Detectors for the future European XFEL

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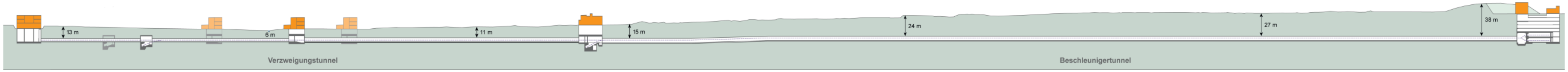
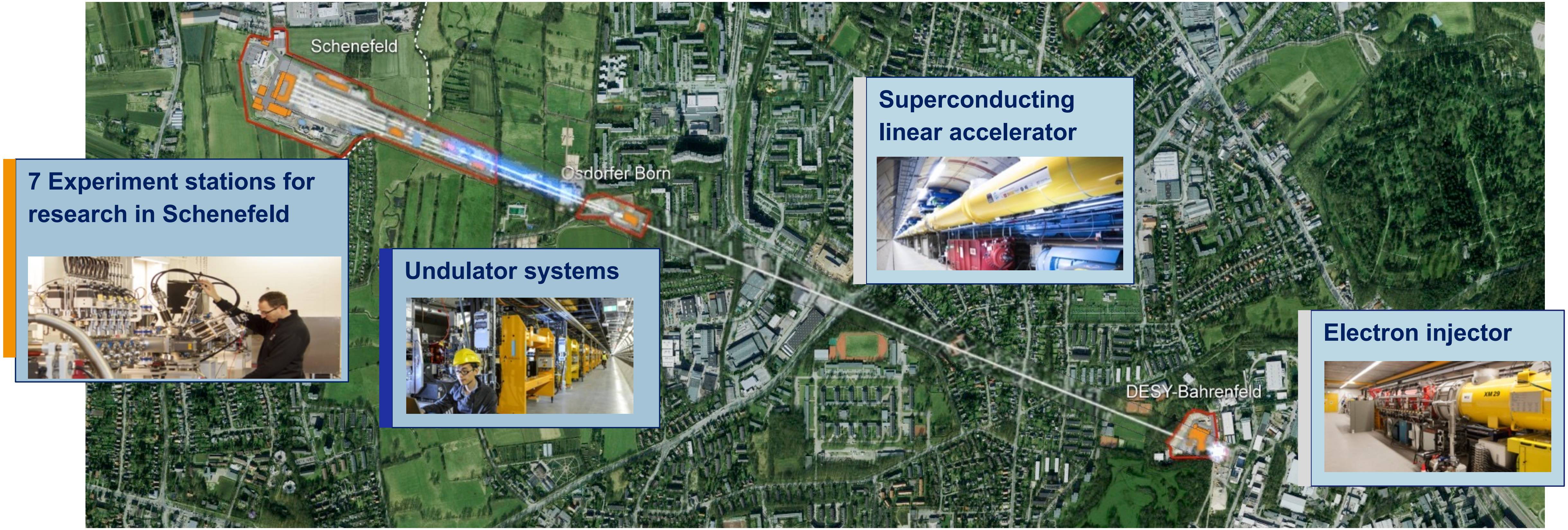
Outline

- The EuXFEL machine and its extraordinary features
  - The 1st generation detectors for the EuXFEL
- Present operation and lessons learnt
- Detector development at the EuXFEL
  - start and first steps

The European XFEL in Schenefeld, Germany

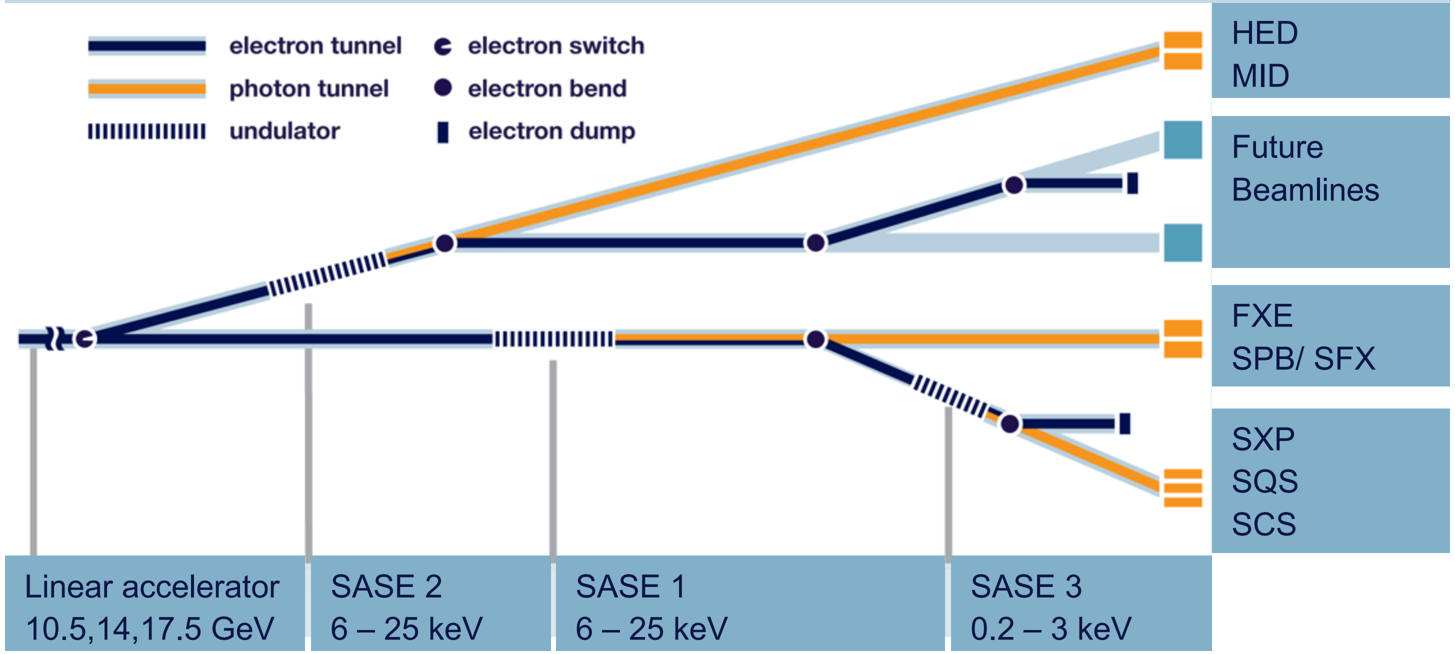


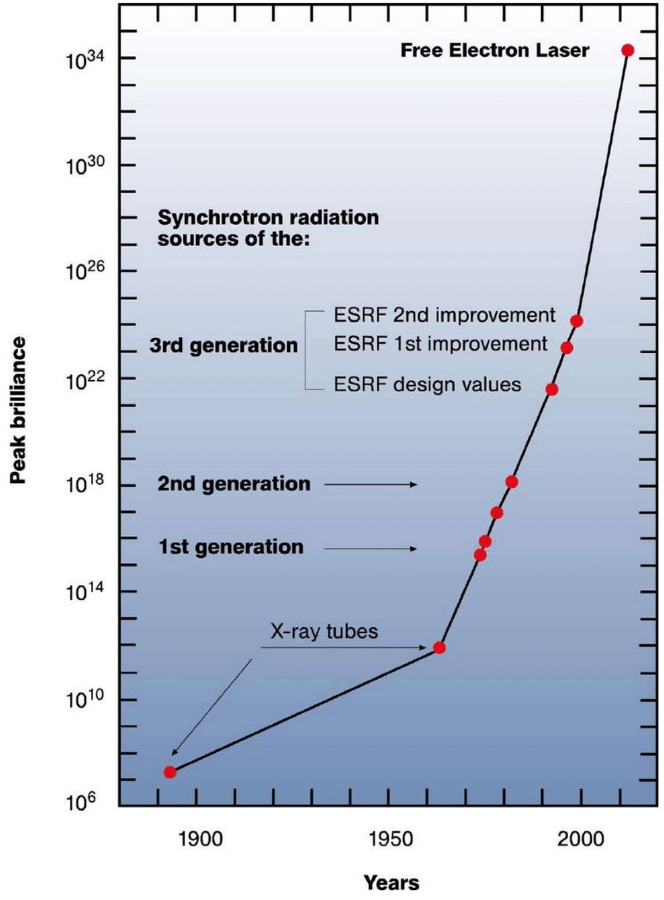
Total length: 3.4 km



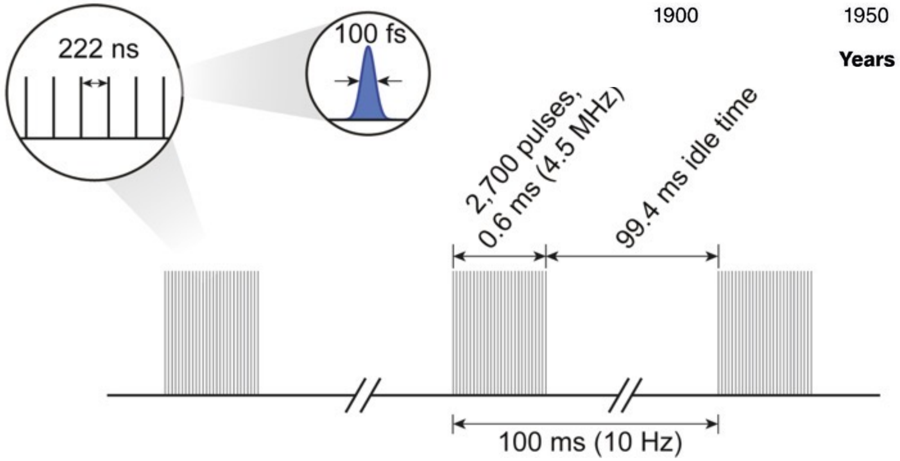
The European XFEL beamlines and instruments

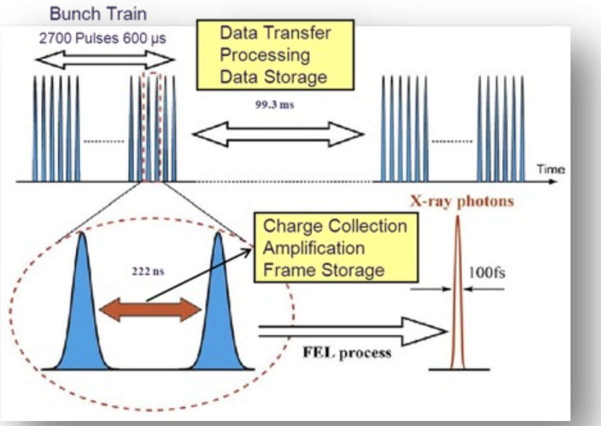
XFEL beam facility: 3 beamlines, 7 Instruments





The specific time structure of the EuXFEL challenges detector design!





What are the challenges for the detectors?

- The time structure of the machine is unique:
  - burst mode operation, with pulses arriving at max 4.5 MHz frame rate
  - 99.4 ms interval between the 0.6 ms bursts, 10 times per second
  - typical experiment rates 0.5-1.1-2.2 MHz
- High dynamic range: up to 10^4 photons / pixel / pulse, with the capability at the same time to detect also single photons
- Radiation resistance
- Large active area (at present, 20x20 to 50x50 cm^2) with relative small pixels (200 – 500 μm pixel pitch)
- Suitable for very different scientific applications

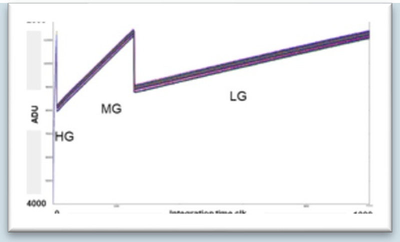
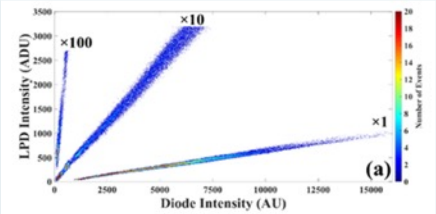
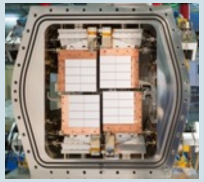
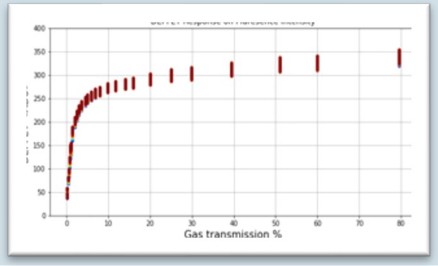
For the first generation detectors we went for a dedicated call for proposals.

External institutes / consortia developed the detectors in cooperation with EuXFEL, especially for integration and calibration

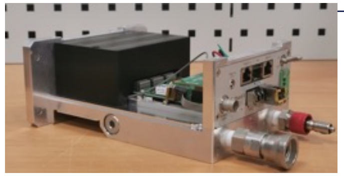
The first detector generation at the EuXFEL

For the first generation detectors we went for a dedicated call for proposals.

- Development time for the first detectors ca 2009-2023
  - AGIPD (SPB/SFX): 2017
  - LPD (FXE): 2017
  - AGIPD (MID): 2018
  - DSSC (SCS): 2019
  - DSSC DEPFET: 2023-24
- New AGIPD generation
  - AGIPD500k (HED): 2020
  - AGIPD4M (SFX): 2023-24
  - AGIPD1M (HED): 2023-24
- Three different projects adopting different solutions to solve the challenges
- Other detectors for specific applications or as backup

Detector	Specs	Gain Mechanism	Gain
AGIPD 	352 memory cells (analog) 200µm x 200µm sq. pixels 1-10^4 12 keV ph 3-20 keV Modular: 16 (1MPix) or 8 (0.5MPix) modules	3 gains with automatic switching	
LPD 	(3x)512 memory cells (analog) 500µm x 500µm sq. pixels 1-10^5 12 keV ph 7- 20 keV Modular: 16 (1MPix) modules	3 parallel gain stages with on front-end selection	
DSSC 	800 memory cells (digital) 204µm x 236µm hex. pixels N x 256 ph @ 4.5 Mhz N x 512 @ f≤2.2 MHz N ≤ 1 for single ph sensitivity 0.5 – 6 keV Modular: 16 (1MPix) modules	Linear response (miniSDD), non-linear signal compression in sensor (DEPFET)	

Gotthard-II



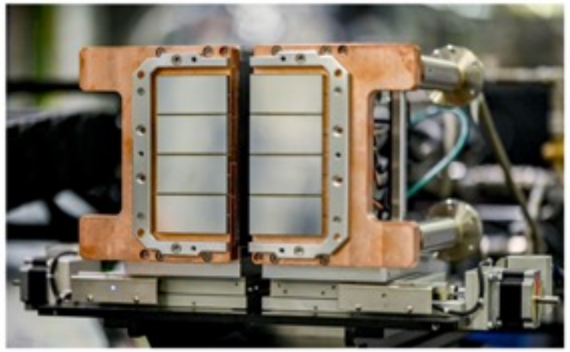
Detectors for EuXFEL

X-ray energy

Hard X-rays 6-25 keV

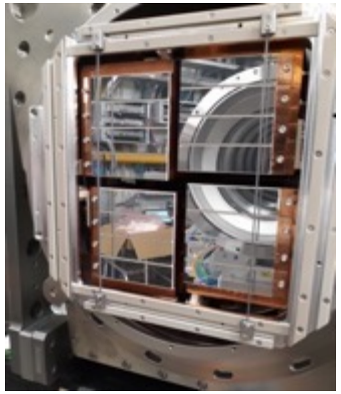
Noise: 50 e- (HG)
Dyn range: 100 8 keV ph

ePix100 (MID, HED)



Jungfrau x 18 (all hard X-ray inst.)
Noise: 80 e- (HG)
Dyn range: 10^4 12 keV ph

AGIPD (SPB/SFX, MID)



Noise: 350 e- (HG)
Dyn range: 10^4 12 keV ph

LPD (FXE)

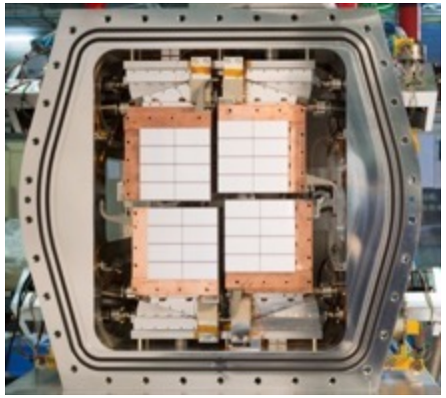
Noise: 2010 e- (HG)
Dyn range: 10^5 12 keV ph

pnCCD (SQS)

Noise: 3 e-
Dyn range: 1500-3000 1 keV ph

Soft X-rays 0.5-3 keV

DSSC (SCS, SQS)



Noise: 40/60 e-
Dyn range:
N x 256 ph @ 4.5 Mhz –
N x 512 @ f≤2.2 MHz
N ≤ 1 for single ph sens.

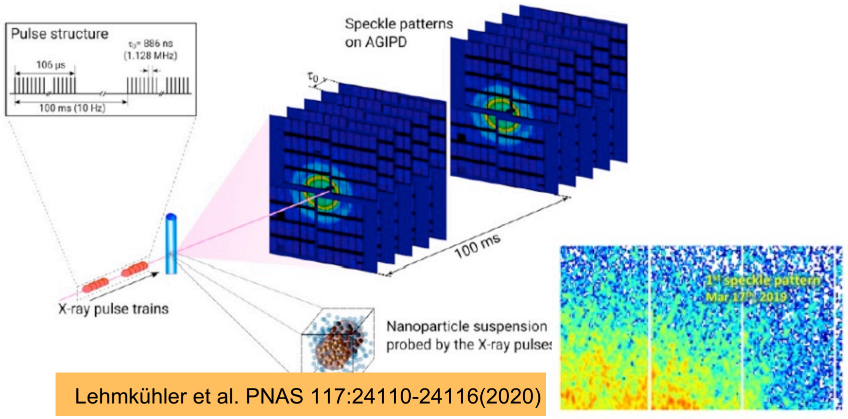
10 Hz

4.5 MHz

Rate

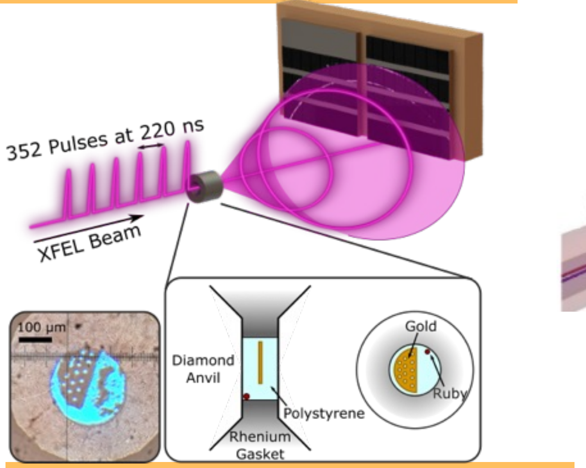
The European XFEL detectors are used to produce excellent scientific results

MHz XPCS to look at system dynamics

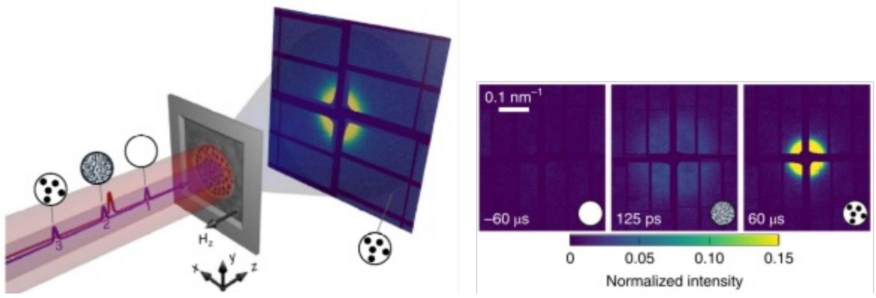


Lehmkühler et al. PNAS 117:24110-24116(2020)

Study of materials in extreme conditions

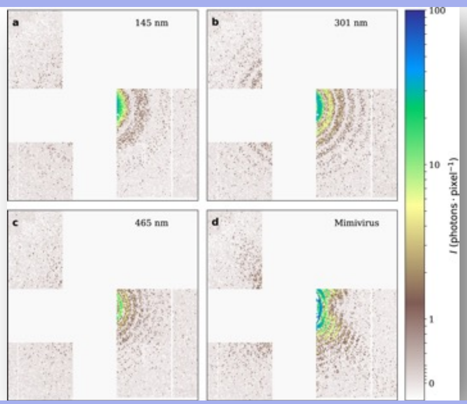


M. Frost et al., accepted by Nature Astronomy (2023)



F. Büttner et al., Nat. Mater., 20, 30-37 (2021)

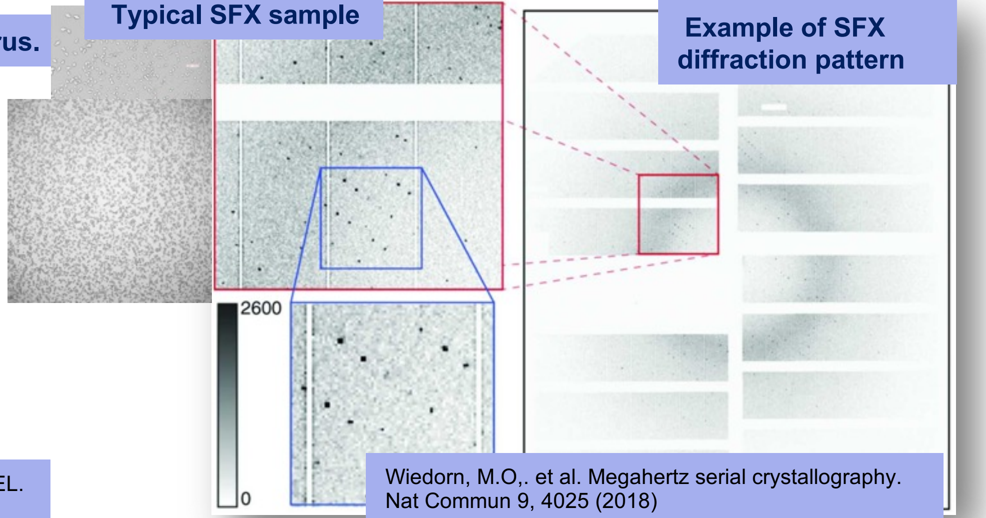
Examples of scattering patterns from IrCl3 and Mimivirus.



Sobolev, E. et al. Megahertz single-particle imaging at the European XFEL. Commun Phys 3, 97 (2020)

Typical SFX sample

Example of SFX diffraction pattern



Wiedorn, M.O,. et al. Megahertz serial crystallography. Nat Commun 9, 4025 (2018)

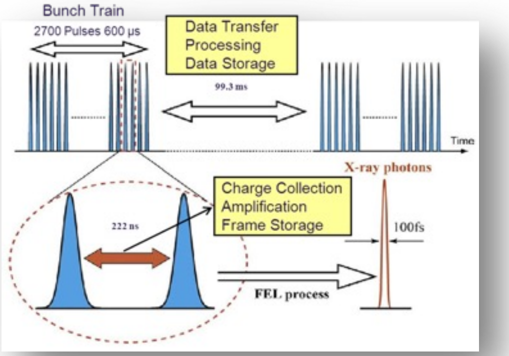
What happens next?

Where do we want to go next with EuXFEL detectors?

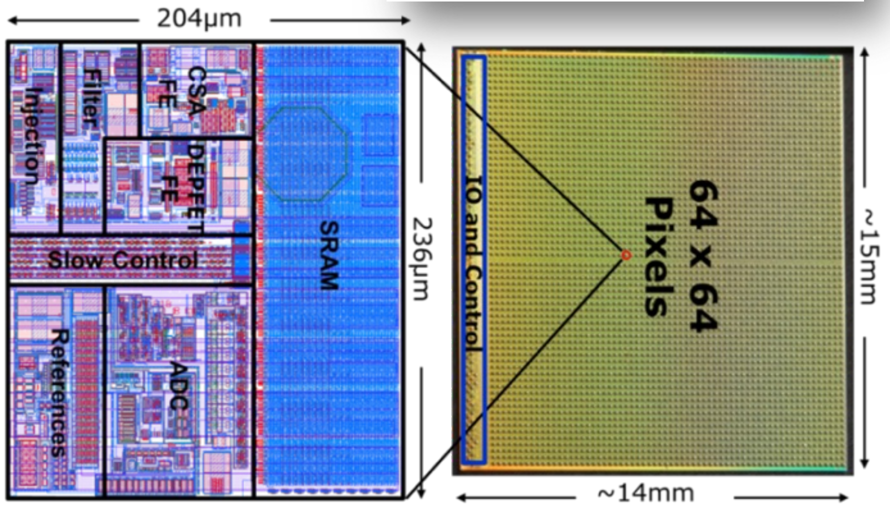
- The first generation detectors were excellent for the start of the EuXFEL program, but to keep EuXFEL as world leading facility and allow producing excellent science we need to provide new possibility also in terms of detectors

- The technology of the 1st detector generation is now old and difficult to reproduce or to update
  - Transferring the same concept and specs to another technology is long and expensive

- What are the main facility upgrades we are facing, and when will they take place?
  - ► **high energy (> 20 keV) operation already started**
  - ► SCU system for photon energies up and above 40 keV → **2028+**
  - ► change of pulse rate, at present under discussion → **not before 2035**



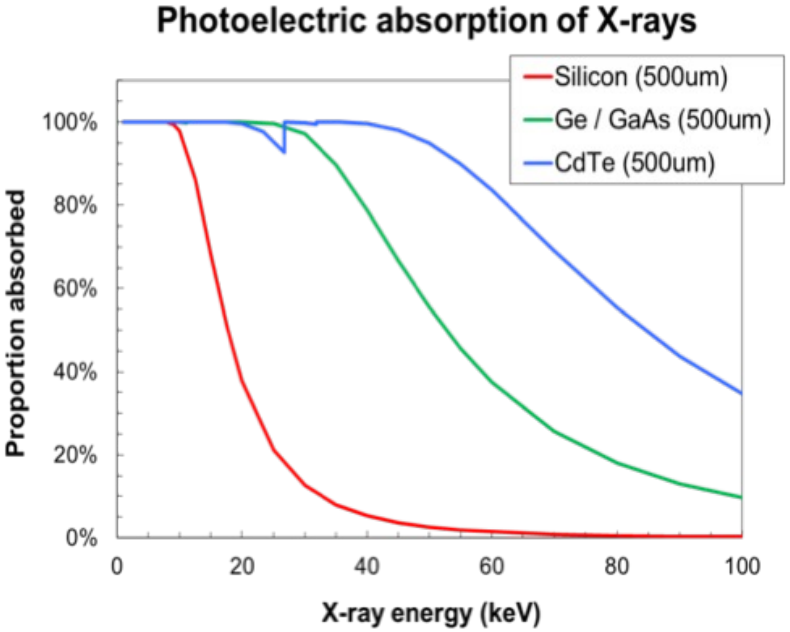
- Which are the main upgrades the instruments are asking for?
  - Main request from **all** instruments, since 2017:
    - ► **smaller pixels, ~100 μm pitch**
  - Present detectors have 200-500 μm pixel pitch
    - ► major upgrade needed, floor space already small
    - ► memory dominates the space consumption in the pixel

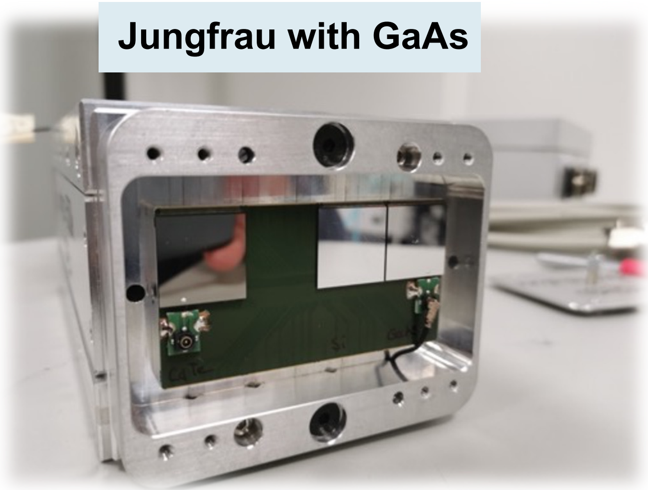


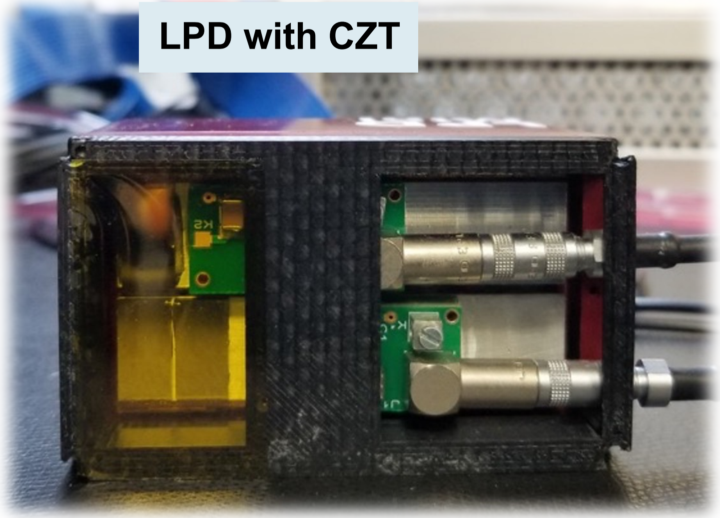
DSSC pixel and ASIC

Running the EuXFEL with harder X-rays: now!

- The recent week in which the machine provided 23 keV photons made very clear the limitations of silicon:
  - only ca 20% of the radiation is absorbed by the sensor
  - electronics damage on the ASIC becomes likely
    - ► need materials able to absorbe these photons: GaAs, Cd(Zn)Te
    - ► the worldwide community is looking for a solution to this problem
    - ► EuXFEL to provide beam and joining sensor qualification activities







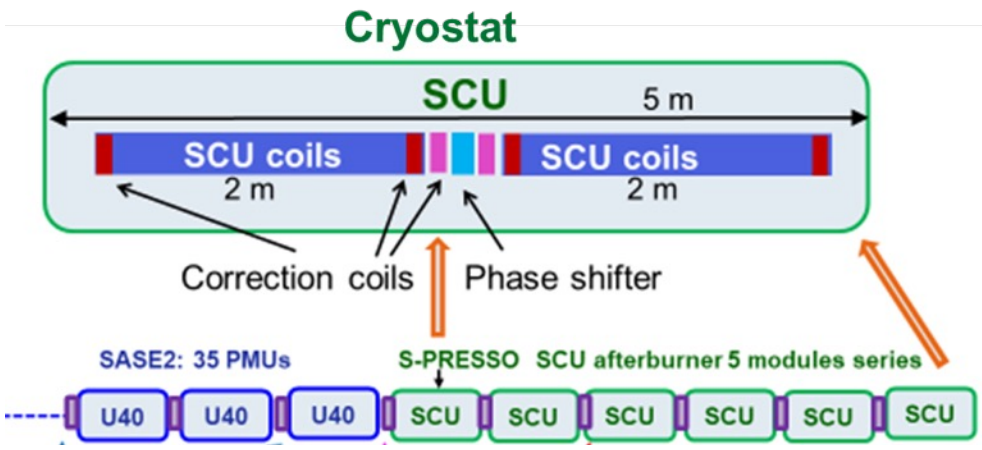
EuXFEL is joining the community of scientists active in this topic

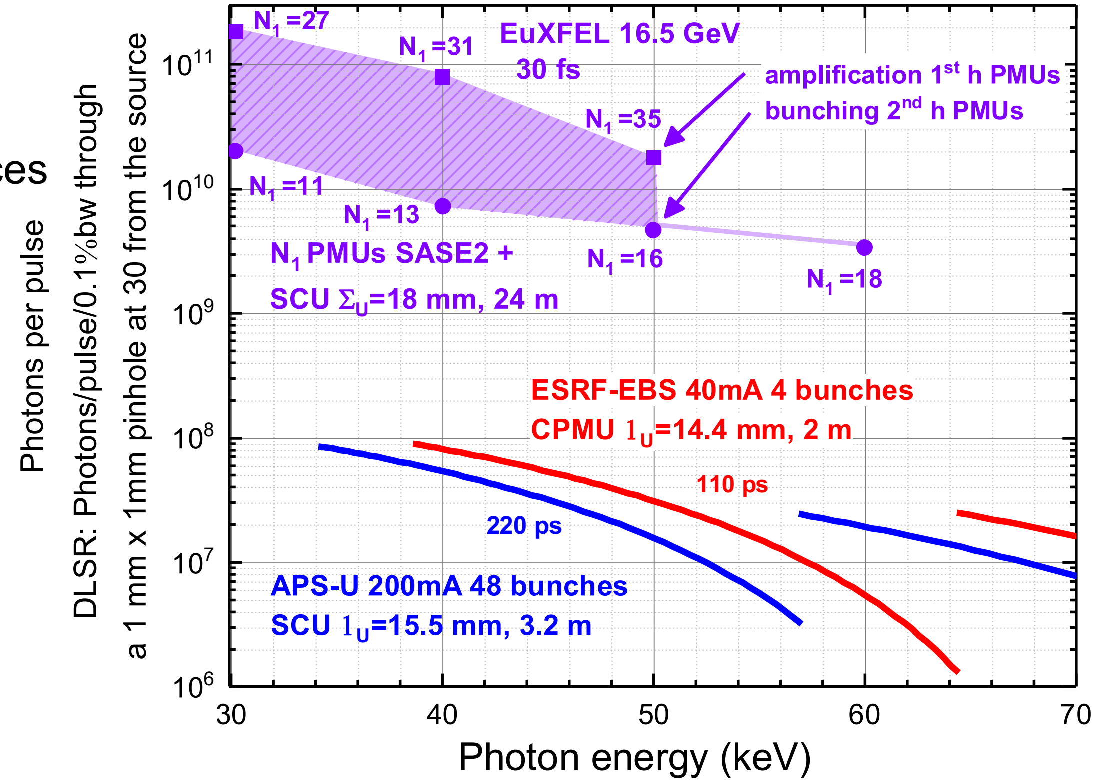
Facility developments: SCU system, 2028+

- Electron beam energy > 16.5 GeV
- Estimated range of photons per pulse achievable by tuning the SCU afterburner to amplify
  - the output of the fundamental of the PMUs
  - the bunching of the second harmonic of the PMUs
- Peak flux ~100 x higher than HE diffraction-limited SR sources
- Large dynamic range detectors needed!

Normalized emittance	0.4 mm mrad
Initial energy spread	3 MeV
Current	5 kA

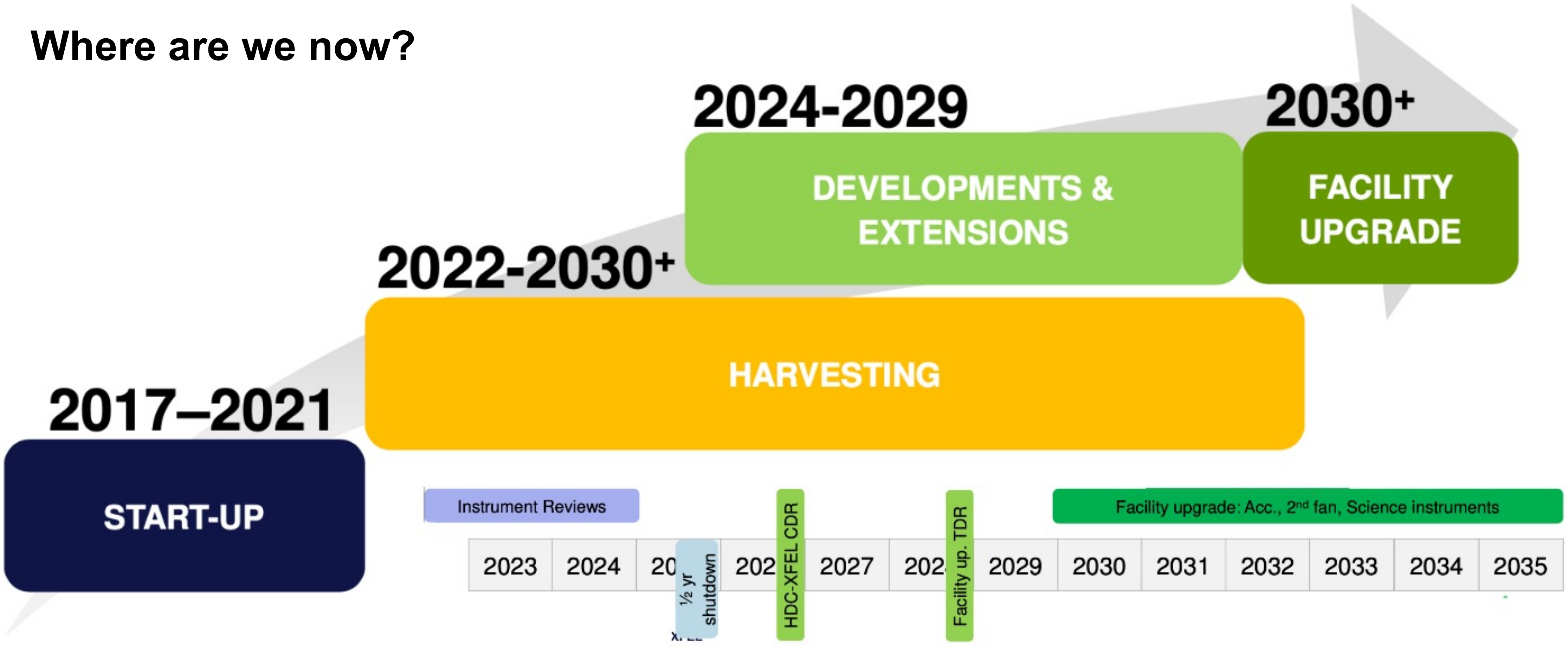
The simulations do not consider wake fields and tapering. A flat top 3 fs bunch is considered





Thanks to Sara Casalbuoni and UND group of EuXFEL

Where are we now?



European XFEL plan for the next decade+

What should be the main features of next generation detectors?

- If you ask users: provide excellent data quality and easiness of analysis
- If you ask Instrument Scientists: they would add ease of operation and maintenance
- If you ask Detector Scientists at EuXFEL: emphasis move on system robustness and ease of integration, maintenance and calibration
- If you ask Detector Developers: the project must also be interesting and feasible from the technology point of view.

At the end of the day, the common goal is excellent data quality, the point of view slightly different → we should combine the views and expertise since the beginning!

What have we learned from the first detector generation?

1. The first detector generation was fully integrated with no EuXFEL available
   - real tests can be done only with the time structure and pulse intensity of the EuXFEL
   - it is important to test prototypes as soon as they become available

2. Last year EuXFEL provided ca 8000 hours for user beamtime
   - ease of operation is a must
   - reliability is a must, ease of intervention facilitates operation a lot
   - reliable hardware interlocks are vital

3. Data quality is the main parameters to judge detector quality
   - need for reliable calibration sources

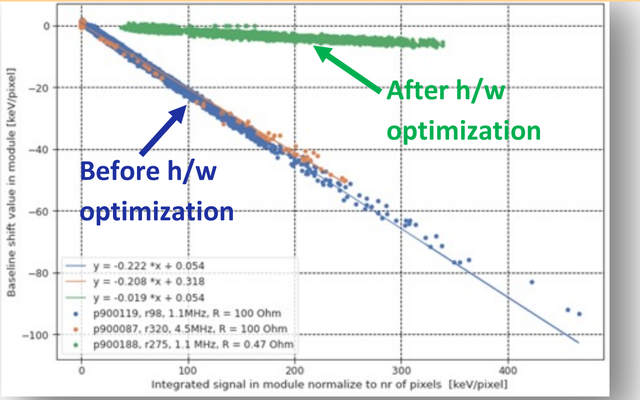
4. Having several different technologies increases the operation burden a lot

5. The volume of the produced data is enormous and reduction strategies must be put in place

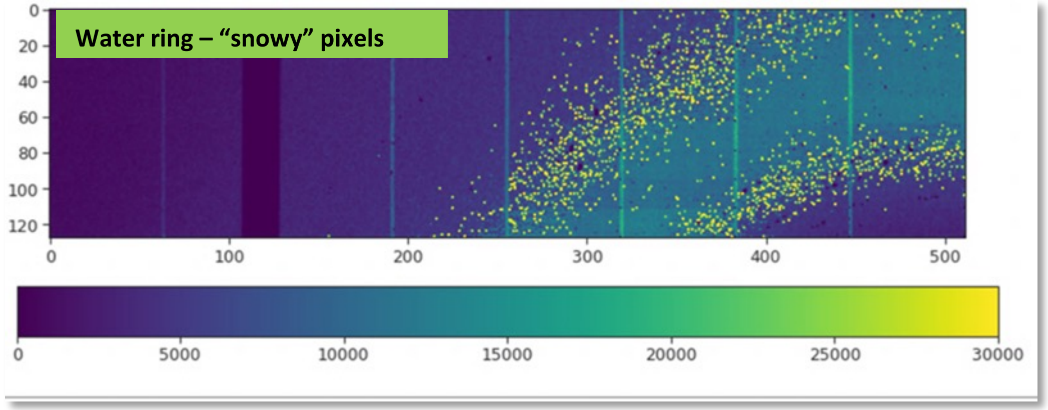
1. The importance of testing in real experimental conditions

- We can test at the same time all detector properties only with the EuXFEL beam
  - Especially features related with the high intensity at high speed are hard to spot
  - two examples from AGIPD: baseline shift and snowy pixels

Baseline shift as a function of X-ray intensity



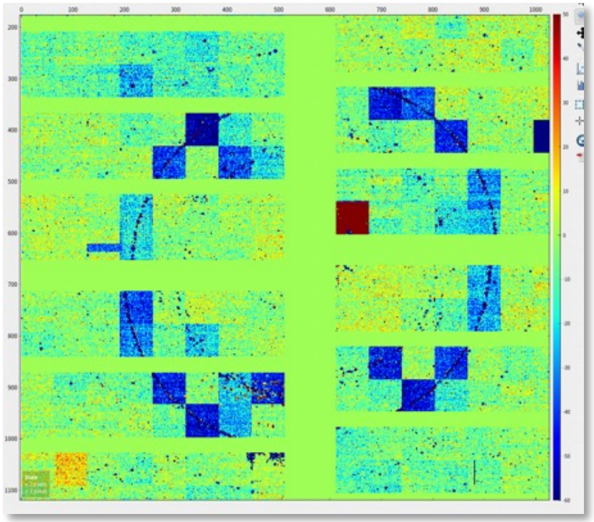
Baseline depending on deposited energy
Corrected via h/w intervention at SPB/SFX
MID intervention to be scheduled



Problem at the transition region b/w high and medium gain
Very much dependent on repetition rate: running with longer integration time helps

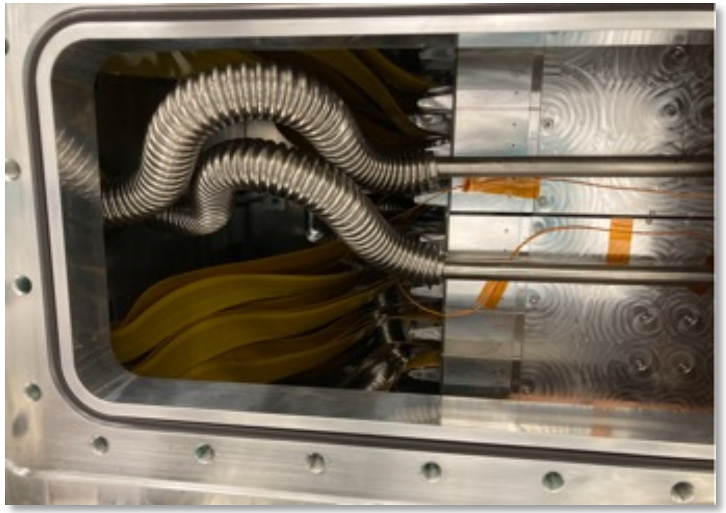
- Similar discoveries also for the other detectors…

Radiation damage on AGIPD



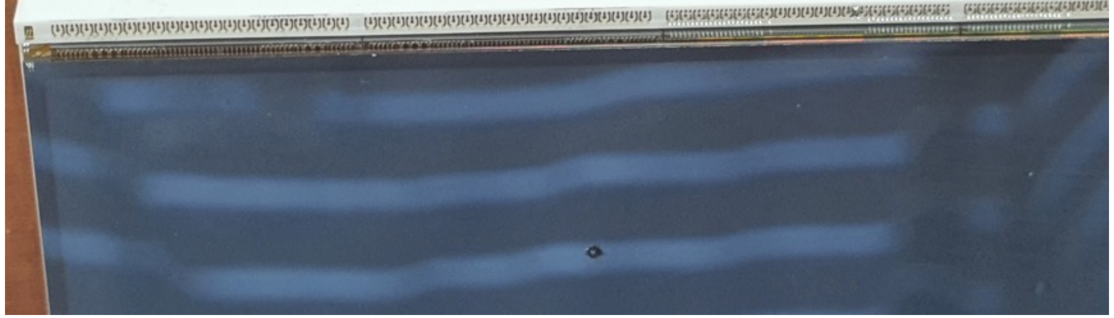
2. The importance of ease of operation and of interlocks

- Detectors are protected by interlocks which saved them already a couple of times:
  - ensure cooling is active when detector on
  - ensure vacuum is kept when detector is cold… etc…
  - switch off detector in case of danger…
- Radiation damage happens
  - easy access is a must, ability to quickly exchange modules
  - fast access to electronics
  - interlock against e.g. ice formation would help, under commissioning
- For future detectors risk minimisation has the highest priority
  - … and ease of installation and part exchange is also vital

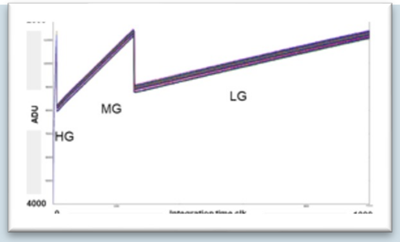
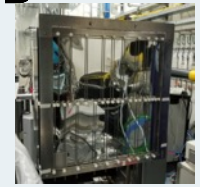
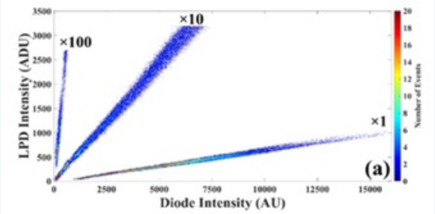
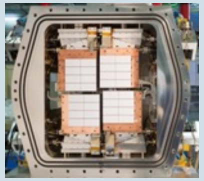
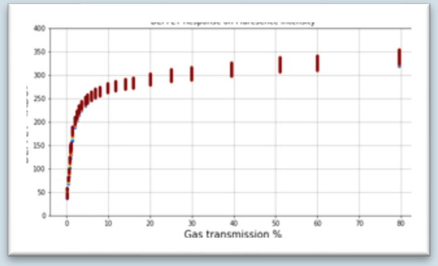


Deformed DSSC cooling pipes

Beam damage on AGIPD



3. The importance of reliable (internal) calibration sources

Detector	Specs	Gain Mechanism	Gain
AGIPD 	352 memory cells (analog) 200µm x 200µm sq. pixels 1-10^4 12 keV ph 3-20 keV Modular: 16 (1MPix) or 8 (0.5MPix) modules	3 gains with automatic switching	
LPD 	(3x)512 memory cells (analog) 500µm x 500µm sq. pixels 1-10^5 12 keV ph 7- 20 keV Modular: 16 (1MPix) modules	3 parallel gain stages with on front-end selection	
DSSC 	800 memory cells (digital) 204µm x 236µm hex. pixels N x 256 ph @ 4.5 Mhz N x 512 @ f≤2.2 MHz N ≤ 1 for single ph sensitivity 0.5 – 6 keV Modular: 16 (1MPix) modules	Linear response (miniSDD), non-linear signal compression in sensor (DEPFET)	

- Calibrating the full dynamic range is a major challenge
  - not yet done for all detectors, also due to radiation damage
- Calibration needs to be done any time there is an accident or major intervention on detector
  - routinely done after each maintenance period for the hard X-ray detectors
- Need of calibration-friendly design!

3. The importance of reliable (internal) calibration sources

Detector	Specs	Gain Mec…
AGIPD		
LPD		
DSSC		

Challenges

AGIPD:
- Three gain stages per pixel
- Analog memory cells
- Analog gain evaluation
- Many operation modes to mitigate artefact

LPD:
- Three gain stages per pixel
- Analog memory cells
- Detector artefacts

DSSC:
- Non-linear gain to be evaluated

Example AGIPD (one operation scenario)

x 1 million pixels
x 352 memory cells
x 3 gain stages
x number of needed calibration constants
→ > 10^9 parameters

The constants have to be generated for different operation scenarios:

→ rep. rate
→ Number of mem. cells
→ Integration time

4. The impact of having a detector 'zoo'

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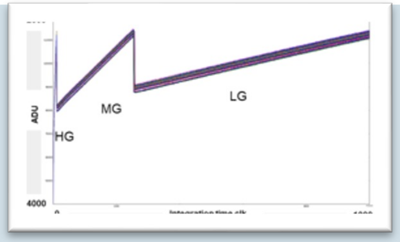
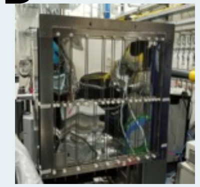
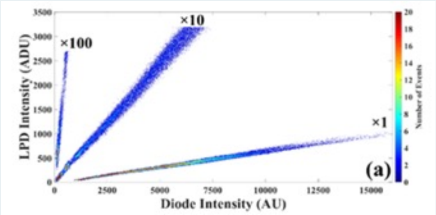
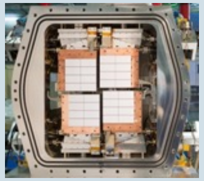
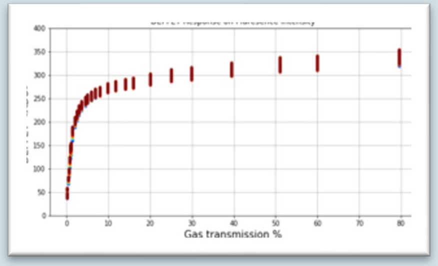
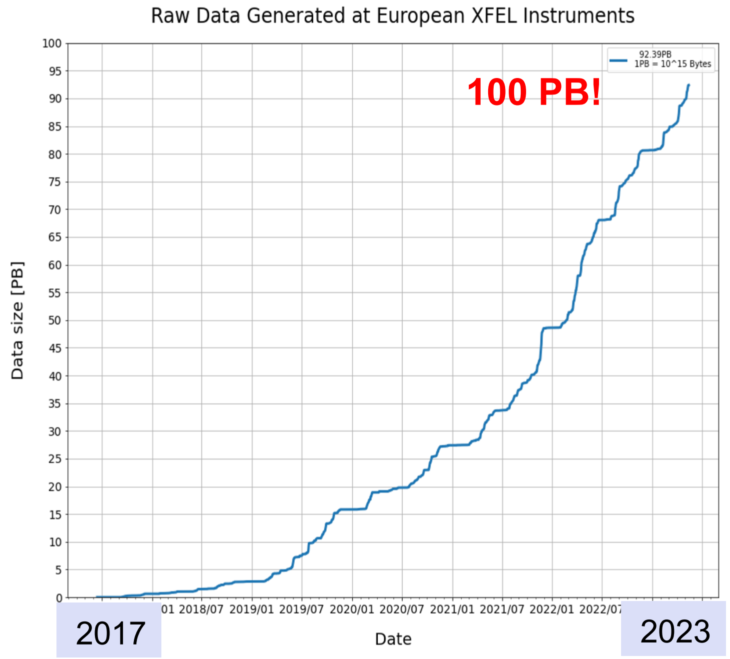
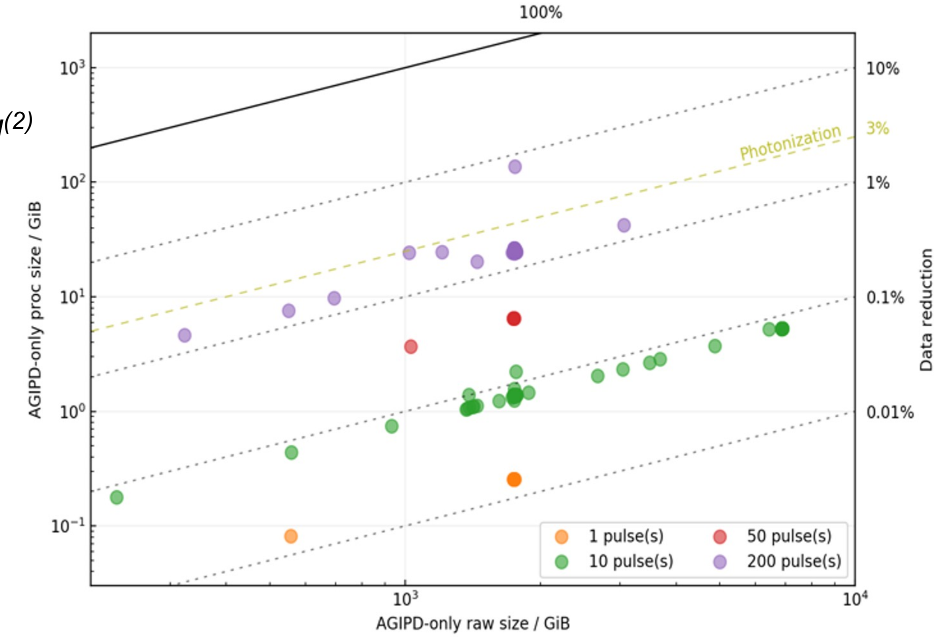
AGIPD 	352 memory cells (analog) 200µm x 200µm sq. pixels 1-10^4 12 keV ph 3-20 keV Modular: 16 (1MPix) or 8 (0.5MPix) modules	3 gains with automatic switching	
LPD 	(3x)512 memory cells (analog) 500µm x 500µm sq. pixels 1-10^5 12 keV ph 7- 20 keV Modular: 16 (1MPix) modules	3 parallel gain stages with on front-end selection	
DSSC 	800 memory cells (digital) 204µm x 236µm hex. pixels N x 256 ph @ 4.5 Mhz N x 512 @ f≤2.2 MHz N ≤ 1 for single ph sensitivity 0.5 – 6 keV Modular: 16 (1MPix) modules	Linear response (miniSDD), non-linear gain in sensor (DePFET)	

- We have three kind of detectors which are one-of-a-kind!
- Different experts needed for different technologies
- Standardisation in controls, interlocks, calibration difficult if not impossible
- Heavily depending on developers for e.g. f/w updates

5. Data reduction efforts

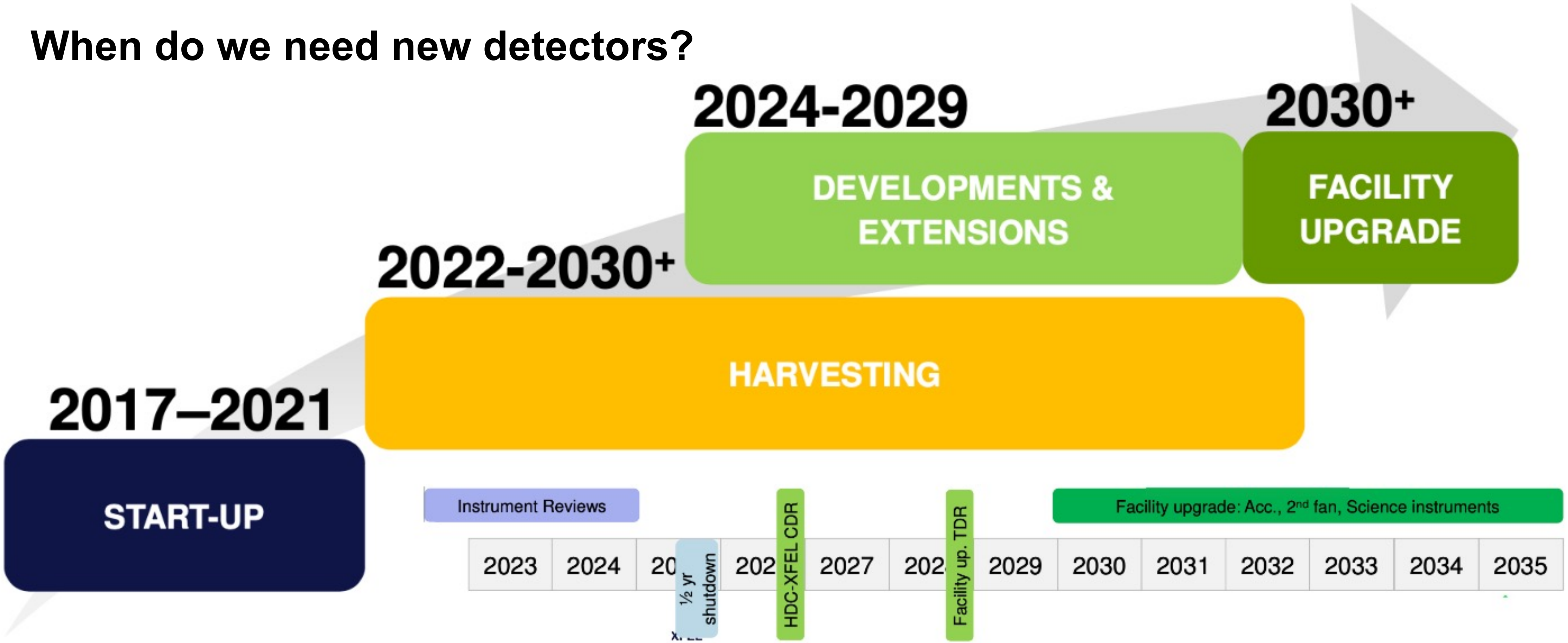
- Initial approach of storing the entire generated data long-term throughout the embargo period and beyond is no longer sustainable
- Data reduction addressed starting from policy down to specific online and offline data reduction implementations:
  - Data management plan (DMP) to include data reduction early and throughout the proposal process
  - Operation-specific, e.g.: automatic detection of non-illuminated frames (*LitFrameFinder*), photonization, pulse-on-demand
  - Technique-specific, e.g. event reconstruction (*REMI*), hit finding (*SFX*, *SPI*), $g^{(2)}$ correlation functions (*XPCS*, *XCCA*)
- *LitFrameFinder* and photonization used now routinely **for processing results**
- First attempts with real-time reduction before saving to disk
- Currently preparing to apply techniques to past data in collaboration with users





Thanks to Philipp Schmidt and DA group of EuXFEL

When do we need new detectors?



Detector development

2023 Phase I – R&D 2026

Phase II – Development and Production 2030

Detector development

Goal: 2nd generation of Large Area Pixel Detectors 2028-2030, matching expected lifetime

Phase I 2023 – 2025

- Areas of investigation:
  - System integration, backend electronics
  - System integration, mechanics and cooling
  - High-Z materials
  - Sensor and ASIC
- Main goals:
  - **increase our expertise in key areas**
  - **identify a feasible project fitting with the timeline, possibly in the direction we want to go in the future**

Phase II 2024 – 2030

- Establish concrete projects to build detectors to be ready for 2030
- Prototyping of selected technologies
- Final designs
- Construction and commissioning at Scientific Instruments

Where is our main expertise right now?

- Our main expertise is integration together with calibration, and some part of mechanics including assembly

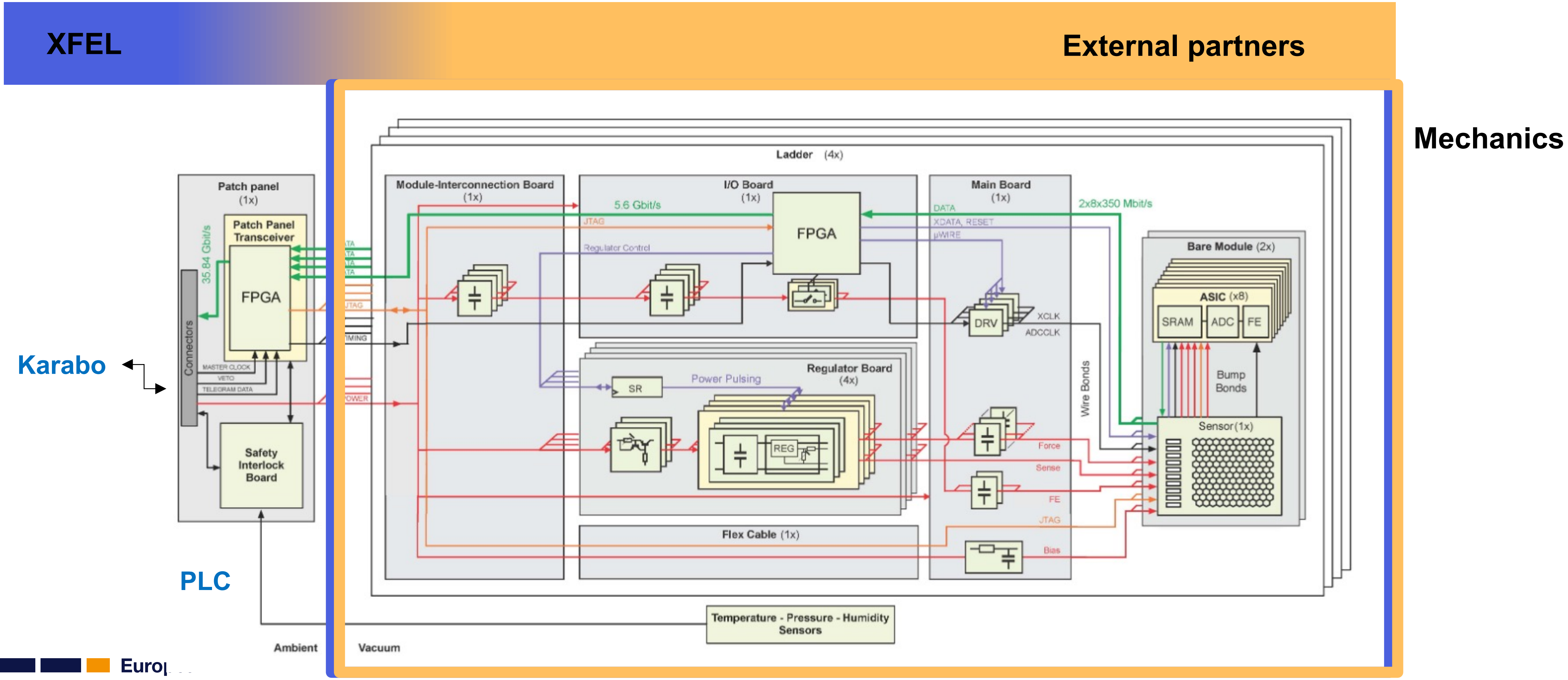


Figure from M. Porro *et al.*, "*IEEE Transactions on Nuclear Science*, vol. 68, no. 6, pp. 1334-1350, June 2021

Where do we want to go? Take over system assembly and integration

- How we plan to be involved: significant engineering resources needed

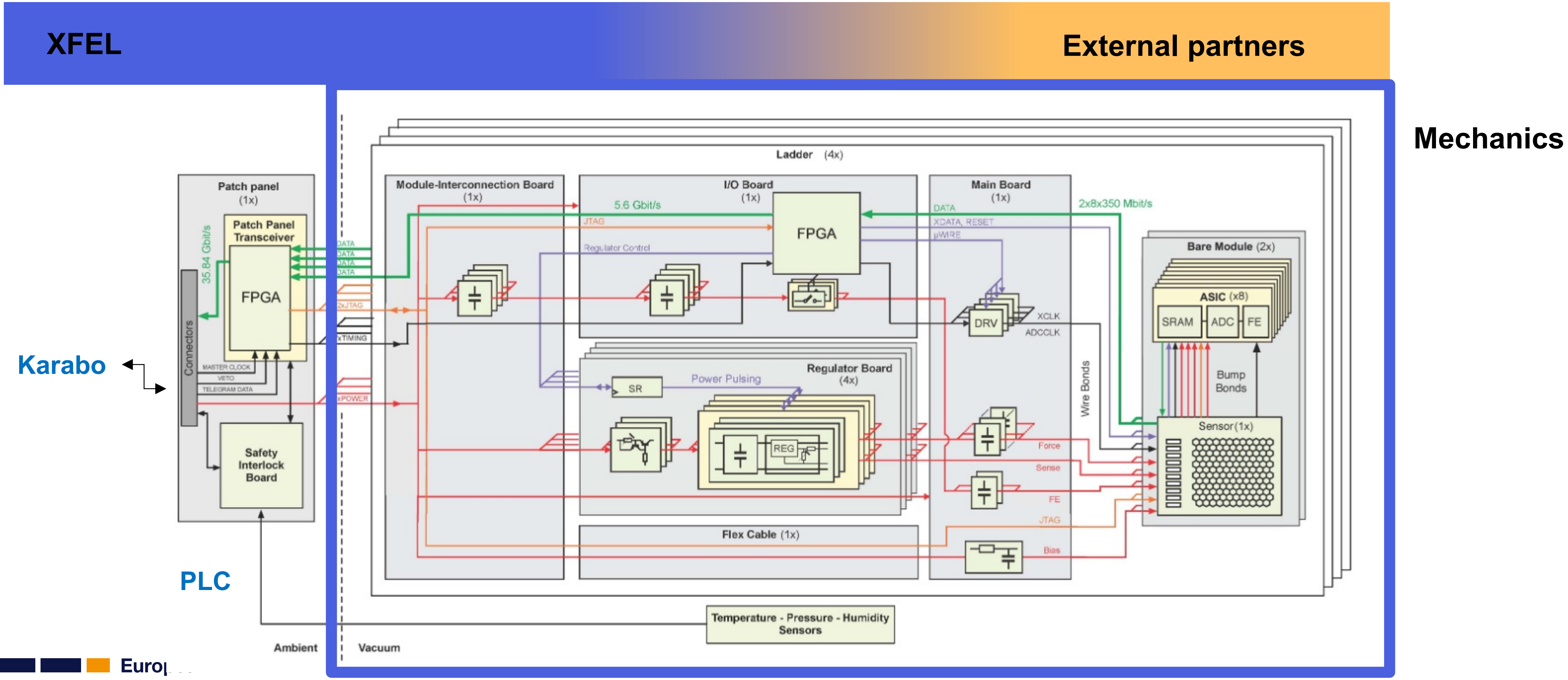
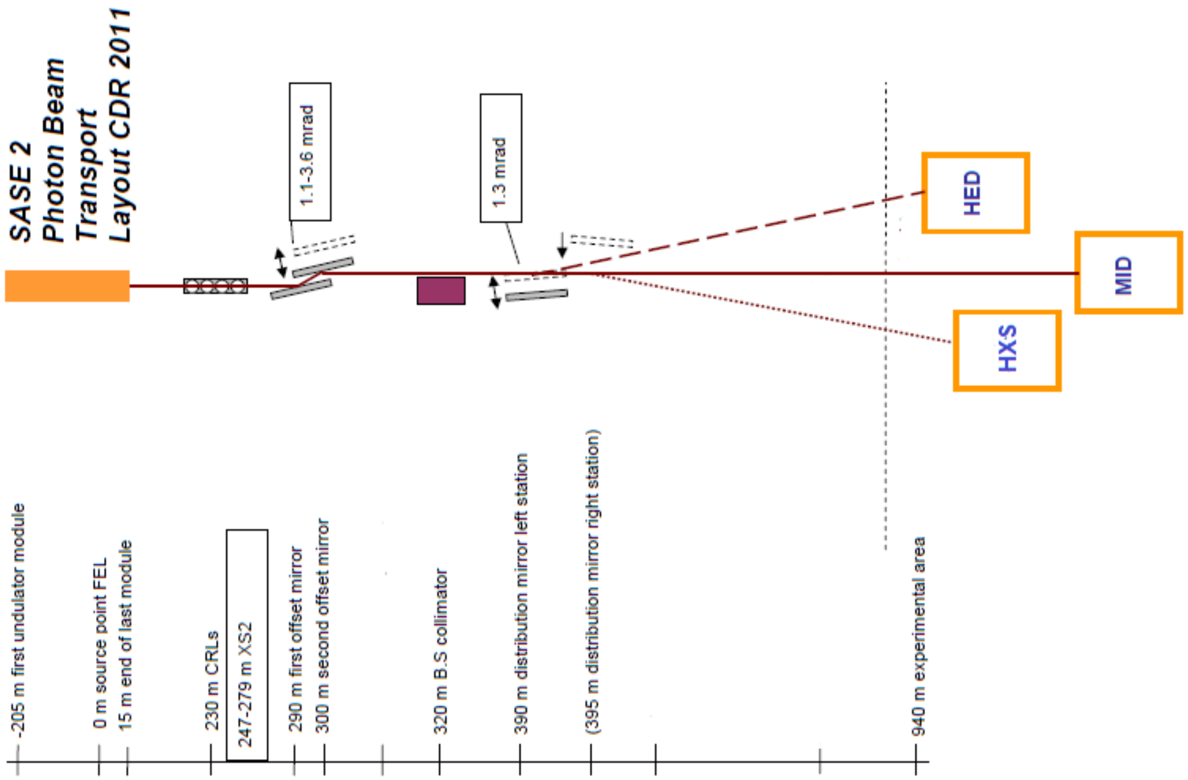
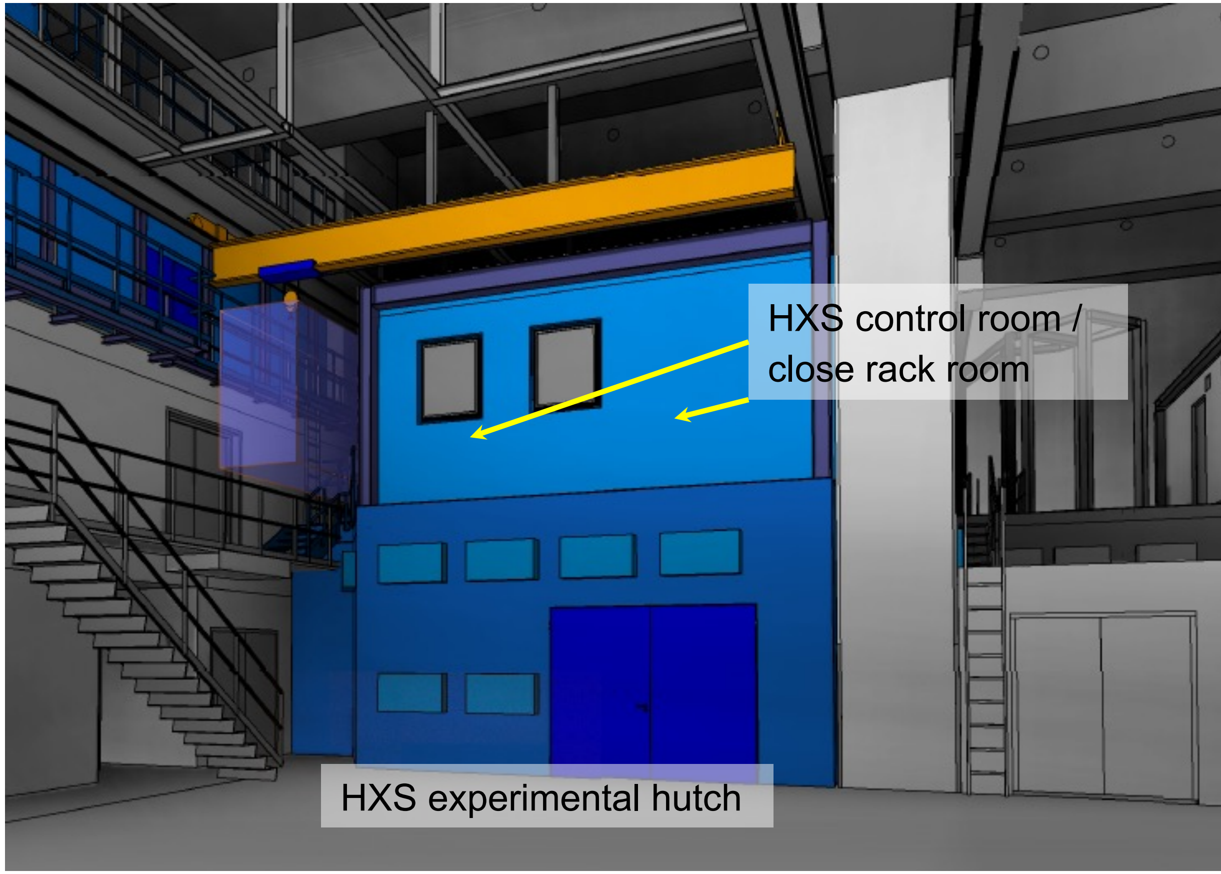


Figure from M. Porro *et al.*, "*IEEE Transactions on Nuclear Science*, vol. 68, no. 6, pp. 1334-1350, June 2021

Third port of SASE2 approved for construction in 2025

- Hutch and beam transport tunnel approved, installation in the 2025 long shutdown until early 2027

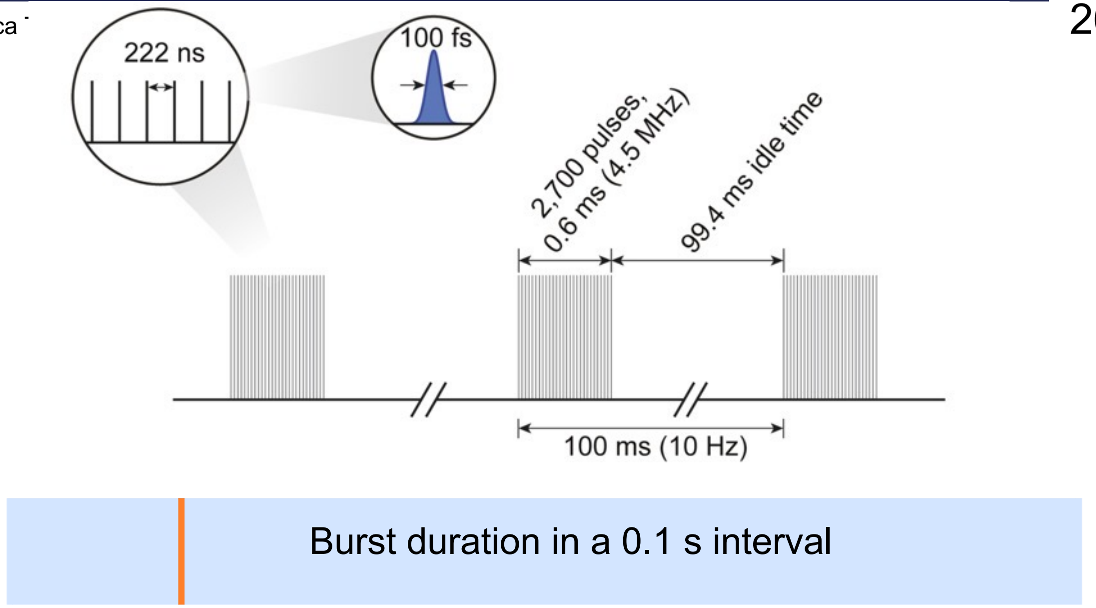


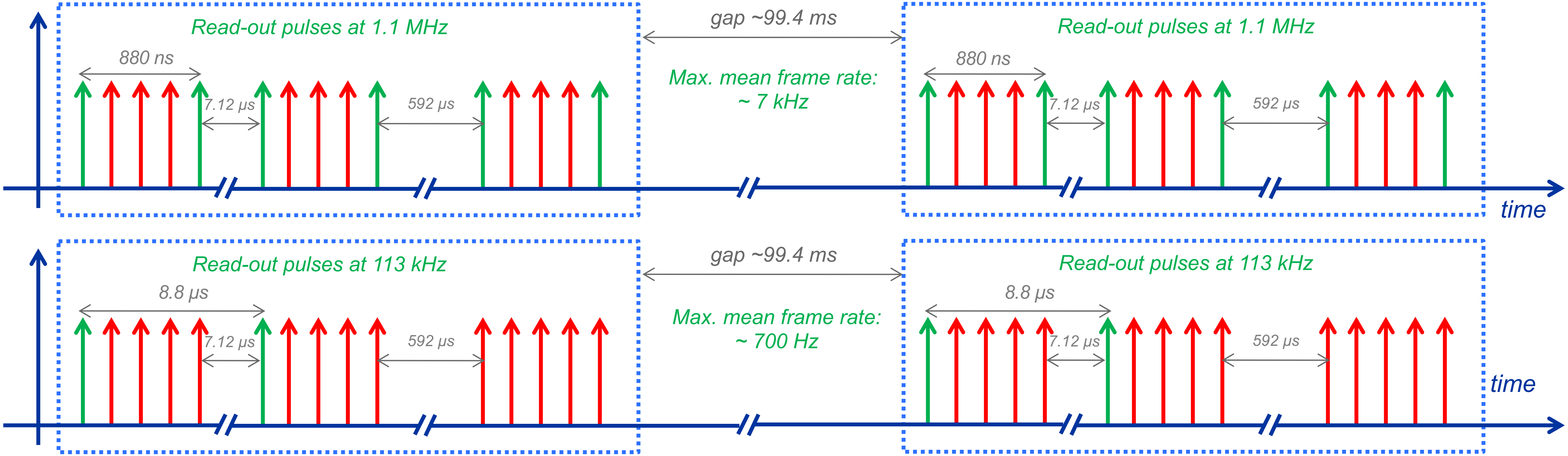


- ***Can offer extra possibilities for detector testing***

How to get to the final requirements?

- **Burst mode will still be our operation mode**
  - this has no equal in the world
  - even a very fast (100 kHz) continuous readout detector will not help
    - ▶ per 0.6 ms burst, we could only read out max 60-70 frames, at present we read out 350-800 per burst
    - ▶ EuXFEL is bound to MHz repetition rate

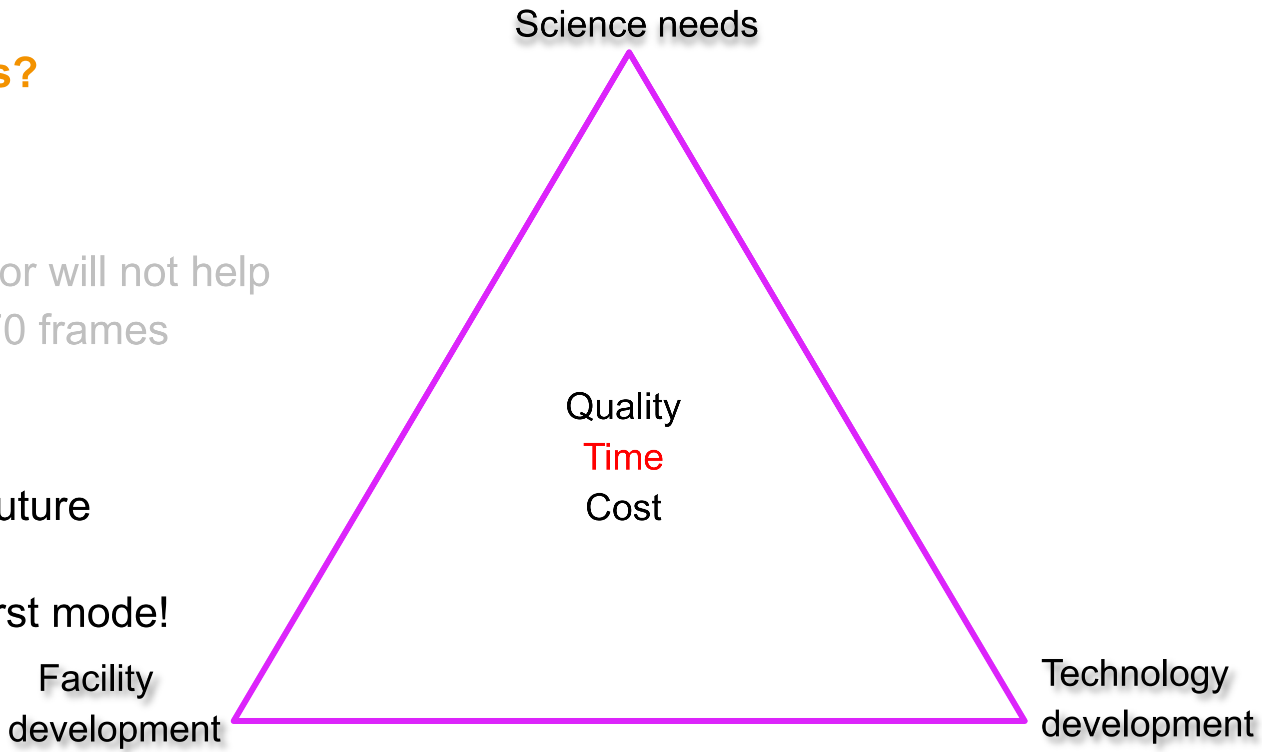




How to get to the final requirements?

How do we get to the requirements for the 2030 detectors?

- Burst mode will still be our operation mode
  - this has no equal in the world
  - even a very fast (100 kHz) continuous readout detector will not help
    - per 0.6 ms burst, we could only read out max 60-70 frames
    - at present we read out 350-800 per burst
    - EuXFEL is bound to MHz repetition rate
  - a continous readout MHz detector is far away in the future
- For 2030 we still need detectors able to cope with our burst mode!
  - **Focus on burst mode for next detector round**
- Can we upgrade our detectors so that we get closer to what we could need in 2035?
  - **Consider facility upgrades, science needs and technology developments all together**



Our preliminary requirements

Not all parameters to be reached at the same time!

Hard X-ray detector

	Target values	Possible variant
Sensitive Energy Range	5-13 keV[1] with Si 13-50 keV with high-Z	3-13 keV[1] with Si
Dynamic range in photons	> 5 x 10^3 12 keV ph./px	500 - 1000 12 keV ph./px, one gain
Noise (ENC)	< 300 el. rms. ~1keV photon in Silicon	
Frame rate	Burst mode, 1.1 MHz	Burst mode, 1.1 - 4.5 MHz
Sensor type	2D pixelated	
Pixel size	80 - 100 µm pitch	
Pixel count	Move away from fixed large detectors, modular approach, max 4 Mpix	
Operating pressure range	Both ambient and vacuum (below 10^{-3} mbar) versions needed	

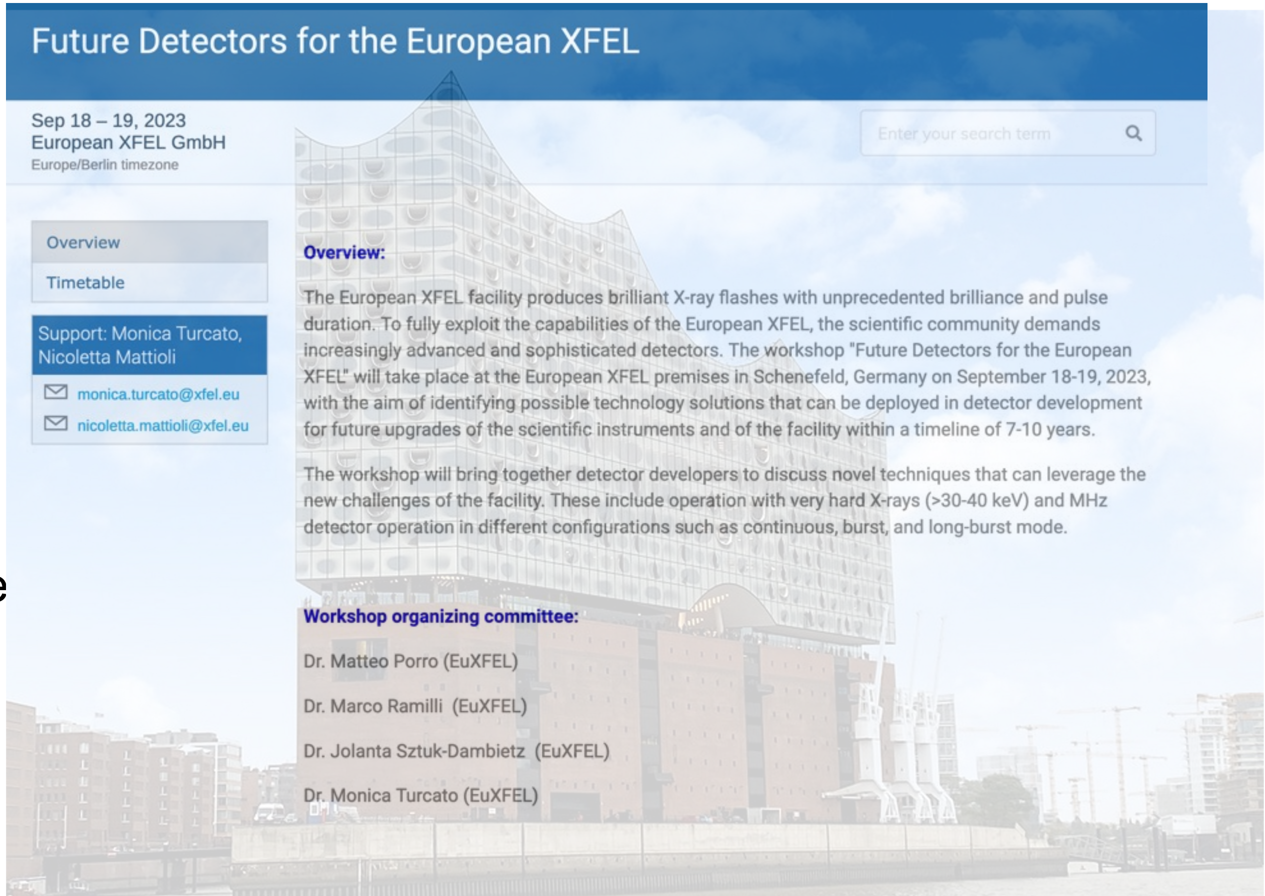
Soft X-ray detector

	Target values	
Sensitive Energy Range	0.4 - 3 keV, possibly higher	
Dynamic range in photons	> 5 x 10^3 1 keV ph./px	500 - 1000 1 keV ph./px, one gain
Noise (ENC)	< 30 el. rms ~0.125 keV photon in Silicon	
Frame rate	Burst mode, 1.1 MHz	Burst mode, 1.1 - 4.5 MHz
Sensor type	2D pixelated	
Pixel size	80 - 100 µm pitch	
Pixel count	Move away from fixed large detectors, modular approach, max 4 Mpix	
Operating pressure range	< 10^{-6} mbar	

[1] *Defined by QE of the sensor. Operation above/below is possible with reduced performance.*

Detector workshop 18-19 September

- Goal of the workshop:
  - illustrate the needs of the EuXFEL in terms of detector performance and operation, including facility upgrade, scientific needs and lessons learned
  - discussion of the ongoing developments
  - identification of interesting technologies for the EuXFEL
  - identification of areas where common developments are possible



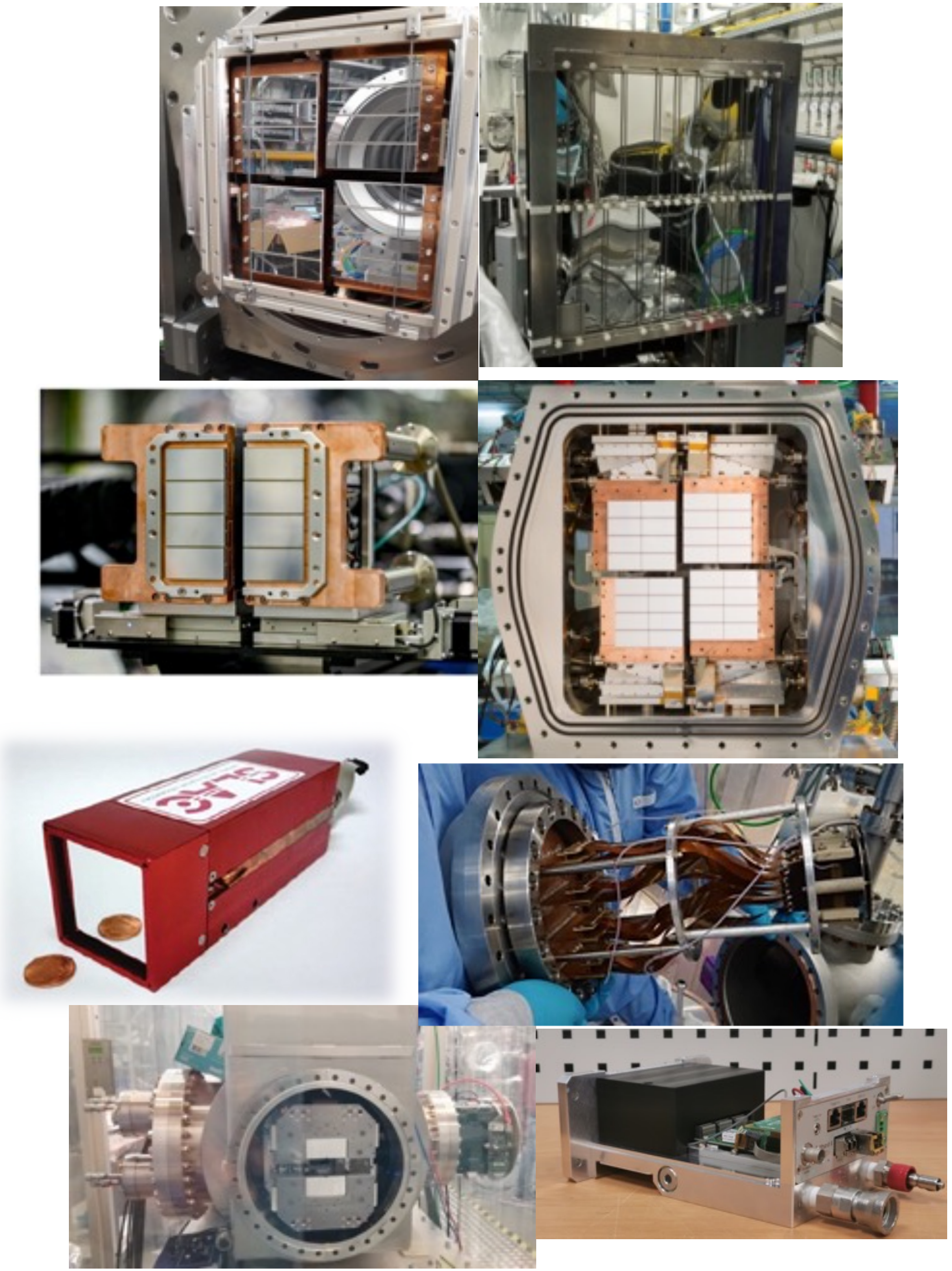
www.xfel.eu → News and Events → Events → Workshops and Conferences

https://indico.desy.de/event/37831/

Conclusions

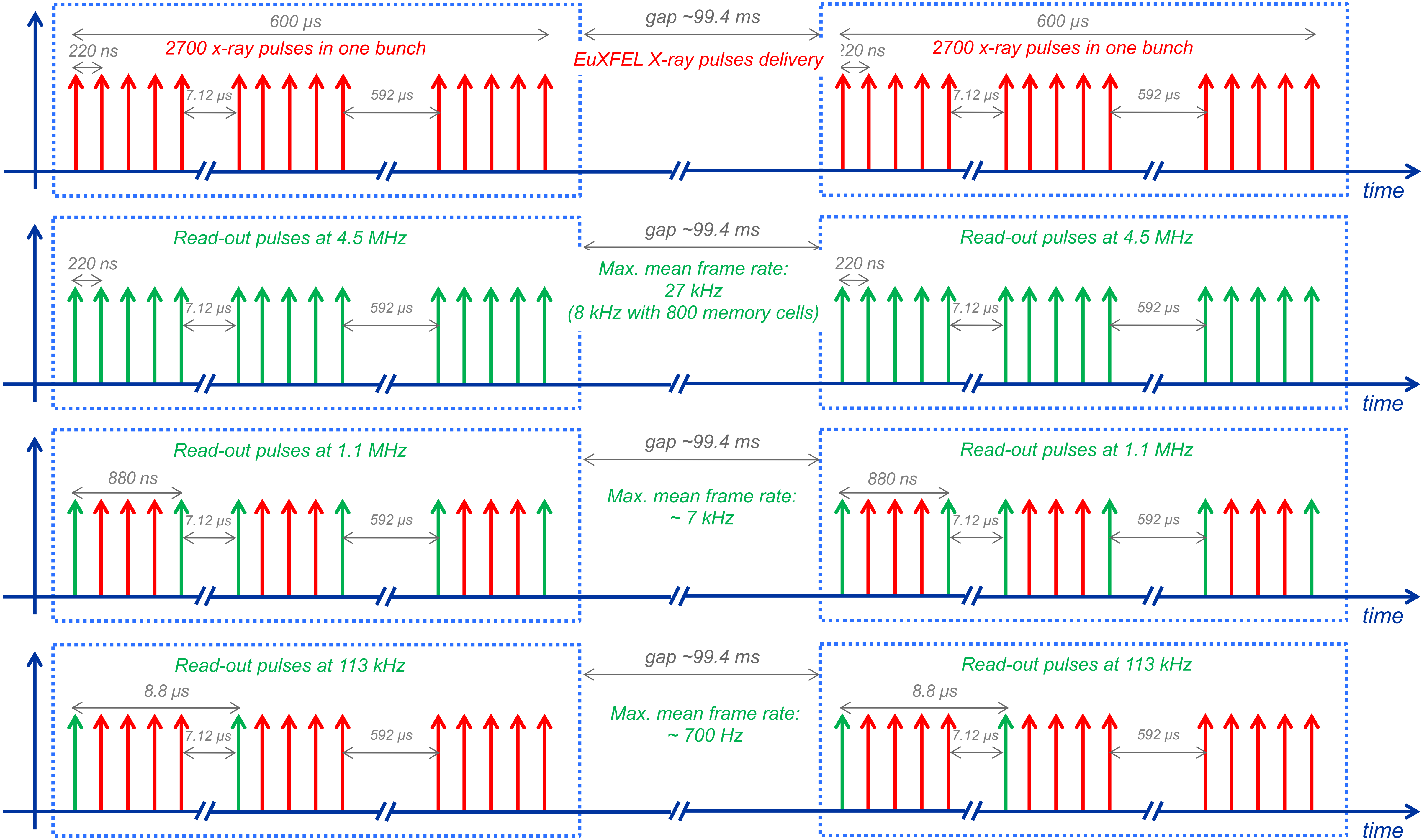
- EuXFEL producing excellent scientific results based on data collected by the present detector generation
- Looking at the future, the next generation detector development program is starting at the EuXFEL
- Phase 1 of the development will serve to increase EuXFEL expertise in certain fields and to define collaboration with external partners in specific topics (ASICs, sensors…)
- Phase 1 is also aimed to define what is possible in terms of detector development and on which time scale

Looking forward to the new challenges!



Thank you!

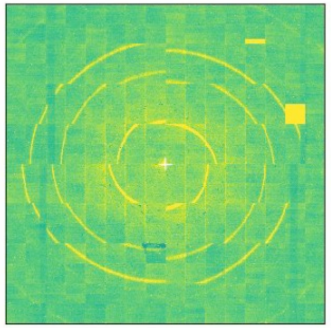
Backup



600 µs
2700 x-ray pulses in one bunch
220 ns
7.12 µs
592 µs
gap ~99.4 ms
EuXFEL X-ray pulses delivery
time
Read-out pulses at 4.5 MHz
Max. mean frame rate:
27 kHz
(8 kHz with 800 memory cells)
Read-out pulses at 1.1 MHz
880 ns
Max. mean frame rate:
~ 7 kHz
Read-out pulses at 113 kHz
8.8 µs
Max. mean frame rate:
~ 700 Hz

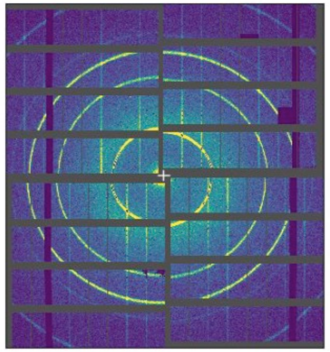
Detectors setups: data correction

- Corrected data proposed for each detector



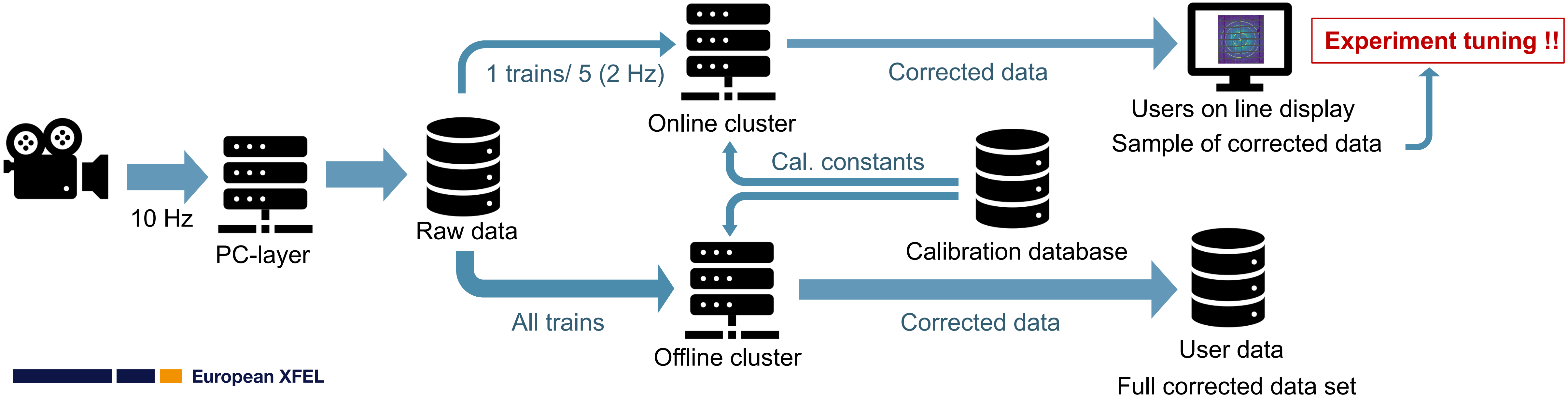
Raw data

- Offset Correction
- Gain corrections
- Bad Pixel Maps
- ….



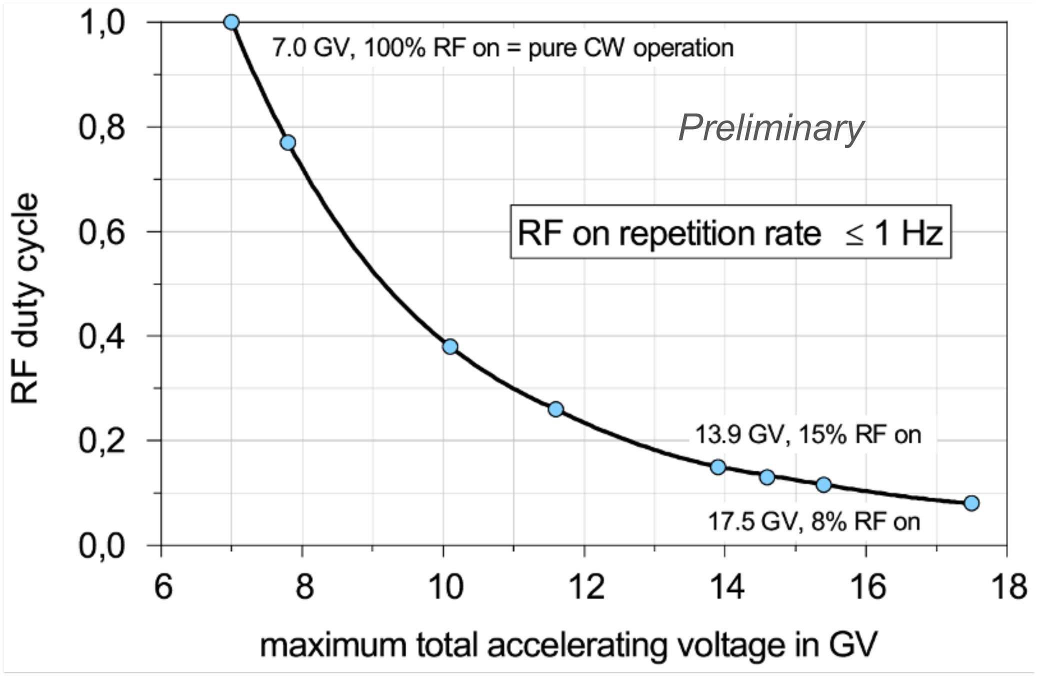
Corrected data

- Online/ off line correction process



Facility developments: new time structure, 2035+?

Time structure not yet defined, some options under consideration



- CW mode implies a max electron energy of 7 GeV (with respect to the 17.5 GeV of now)
- Energy can be gained by running in high duty-cycle mode, when RF is on for a fraction of time (the present burst mode corresponds to a duty cycle of 0.006)
- This choice impacts dramatically on detector design
- Timeline: CDR end of 2027, implementation 2035+
  - not thinkable to run with present detectors until then

Thanks to the accelerator team, in particular J. Sekutowicz and E. Vogel