R&D status of PAL-XFEL

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on behalf of PAL-XFEL beam physics group

November 14, 2023

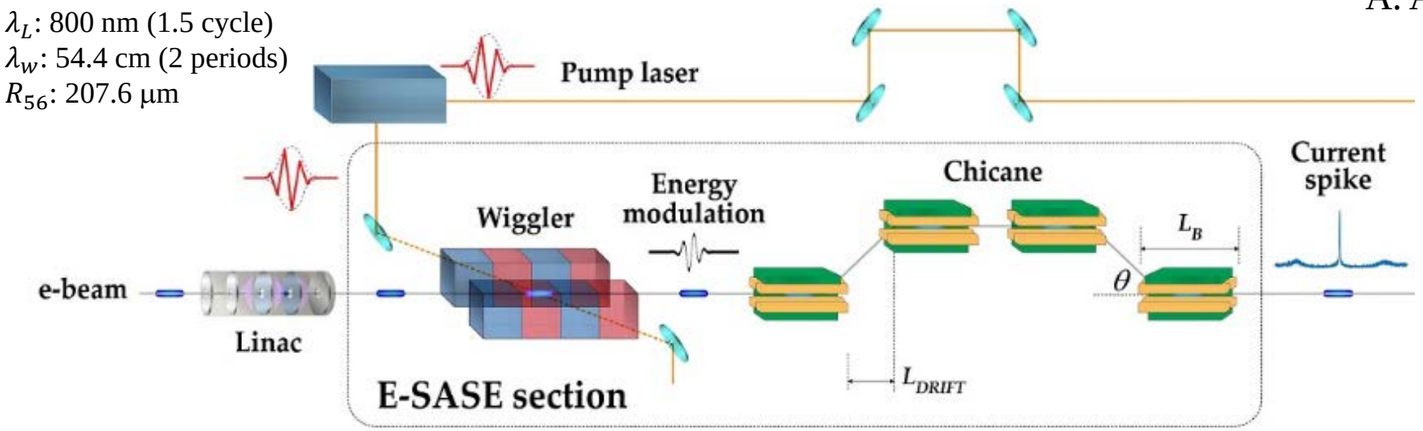
Contents

- ❖ Attosecond soft X-ray FEL
- ❖ Terawatt-scale hard X-ray FEL
- ❖ Two-color XFEL with time delay and pulse duration control
- ❖ Time-synchronized two-color XFEL using phase shifters
- ❖ R&D future plan

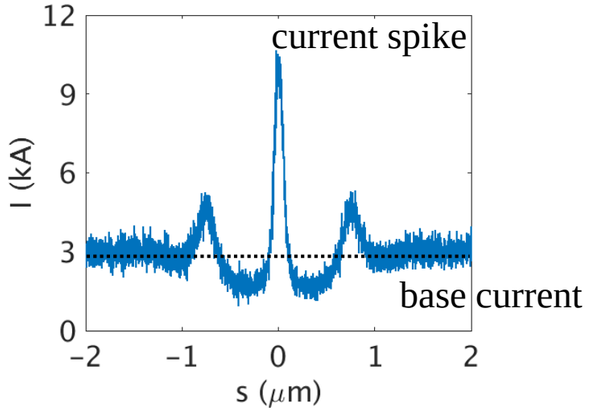
Attosecond soft X-ray FEL

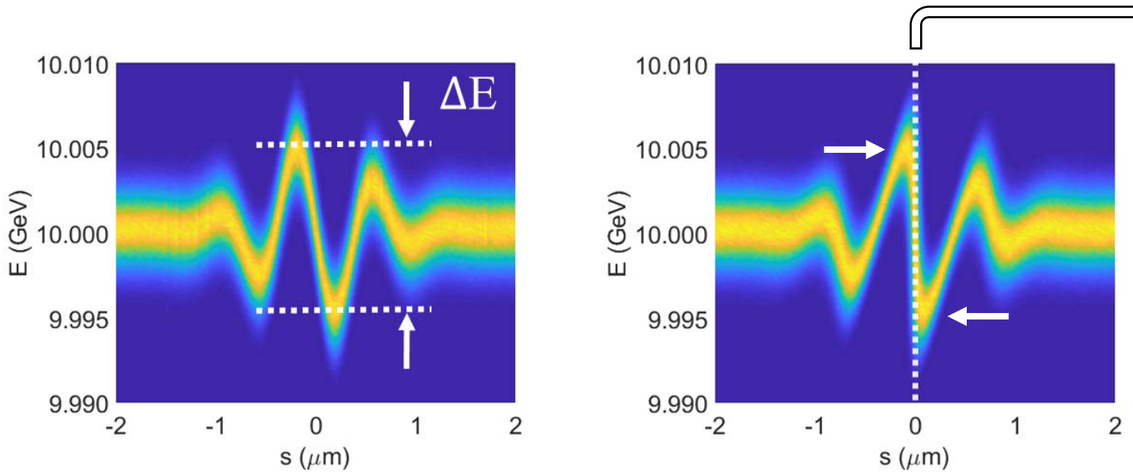
E-SASE method

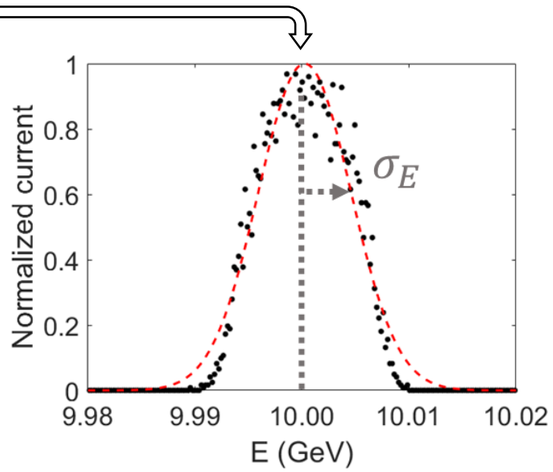
λ_L: 800 nm (1.5 cycle)
λ_w: 54.4 cm (2 periods)
R_{56}: 207.6 μm



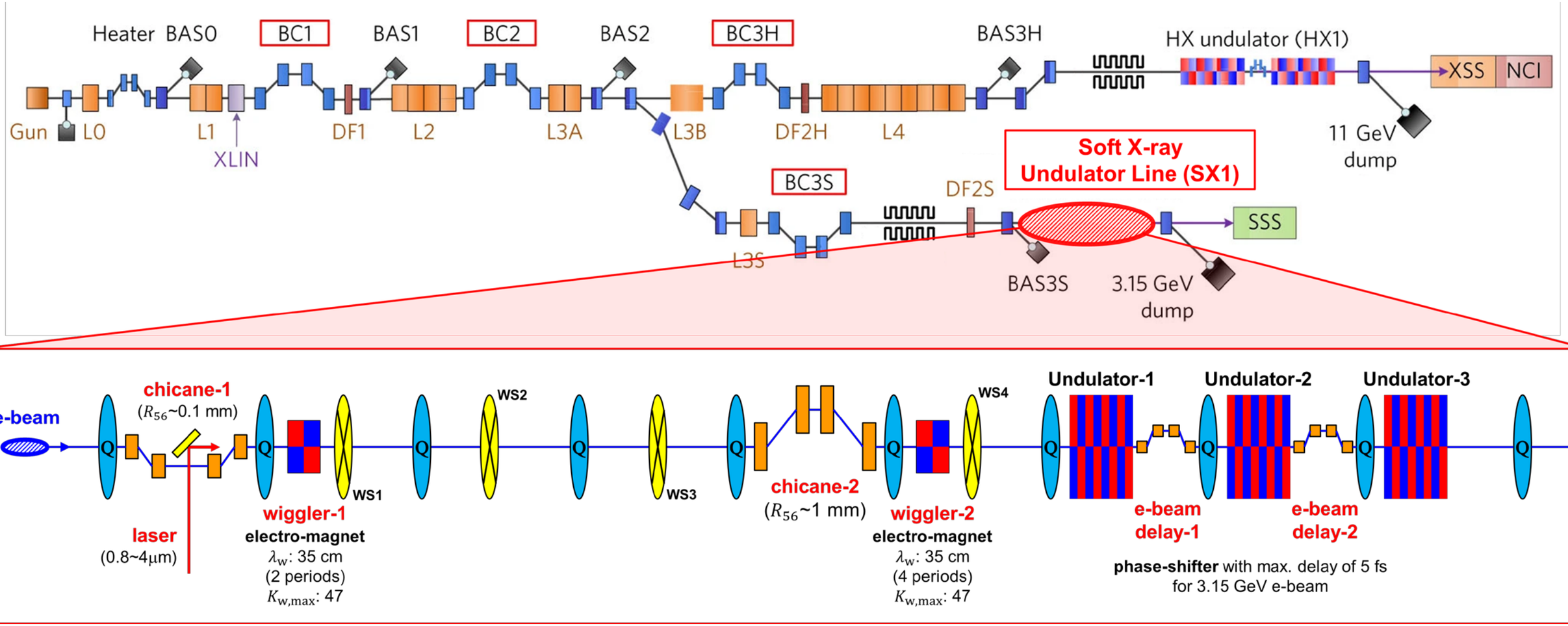
A. A. Zholents. *Phys. Rev. ST Accel. Beams* **8**, 040701 (2005).







Layout for attosecond XFEL at PAL-XFEL

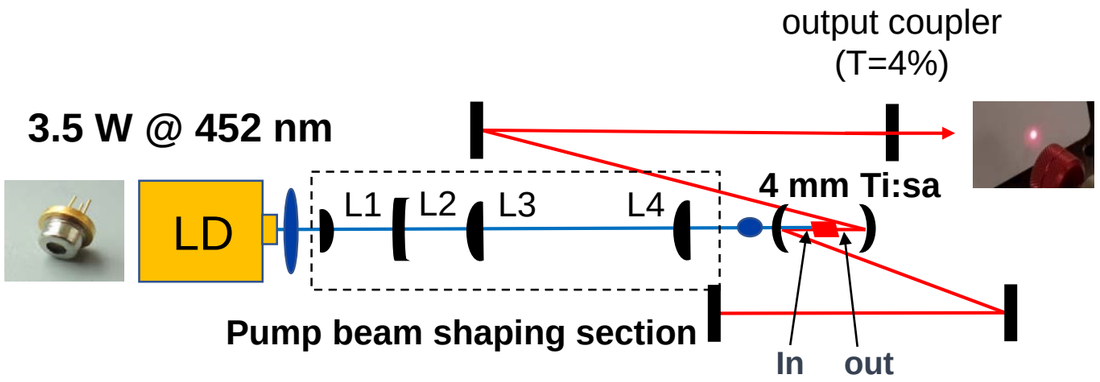


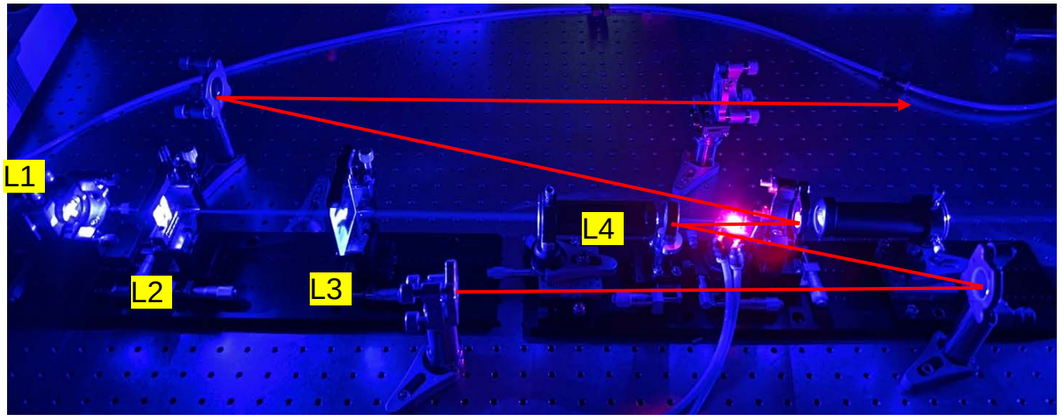
Planning a High-Power Laser System for SX-FEL

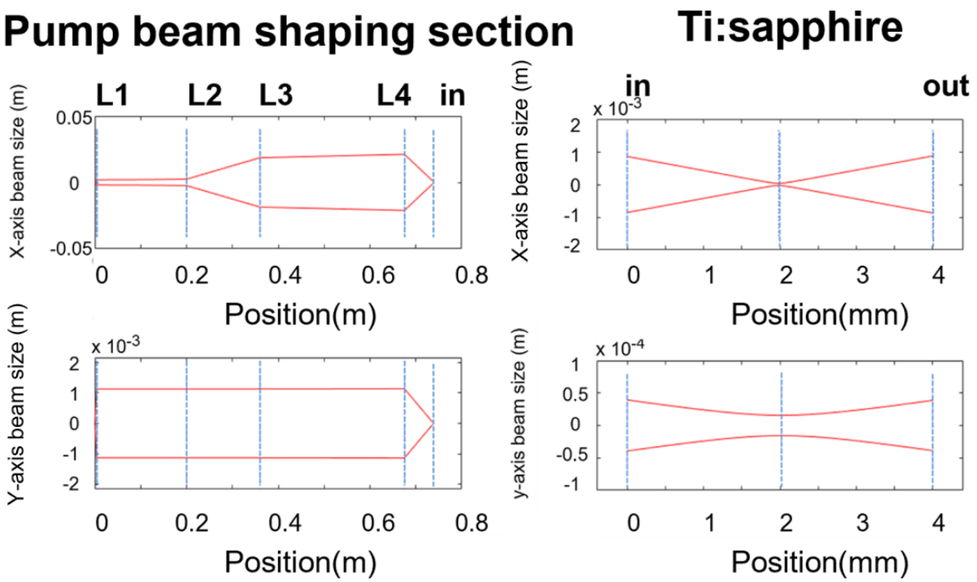
Output

Laser clean room for SX-attos FEL

LD pumped laser oscillator







Pump beam shaping calculation

Characterization of LD pumped laser oscillator

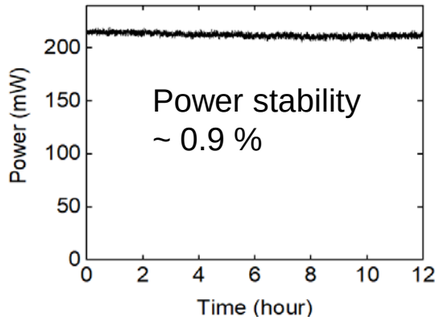
P_{avg} = > 200 mW

Rep rate = 79 MHz,

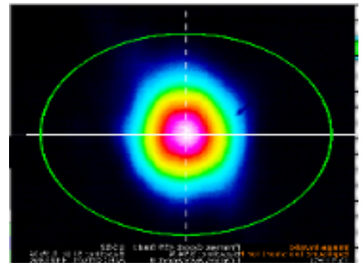
E_{pulse} = 2.5 nJ

Bandwidth 10 ~ 50 nm

Power stability ~ 0.9%



Power stability



Output profile

Laser amplifiers (now being developed)

Regenerative amplifier

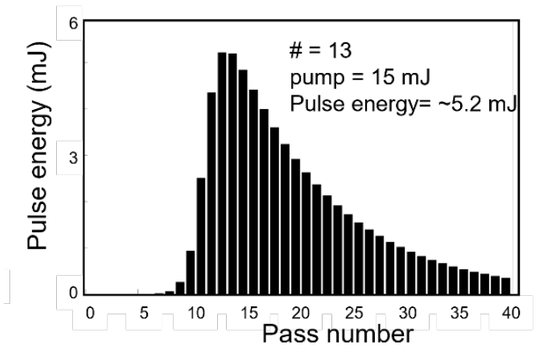
LD oscillator

2.5 nJ, ~200 fs @ 79.3 MHz

~ 500 ps, 5 mJ @ 120 Hz

pump laser (15 mJ @ 120 Hz)

Simulation of amplified pulse energy



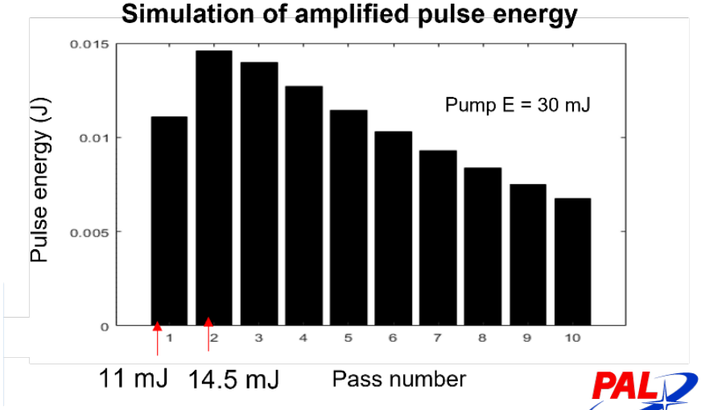
Single pass amplifier

~300 fs, ~10 mJ @120 Hz

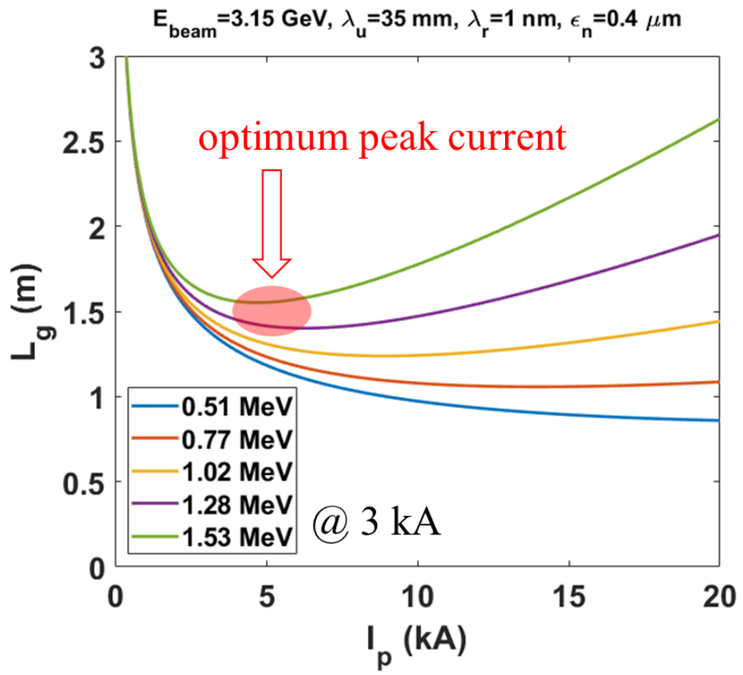
5 mJ

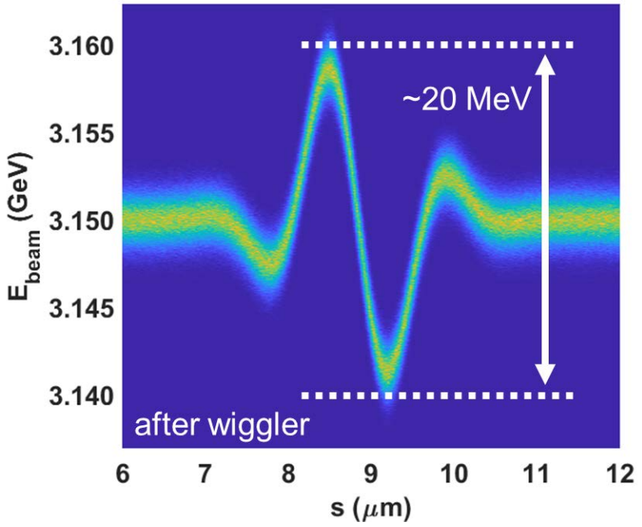
pump laser (30 mJ @ 120 Hz)

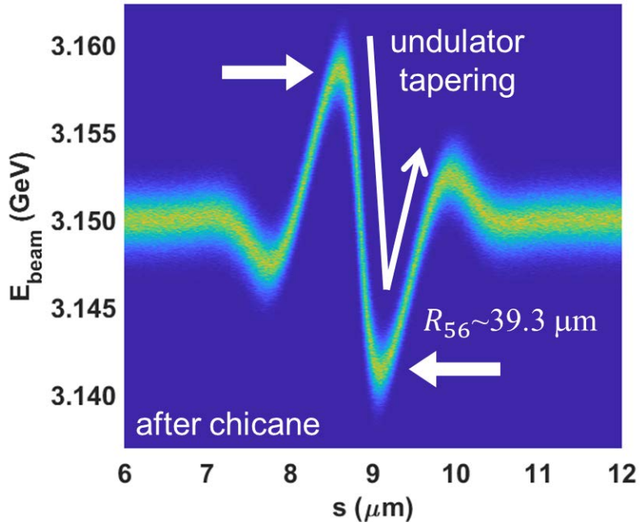
Simulation of amplified pulse energy

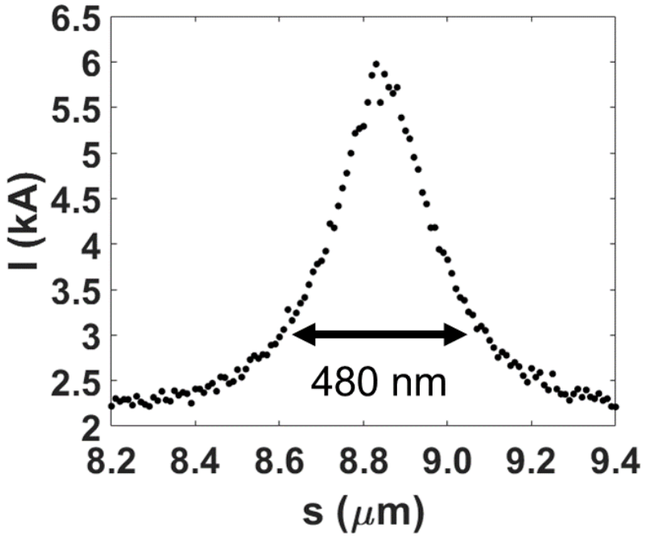


FEL simulation results (GENESIS)

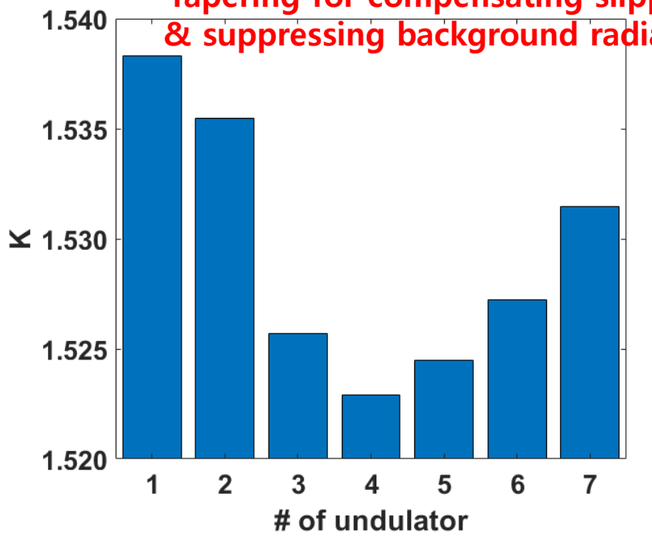








Tapering for compensating slippage & suppressing background radiation



E_{beam}: 3.15 GeV

I_{base}: 3 kA

σ_{E}: 1.02 MeV (at 3 kA)

λ_{mod}: 1.6 μm

K_{w}: 26.32

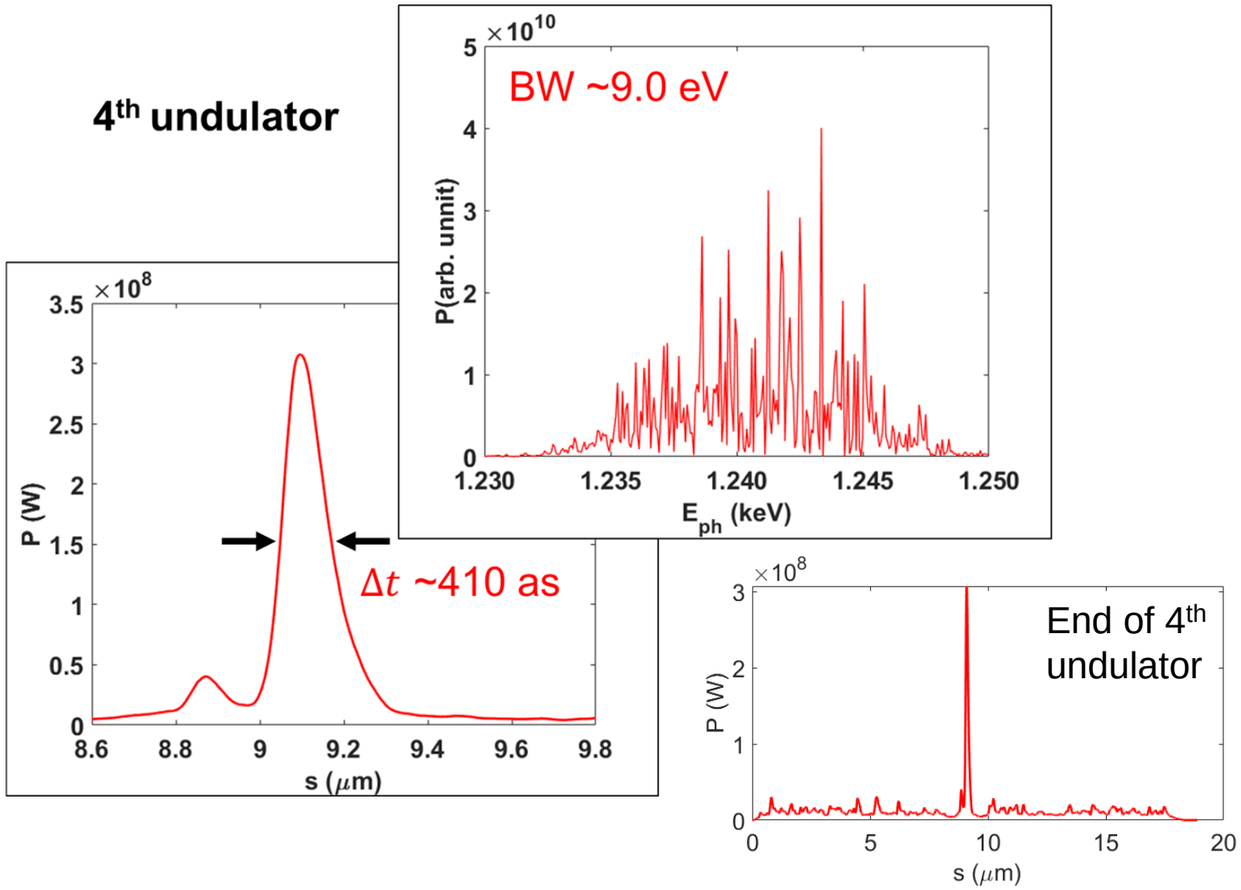
ϵ_{n}: 0.4 mm-mrad

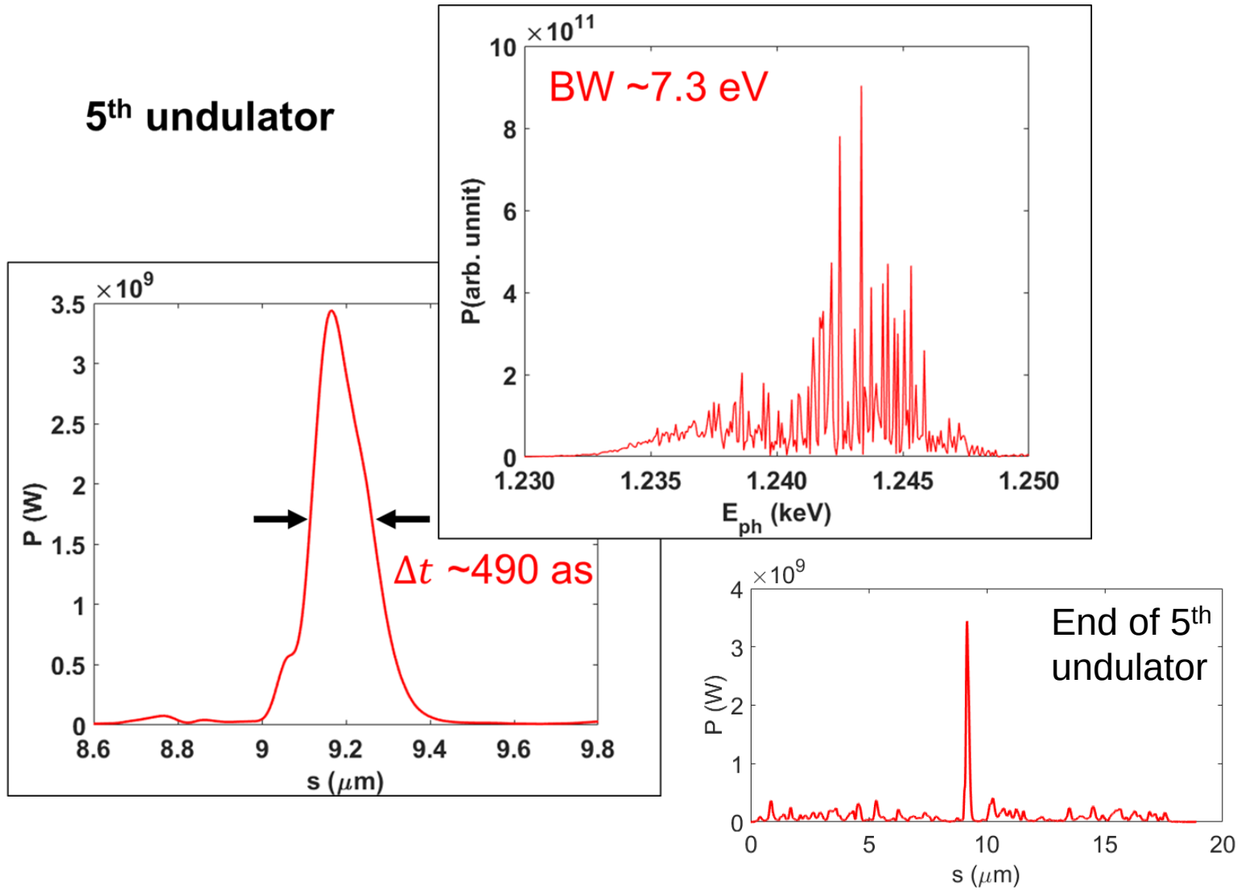
λ_{r}: 1 nm (1240 eV)

λ_{u}: 35 mm

L_{u}: 4.97 m ($142\lambda_{\mathrm{u}}$)

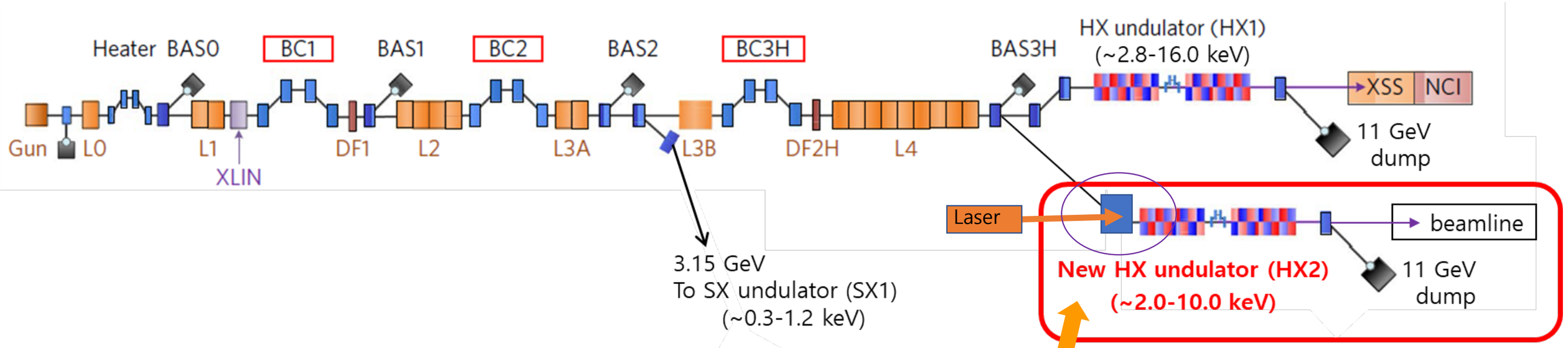
FEL simulation results (GENESIS)





Terawatt-scale hard X-ray FEL

Terawatt-scale hard X-ray FEL

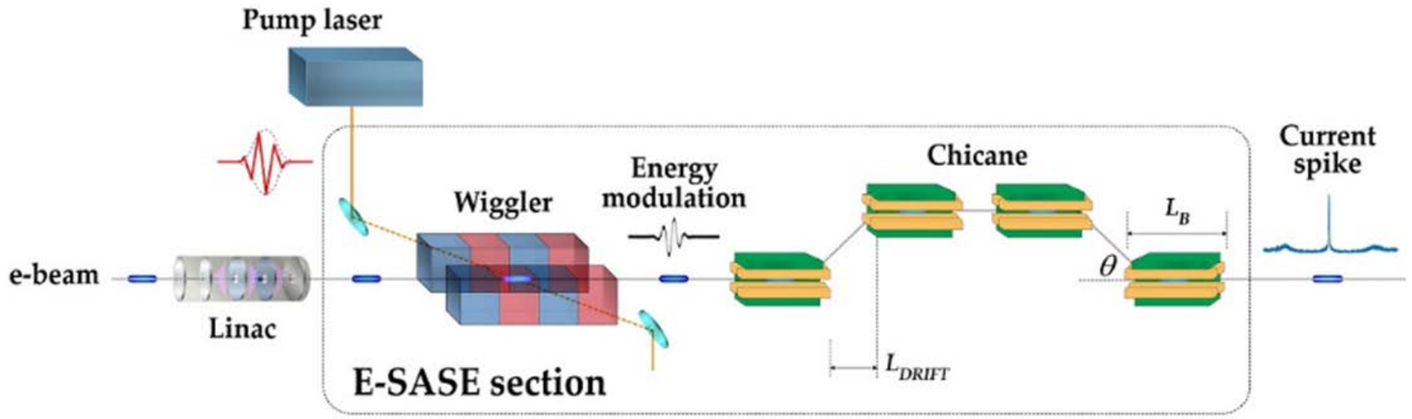


New hard X-ray undulator line (HX2) is proposed

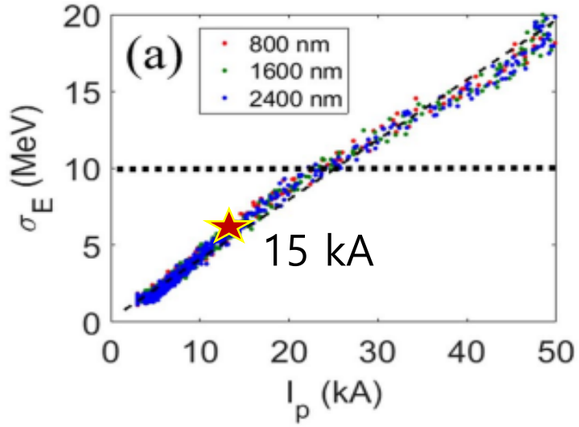
- More beam time to hard X-ray users
  by operating HX1 and HX2 simultaneously
- Increase FEL intensity at photon energies lower than 10 keV
  by increasing E_{beam} with larger of K 3.5 (1.87 for HX1)
- Expand new operation modes by applying laser modulation scheme
  such as terawatt (TW) scale x-ray, attosecond x-ray, and etc.

- **TW- XFEL: Laser modulation section:**
  Peak current enhancement by enhanced SASE
  scheme using the laser modulation of electron beam

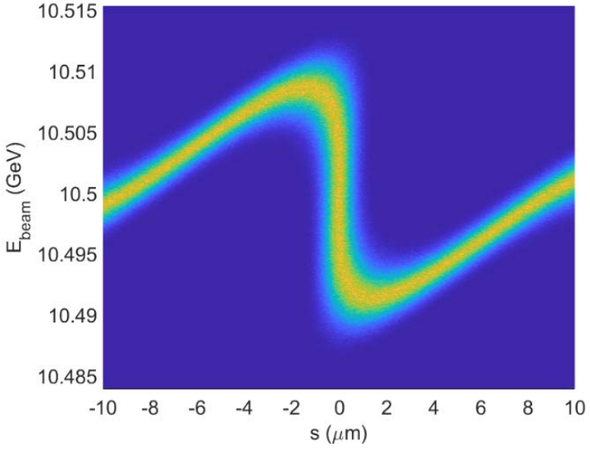
Electron beam manipulation with external laser



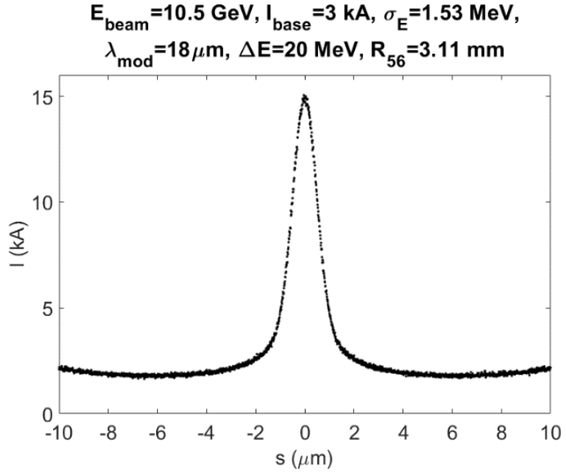
Energy spread vs Peak current



Enhanced peak current spike

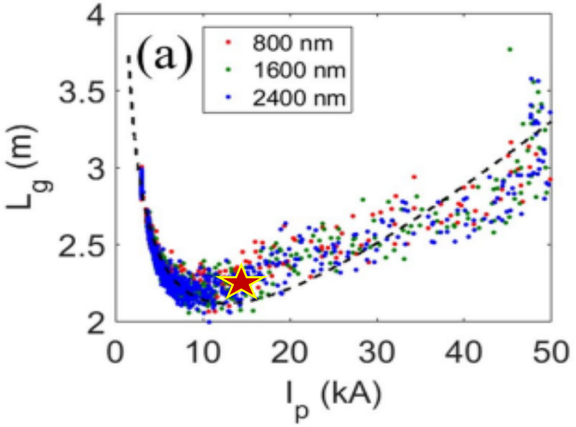


Density modulation after modulator
with the laser having a wavelength of 18μm



Enhance peak current after chicane
with a duration of 5 fs, peak current of 15 kA

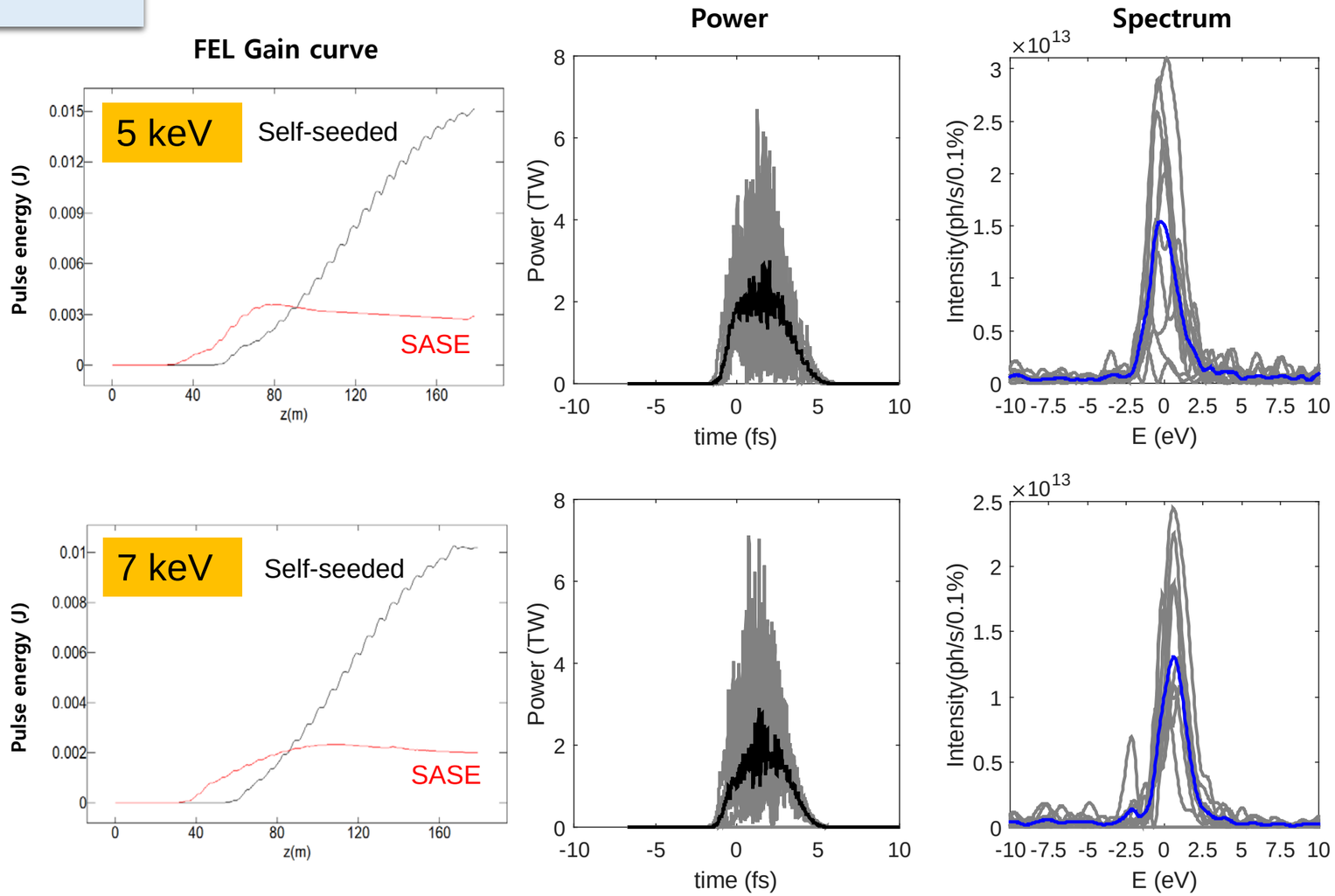
3D FEL gain length vs peak current



C. H. Shim, *et al.*, *Sci Rep* **10**, 1312 (2020).

FEL simulation results (SIMPLEX)

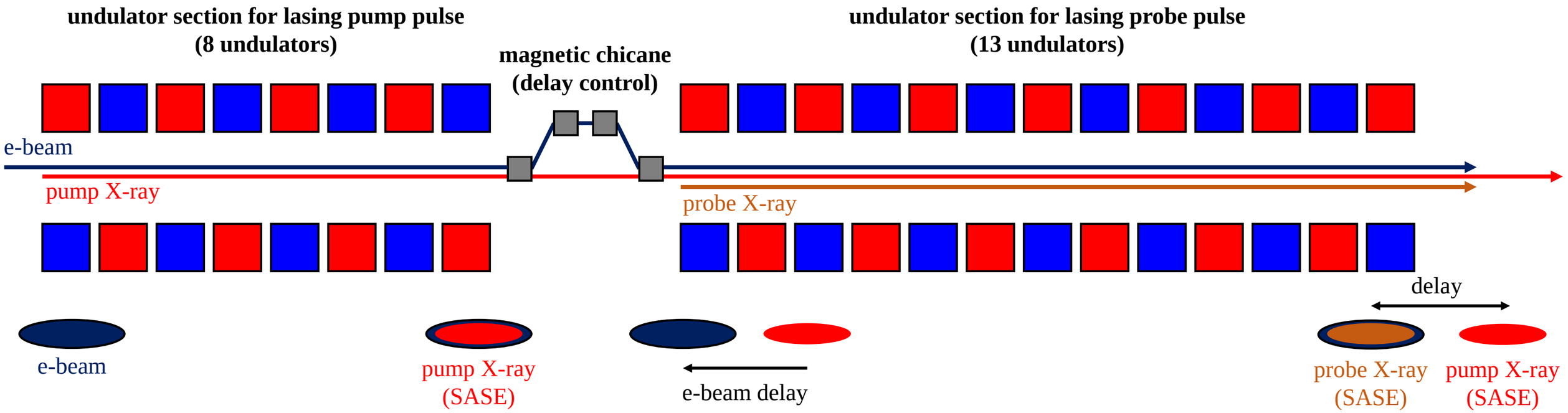
Electron beam		
Photon energy	5 keV	7 keV
e-beam energy	11 GeV	11 GeV
Peak current	15 kA	15 kA
Pulse length (FWHM)	5 fs	5 fs
Energy spread	5 x 10^{-4}	5 x 10^{-4}
Undulator K	3.5	2.7
# of undulator	30	30
Tapering undulator start	5	10
Self-seeding parameters		
Crystal type	[110]	[110]
Bragg orientation	220	220
Crystal thickness	30 μm	100 μm
Time delay	22 fs	16.5 fs



high-resolution, single molecule imaging, strong field physics, nonlinear x-ray science

Two-color XFEL
with time delay and pulse duration control

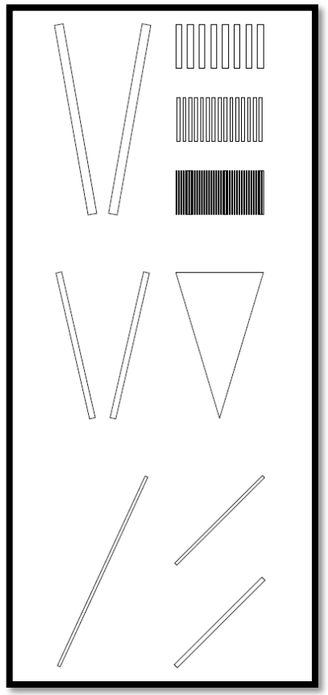
Two-color XFEL with time delay control



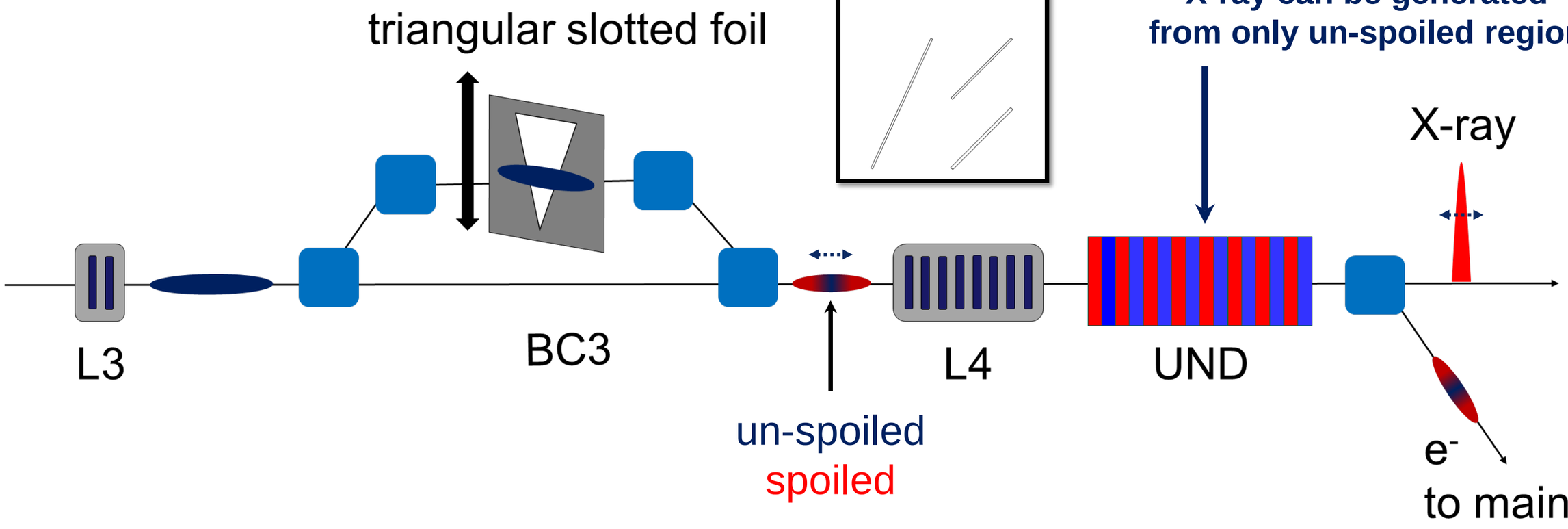
- ✓ By utilizing variable gap undulator and dipole magnet for self-seeding section, two-color pump-probe XFEL pulses can be generated from single electron bunch
- ✓ Time delay between pump and probe pulse can be controlled by changing the current of the dipole magnet (**max. time delay is 120 fs**)

Pulse duration control using slotted foil at BC

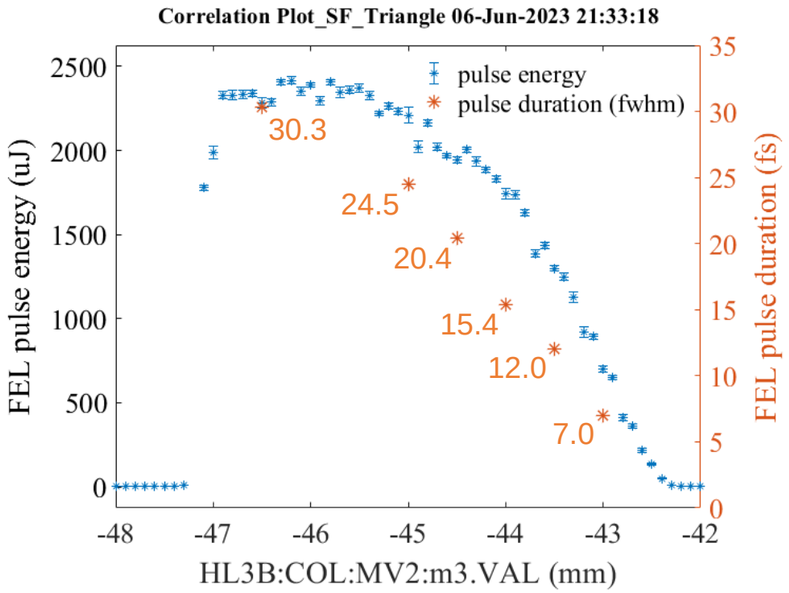
Longitudinal properties can be manipulated by using slotted foil at bunch compressor



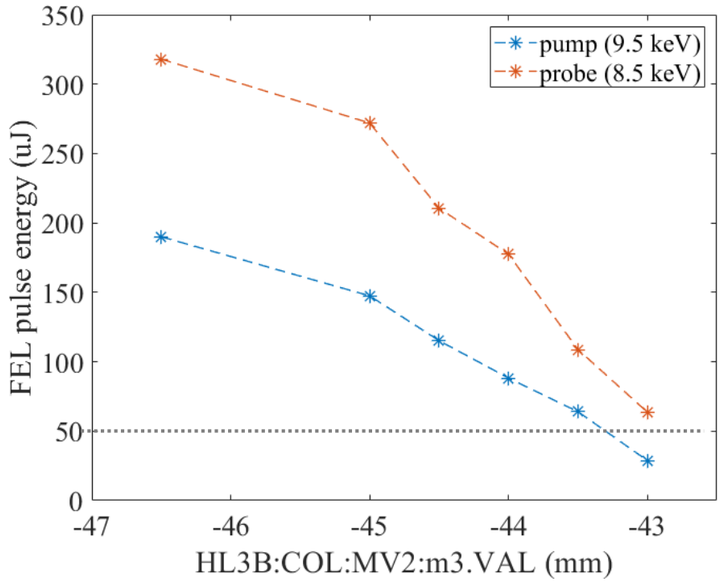
slotted foil installed at BC3

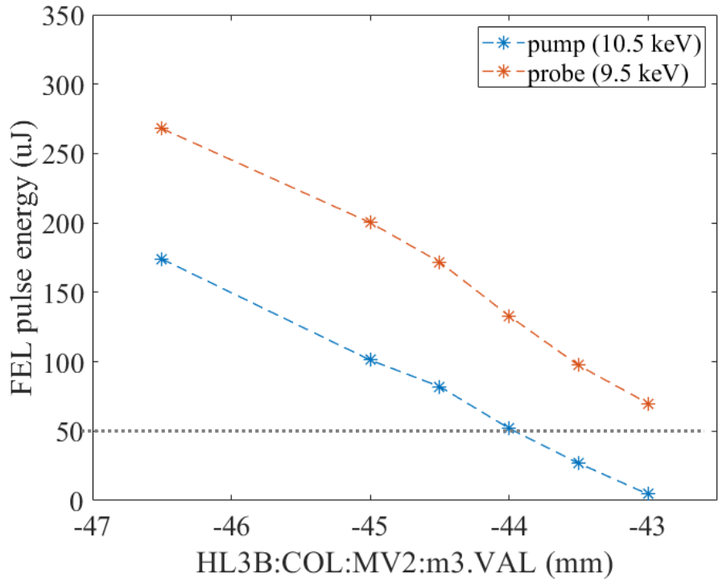


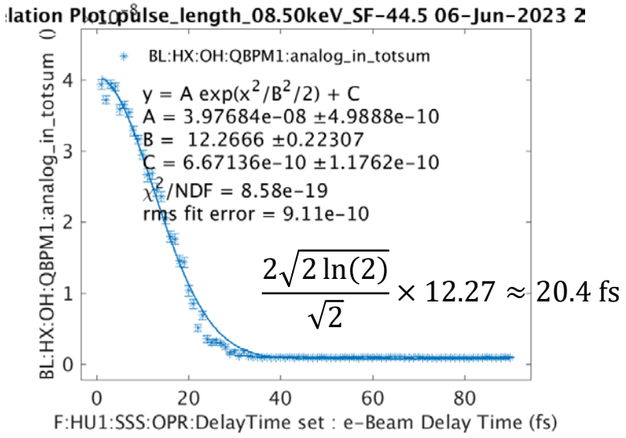
Two-color XFEL for user service



For user service (2023.6.8~6.9)





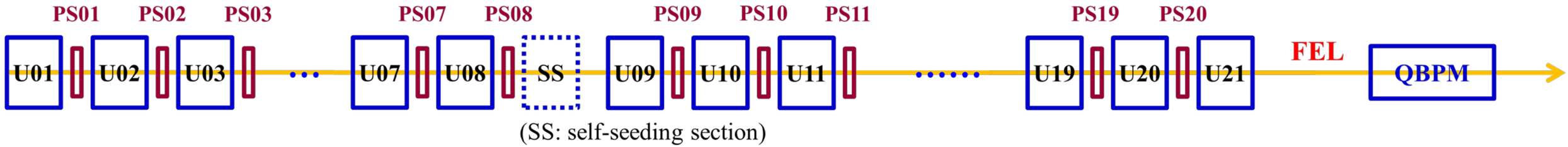


$$\frac{2\sqrt{2\ln(2)}}{\sqrt{2}} \times 12.27 \approx 20.4 \text{ fs}$$

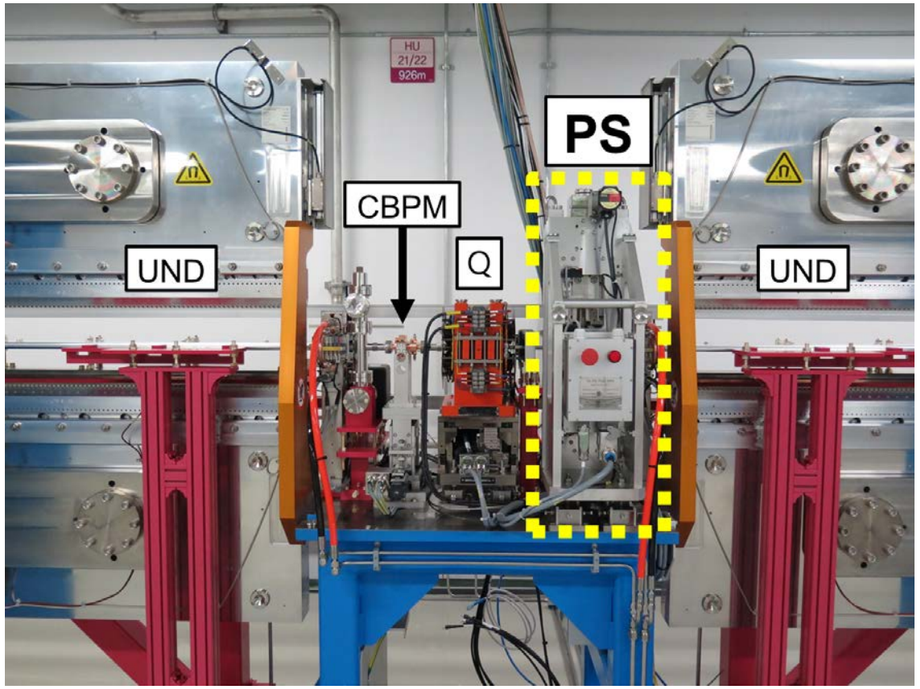
- ✓ Pulse duration is measured by using intensity autocorrelation with magnetic chicane installed in the self-seeding section.
- ✓ We assumed that the XFEL pulse is a Gaussian pulse.
- ✓ Pulse duration according to SF position is measured by using single-color SASE XFEL

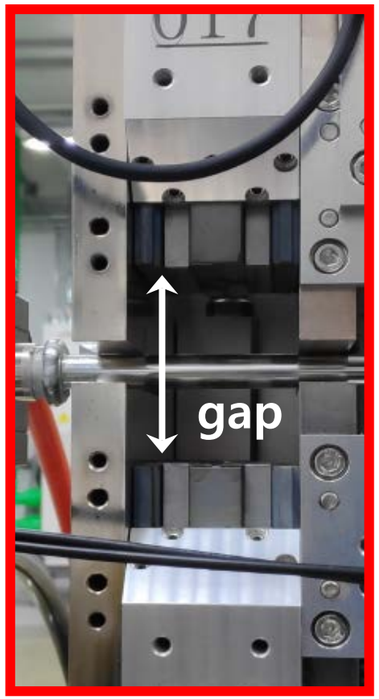
Time-synchronized two-color XFEL using phase shifters

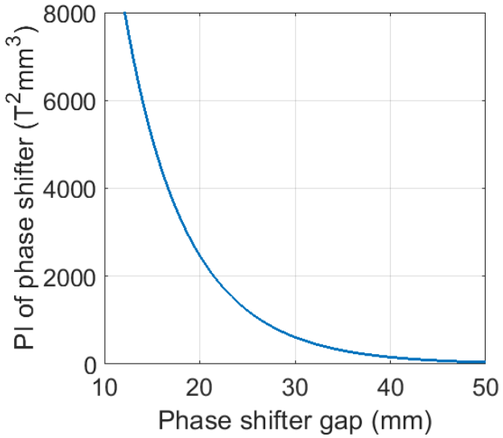
Phase shifter between undulators

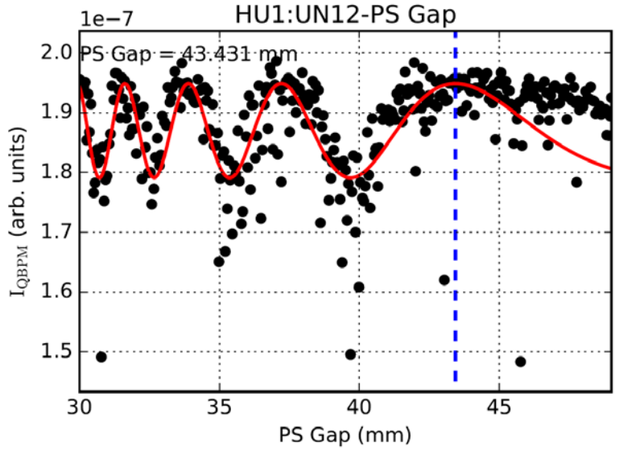


(SS: self-seeding section)









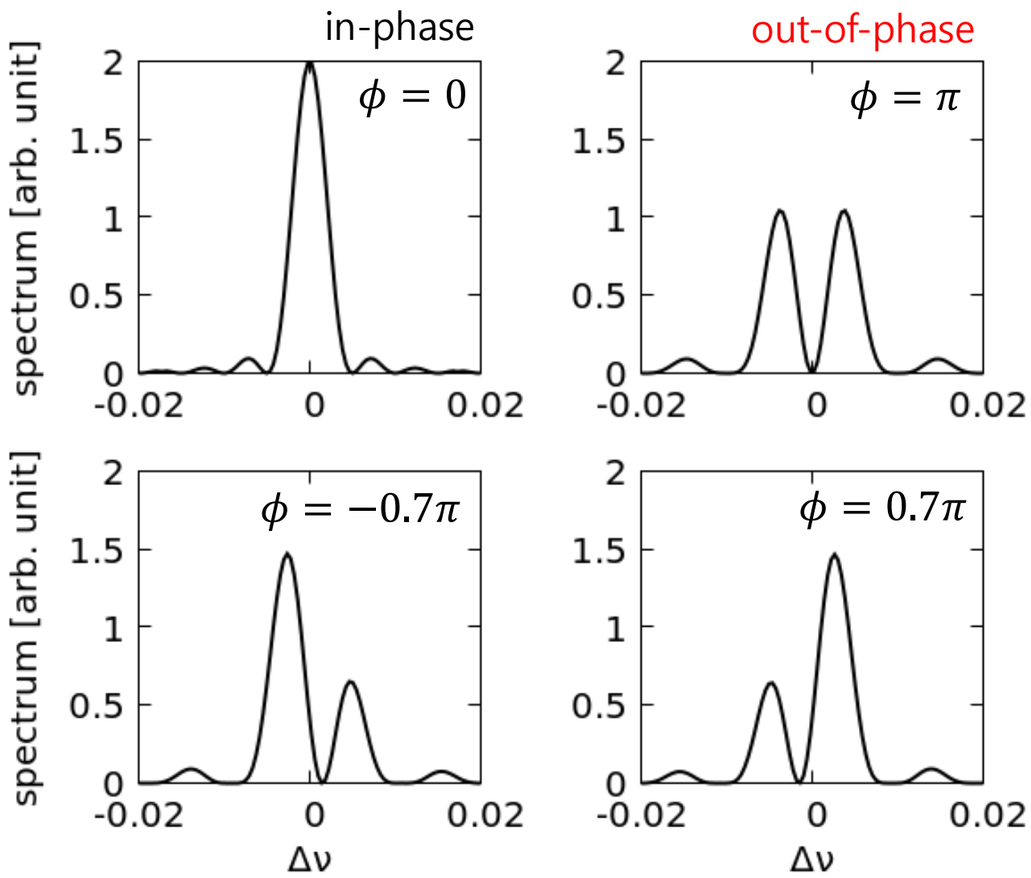
$$s = \frac{1}{2\gamma^2}\left(L_{int} + \left(\frac{e}{mc}\right)^2 \cdot PI_{PS}\right) = n \times \lambda_u$$

To match the phase between FEL pulse and electron beam

*M.-H. Cho *et al. Sci. Rep.* **13**, 13786 (2023).

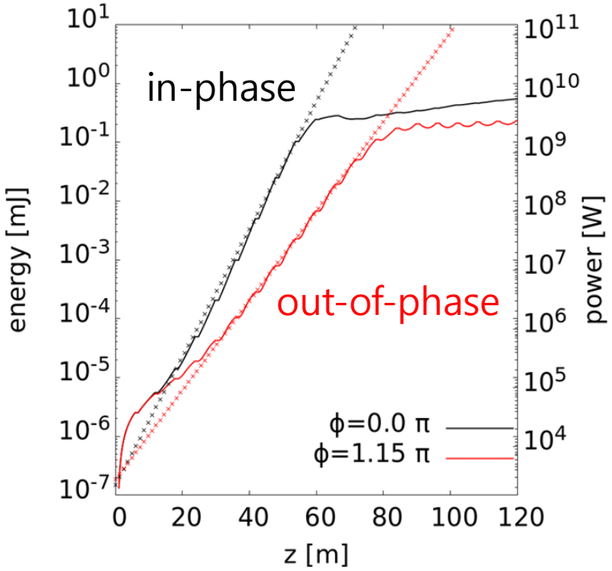
Time-synchronized two-color XFEL

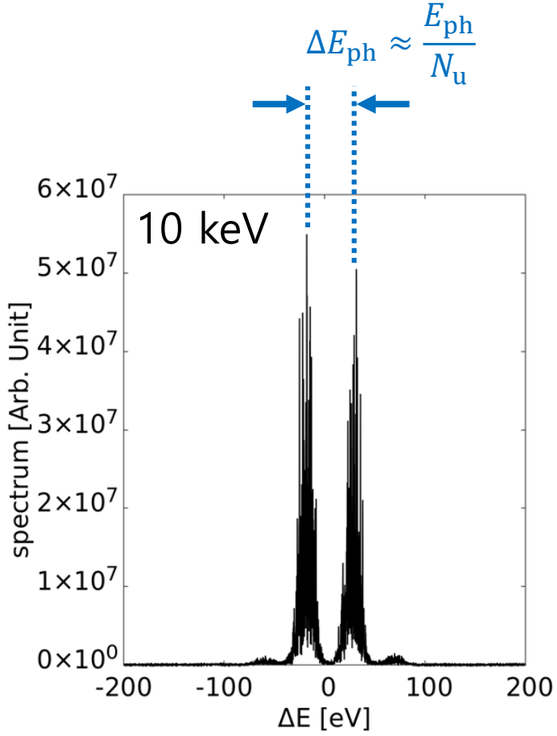
Spectrum calculation (low gain theory)



Assume that 2 undulators and 1 phase shifter are used

3D simulation (GENESIS)





Only linear undulator tapering is applied

*M.-H. Cho *et al. Sci. Rep.* **13**, 13786 (2023).

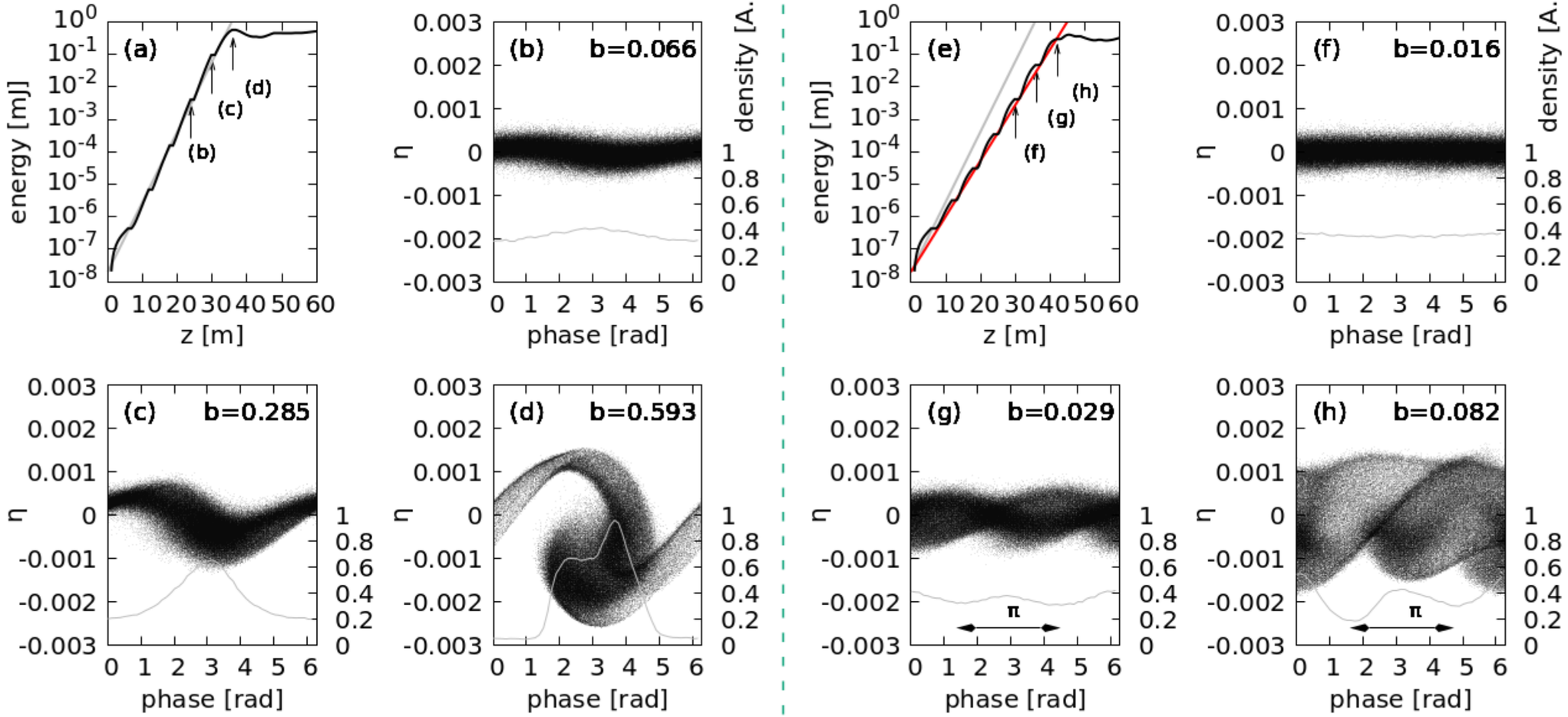
1D simulation (coded by Dr. M.-H. Cho)

in-phase vs. out-of-phase condition

in-phase (normal condition) **phase=0**

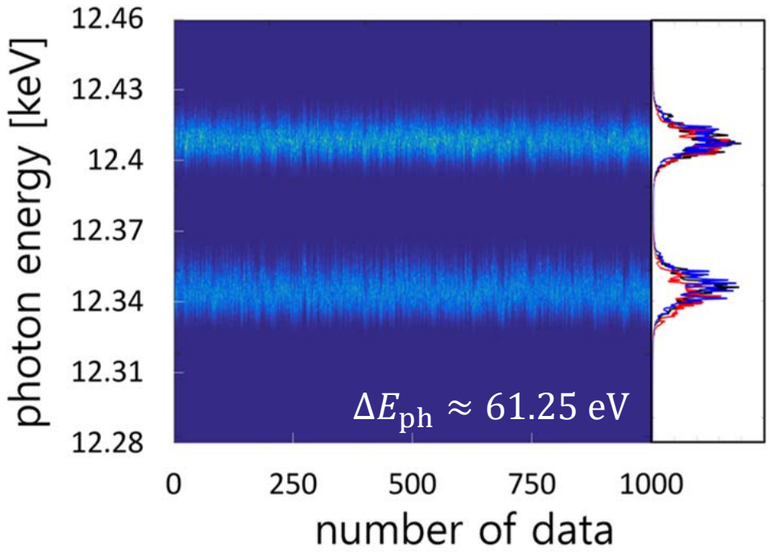
out-of-phase
(time-synchronized two-color XFEL mode)

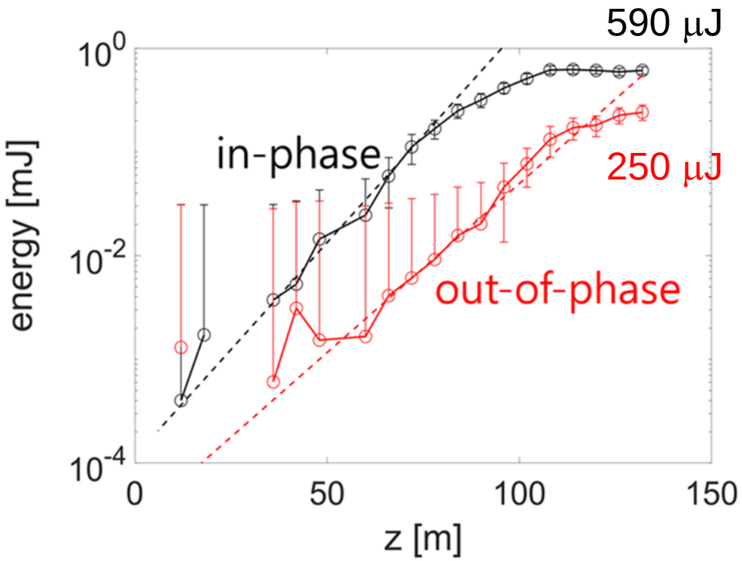
phase=1.15 π

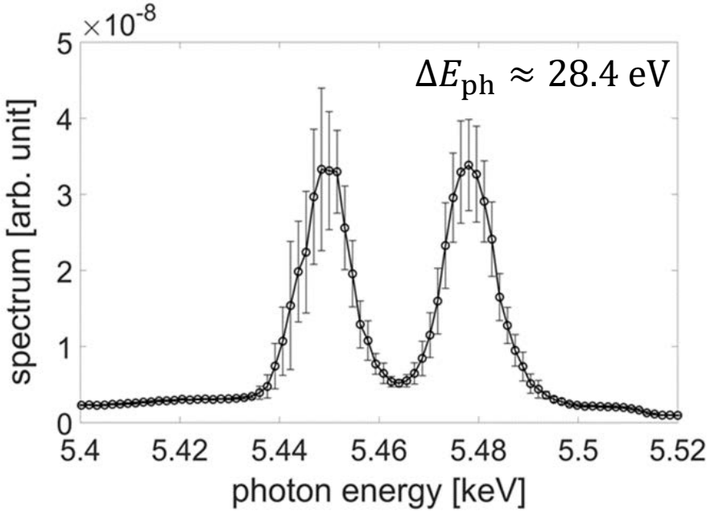


*M.-H. Cho *et al. Sci. Rep.* **13**, 13786 (2023).

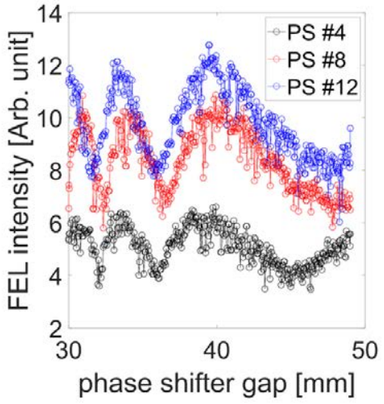
Experimental results

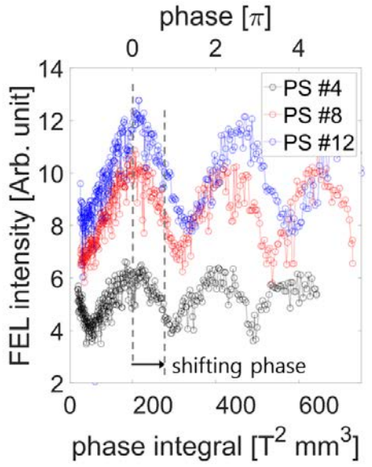


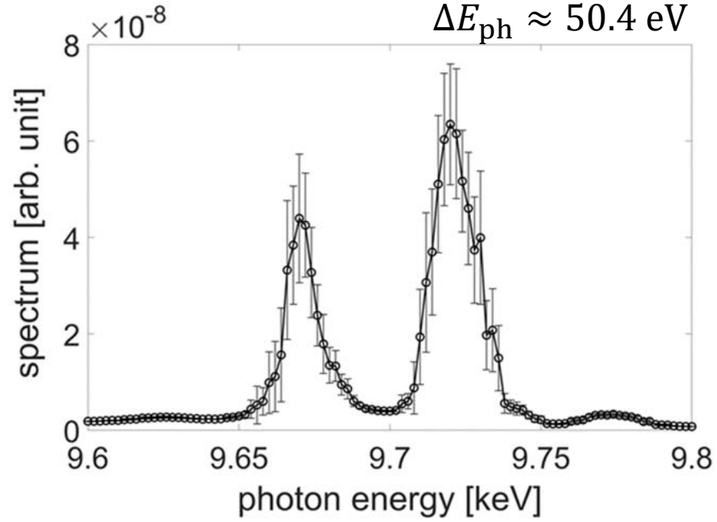




- Only linear undulator tapering is applied.
- The optimal condition (max. FEL intensity) is considered as ‘in-phase’ condition.
- Out-of-phase condition is set by applying shifting phase to all phase shifters.







R&D future plan

❖ **Beam manipulation by using laser heater**

- Laser collimator
- Short pulse operation

❖ **Installation of additional corrugated pipe at HX1**

- Phase-locked self-seeding FEL with slotted foil (collaboration with SwissFEL)

❖ **Research on deflector using wakefield**

- To diagnose longitudinal electron beam properties

❖ **Virtual machine / Machine learning**

Thanks to:

All members in PAL-XFEL and domestic/international collaborators