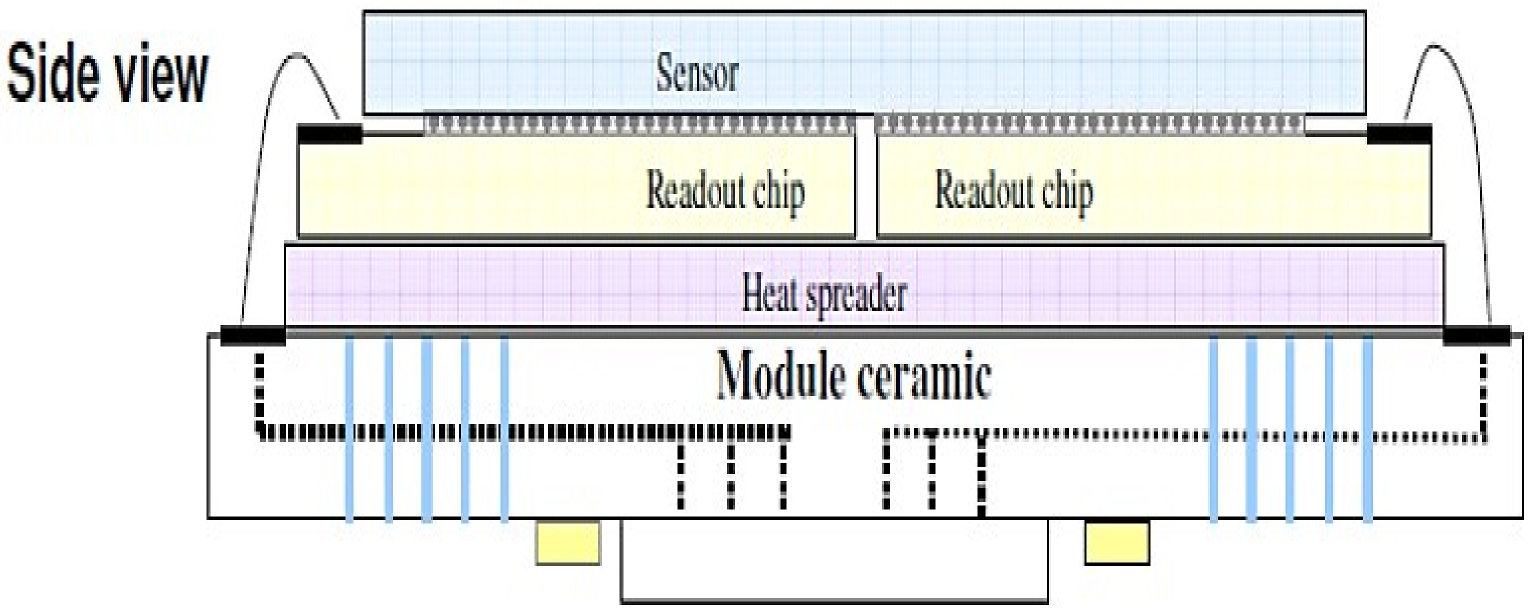




Courtesy: Ch. Brönnimann, PSI SLS Detector Group


Sensor
Chip
Baseplate
Hybrid
720µm

Current State-of-the-art



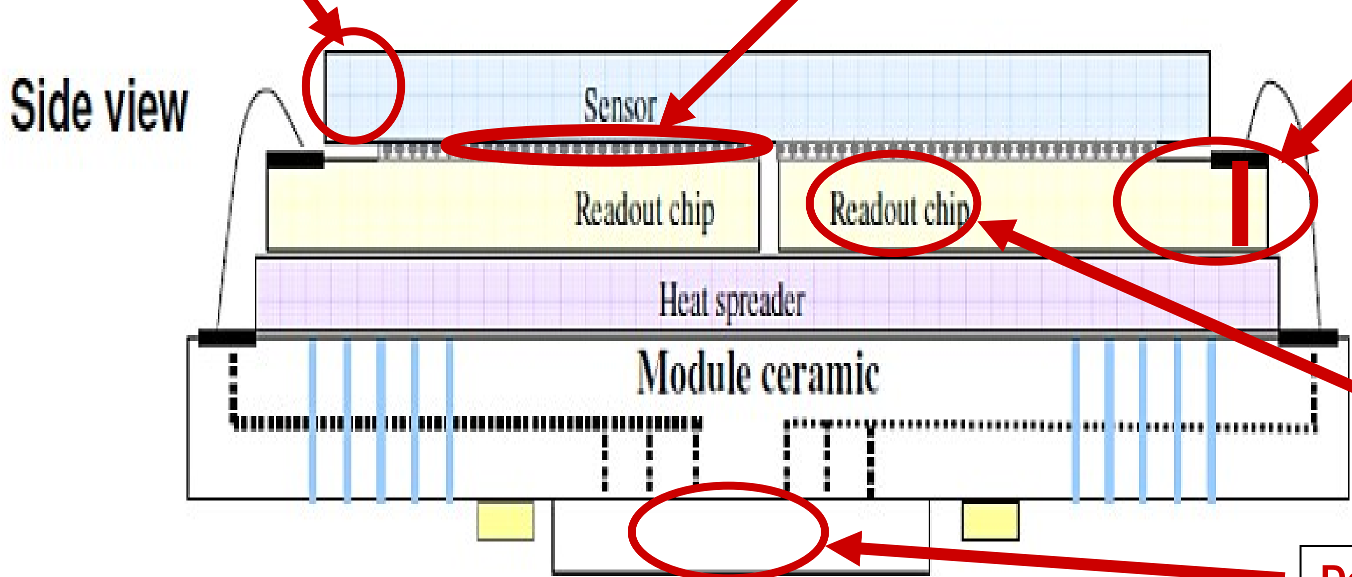
The "Helmholtz-Cube"

Vertically Integrated Detector Technology

Replace standard sensor with: 3D and edgeless sensors, as well as High-Z

Replace standard bump-bonds with new interconnect techniques

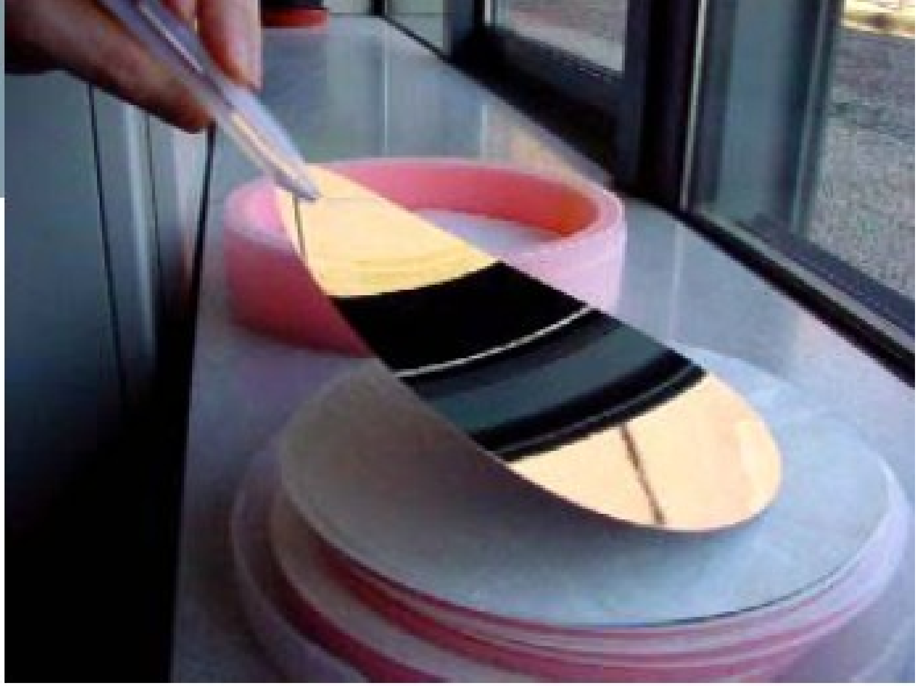
Replace standard ASIC and wire bonds with thinned ASICs and TSV as well as ball-grid arrays



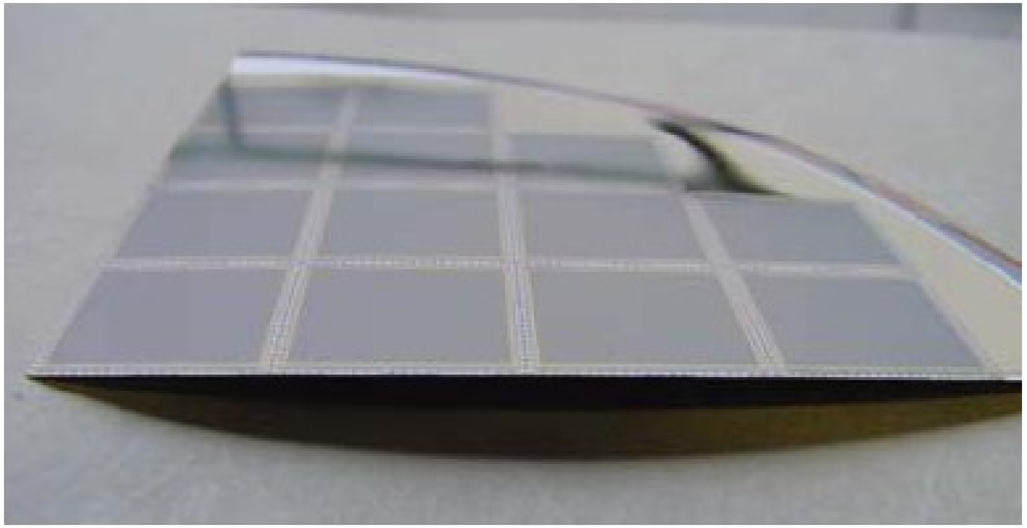
Replace standard ASIC with 3D-ASICs

Develop new high speed IO's

Technology enablers:
Wafer thinning

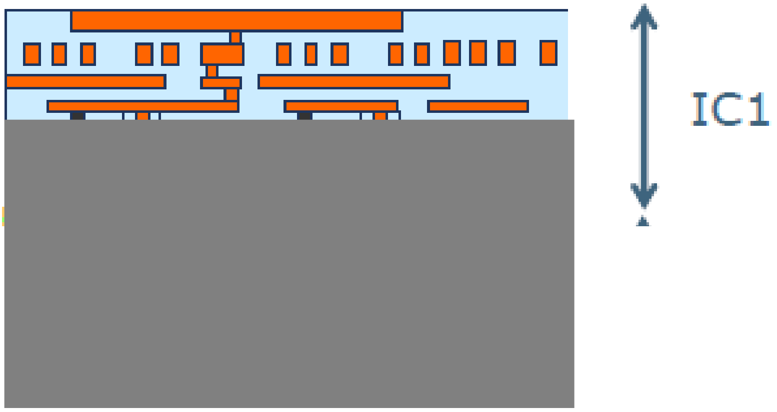


- Technology:
  - rough/fine grinding, dry/wet etch at wafer level
  - Si, glass, GaAs, ...
  - critical: thinning damage, impact on devices
  - very thin wafers (< 100 um): use of carrier wafers and temporary (de-)bonding technology
- Features:
  - thinning down to 15 um
  - total thickness variation < 1 um
- Advantages/Applications:
  - thin (3D) integration
  - embedding in flexible substrates
  - backside illuminated imagers
  - ultra low X_0 -> tracking detectors



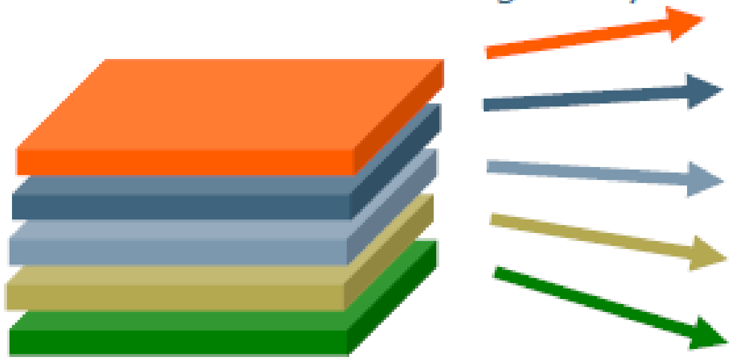
Technology enablers:
TSV processing during CMOS process

- 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 um
  - via diameter: 3 – 5 um
  - via pitch: 10 um
- Applications:
  - Pixel level interconnect
  - imager/processor/logic/memory stacking



Conclusions & outlook II

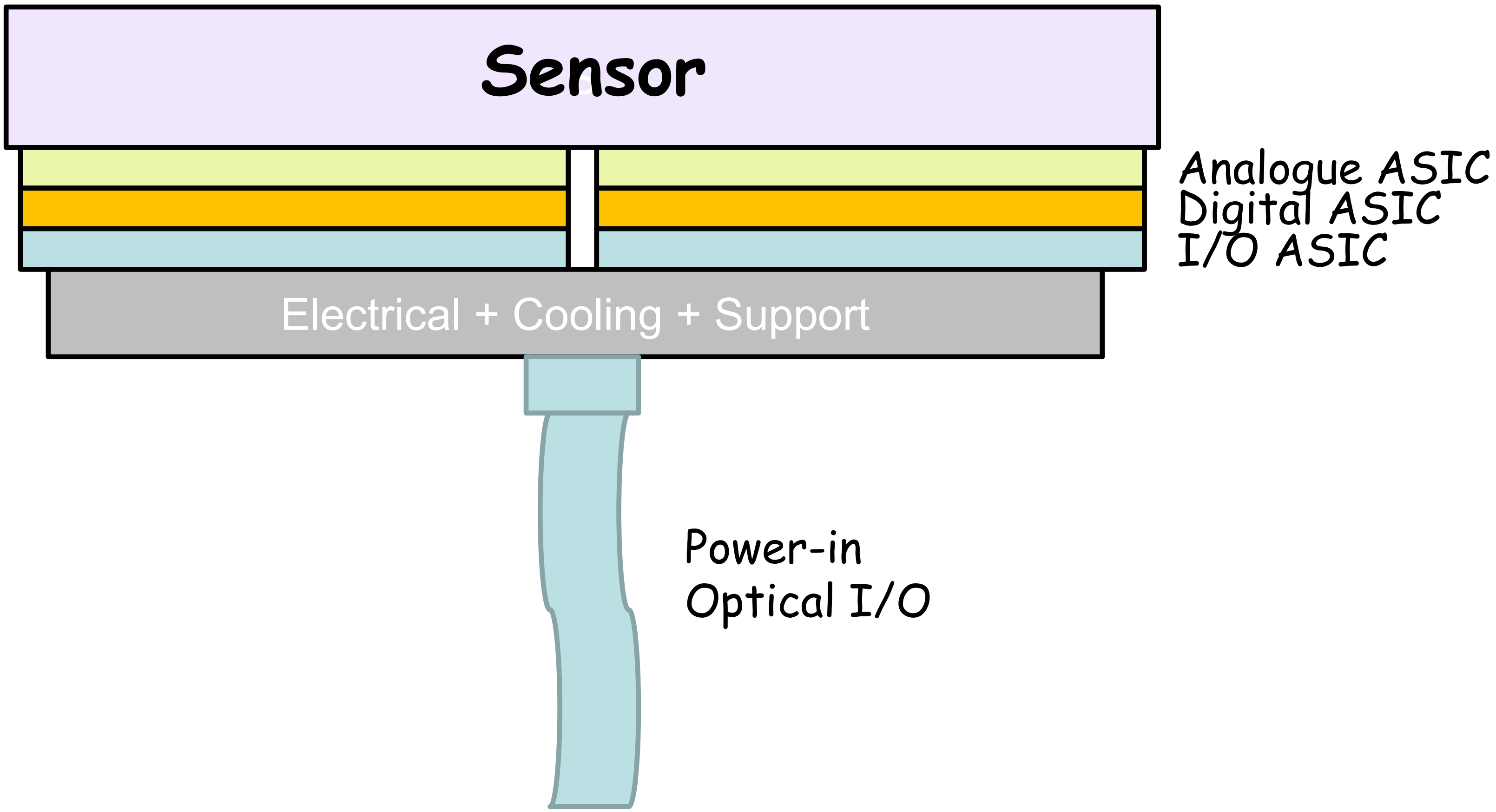
- High **sensitivity** by extreme thinning and backside illumination
- **3D integration technology** will allow manufacturing of **advanced detection systems**:
  - **complex** imaging detectors using high density 3D interconnects (≥1 per pixel) between different intelligent layers:



- Economical aspects:
  - (large) commercial foundries will offer 3D in (near) future
  - But: typically large volume
  - Solution: IMEC prototyping/small scale production "CMORE"

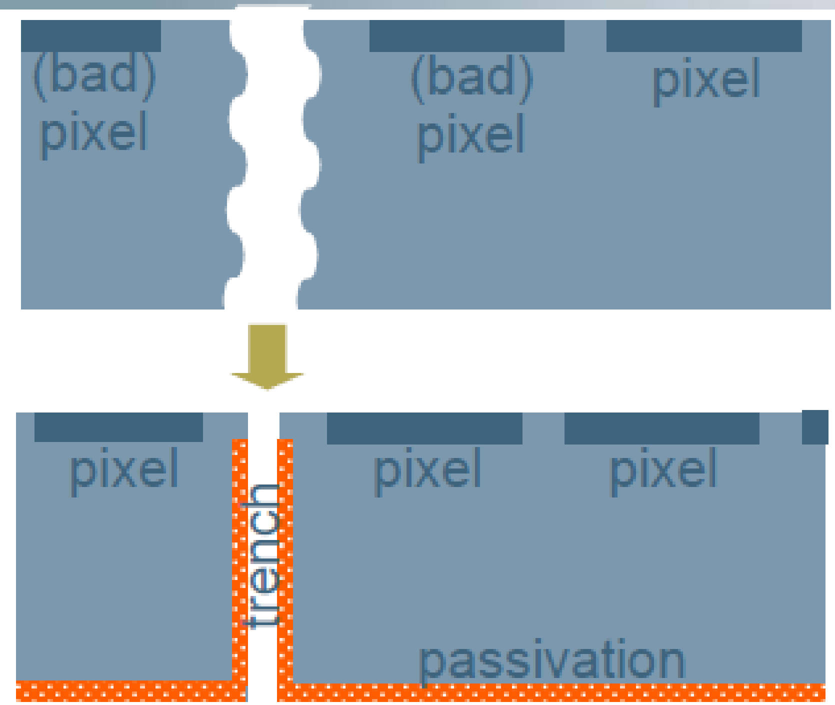
The “Helmholtz-Cube”

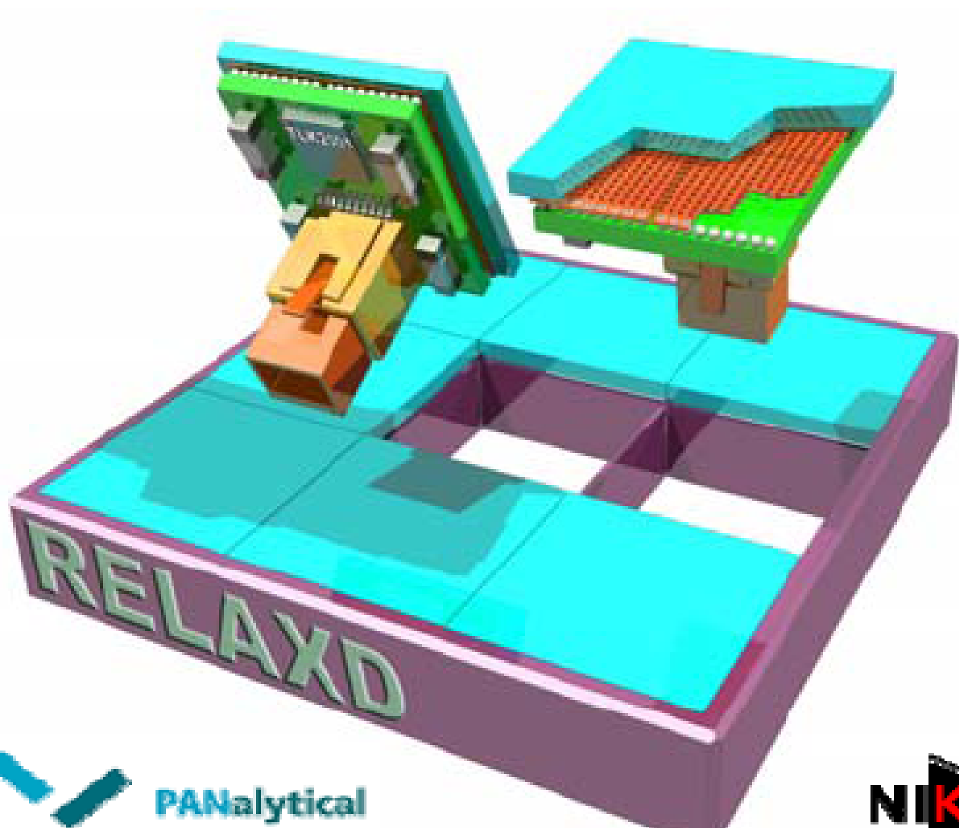
Vertically Integrated Detector Technology



Detector systems:
RelaxD: tilable X-ray imagers

- Issue: bad pixels at imager boundary due to damage by dicing
- Solution: edgeless detector concept:
  - Replace dicing by trench etching and proper passivation





- Status:
  - 3D integration ongoing
  - minimal dead area by trench singulation and in situ passivation

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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.