

The European XFEL infrastructure and science



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ELI Ultrafast Science Workshop
Held at European XFEL, Feb 12, 2026
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Welcome to European XFEL !



European XFEL overview



3 FEL sources (perm. Magnets, planar)
SASE1 – Hard x-rays 5 – 30 keV
SASE2 – Hard x-rays 5 – 30 keV &
Self-seeding (8 – 14 keV)
SASE3 – Soft & Tender x-rays (0.27 – 3 keV) &
var. polarisation afterburner

7 scientific instruments
SPB/SFX – SFX, SPB, imaging
FXE – XRD, XAS, XES, EXAFS
MID – imaging, XRD
HED – XRD, XES, SAXS
SQS – part. spectros., imaging
SCS – XAS, RIXS, XRD, imaging
SXP – open port, XPS, EBIT

Superconducting electron accelerator
17.5 GeV, 1.3 GHz,
4.5 MHz, 10 Hz burst-mode
0,6% duty cycle
Highly flexible electron distribution



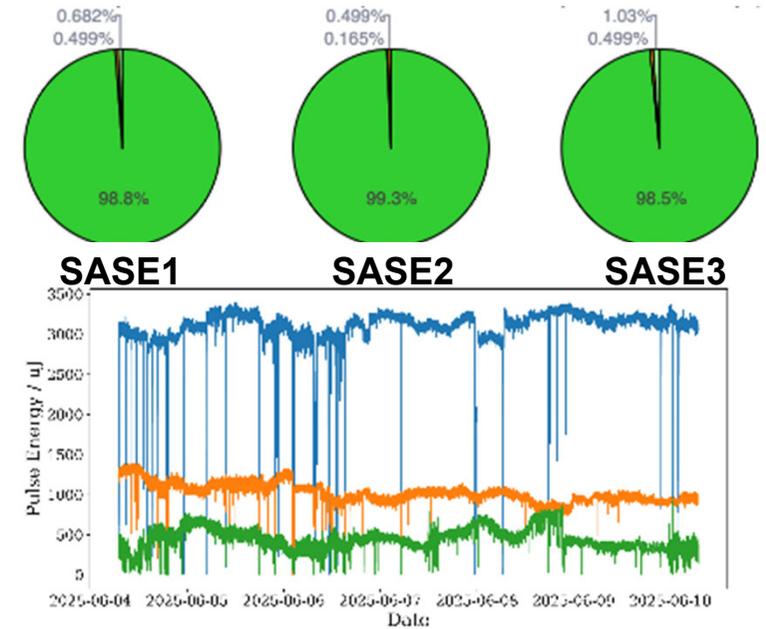
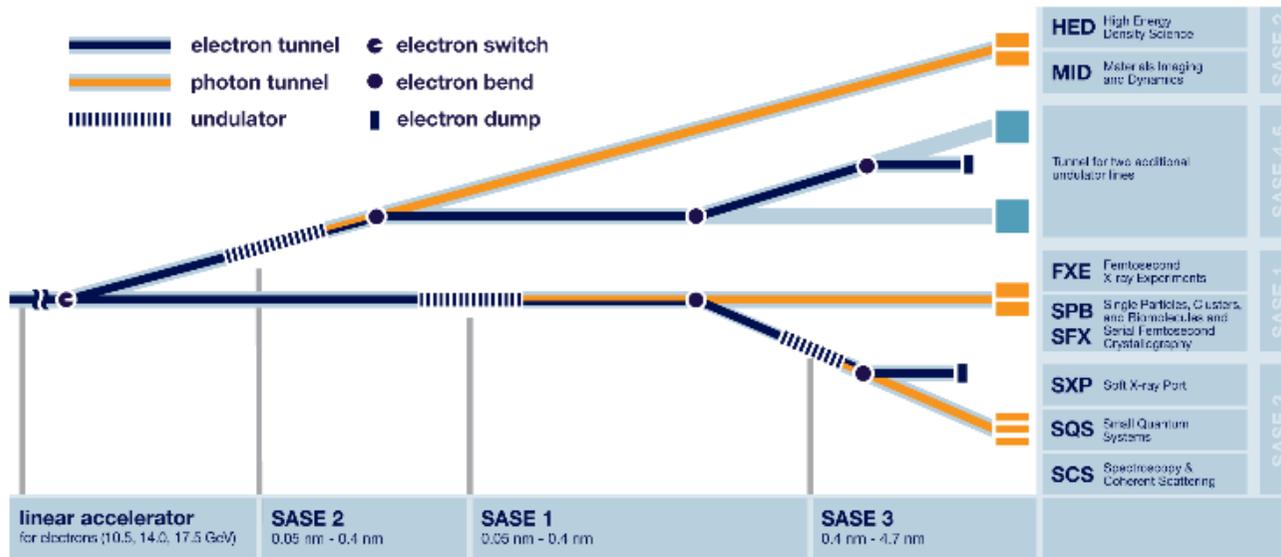
International User Facility

~ 1200 users/yr, ~2000 user visits/yr, 90 – 100 experiments
Start of operation: 2017

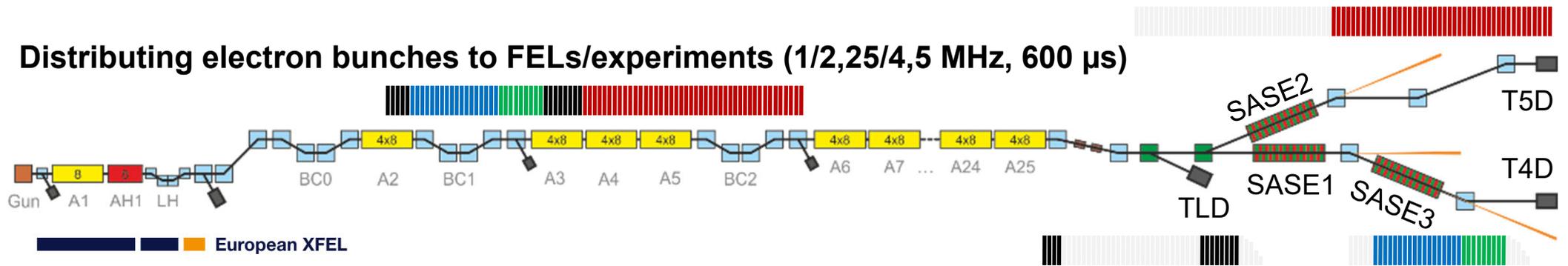


ESFRI Landmark

European XFEL as a Multi-user facility



Distributing electron bunches to FELs/experiments (1/2,25/4,5 MHz, 600 μs)

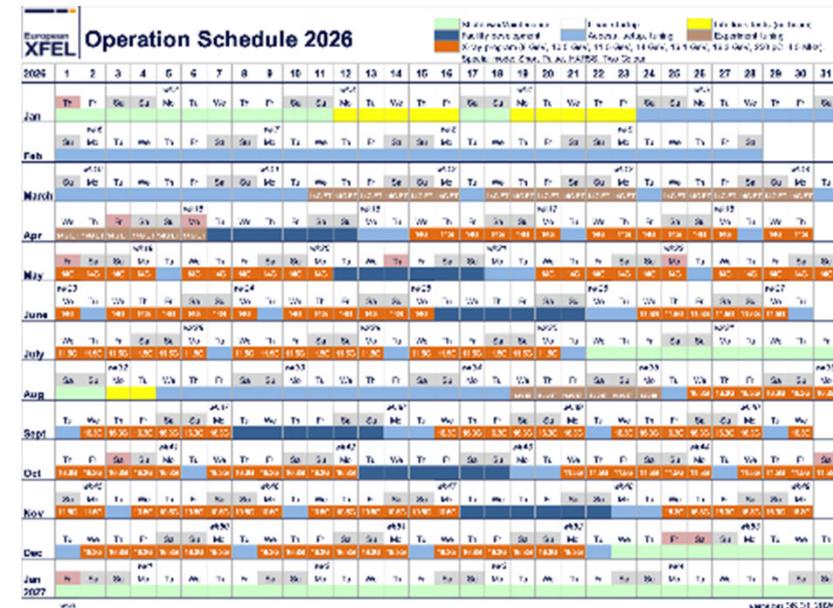


Status European XFEL

- Start of operation
- Regular operation
- 1st longer shutdown
- Startup
- Cool-down went very well
- Currently first tuning of FELs
- Regular operation
- About 32 wks of x-ray delivery program per yr (24/6 operation)
- Pattern with 4wks x-ray delivery and 1 wk facility development
- 2 short maintenance periods in summer & winter
- 2 allocation periods per yr for experiments: Feb/Mar to June & Aug to Nov/Dec

Sep 2017
 2017 – 2025
 Jun '25 – Jan '26
 Feb & Mar '26
 Apr '26 to

■ European XFEL

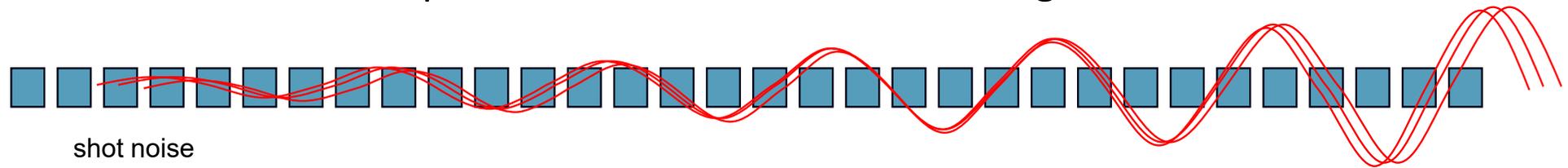


Development and science highlights

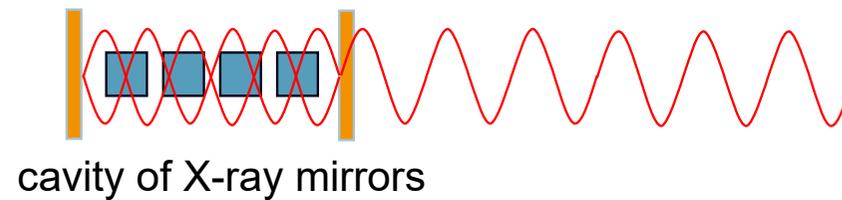
- FEL sources and variety of delivery modes
 - X-ray oscillator
 - Attosecond generation
- Science examples
 - A selection ...
- Outlook
 - 2030+ strategy
 - Instrument for fusion science research

What is an XFEL Oscillator*?

„SASE“ process: 32 undulators 200 m long

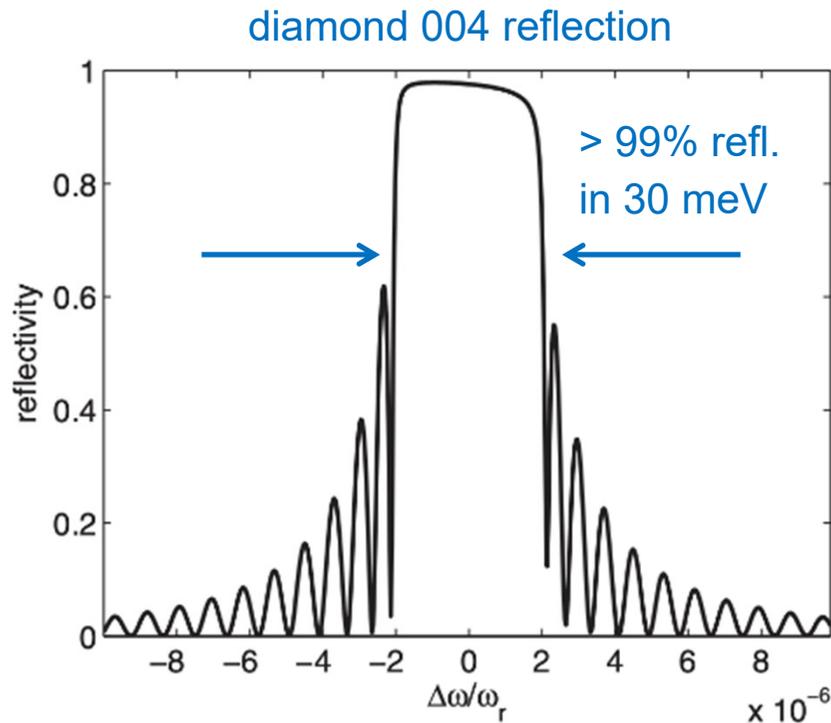


XFELO: 4 undulators



* names used in literature: Cavity-Based XFEL (CBXFEL), XFELO, or XRAFEL

Are there suitable X-ray mirrors for an XFEL cavity?



from: 1.) Huang, Ruth, PRL96, 144801 (2006), proposal 'XRAFEL'
 2.) Kim, Shvyd'ko, Reiche, PRL100, 244802 (2008), proposal 'XFEL'

4 mm



Single crystal diamond (TISNUM 2013)

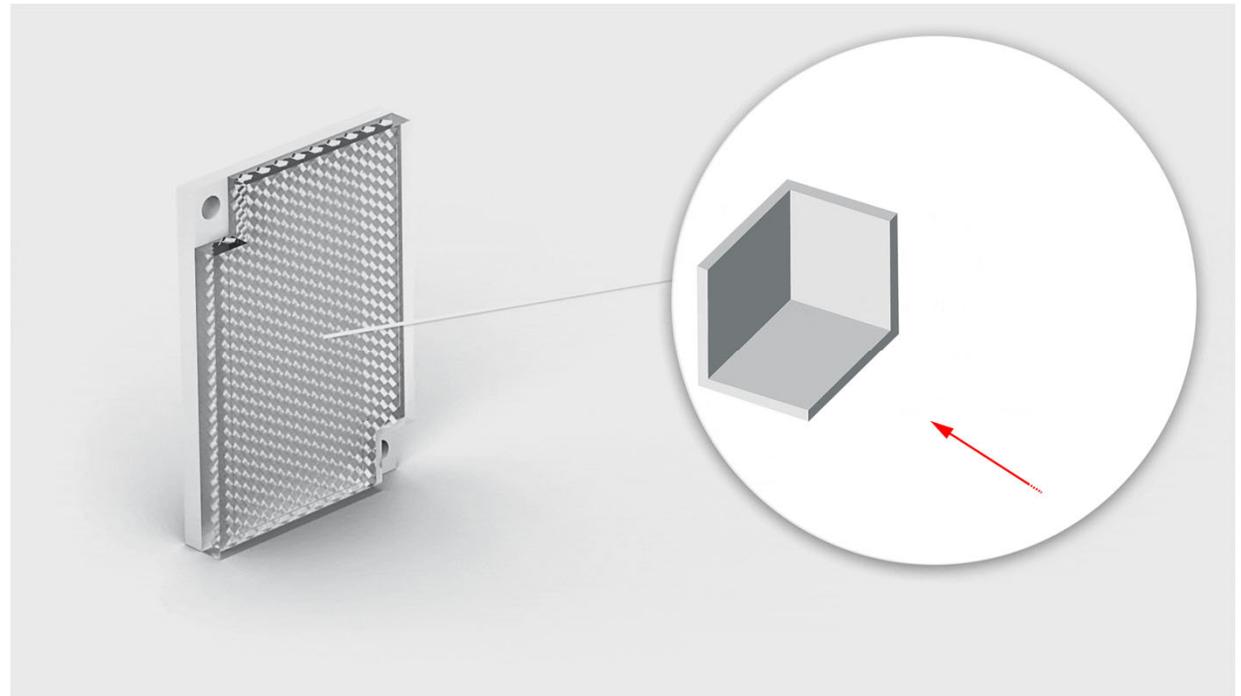
Can deflect X-rays up to 180°

Perfect alignment: About 50 nrad stability is required between mirrors!

X-ray cavity is built out of two cat-eyes

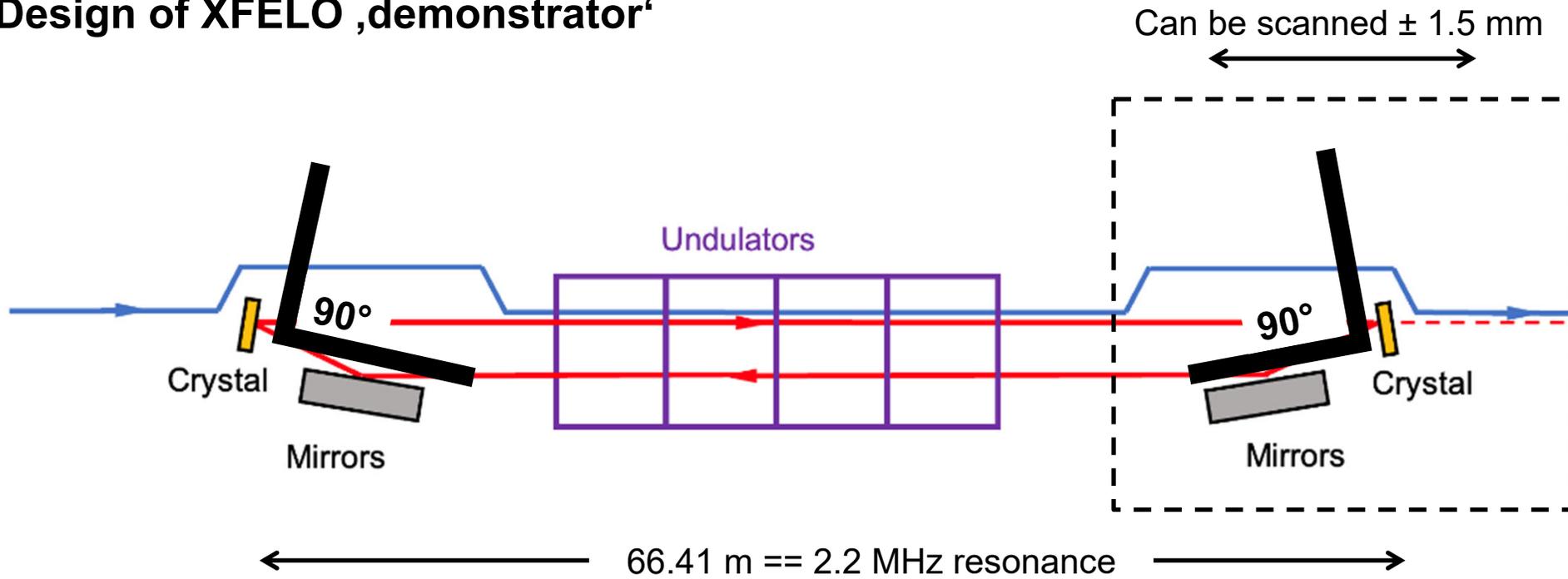


Retro-reflector principle

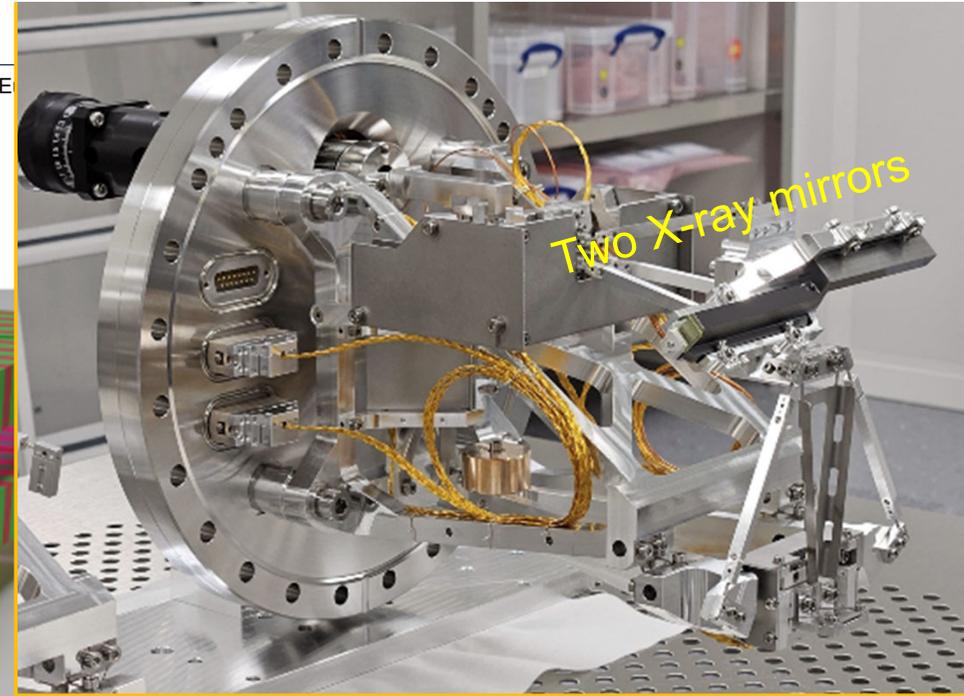
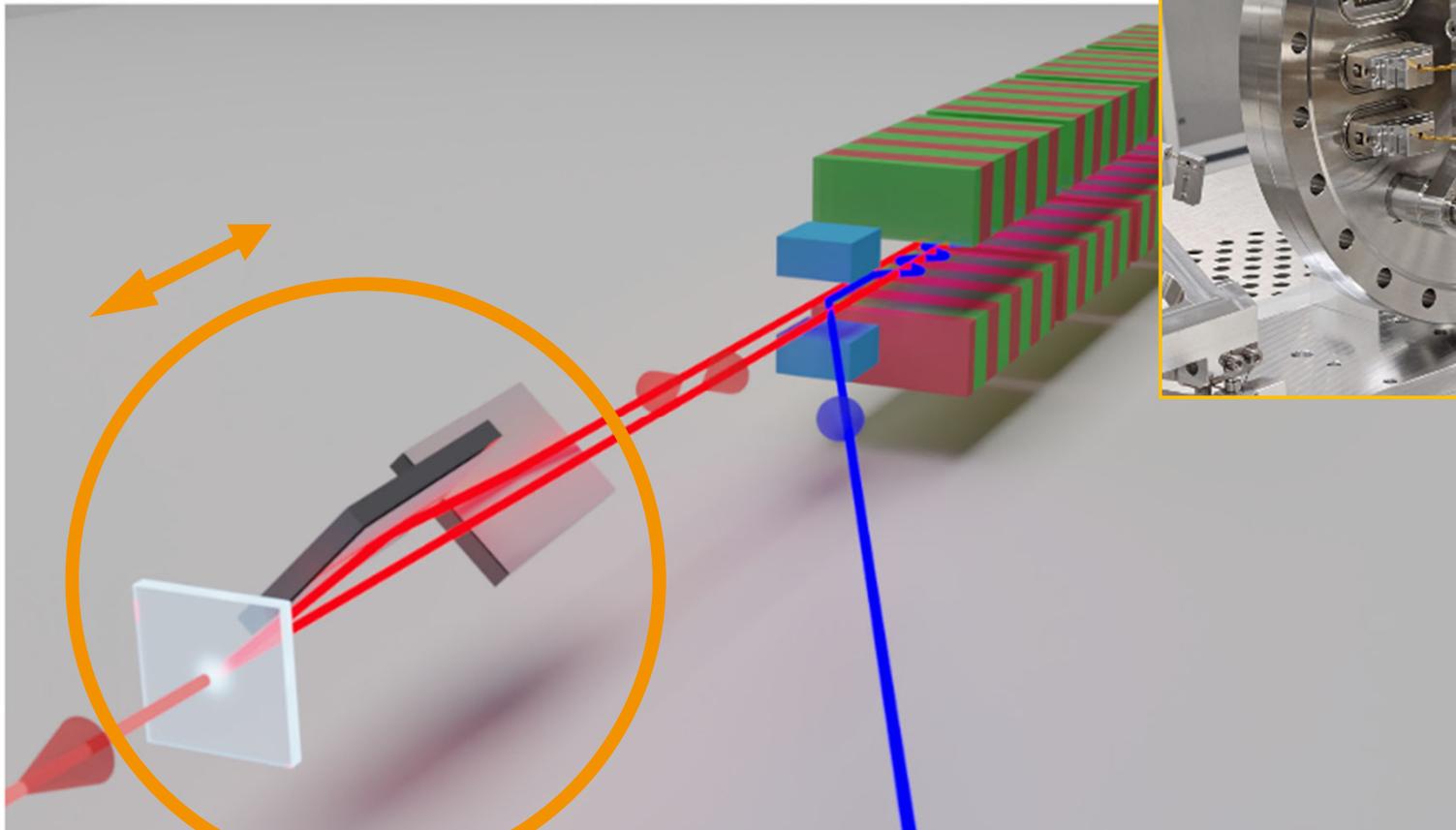


from www.wenglor.com

Design of XFELO ,demonstrator'



Retro-reflector at each end

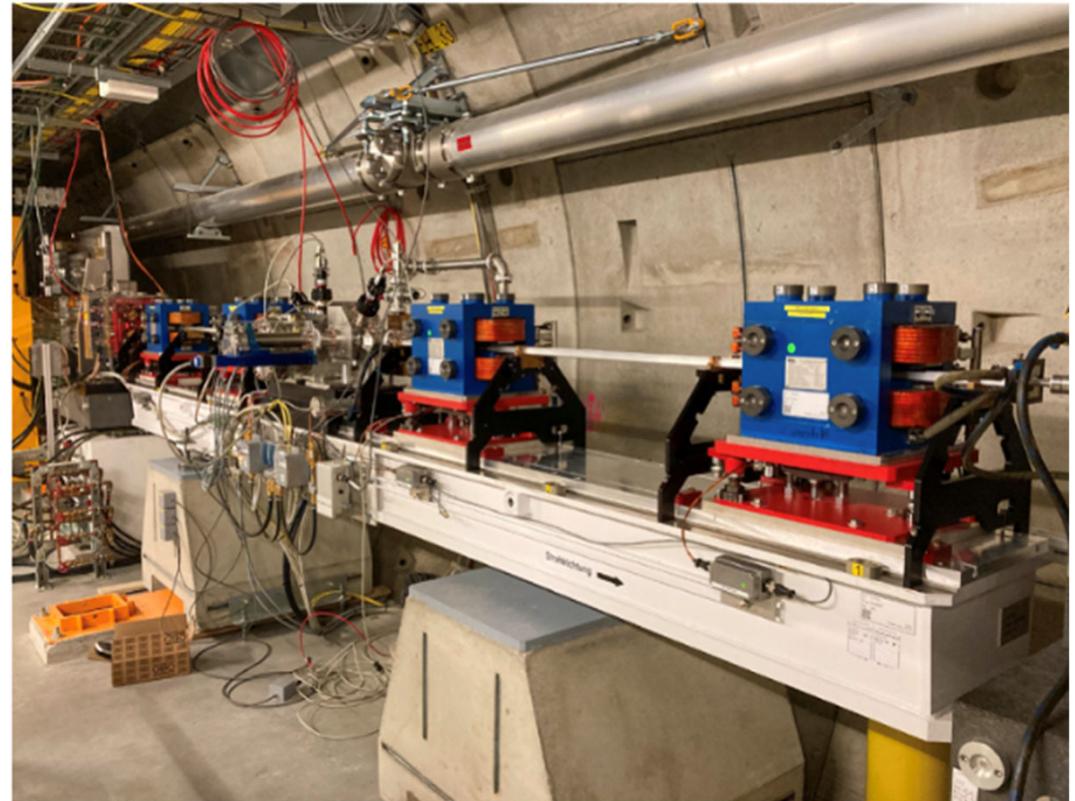


Bertram Friedrich (EuXFEL)

X-ray mirrors also re-focus beam towards the middle of the cavity

The project 'XFELO demonstrator'

- May 2020: Concept completed, internal R&D proposals submitted
- 2021 Start of funding. 2 postdocs, 8 work packages, > 30 people from EuXFEL, DESY, Uni HH involved
- 2021-22 Design, manufacturing ..
- 2023/24 Installation during shutdowns



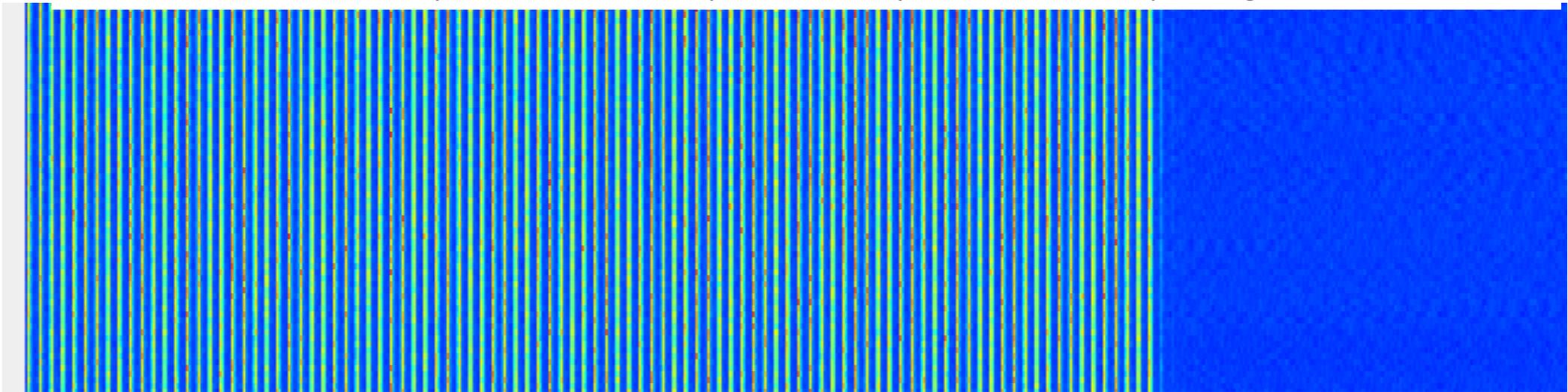
upstream chicane

May 2025: XFEL aligned in closed cycle: ring-down observed

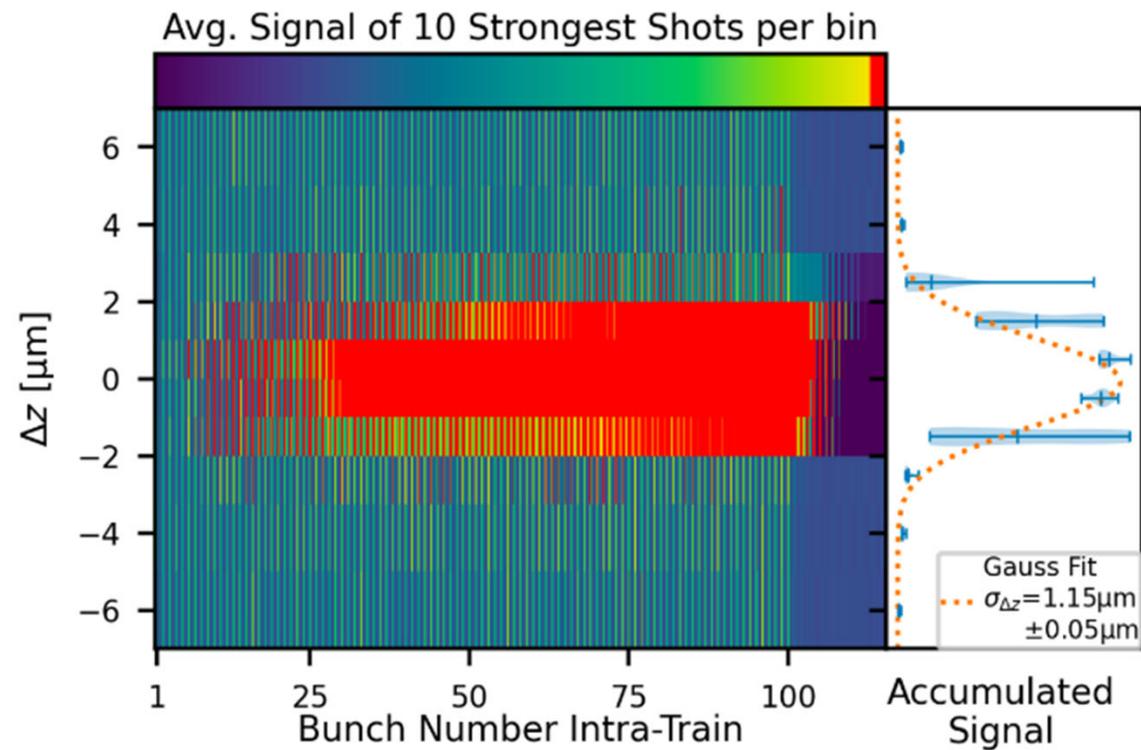
Measurement inside cavity: 100 bunches are put into cavity.

| → ring down (6 turns)

← Tuning of cavity length



Sensitivity to cavity tuning: 1 μm ! (calculated: 5 μm)

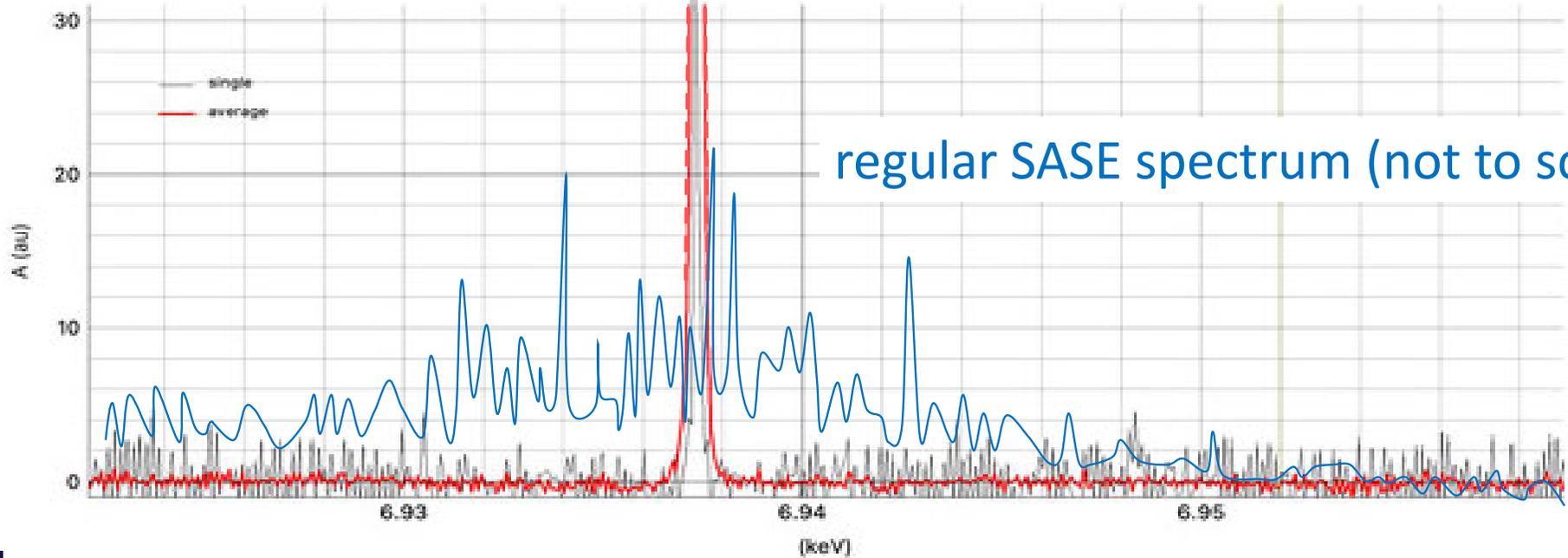


XFEL0 spectrum

10x more in integral than SASE

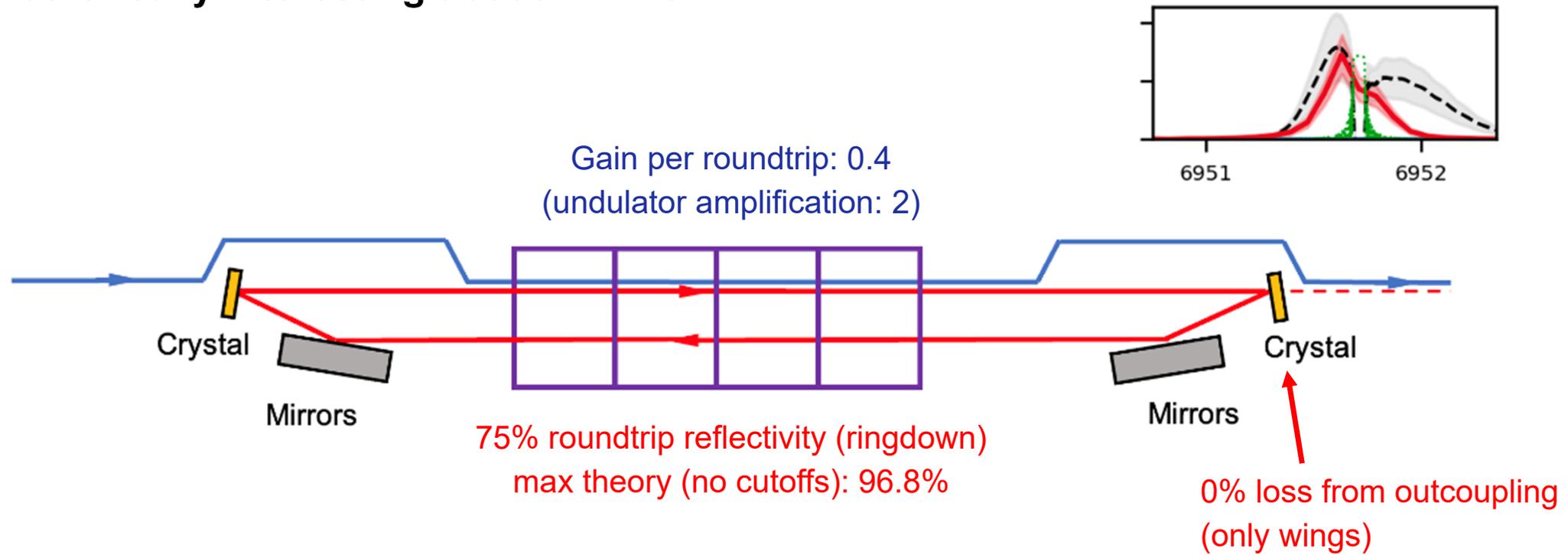
$x=0062.0, y=-1.0$

XGM: 2.50 μJ SPEC.INTEGRAL: 199687577.88 μJ @ 6937.4 eV



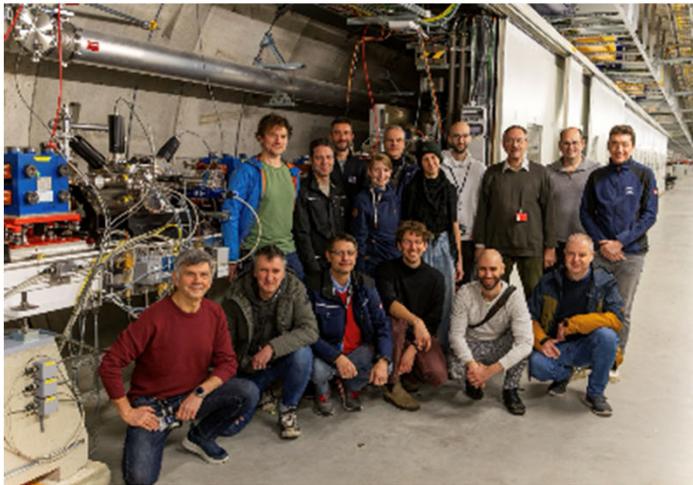
regular SASE spectrum (not to scale)

What is really interesting about XFELO

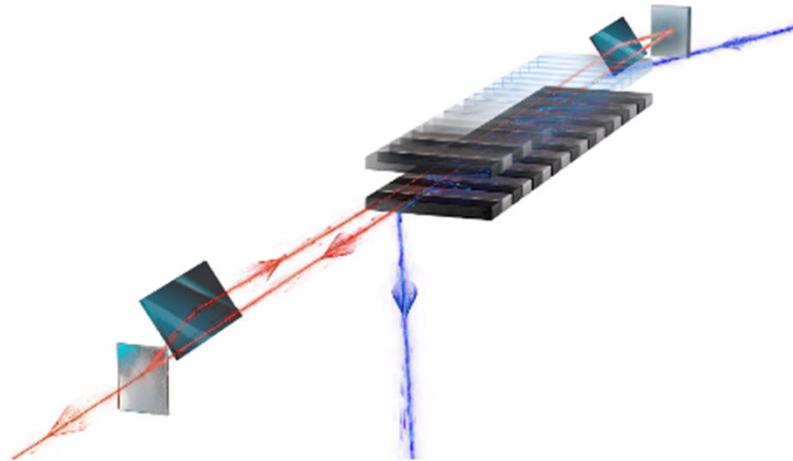


Conclusion

- For the first time an XFELO (CBXFEL, XRAFEL) achieved lasing
- The demonstrator setup has shortfalls (thermal effects, fixed energy) that need to be overcome before its really usable
- The XFELO principle has the potential for improved pulse-to-pulse stability, and higher order coherence



European XFEL



Article

Lasing of a cavity-based X-ray source

<https://doi.org/10.1038/s41586-025-10025-x>

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Open access

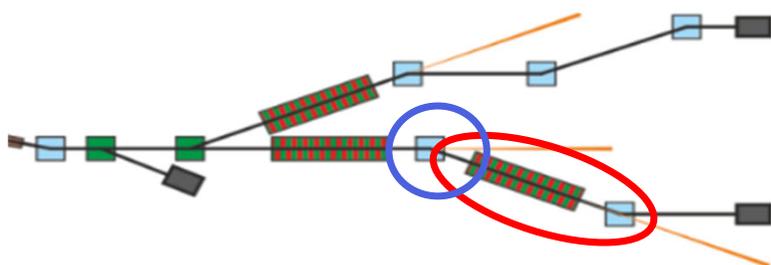
Check for updates

Patrick Rauer^{1,2}, Immo Bahns^{3,4}, Bertram Friedrich⁵, Sara Casabuoni⁶, Massimiliano Di Felice⁷, Martin Dommach⁸, Idola Freiljo Martin⁹, Wolfgang Freund², Jan Grunert¹, Marc Guetg¹, Ivars Karpics⁵, Suren Karabekyan⁷, Andreas Koch⁷, Manish Kujala¹, Daniela La Civita², Jia Liu², Theophilos Maltzopoulos², Mikako Makita², Frank Mayet¹, Lukas Müller¹, Benoît Rio², Liubov Samoylova², Silja Schmidtchen², Matthias Scholz¹, Alessandro Silenzi², Vivienne Strauch¹, Daniel Thoden¹, Torsten Wohlenberg¹, Maurizio Vannoni², Fan Yang², Winfried Decking¹, Joerg Rosebach⁷ & Harald Sinn²

The invention of the laser transformed optics by providing intense, coherent light in the visible region, but extending this concept to X-rays has been hindered by a lack of suitable gain media and mirrors. Current hard X-ray free-electron laser (XFEL) facilities^{1–3} overcome this by amplifying shot noise from a high-peak-current electron bunch via self-amplified spontaneous emission⁴ in a single pass through long undulators, delivering very high brightness but with a noisy, multi-spiked temporal and spectral profile. Cavity-based XFELs (CBXFELs)^{5–9} were proposed to close this gap by recirculating spectrally filtered X-ray pulses in a Bragg-reflecting cavity synchronized to a high-repetition-rate electron beam. Here we show lasing with multi-pass gain at 6.952 keV in a 132.8-m round-trip diamond-based Bragg cavity¹⁰ at the European XFEL, matched to the 2.23-MHz bunch spacing of the superconducting accelerator⁶. Under stringent length and angular stability requirements, a ring-up in the cavity across successive bunches was observed, producing spectrally pure, microjoule-level pulses. This establishes the feasibility of CBXFELs in an accelerator environment and validates diamond Bragg optics for X-ray resonators. The demonstrated spectral purity opens a path to next-generation X-ray science, which demands highly coherent, stable sources.

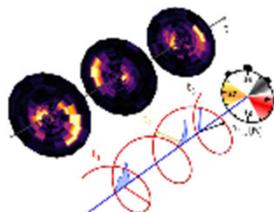
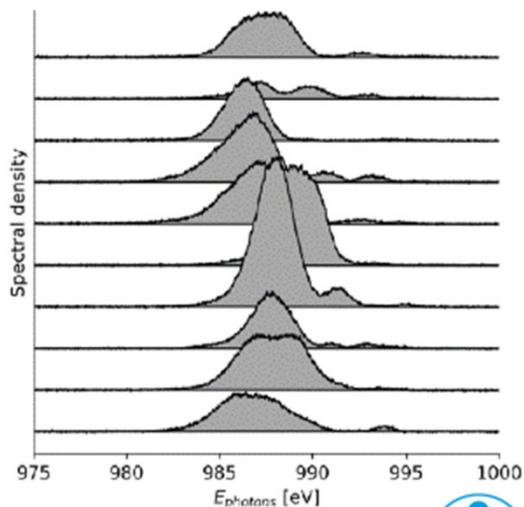
Rauer, Sinn, et al.,
Nature **650**, 93 (2026)

Atto pulse capabilities at sX (SASE3)



- First demonstration already in 2021
- Consecutive shots
- Since then: demonstrated and delivered several times
- (*) **Direct pulse duration diagnostics: further campaigns in 2023 and 2024**

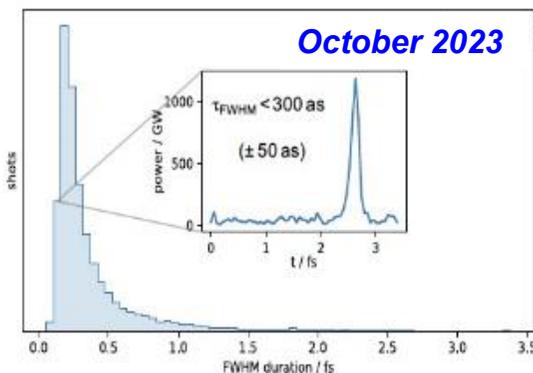
June 2022, 600 μJ (*)



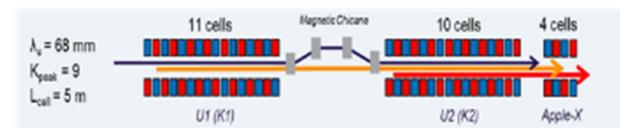
Nature Phot. 12, 215 (2018)
Circ. polarized streaking laser

QUACK
D. Ferreira de Lima (DA)

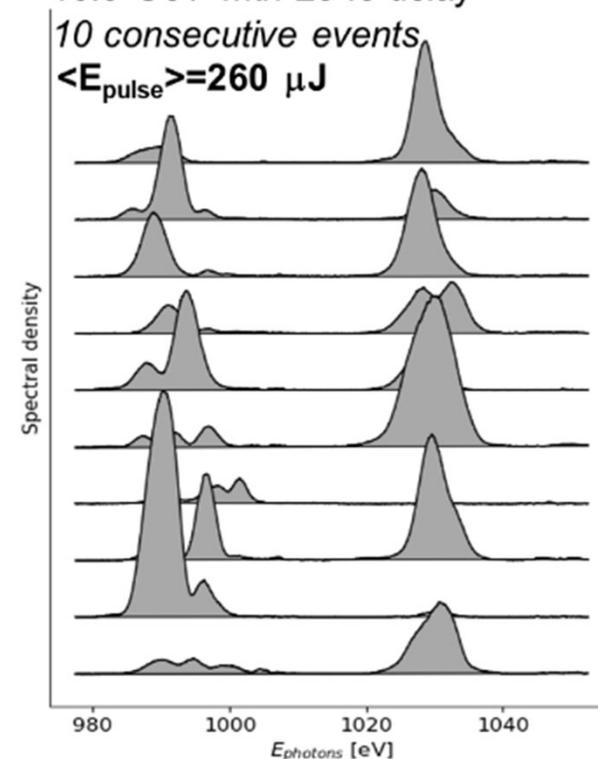
October 2023



Lead: S. Serkez

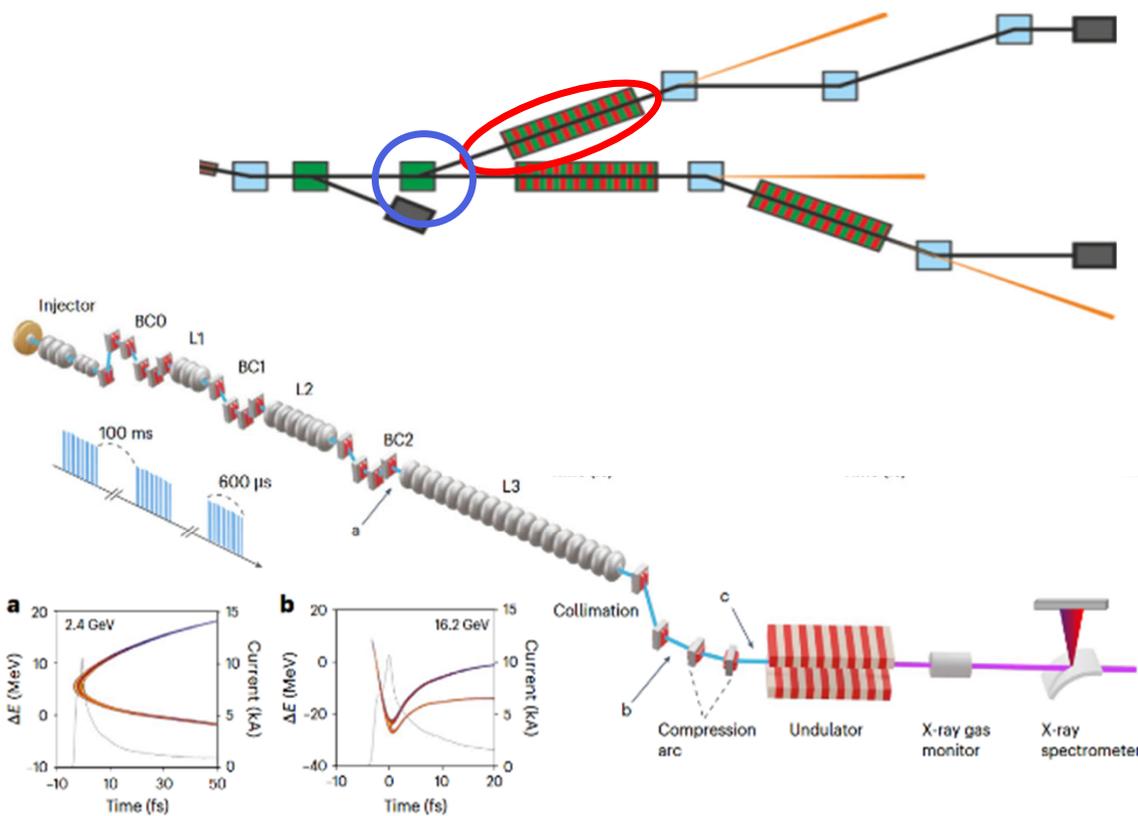


16.5 GeV with 25 fs delay
10 consecutive events
 $\langle E_{\text{pulse}} \rangle = 260 \mu\text{J}$



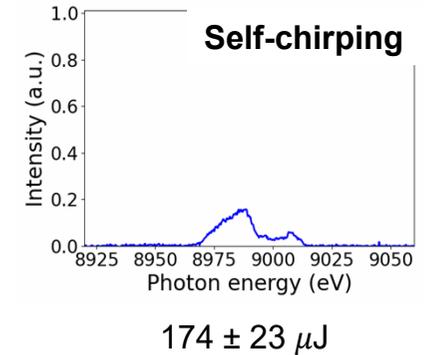
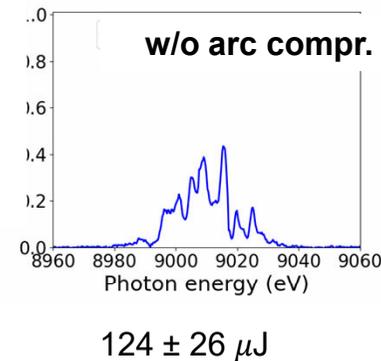
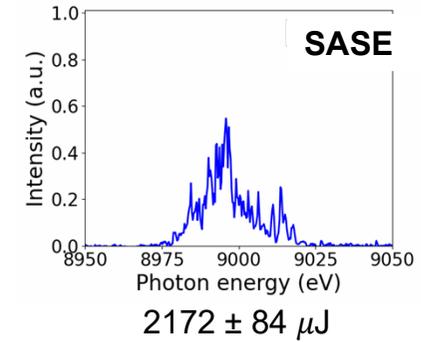
Two-color pulses; and since end 2024 polarization control for the second color in U2 using the Apple-X afterburner

Current capabilities for hX (SASE2)



European XFEL

Lead: Jiawei Yan



Terawatt-attosecond hard X-ray free-electron laser at high repetition rate

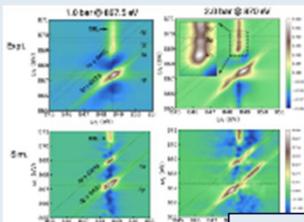
Jiawei Yan , Weilun Qin, Ye Chen, Winfried Decking, Philipp Dijkstal, Marc Guetg, Ichiro Inoue, Naresh Kujala, Shan Liu, Tianyun Long, Najmeh Mirian & Gianluca Geloni

Nature Photonics 18, 1293–1298 (2024) | [Cite this article](#)

Science examples

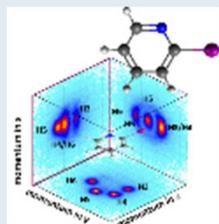
Selection publications Jan-Aug 2025

Super-resolution Stimulated X-ray Raman Spectroscopy



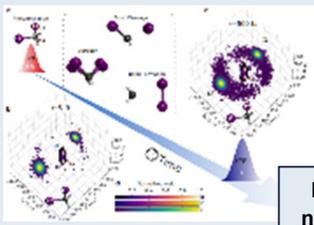
Li Nature

Imaging collective quantum fluctuations of the structure of a complex molecule



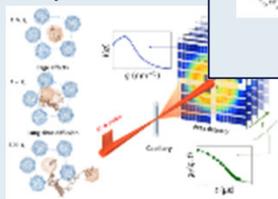
Richard Science

Imaging a light-induced molecular elimination reaction with an XFEL



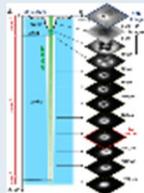
Li Nat. Comm.

Coherent X-rays reveal anomalous molecular and cage effects in a protein solution



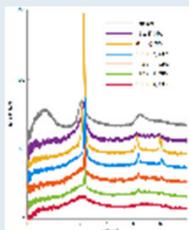
Girelli Nat. Comm.

Formation of high-angle nanocavity in LiF crystal femtosecond x-ray



Makarov Nat. Comm.

The structure of liquid carbon elucidated by in-situ X-ray Diffraction



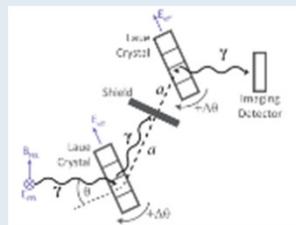
Kraus Nature

Pr and Pfr structures of plant phytochrome A



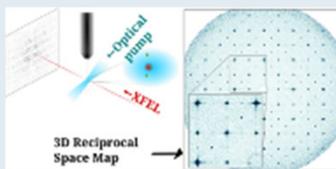
Nagano Nat. Comm.

Bounds on heavy axions with a X-ray Free Electron Laser



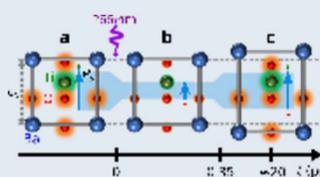
Halliday Phys. Rev. Lett.

Direct observation of the exciton-polaron in single CsPbBr₃ quantum dots



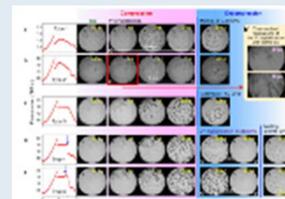
Shen ACS Nano

Ultrafast decoupling of polarization and strain in ferroelectric BaTiO₃



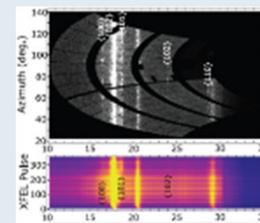
Hoang Nat. Comm.

Multiple freezing-melting pathways of high density ice at room temperature



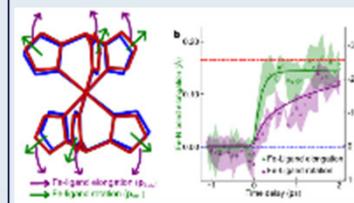
Lee Nat. Materials

Synthesis of Gold Hydride at High Pressure and High Temperature



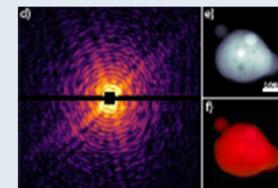
Frost Angew. Chem. Int. Ed.

Capturing the ultrafast dynamics with atomic resolution in spin-crossover materials



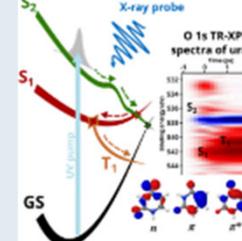
Vinci Nat. Comm.

SPRING, an effective and reliable framework for image reconstruction in single particle CDI



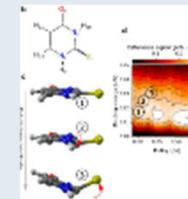
Colombo npj Comp. Mat.

Unraveling the relaxation dynamics of Uracil



Faccialà JACS

Direct observation of ultrafast symmetry reduction during internal conversion of 2-thiouracil

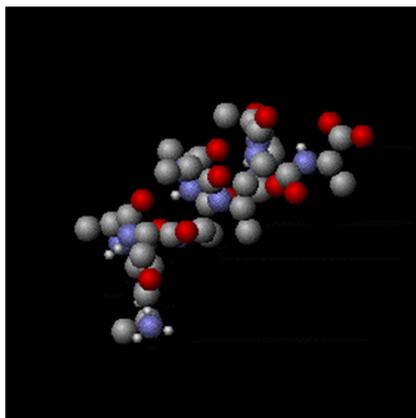
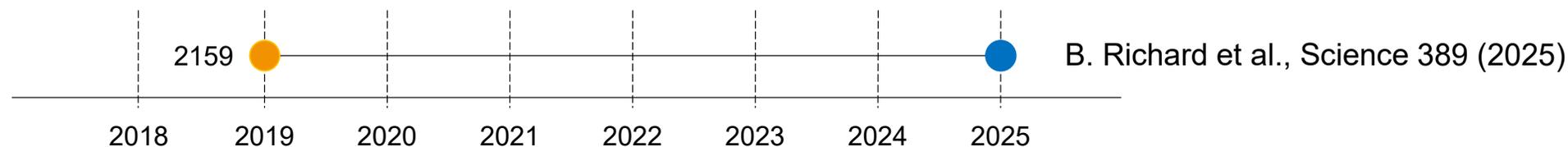


Jahnke Nat. Comm.

SQS: Imaging collective quantum fluctuations of the structure of a complex molecule

PI: R. Boll (SQS@EuXFEL)

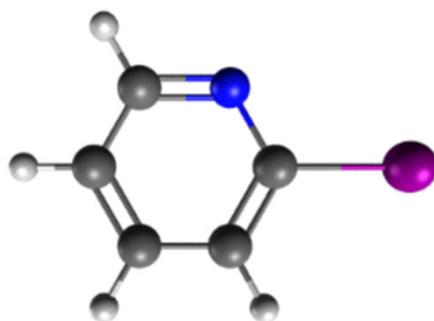
Collaboration: SQS, CFEL, DESY, U Hamburg, U Frankfurt, Kansas SU, SLAC, FHI



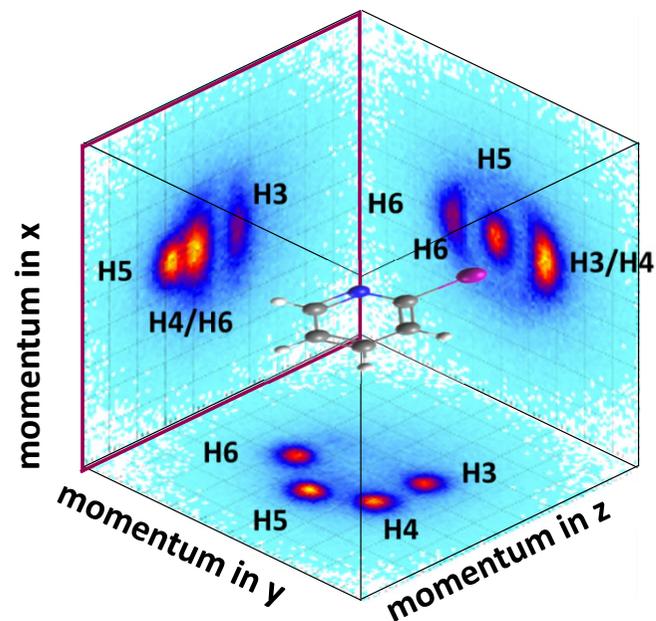
- Intense short X-ray pulses ionize all atoms within a molecule to an extent that the remaining ion undergoes Coulomb explosion
- Coincident ion momentum imaging allows to reconstruct 3D momentum of all atoms
- Molecular structure is very well reflected in the measurement and there is no evidence of deformation or rotation before Coulomb explosion

SQS: Imaging collective quantum fluctuations of the structure of a complex molecule

Iodopyridine

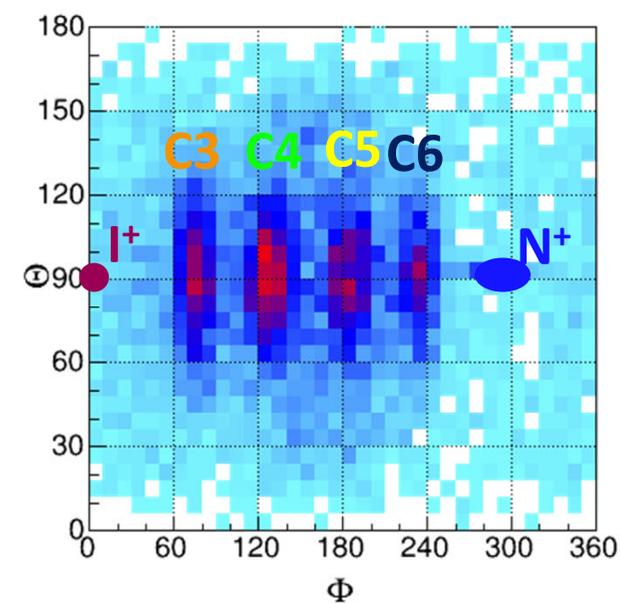
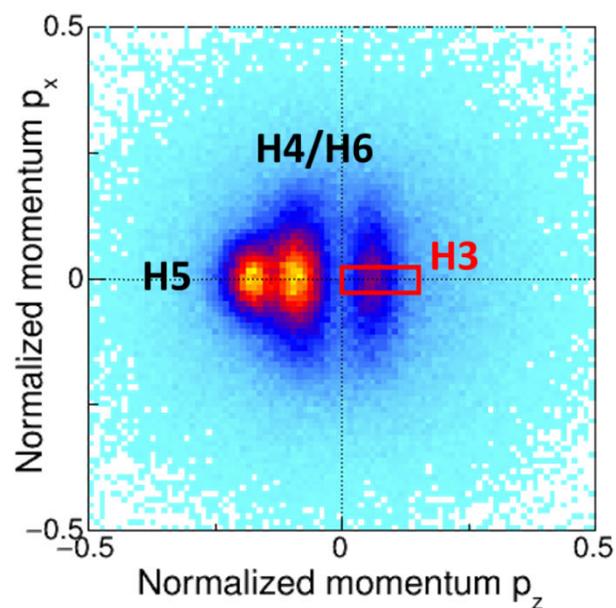


- Even in the ground state molecules are not static but undergo collective structural motions
- These motions are extremely small, but momentum imaging is an exquisitely sensitive tool to observe such small motions



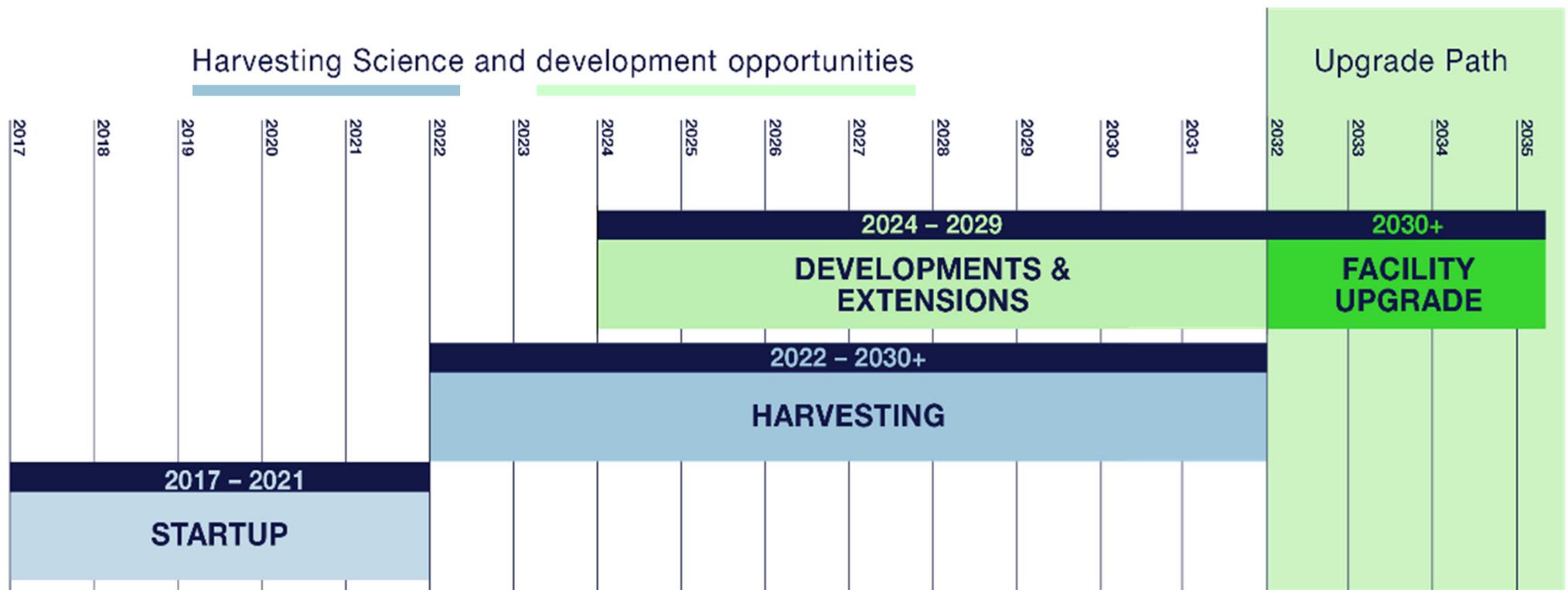
SQS: Imaging collective quantum fluctuations of the structure of a complex molecule

- The emission directions of the atoms are correlated
- Coincidence analysis reveals correlations of the emission directions of hydrogen and carbon atoms perpendicular to the iodine and nitrogen momenta which result from ground state fluctuations



Outlook

Strategy 2030+ – Two-level approach



Culture, values, leadership and staff management

Improve administration and budget structure

Environmental sustainability

Data science

Data infrastructure

User support and experience

Inertial Fusion Energy

Hard X-ray Scattering

High Photon Energies

Continuous wave technology

Preparation of facility upgrade

Enhancing user operation

New science opportunities

Advanced accelerator concepts

Laser

Detectors

Superconducting Undulators

Diamond based optics and beam sharing

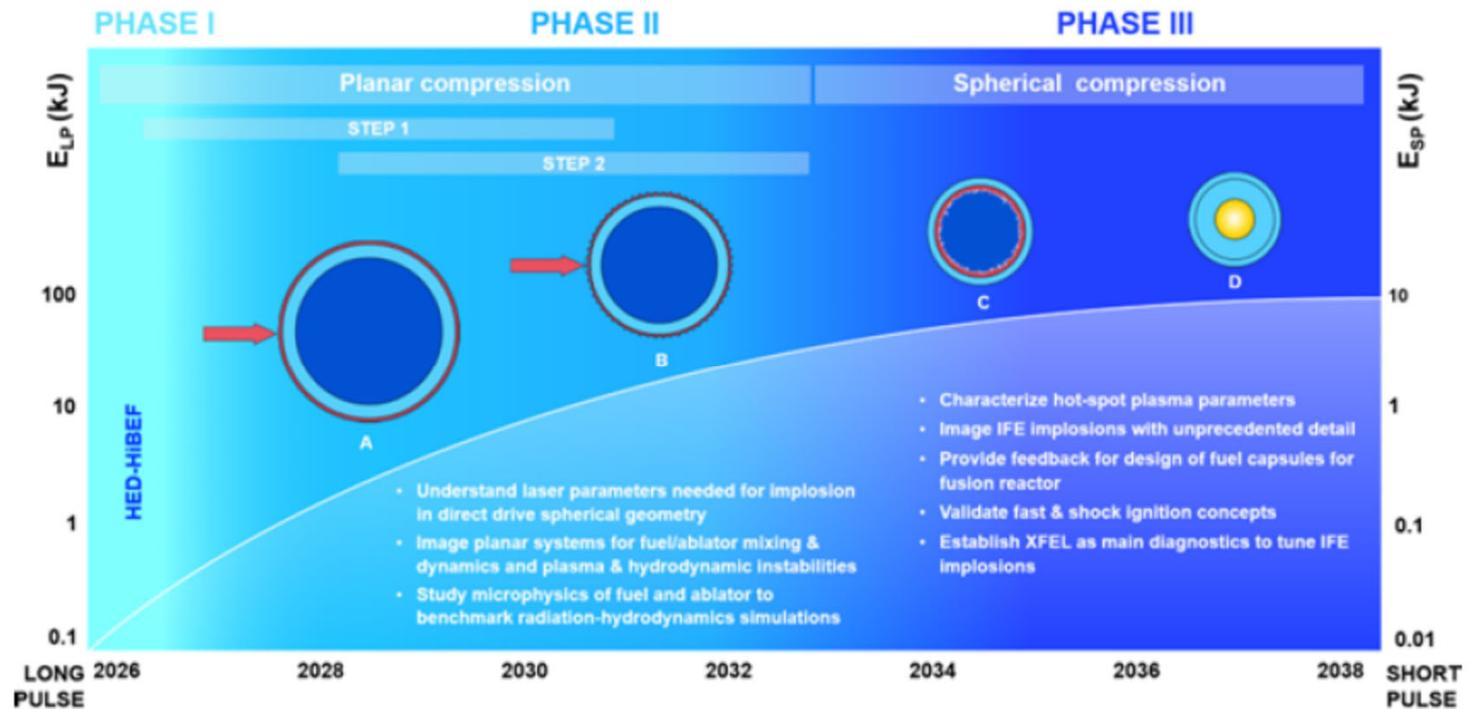
Accelerator extensions

Intelligent process control and robotics

Accelerator improvements

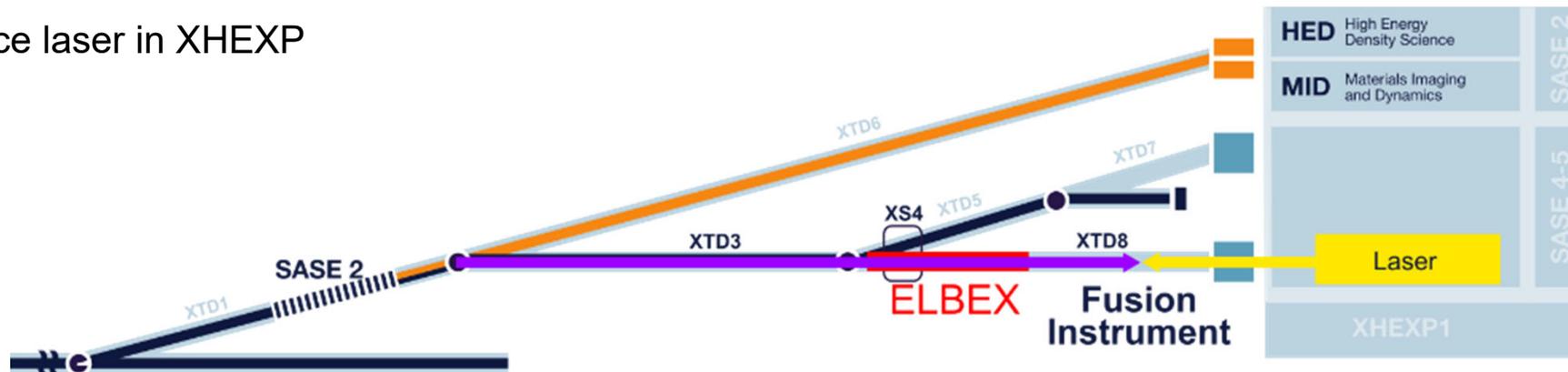
Instrument for fusion research

- Make use of exquisite properties of x-ray FEL beam to study physics of fusion targets during initial states of laser excitation/compression.
- “initial hydrodynamic instabilities and the impact of small target or driver non-uniformities can be investigated with imaging at the 200 nm spatial scale and femtosecond temporal resolution”



Instrument for fusion research

- Make use of exquisite properties of x-ray FEL beam to study physics of fusion targets during initial states of laser excitation/compression.
 - “initial hydrodynamic instabilities and the impact of small target or driver non-uniformities can be investigated with imaging at the 200 nm spatial scale and femtosecond temporal resolution”
- Use SASE 2 x-ray beam,
- place instrument in XTD8
- place laser in XHEXP



Visitor and Conference Center Lighthouse



Exhibitions

- Permanent exhibition (350m²)
- Special exhibition area



Xcool Lab

- Physics
- Molecular biology



Conference Center

- Auditorium (150 seats)
- Two seminar rooms
- All three rooms combined (300 seats)

Summary

- European XFEL is in full swing of its operation
- Opening a window to new x-ray science we are constantly developing new methods, opportunities and scientific applications
- Expect to initiate a major upgrade after approx. 15 - 20 yrs of operation

