Detector Challenges in Photon Science.

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Outline

> Photon Science and the detector challenge

> Synchrotron storage rings

- The LAMBDA system

> X-ray Free Electron Lasers

- The DSSC system
- The AGIPD system

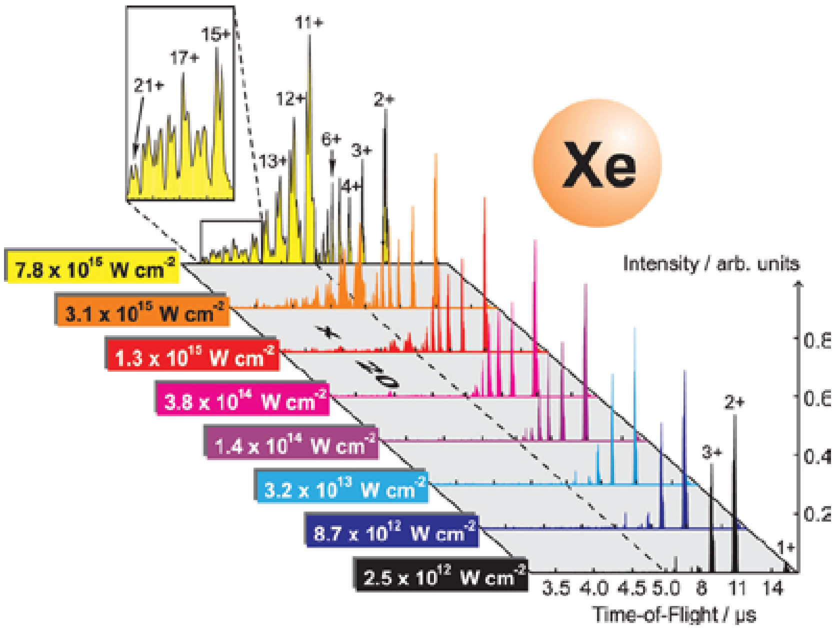
> XUV Free Electron Lasers

- The PERCIVAL system

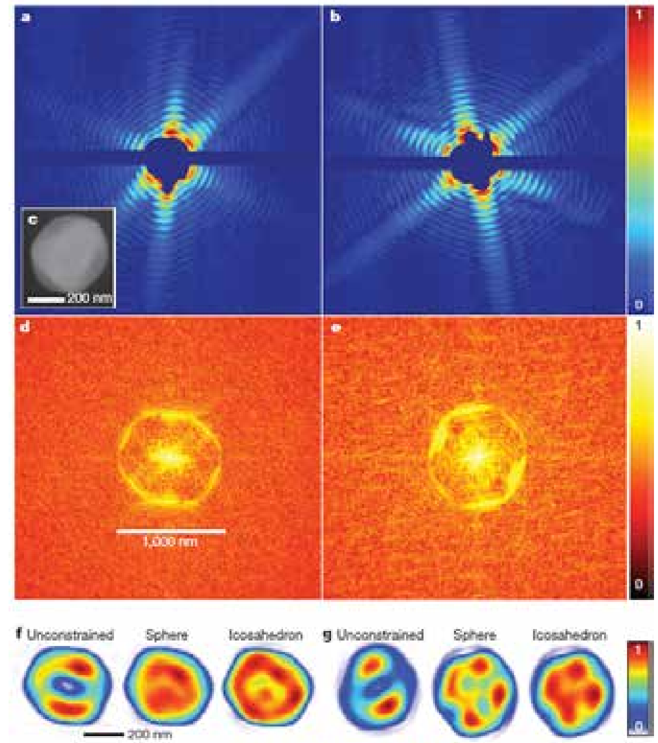
> Future directions

From fundamental to applied science

Study of extremely charged ions



Structure of viruses



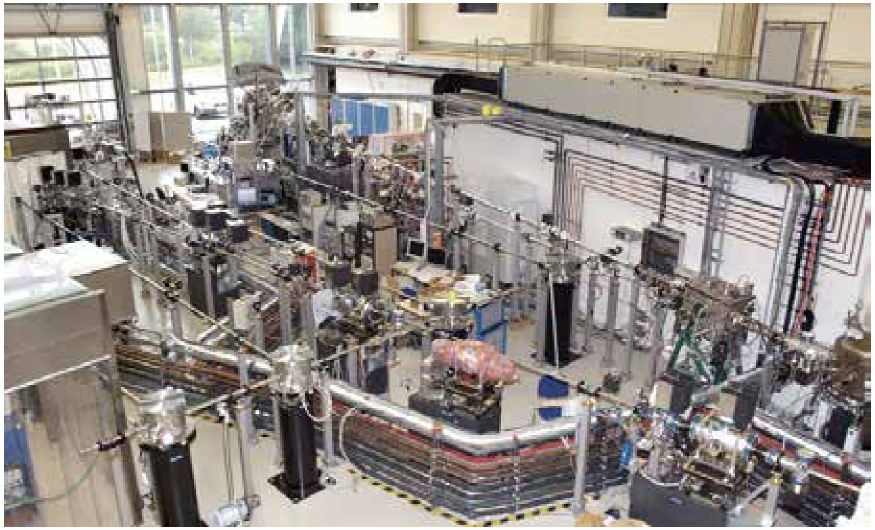
Nature 470, 78 (2011)

Authentication of paintings

Photon-Science at large scale X-ray facilities

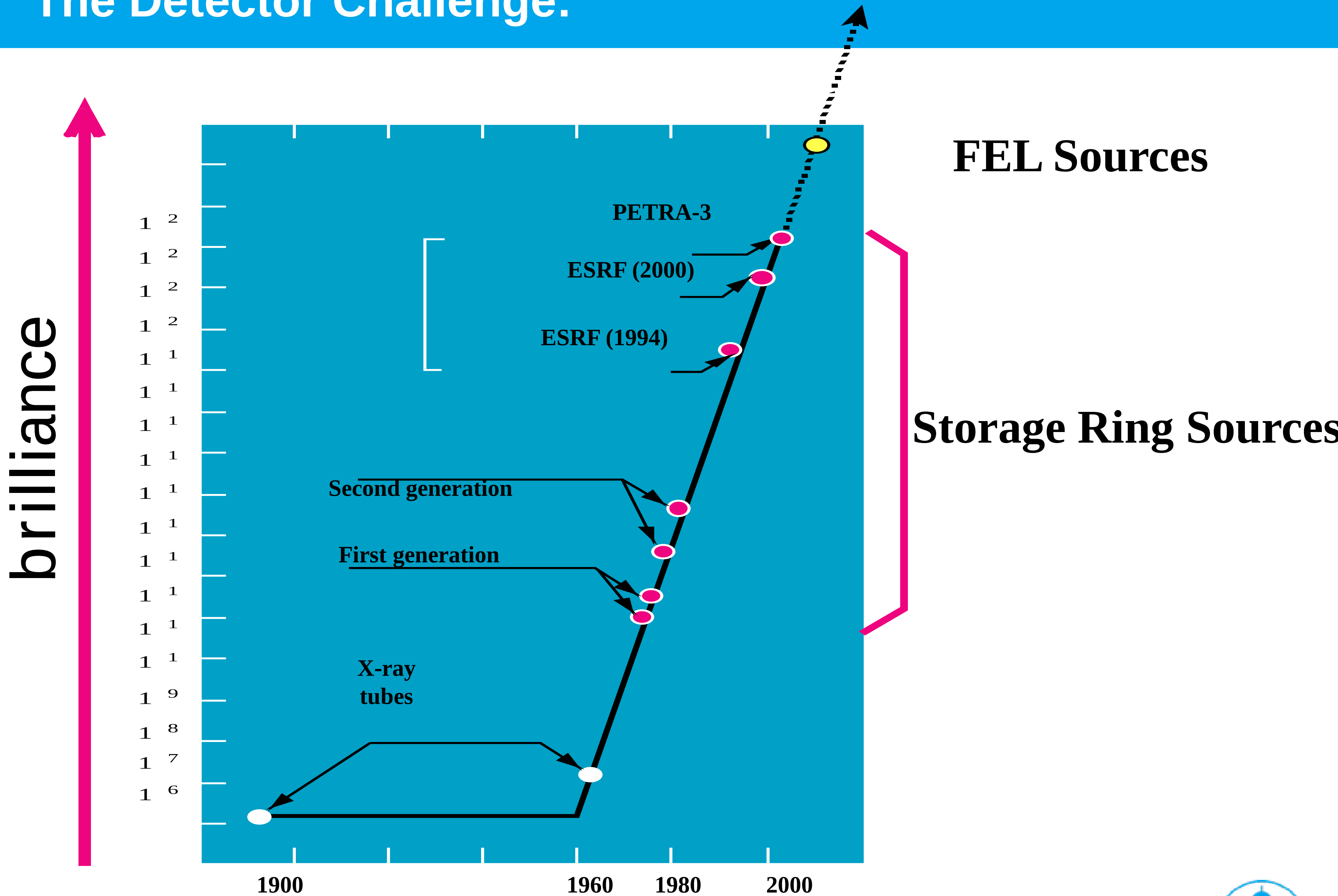
PETRA III

FLASH I + II



European XFEL

The Detector Challenge:



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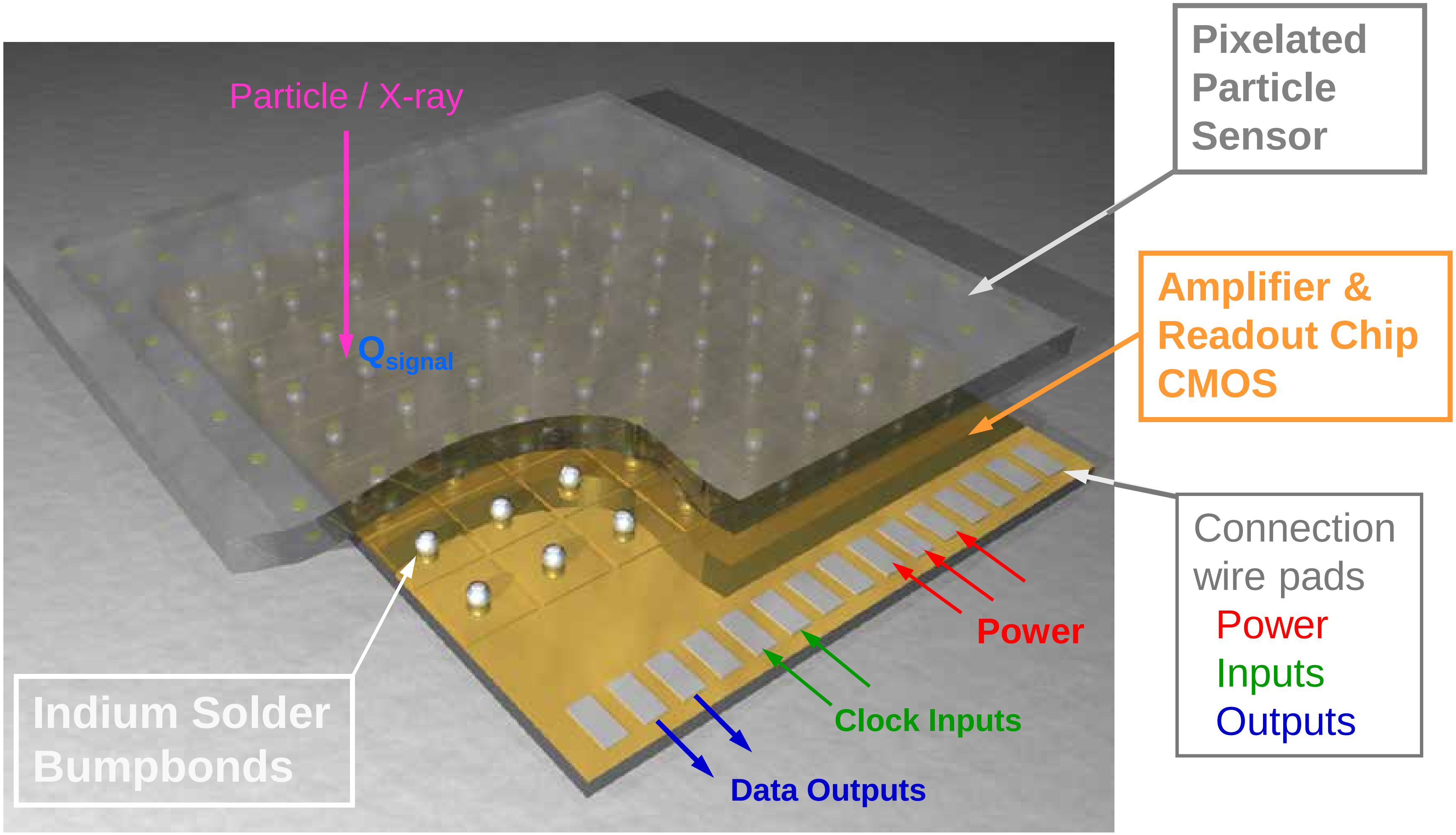
Storage Ring Sources: general observations

- Pulsed X-ray source
- ~ Giga Hz rep-rate
- Treated as a continuous, random source
- Main photon range: 5-30 keV
- Few stations <1 keV
- Few stations > 100 keV
- 30 large synchrotrons world-wide
- ~ 800 end-stations

PETRA III

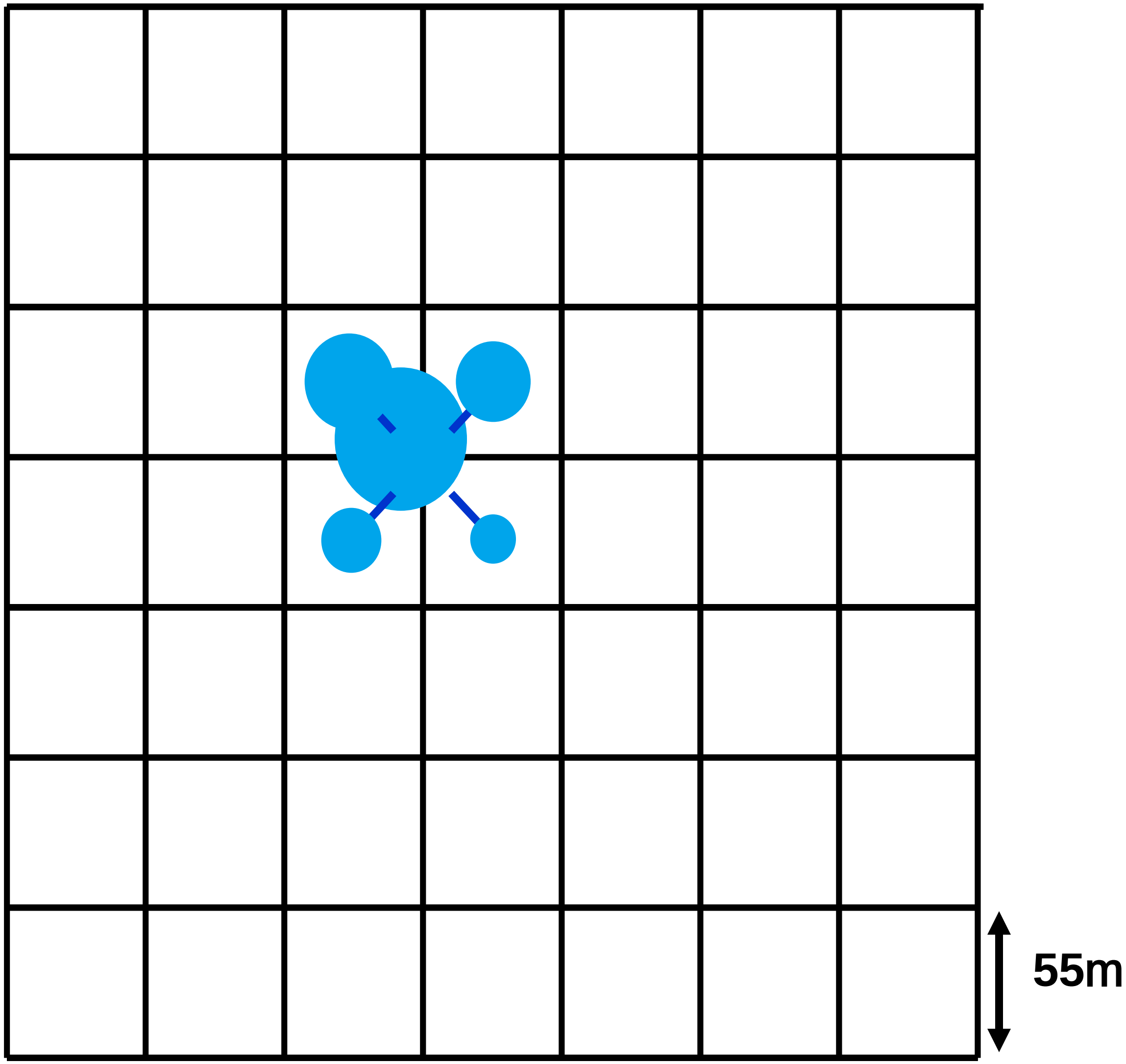
Hybrid Pixel Array Detectors (HPADs)



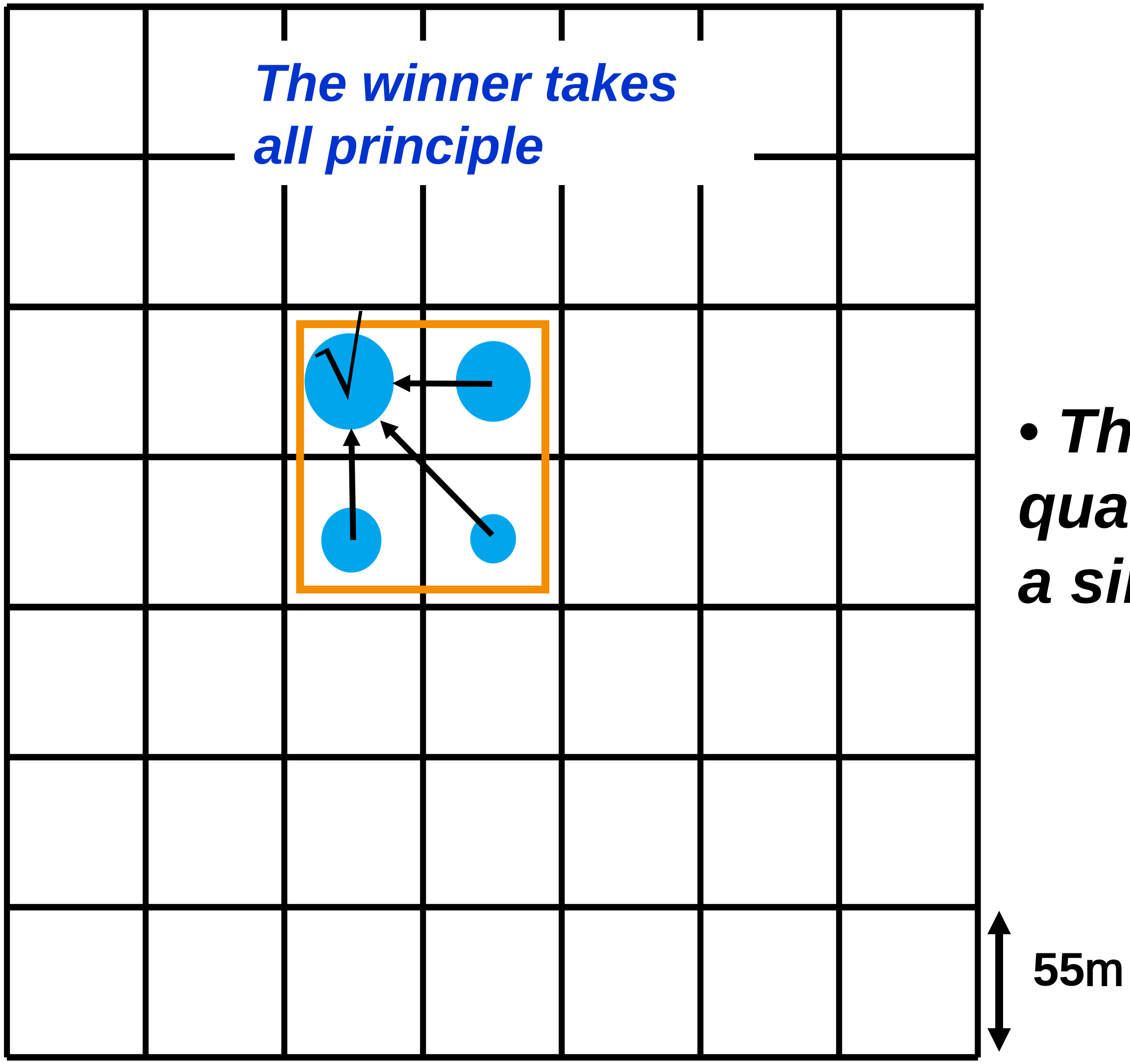
Particle / X-ray à **Signal Charge** à **Electr. Amplifier** à **Readout** à **Digital Data**

DESY

Medipix-3: Communicating pixels

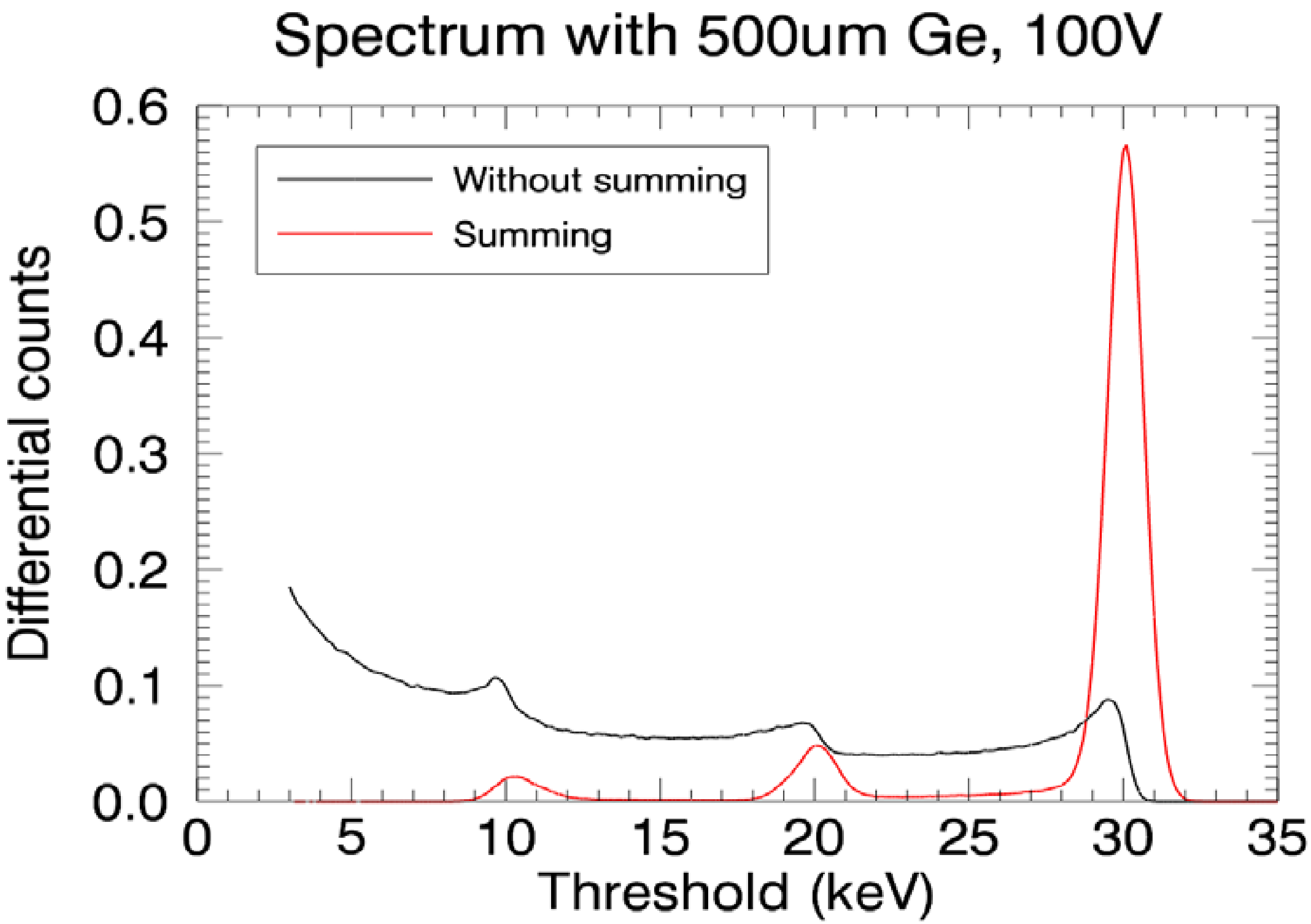


Medipix-3: Communicating pixels



- ***The incoming quantum is assigned as a single hit***

Communicating pixels è better energy resolution



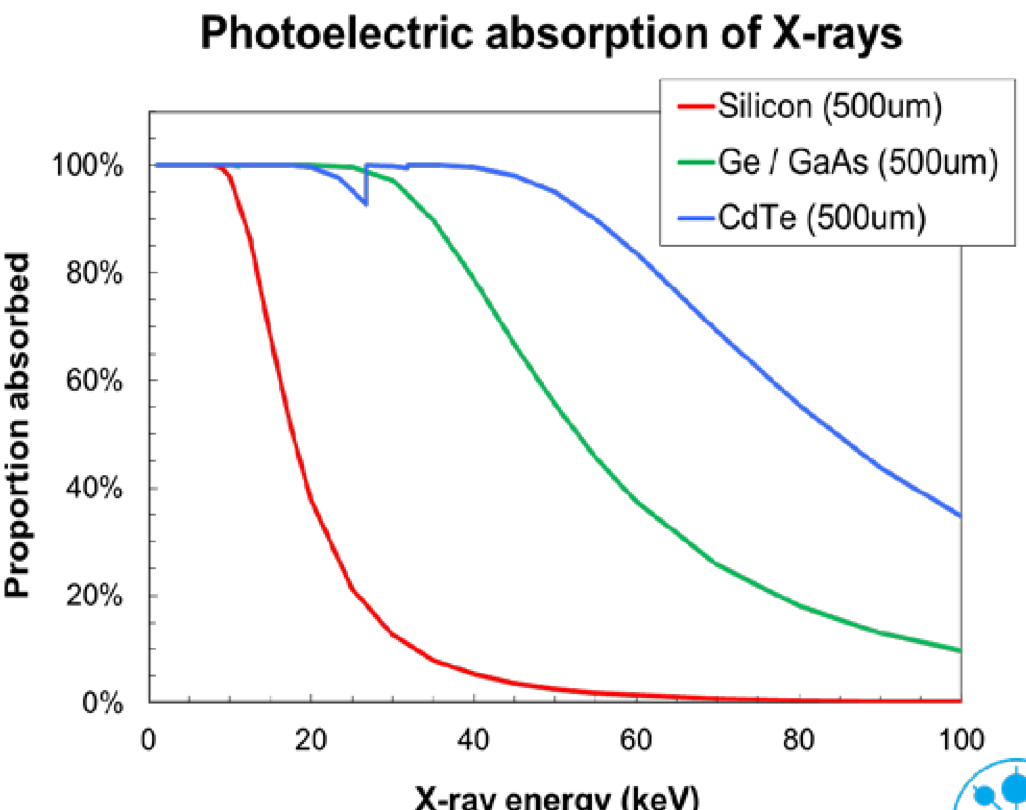
Medipix3 readout chip

- Collaboration of ~20 groups led by CERN
- Flexible pixel design
  - 2 counters and thresholds per 55µm pixel, plus interpixel communication
- Applications:
  - Fast, deadtime-free frame readout
    - 2000 fps @ 12 bit depth
  - Energy binning with charge summing
  - Pump / probe…

Large Area Medipix3 Based Detector Array (LAMBDA)

High-Z pixel detectors

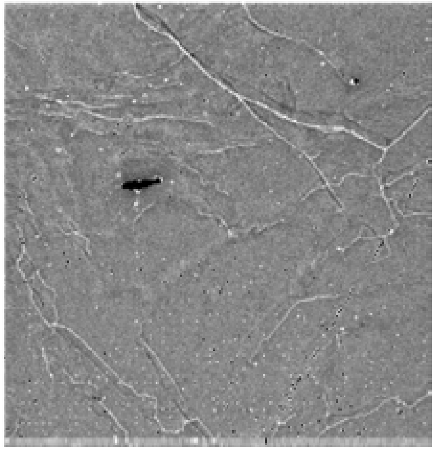
- Aim: Increase efficiency at 50 keV by factor of 10
  - Replace silicon sensor in LAMBDA with high-Z semiconductor
  - Combine high QE with hard X-rays, high frame rate, high signal-to-noise
- Investigating different materials in collaboration with other institutes and industry
  - Cadmium telluride
  - Gallium arsenide
  - Germanium



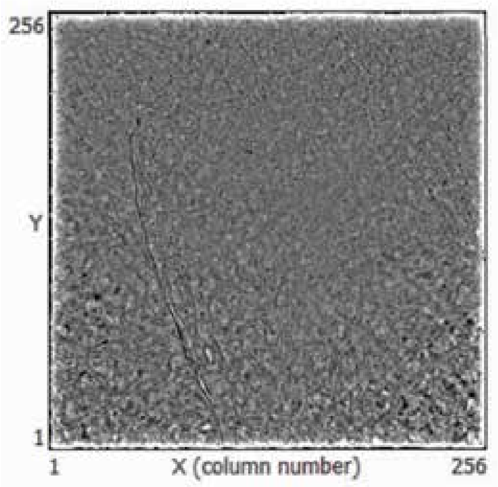
High-Z sensors

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

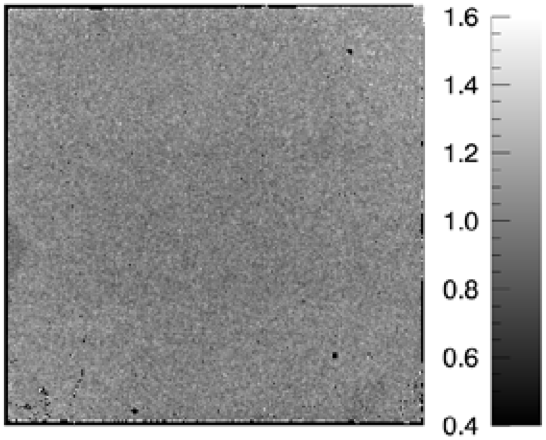
CdTe



GaAs



Ge



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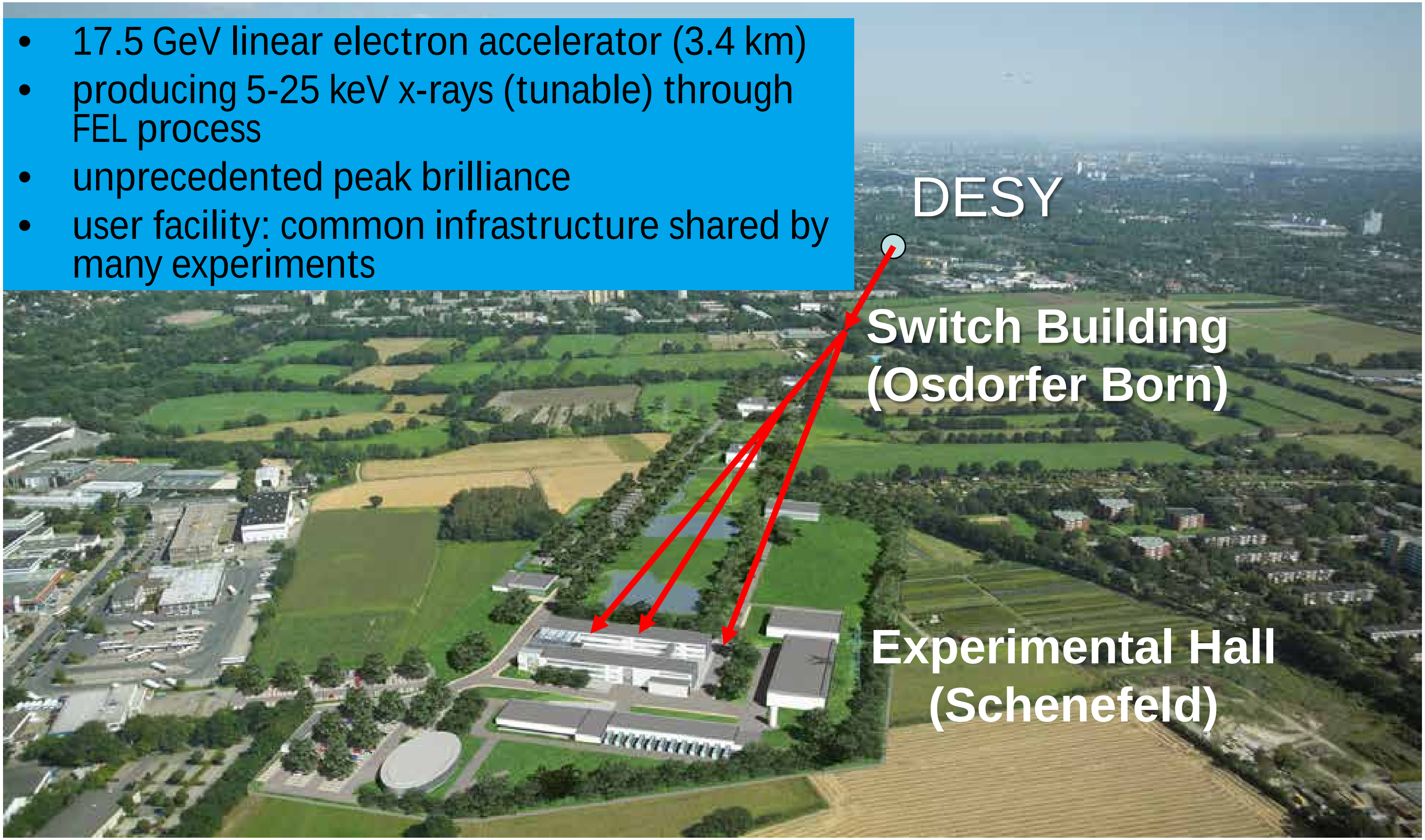
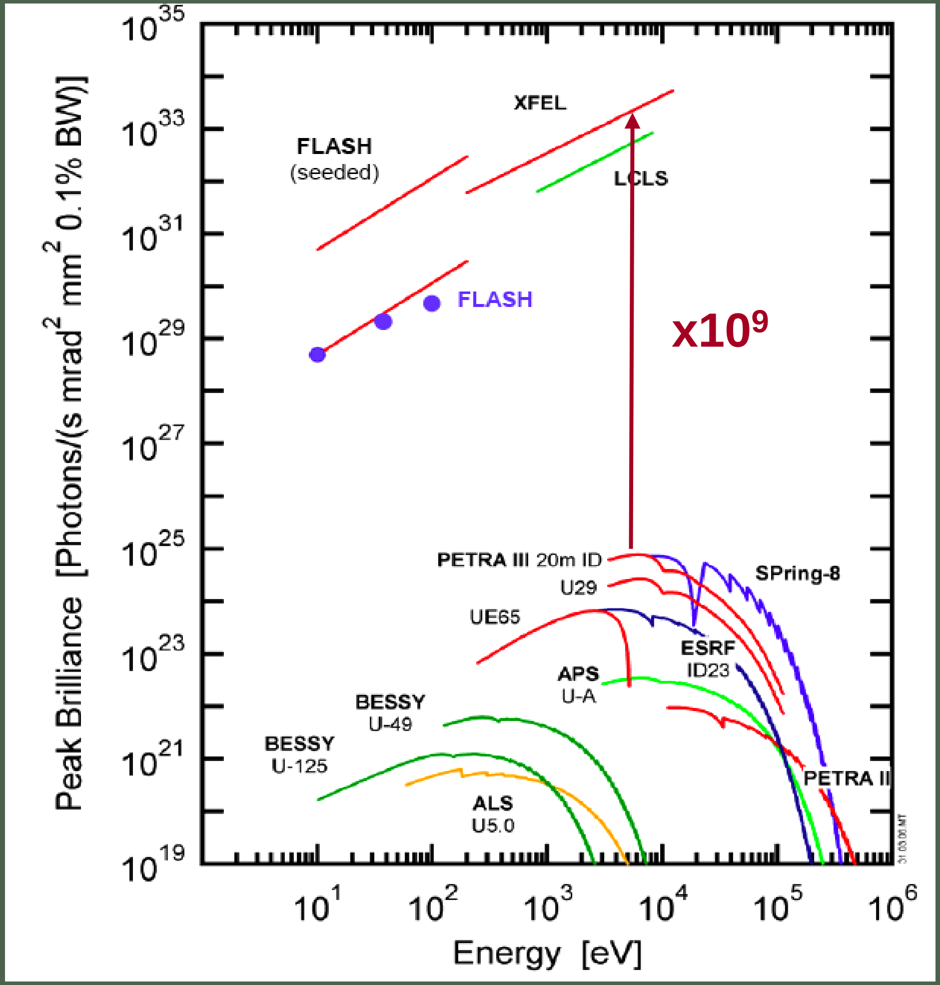
The European X-ray Free Electron Laser

- 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

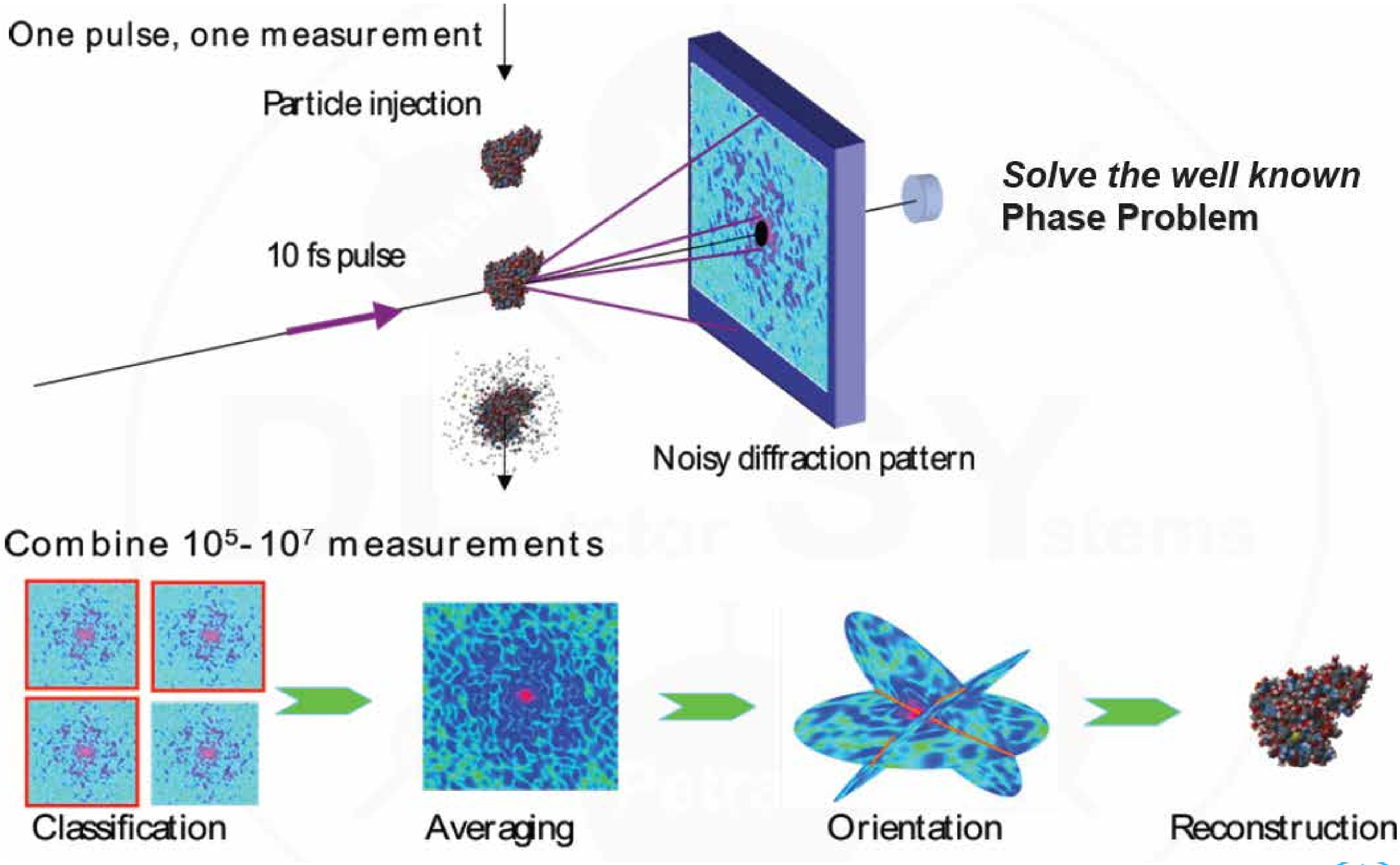


The XFEL-Challenge: Different Science



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

The Holy Grail ?

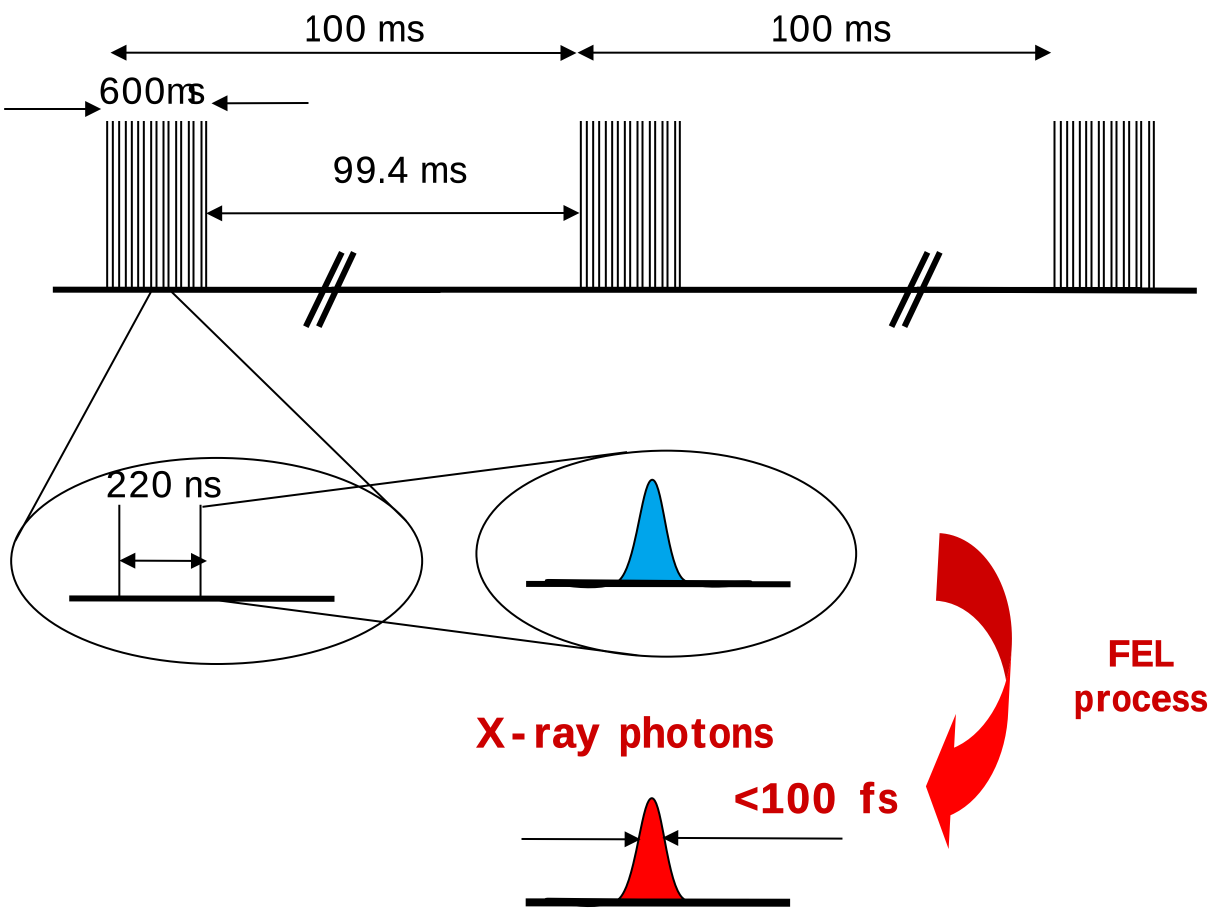


***Solve the well known* Phase Problem**

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

European XFEL Linac: Time Structure Challenge

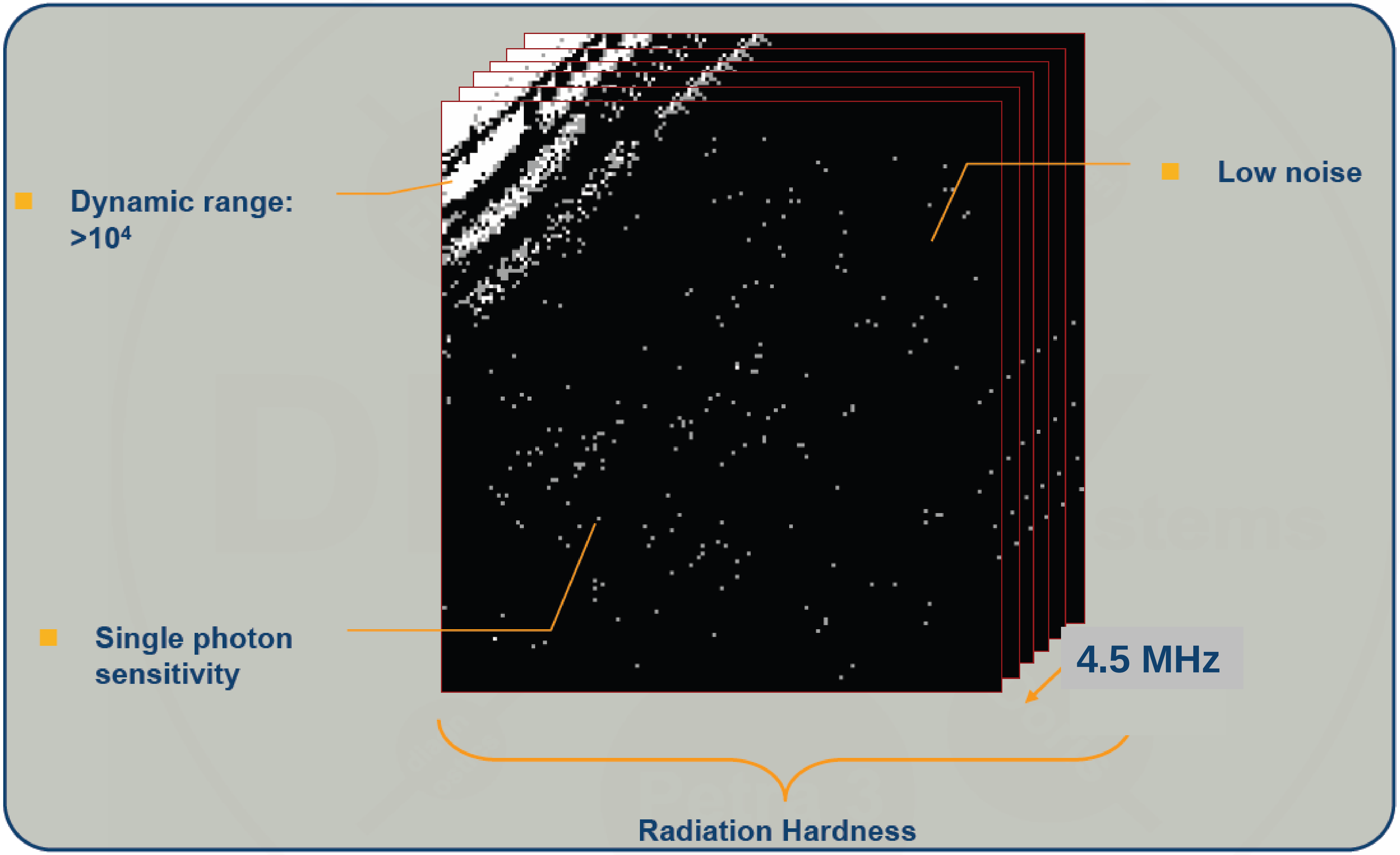
Electron bunch trains; up to 2700 bunches in 600 msec, repeated 10 times per second.
Producing 100 fsec X-ray pulses (up to 27 000 bunches per second).



27 000 bunches/s
with
4.5 MHz
repitition rate

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

What are the challenges ?



Three dedicated Projects:

- **Depfet Sensor with Signal Compression**

  Non-linear gain, digital storage

- **Adaptive Gain Integrating Pixel Detector**

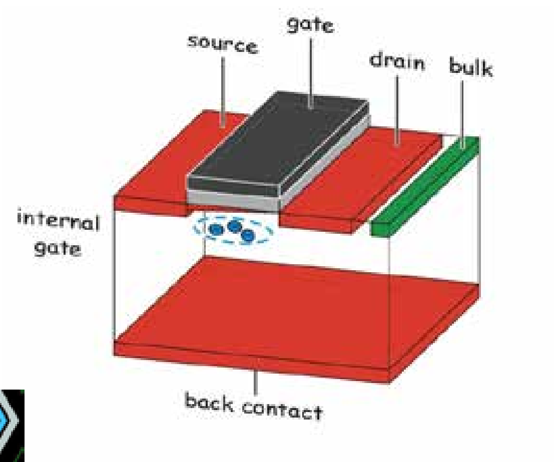
  Automatic adaptive gain, analogue storage

- **Large Pixel Detector**

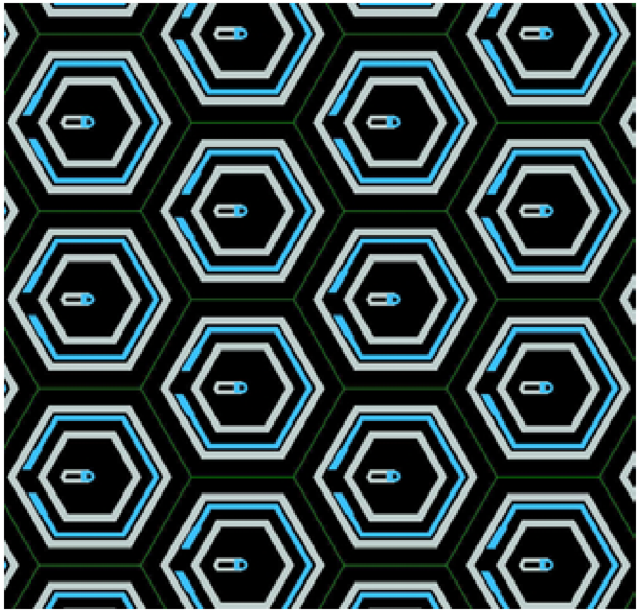
  Three parallel gains, analogue storage

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 200mm pitch**

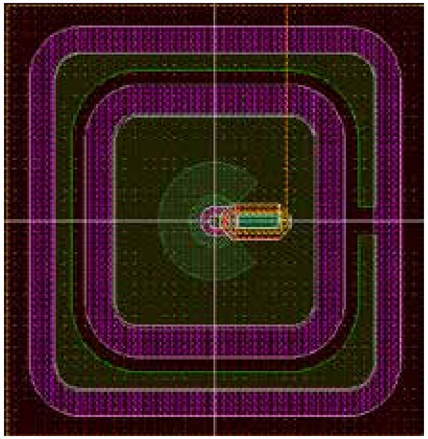


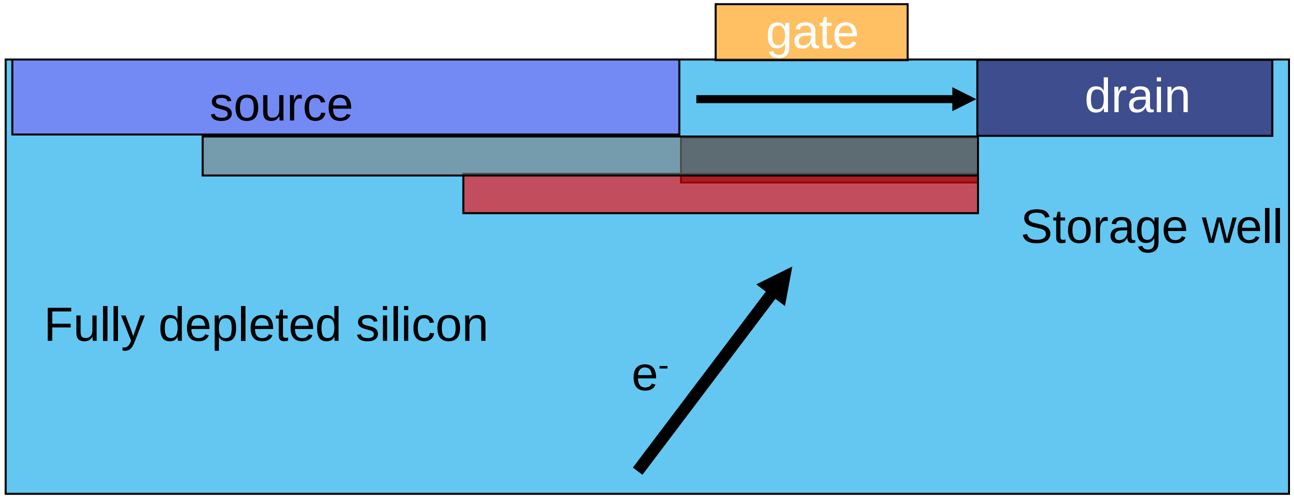
- combines DEPFET
- with small area drift detector (scaleable)

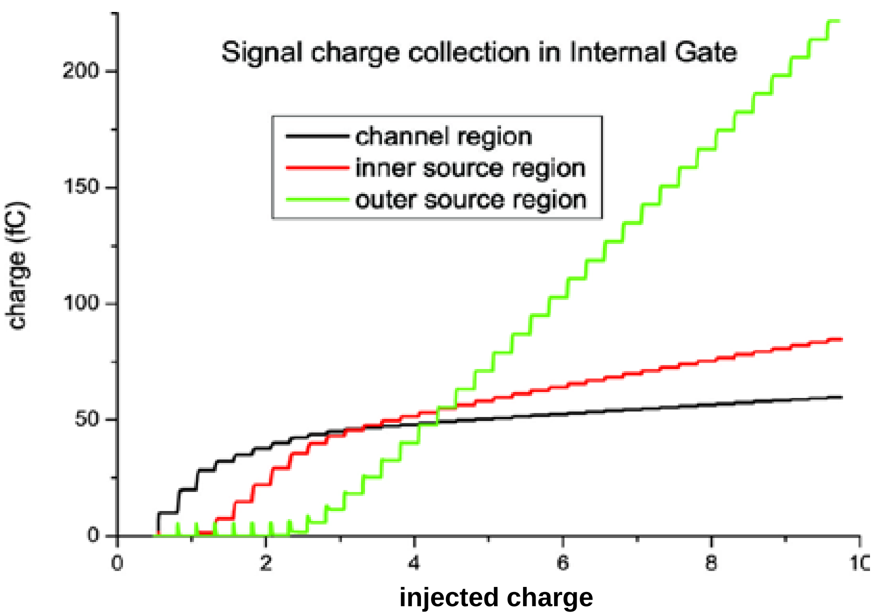
- > MPI-HLL, Munich
- > Universität Heidelberg
- > Universität Siegen
- > Politecnico di Milano
- > Università di Bergamo
- > DESY, Hamburg

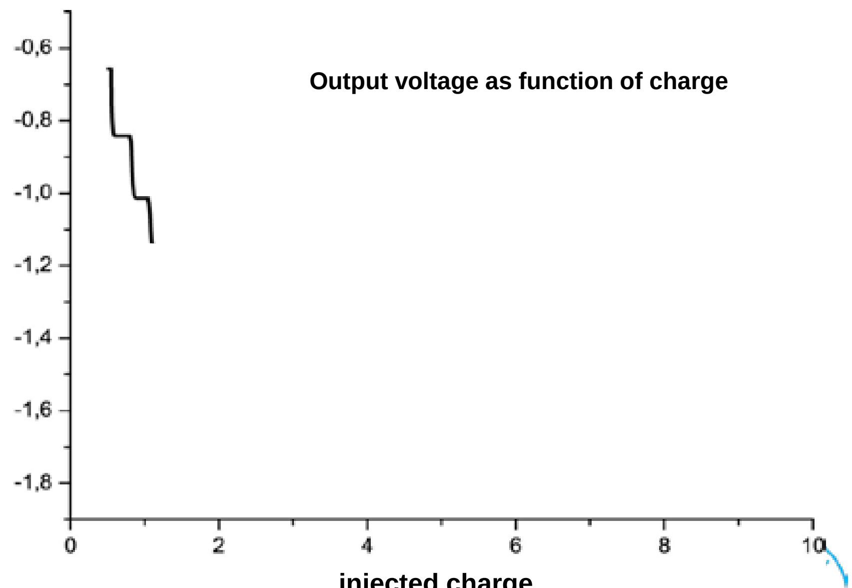
DSSC - DEPFET Sensor with Signal Compression

DEPFET: Electrons are collected in a storage well ⇒Influence current from source to drain







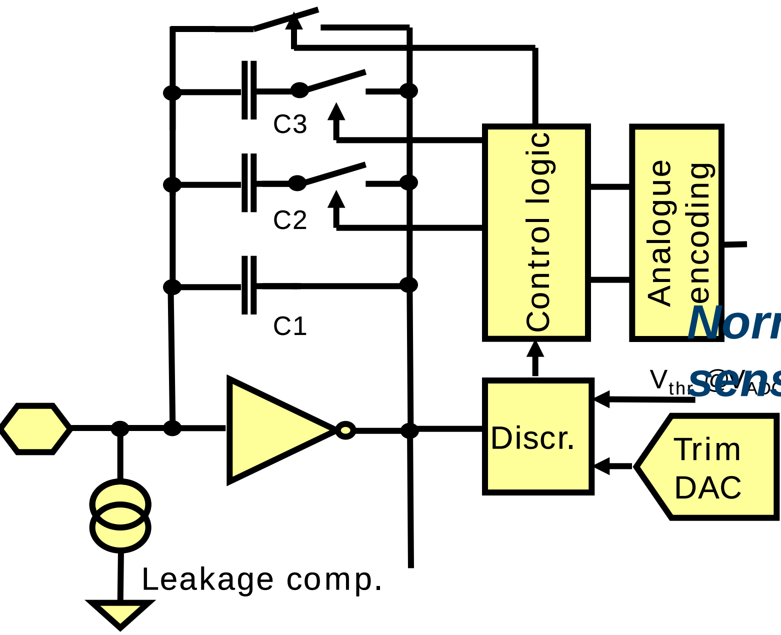


The Adaptive Gain Integrating Pixel Detector (AGIPD)

Adaptive Gain principle

High dynamic range:

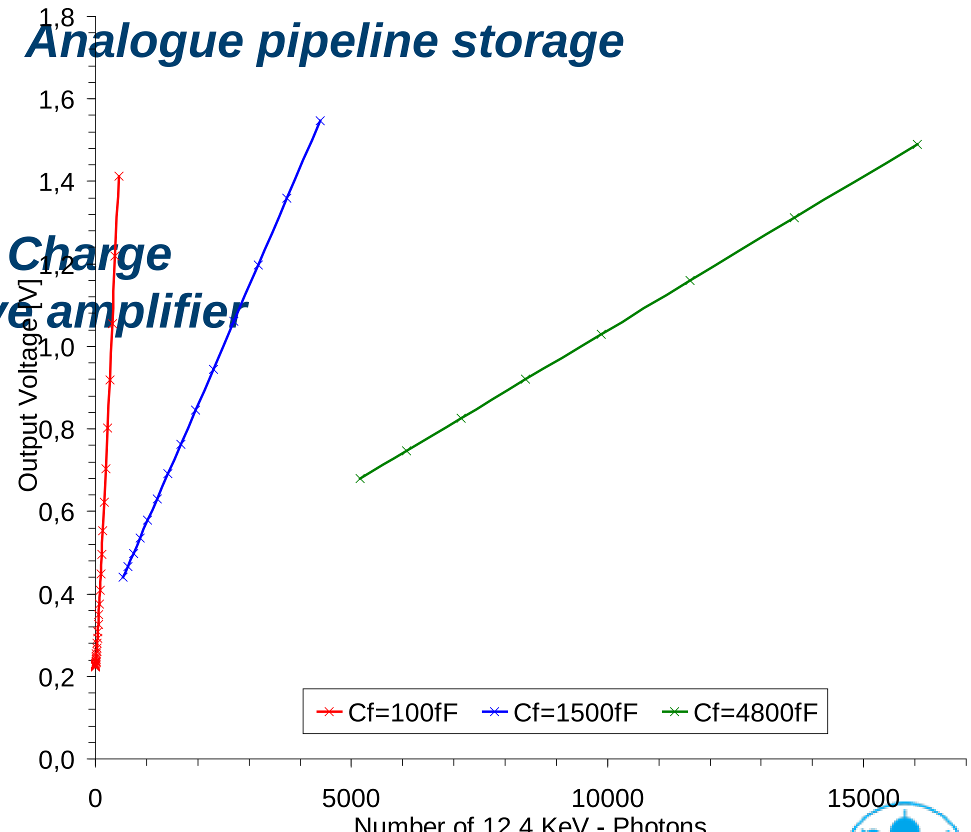
Dynamically gain switching system



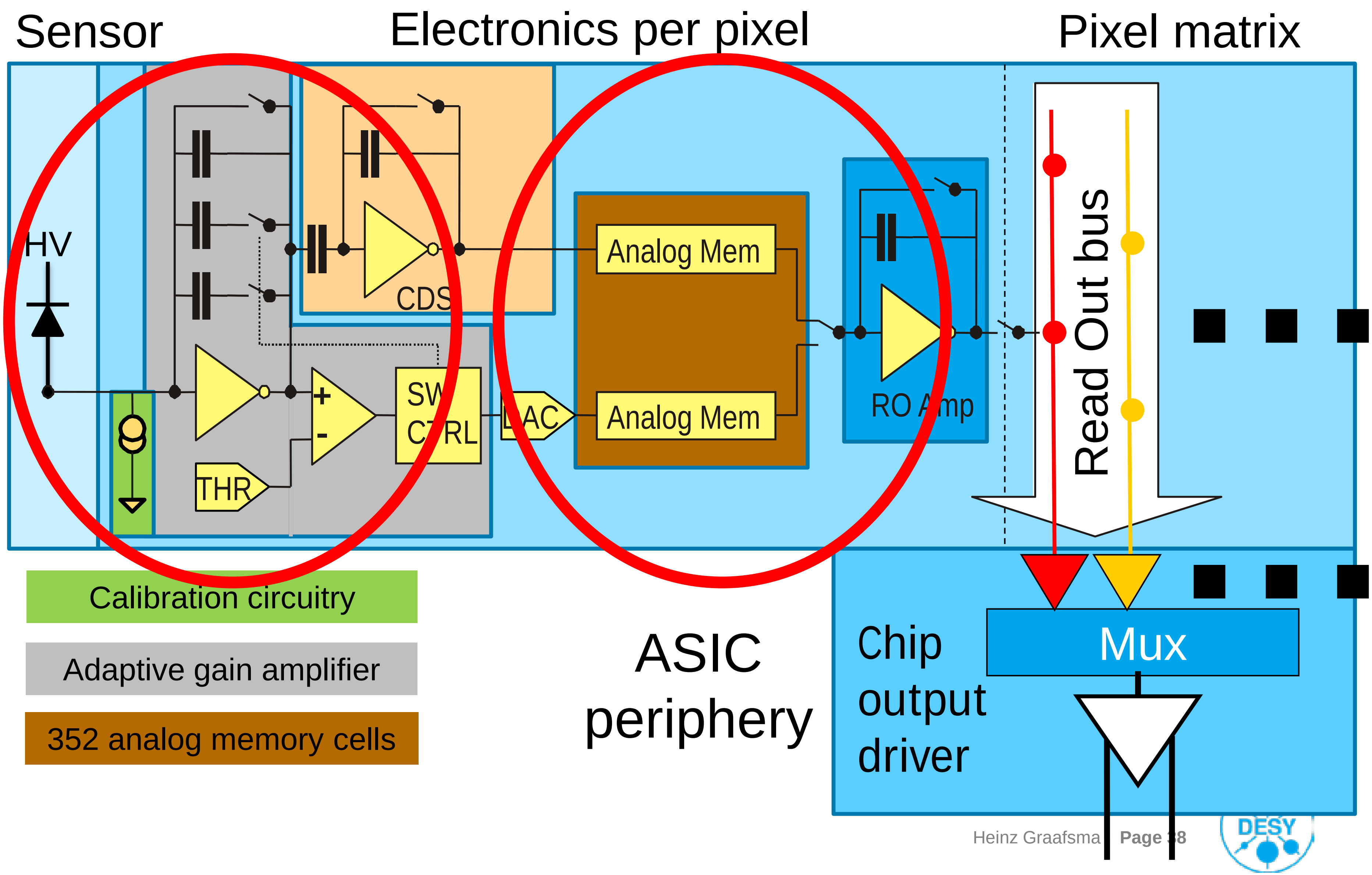
Extremely fast readout (200ns):

Analogue pipeline storage

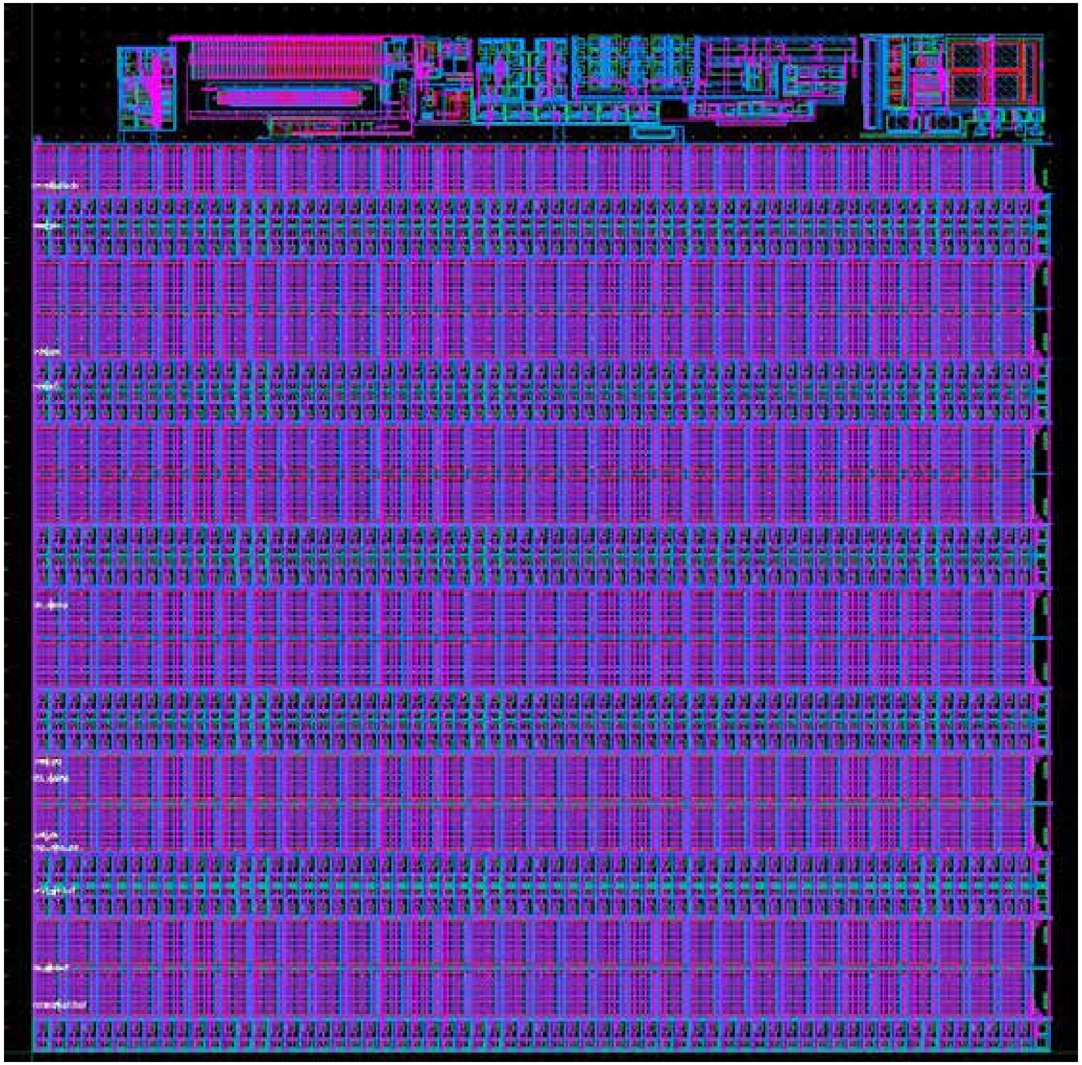
Normal Charge sensitive amplifier



AGIPD readout principle

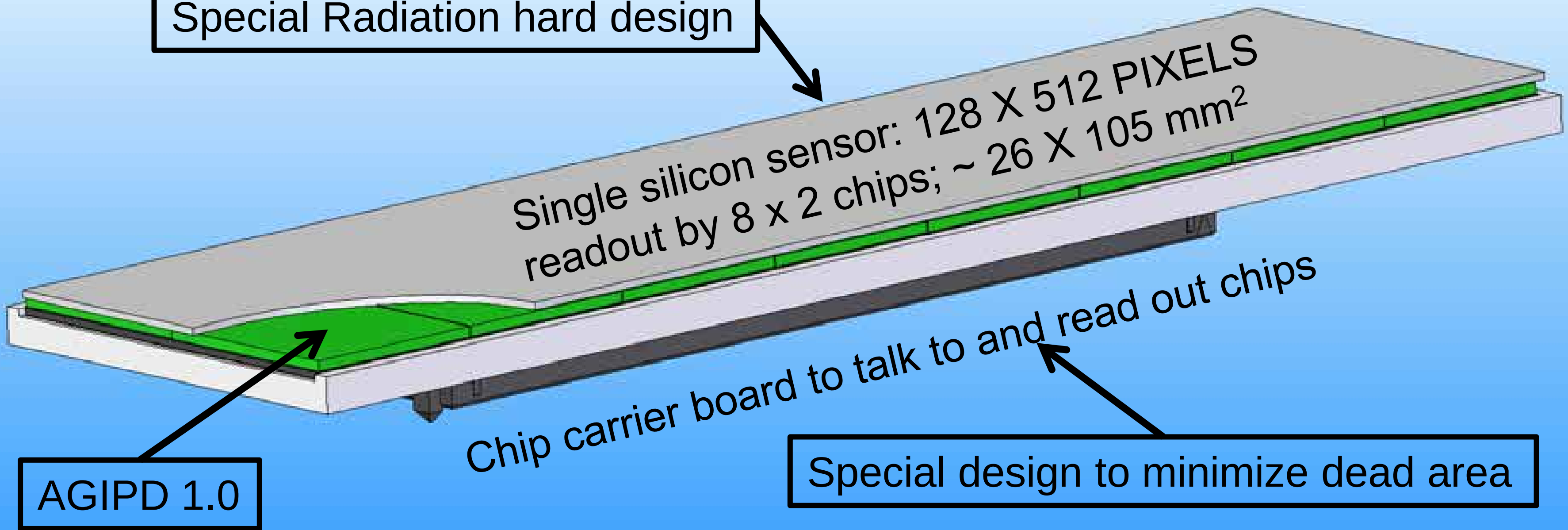


AGIPD Pixel Electronics

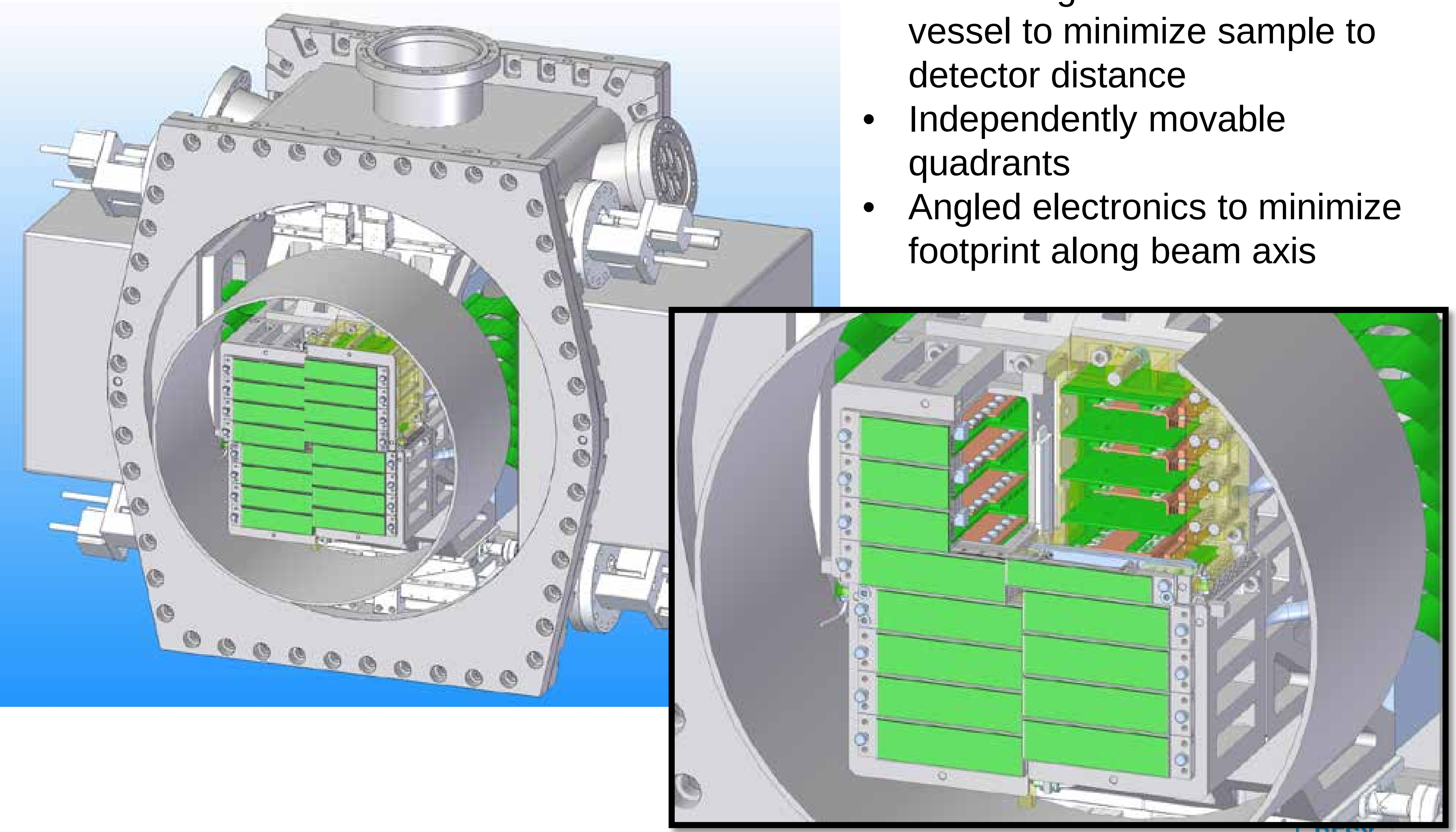


- 200 x 200 micron^2 pixels
- 352 storage cells + veto possibilities.
- Minumum signal ~ 300 e^- =
  0.1 photon of 12.4keV
- Maximum signal ~ 33 10^6 e^- =
  10^4 photons of 12.4keV
- 4.5 MHz frame rate
- 64 x 64 pixels per ASIC
- 2 x 8 ASICs per module (128x512 pixels, no dead area)
- 4 modules per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

AGIPD modules

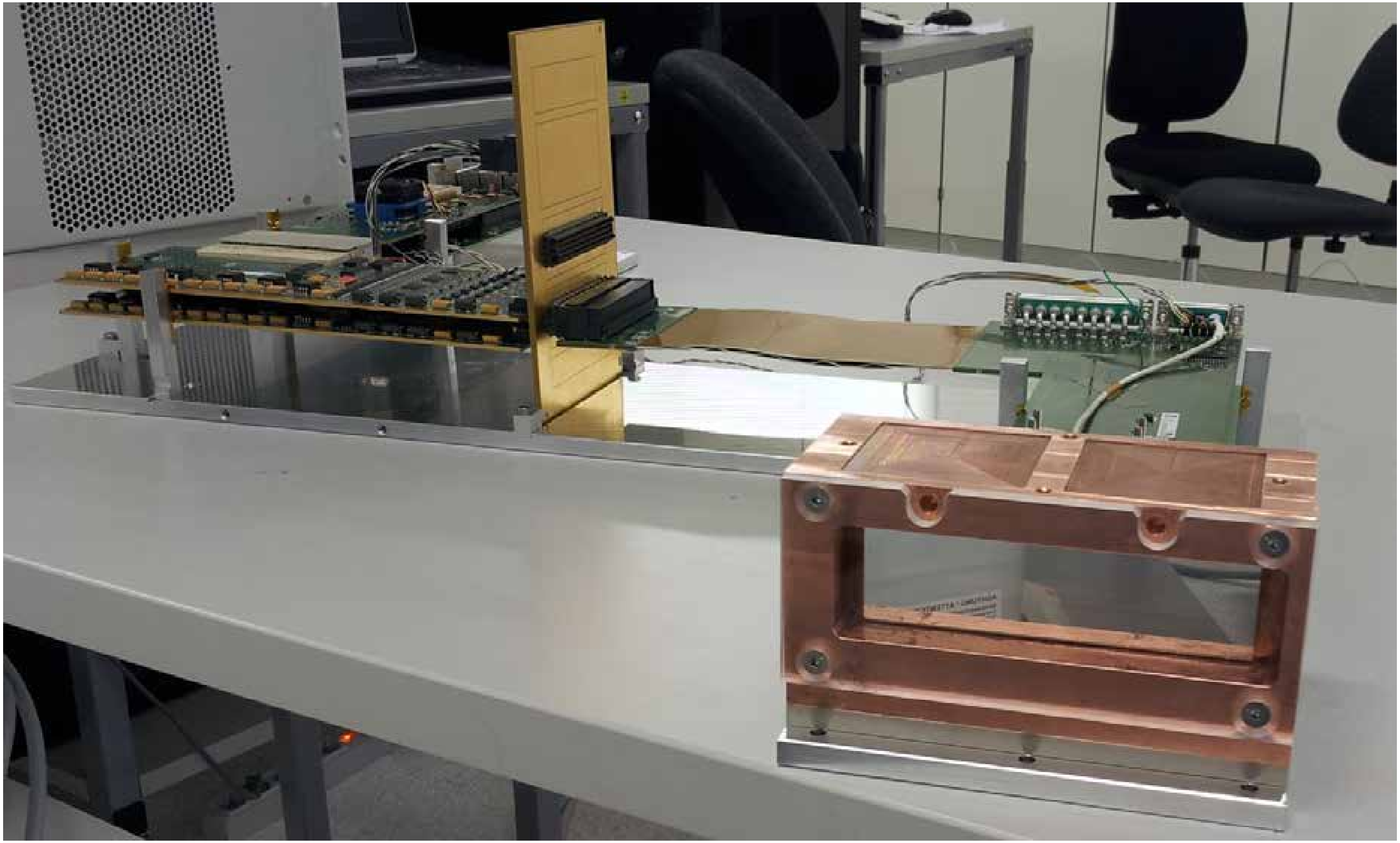


A 1M pixel camera with a variable hole



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

The Real thing



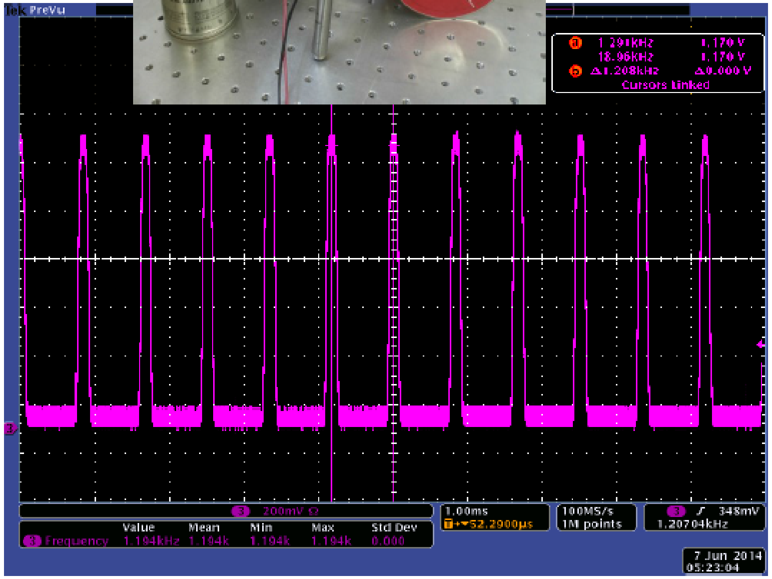
Experiments: AGIPD module @APS

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



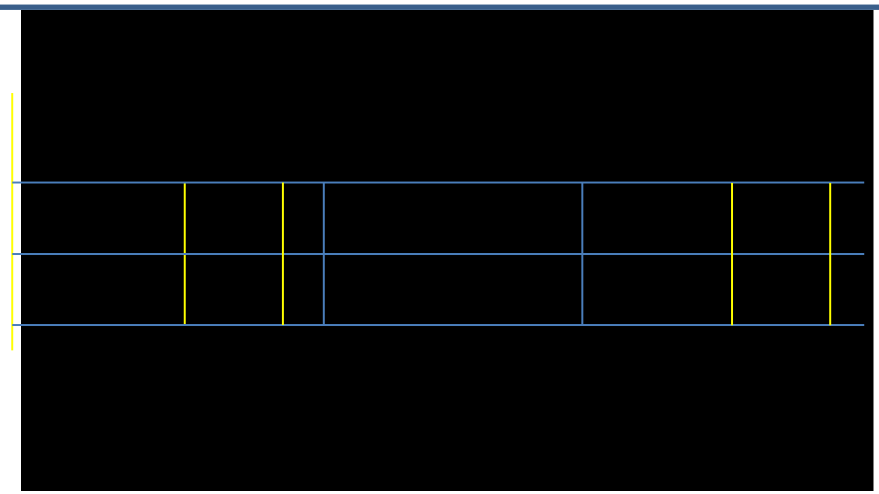
Experiments: AGIPD module @APS

Calculation for burst imaging

Result from laser measurement

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

Vdisc, AGIPD = 29.51m/s ≈ **Vdisc, Laser = 29.83m/s**



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

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PERCIVAL

(Pixelated Energy Resolving CMOS Imager, Versatile And Large)

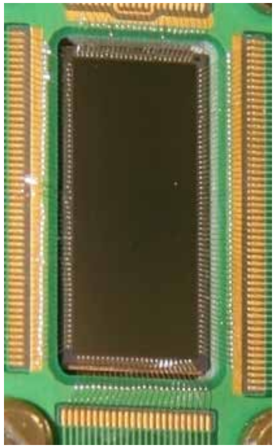
Soft X-ray imaging MAPS for (X)FELs and synchrotrons

HELMHOLTZ | ASSOCIATION

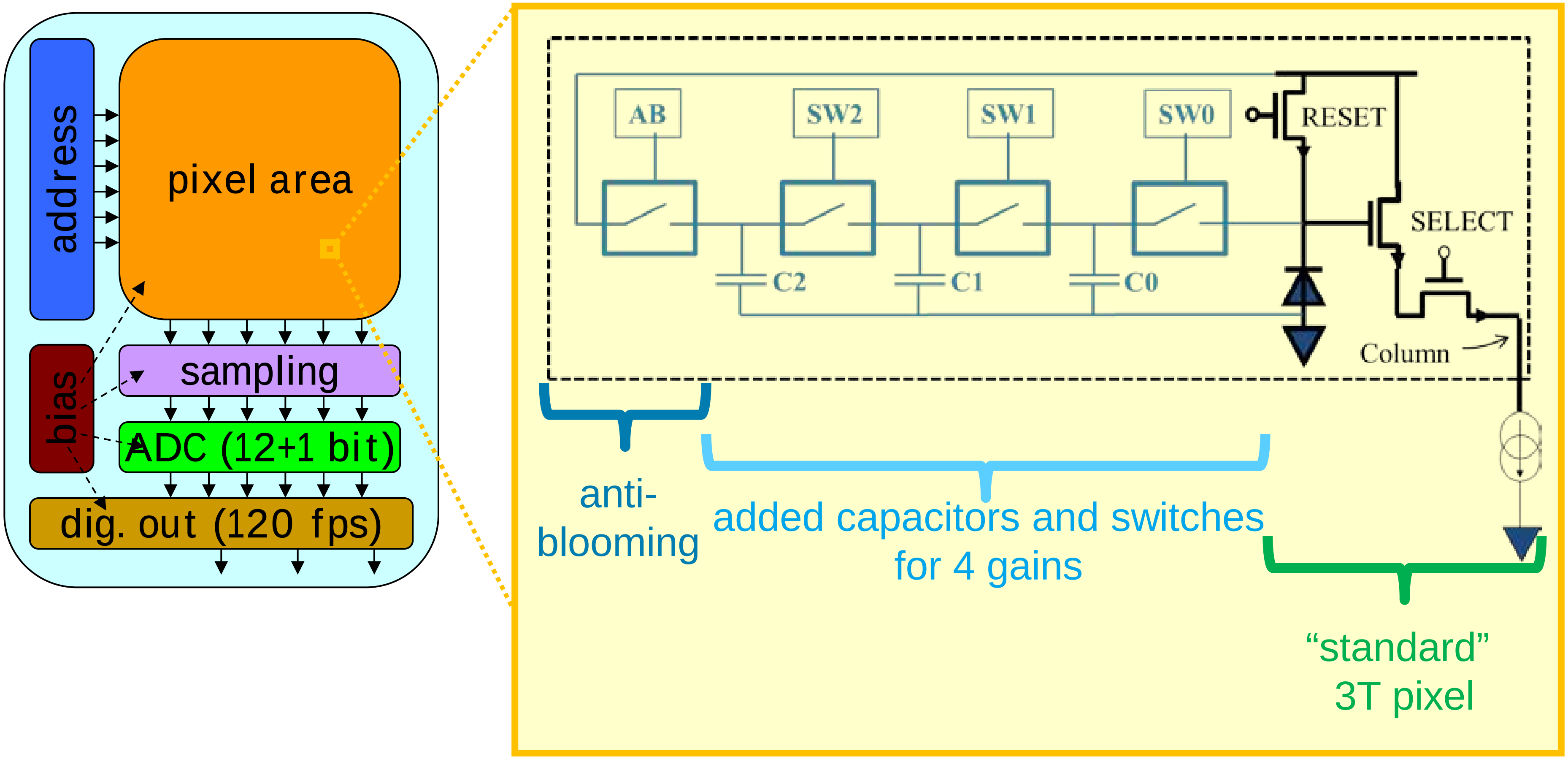
DESY

PERCIVAL in a nutshell

- Aim: develop X-ray imager for FELs' and Storage Rings
- **250eV-1keV, 2Mpixel & 13Mpixel, 27 micron pixels, 120Hz frame rate, 1-10^5 photons/pixel. Fully functional below 250 eV and above 1 keV.**
- Partners: DESY, RAL/STFC, Elettra, Diamond (DLS) & Pohang Light Source (PAL)
  - Sensor developed at RAL,
  - System developed DESY, Elettra, DLS and PAL
  - Only digital information coming off the chip
  - Readout development build upon / re-use XFEL and AGIPD developments
- Project timeline
  - TS1.2 to be tested this summer
  - First full 2M system 2016



Sensor


address
pixel area
bias
sampling
ADC (12+1 bit)
dig. out (120 fps)
AB
SW2
SW1
SW0
RESET
SELECT
C2
C1
C0
Column
anti-
blooming
added capacitors and switches
for 4 gains
“standard”
3T pixel

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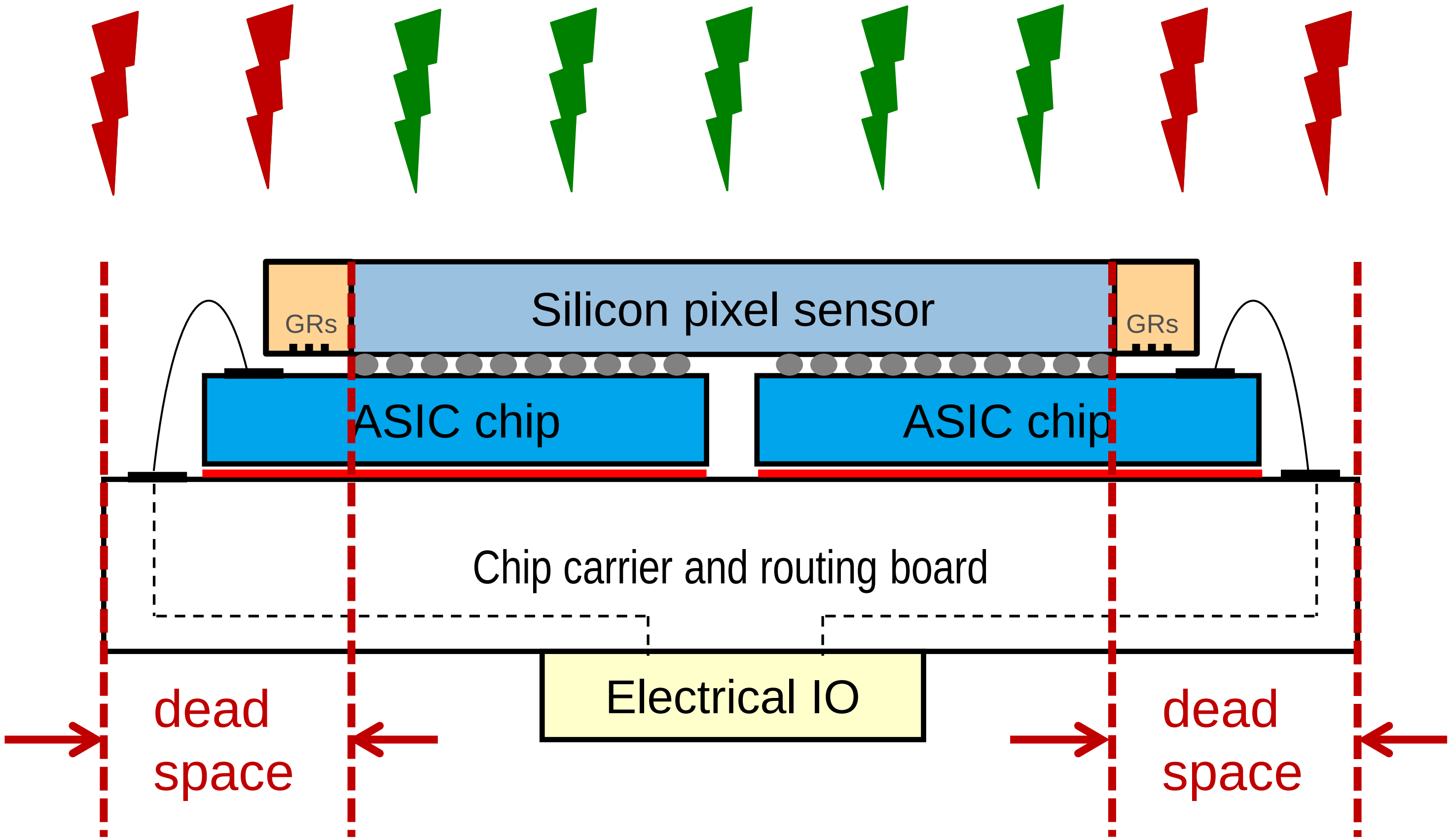
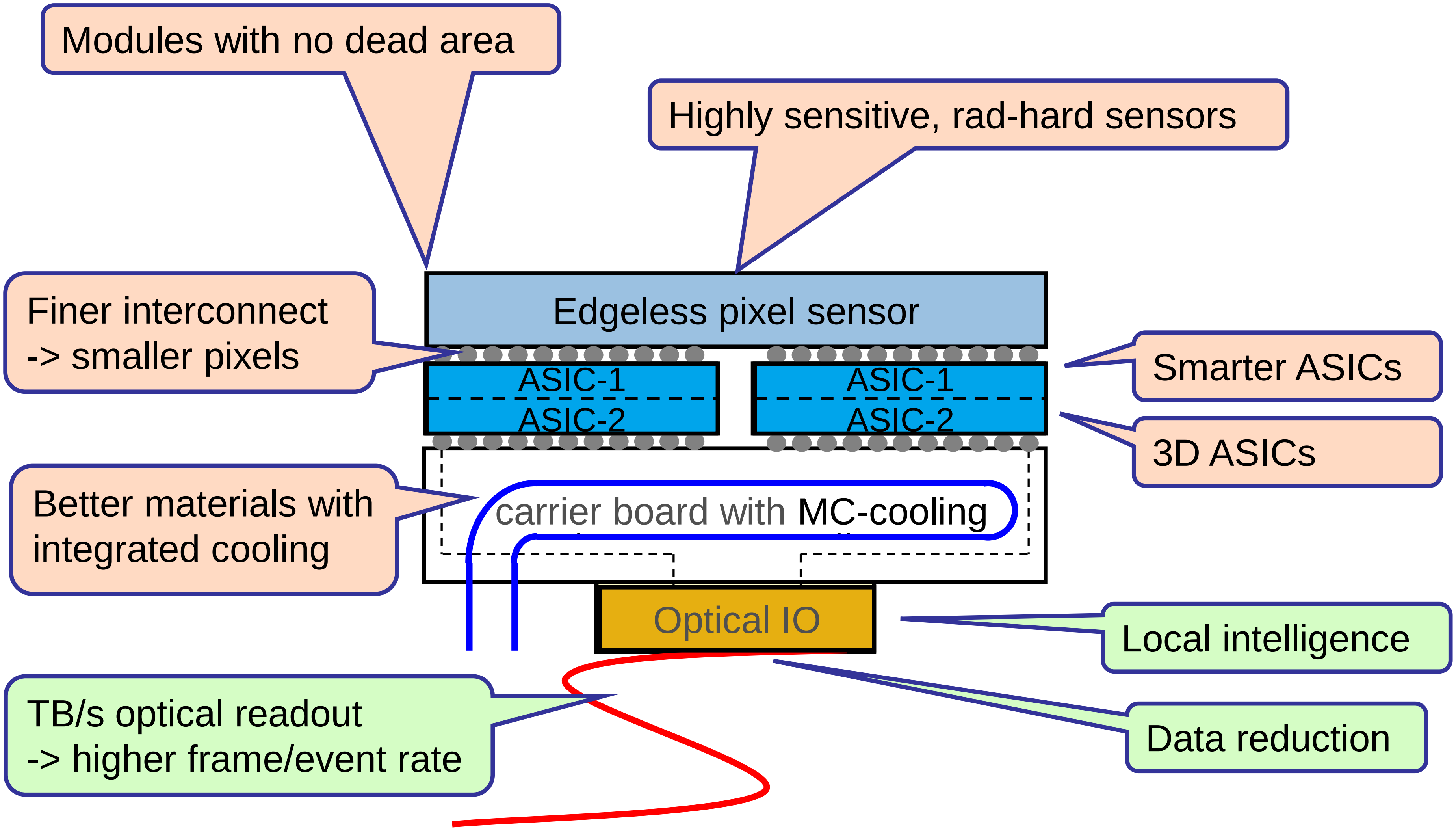
Hybrid pixel detectors for future experiments



Current hybrid pixel technology

Hybrid pixel detectors for future experiments

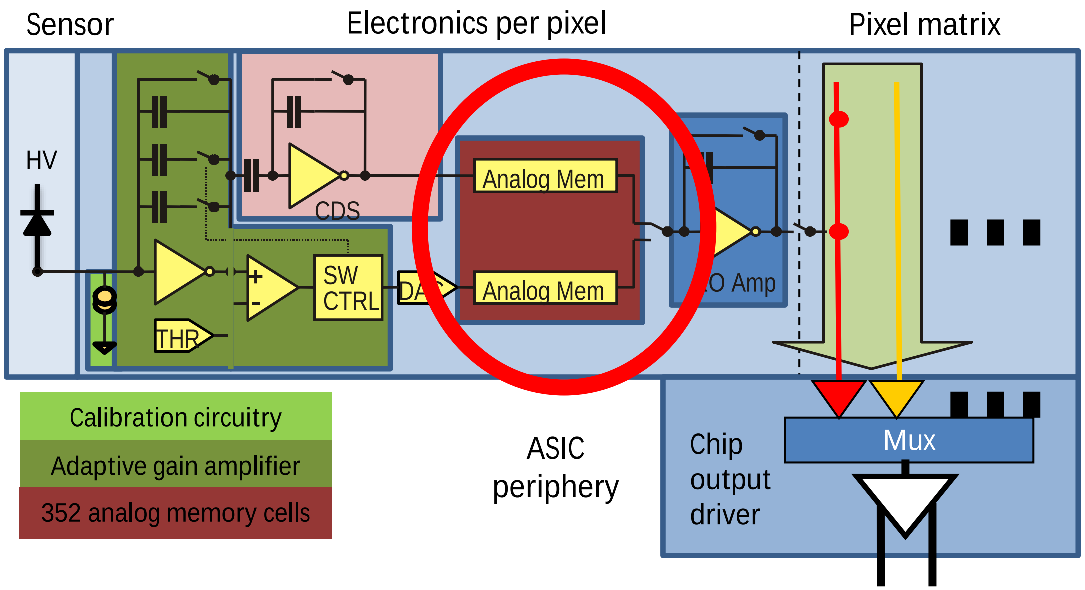


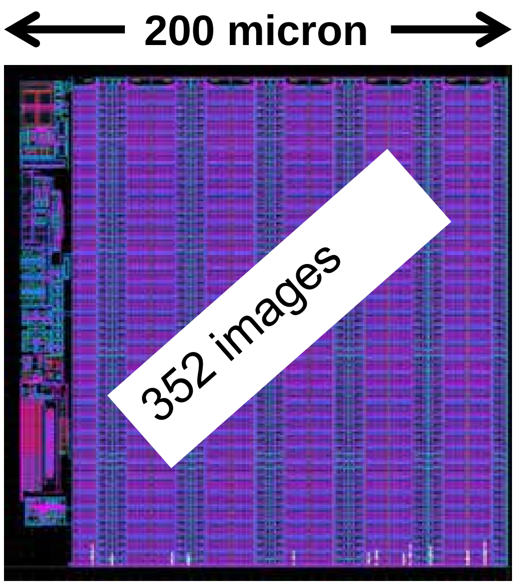
Future hybrid pixel technology

ASIC developments

- Profit from Moore's law: increased functionality per unit area
  - è smaller pixels or smarter pixels or both.
- Profit from increased radiation hardness for deep sub-micron CMOS

Example: Detectors for the European XFEL: 4.5 MHz, 2700 images, tens of MGy

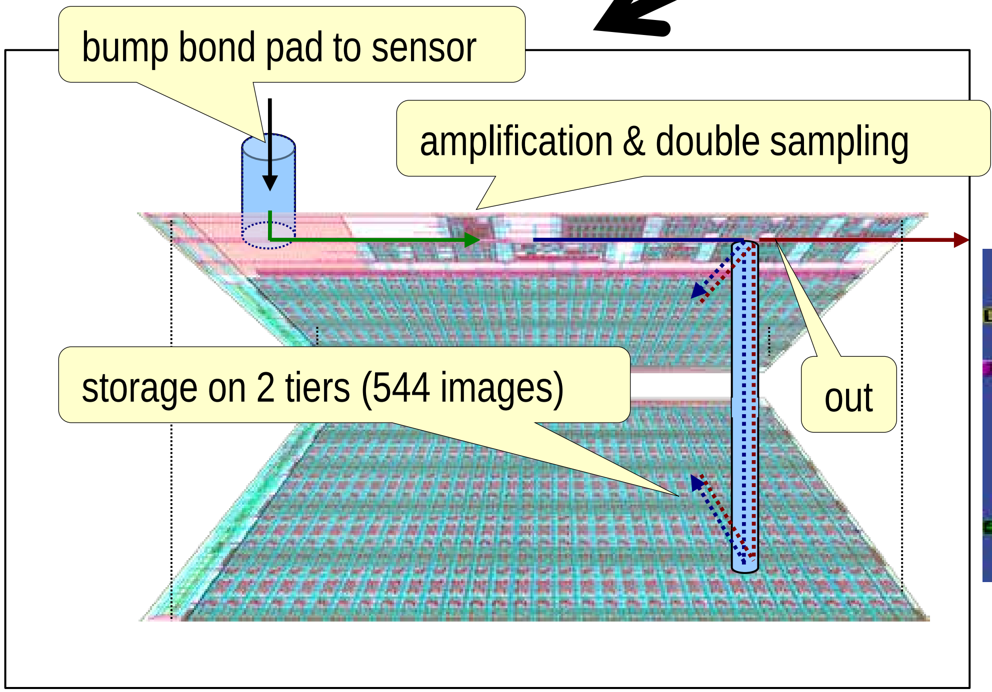




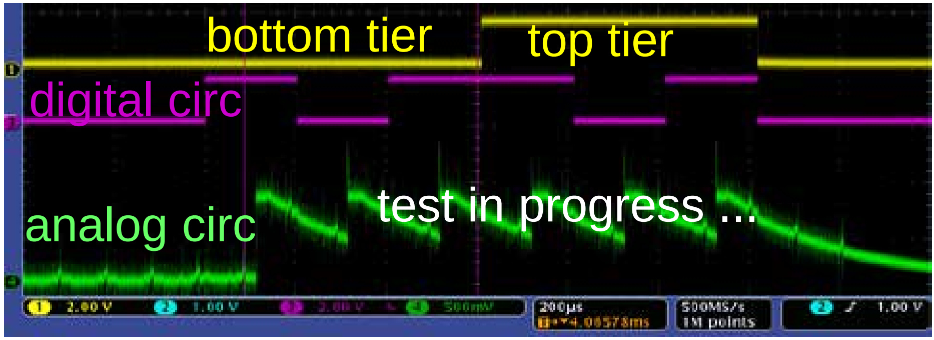
3D Evolution of the AGIPD ASIC

Scientific goal: most efficient Serial Femto-second Crystallography (SFX), Single Particle Imaging, etc

Technical goal: record as many images as possible during bunch train.
è Design a two-layer ASIC with more storage cells in second layer

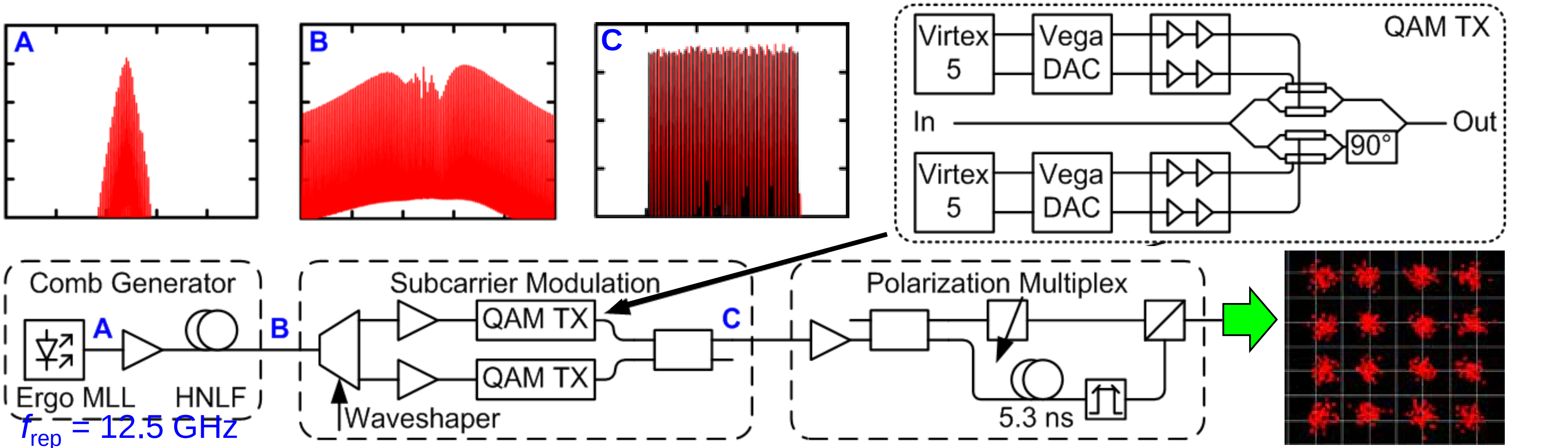


First results: achieved connectivity between two layers!!



Terabit communications: Proof-of-principle

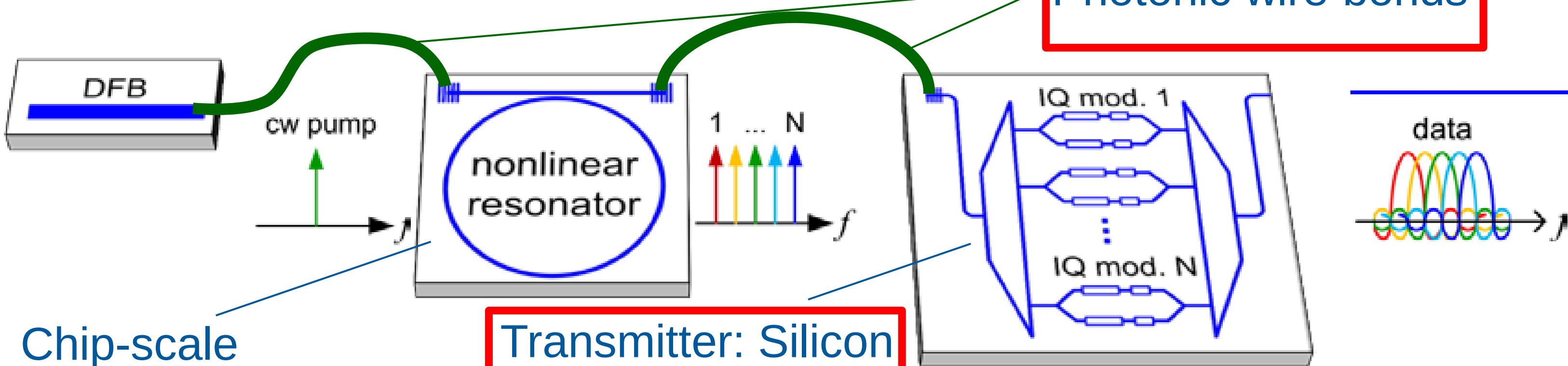
Frequency comb source: 325 channels, 12.5 GBd, 16 QAM, PolMUX => **32.5 Tbit/s**



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

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

Photonic wire bonds

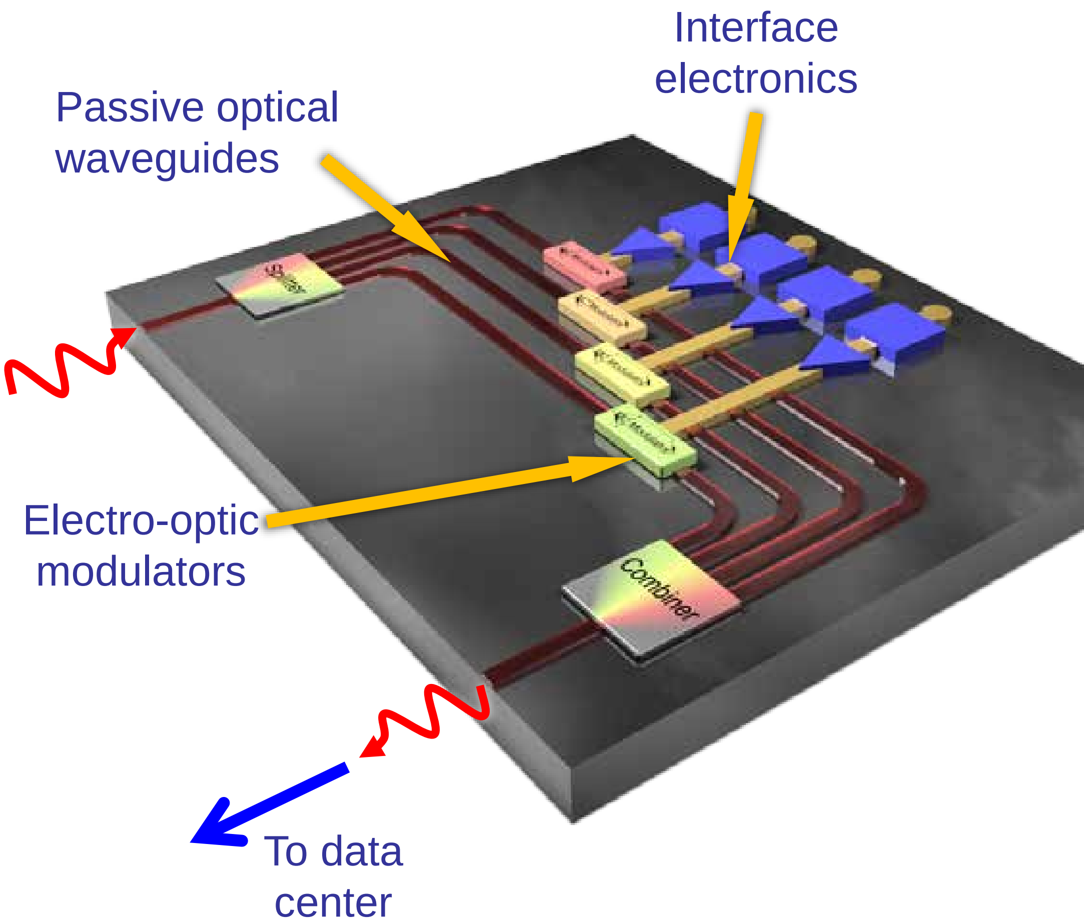


Chip-scale frequency comb sources

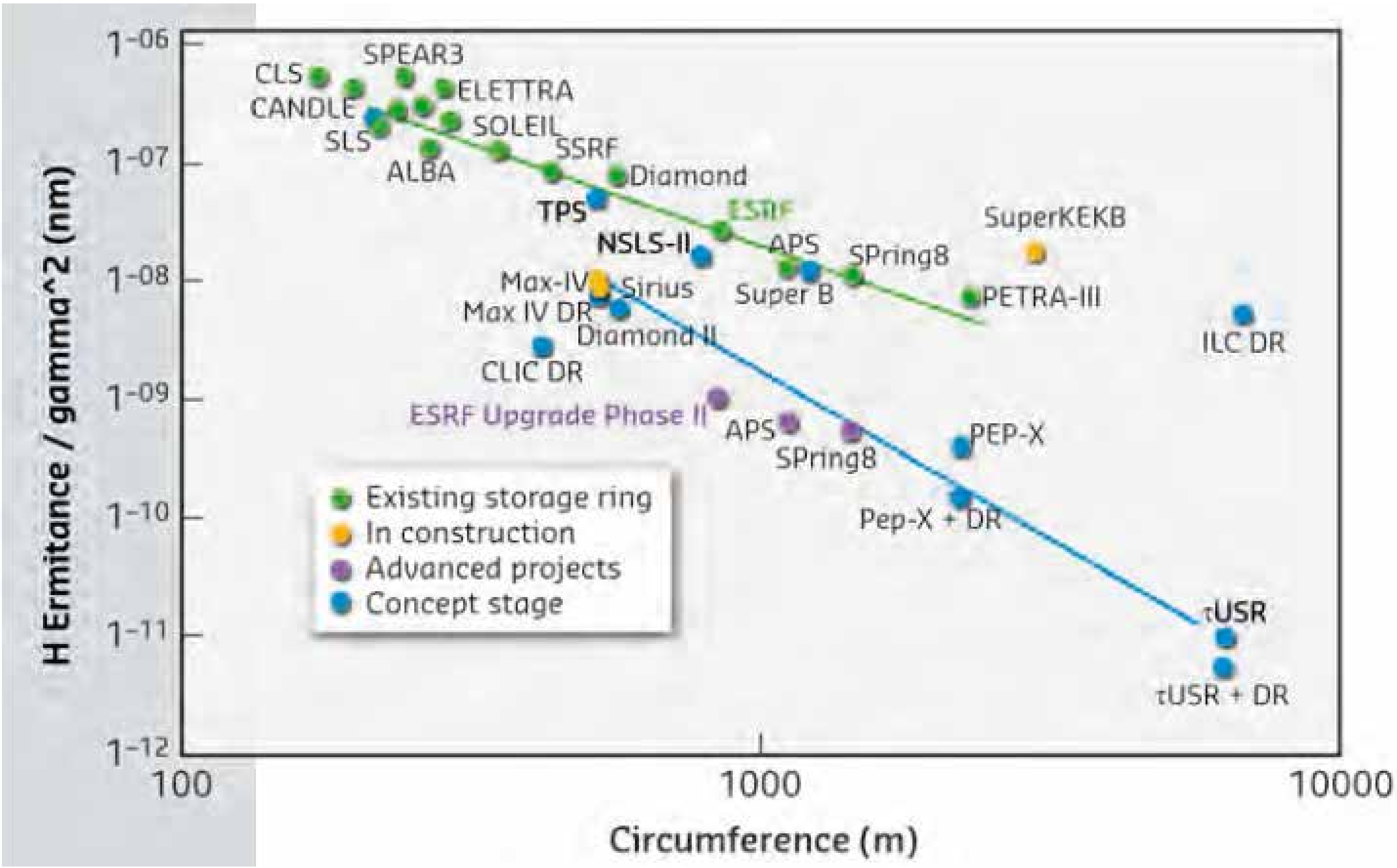
Transmitter: Silicon photonics and hybrid integration

The Vision: Terabit/s I/O 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



Diffraction limited storage rings



ESRF “orange book”; phase-II upgrade.

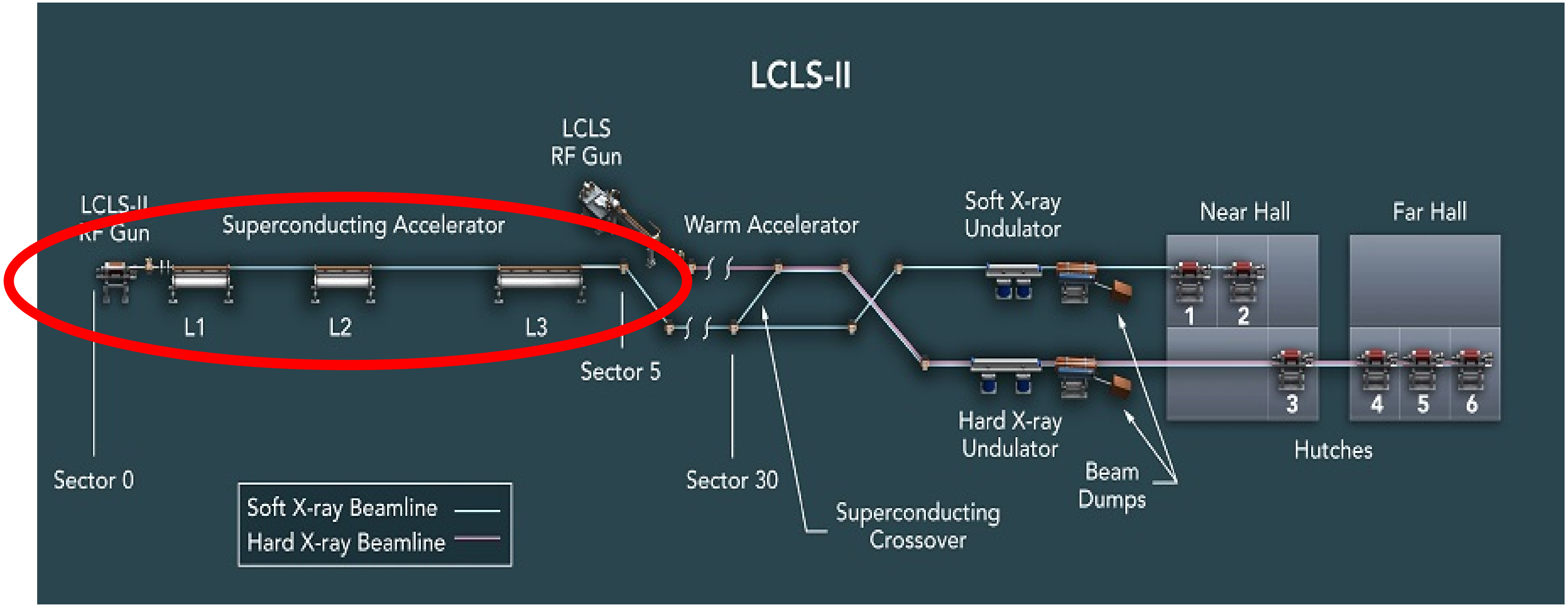
Diffraction limited storage rings (ESRF)

Lattic
Circu
Beam
Beam
Natur
Energ

	Lattice	RMS source size [µm]		RMS divergence [µrad]	
		H	V	H	V
10 keV	Present low beta	49.8	6.2	105.6	5.1
	Present high beta	411.6	6.2	11.5	5.1
	New lattice	**28.2**	**6.1**	**7.2**	**5.1**
50 keV	Present low beta	49.6	4.4	105.5	4.5
	Present high beta	411.6	4.4	11.2	4.5
	New lattice	**27.8**	**4.4**	**6.8**	**4.4**

Small AND parallel beam

LCLS-II: a CW X-ray Free Electron Laser



LCLS-II

The conceptual design:

- Adds a new, 4 GeV superconducting linac in an existing SLAC tunnel, avoiding the need for excavation.
- Increases the repetition rate from 120 pulses per second to 1 million per second. It will be the world's only X-ray free-electron laser capable of supplying a uniformly-spaced train of pulses with programmable repetition rate.
- Provides a tunable source of X-rays, by replacing the existing undulator (used to generate X-ray laser pulses) with two new ones. This ability to tune the X-ray energy on demand will enable scientists to scan across a wide spectrum – opening up new experimental techniques and making efficient use of the valuable beam time.
- Provides access to an intermediate X-ray energy range that is currently inaccessible with LCLS, but which is likely critical for studies of new materials, chemical catalysis and biology.
- Extends the operating range of the facility from its current limit of ~11 keV x-rays to ~25 keV.
- Supports the latest seeding technologies to provide fully coherent X-rays (at the spatial diffraction limit and at the temporal transform limit)
- Maintains the existing copper-based warm linac and upgrades parts of the existing research infrastructure to take advantage of the new configuration

Summary

- New detectors have and will enable new photon-science
- Dedicated detector developments are needed to profit from source developments
- Detector developments for photon-science are at the forefront
- The next 5 years will see a continued development detectors at photon sources
- The new photon sources will require new detector concepts

- The End -