Introduction to this meeting & preparation for European XFEL upgrade

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Expert meeting Spectroscopy

September 16, 2026

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Scope of this meeting & agenda

- Introduction to European XFEL upgrade preparation
  - **Target and motivation**
  - **Boundary conditions**
  - **Options**
- Activities to prepare upgrade proposal
  - **Sequence of *expert meetings***
  - **Science workshops and down selection**
  - **Time path to proposal and upgrade**
- Agenda for today
  - **Welcome & Introduction**
  - **Discussion**
  - **Tea/coffee break**
  - **Brainstorming & discussion (in full or smaller groups)**
  - **Wrap-up and summaries**
- Informal get-together (w. more discussion)

Expert meetings

Idea is to invite in a first step the expert Users of European XFEL and get your input:

- **Feedback of what could be better**
- **Ideas for future experiments (currently not feasible)**
- **Ideas for scientific application thereof**

Follow-up

Have prepared short (2-page) questionaires to collect your thoughts. Print-outs available, but will send you after meeting. Please use one per experiment (idea). These docs will be used to gear up and organize, not enter directly into future proposal.

Intro to European XFEL upgrade

Motivation for upgrading European XFEL

- Offer new opportunities for science applications following request by User communities
- Offer better conditions for science applications following experience from current operation
- Offer more instruments/beamtime to respond to proposal demand by User communities
- Stay ‚state-of-the-art' and competitive in international context
- Renew/refurbish aged components to increase facility lifetime

Scientific usage & user facility aspects are the critical drivers

- Extending installation and/or performance of the accelerator, the FEL sources, the beamlines, the scientific instruments, and of the ‚user services' should be motivated by their scientific usage and the needs of the User community.
- Technical advances and new installations/methods/techniques are important and needed to achieve certain performances, but should not be seen as the driver of the upgrade.

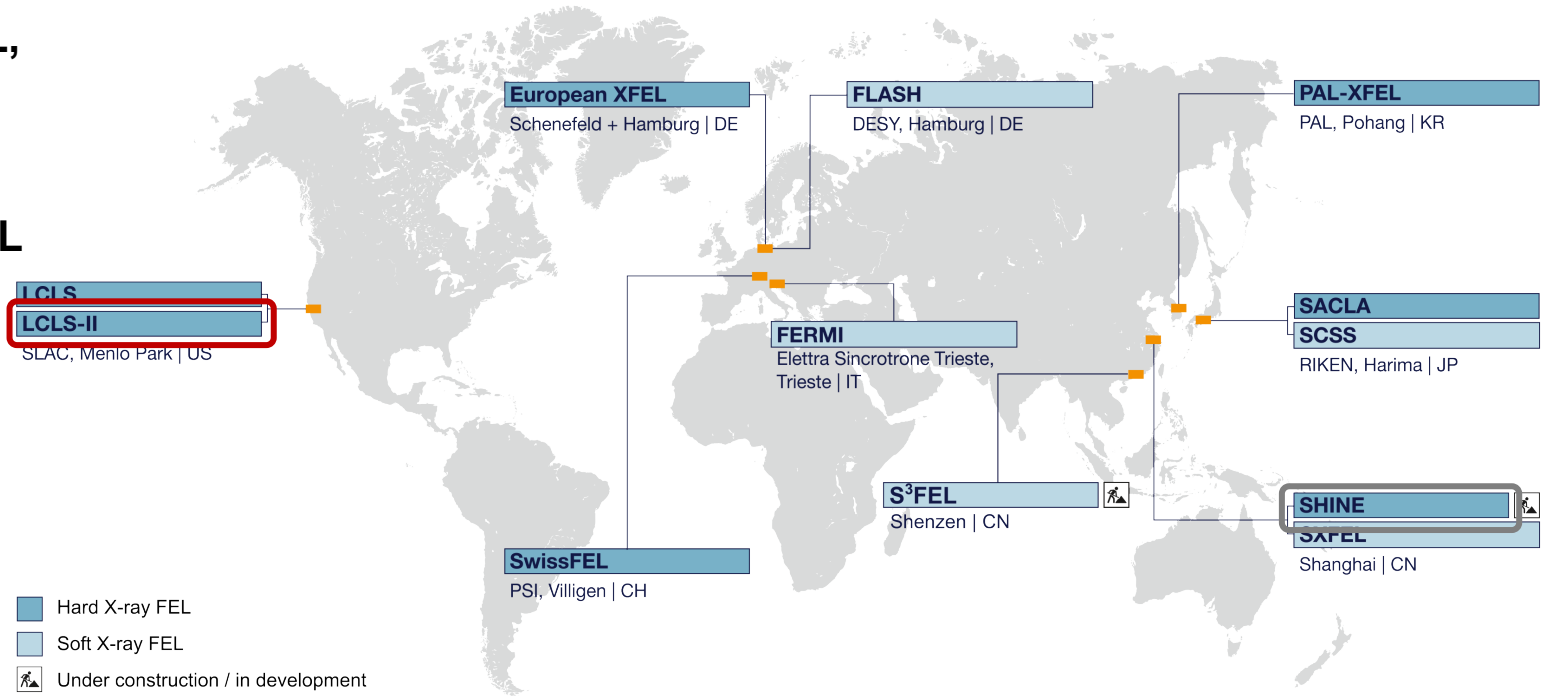
European XFEL (at present) stands for

- High electron energy (up to 17.5 GeV) → high photon energies (20 – 30 keV)
- High repetition rates (up to 4.5 MHz) → average ‚flux' from p.o.d. to 1000s of x-ray pulses/s
  → sampling 100 ns to µs time scales
- Medium high bunch charges & long FELs → high x-ray pulse energies
- Long FELs & afterburners → HXRSS, variable polarization, very high $\hbar\omega$
- Multi-FEL facility operation → 5 FEL sources, O(10) scientific instruments
- Flexible delivery schemes → user requested, attoseconds, …
- Stable delivery through feedback mechanisms → in particular inside pulse train

- Burst-mode operation → cycling load
  → >10 Hz – 50 kHz rep rate are not accessible
  → Requirement of large pulse number = high rep rate

Landscape analysis I – X-ray FEL facilities

- Hard x-ray facilities
  - **LCLS, SACLA, PAL-XFEL, EuXFEL, SwissFEL, SHINE**
- High repetition rate facilities
  - **EuXFEL, LCLS-II-HE, SHINE, S^{3}FEL**
- Proposed facilities
  - **Next Generation XFEL (UK)**
- Other sources
  - **Seeding/coh.: FERMI**
  - **Laser-driven: EuPRAXIA, …**



- Competitors (keeping current strengths)
  - **LCLS-II, SHINE, Next-Generation XFEL**

Operating hard x-ray FELs

- Only EuXFEL operates high rep. rate
- X-ray pulse energy provided by EuXFEL is signifciantly higher than available at other hard x-ray FELs

Facility	EuXFEL	LCLS-I	SwissFEL	SACLA	PAL-XFEL
lab, country	DE	SLAC, US	PSI, CH	RIKEN, JP	PAL, KR
Accelerator parameters					
Accelerator type	SC	NC	NC	NC	NC
Max. beam energy /GeV	17.5	15	5.8	8.5	10
Repetition rate / Hz	4.5×10^6 (in BM)	120	100	30 (60 max)	50
Max. # of pulses/s	27000	120	200	60	50
Bunch charge /pC	250	180	10–200	200–300	150
Photon parameters					
Photon energy range / keV	0.25–30	0.2–23	0.25–12	0.04–20	0.25–15
max. photon pulse energy for hard X-rays / μJ	5×10^3 @ 7 keV	$> 2 \times 10^3$	$> 10^3$ @ 12 keV	$> 6 \times 10^2$ @ 10 keV	$> 10^3$
std. pulse duration / fs	20–30	10–250	24	2–10	10–35
Facility characteristics					
# of FEL sources	3	2	2	3	2
# of end stations	7	9	5	6	3
Special modes					
	as, two colour, self seeding, pol. control	self seeding, multi colour, multi pulse, as	short pulse, EEG, mode coupled, high brightness	two colour, self seeding	self seeding

Future competitors

- LCLS-II-HE will be operational in 2-3 yrs (new instruments later)
- SHINE similar, but direct comparison is not suitable
- Next-Generation XFEL (UKXFEL) has been proposed, but is unlikely to be funded (at present)

→ Look at LCLS-II-HE and Next-generation XFEL science cases

Facility	LCLS-II-HE	SHINE	UKXFEL
lab, country	SLAC, US	CN	UK
Accelerator parameters			
Accelerator type	SC	SC	SC/+NC
Max. beam energy /GeV	8	8.6	8 / 12–15
Repetition rate / Hz	~ 0.9×10^6	1×10^6	0.1×10^6 / up to 200
Bunch charge /pC	10–300	10–300	75–300
Photon parameters			
Photon energy range / keV	0.25–12.8 (20)	0.2–15	0.1–20 / 5–45
Photon pulse energy / μJ	?	10–300 (SASE)	7×10^3–1.5 / 2.5×10^4–150
std. pulse duration / fs	?	1–100	0.2–100 / ~ 30
Facility characteristics			
# of FELs	2	2	7
# of end stations	9	6	13
Special modes			
	self seeding, multi colour, multi pulse, as	...	...

Source: Background document (v. Aug 2026)

Landscape analysis II – science drivers

LCLS-II-HE

- X-ray delivery features
  - **Hard X-rays at decent high average brightness**
    - ► Highest $\hbar\varpi$ & E_{pulse} use Cu linac
  - **Uniform/programmable timing at rep. rates to 1 MHz**
    - ► Make use of the high average spectral flux for high-resolution spectroscopy applications.
- Science applications
  - **Coupled dynamics of energy and charge in atoms and molecules**
  - **Catalysis, photocatalysis, and environmental and coordination chemistry**
  - **Imaging biological functions and dynamics**
  - **Materials heterogeneity, fluctuations and dynamics**
  - **Quantum materials and emerging properties**
  - **Materials in extreme environments**
  - **Nonlinear X-ray matter interaction**

Next-Generation XFEL

- X-ray delivery features
  - **Exceptional X-ray pulse qualities, including laser-like X-rays**
  - **High-repetition-rate, high-efficiency, multi-user facility**
  - **World-class endstations & sync. sources, data, and AI**
- Science applications
  - **Imaging complexity: Brain function, tissue imaging, cultural heritage**
  - **Imaging dynamics: Adv: manufacturing, fusion energy, nanotechn.**
  - **Dynamics of life: Molecular machines, engineering biology, anti -bacterials, anti-virals, and medicines**
  - **Matter at extremes: Stars, planets, aerospace, and weapons**
  - **Advanced materials: Efficient batteries, superconductors, green chemistry, and lean combustion**
  - **Radiation resistance**
  - **Fundamental science: Tests of the standard model, nuclear clocks, and advanced accelerators**
  - **Advanced probes: Surfaces, explosives, rocket propulsion, and charge motion**
  - **Advanced electronics: Solar energy, quantum technology, semiconductors, and efficient data storage**
  - **Frontiers of measurement: Attosecond technology, light -driven states, and PHz electronics**

Competitor analysis

- LCLS-II-HE and SHINE
  - **These facilities will target 10-100 kHz operation and experiments requesting high average flux**
  - **Pulse energies will remain limited (less ~1 mJ) and photon energies will be conv. hard x-rays (8-12 keV)**
  - **Initially they will have only few FEL sources, potentially expanding here in future.**

- Next-Generation XFEL
  - **Aiming at more transform-limited x-ray pulses (using various methods) & less stochastic properties**
  - **Dedication of FEL sources & instruments to specific applications requests many FEL sources**

- European XFEL options to fill gaps
  - **Keep BM and deliver pulse properties not achievable by competitors: high E_{pulse}, highest rep rate, high $\hbar\omega$**
  - **Deliver MHz cw operation at high electron energy and with many FELs**
  - **Focus on transform-limited hard X-ray FEL sources**
  - **Aim at parameter regime targeted by LCS-II-HE and SHINE, but for European scientific community**

European XFEL upgrade– Science drivers

- Past/current cases
  - **ultrafast chemistry (nuclear dynamics …)**
  - **structural life sciences**
  - **material science,**
  - **AMO fundamental physics**
- Recent cases (method-oriented)
  - **Attoseconds** – Electron dynamics**
  - **Non-linear spectroscopy - ???**
  - **High resolution spectroscopy – Materials**
  - **High photon energies** – Materials**
- Recent cases (application oriented)
  - **ultrafast (material) processes – (3D) imaging**
  - **material particles & aerosols – SPI**

** recently prioritized

The scrutiny and development of the scientific drivers will be a very important part of the upgrade proposal.

This is only a start to categorize scientific drivers/applications.

Upgrade options

Current and future assets of European XFEL

- Layout and systems
  - **Long(est) accelerator with possibility to have 2 injectors and branch into 2nd FEL fan**
  - **Long FEL sections with very long FELs**
  - **Still 1 FEL and 1 beamline unassigned**
  - **2nd FEL fan and 2nd experiment hall have been requested and are possible**

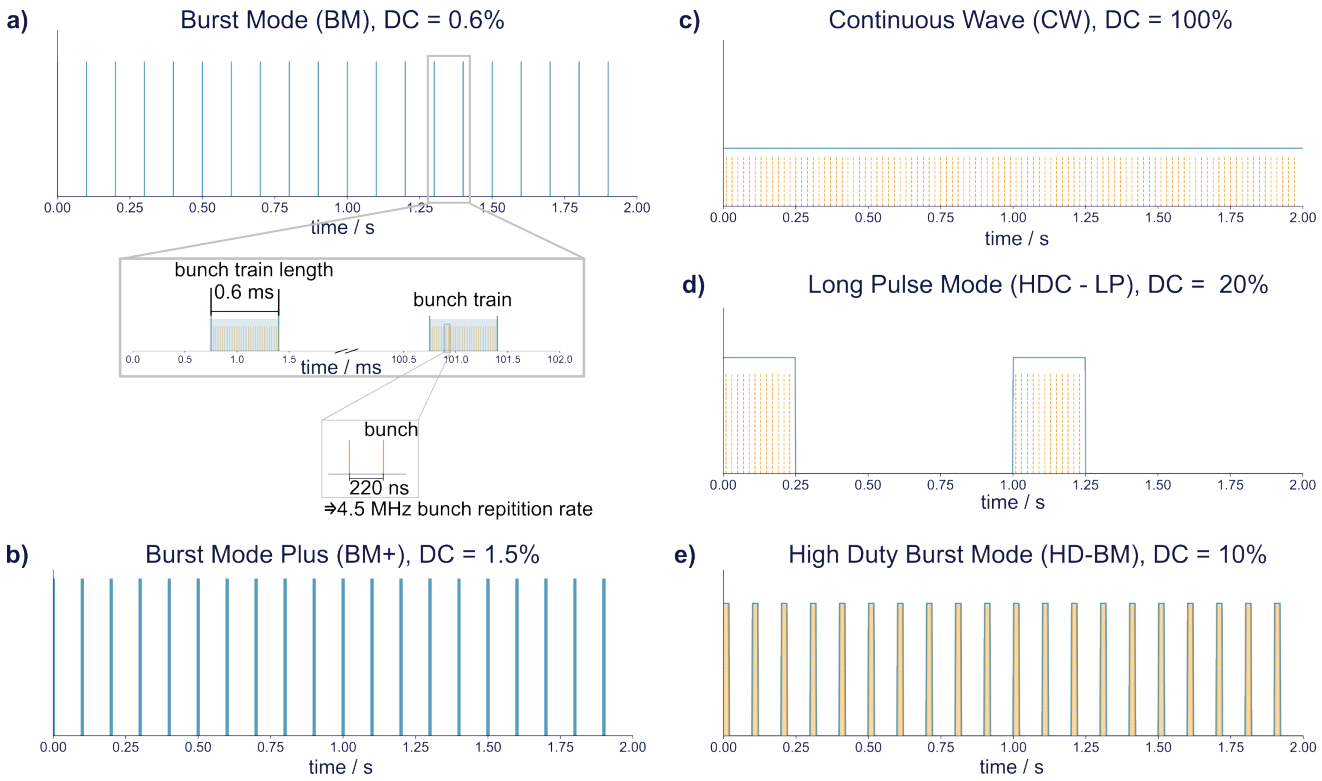
- Operation experience
  - **Extreme high stability in electron bunch / x-ray pulse delivery**
  - **Injector operational with low emittance and high repetition rate**
  - **First FEL facility operating in multiplexing mode delivering bunches with dedicated parameters to different FELs (most other FELs still to date operate for 1 experiment at a time)**

Possible elements of a European XFEL upgrade proposal

- Accelerator upgrade
  - **Several options to make best use of the sc Linac**
- Additional FEL sources and scientific instruments
  - **Add SASE5 with FEL, beam transport, scientific instruments**
  - **Build second electron beam distribution with new FELs & new experiment hall**
- Modifying and refurbishing existing instrumentation
  - **Accelerator, FEL, x-ray beam transport or scientific instruments**
  - **Some age-driven refurbishments are required**
- Expanding the experiment and User infrastructure
  - **Add. secondary sources, special instruments, data infrastructure**

Accelerator upgrade options

- Increasing the duty-cycle (DC) allows to increase the number of pulses and the accessible repetition rates. Sum-rules & limits exist.
- Modes
  - **BM+ → Optimize present BM**
  - **CW → 1 MHz cw delivery at red. E_e**
  - **HDC → Trade E_e vs DC**
  - **HD-BM*→ Combine 10 Hz nd HDC**
- Assumptions (under scrutiny)
  - **High DC requires new injector**
    - ► emittance to be scrutinized
  - **FELs agnostic of accelerator mode**
  - **Bunch charge becomes a variable**
    - ► E_{pulse} may vary



Option	Present BM	BM+	HDC-LP	HDC-CW	HD-BM
Accelerator parameters					
Duty cycle	0.006	0.015	0.1	1	0.1
Max. beam energy /GeV	16.3	17–20	14	8	16
Train rate /Hz	10	10	1	n.a.	10
Bunch train duration /ms	0.6	1.5	200	n.a.	10
Max. repetition rate / MHz	4.5	9	1	1	4.5 (?)
Max. # of pulses/s	27000	50000	100000	1000000	100000
Bunch charge /pC	250–1000	250–500	100	100	200 (?)

*** parameters are still worked out**

Higher Duty Cycle with new, modified cryo modules

Similar to LCLS-II / SHINE approach

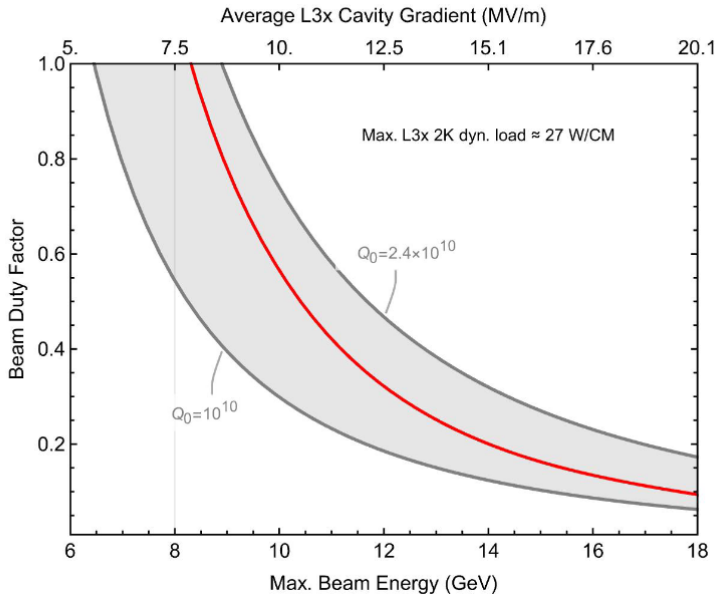
- **Optimized 2-phase He transport**
- **Improved cavity quality factor → reduced dynamic 2K load**

1) Rebuild the entire linac for max energy reach at CW operation

- **Very high cost ~1B€ (or more), very long dark time**

2) Rebuild only L1+L2 (+new 2nd injector), keep L3 (optionally extend it by modules from old L1+L2)

- **CW high gradient in L1+L2 with high-performance modules, keep beam energy up to BC-II constant @ ~2. – 2.5GeV, very beneficial for beam dynamics**
- **L3 in CW mode at low gradient and/or higher g pulsed mode with possibly increased d.c.**



Prospects for CW and LP operation of the European XFEL in hard X-ray regime

R. Brinkmann, E.A. Schneidmiller, J. Sekutowicz, M.V. Yurkov

Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany

NIM A 768 (2014)

High Duty Cycle Upgrade (as described in FOS report)

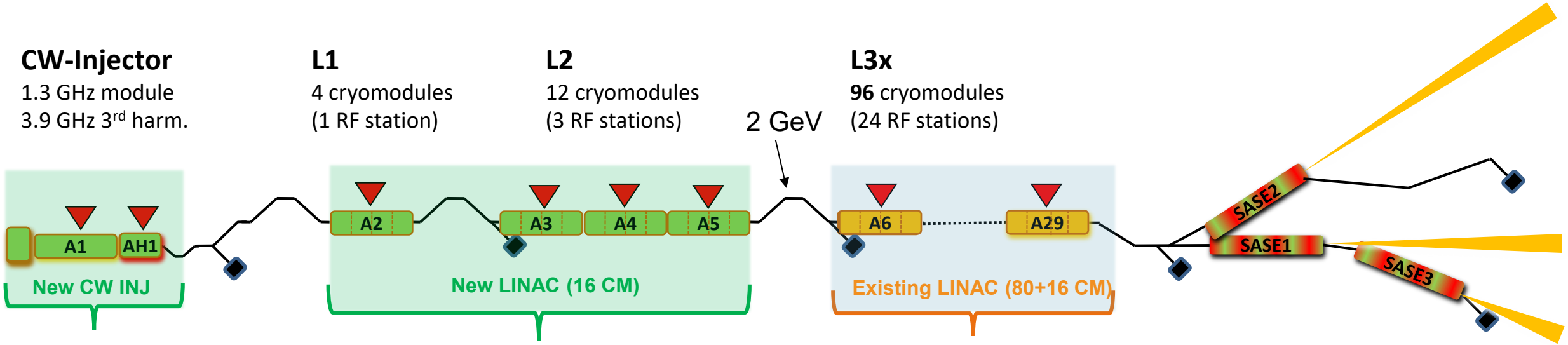
CW-Injector
1.3 GHz module
3.9 GHz 3rd harm.

L1
4 cryomodules
(1 RF station)

L2
12 cryomodules
(3 RF stations)

2 GeV

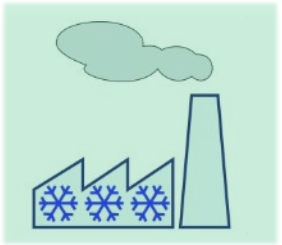
L3x
96 cryomodules
(24 RF stations)



New SRF injector
TS4i
How to maintain beam quality

16x new CW-cryomodules
Based on new high-Q_0 cavities
How to modify the cryomodules

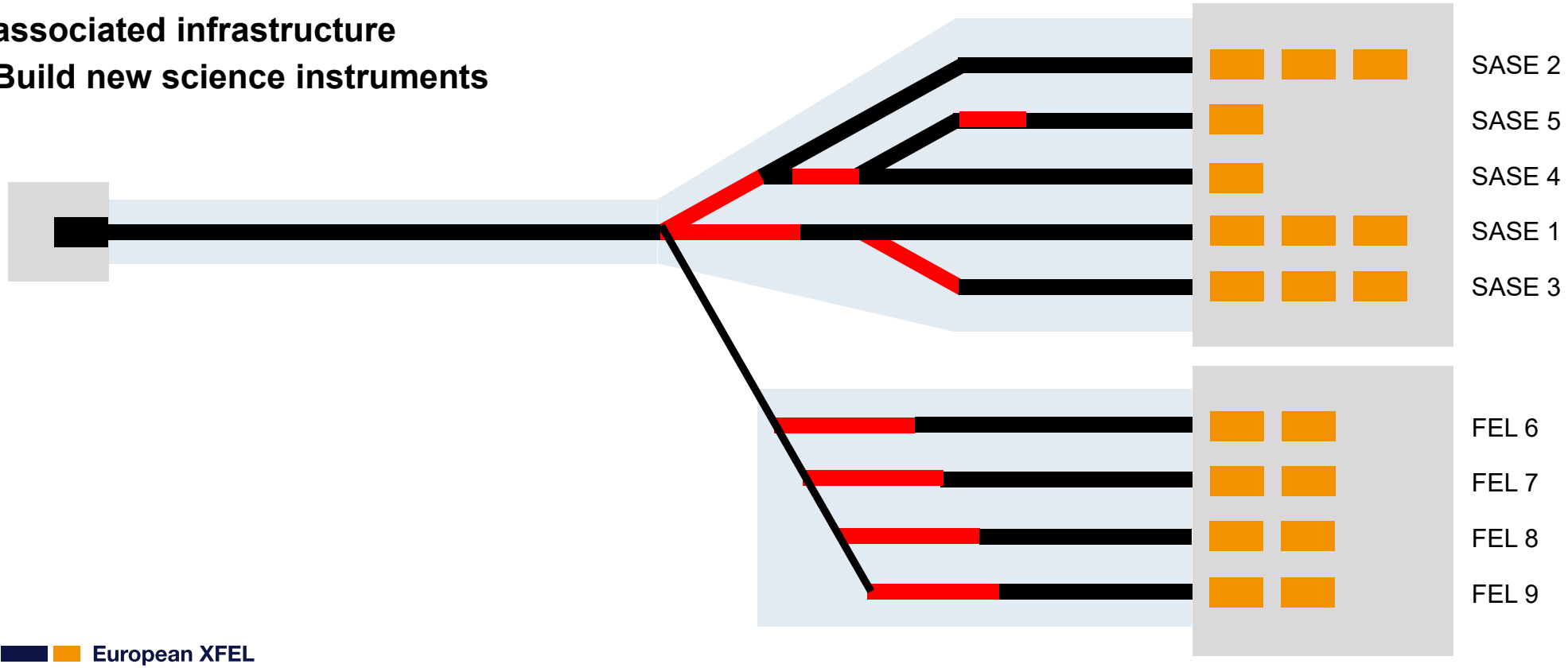
Maximum heat load supported by 2 phase pipe ?
What are the limits of our existing CMs
Maximum RF power supported by input couplers ?
How to optimize their operation



Slide prepared by J. Branlard/N. Walker/W. Decking (DESY)

FEL sources and scientific instruments

- Possible elements
  - **Complete SASE4 and SASE5**
  - **Build new electron beamlines & associated infrastructure**
  - **Build new science instruments**



X-ray pulse properties

- For the applications and science drivers, these are the properties to be discussed (not the ACC options)
- Standard beam properties (or ranges thereof)
  - **Photon energy (keV)**
  - **Pulse energy (µJ at sample)**
  - **Pulse duration (fs, FWHM)**
  - **Repetition rate (Hz; as needed for sampling physical property)**
  - **Number of pulses (needed to obtain single data point, e.g 1 means single pulse; 10^8 for protein structure)**
- Beyond std properties
  - **Transverse & long. Coherence (spectral resolution)**
  - **Full and higher order coherences (Glauber-like states)**
  - **Transform-limited pulse properties, e.g. pulse duration and spectral width**
  - **Phase control of the FEL field**
  - **Polarization & orbital angular momentum radiation**

Development of European XFEL pulse properties

How do different acc. modes extend x-ray pulse properties

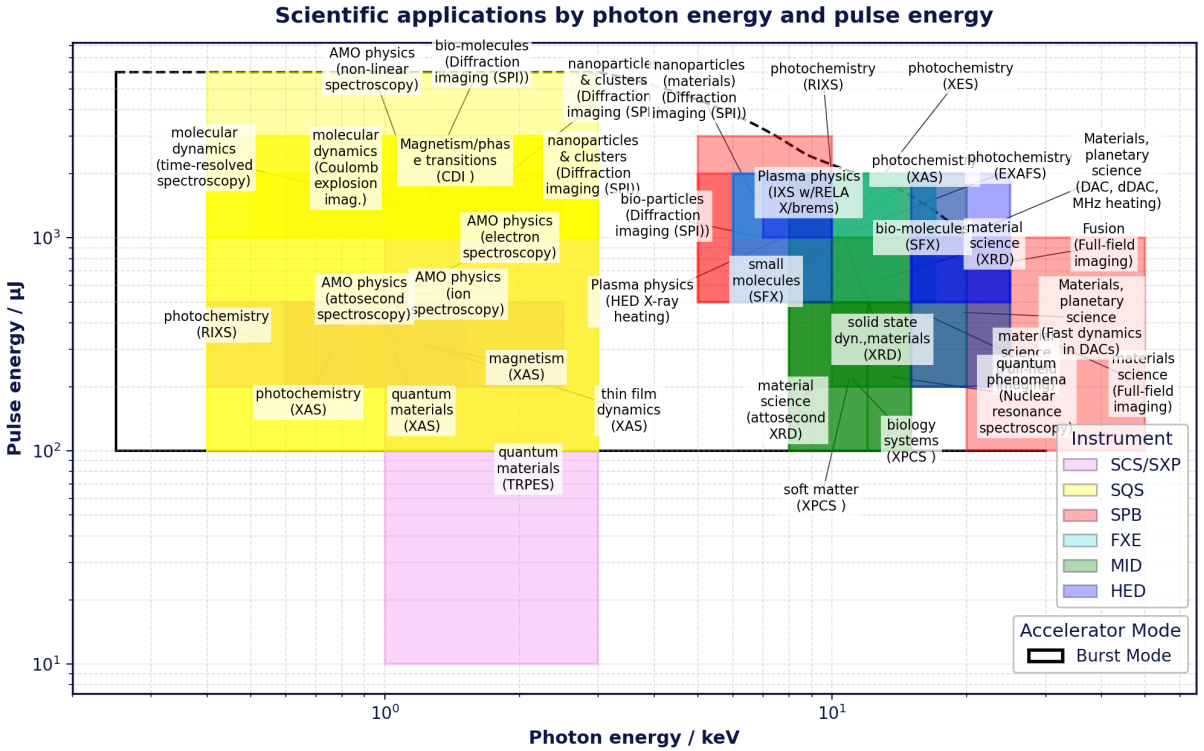
X-ray parameter	Unit	Presently achieved	Pot. extension	Mode
Min. photon energy	keV	0.25	keep	all
Max. photon energy	keV	30	60–80	BM+; HDC-LP; HD-BM
Std. pulse energy (8–12 keV)	mJ	≥ 1	keep	all
Max. pulse energy (8–12 keV)	mJ	≈ 5	keep	BM+
Std. pulse energy (0.5–2 keV)	mJ	≥ 2	keep	all
Max. pulse energy (0.5–2 keV)	mJ	≥ 15	keep	BM+
Std. pulse duration (FWHM)	fs	20-30	keep	all
Min. pulse duration (FWHM)	fs	0.2	≤ 0.1	all
Min. pulse rep. rate	Hz	shot-on-demand	keep	all
Max. pulse rep. rate	Hz	4.5×10^6	9×10^6	BM+
Excluded rep. rate regime	Hz	$10-5\times10^4$	none	HDC-CW
Max. number of pulses	1/s	27000	1×10^6	HDC-CW

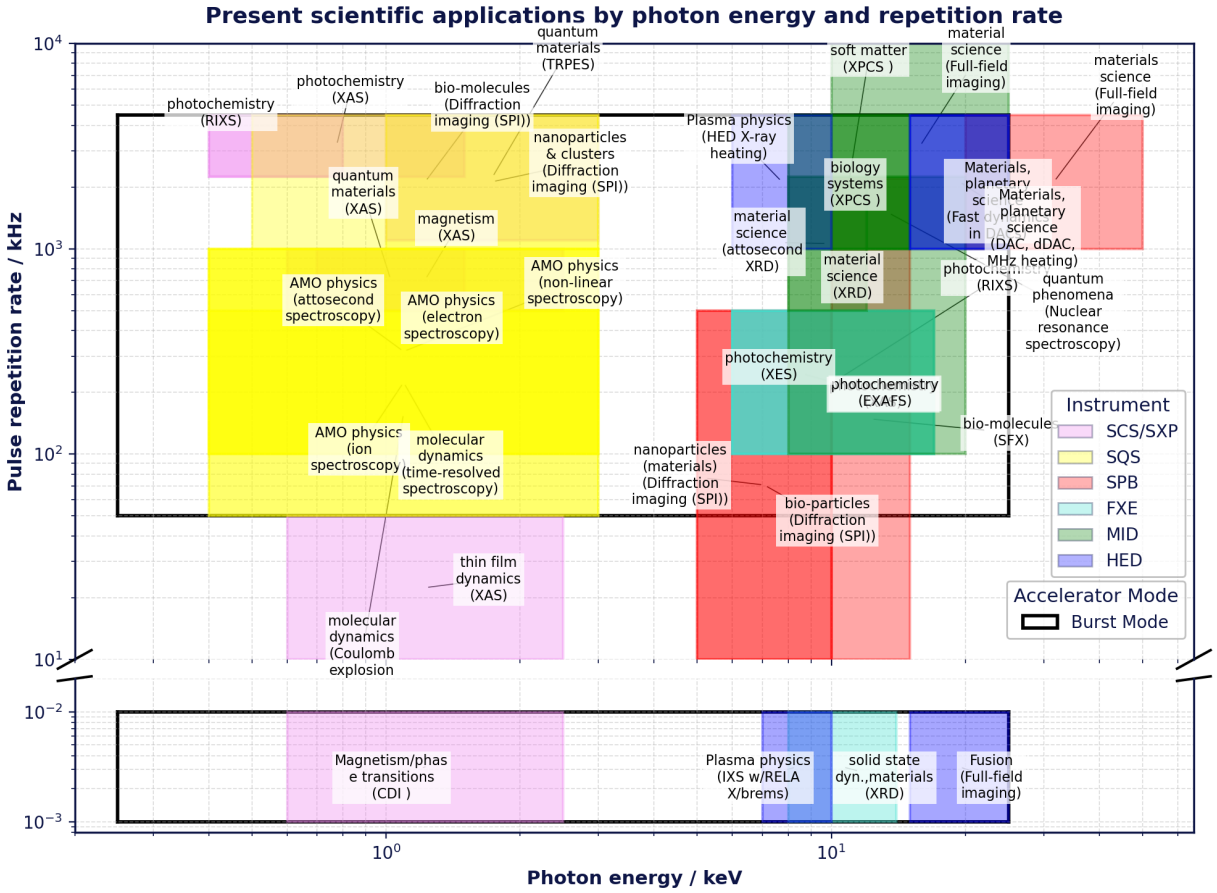
HD-BM might present meaningful baseline

X-ray parameter	Unit	Presently achieved	HD-BM mode	Option
Min. photon energy	keV	0.25	0.25	–
Max. photon energy	keV	30	30	ext. to 60 keV
Std. pulse energy (8–12 keV)	mJ	≥ 1	1	–
Max. pulse energy (8–12 keV)	mJ	≈ 5	2-3	–
Std. pulse energy (0.5–2 keV)	mJ	≥ 2	2	–
Max. pulse energy (0.5–2 keV)	mJ	≥ 15	5-8	–
Std. pulse duration (FWHM)	fs	20-30	20-30	–
Min. pulse duration (FWHM)	fs	0.2	0.2	≤ 0.1
Min. pulse rep. rate	Hz	shot-on-demand	shot-on-demand	–
Max. pulse rep. rate	Hz	4.5×10^6	1×10^6	??
Excluded rep. rate regime	Hz	$10-5\times10^4$	$10-5\times10^3$	–
Max. number of pulses	1/s	27000	1×10^5	??

Analysing scientific application requirements to x-ray parameters

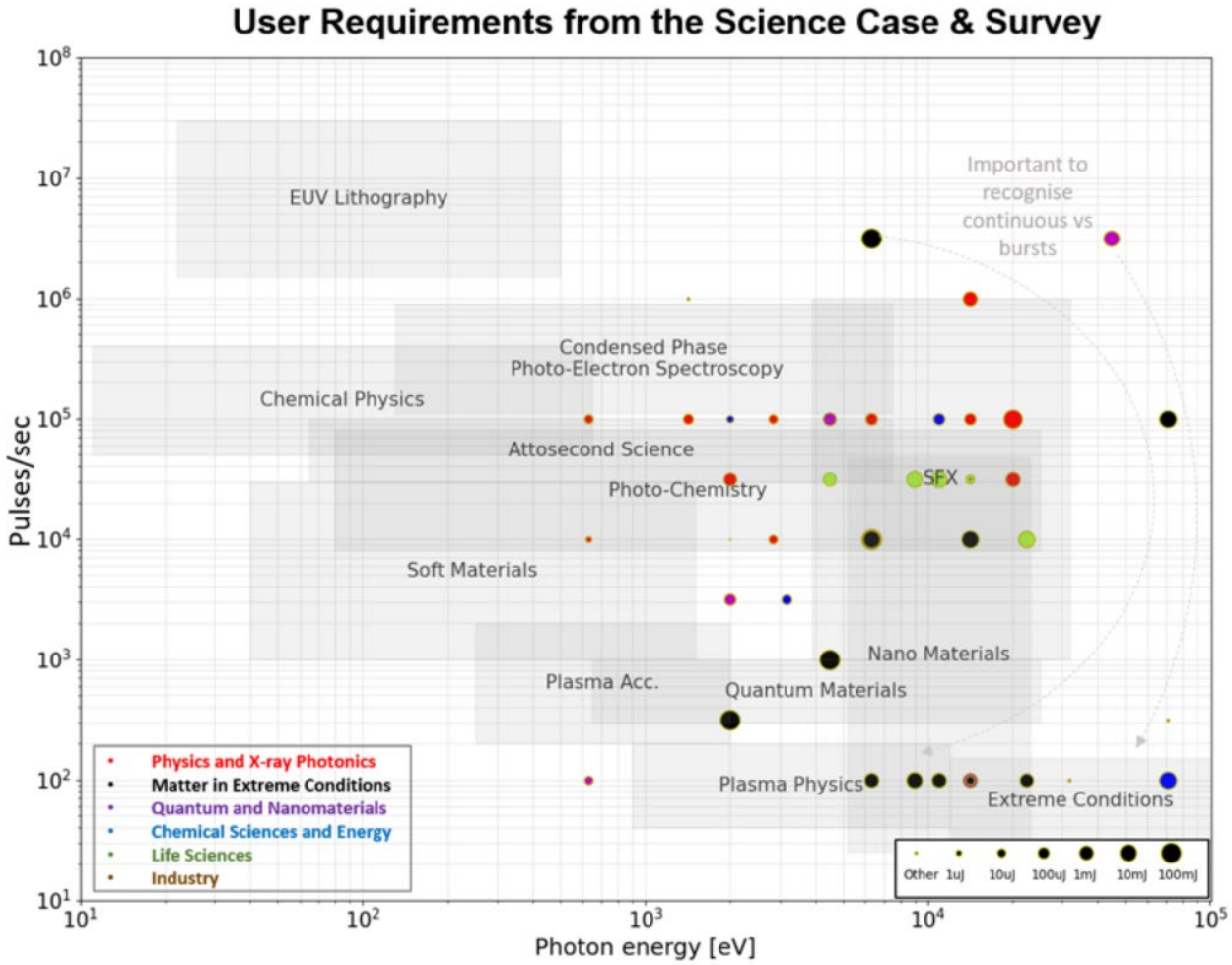
- European XFEL (present, only initial data collection)

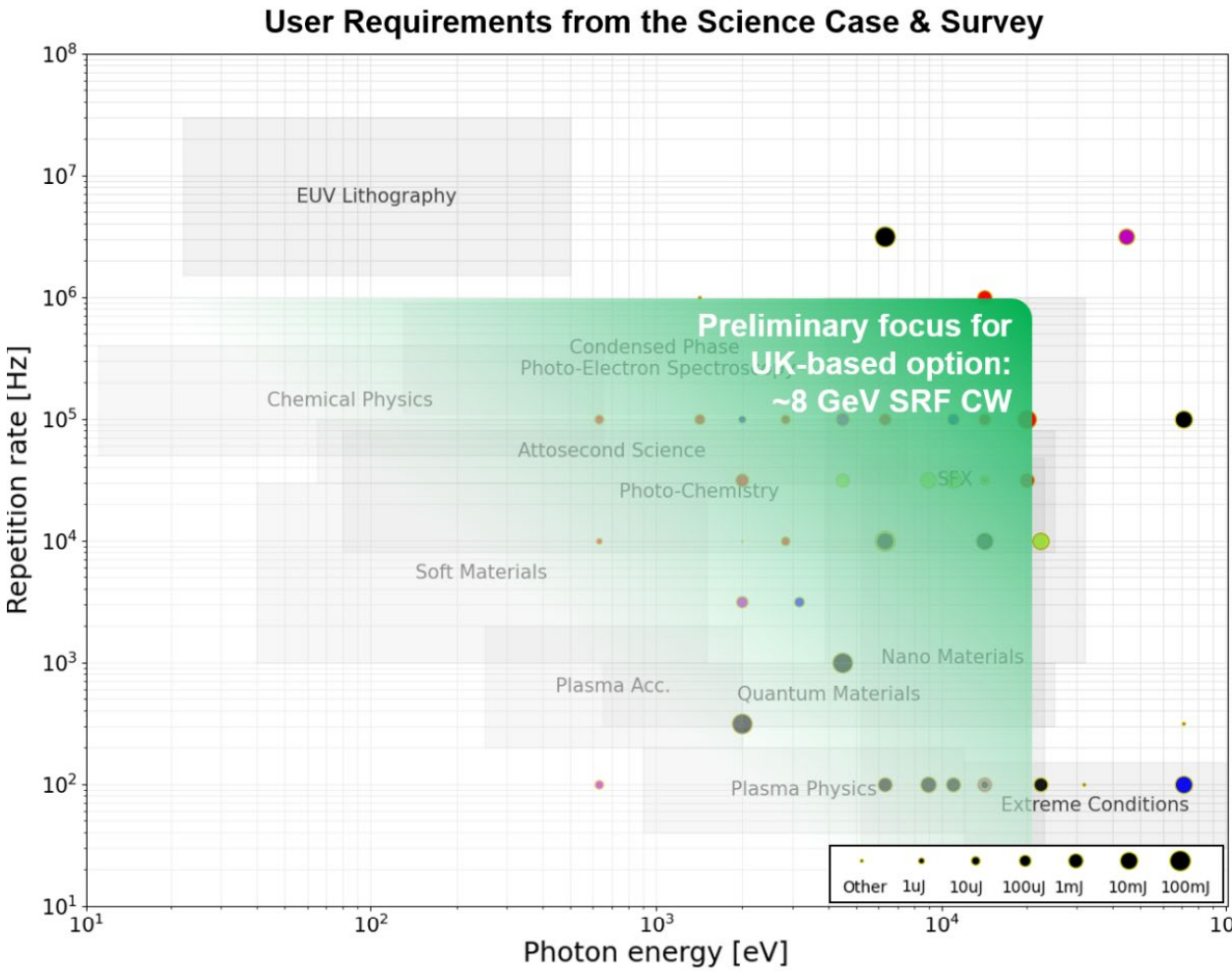




For comparison

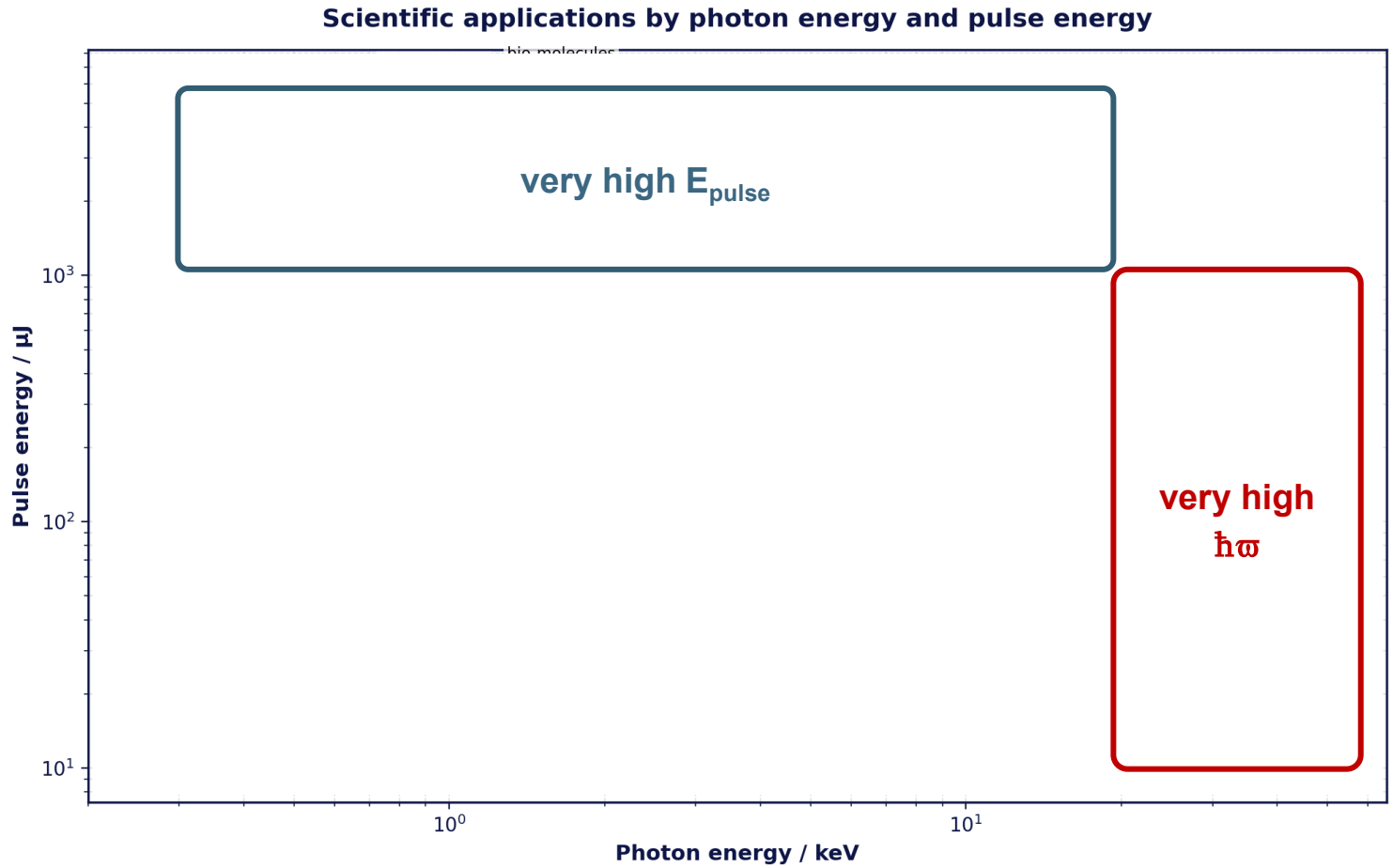
- Next-Generation XFEL





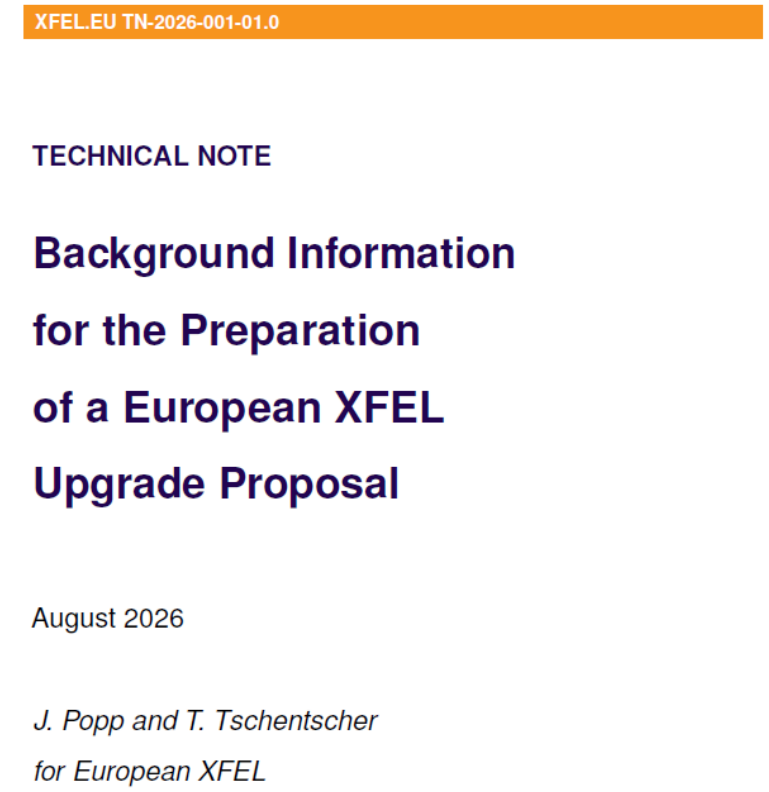
‚To do' for upgrade proposal

- Populate x-ray parameter with those scientific applications considered crucial for upgrade.
  - **define most important areas of this phase space**
  - **e.g. for $E_{pulse}(\hbar\omega)$ space**



Documents

- Feasibility & Options Study (Jun 2026, status: DRAFT)
- FOS Addendum 10Hz (expected Oct/Nov 2026)
- Background info (vers. Aug 2026)



XFEL.EU TN-2026-001-01.0

TECHNICAL NOTE

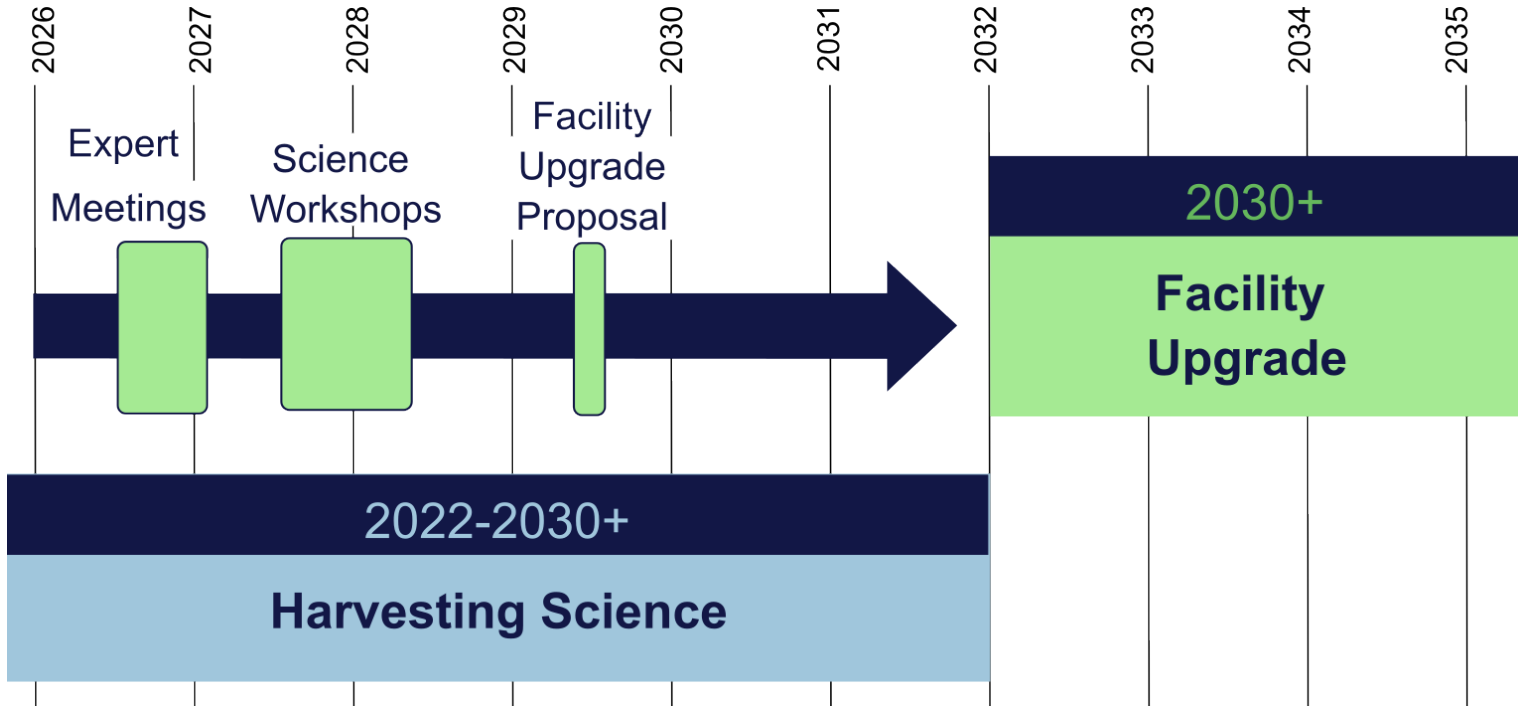
Background Information for the Preparation of a European XFEL Upgrade Proposal

August 2026

J. Popp and T. Tschentscher
for European XFEL

European X-Ray Free-Electron Laser Facility GmbH
Holzkoppel 4
22869 Schenefeld
Germany

Activities to prepare upgrade proposal



Expert meetings

- Mostly during 2nd half 2026
- Focussed on experimental FEL techniques
  - **Spectroscopy, 16. Sep 2026**
  - **Imaging, 22. Sep 2026**
  - **…**
- Expected outcome
  - **Ideas for improvement of radiation parameters, experiment conditions, ancillary instrumentation**
  - **Future experiment ideas (not feasibly at present)**
  - **Potential scientific applications area (topics, speakers, … → Science Workshops)**
  - **Documents: Collection of questionaires; internal reporting**

Science workshops

- Probably starting early summer 2027 … (need to define dates timely …)
- Shall take place in Shareholder countries (co-organized with EuXFEL) → suggestions welcome !
- Focussed on scientific application areas (with dedicated sessions to establish common ground)
  - **AMO**
  - **Photochemistry**
  - **Solid-state problems**
  - **Materials science issues**
  - **Extreme states**
  - **Fundamental physics**

  } **to be reviewed (and session topics to be defined)**
- Expected outcome
  - **Scientific applications for the 2035-2045 time**
  - **Requirements to FEL radiation properties, instruments, data preparation**
  - **Workshop reports**

Preparing upgrade proposal

Based on the collection of scientific applications and experiment proposals (Science Workshops & follow-up), complemented by the results of accelerator, FEL source, x-ray instrumentation, ancillary instrumentation, and computational methods R&D a proposal for **specific upgrade activities for the European XFEL** will be worked out.

- **Accelerator layout and technologies**
- **FEL sources and x-ray beam transports**
- **Specific science intruments and technology developments**

- Upgrade proposal document (of CDR character)
  - **Description of the upgrade proposal and its technical elements, ideally one option,**
  - **Definition of the supporting science case for the upgrade.**
- Upgrade proposal supplements
  - **Estimate of costs, effort and timeline approx. 1 yr later.**
  - Societal relevance analysis
  - Innovation potential report

Agenda
How we thought to continue today

Parallel sessions : what's happening where?

- **"Ultrafast Spectroscopy of (bio-)chemical processes"** in Seminar Room 1
  - **Session chairs: Benjamin van Kuiken, Chris Milne, Fred Lima**
  - **Invited experts: Markus Gühr, Phillipe Wernet**

- **"Spectroscopic analysis of solid state material properties"** in the Auditorium
  - **Session chairs: Justine Schlappa, Harald Sinn**
  - **Invited experts: Hermann Dürr, Giacomo Ghiringhelli, Ralf Röhlsberger**

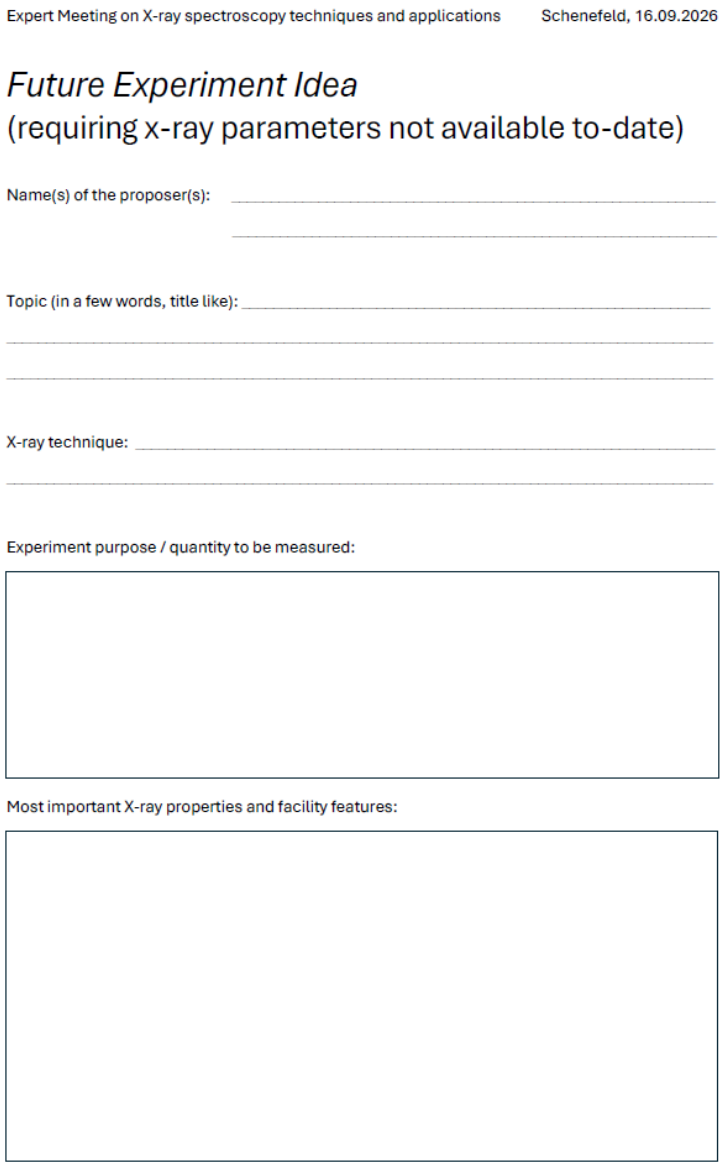
- **"Photo-emission and AMO spectroscopy"** in Seminar Room 2
  - **Session chairs: Giuseppe Mercurio, Michael Meyer**
  - **Invited experts: John Bozek, Till Jahnke, Kai Rossnagel**

Parallel sessions: how we think to do them

- We are a relative small number of people per group and should offer everybody time for statements and ideas. Proposal is to gather feedback from each participant on each topic, before going to the next topic.
- There are the three topics we have in mind:
  - **Feedback about FEL experiments you did**
    - ► How could these significantly improve? …beam properties, other major instrumentation (or organization) aspects
  - **Ideas for future experiments**
    - ► What kind of experiment(s) could you imagine which would require FEL parameters or instrumentation or .. not available today ? Think BIG !
  - **Science and/or scientific applications these could support**
    - ► Scientific areas or research topics which might be interested
    - ► People working in these areas, possibly interested to engage
    - ► Science workshops: topical sessions and ideas for speakers/contributors
- Documentation of what is discussed:
  - **Notes (Jennifer, me, session chairs)**
  - **Flipchart**
  - **Questionaire (in parallel and/or later)**

Questionaire

- Gather ideas for FEIs
- simple (2-page)
- informal
- to support further discussions



Expert Meeting on X-ray spectroscopy techniques and applications Schenefeld, 16.09.2026

Future Experiment Idea
(requiring x-ray parameters not available to-date)

Name(s) of the proposer(s): _____

_____

Topic (in a few words, title like): _____

_____

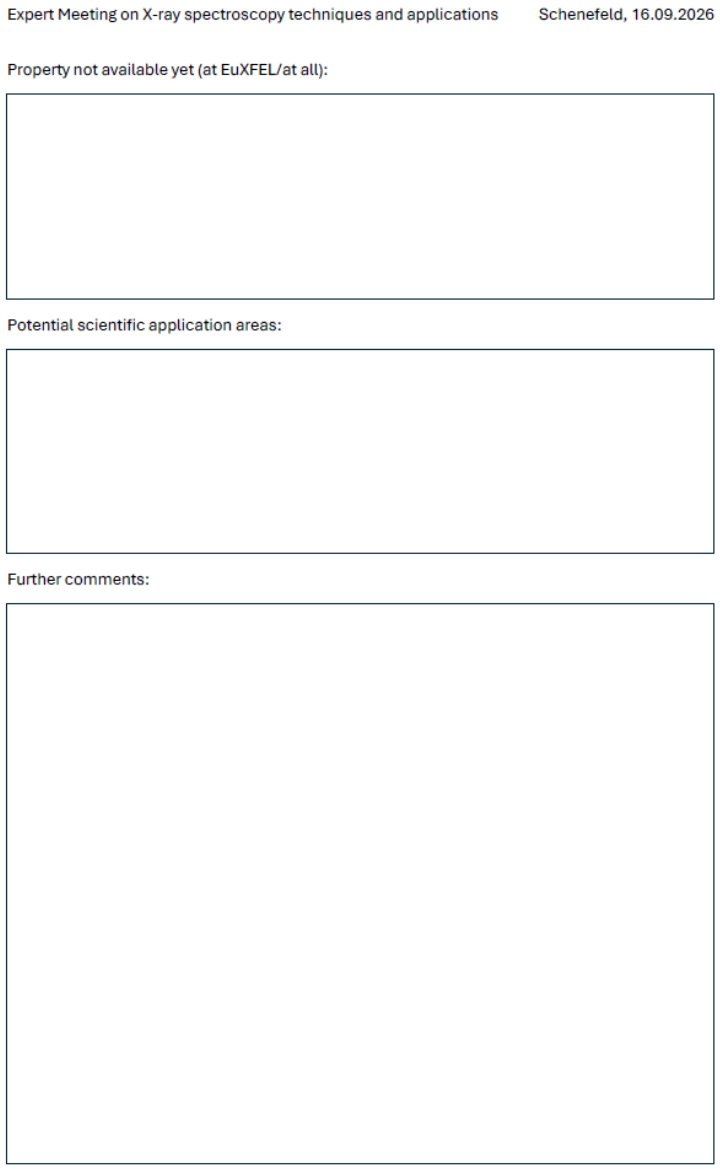
_____

X-ray technique: _____

_____

Experiment purpose / quantity to be measured:

Most important X-ray properties and facility features:



Expert Meeting on X-ray spectroscopy techniques and applications Schenefeld, 16.09.2026

Property not available yet (at EuXFEL/at all):

Potential scientific application areas:

Further comments:

Let‘s wrap up