X-ray Detectors for Storage Rings

Data Acquisition Issues and Challenges

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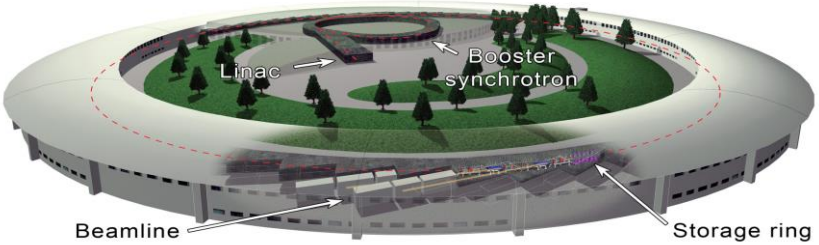


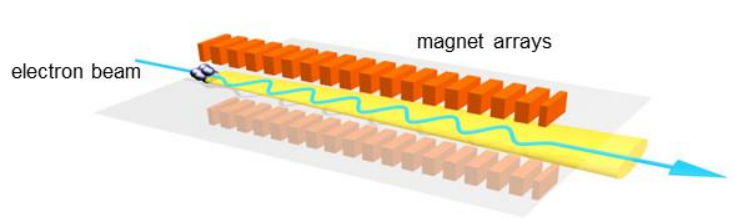
ESRF | The European Synchrotron

OUTLINE

- About storage rings and X-ray detectors
  - Characteristics of storage rings
  - Requirements for 2D detectors
  - Development live cycles and technology limitations
- Data acquisition at storage rings
  - Experiments requiring high data throughput
  - Fundamental limits
  - Wishes for future DAQ systems

SYNCHROTRON RADIATION FACILITIES

Relativistic charged particles in high magnetic fields



FACILITIES

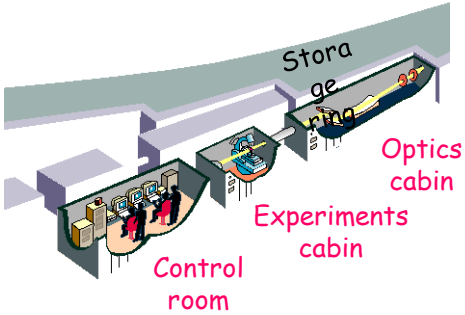
FREE-ELECTRON LASERS (LINACs)

- *Pulsed sources*
- *Extreme peak brilliance*
- *Femtosecond resolution*
- *Fully coherent radiation*

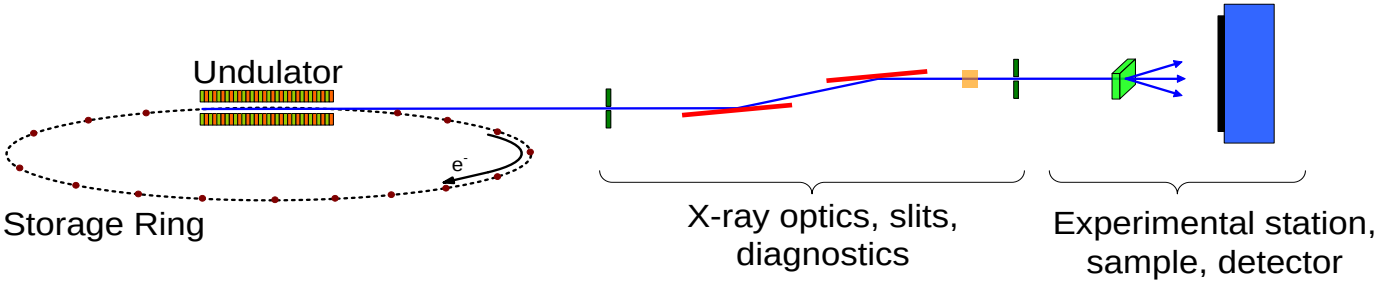
STORAGE RINGS (Synchrotrons)

- *Quasi-CW sources*
- *High average brilliance*
- *Wide and flexible energy range*
- *Very high beam stability*
- *High experimental capacity*

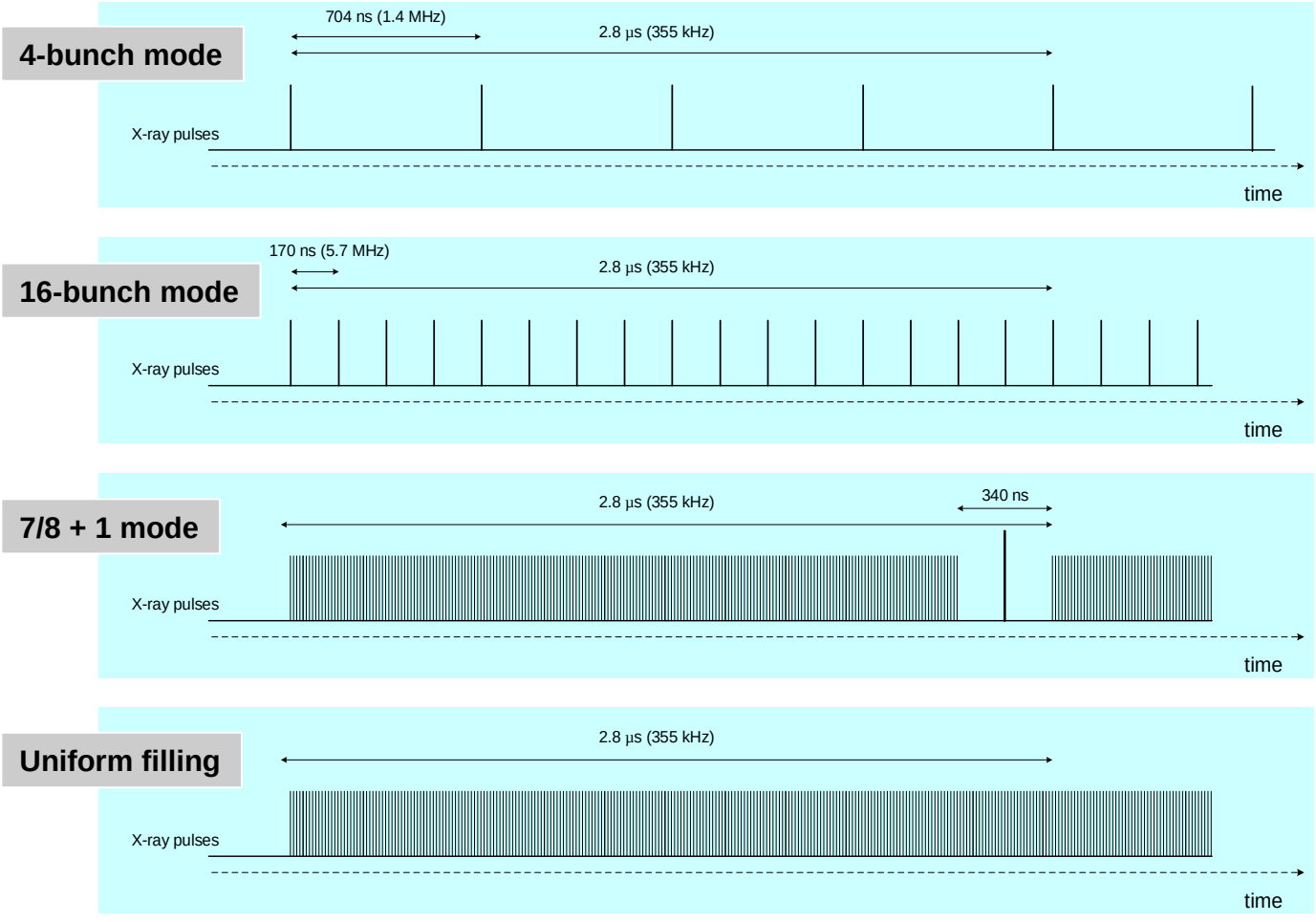
SYNCHROTRON RADIATION BEAMLINES



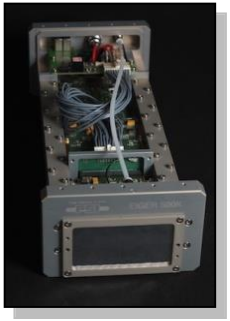
Simultaneous operation of all beamlines

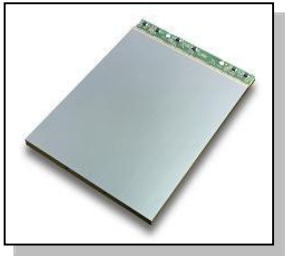


EXAMPLES OF TIME/FILLING PATTERNS (ESRF)



EXAMPLES OF 2D DETECTORS





X-RAY CONVERSION PROCESS/SENSORS

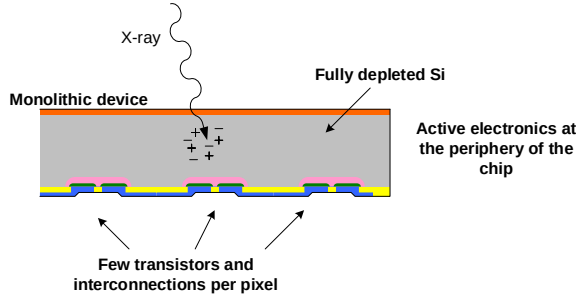
***Types of conversion sensors in X-ray detectors*:**

semiconductors	X-rays → electron-hole pairs
scintillators	X-rays → visible light + light sensor
photocathodes	X-rays → photoelectrons
gas	X-rays → ions
microbolometers	X-rays → phonons + precision thermometer (TES, MMC)
superconductors	X-rays → charged quasiparticles (STJ)

2D DIRECT DETECTION (SEMICONDUCTORS)

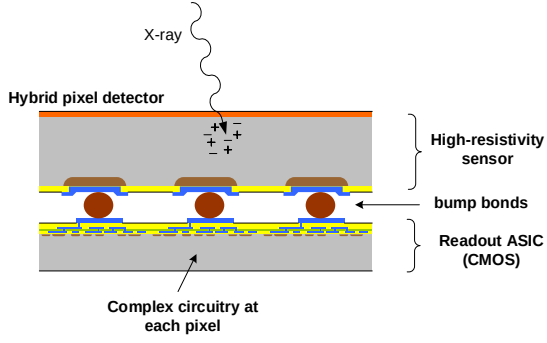
Monolithic devices (CCD, CMOS)

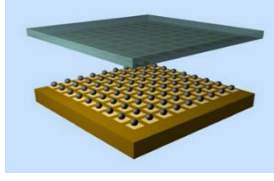
- Combine in the same device the detection volume and the readout structures (silicon only)
- Few active devices per pixel (transistors, gates, …)
- Signal is “transferred” towards the readout electronics at the periphery of the chip



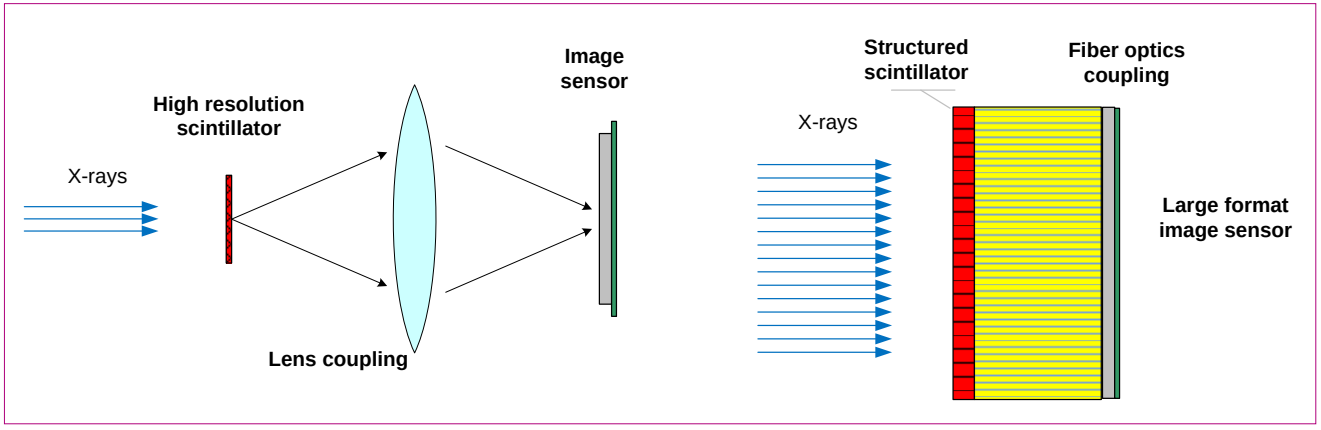
Hybrid pixel detectors

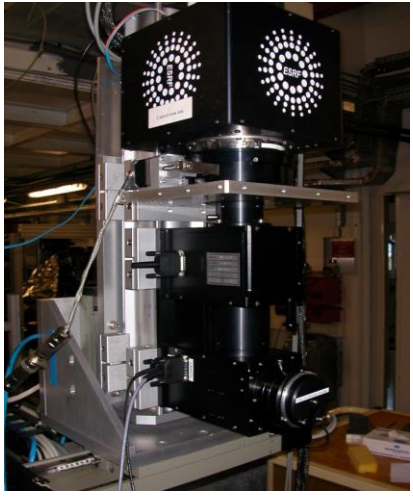
- A pixellated Si sensor “bump-bonded” to a readout chip
- A complete/complex readout channel per pixel
- Parallel transfer of information from the sensor to the readout chip, but then the data, analog or digital, has to be transferred to the periphery of the readout chip.

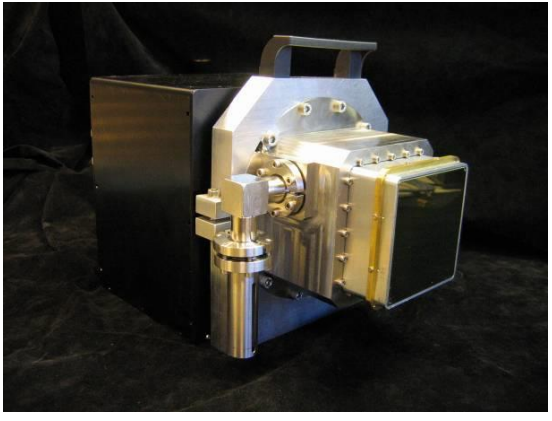




INDIRECT DETECTION (SCINTILLATORS)

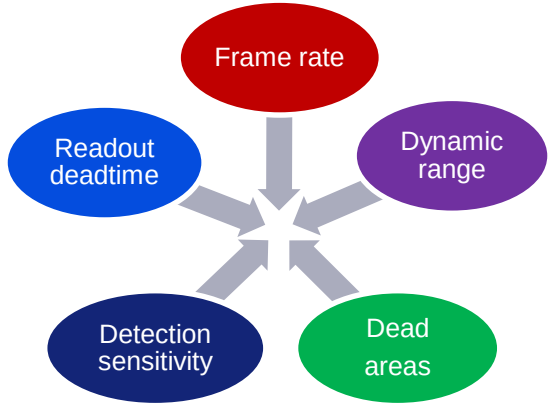






ABOUT DETECTOR REQUIREMENTS

Selecting detector requirements for a given application is always a tricky compromise



"HARD" REQUIREMENTS → **RESOLUTION**
(time, spatial, intensity,..)

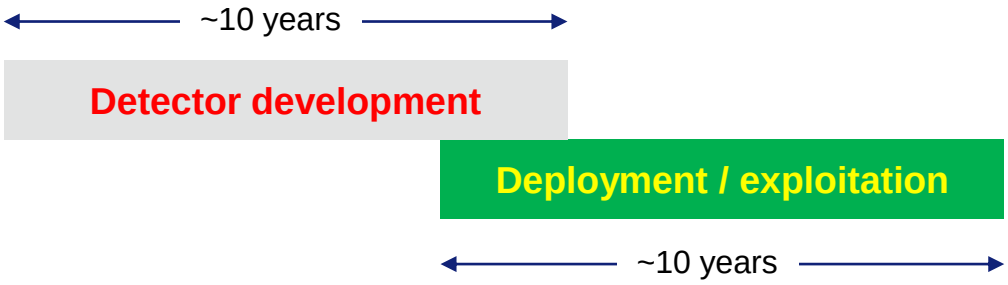
"SOFT" REQUIREMENTS → **EFFICIENCY**
(QE, active area, duty cycle, deadtime ,...)

DETECTION EFFICIENCY IN SYNCROTRON EXPERIMENTS

Data collection efficiency is crucial to shorten the experiments:

- High cost of beamtime (true for any large facility)
- Detector efficiency may open the door to shorter time scales (study of dynamic processes). Often the number of photons is not the limit.
- Radiation damage limits the duration of the experiments
  - Samples may receive dose rates of ~Grad/sec with focused beams
  - Detectors suffer also high irradiation doses
- Long experiments may be impossible due to beam or sample drifts.

LONG DETECTOR DEVELOPMENT LIVE CYCLES



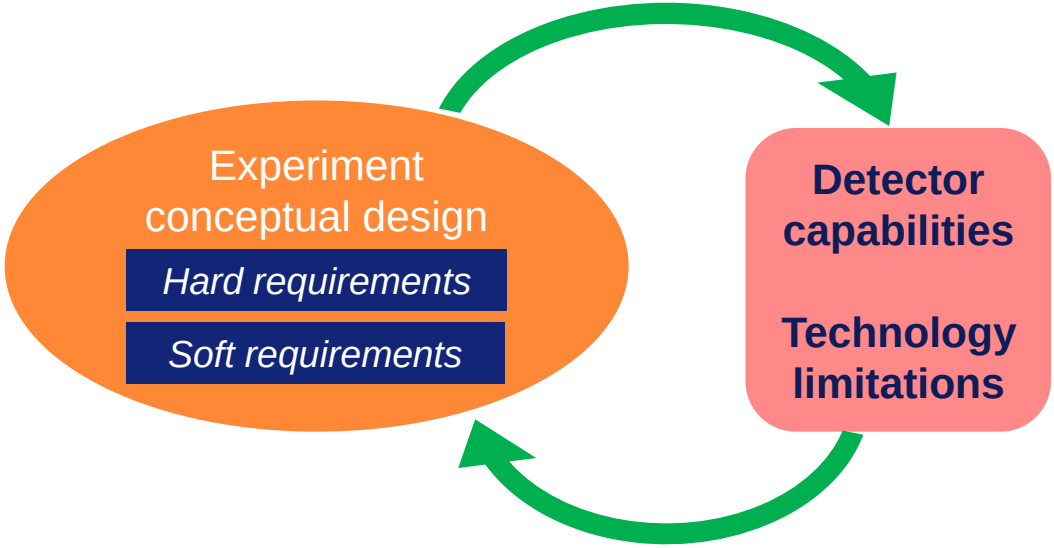
Development times are very long

Many applications are identified during of after detector development

And even well established applications are often ‘moving’ targets

TECHNOLOGY LIMITATIONS

New experiments have to be unavoidably adapted to the expected capabilities of the instrumentation (including the detectors)



TYPES OF EXPERIMENTS REQUIRING HIGH DATA THROUGHPUT

Techniques requiring 2D detection and fast sample scanning

- High resolution raster scanning (diffraction imaging, ptychography, …)
- Sample rotation (tomography, single crystal diffraction, …)
- Fast sample replacement (serial crystallography)

Time resolved experiments:

- The experiment aims at following a fast process in the sample
- Particularly demanding if the process is irreversible

TIME RESOLVED EXPERIMENTS

How to achieve a required sampling time and rate

A. If the detector does not reach the required time resolution:

- The only option is to use the time structure of the X-ray beam (source, choppers, fast shutters)
- Cannot investigate irreversible process in the same sample

B. If the detector can only discriminate single samples but not follow the sampling rate:

- Use fast gating and repeat the measurement with variable delay
- Cannot investigate irreversible process in the same sample

C. The detector can follow the full process (and store the data):

- Only at the pixel level (usually up to few hundred samples maximum)
- At the detector head (internal memory buffers up to few GB)
- Or at the backend (~1TB RAM disks)

TIME RESOLVED EXPERIMENTS

Examples of fast scientific CMOS cameras used for indirect detection

‘In pixel’ (burst) storage : SHIMADZU HPV-X2

- image: 400×250 pixels
- frames / rate: 128 frames @ 5 Mfps
- Readout: GbE

http://www.shimadzu.com

‘In-camera’ buffering: pco.dimax HS1

- image: 1000×1000 pixels
- frames / rate: ~50 kframes @ 7 kfps
- Readout: USB 3.0, CameraLink

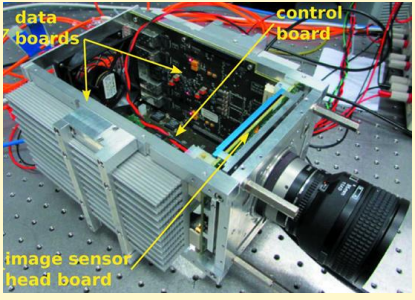
http://www.pco.de

Continuous data streaming: pco.edge CLHS

- image: 2048×2048 pixels
- frame rate: > 100 fps
- Readout: CameraLink HS (> 1 GB/s)

http://www.pco.de

GigaFRoST



pco.dimax front end (4 Mpixel)

Continuous readout:
7.7 GB/s (8×10GbE)

R. Mokso *et al.*
J. Synchrotron Rad. (2017). 24

MODULAR DETECTORS

X-ray imaging detectors are often based on a single sensor / chip

- small pixels
- optical coupling (indirect detection)
- gaps and dead areas are very detrimental

Diffraction/scattering detectors are better adapted to build modular systems

- large detection area
- more tolerant to dead zones / gaps
- modular construction favours/extends highly parallelised readout

Pilatus 6M

6 Mpixels
(60 modules)

Rayonix MX425-HS

90 Mpixels
(25 CCDs)

PSI/Eiger

2 Mpixels (4 modules)
~8 GByte/s (8 × 10GbE)

9 Mpixels (18 modules)
~35 GByte/s (36 × 10GbE)

MAXIMUM DATA THROUGHPUT: FUNDAMENTAL LIMITS

Is there a limit of a maximum 'sensible' frame rate ?

Increasing the frame rate reduces the exposure/integration time per image and the signal at the detector. The answer to the question above depends on how the useful information is actually encoded in the detector images.

The answer is:

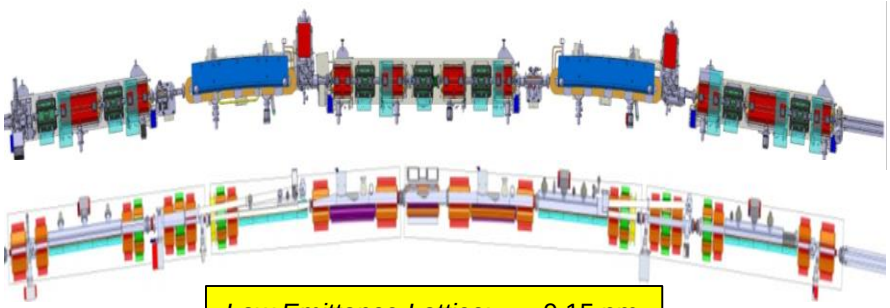
NO, for time-resolved experiments that look at reversible (stroboscopic experiments) or time invariant processes (e.g. XPCS) in which the information is encoded in time (the sampling rate) but the results extracted over longer periods can be averaged.

Note 1: the ultimate time resolution is limited by the accelerator bunch structure (~500MHz)
Note 2: At certain point it becomes be more efficient to operate the detector with sparse readout (timestamped X-ray detection events)

YES, for all other cases in which every frame must contain information that is statistically meaningful (X-ray photon statistics).
Running an experiment at frame rates at which the S/N of the extracted features are too low does not make any sense: → **One needs sufficiently high intensities**

TOWARDS DIFFRACTION LIMITED STORAGE RINGS

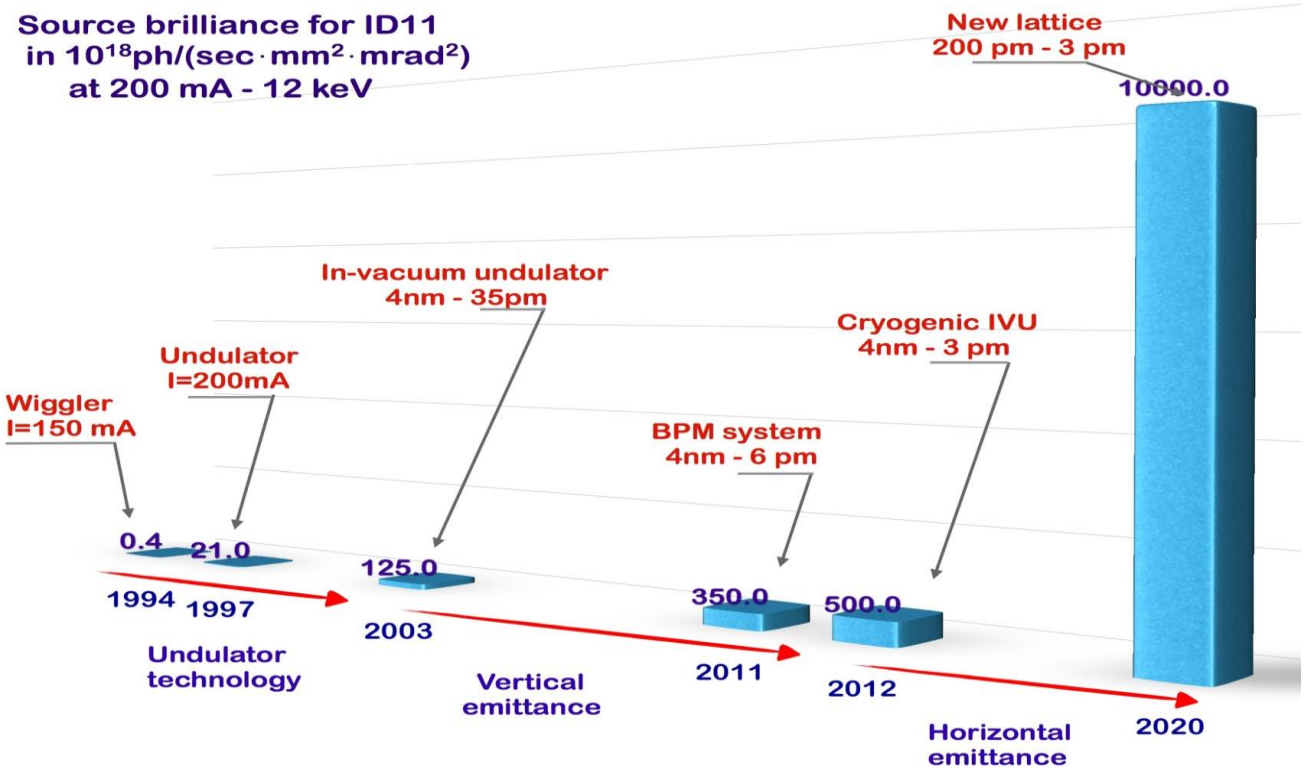
Present ESRF Lattice: ε_x= 4 nm



Low Emittance Lattice: ε_x= 0.15 nm

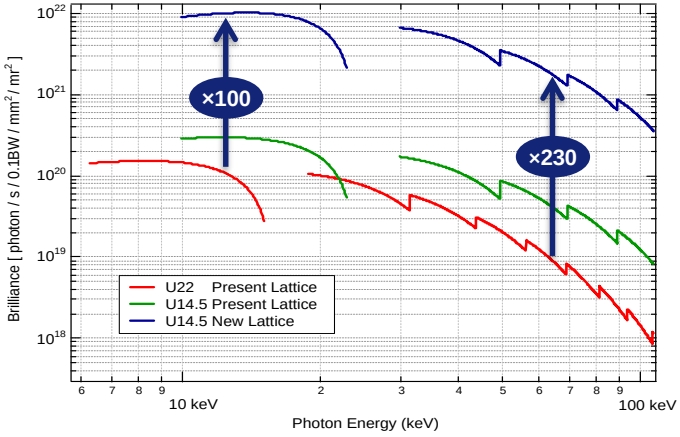
A new Storage Ring with reduced emittance → Higher photon beam brilliance → More “usable” X-ray photons at the sample

NEW STORAGE RING – A QUANTUM LEAP FOR NEW SCIENCE

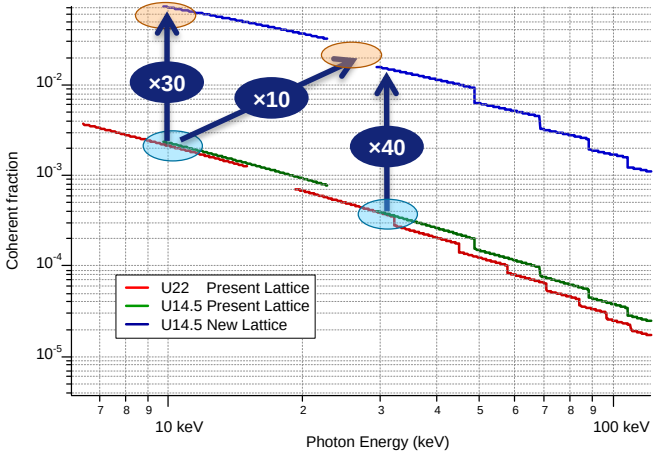


NEW DIFFRACTION LIMITED STORAGE RINGS

Brilliance



Coherent fraction



Detector Challenges

1. Improvement of efficiency for high energy X-rays

- ✓ The increase of brilliance will push many experimental techniques to higher energies:
  - *Reduction of sample radiation damage*
  - *Complex sample environments*
  - *Larger q-space*
  - *Access to buried structures and interfaces*

2. Higher photon fluxes and shorter exposure times

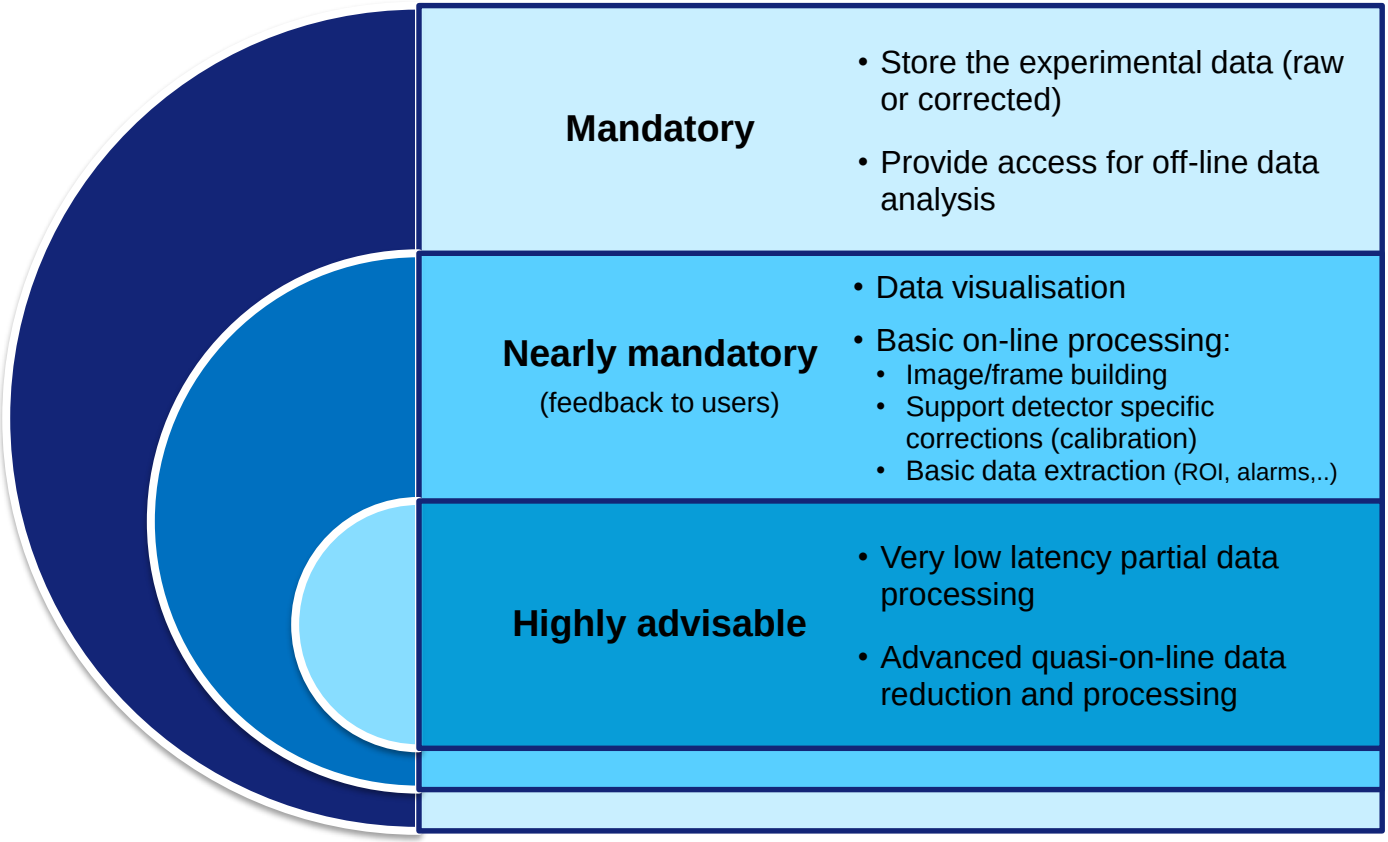
- ✓ Detectors will require extended dynamic range
- ✓ Photon counting detectors will be challenged by the higher fluxes
- ✓ Better photon statistics will make **shorter exposure times** and **higher frame rates** possible.

3. Combine high spatial resolution with single-photon sensitivity:

- ✓ Coherent scattering techniques will need higher detection angular resolution:
  - *The increase of transversal coherence length will allow to image bigger samples*
  - *Coherent diffraction techniques at high photon energy (~30keV) will become accessible*
- ✓ Practical implementation will require detectors with better spatial resolution

WHAT THE ACQUISITION SYSTEM SHOULD DO?

Main functional features of the DAQ system



A «WISH LIST» FOR FUTURE DAQ SCHEMES

If the perspective of detectors and DAQ schemes to be used and deployed in a large variety of cases:

- Continuous operation at the **full throughput** of the detector front-end (including storage?)
- Detector operation **synchronous with the orbit** clock
- Do **not compress** the data (at least before archiving)
- Be **scalable "downwards"** to be able to operate with simple back-ends when the applications do not need full performance
- Include a **substantial buffering** in the detector head to cope with lower performance backends
- **Separate detector specific corrections** (calibration) from application related data processing
- Integrate calibration **corrections on-line** and as early as possible in the chain, ideally in the detector head
- Support for **distributed on-line data processing**:
  - Implicit frame/image building/distribution
  - Very low latency (few ms) - partial data processing for experiment automation
  - Medium latency (~1s) - full data processing for:
    - Simple treatments for user feedback (ROIs, …)
    - Data reduction

THANK YOU!