Recent Status of PAL-XFEL

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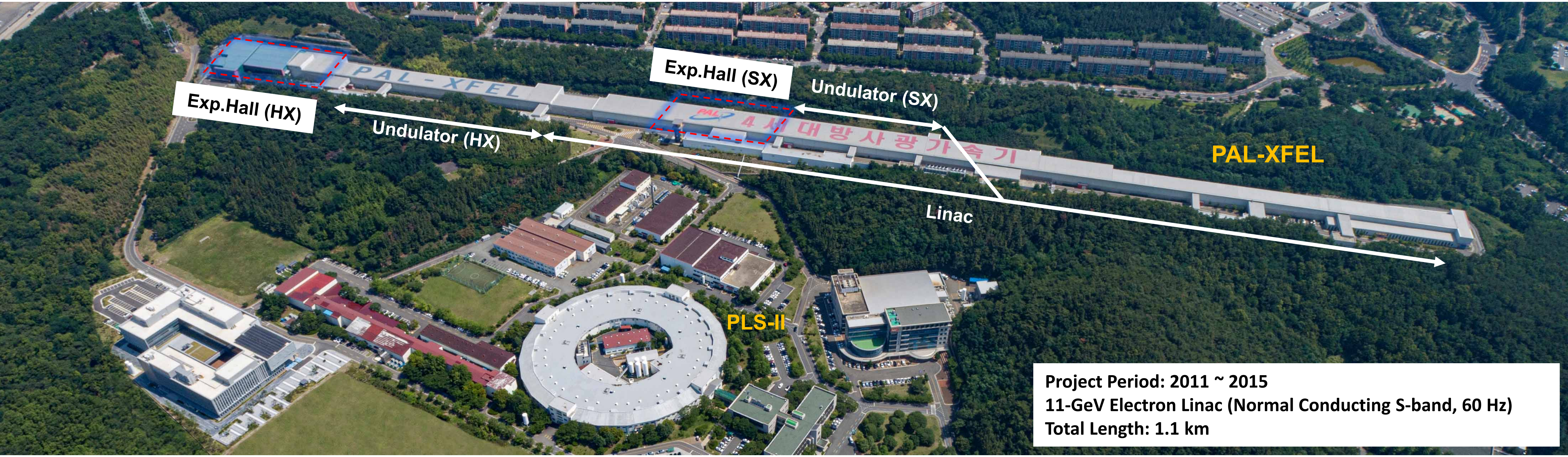
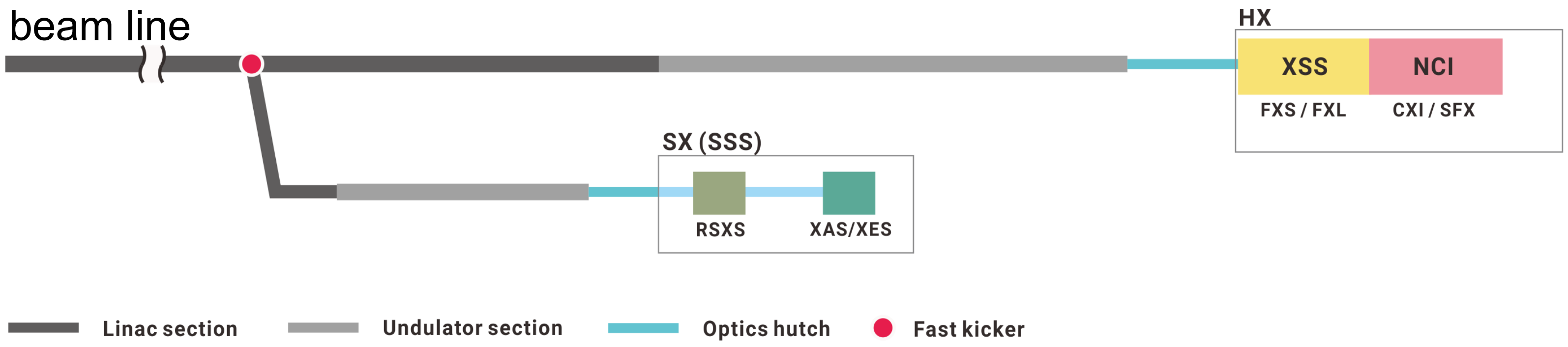
2023-09-04

PAL-XFEL overview



Project Period: 2011 ~ 2015
11-GeV Electron Linac (Normal Conducting S-band, 60 Hz)
Total Length: 1.1 km



	Hard X-ray	Soft X-ray
Photon energy	2.0 ~ 15 keV (0.6 ~ 0.08 nm)	250 ~ 1250 eV (5 ~ 1 nm)
Beam energy	4 ~ 11 GeV	3 GeV
Repetition rate	60 Hz	60 Hz
Band width of pink beam (ΔE/E)	~ 0.4 %	~ 0.5 %
Photon flux (pink beam)	> 1.0×10^{11} phs/pulse	> 1.0×10^{12} phs/pulse

XFEL performance

PAL-XFEL is delivering stable FEL beams.

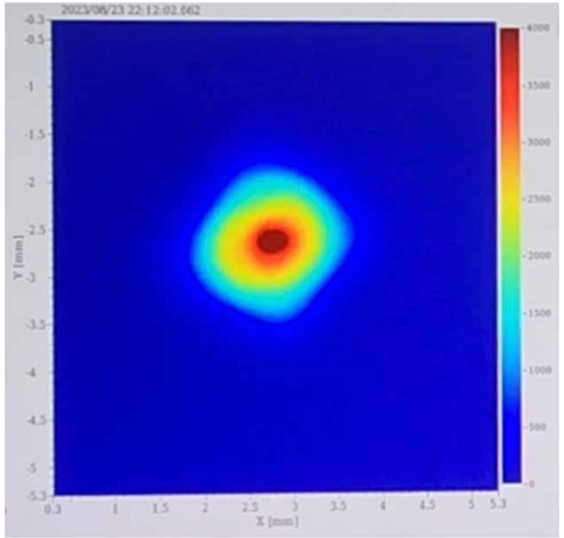
1) Machine operation

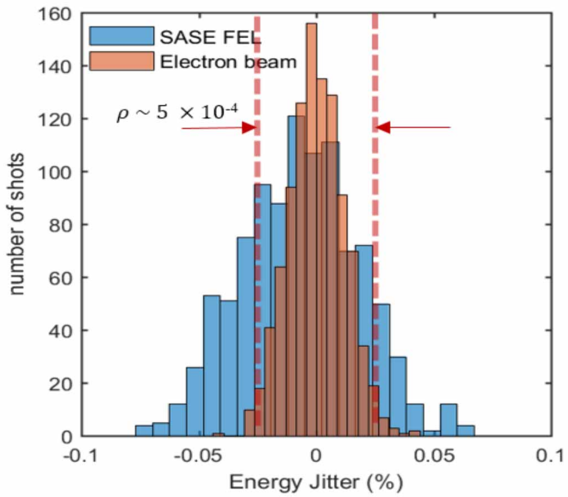
- HX : 2.0 ~ 15.0 keV : mJ level intensity (> 1 mJ)
  15 ~ 20 keV : 0.4 ~ 1 mJ
- SX : 0.25 ~ 1.25 keV : 0.3 ~ 0.7 mJ
- Beam availability : > 98%

2) FEL performance
- FEL intensity jitter < 5% RMS
- FEL position jitter < 10% of beam size
- FEL central wavelength jitter 0.024 % (1/5 of SASE band width)

3) Electron beam performance
- Relative electron beam energy jitter : 1.2×10^{-4}
- Electron beam arrival time jitter : 12 fs

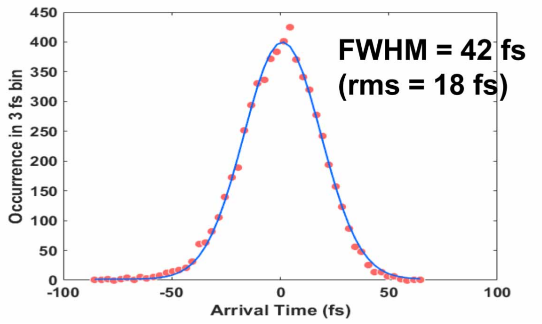
4) Timing jitter
- Timing jitter 18 fs (rms) between X-ray pulses and optical pulses
- No timing jitter correction when measuring timing delay scan



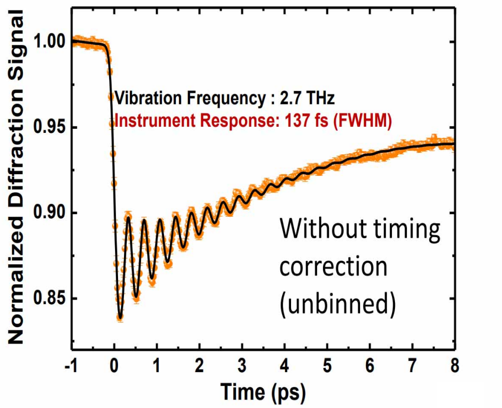


Electron energy jitter: 0.012% rms
Photon wavelength jitter: 0.024% rms

Timing Jitter Histogram
(between Laser and XFEL at sample)

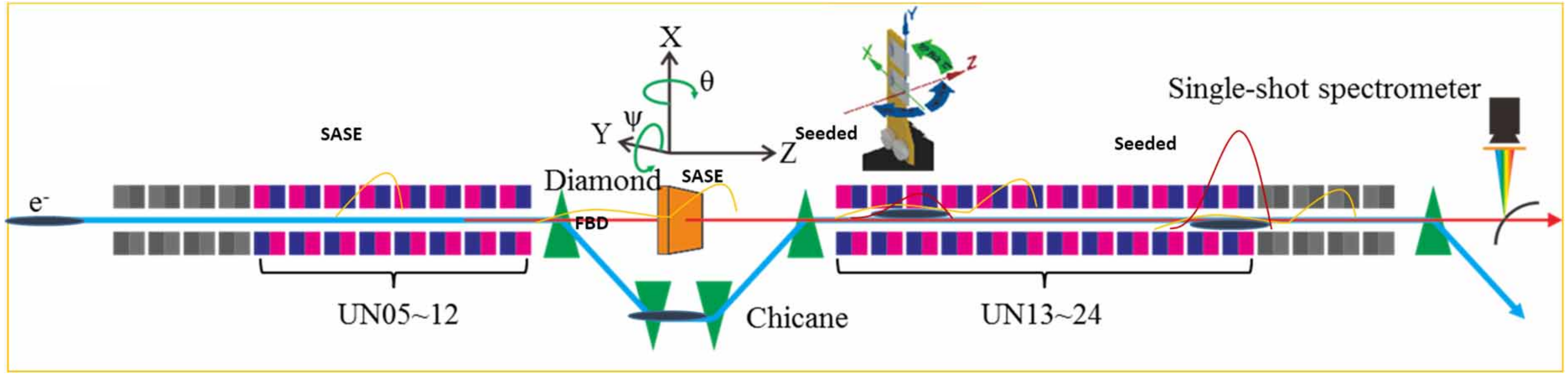


Time-resolved diffraction of Bi (111) thin film

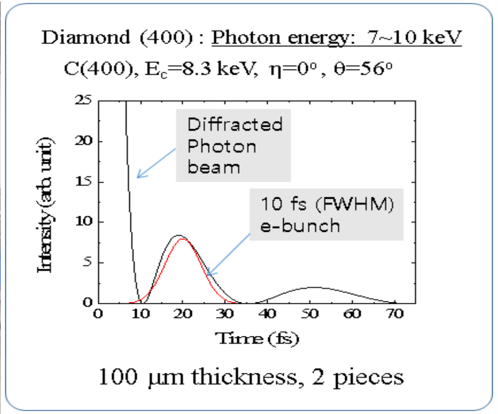


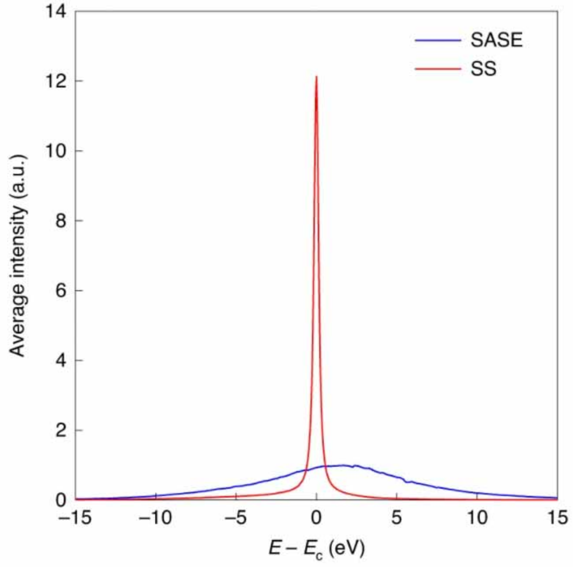
Hard X-ray self seeding at PAL-XFEL

Since installed the self-Seeding monochromator in 2018, many efforts are dedicated to operate in stable and high intensity generation.



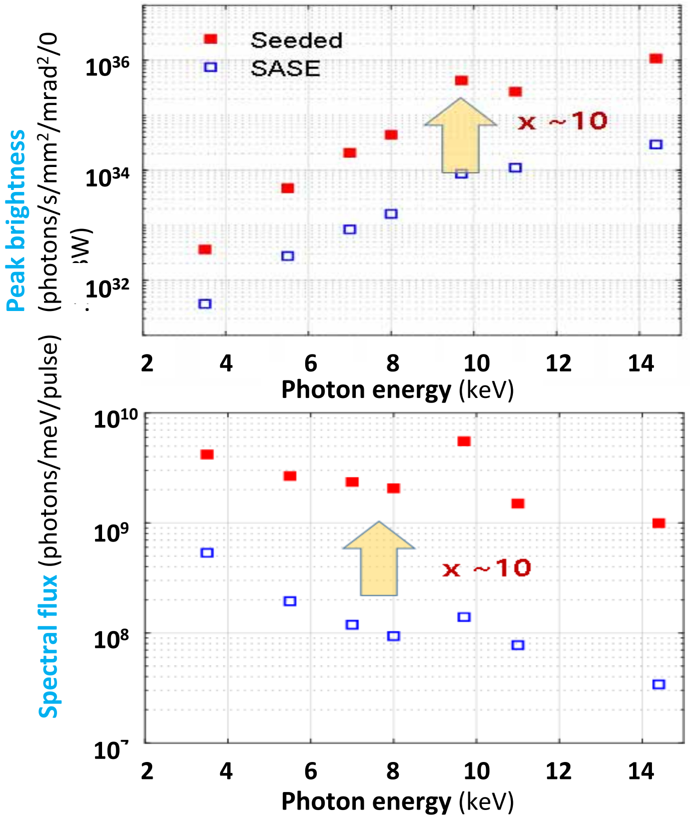
Picture of self-seeding section





I. Nam et al. *Nat. Photon.* 15, 435 (2021)

- *example*
- Photon energy (Ec) = 9.7 keV
- SASE bandwidth (FWHM) = 27 eV
- Self-seeding bandwidth (FWHM) = **0.22 eV** (deconvoluted)
- Averaged pulse energy: **~850 μJ**
- FEL Pulse duration = ~ 20 fs

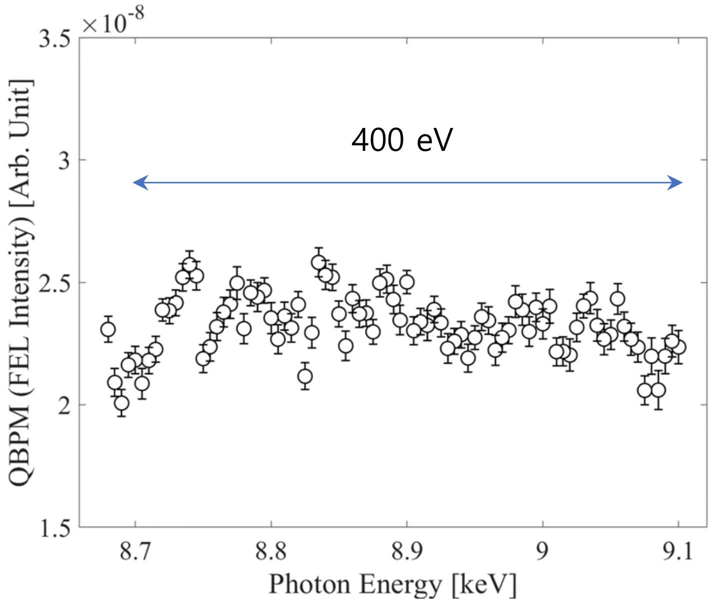


Hard X-ray self seeding at PAL-XFEL

- Up to the first half year in 2023, 30% of beam times had been used for the self-seeded FEL.
- Operation of photon energy scan was started.

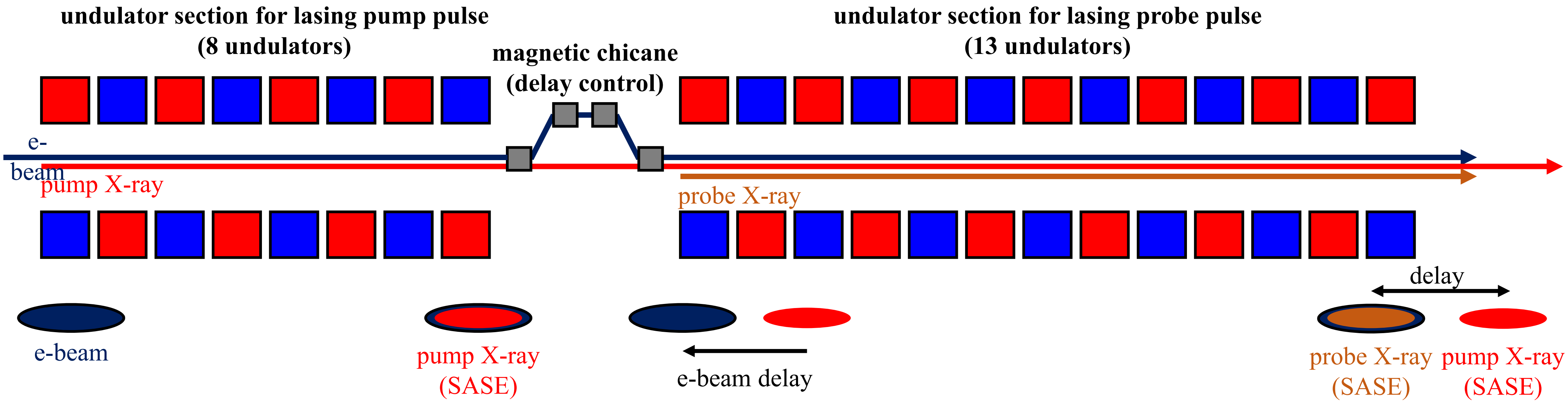
  → FEL intensity was not changed significantly during 400 eV energy scan.

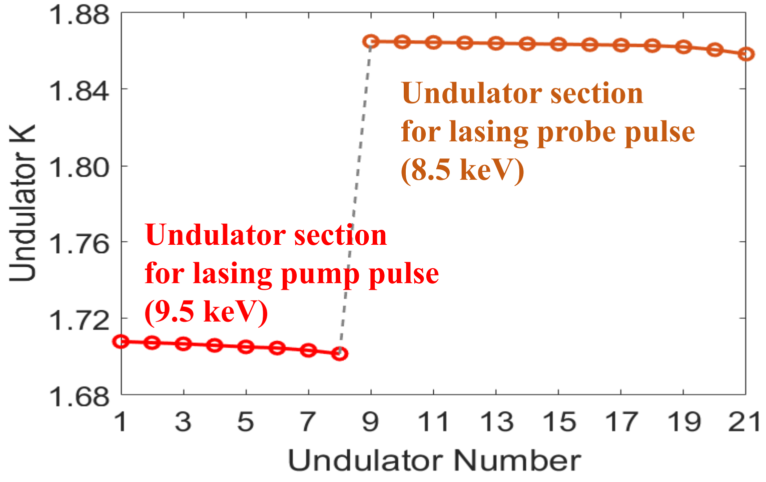
Long term operation of the self-seeded XFEL

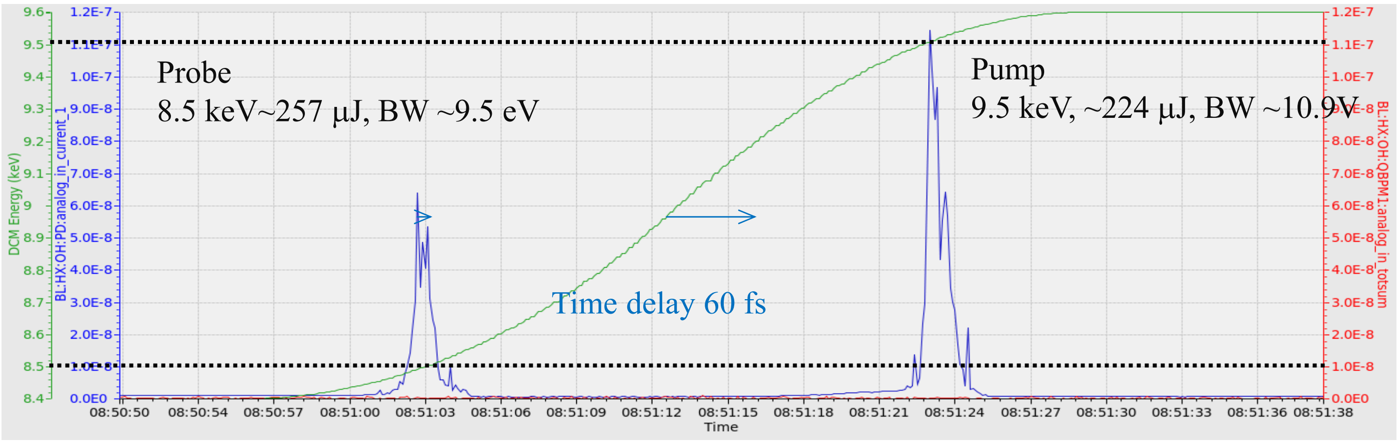


Two-color XFEL by dividing undulator section

- Two color FEL had been started but time delay is limited in 100 fs.







XFEL photon energy scan

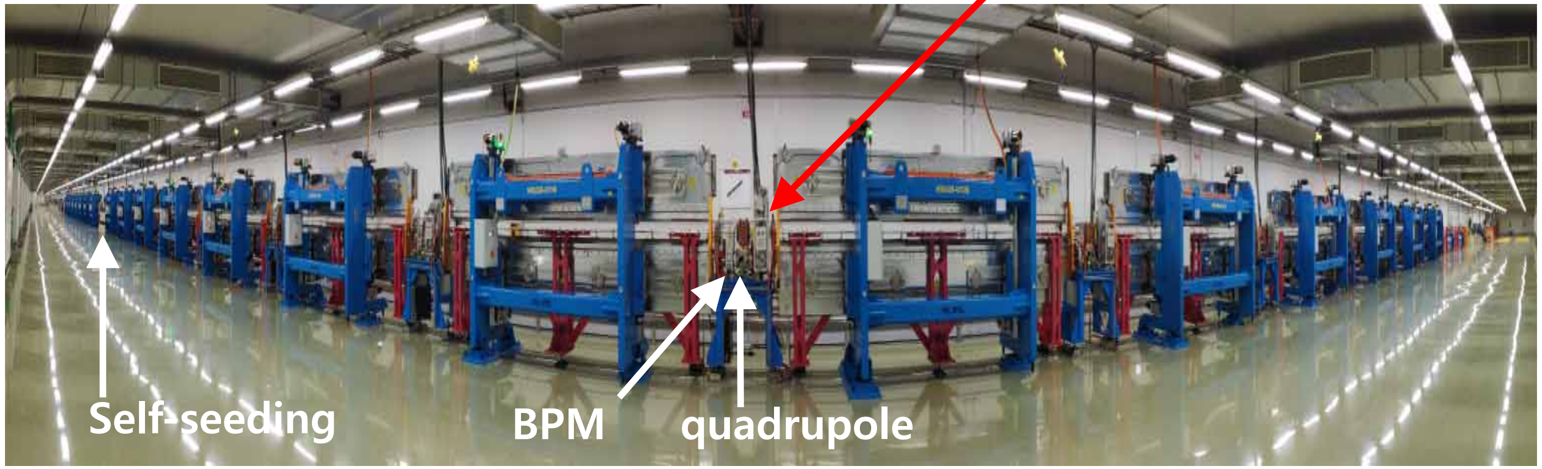
Time-synchronized two-color XFEL using phase shifter

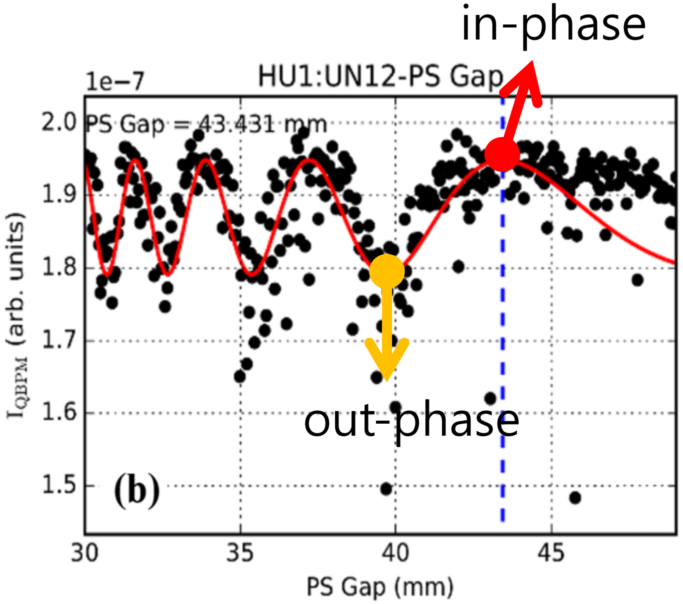
poster TU4P15

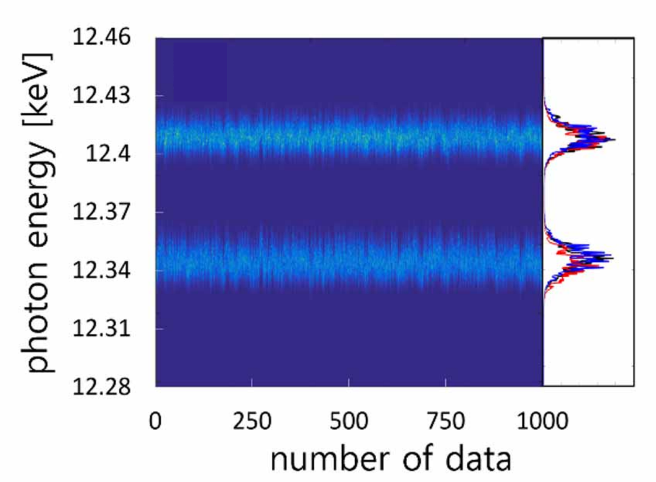
- Time-synchronized Two color FEL using phase shifters was developed.

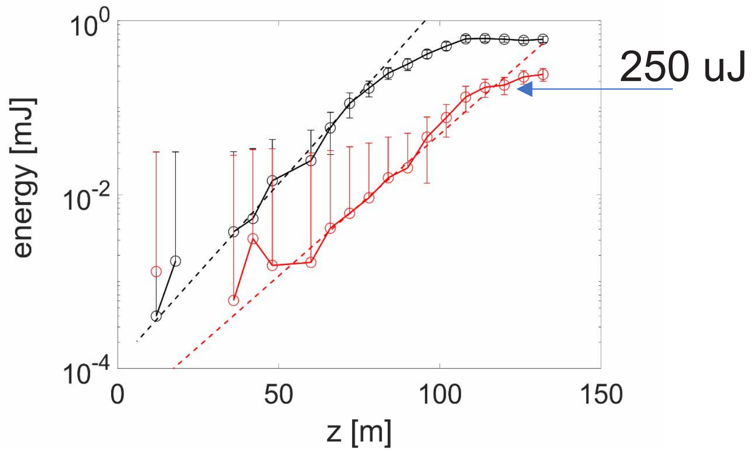
Scientific Reports ***13*** *13786 (2023)*

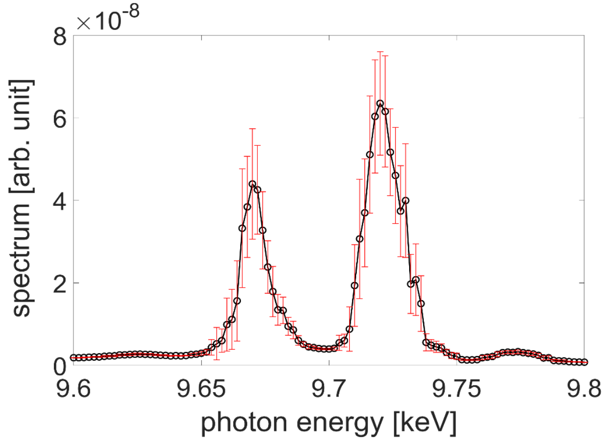
- PAL-XFEL undulator line











PAL-XFEL beamline instruments

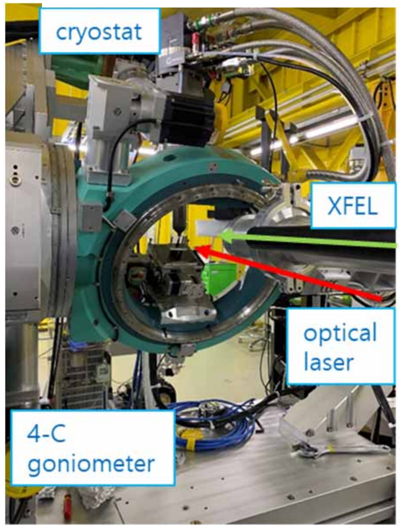
XSS (X-ray Scattering and Spectroscopy)

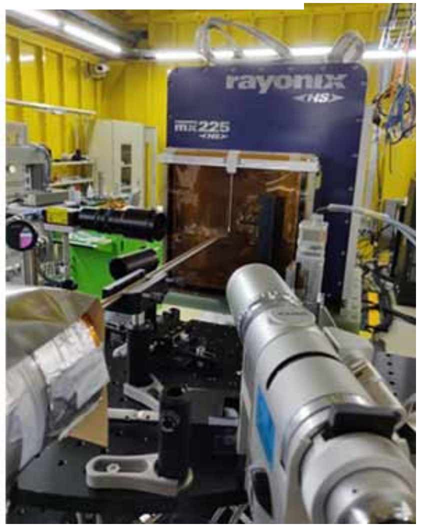
- **Instrumentations**

  Femtosecond X-ray Scattering (FXS)
  Femtosecond X-ray Liquidography (FXL)
  X-ray emission spectroscopies (XES)

- **Specifications**

  Focusing optics: Be CRL (focusing lens ~10 μm)
  2-circle and 4-circle diffractometers
  Cryostream cryostat: 40 – 300 K
  Sample chamber for vacuum and gas conditions
  Liquid injector (100 μm jet)





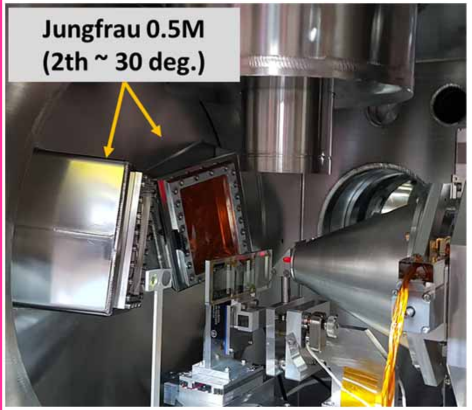
NCI (Nano Crystallography and coherent Imaging)

- **Instrumentations**

  Coherent X-ray Imaging / Scattering (CXI)
  X-ray Absorption Near Edge Spectroscopy (XANES)
  Serial Femtosecond Crystallography (SFX)
  Wide angle X-ray scattering (WAXS)

- **Specifications**

  Focusing optics: KB mirrors (~2 μm focusing)
  Dedicated sample chambers for CXI/SFX/XANES with vacuum or He environment
  tunable nanosecond laser for SFX experiments



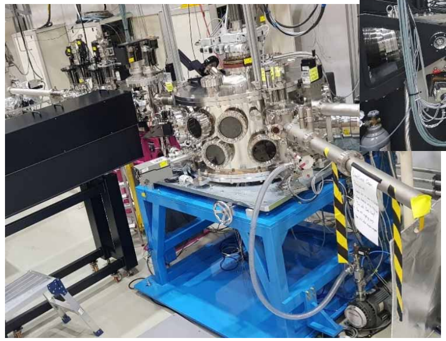
SSS (Soft X-ray Scattering and Spectroscopy)

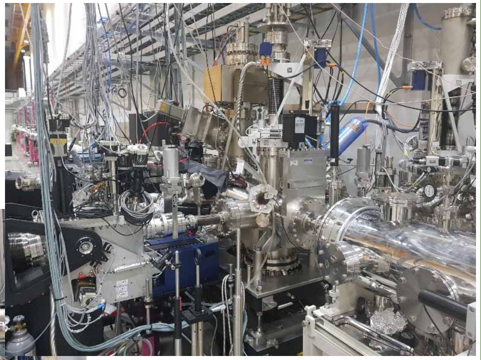
- **Instruimentations**

  Resonant Soft X-ray Scattering (RSXS)
  X-ray Absorption/Emission Spectroscopy (XAS/XES)
  Fourier Transform Holography (FTH)

- **Specifications**

  6-axis manipulator with cryostat (RSXS)
  VLS grating for 200 – 1200 eV (XAS/XES)
  Ion/electron time-of-flight (XAS/XES)

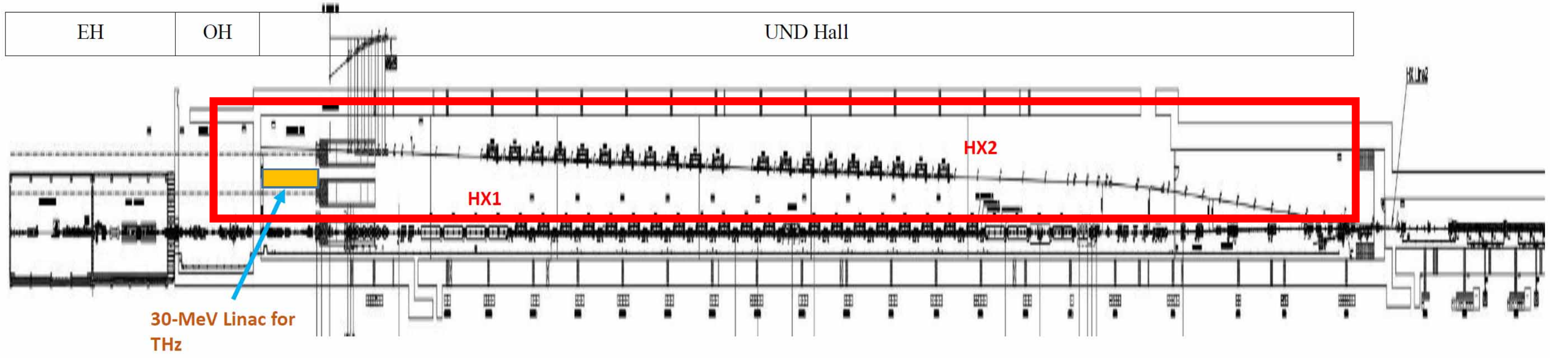




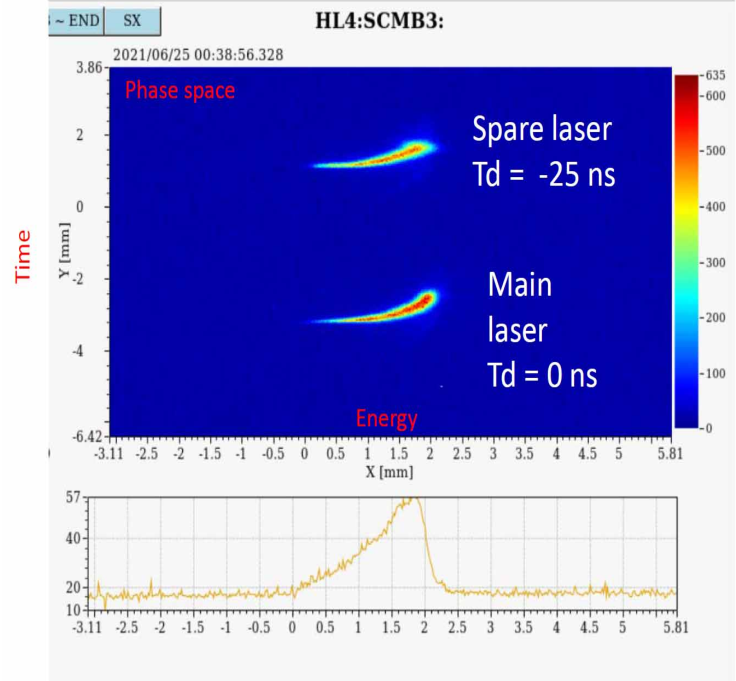
Upgrade plans for PAL-XFEL

Second Hard XFEL Line (HX2)

- Second hard XFEL line is planned and different FEL modes will be developed.

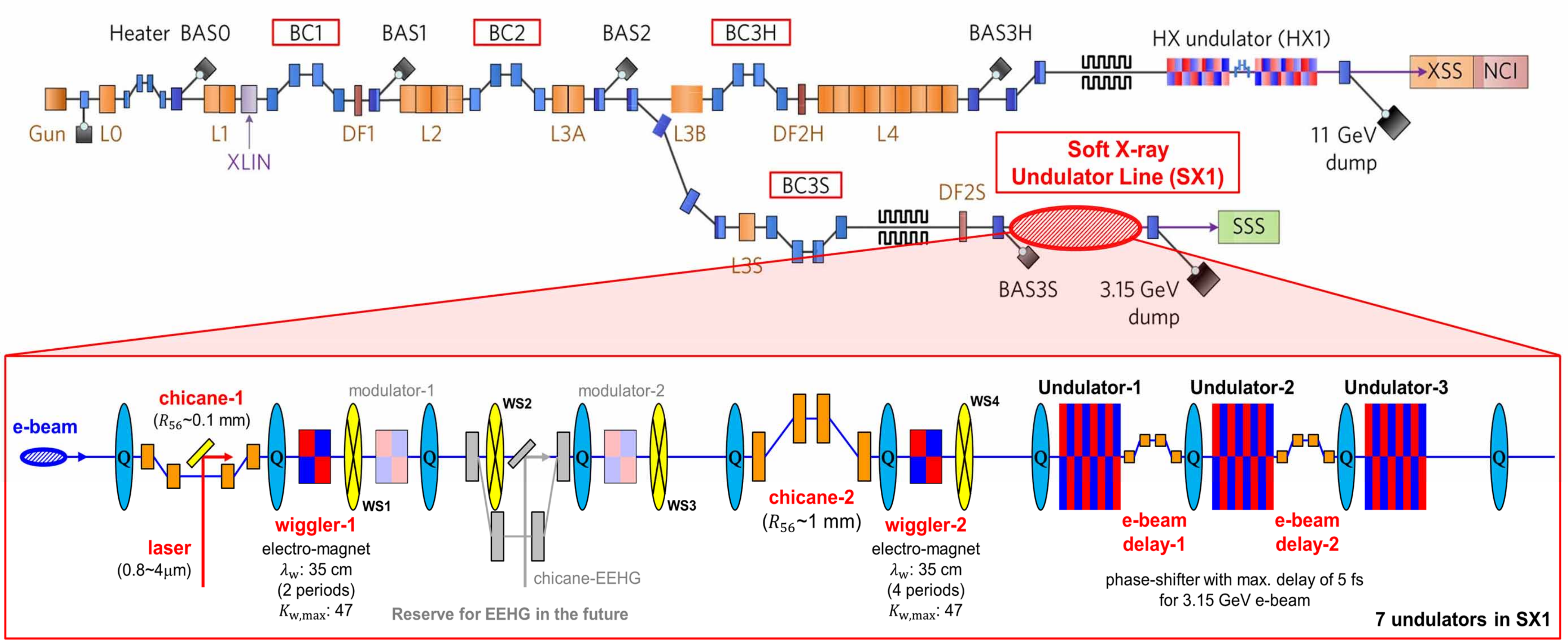


	HX1	HX2
Undulator period	26 mm	35 mm
Undulator K	1.87	3.5
Photon energy	6.5 ~ 20 keV	2 ~ 10 keV
FEL modes	SASE, self-seeded	SASE, self-seeded, E-SASE, etc.



- 60 Hz operation is possible by driving two bunch electron beam using two separated laser systems.

Attosecond soft X-ray generation



Conclusion

1. PAL-XFEL now is delivering stable FEL beams.

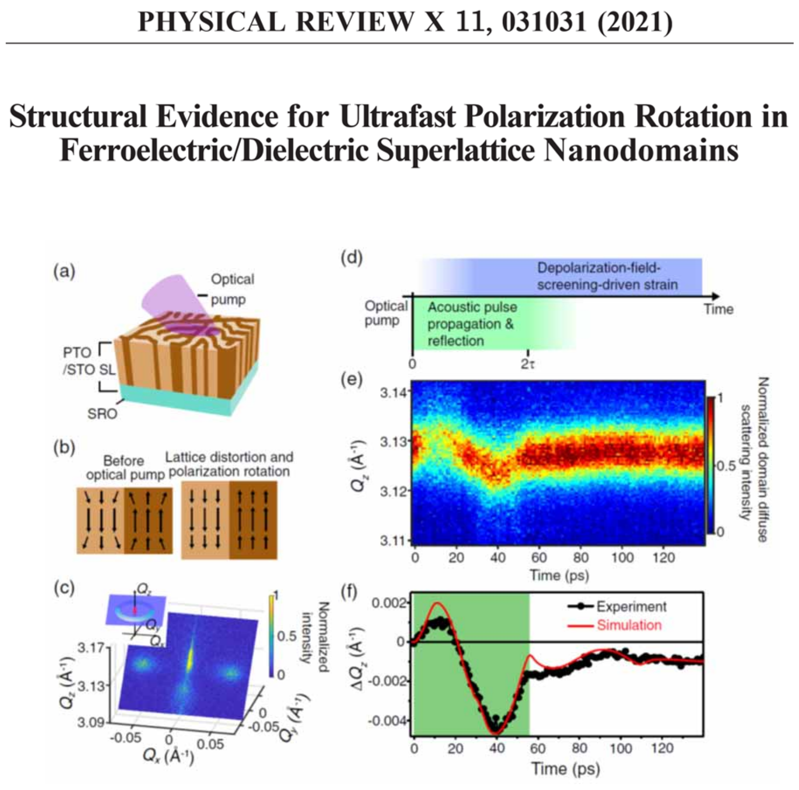
2. This year operating photon energy scan for self-seeding was started.

3. Two color FEL operation in different types are ready.

4. PAL-XFEL is preparing the 2nd hard XFEL line and atto-second soft XFEL.

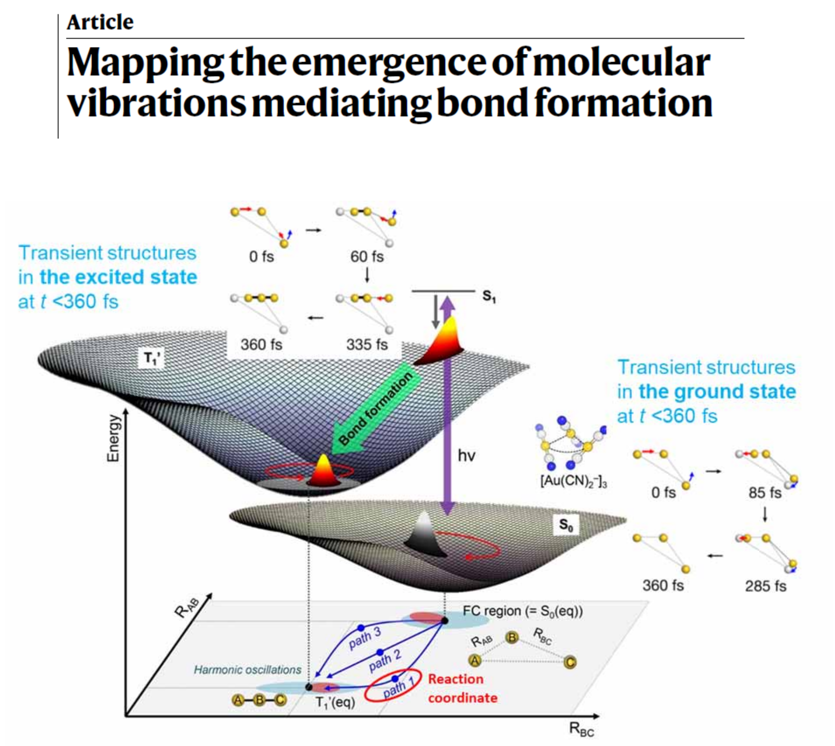
Appendix

Research highlights from XSS



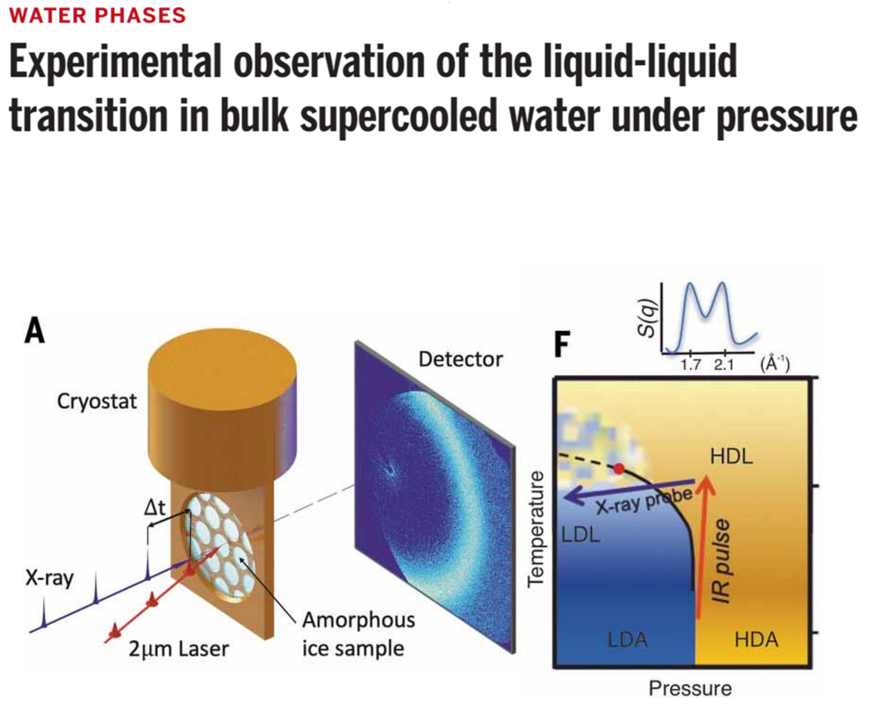
Structural evidence for ultrafast polarization rotation induced by the above-bandgap photoexcitation

Lee et al., Phy. Rev. X. **11**, 031031 (2021).



The real-time trajectories in the ultrafast bond formation were obtained purely on the basis of the experimental data.

J. G. Kim et al., Nature. **582**, 520 (2020).



A discontinuous structural change (a first-order phase transition) between high-density and low-density supercooled water

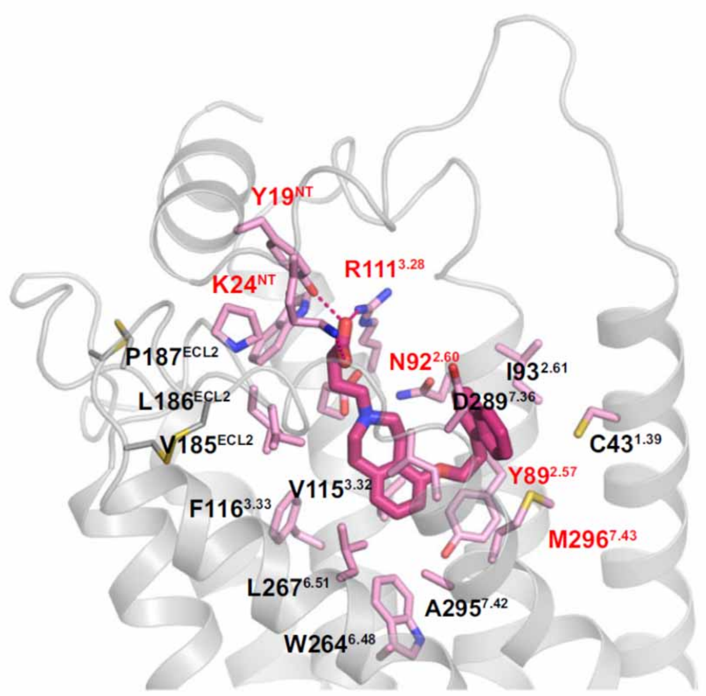
K. H. Kim et al., Science, **370**, 978 (2020).

Research highlights from NCI

nature communications

Article https://doi.org/10.1038/s41467-022-32447-1

Structural basis for receptor selectivity and inverse agonism in S1P$_5$ receptors



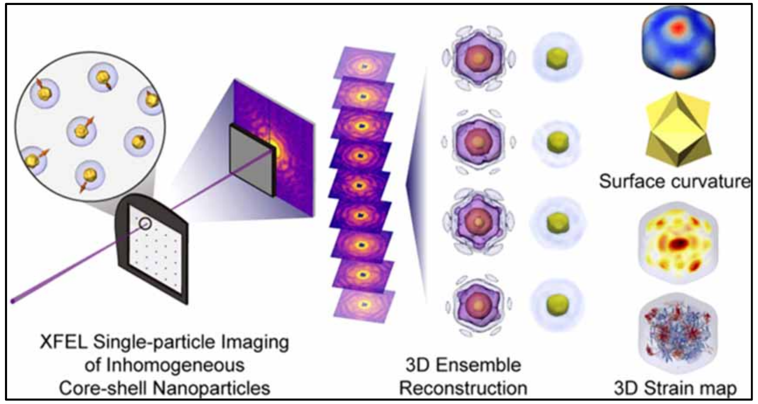
Unveil the structure of Ligand binding pocket of S1P$_5$ receptor

E. Lyapina et al., Nat. Comm., **13**, 4376 (2022).

ACS NANO

www.acsnano.org

High-Throughput 3D Ensemble Characterization of Individual Core–Shell Nanoparticles with X-ray Free Electron Laser Single-Particle Imaging



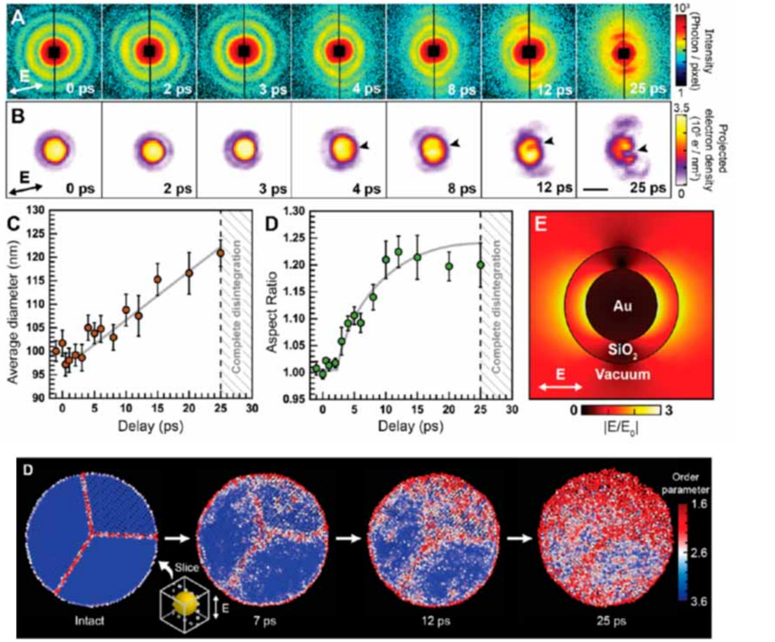
Single-particle 3D imaging revealing 3D structural information at 20 nm resolution

D. H. Cho et al., ACS nano, **15**, 4066 (2021).

NANO LETTERS

pubs.acs.org/NanoLett Letter

Ultrafast Energy Transfer Process in Confined Gold Nanospheres Revealed by Femtosecond X-ray Imaging and Diffraction



The ultrafast energy transfer process in the confined nanoparticle system.

J. Shin et al., Nano Lett., **23**, 1481 (2023).

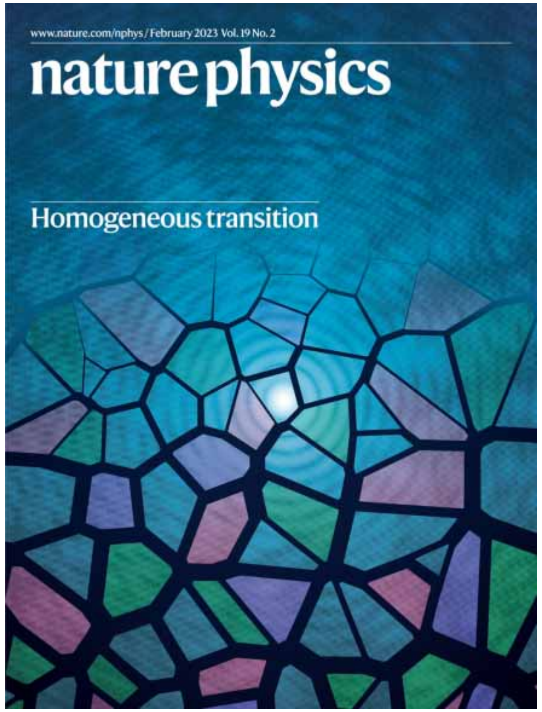
Research highlights from SSS

nature physics

Article

https://doi.org/10.1038/s41567-022-01848-w

Ultrafast X-ray imaging of the light-induced phase transition in VO_2

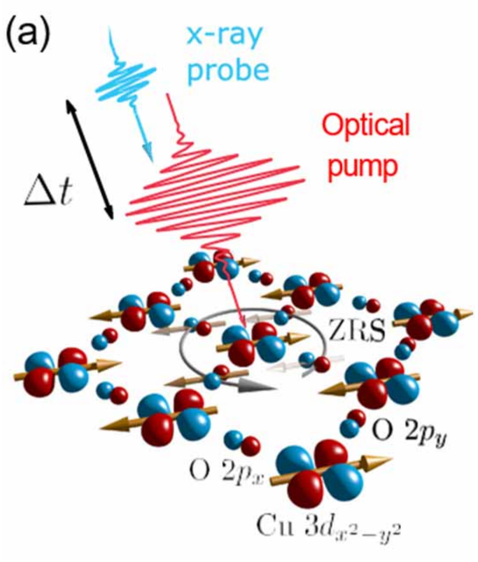


Light-induced insulator-to-metal phase transition dynamics in VO_2 by FTH

Johnson et al., Nature Physics **19**, 215 (2023)

PHYSICAL REVIEW X 12, 011013 (2022)

Ultrafast Renormalization of the On-Site Coulomb Repulsion in a Cuprate Superconductor



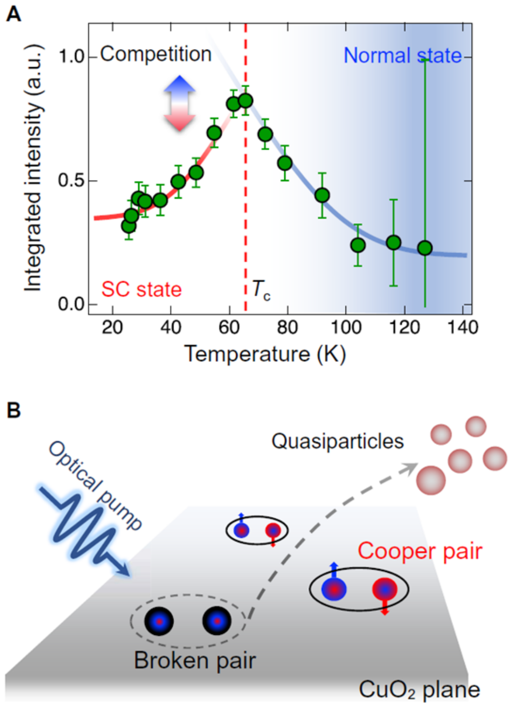
The manipulation of superconductivity and magnetism

Baykusheva et al., Phy. Rev. X. **12**, 011013 (2022).

SCIENCE ADVANCES | RESEARCH ARTICLE

CONDENSED MATTER PHYSICS

Characterization of photoinduced normal state through charge density wave in superconducting $YBa_2Cu_3O_{6.67}$

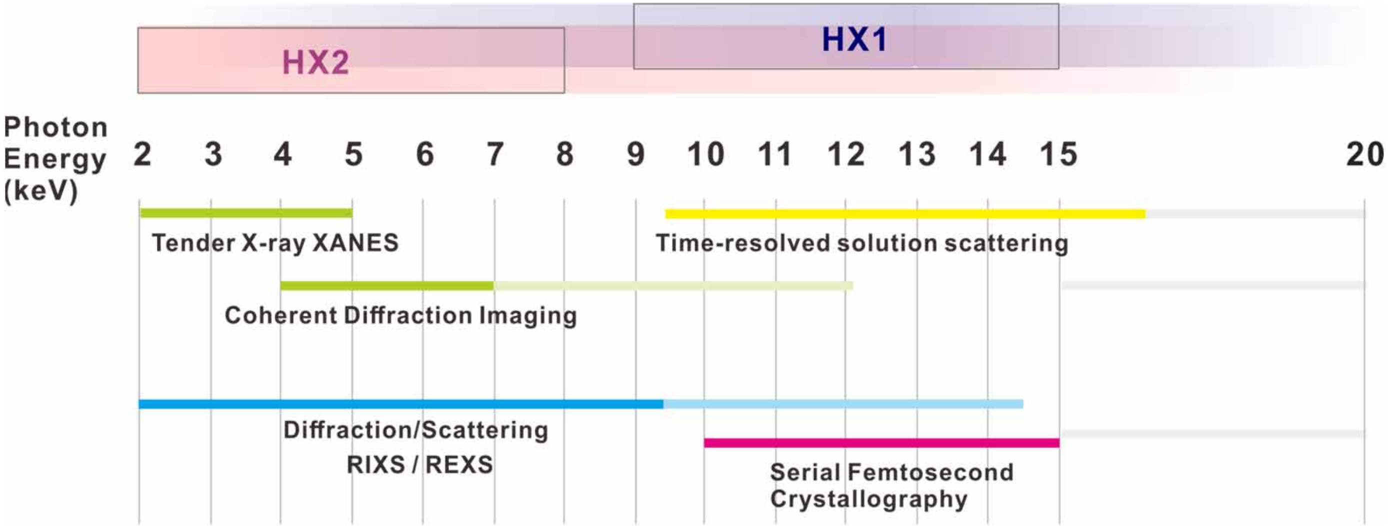


Competition of CDW (charge density wave) and SC (superconductivity) manifested in the time domain

Jang et al., Science Advances **8**, eabk0832 (2022)

Construction plan for 2nd Hard X-ray undulator line of PAL-XFEL

	HX1	HX2	SX1
Undulator period, mm	26	35	35
Undulator K (max)	1.87	3.5	3.5
FEL photon energy, keV	6.5 ~ 20	2.0 ~ 10.0	0.3 ~ 1.2
Specialized range, keV	9~15 keV (> 1 mJ)	2 ~ 8 keV (> 3 mJ)	



- 20 undulator units & 2 experimental hutches (HX2)
- HX2 undulator parameter will be the same as SX1.

- HX1/HX2 simultaneous operation
- Construction period, including commissioning (estimated)

  : 3 years without HX1 shutdown