Detector Requirements
For FEL and Synchrotron Sources

Heinz Graafsma

Photon Science Detector Systems

DESY-Hamburg; Germany

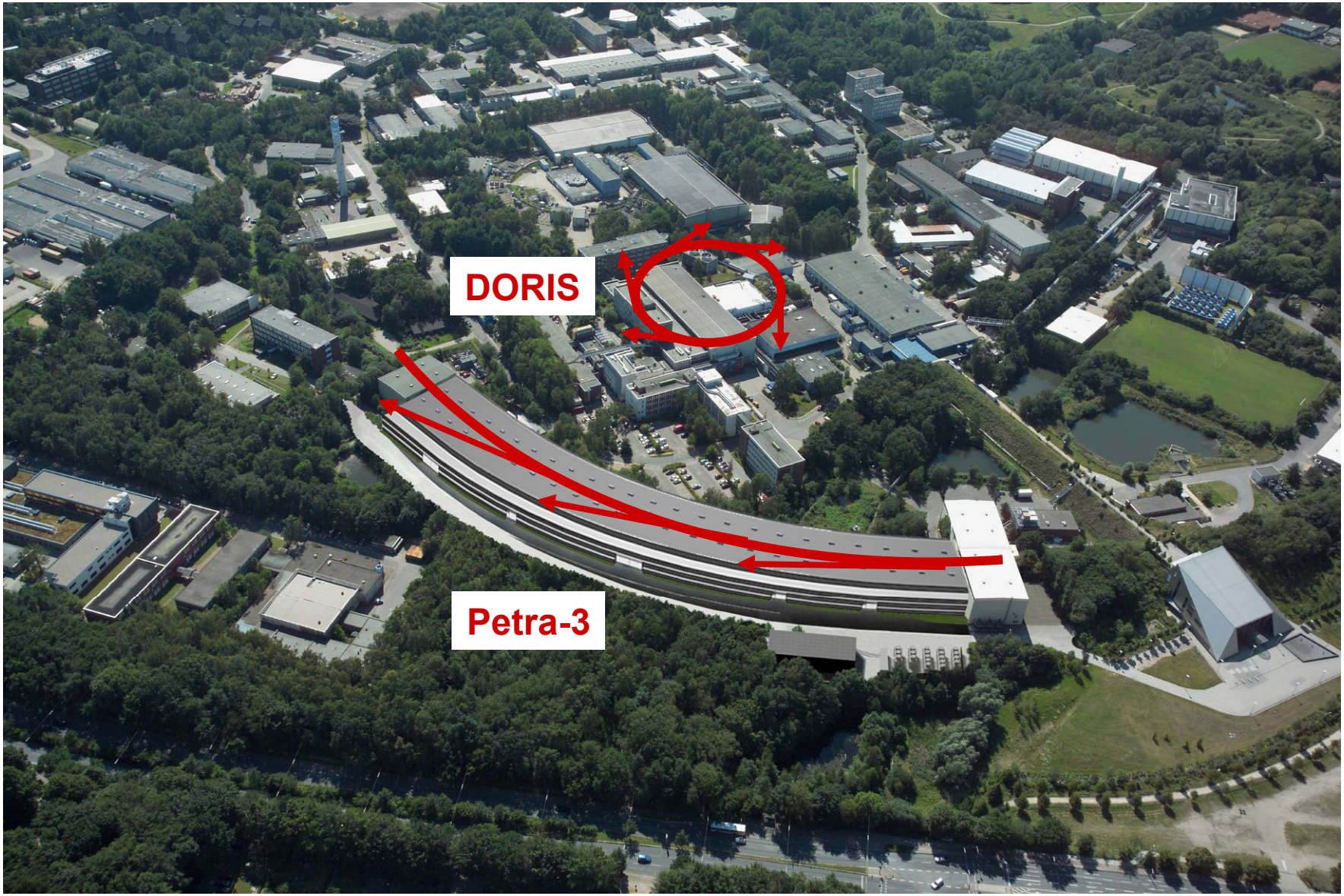
Vertical Integration Workshop; 7- 8 April 2008; Ringberg Castle; Germany

What will we cover?

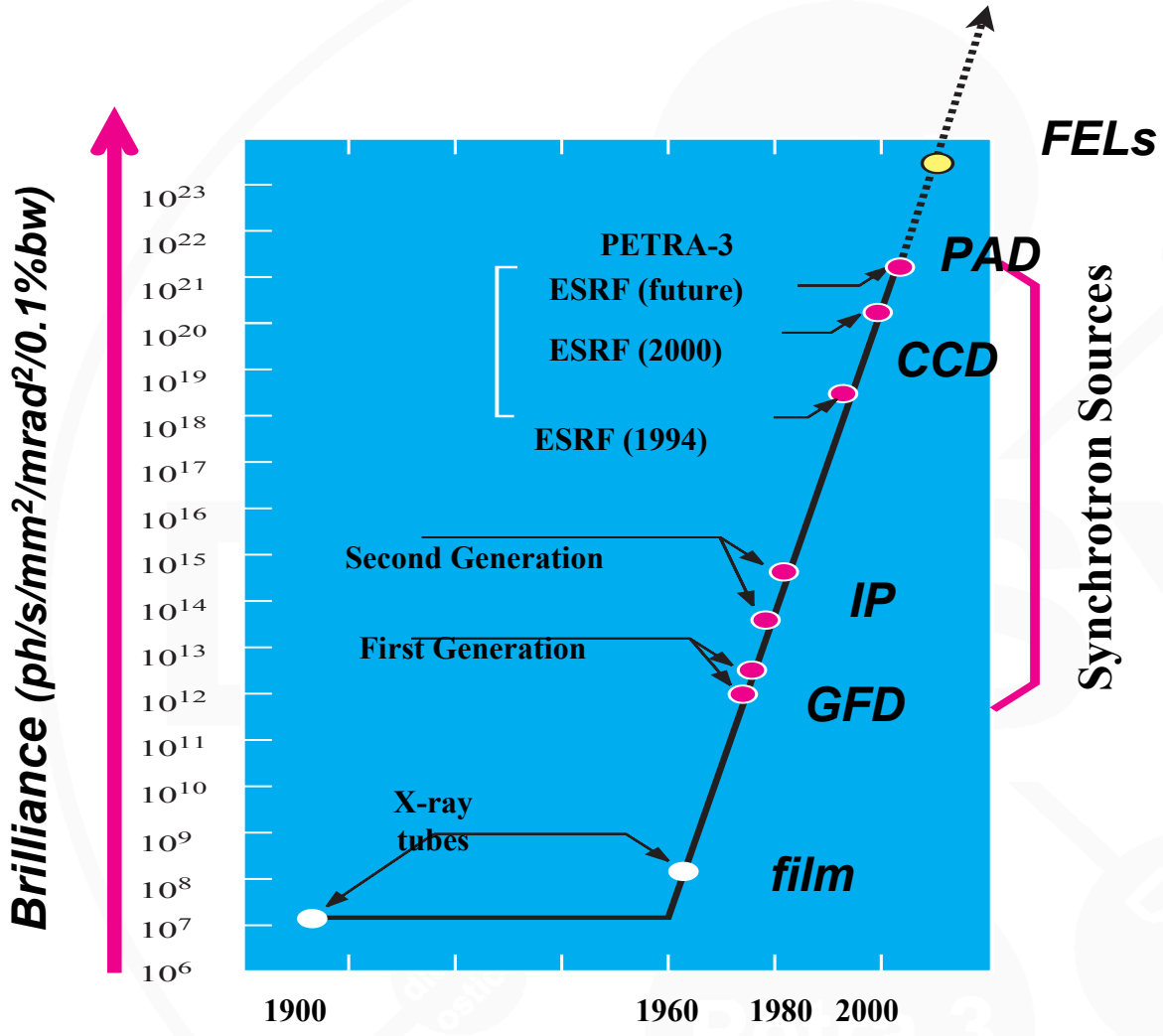
- The Synchrotron Revolution
- The (X-ray) Free Electron Laser
- The impact on the detector requirements
- One solution: Hybrid Pixel Array Detectors
- Some wishes or are they dreams?
- A provocative observation/statement

Light Sources in Europe

Light Sources in Hamburg



The Synchrotron revolution



Timing modes in SR; ~100 psec pulses

Beam mode & characteristics	Intensity	Lifetime	Beam
Uniform filling mode 992 bunches are equally distributed around the whole circumference of the storage ring. Refill time: ~3 minutes	200 mA	60 hours	Low emittance (4 nm) with 1% coupling
2*1/3 filling mode 2 times one third of the storage ring is filled. an emp Top up	200 mA	55 hours	Low emittance
7/8 + 1 A train Ring c (0.23 r Both e mA si The re center Filling			
Hybri One cl diametrically opposed to a ~ 196 mA multi-bunch beam composed of 24 groups of bunches spread over 3/4 of the storage ring circumference. Filling time: ~ 10 minutes.		resulting lifetime ~ 40 hours	(4 nm) with 1 % coupling.
16 bunch filling mode 16 highly populated and equally spaced bunches. Purity < 10^{-7} Filling time: ~5 mins.	90 mA	10 hours	Low emittance (4 nm) with 2% coupling
4*10 filling mode 4 equidistant bunches _ 10 mA/bunch Filling time: ~ 5 minutes	40 mA	6 hours	Low emittance (4 nm) with 2% coupling.

3 ns pulse spacing

3 ns pulse spacing

gaps

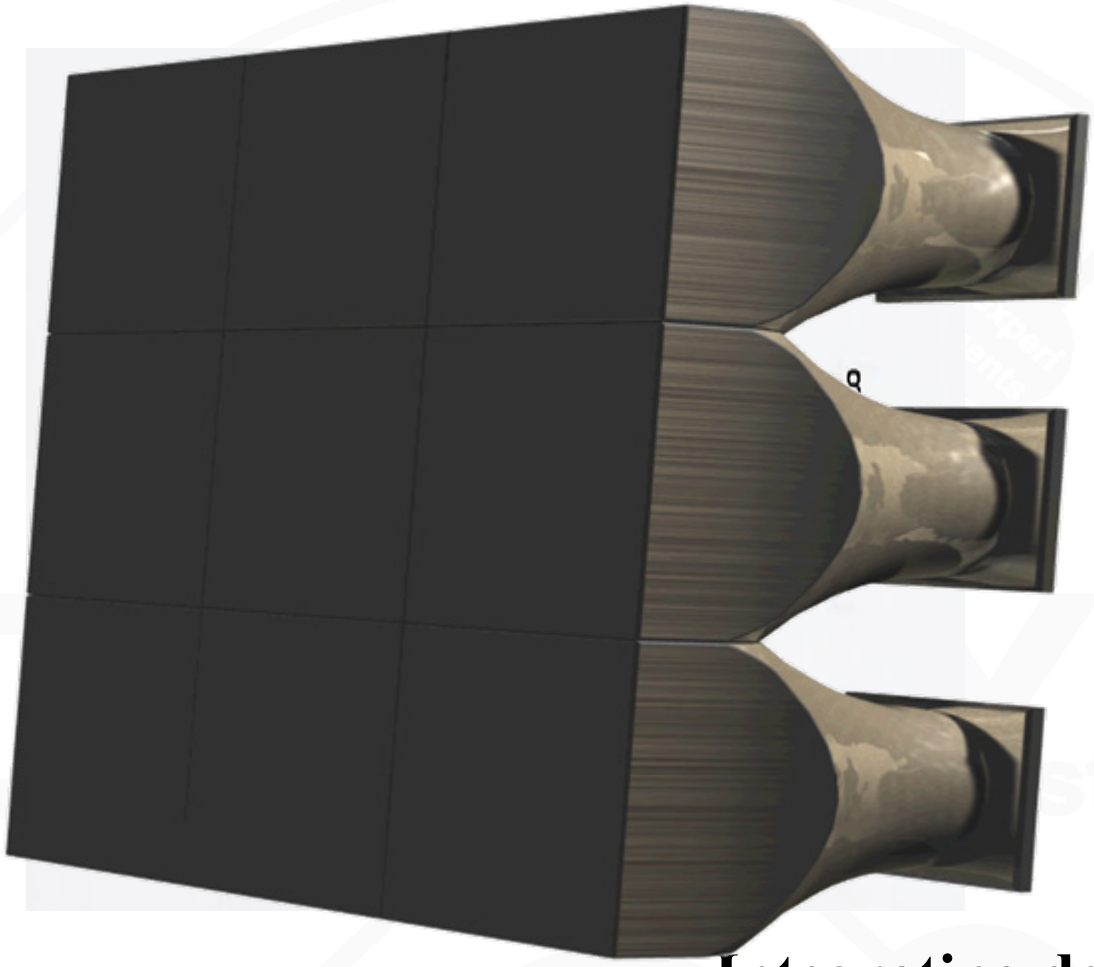
Mostly used as a continuous source;

very often "imaging"

200 ns pulse spacing

800 ns pulse spacing

Our workhorse: CCD based systems



– Indirect detection
==> losses & spreading

– Integrating detector
==> noise & information loss

Timing modes in SR; ~100 psec pulses

Beam mode & characteristics	Intensity	Lifetime	Beam
Unifor 992 bu around storage Refill			
2*1/3 2 time filled. an emp Top up			
7/8 + 1 A train Ring c (0.23 r Both e mA sin The re center Filling			
Hybri One cl diamet multi-b groups storage Filling			
16 bun 16 hig bunche Filling			
4*10 f 4 equi Filling time: ~ 5 minutes			with 2% coupling.

Mostly used as a continuous source; very often "imaging" with few scattered photons per pulse

➔ ***photon counting pixel detectors***

pacing

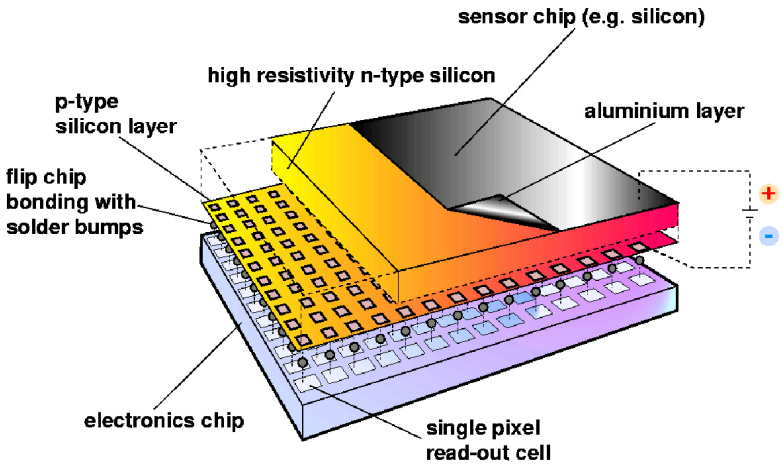
pacing

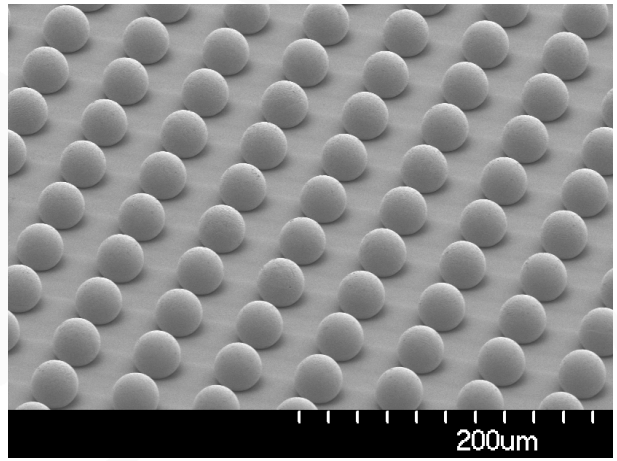
gaps

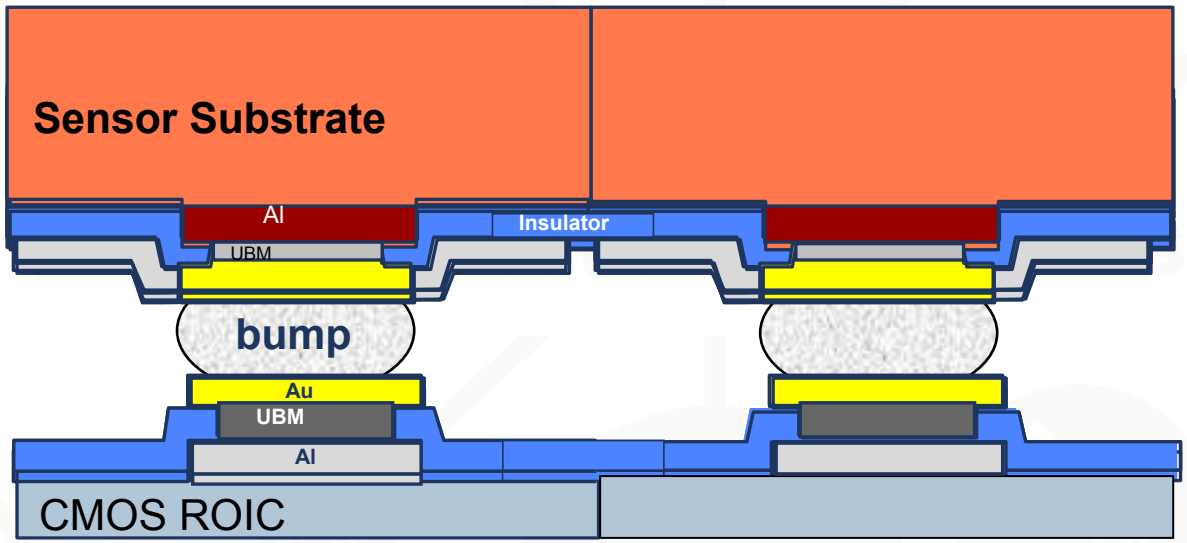
spacing

spacing

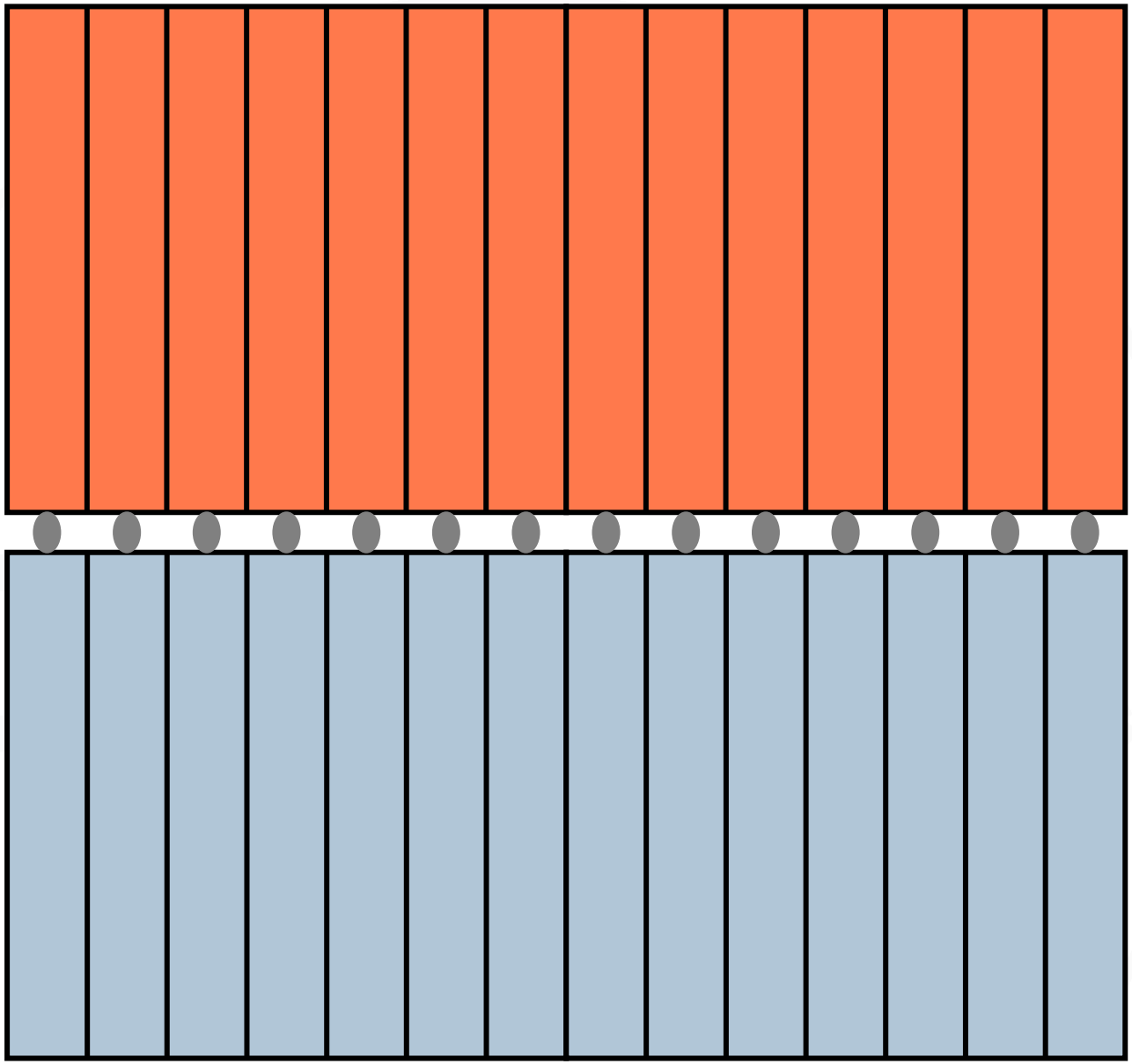
The Medipix


sensor chip (e.g. silicon)
high resistivity n-type silicon
p-type
silicon layer
aluminium layer
flip chip
bonding with
solder bumps
+
-
electronics chip
single pixel
read-out cell

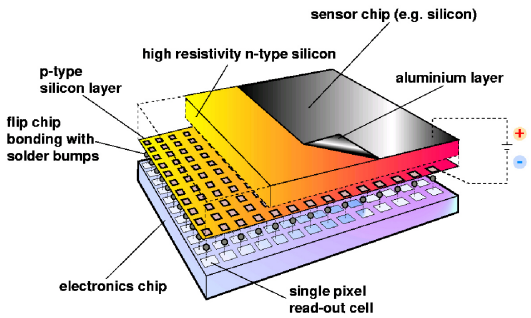

200um


Sensor Substrate
Al
Insulator
UBM
bump
Au
UBM
Al
CMOS ROIC

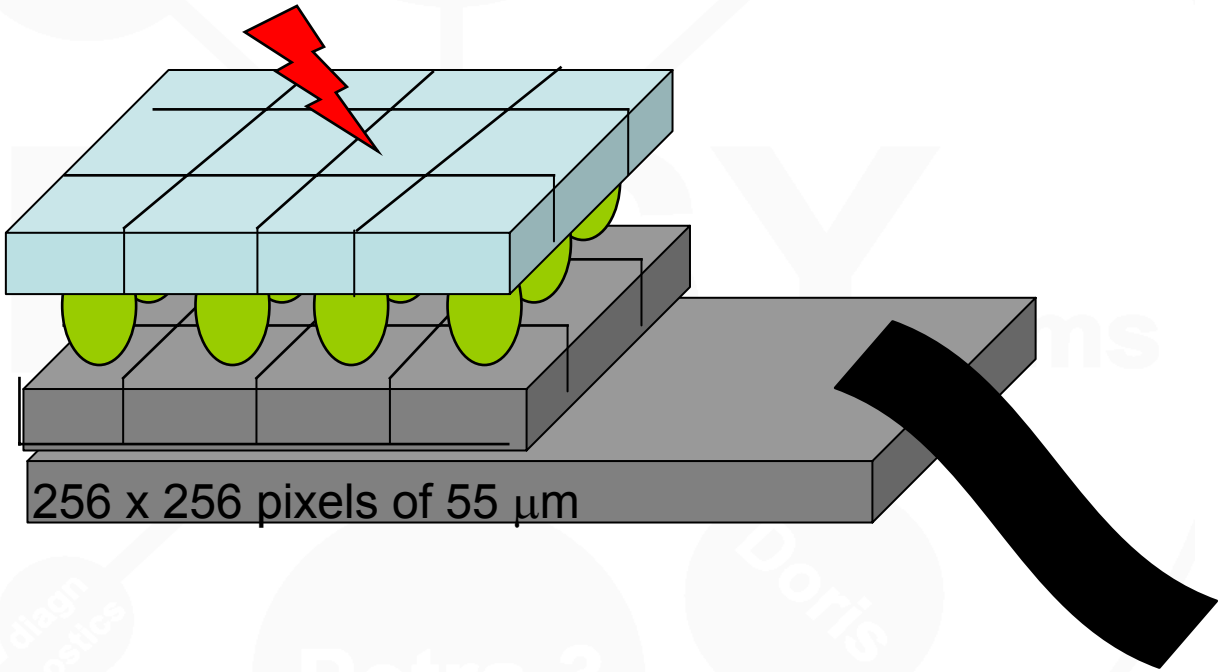
Reality



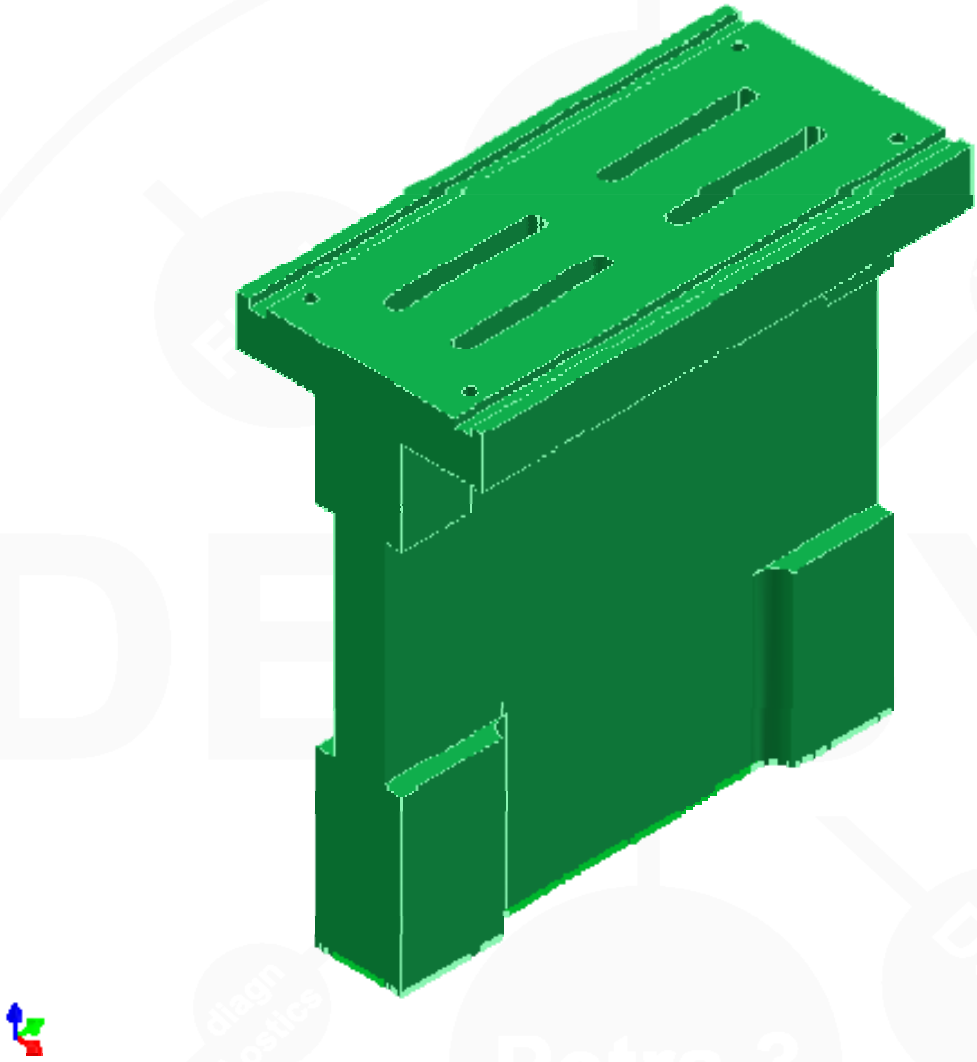
Reality



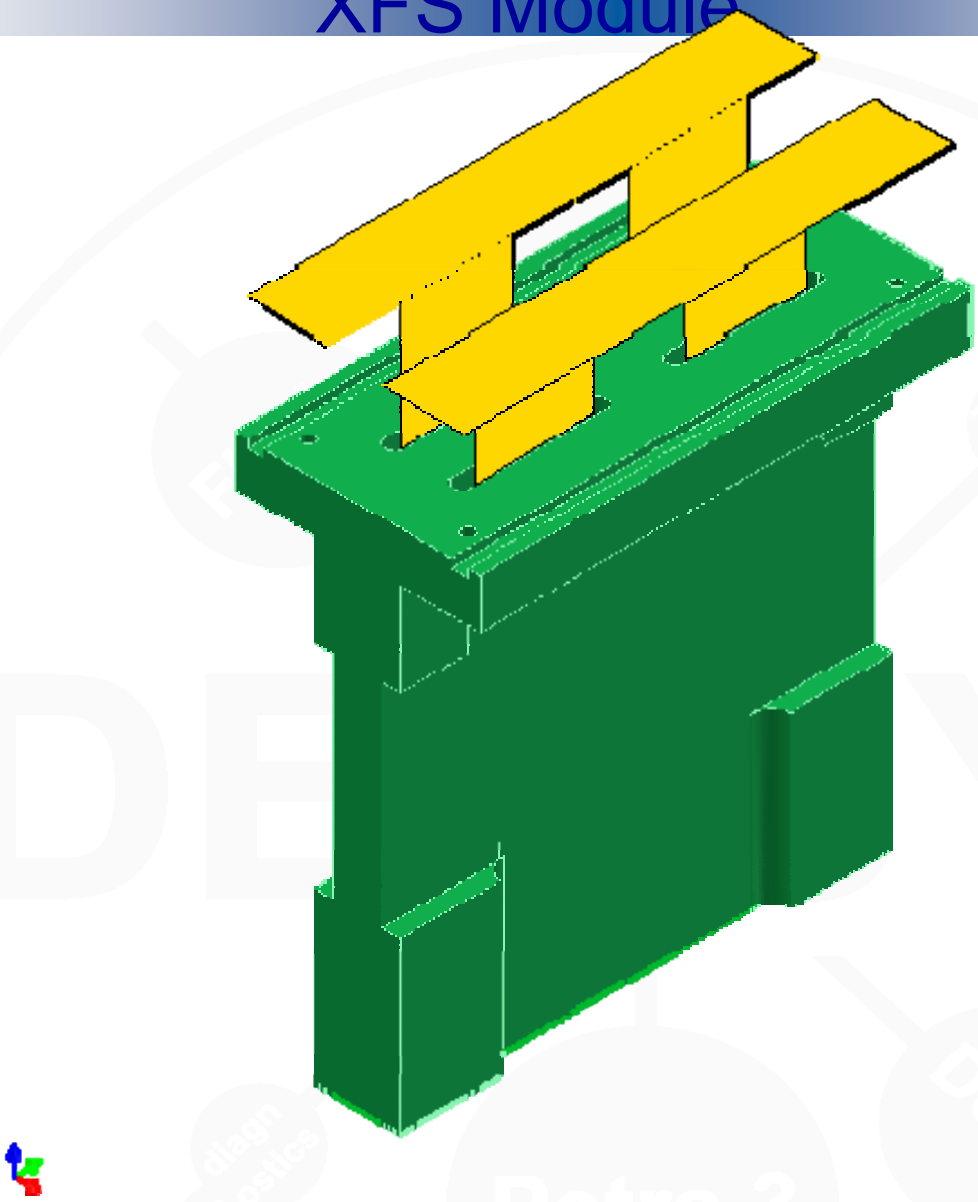
X-ray photon



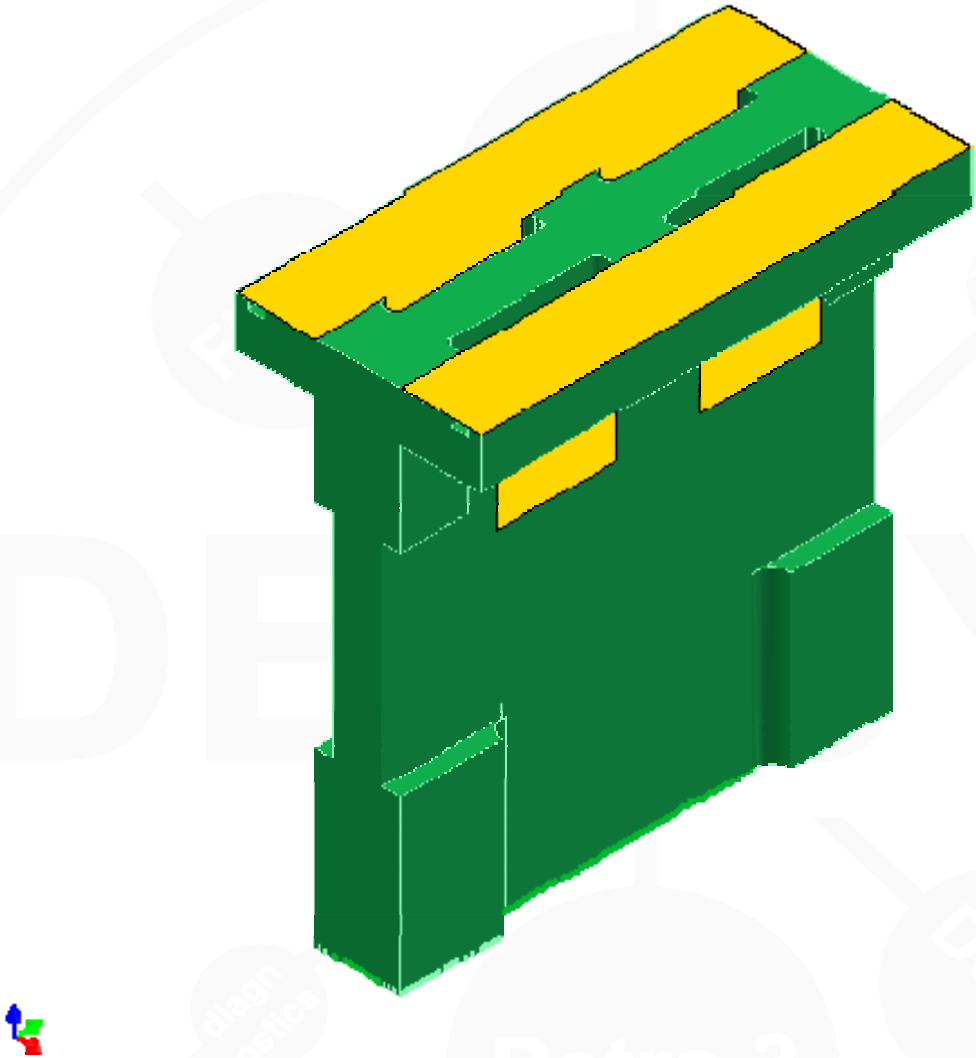
XFS Module



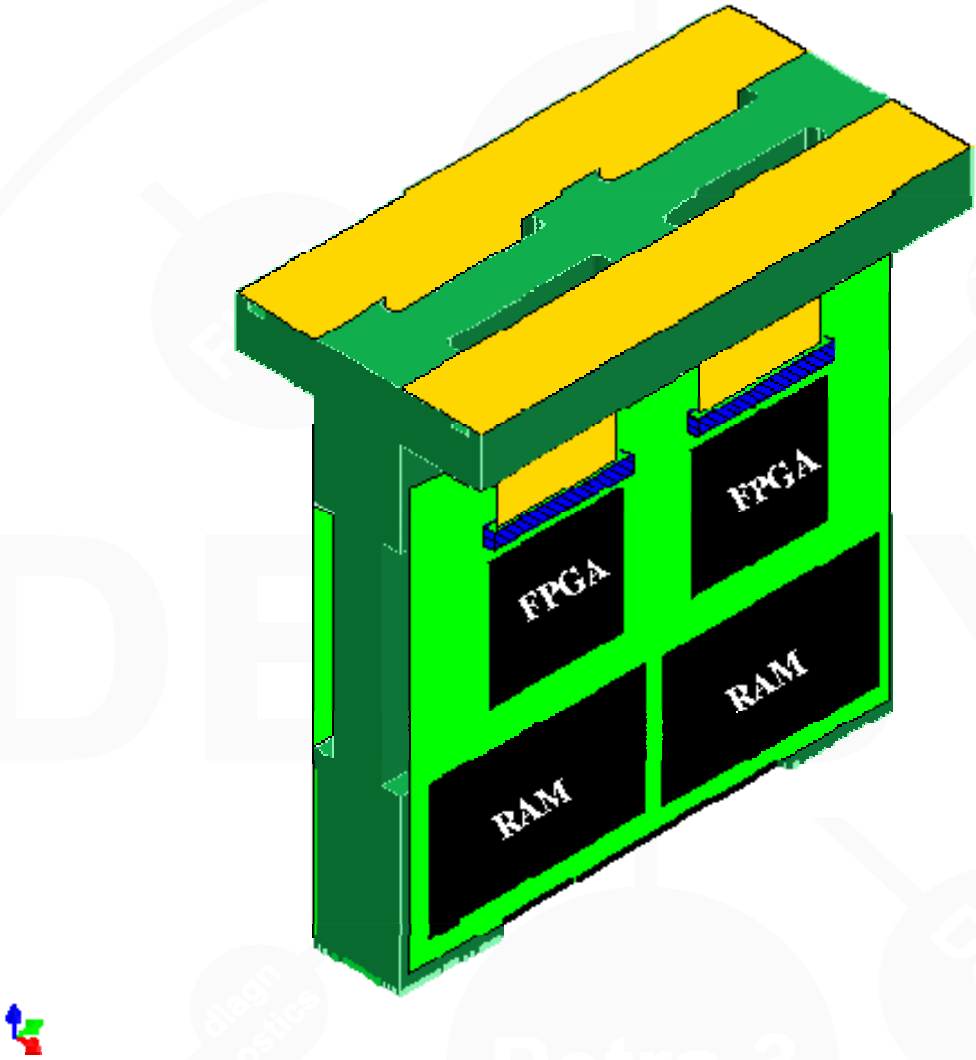
XFS Module



XFS Module

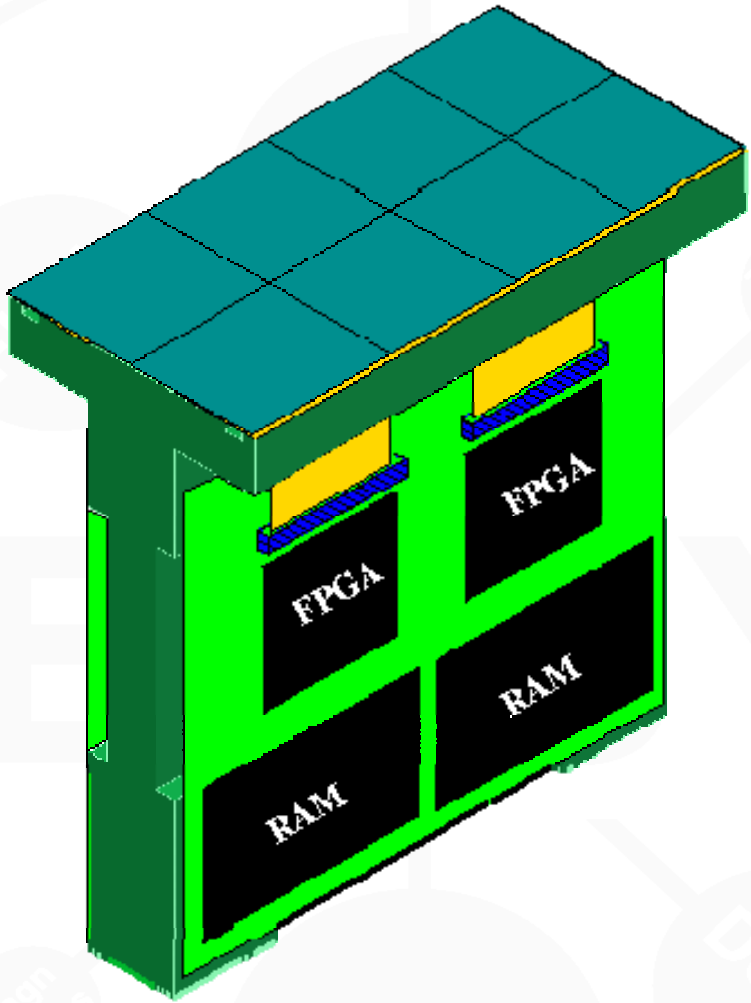


XFS Module

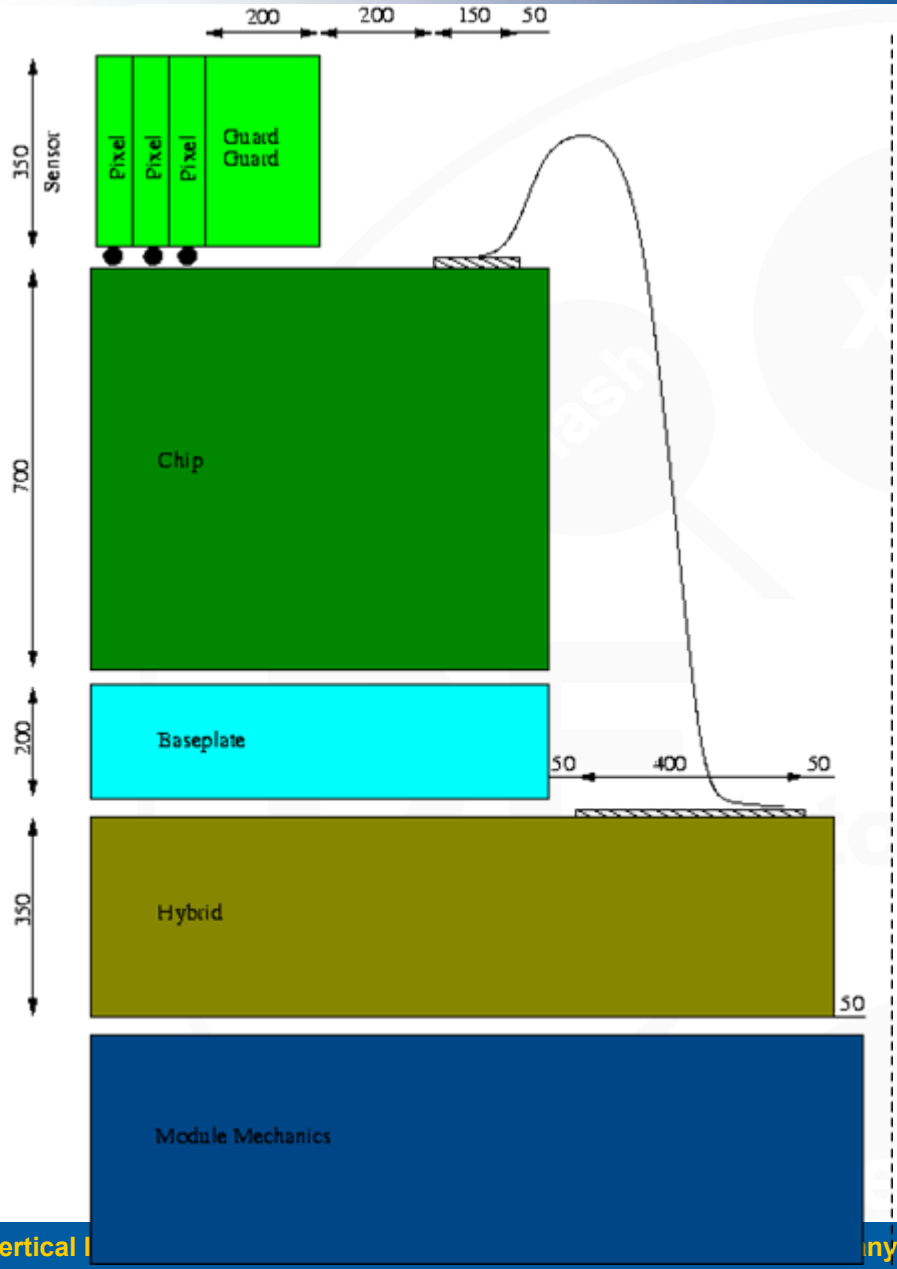


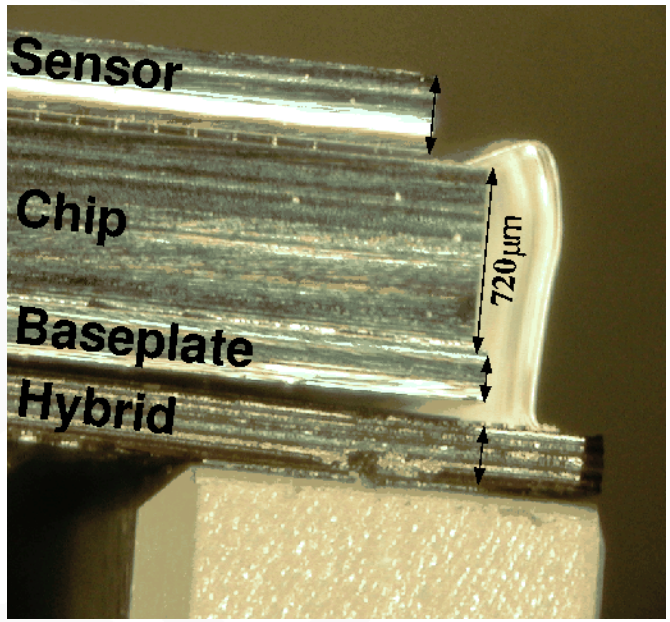
XFS Module Specification

Operate **2x4 (8)** Chips per Module. **~78 x 39 mm²**



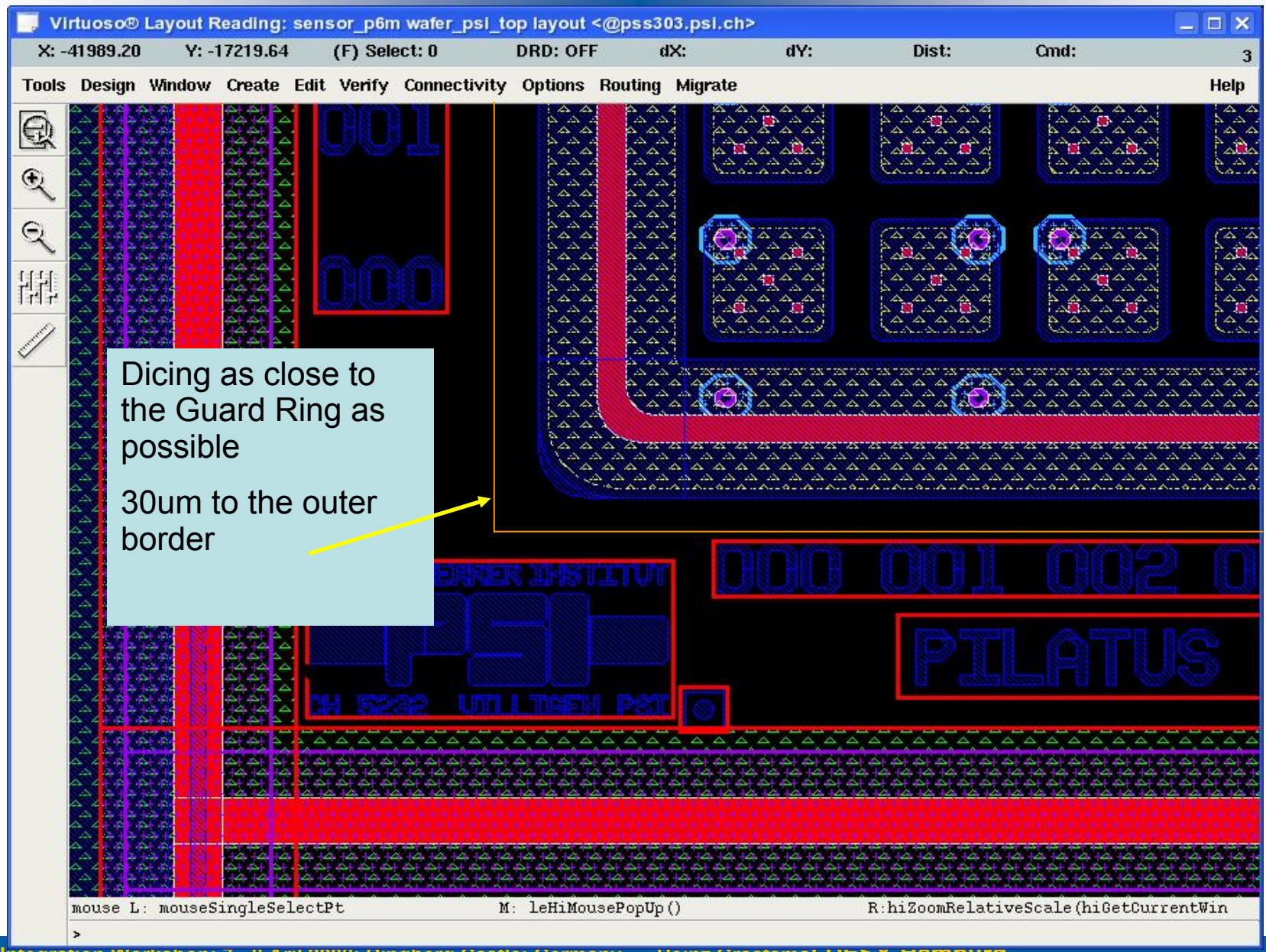
Hybridization



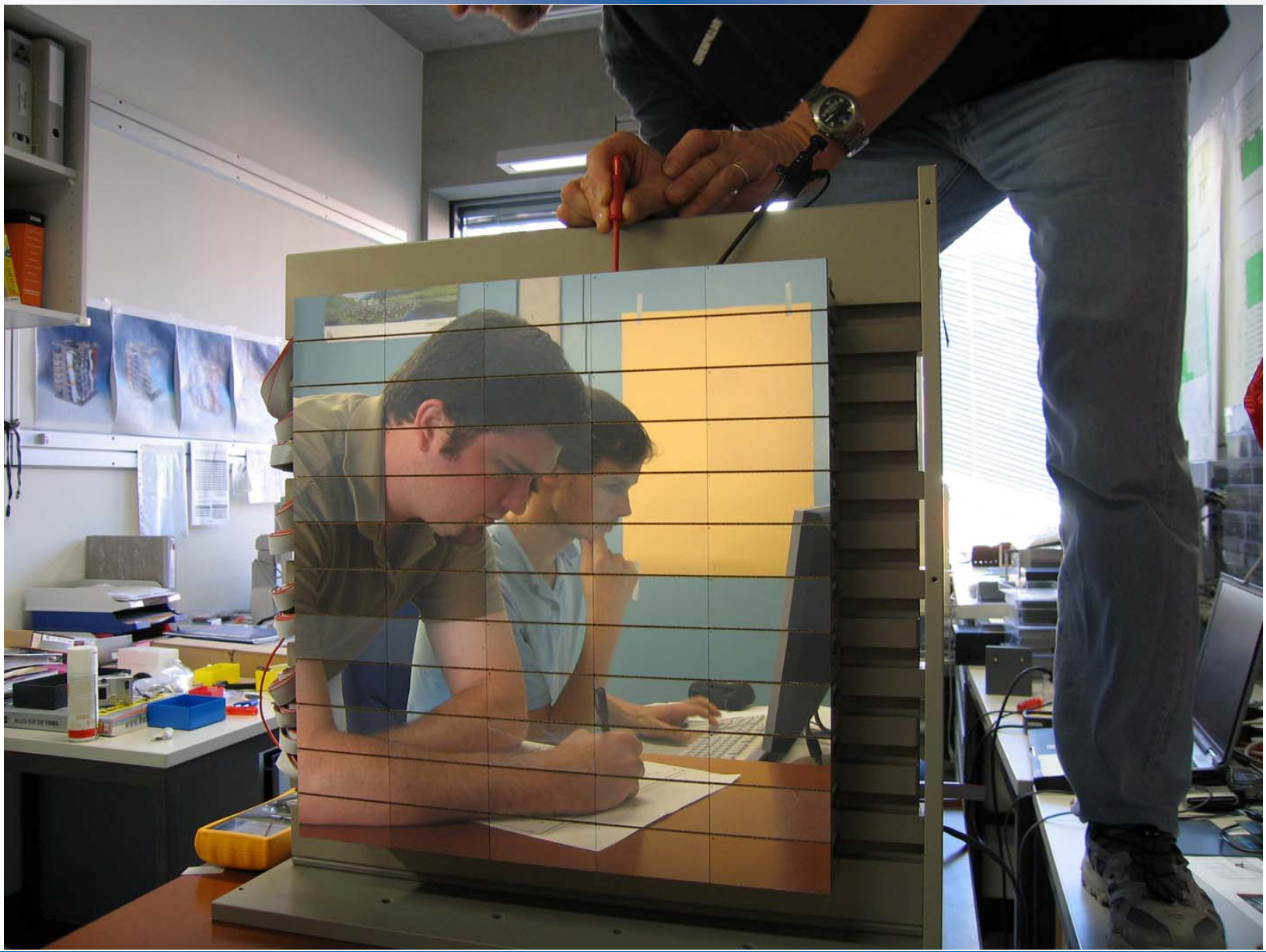


- Cut the sensor as close as possible
- Use thinned readout chips
- Stay within the exact n-fold pixel pitch

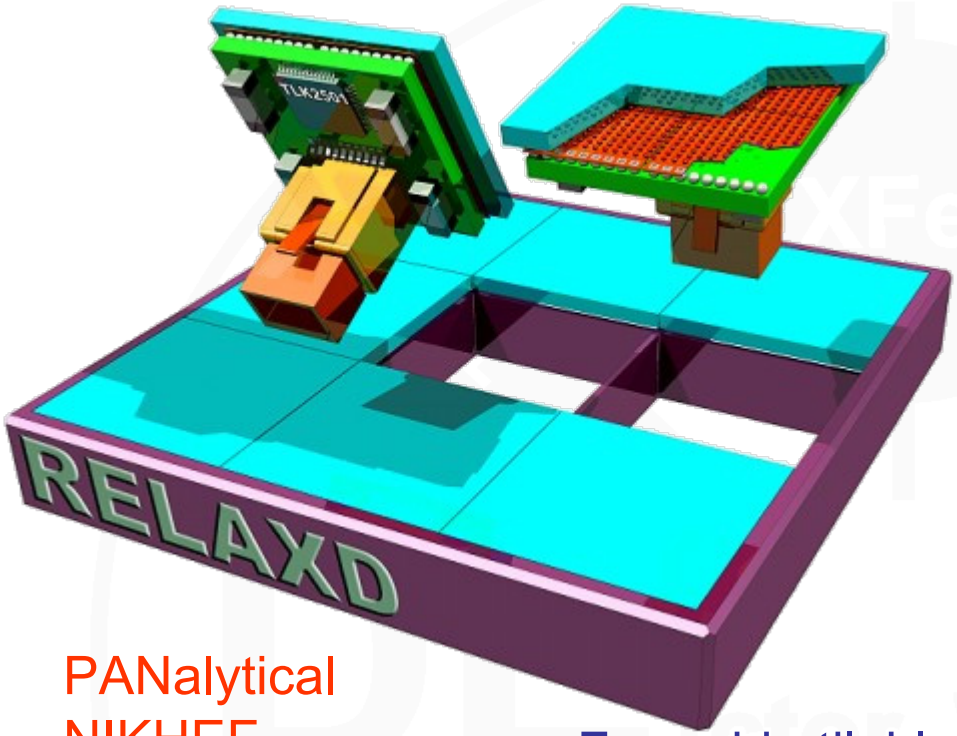
Special Dicing



The PILATUS 6M of the SLS@PSI



R&D: RELAXD



High **RE**solution **L**arge **A**rea **X**-ray **D**etector

PANalytical
NIKHEF
CANBERRA
IMEC

2006-2010

Four-side tilable Quad-Medipix modules

Fast serial readout at 3.125 Gigabit/s

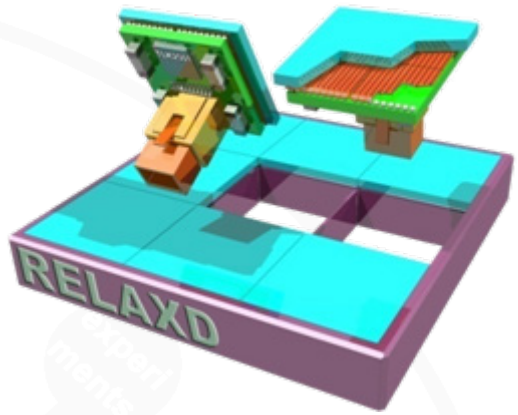
http://www.nikhef.nl/pub/experiments/medipix

Courtesy Jan Visschers; NIKHEF

RELAXD: Vision

- Edgeless Silicon Sensors
- (Pixel redistribution)
- Thinned CMOS pixel ASICs
  with Through-Silicon Via contacting
- High bandwidth readout (Gigabit Ethernet)

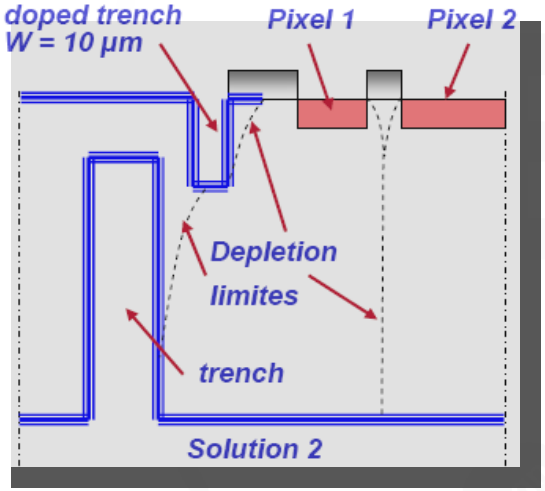
➢ Tile-able Microsystems, produced in Industry

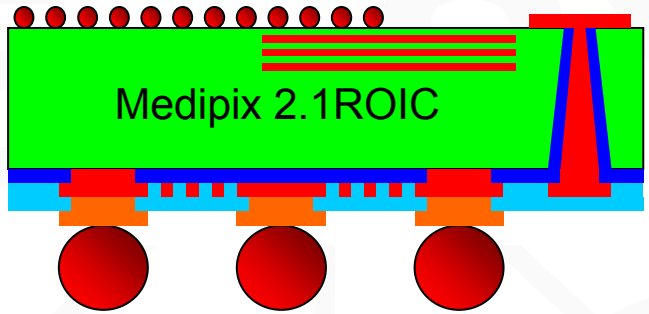


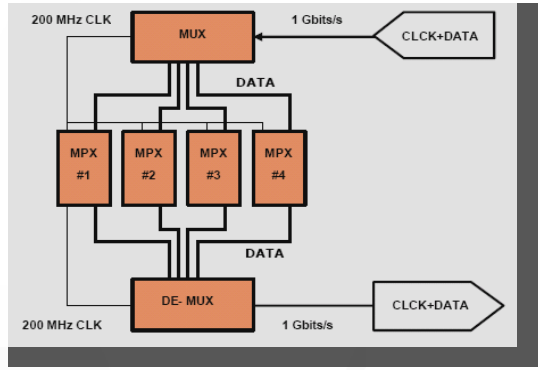
Canberra

IMEC

NIKHEF





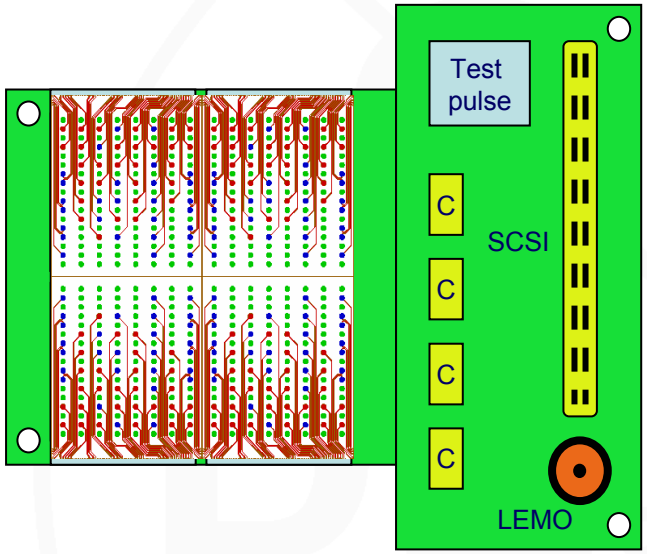


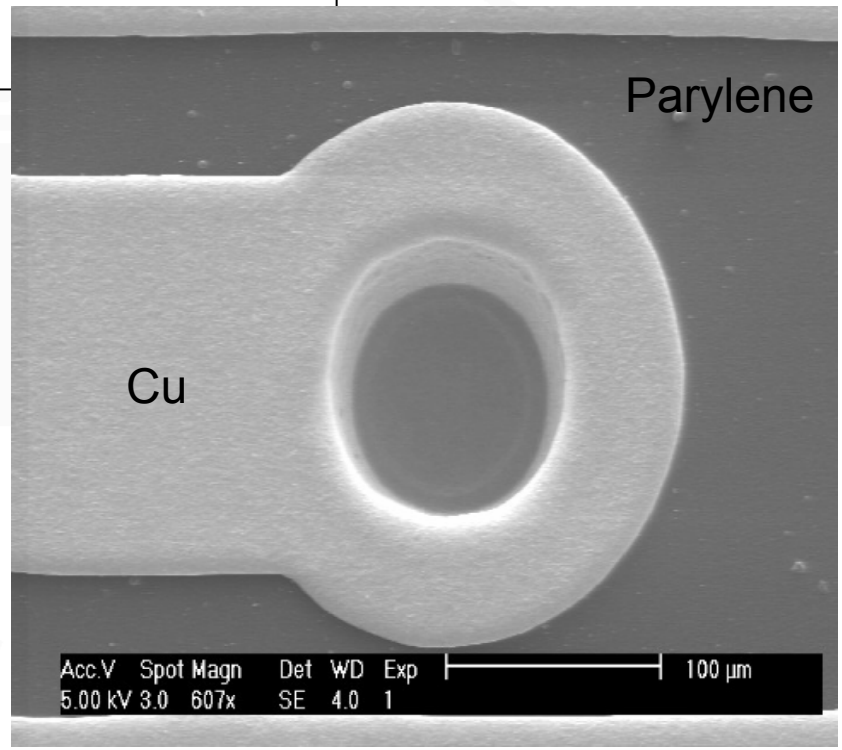
Courtesy Jan Visschers; NIKHEF

Through-via interconnect

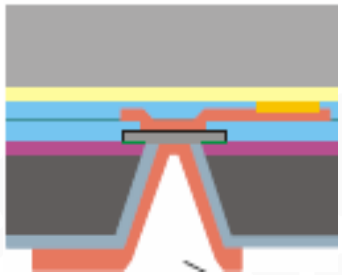
Courtesy Jan Visschers; NIKHEF

Ball-Grid-Array replaces wire bonds
Robust, Easy Carrier design, better HF,
Thermal conductivity, Cooling



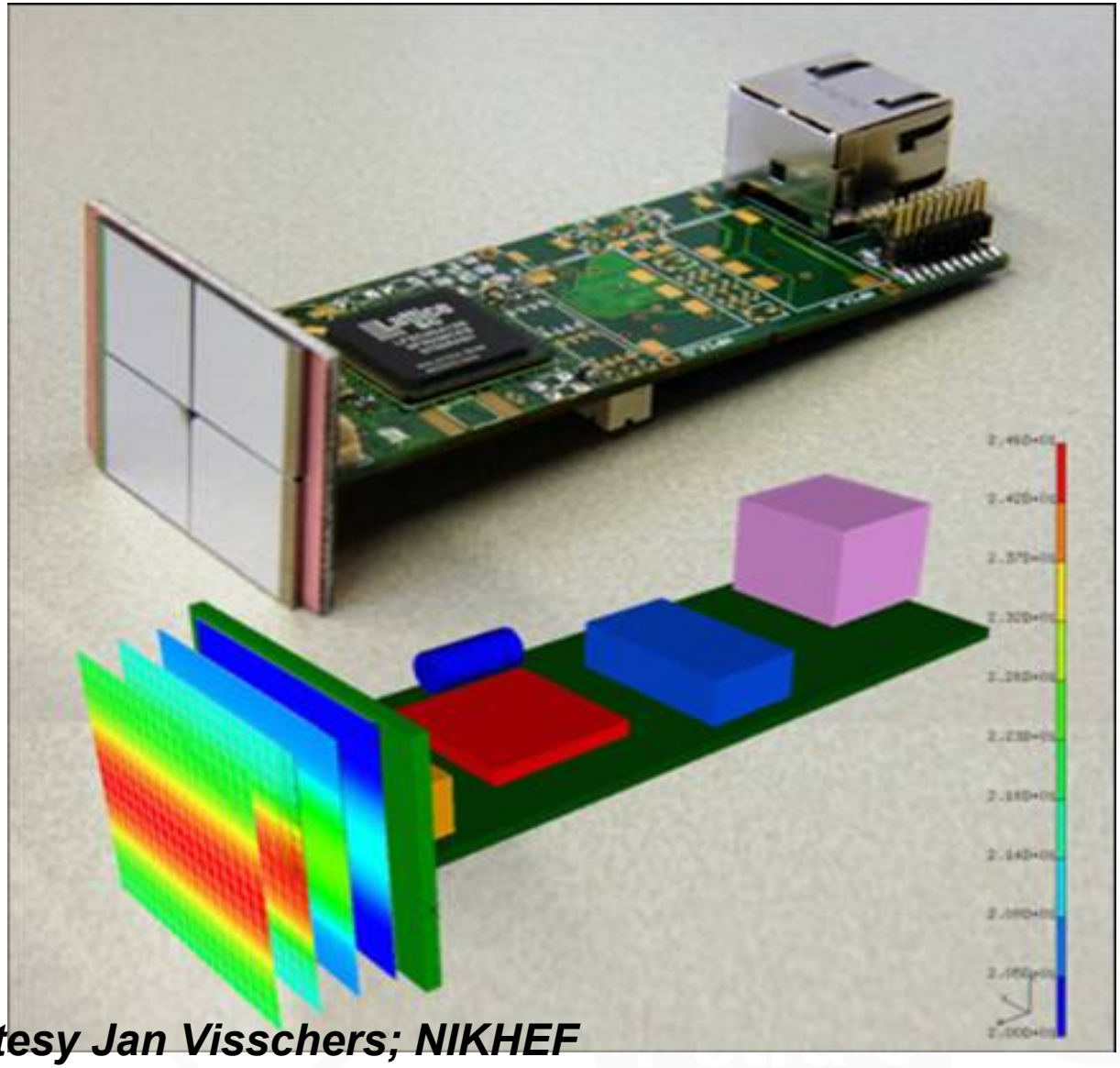


Zdenek Vykydal



First Through-Si via's
Made by IMEC
in dummy wafers

First Prototype



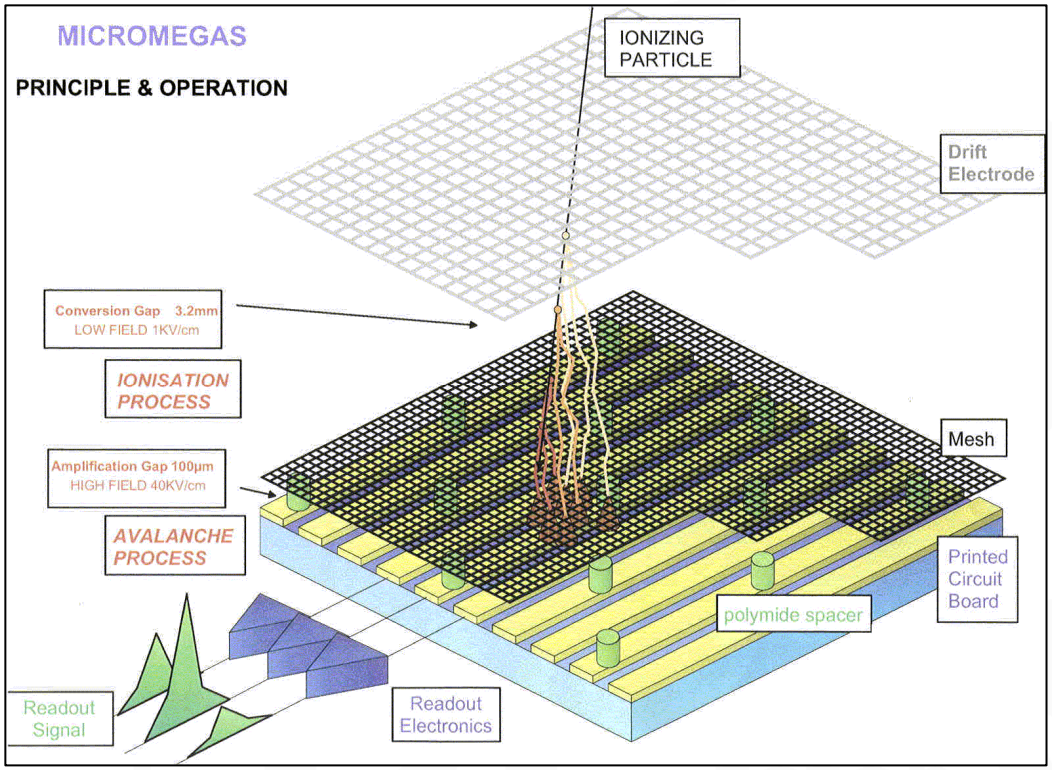
Chip Carrier
Still Dummy

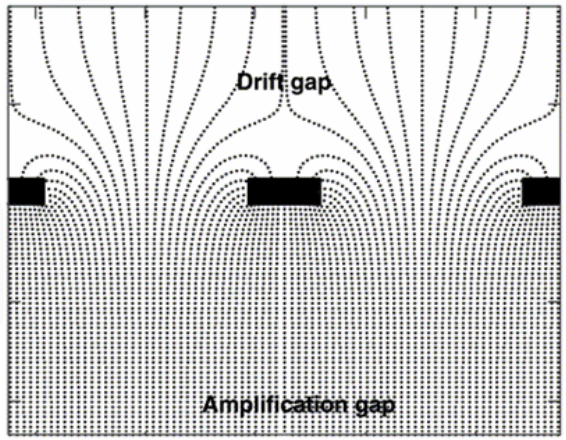
Heat Flow
Simulation

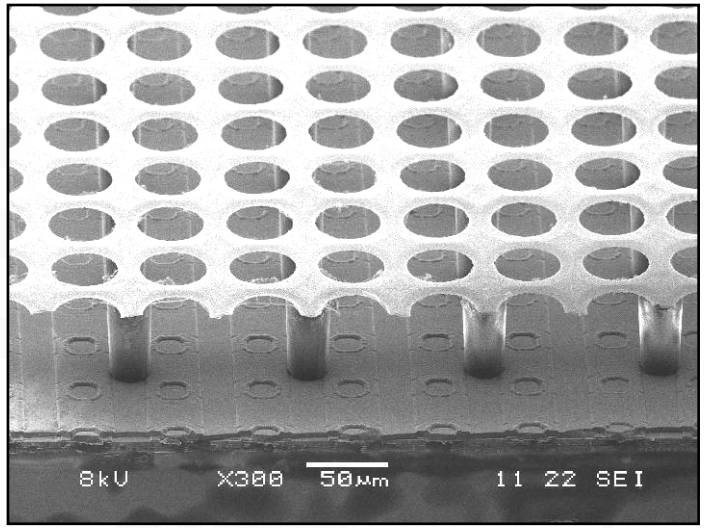
Red-Green is
~ 3 Celsius

Courtesy Jan Visschers; NIKHEF

Micro-Patterned Gaseous Detectors



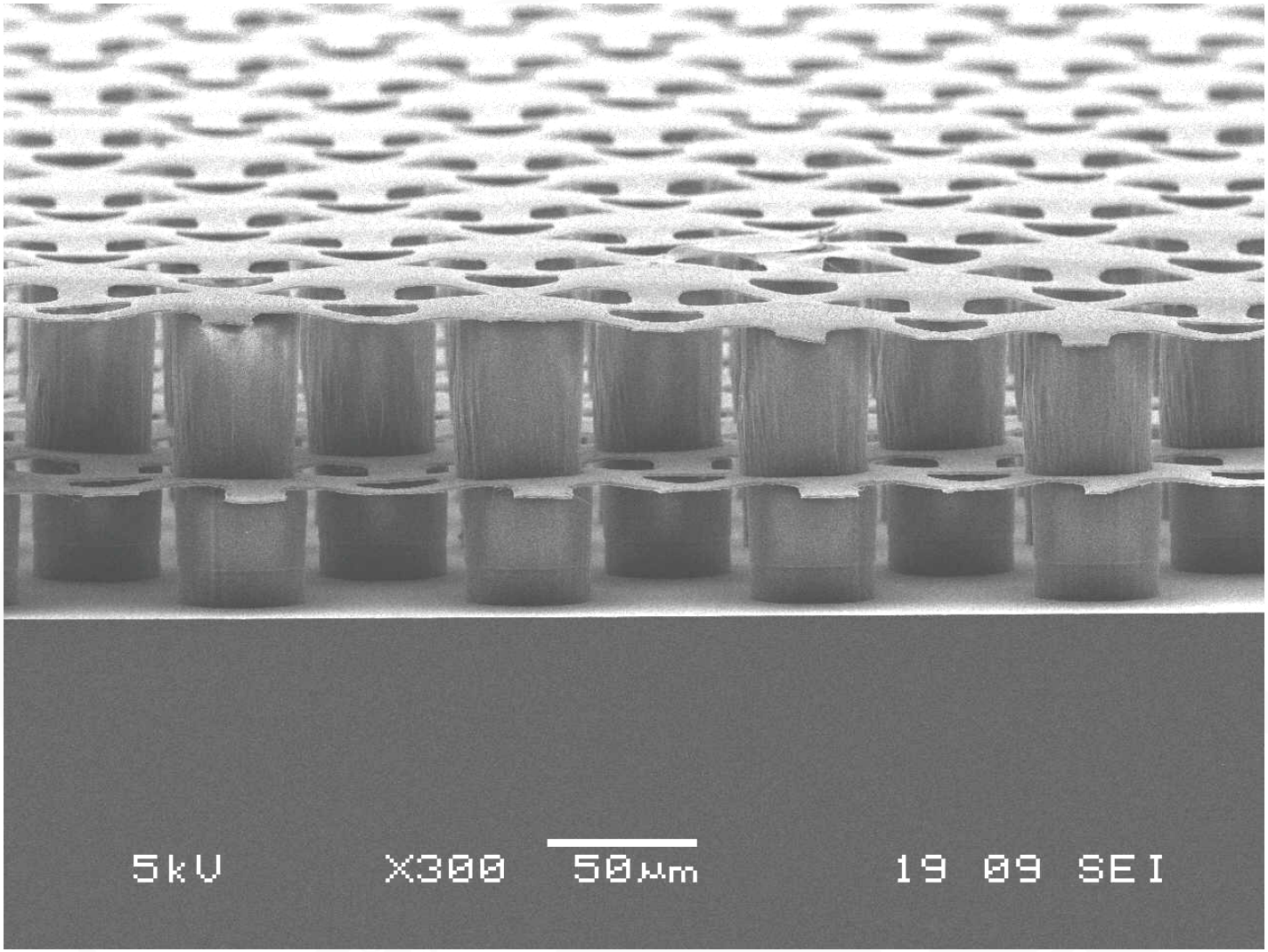




Bare CMOS pixel readout chip as Anode
Integrate a Metal Grid with Post-processing

Courtesy Jan Visschers; NIKHEF

TWINGRID (Mesa+, U-Twente)



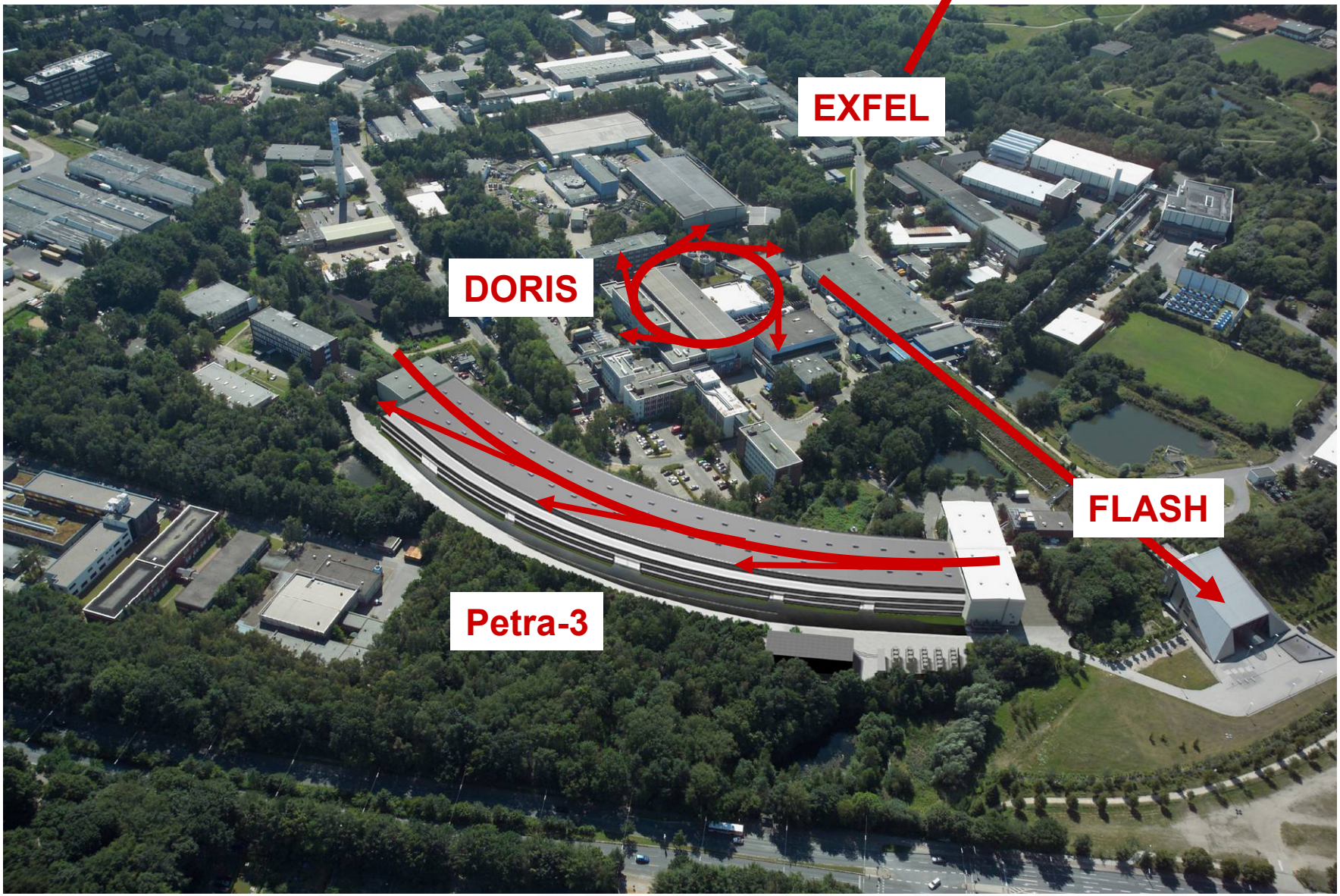
Courtesy Jan Visschers; NIKHEF

Victor B. Carballo U-Twente

- For Synchrotron's large HPAD's do now exist (even commercially: PILATUS).
- They will become excellent workhorses, but not cover all fields at SRs.
- Vertical integration initiatives have started.

- Why develop new detectors for Free-Electron-Lasers?

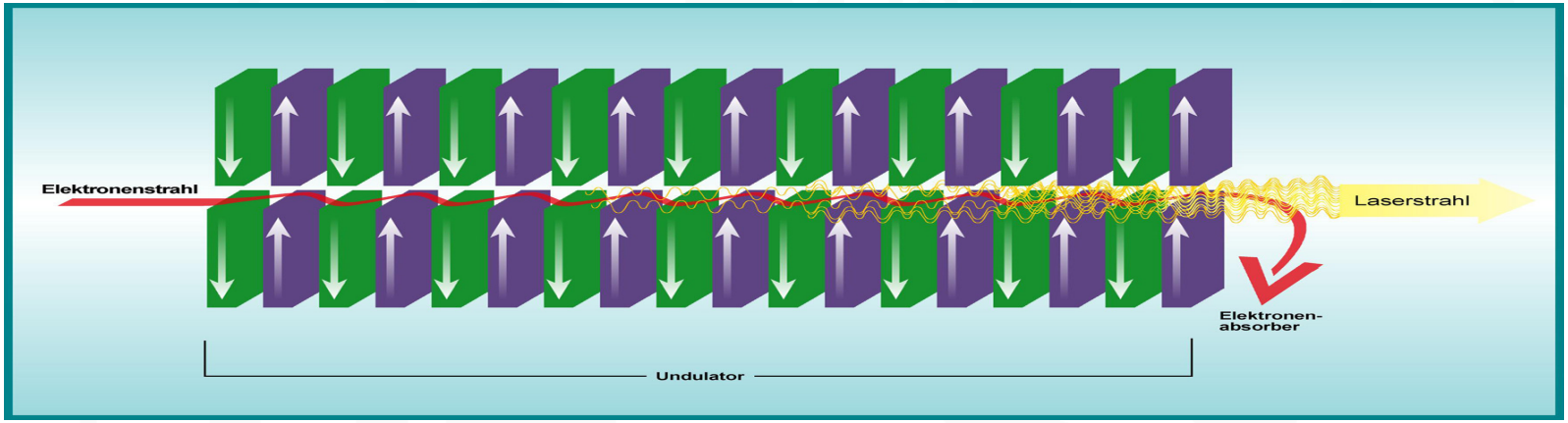
Light Sources in Hamburg

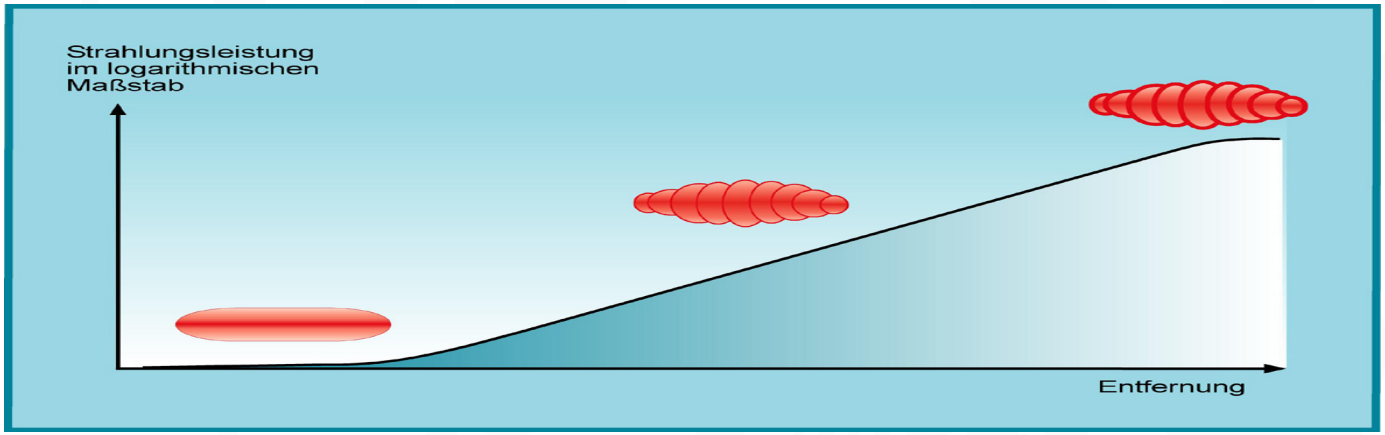


X-ray Free Electron Lasers

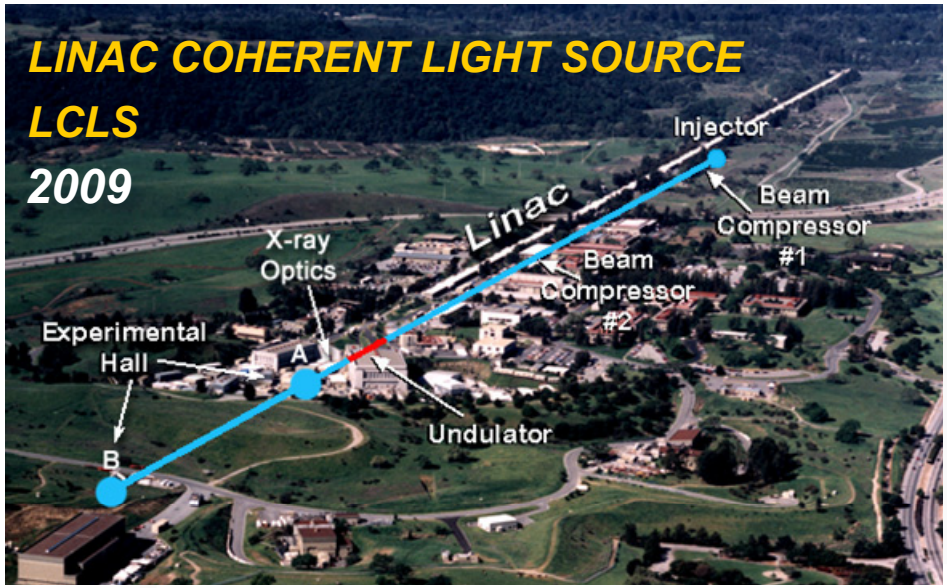
How to get it?

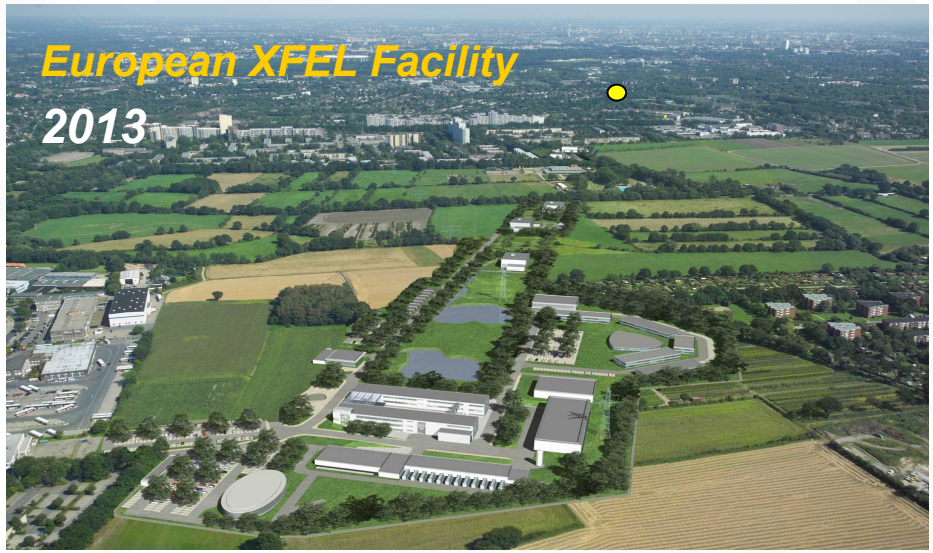
- What is the difference between storage rings and FEL's?
- What is SASE?





Hard X-ray SASE Free Electron Lasers

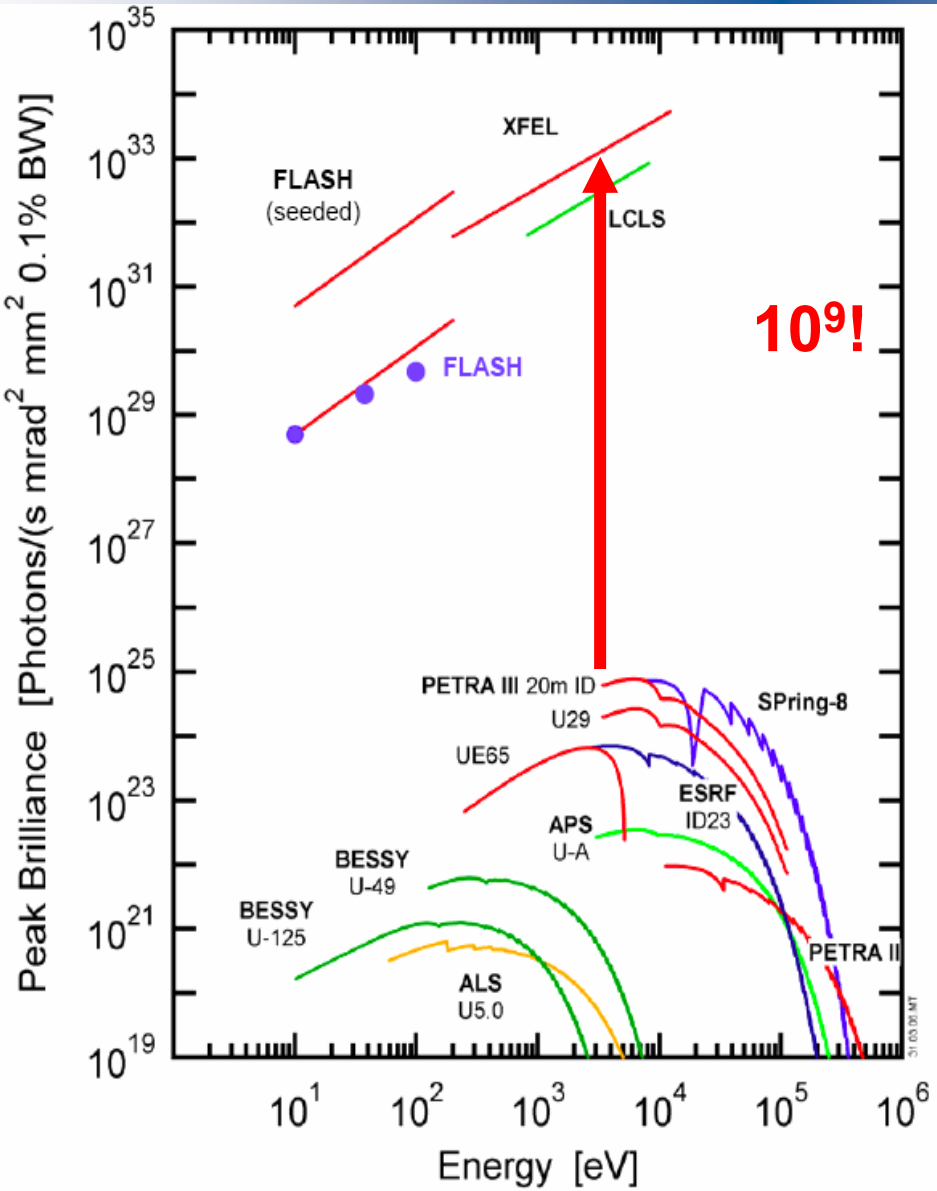




Experimental Hall Building

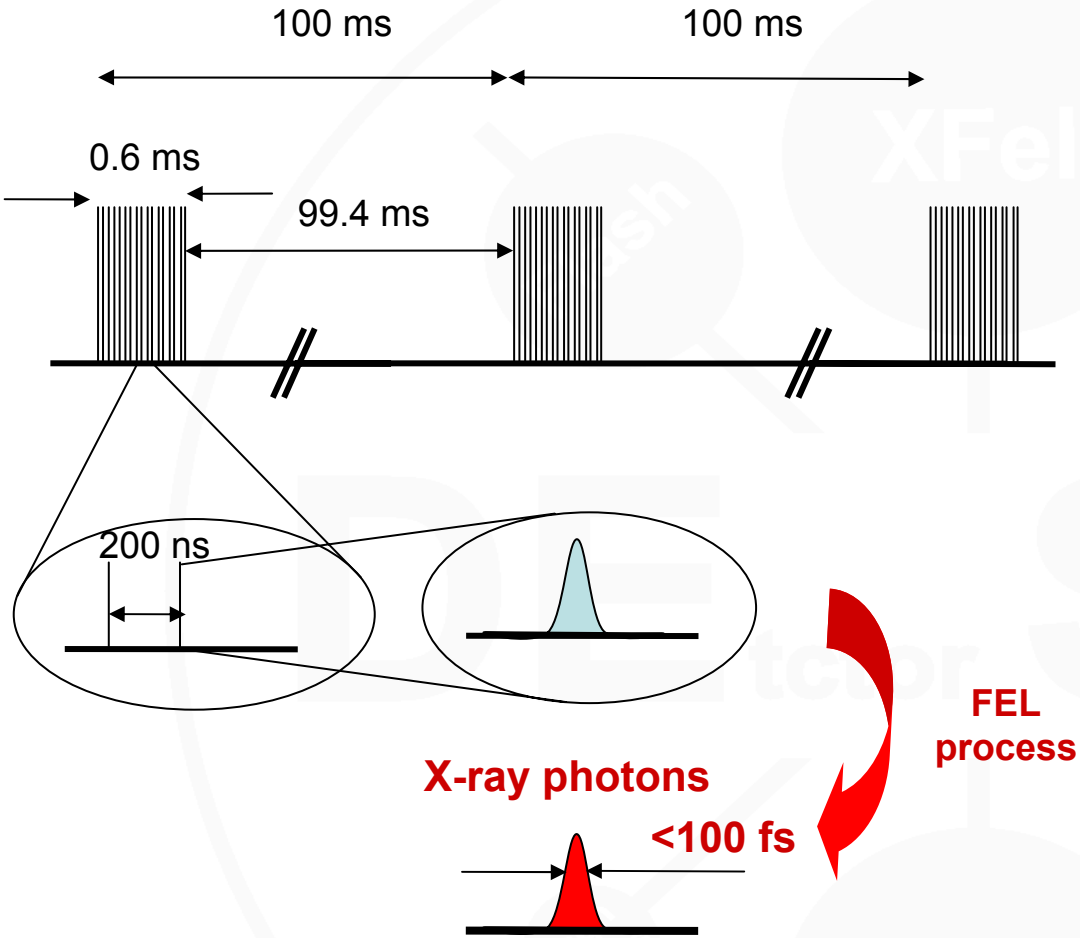
Bildmontage des Hauptgebäudes mit unterirdischer Experimentierhalle, Architekturbeispiel, Planungsstand April 2005, © DESY

Where is the challenge?



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

Where is the challenge?



Challenges:

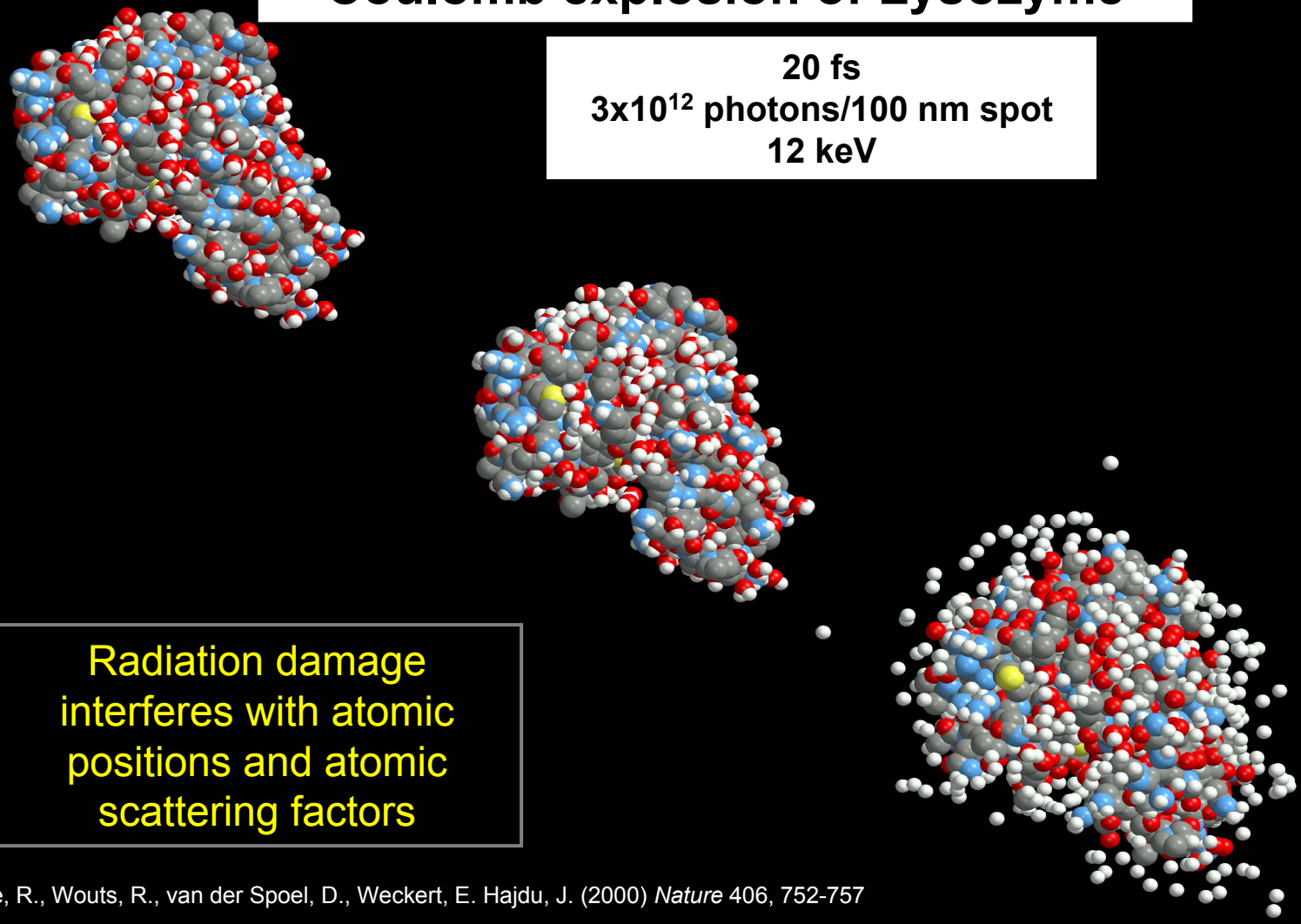
- up to 30,000 bunches per second
- very high intensities (up to $10^{12}\gamma$/bunch)
- „instantaneous“ energy deposition
- very high repetition rates (up to 5 MHz)
- large variability
  - pulse patterns
  - pulse to pulse variations

Where is the challenge?

- 9 orders increase in peak brilliance ➔ experimental details are difficult to predict
- Femto-second time resolution
- Single shot imaging, with 5 MHz repetition rate
- Data volumes could get enormous

Coulomb explosion of Lysozyme

20 fs
$3x10^{12}$ photons/100 nm spot
12 keV

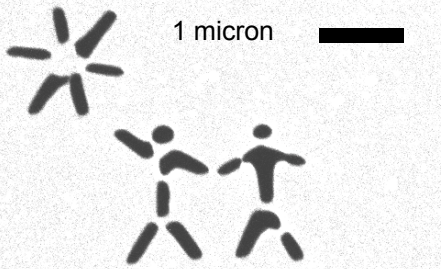


Radiation damage interferes with atomic positions and atomic scattering factors

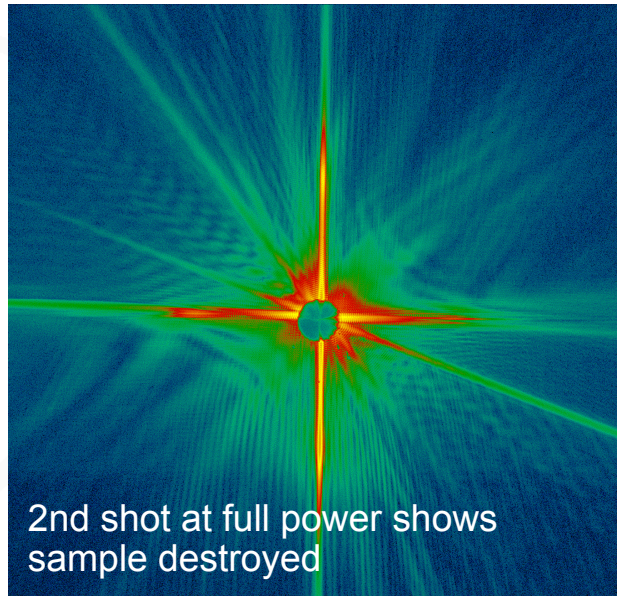
Neutze, R., Wouts, R., van der Spoel, D., Weckert, E. Hajdu, J. (2000) *Nature* 406, 752-757

Image reconstructed from an ultrafast FEL diffraction pattern

Starting Image



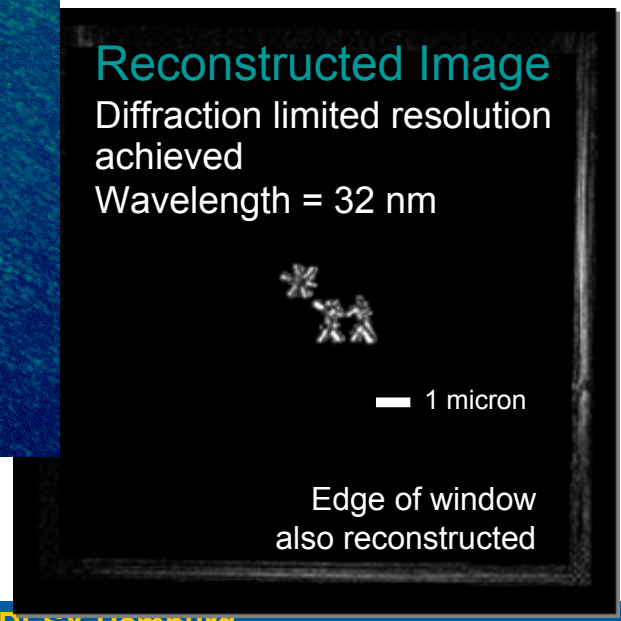
SEM of structure etched into silicon nitride membrane



Reconstructed Image

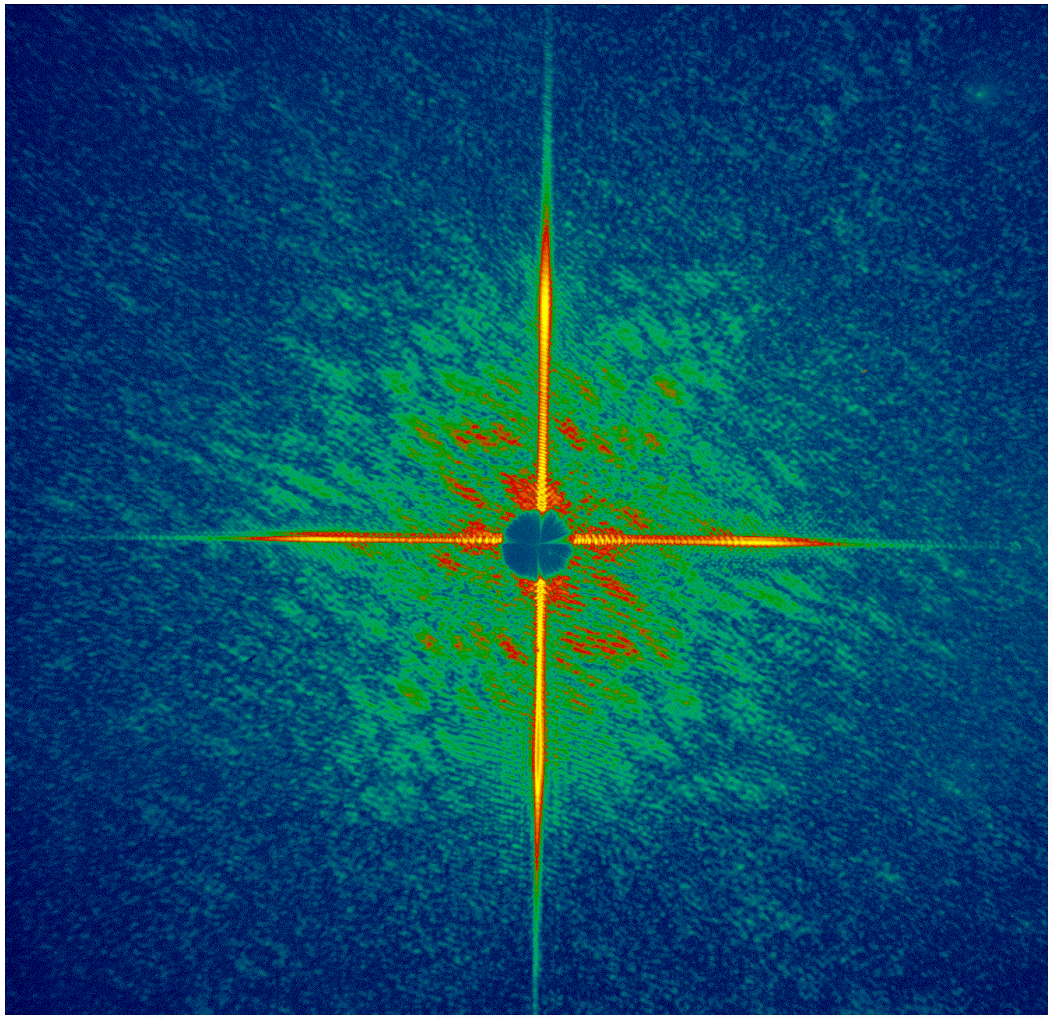
Diffraction limited resolution achieved

Wavelength = 32 nm



Reconstruction by A.Barty, 14 Feb 2006

Single shot 2D-imaging



Minimum requirements:

- *1k x 1k pixels (2k x 2k would be better)*
- *10^4 dynamic range*
- *noise free detection (single photon detection)*
- *< 200 micron pixels (100 is better)*
- *record image for every (useful) shot*
- *80 % efficiency*
- *central hole*
- *minimal dead areas*
- *…*

Other general challenges

- High radiation dose at small angles: 10^4 photons per pixel per shot ➔ over 3 years 1 GGy
  - Radiation damage of silicon sensor
  - Radiation damage of underlying electronics

  ➔ Program for radiation damage studies needed

- High radiation dose at specific pixels: 10^5 photons in 10 x 10 microns (“charge explosion”)
  - 10^5 photons of 12 keV create: (10^5 x 12 x10^3)/ 3.6 = 3 x 10^8 electron-hole pairs ➔ “plasma effect” gives shielding of drift field ➔ diffusion before drift ➔ peak broadening (space and time).

Hybrid Pixel Array Detector (HPAD)

Diode Detection Layer

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

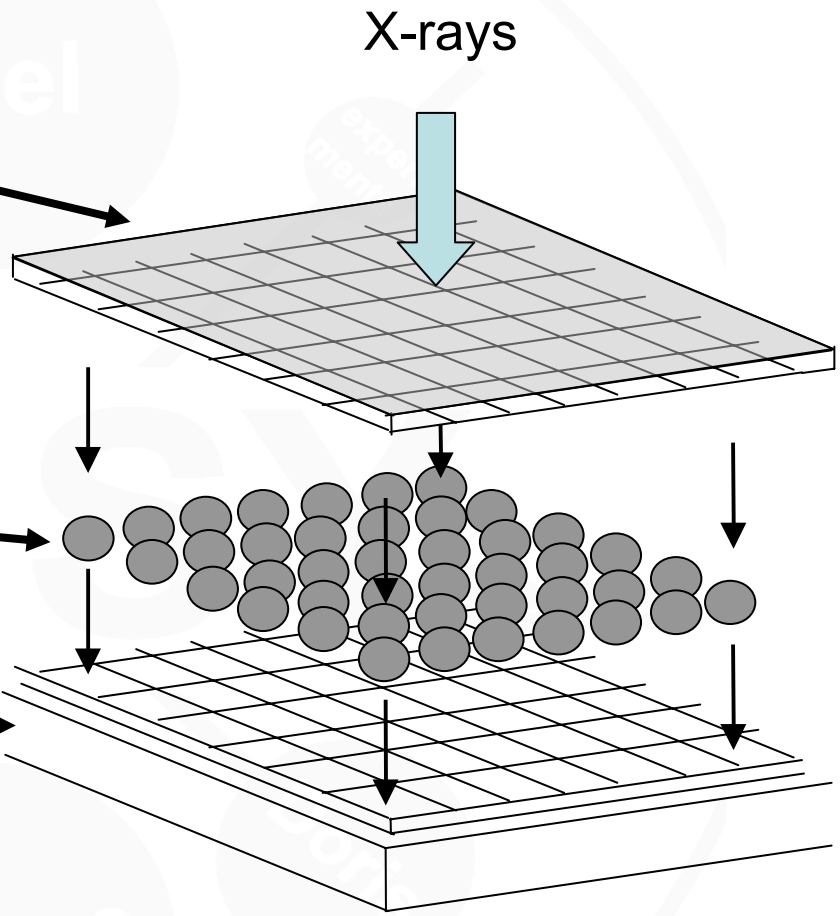
Connecting Bumps

- Solder or indium
- 1 per pixel

CMOS Layer

- Signal processing
- Signal storage & output

Gives enormous flexibility!



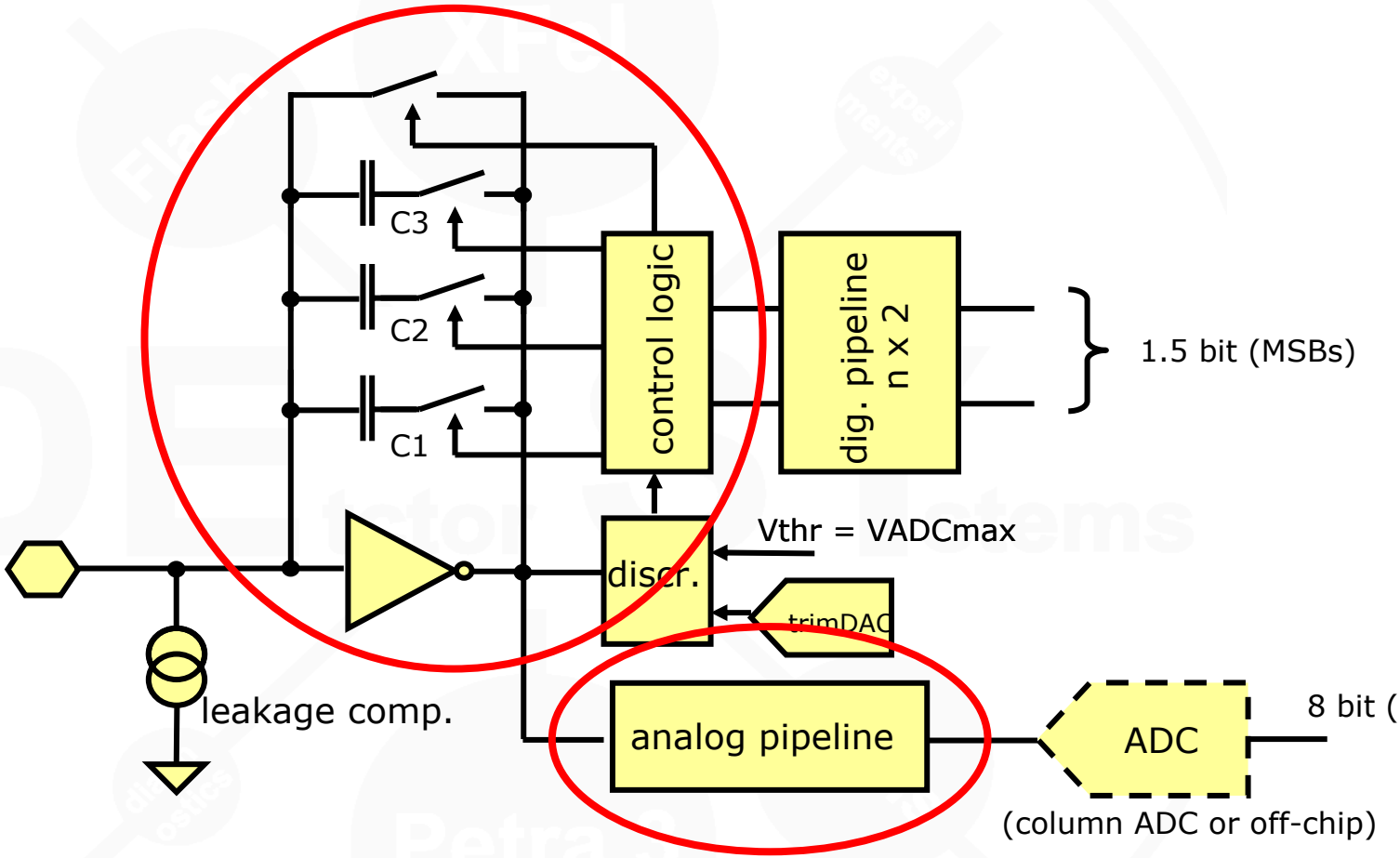
The HPAD consortium

- PSI/SLS: chip design; interconnect and module assembly
- Uni-Bonn: chip design
- Uni-Hamburg: Radiation damage tests, “charge explosion studies; and sensor design
- DESY-Hamburg: chip design, interface and control electronics, mechanics; overall coordination

Hybrid Pixel Array Detector (HPAD)

- wide dynamic input range
- multiple (3) scaled feedback capacitors
- reduced ADC resolution (8 bit instead of 10 bit)
- analog + digital (2 bit) pipeline
- in-pixel CDS ?

New concepts

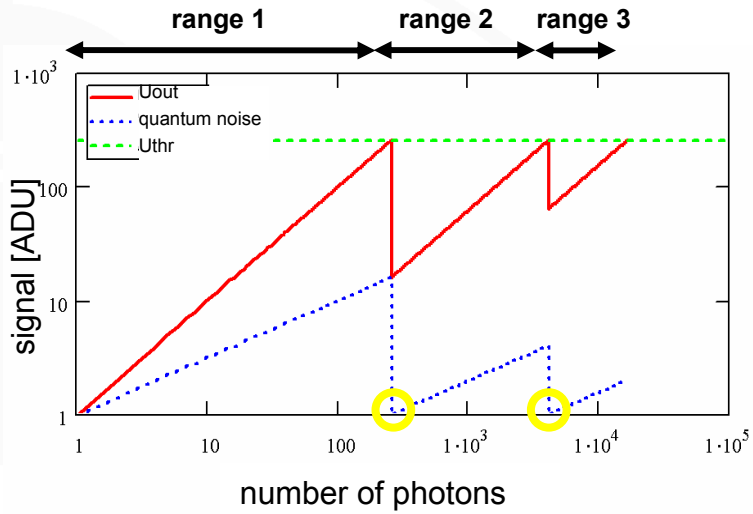


Hybrid Pixel Array Detector (HPAD)

Dynamic Range

Integrator gain calculations:

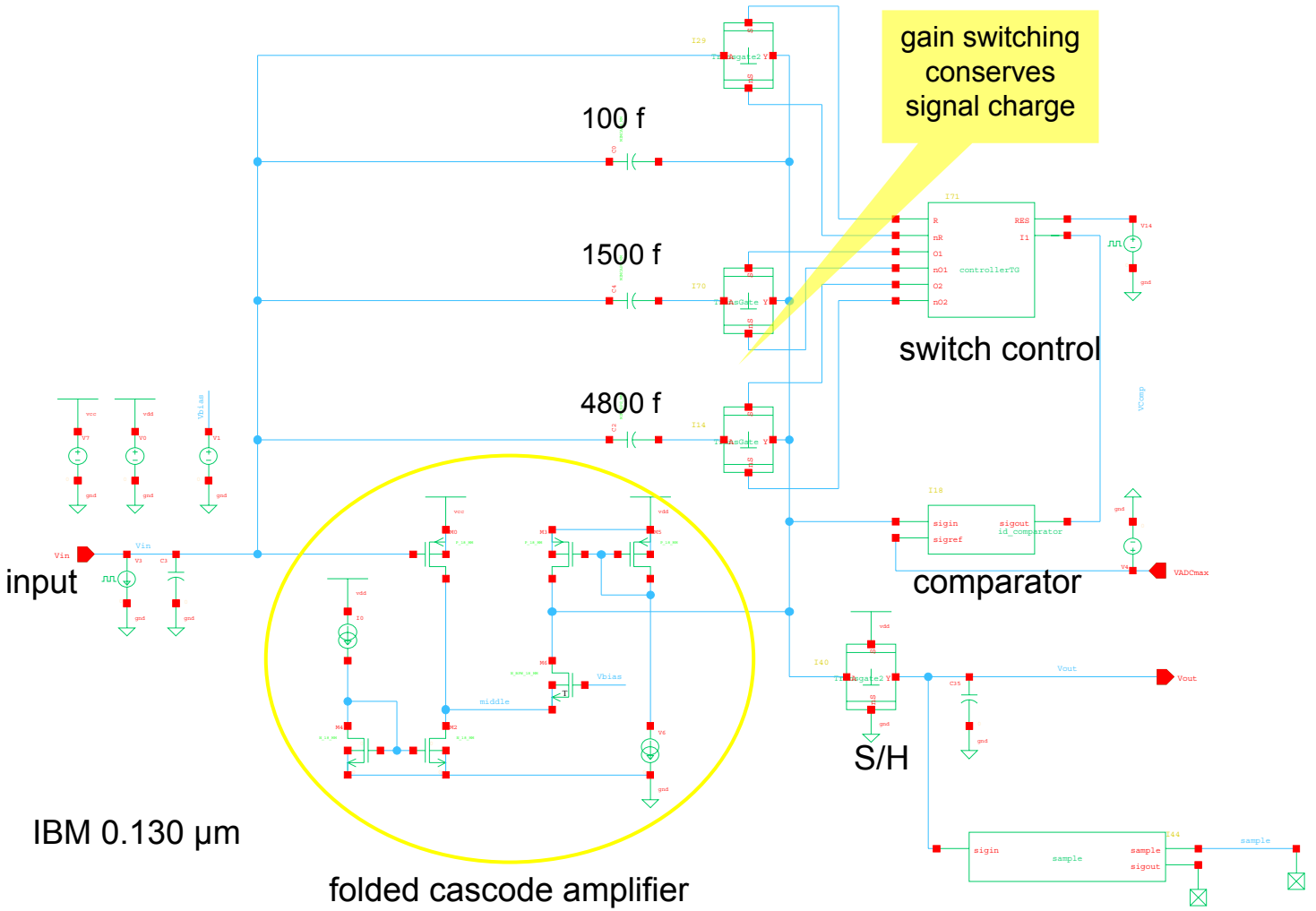
- effective analog resolution ≥ 8 bit
- keep analog resolution always better than "quantum noise" $\sqrt{n_{ph}}$
- maximum signal ≥ 10^4 photons



range	norm. gain	Cf [fF]	max n_{ph}
1	1	100	256
2	1/16	1600	4096
3	1/64	6400	16384

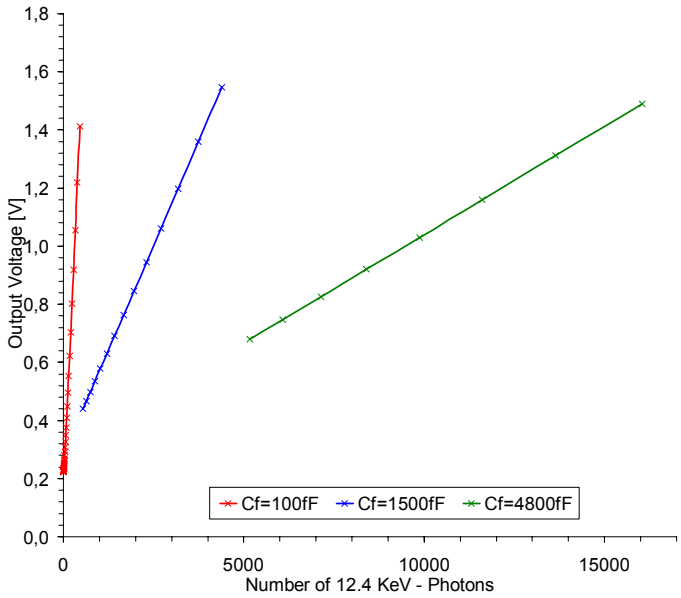
Hybrid Pixel Array Detector (HPAD)

Implementation of the Variable Slope Integrator

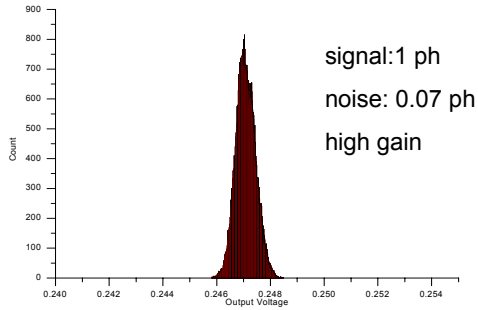


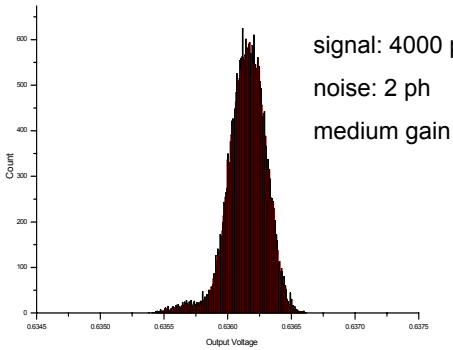
Hybrid Pixel Array Detector (HPAD)

Simulation Results



output voltage as a result of the dynamic gain switching

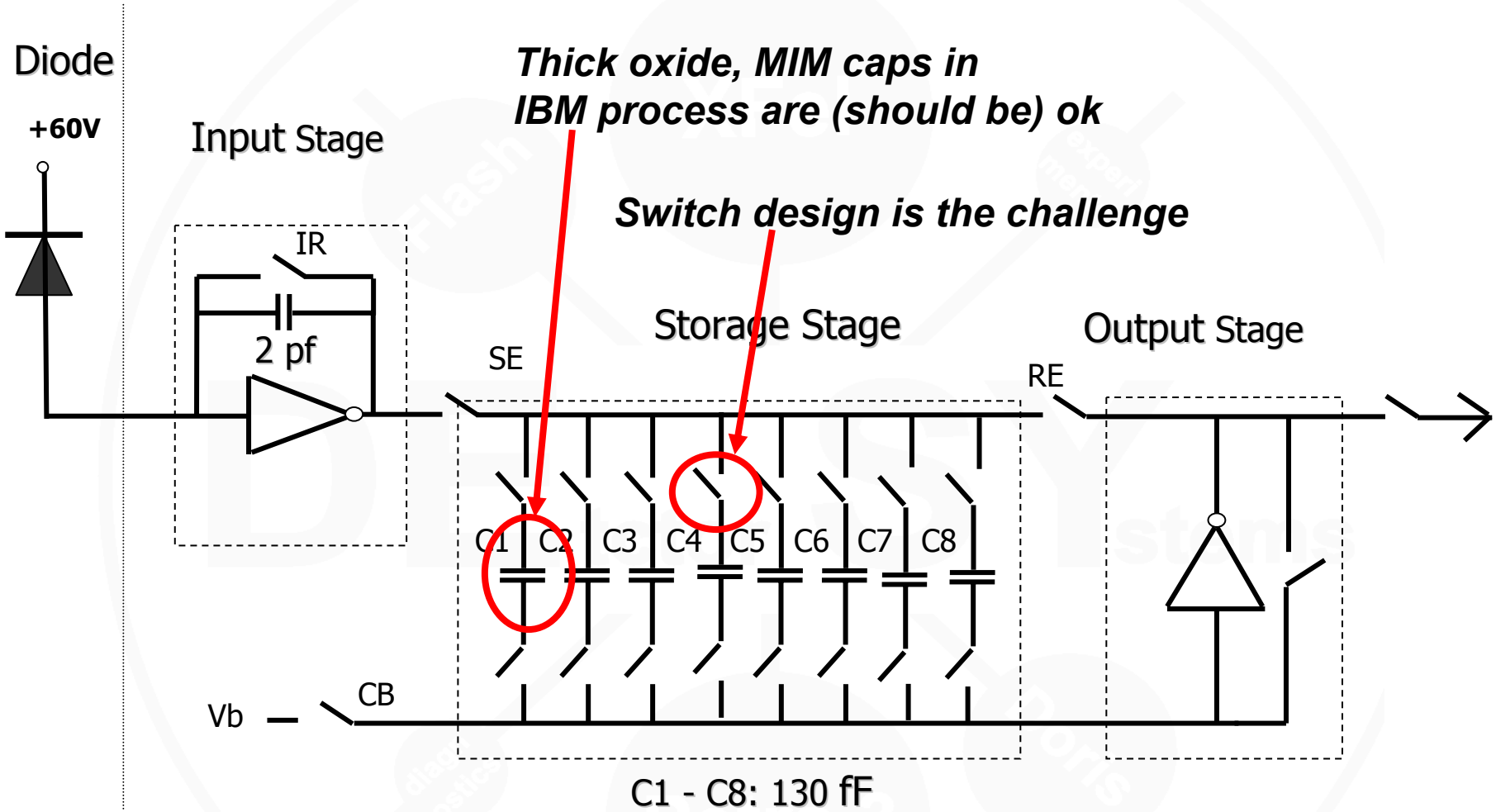




output noise for two different input signals (preliminary)

Single shot 2D-imaging

Store charge in analogue pipeline for 100 msec; "loss free"



Single shot 2D-imaging

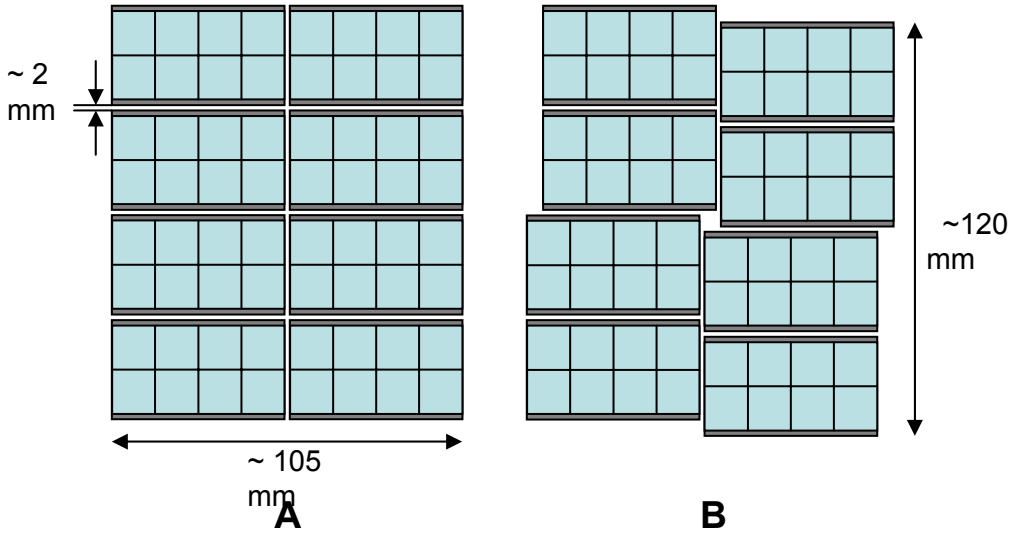
Basic Parameters HPAD

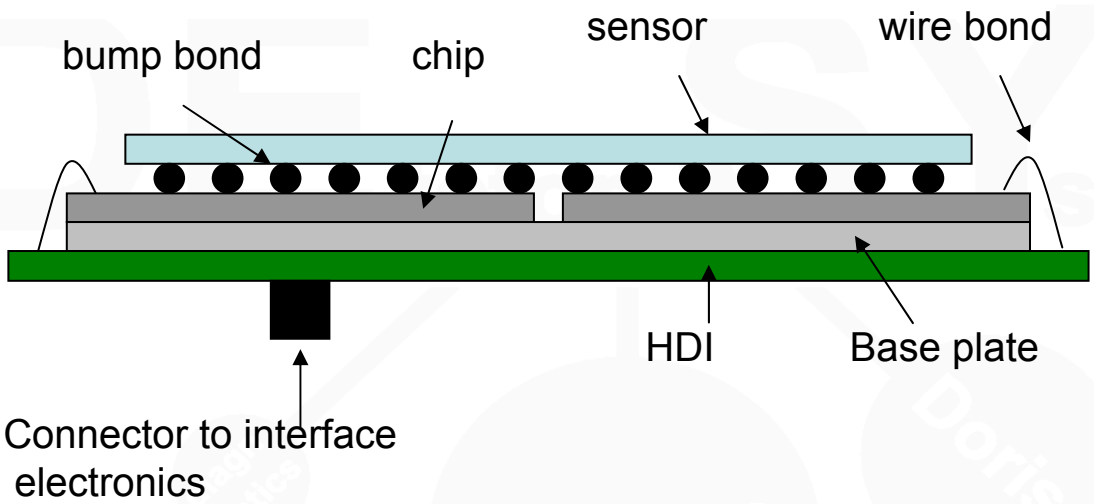
- 200 μm pixels
- 5 MHz framing speed
- Single photon sensitivity at 12 keV
- 2 x 10^4 dynamic range, using 3 switched gains
- 400 image storage depth
- 128 x 256 monolithic tiles
- Flat detector

Current status and planning

- ASIC Test structures were submitted last week 0.13 micron MOSIS
- Detector response and science simulations started
- Irradiations done up to 1 GGy (this is a lot!!!!)
- Simulations on charge explosion started
- Equipment for experiments on charge explosion in place

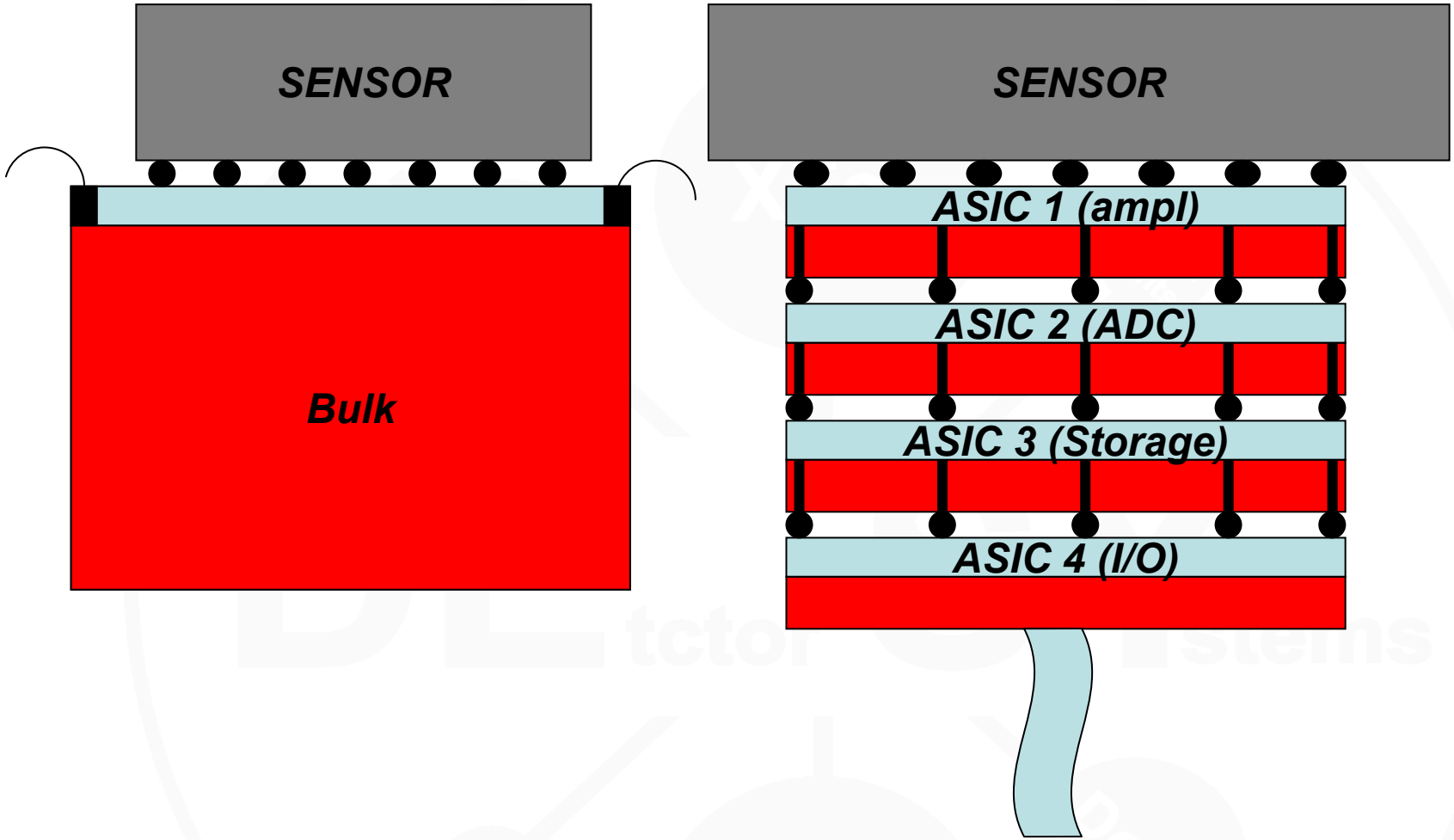
Single shot 2D-imaging



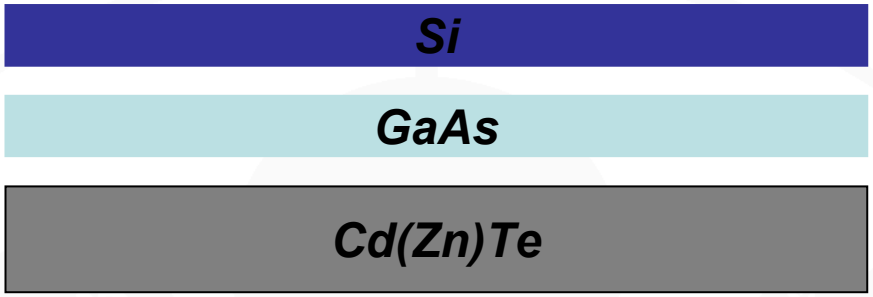


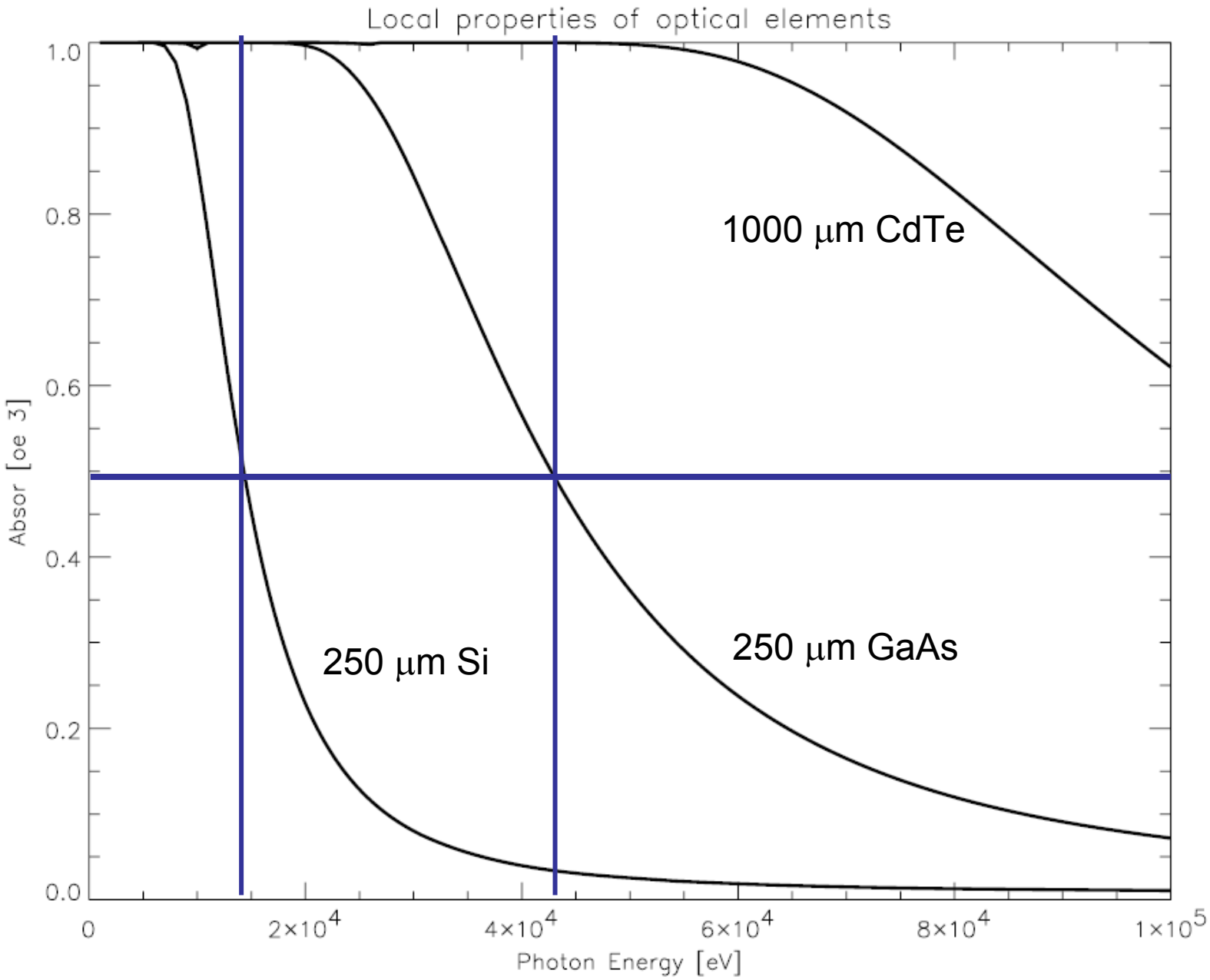
Guillaume Potdevin; DESY

Some Dreams

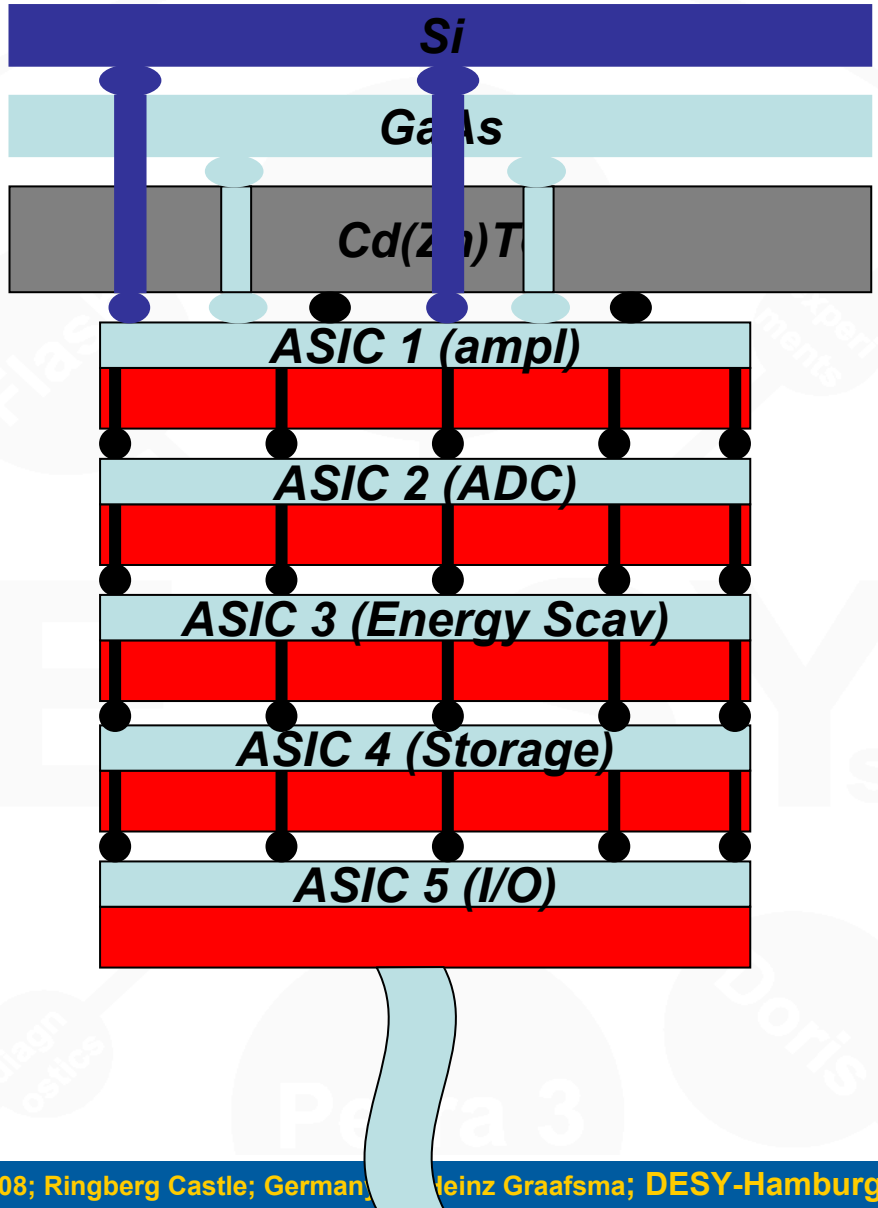

SENSOR
Bulk
SENSOR
ASIC 1 (ampl)
ASIC 2 (ADC)
ASIC 3 (Storage)
ASIC 4 (I/O)

Dream on hon….




Local properties of optical elements
Absor [oe 3]
1.0
0.8
0.6
0.4
0.2
0.0
0
2×10^4
4×10^4
6×10^4
8×10^4
1×10^5
Photon Energy [eV]
1000 μm CdTe
250 μm Si
250 μm GaAs

Dreams….


Si
GaAs
Cd(Zn)T
ASIC 1 (ampl)
ASIC 2 (ADC)
ASIC 3 (Energy Scav)
ASIC 4 (Storage)
ASIC 5 (I/O)

Scope of this workshop

- The interconnection of different technologies like for the sensors, analogue, and digital ASICs offers obviously a lot of advantages but R&D and prototyping in this field can be very cost intensive.
- One of the goals of this workshop is the **formation of a common platform** for the R&D on vertically integrated pixel detector systems which then would give the opportunity to share the experience and open new possibilities for the organization of common projects…

…for LHC and ILC detector development.

"And the world remains divided?"