Introduction to PAL-XFEL and Beam Diagnostics at PAL-XFEL

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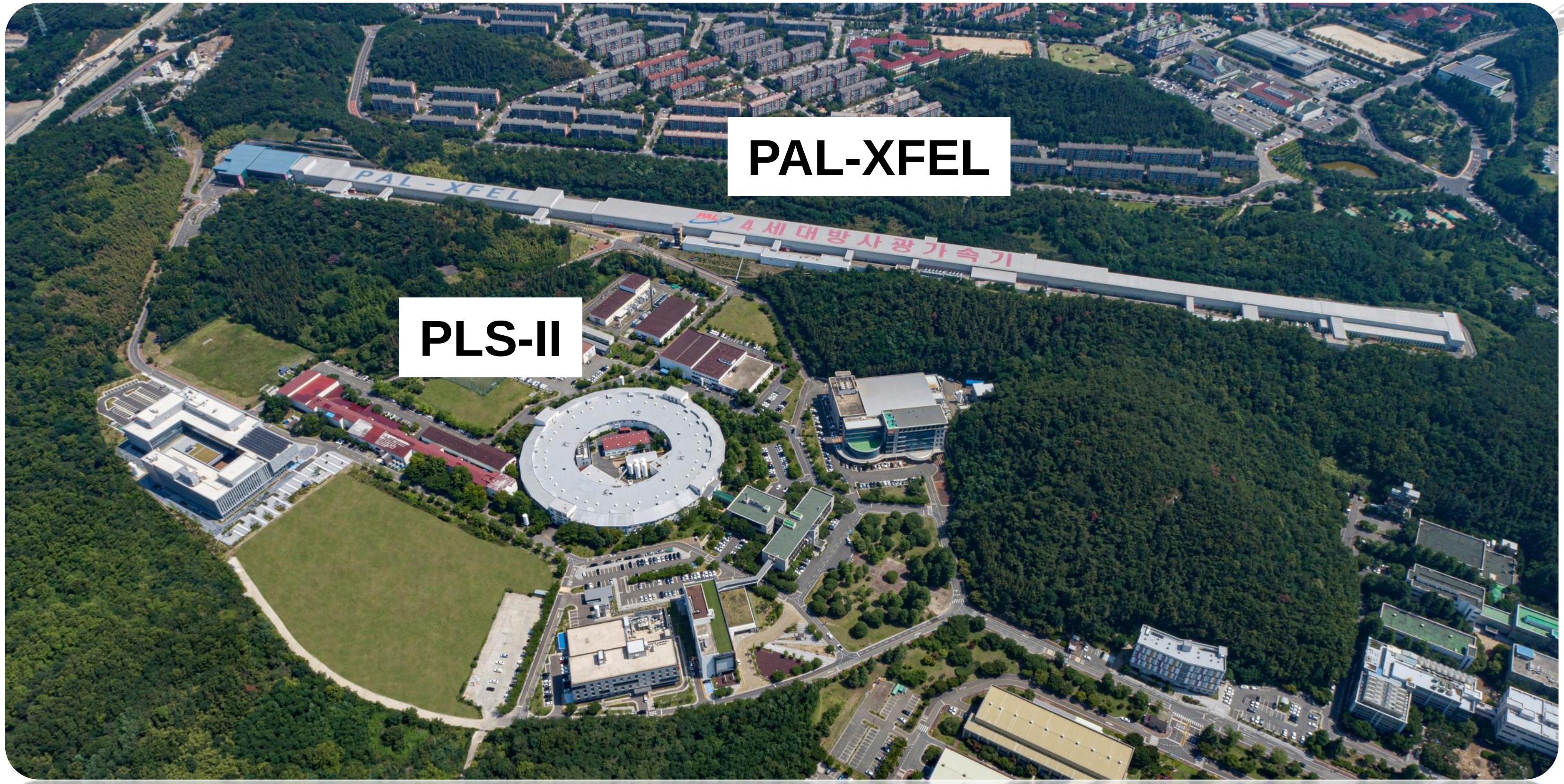
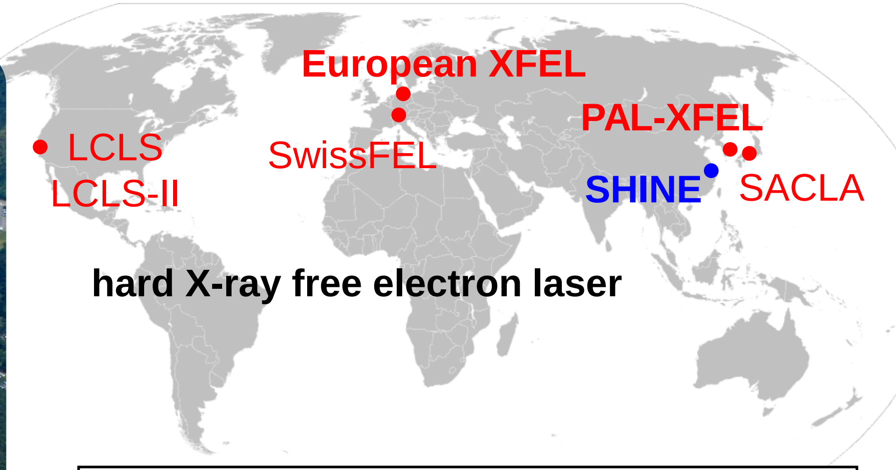
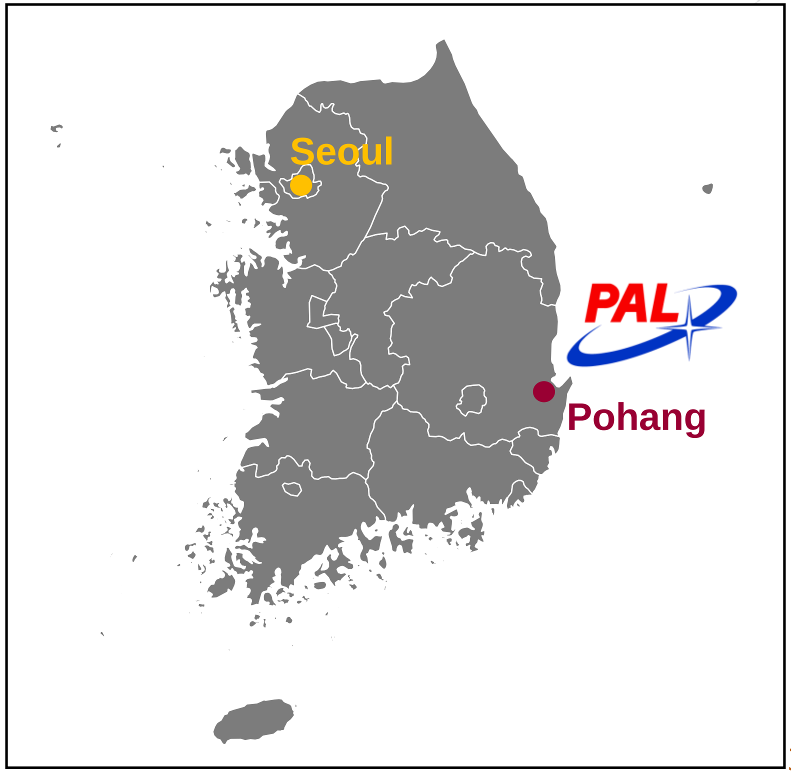
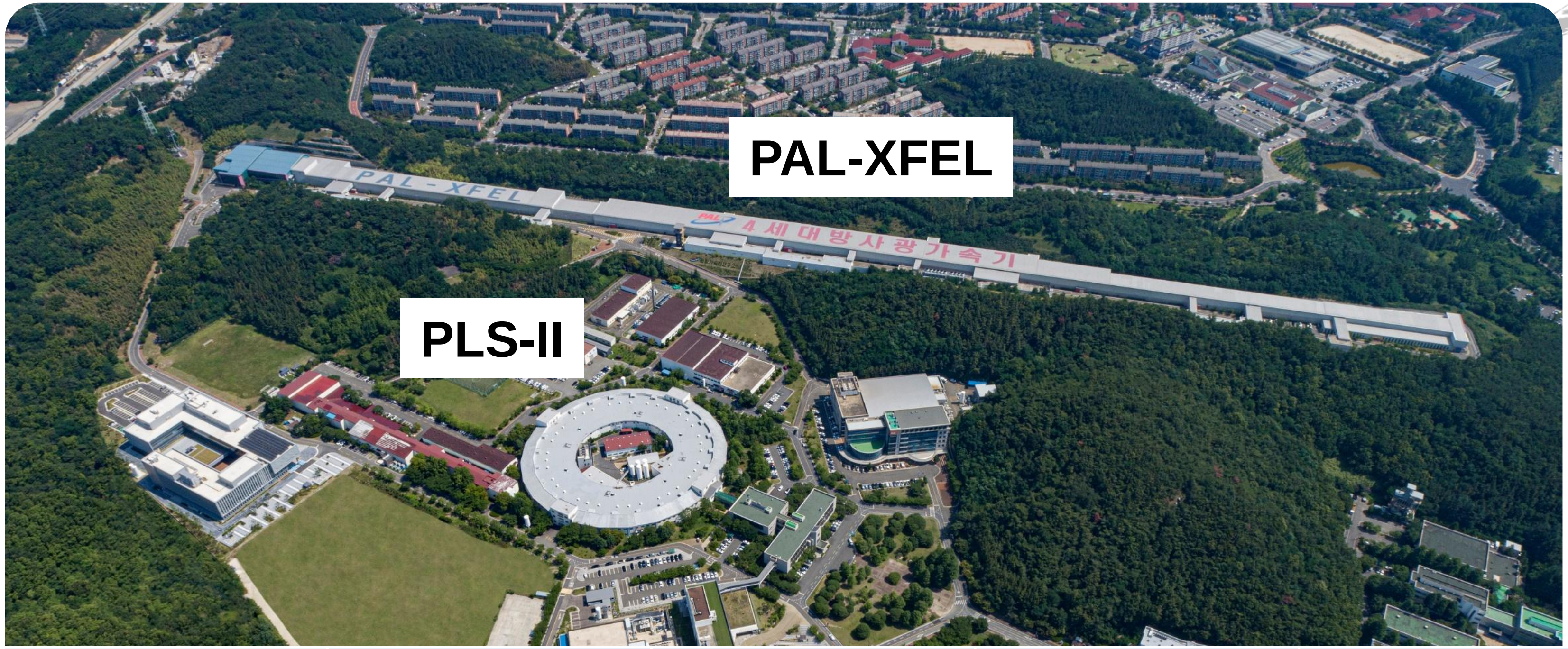
Pohang Accelerator Laboratory X-ray Free-Electron Laser

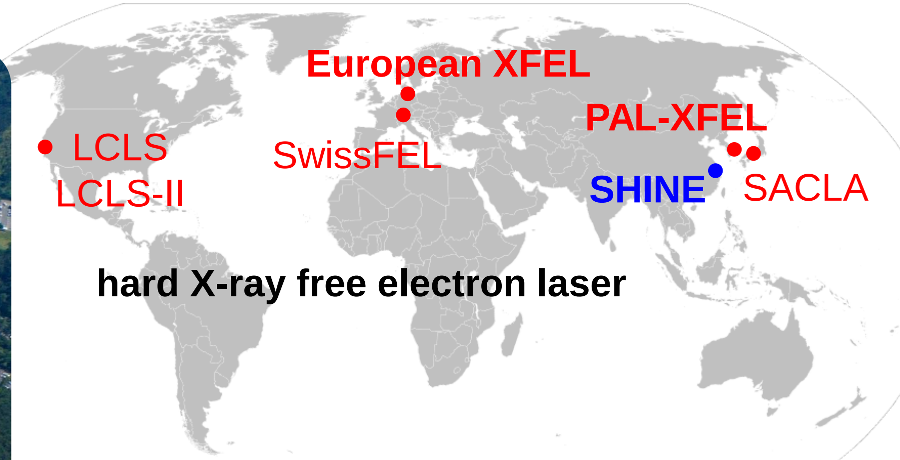


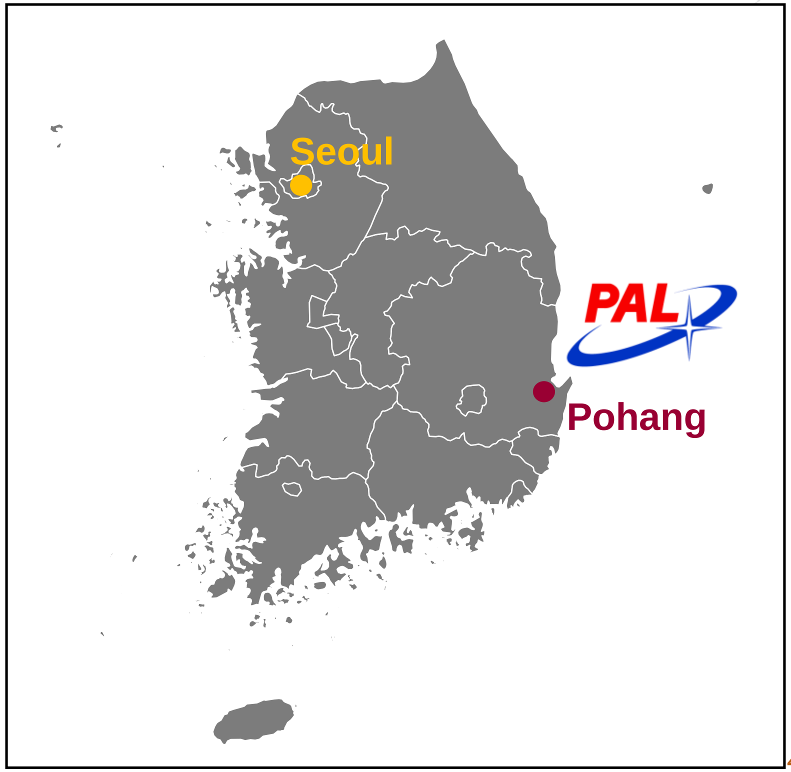




Pohang Accelerator Laboratory X-ray Free-Electron Laser

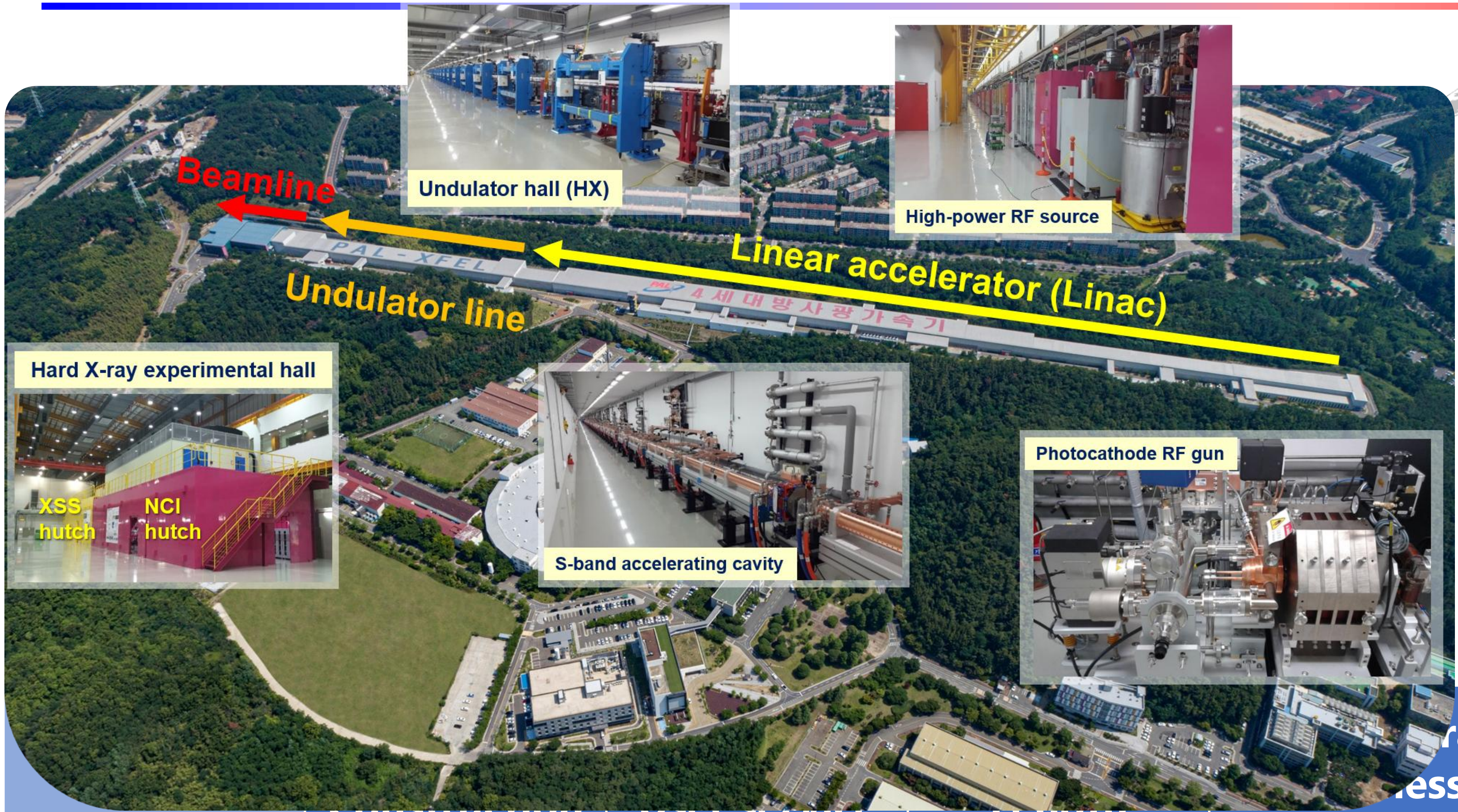


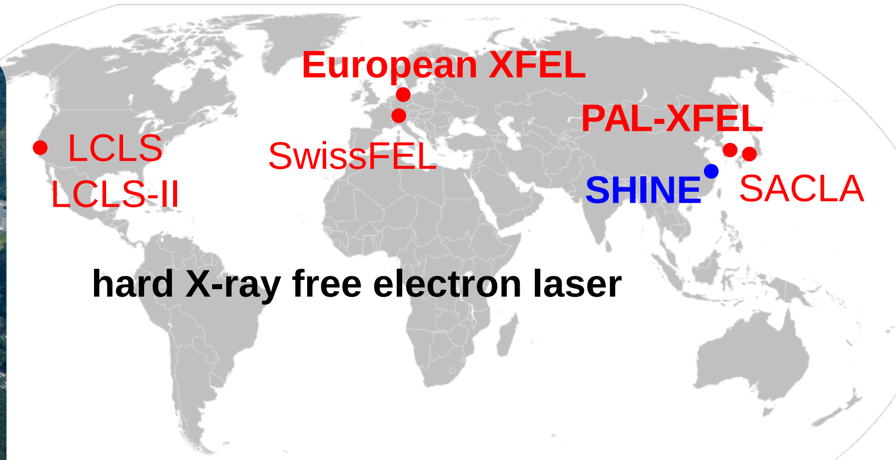


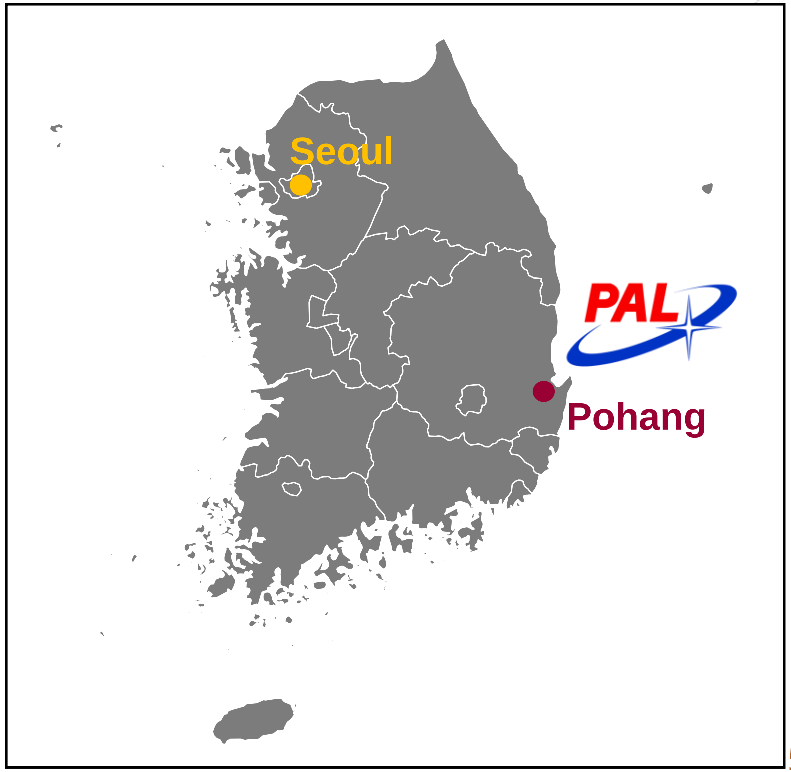


PAL-XFEL information	Construction	User service	Length	Peak spectral brightness photons s^{-1} mm^{-2} $mrad^{-2}$ 0.1% bandwidth $(BW)^{-1}$
	2011-2016	June 2017	1.1 km (the longest building in Korea)	3.2×10^{35} (World's highest brightness)

Pohang Accelerator Laboratory X-ray Free-Electron Laser







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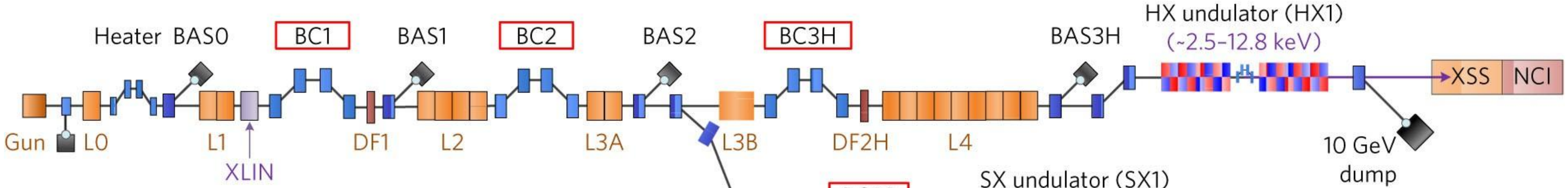
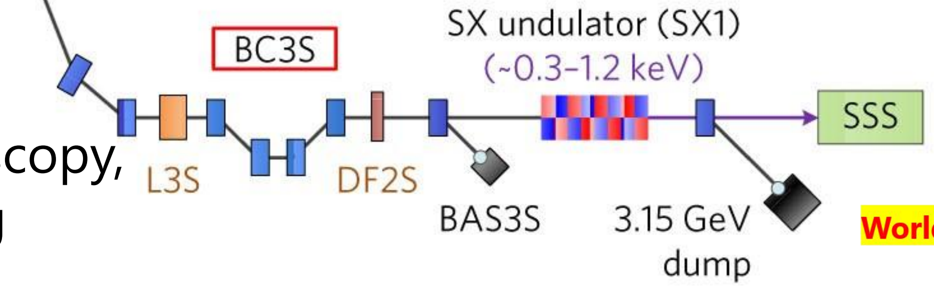
Introduction to PAL-XFEL



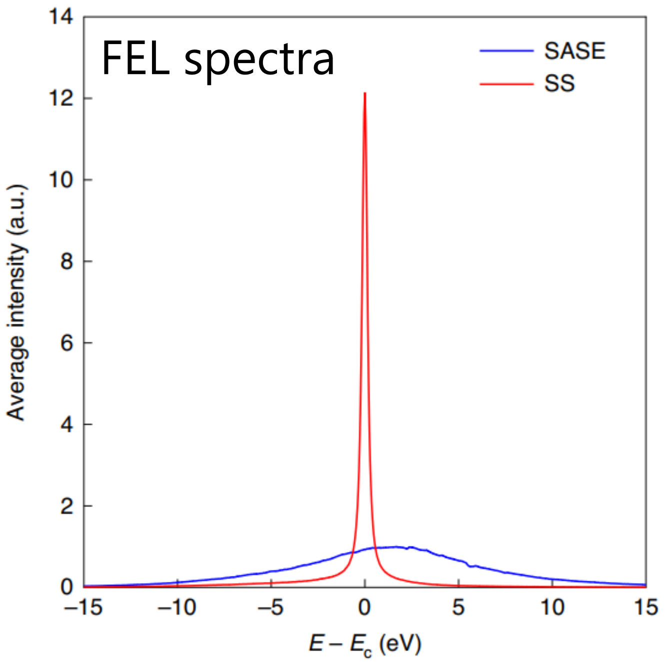


- <u>**High-brightness X-ray laser source**</u>
- **Applications**: X-ray scattering and spectroscopy, nano crystallography and coherent imaging
- 190 days for user (24h, >95 % availability)
- **FEL generation mode**: SASE*, Self-seeded, Two-color XFEL, Fresh-slice, *PHLUX***

Undulator Line	Hard X-ray	Soft X-ray
Photon energy [keV]	**2.0 ~ 20.0**	**0.25 ~ 1.25**
Beam Energy [GeV]	**4 ~ 11**	**3.0**
Wavelength Tuning	**Energy**	**Gap**
Undulator Type	**Planar**	**Planar**
Und. Period / Gap [mm]	**26 / 8.3**	**35 / 9.0**

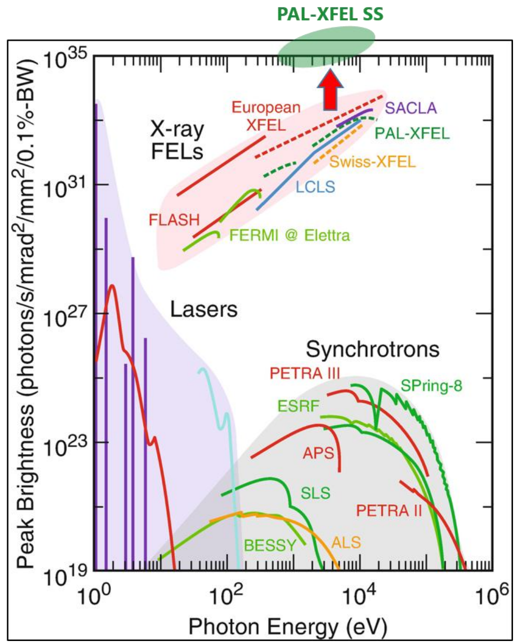
*SASE: self-amplified spontaneous emission **PHLUX: Phase-Locked Ultrafast X-ray pulse

※ User service // Studying // *Collab. w/ PSI (Swiss)*



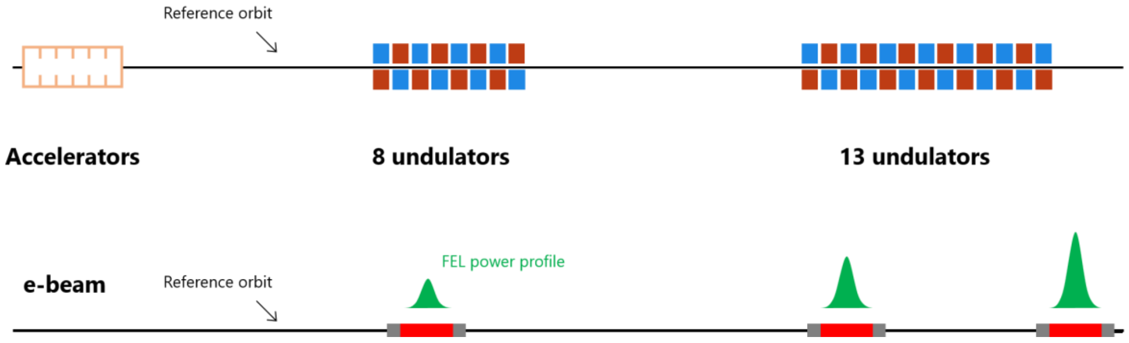
[I. Nam, Nat. Photonics (2021)]

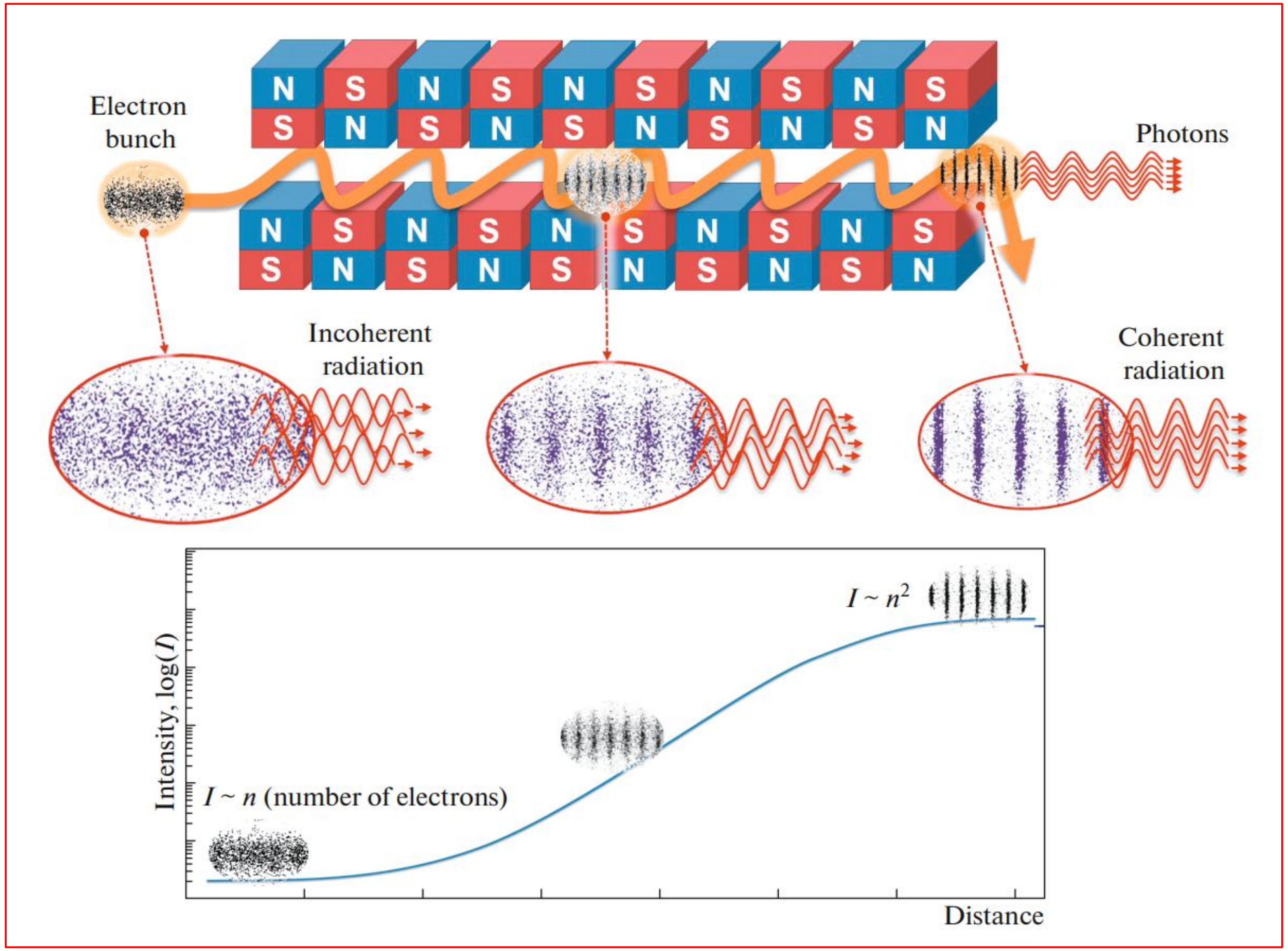
World record peak brightness!



FEL generation modes at PAL-XFEL: SASE

❖ Self-amplified spontaneous emission (SASE): Fundamental mode (in general, ~2 mJ // 40 fs // 50 GW // 10 eV BW)





[Ref] M. V. Kovalchuk, A.E. Blagov, European X-ray Free-Electron Laser (2022)

- Undulator radiation with wavelength determined by resonance condition:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

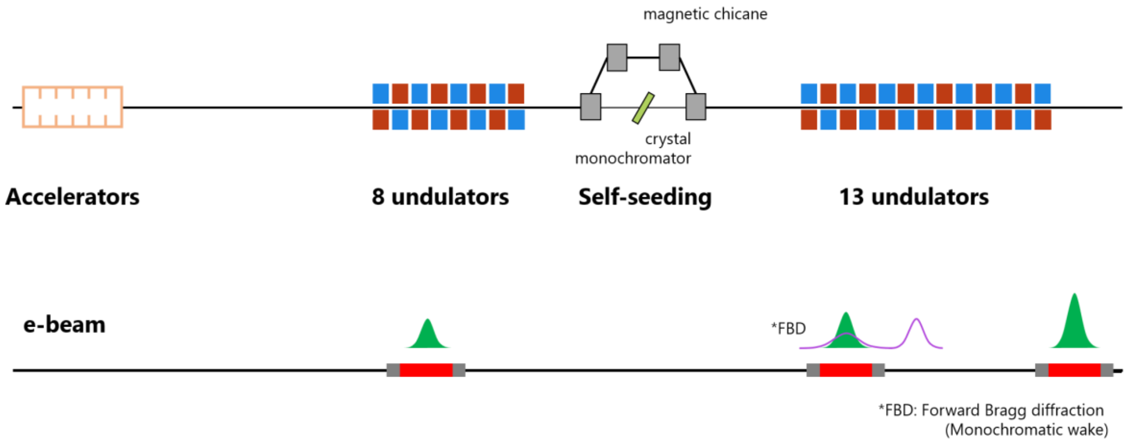
※ ***K***: undulator parameter (determined by magnetic field or undulator gap for permanent magnet undulator)

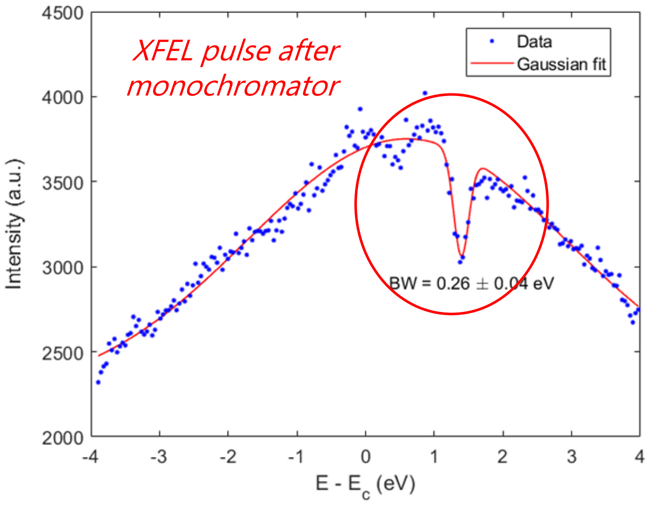
- Undulator radiation (incoherent radiation, i.e., shot noise) and electron beam exchanges energy and induces density modulation ➔ **Microbunching**

- Radiation generated from microbunching beam (spacing with λ) is coherent and its intensity exponentially ➔ Free-electron **laser**

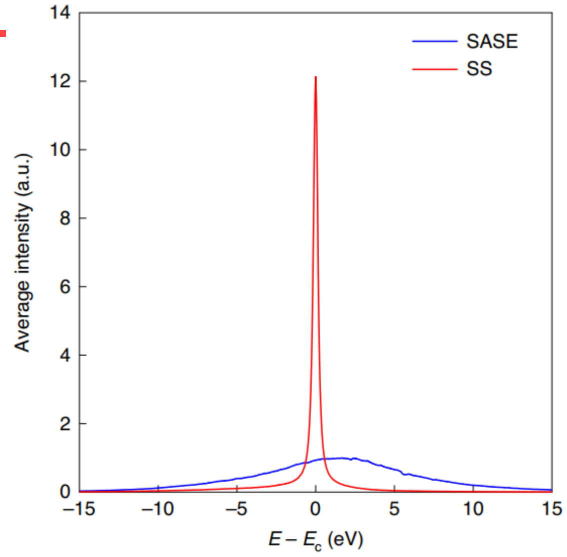
FEL generation modes at PAL-XFEL: Self-seeding

❖ Self-seeded FEL: **(Spectral intensity ↑)**



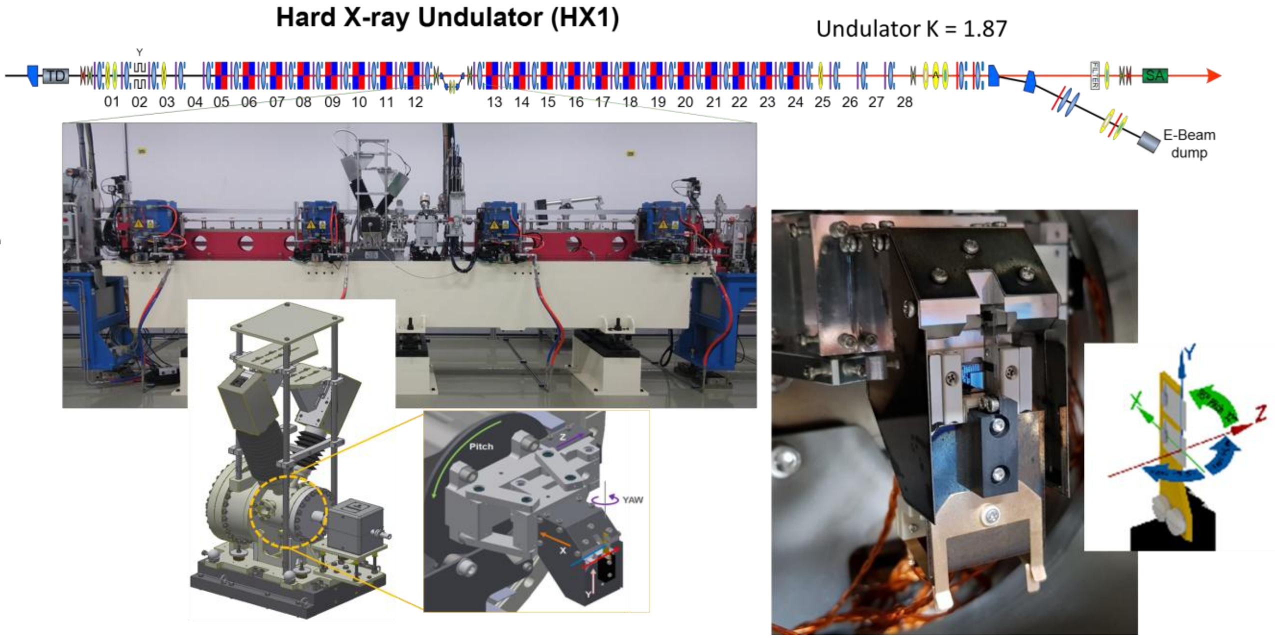


➢ Spectrum of seed pulse [1]



➢ FEL spectra [1]

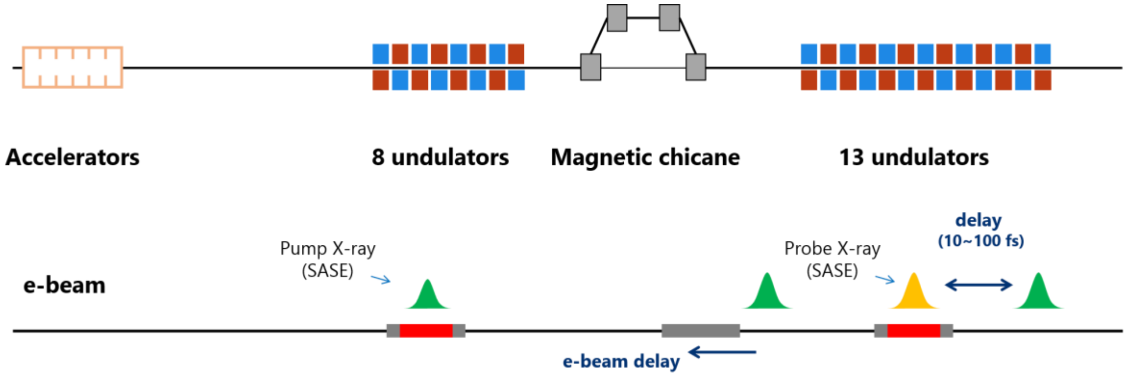
- SASE FEL becomes monochromatic seed laser by crystal monochromator (just as notch filter)
- Filtered radiation with narrow bandwidth behind the notched pulse (monochromatic wake), and amplified by the electron beam delayed by chicane
- <u>Fully coherent hard X-ray FEL</u> [1]:
  - ➢ **Narrowband FEL: 10 eV (SASE) → 0.2 eV**
  - ➢ **Spectral intensity: 10 times higher than SASE**

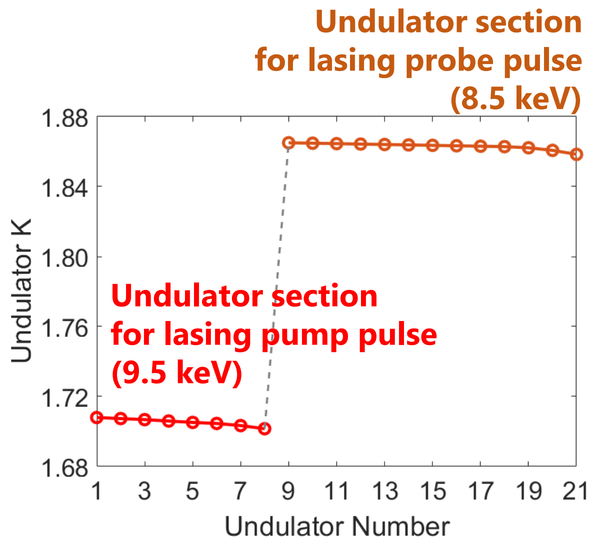


[1] I. Nam, et. al., Nat. Photonics (2021)

FEL generation modes at PAL-XFEL: Two-Color XFEL

❖ Two-Color XFEL: X-ray pump X-ray probe (in general, optical pump X-ray probe)



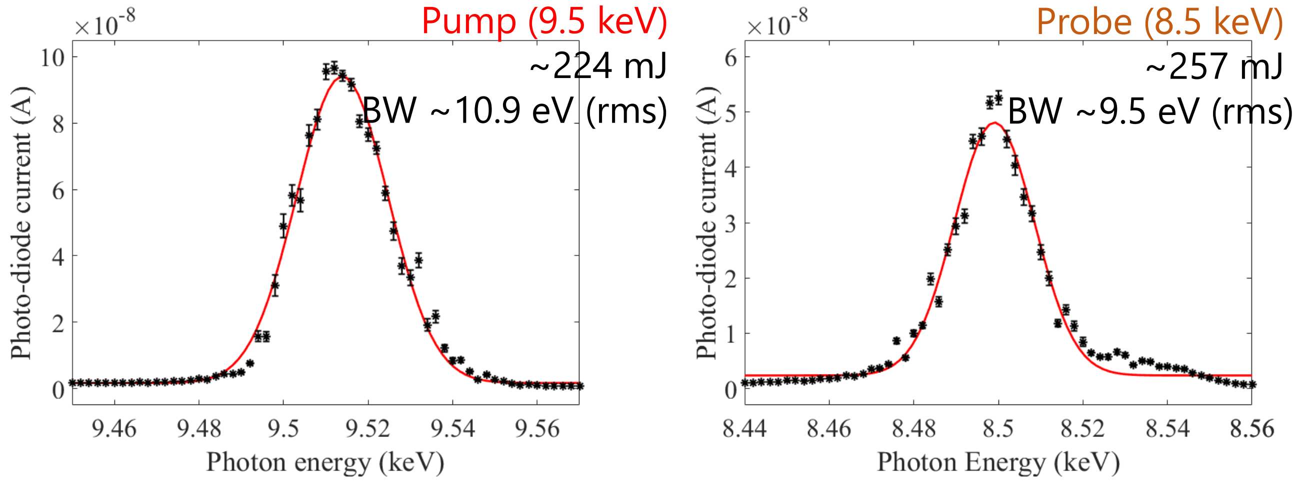


- Undulator splitting method with **variable-gap undulator**
- Fixing electron beam energy and separately setting the undulator gap (i.e., undulator parameter K and thus the X-ray wavelength)

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_1^2}{2}\right)$$

$$\lambda_2 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_2^2}{2}\right)$$

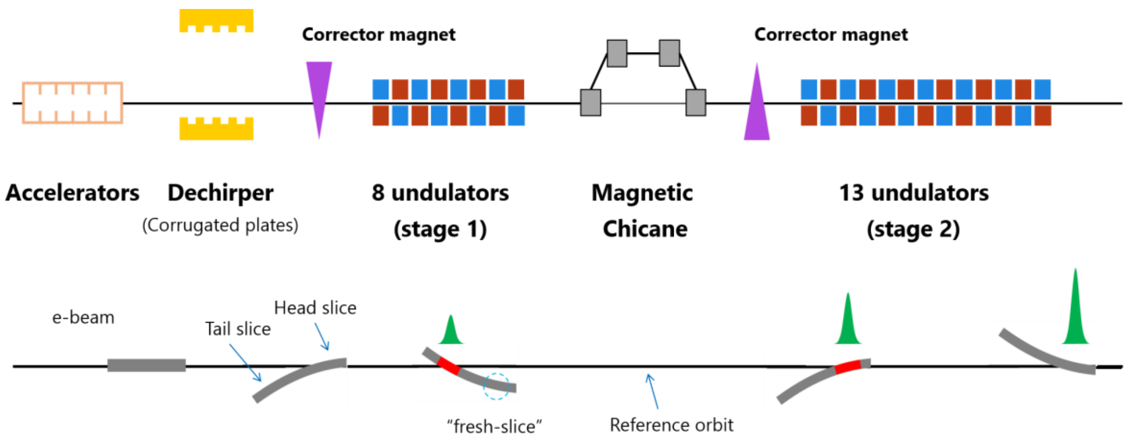
- 2-3 users/year (@PAL-XFEL)

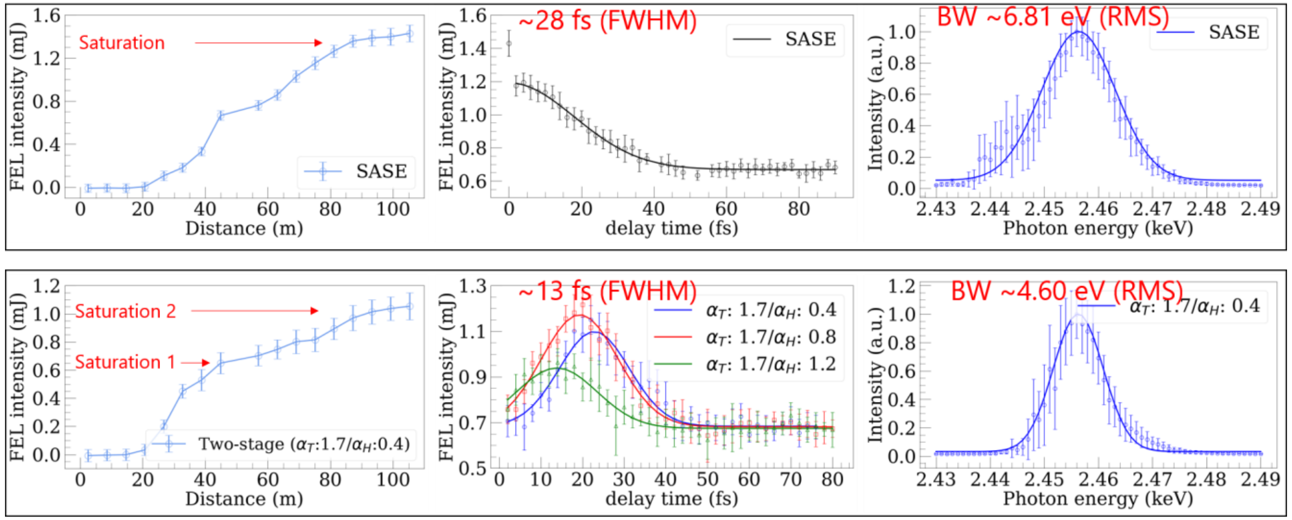


C. H. Shim, IPAC'24 WEAD1 (2024)

FEL generation modes at PAL-XFEL: Fresh-slice XFEL

❖ Multi-stage fresh-slice **(temporal density ↑)**





❖ Gain curve ❖ Pulse length measurement (Cross-Correlation [1, 2]) ❖ FEL spectrum

➢ SASE and fresh-slice FEL [1]

- Transversely tilted beam and selectively lasing in bunch slice
- Experimentally demonstrated improvement in peak pulse power (temporal density) than SASE FEL in higher photon energy at PAL-XFEL
- Not in service yet

	PAL-XFEL [1]	LCLS [2]	SwissFEL [3]
Photon energy	2.47 keV	670 eV	520 eV
FEL performance	1.1 mJ, 8.3 fs rms <~100 GW (avg)	~10^2 μJ, <10 fs rms	1.05 mJ, 1.9 fs rms ~300 GW (peak)
Undulator stages	2	3	4
Beam tilt method	Dechirper (wakefield)	Dechirper (wakefield)	Dispersion in dog-leg section

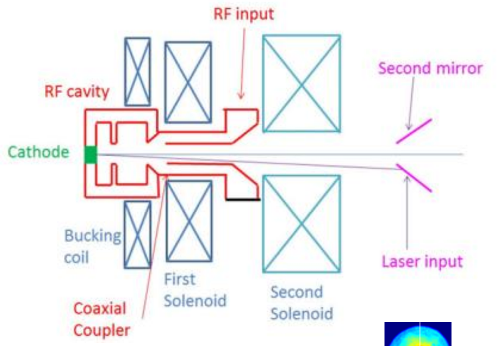
[1] **C. Sung**, et. al., NIMA **1076** 170458 (2025)

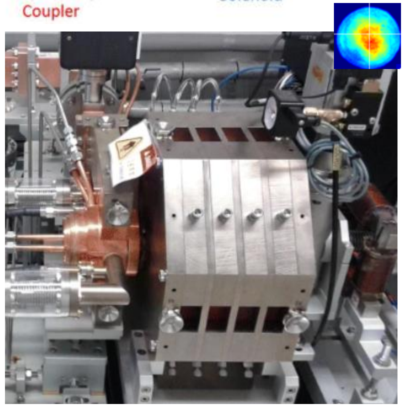
[2] PRL **120** 264801 (2018)

[3] PRL **132** 035002 (2024)

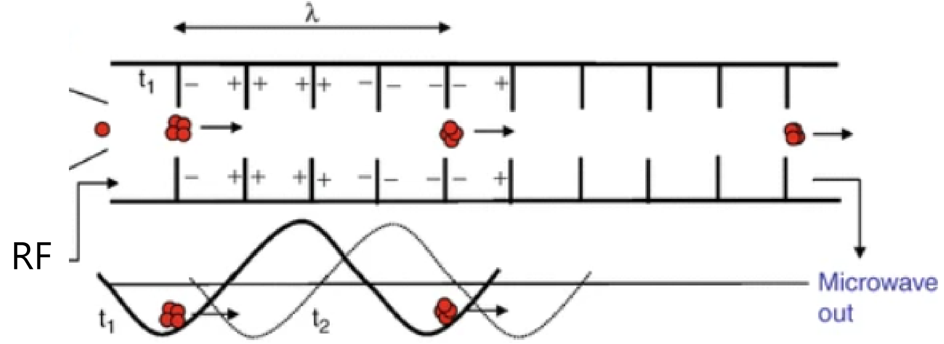
Beam Source, Accelerator and Undulator of PAL-XFEL

- Photocathode RF GUN

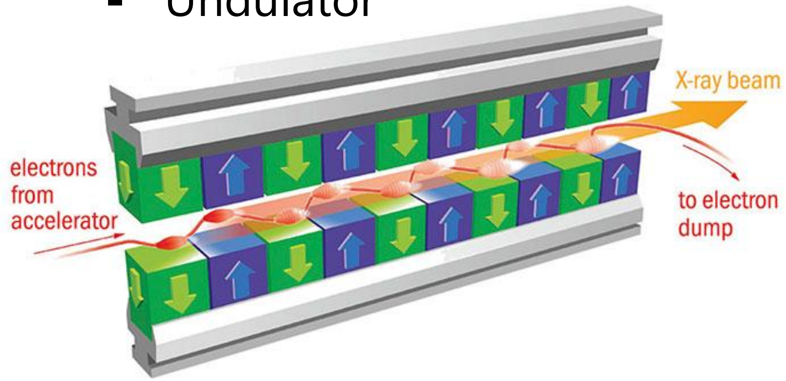




- RF LINAC (S-band NC)



- Undulator



- RF cavity, solenoid, UV laser
- Injector emittance significant for FEL performance
- Requirement: <0.5 um

  *~0.3 um at best performance (2024. Nov.)

- Acceleration, bunch compression (down to tens of fs) and maintaining injector emittance

- Variable-gap undulator with permanent magnet
- ~9 mm at minimum gap
- 26 mm period and 5.0 m length
- 21 (HX) // 7 (SX)

❖ **Electron beam requirement**: 2~3 kA, <0.5 um norm. emittance, ± 5 um position offset

PAL-XFEL Diagnostics

❖ Machine optimization* and advanced XFEL generation based on **high-resolution beam diagnostics**

Parameter	Instruments	Number	Resolution
Beam Position & Beam Energy	Stripline BPM	160	< 5 um
	Cavity BPM (X-band 11.424 GHz)	49	< 1 um
Beam Size	Screen Monitor	55	< 10 um
	Wire Scanner (tungsten and carbon wire)	21	< 10 um
Bunch Length	Coherent Radiation Monitor	4	-
	Transverse Deflecting Cavity (s-band, 2.856 GHz)	3	< 10 fs
Beam Charge	Turbo ICT	10	< 1 pC
Beam Arrival Time	Beam Arrival Time Monitor (~10 fs RMS jitter)	10	< 30 fs
Beam Loss	Beam Loss Monitor	26	-

*Beam tuning once in a week

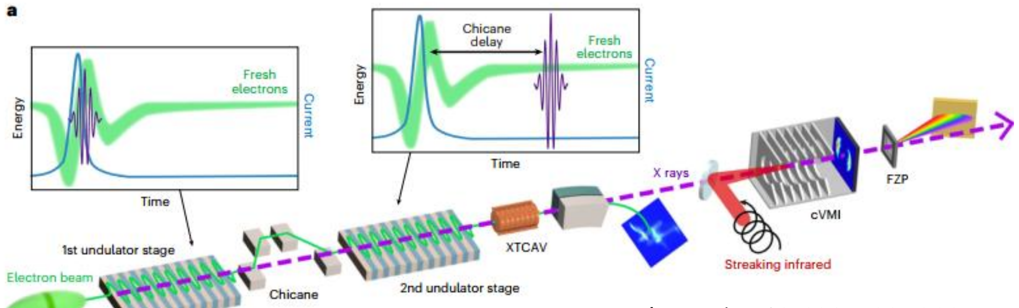
PAL-XFEL Diagnostics for advanced XFEL generation

- ❖ Advanced XFEL: Ultrafast pulse (femtosecond → attosecond), High power (GW → TW)

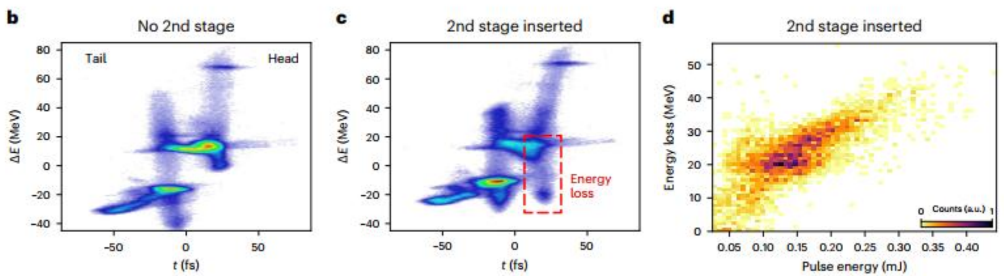
※ In general, ~2 mJ // 40 fs // 50 GW from fundamental mode (SASE) at PAL-XFEL

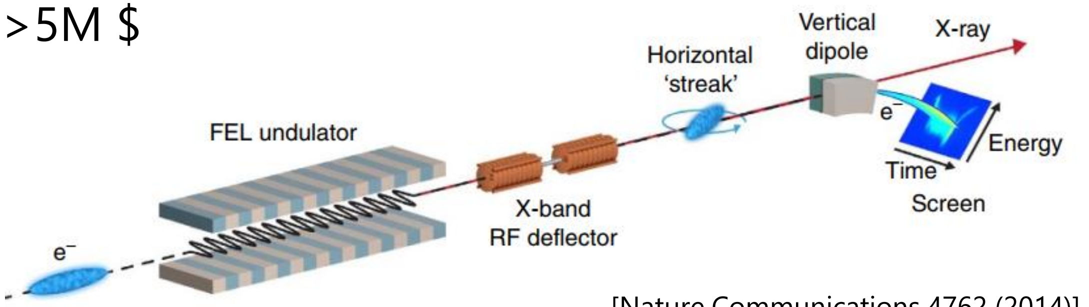
- ▪ Various methods were proposed and demonstrated, e.g., Enhanced SASE (ESASE), nonlinear compression
- ▪ Key technique: **Longitudinal bunch shaping** (for current spike of >~10 kA)
- ▪ High-resolution **longitudinal diagnostics** is essential for bunch shaping and XFEL generation
  - ➢ X-band transverse deflecting cavity (XTCAV) → fs or sub-fs resolution (used at LCLS, EuXFEL, SwissFEL)

    → XTCAV can also be used for XFEL temporal profile diagnostics
  - ➢ Not installed at PAL-XFEL and expensive for development >5M $

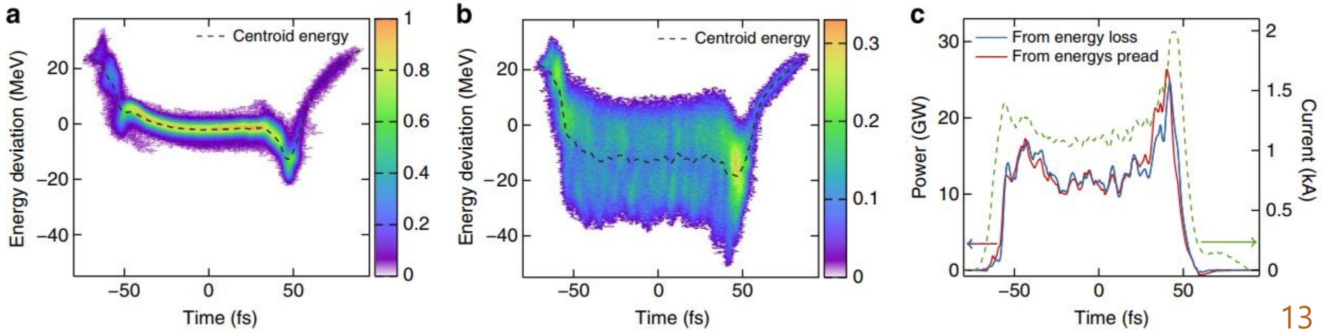


[Nature Photonics 18 698-703 (2024)]



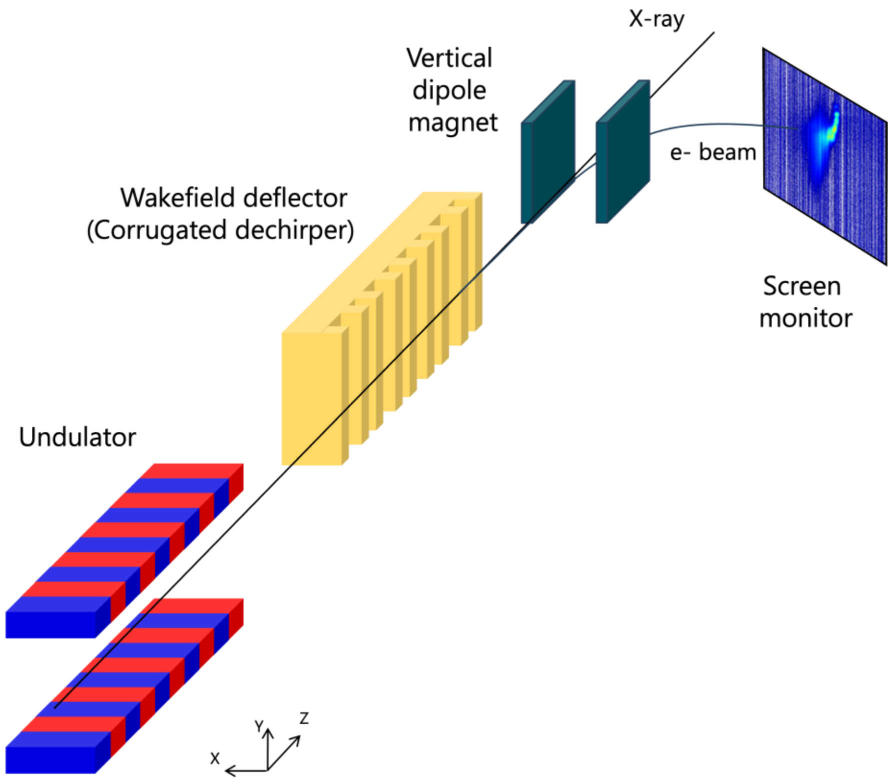


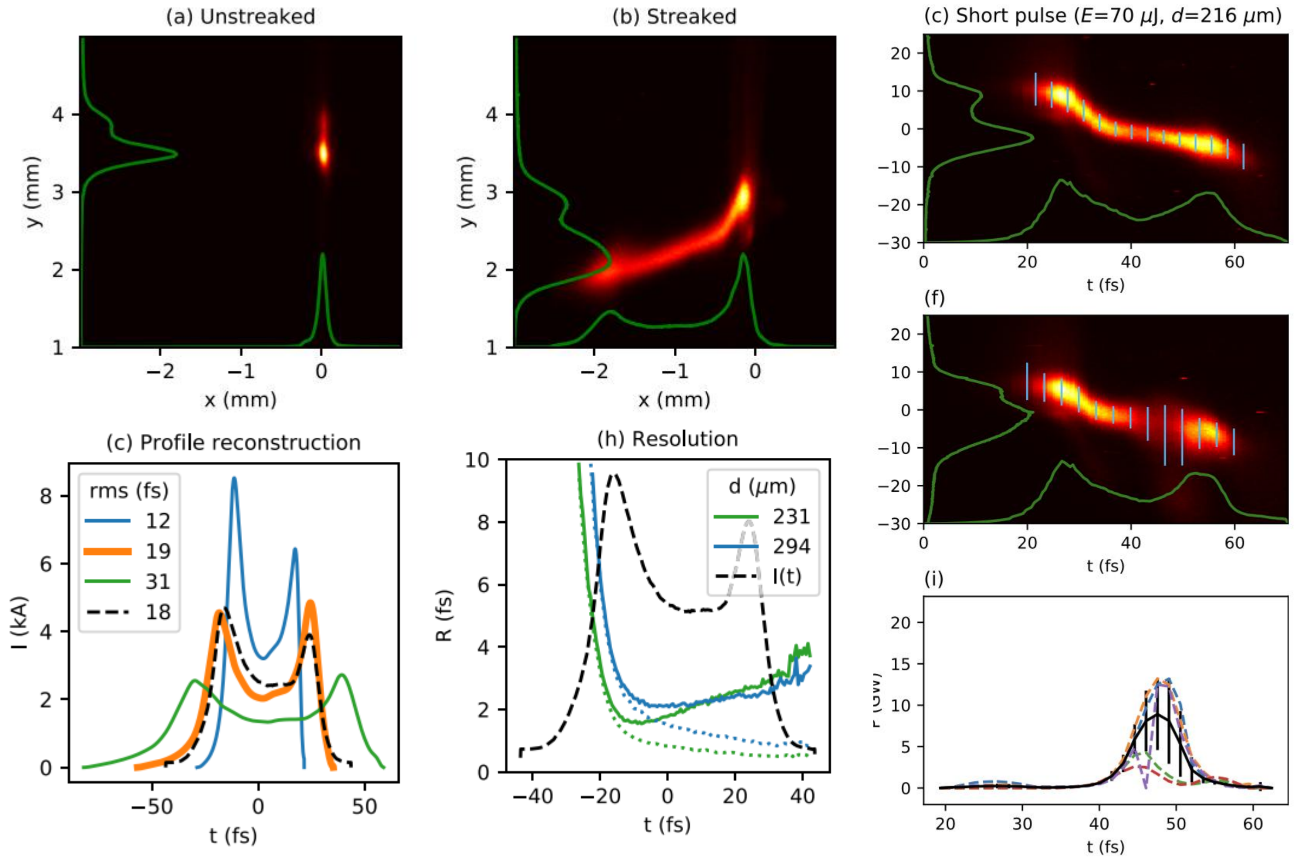
[Nature Communications 4762 (2014)]



Wakefield Deflector for Longitudinal Phase Space Diagnostics

- Wakefield deflector (passive device): Alternative method to XTCAV
  - ➢ Self-generated **time-dependent wakefield** for beam deflection (t → x or y) (no need for external power source)
  - ➢ Experimentally demonstrated at SwissFEL (~2 fs resolution)
  - ➢ Due to nonlinearity of wakefield, higher resolution at bunch tail is achieved
  - ➢ Installed at SX undulator line of PAL-XFEL

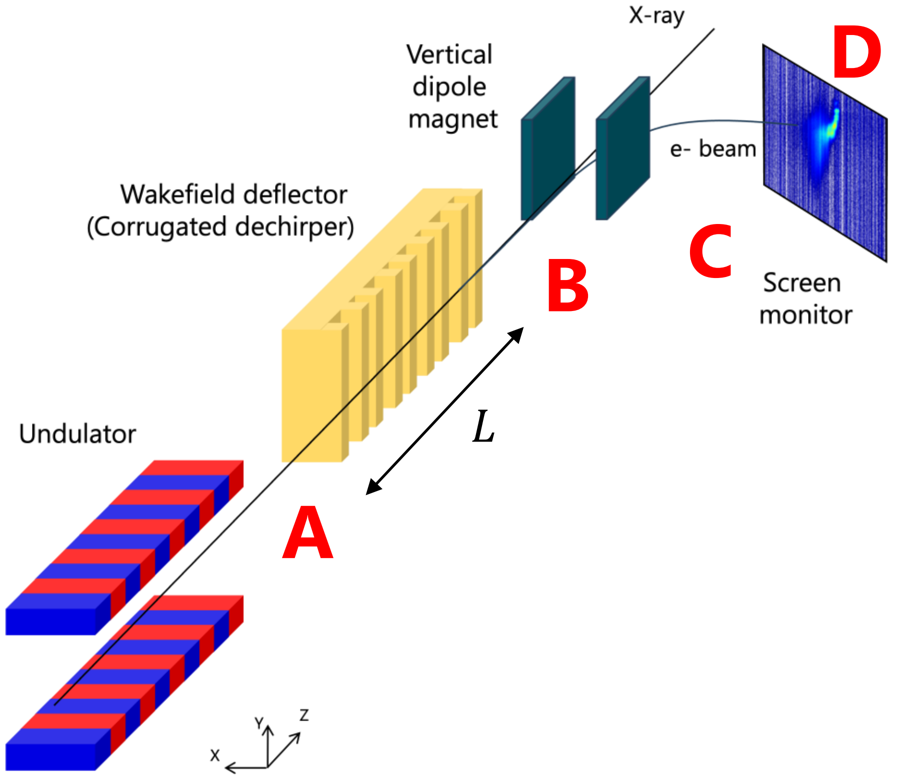


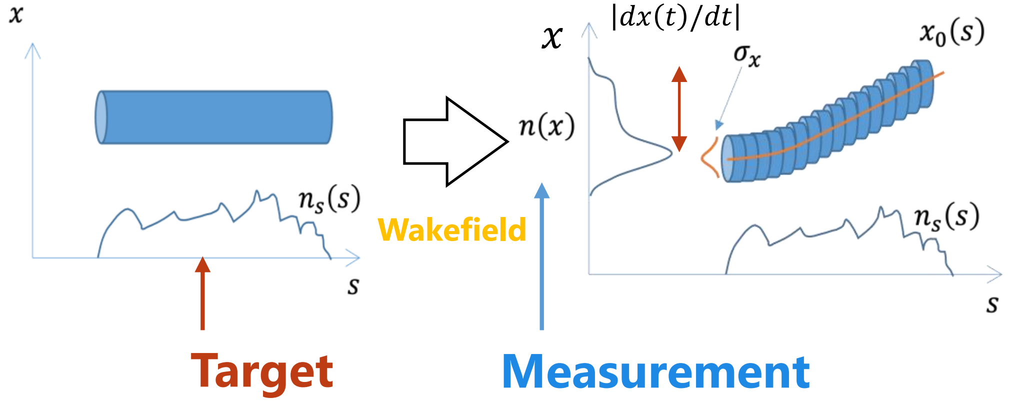


➢ Experimentally demonstrated of LPS reconstruction from wakefield deflector at SwissFEL [PRR 4 013017 (2022)]

How Wakefield Deflector Works for Longitudinal Diagnostics

- Electron beam longitudinal phase space and XFEL temporal profile reconstruction





A. Electron bunch after FEL lasing → slice energy spread increases

B. Time-dependent momentum kick by wakefield streaks electron beam horizontally

C. Dipole magnet bypasses e- beam to dump as dispersed vertically

D. Screen XY profile → Longitudinal phase space

<Reconstruction strategy>

1. Horizontal beam distribution in screen → Current profile

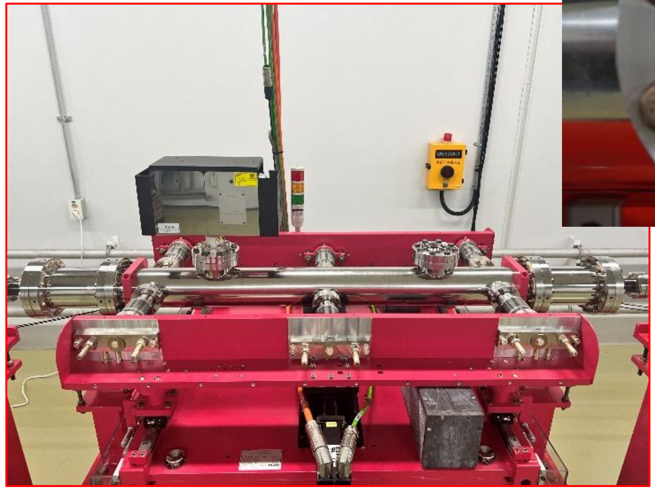
2. Current profile and energy spread from vertical distribution → time-energy correlation (longitudinal phase space)

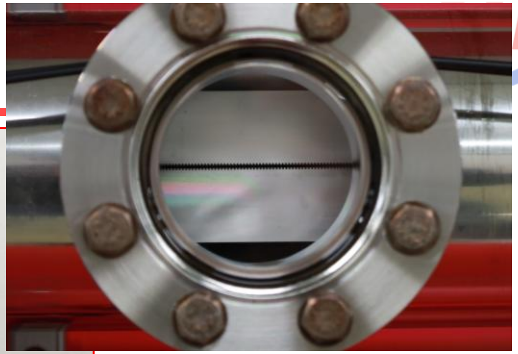
3. Time-resolved slice energy spread variation with and without FEL lasing → XFEL pulse temporal profile

❖ Reconstruction approach: Deconvolution problem of wakefield and current profile (e.g., iterative method)

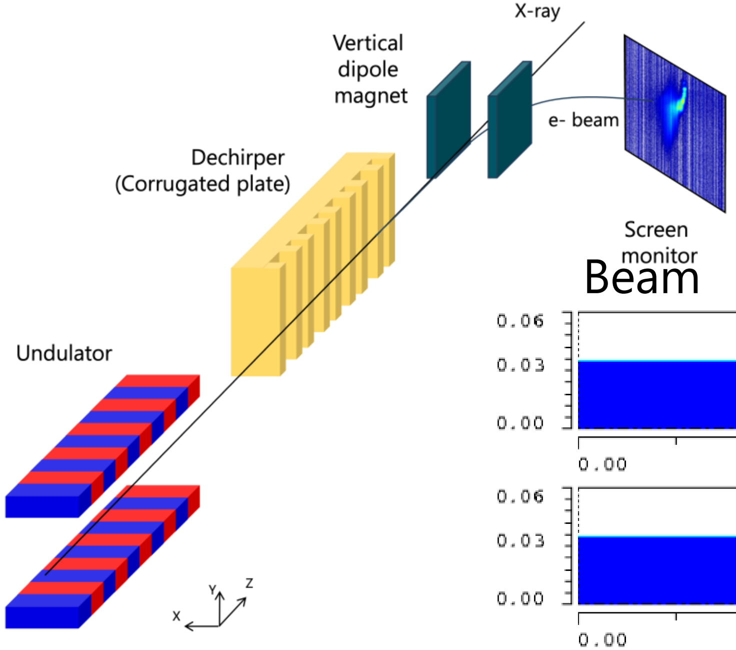
Wakefield Deflector at PAL-XFEL

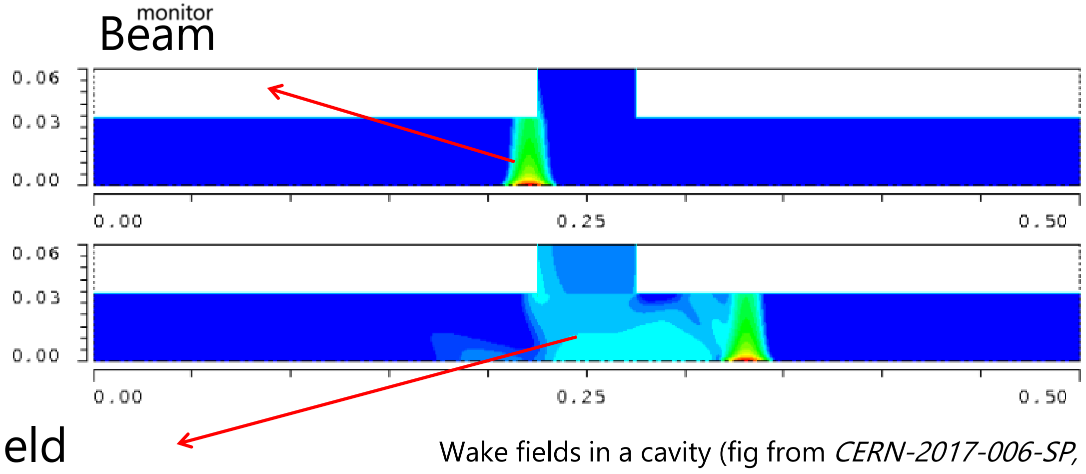
- Corrugated flat plate for wakefield generation
  - Two parallel plates with movable gap (0.2 mm minimum)
  - In normal operation, plates are away from beam axis (10 mm)
  - Corrugation introduces discontinuity to vacuum chamber and becomes wakefield source
  - Two additional structures are installed at HXU line, however, vertically moving so not used for the diagnostics but for the advanced FEL generation such as fresh-slice, PHLUX



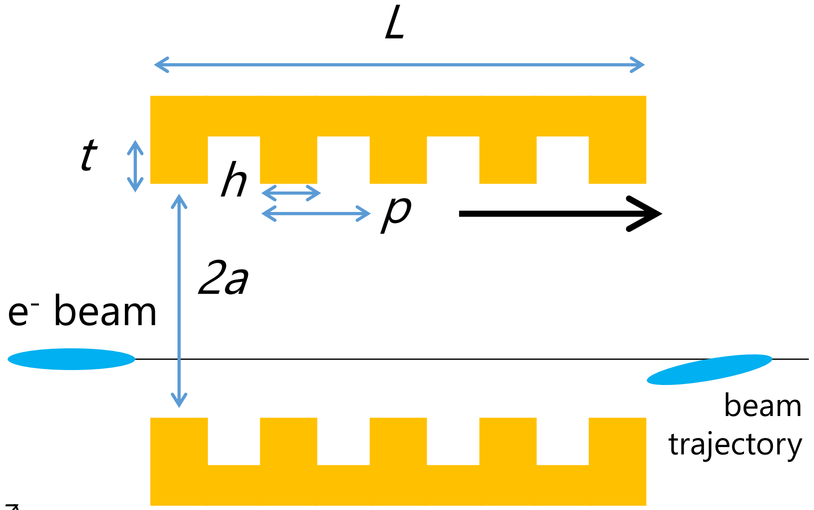


Parameter	Value
p	1.0 mm
h	0.5 mm
t	0.5 mm
a_{min}	0.2 mm
L	1.0 m



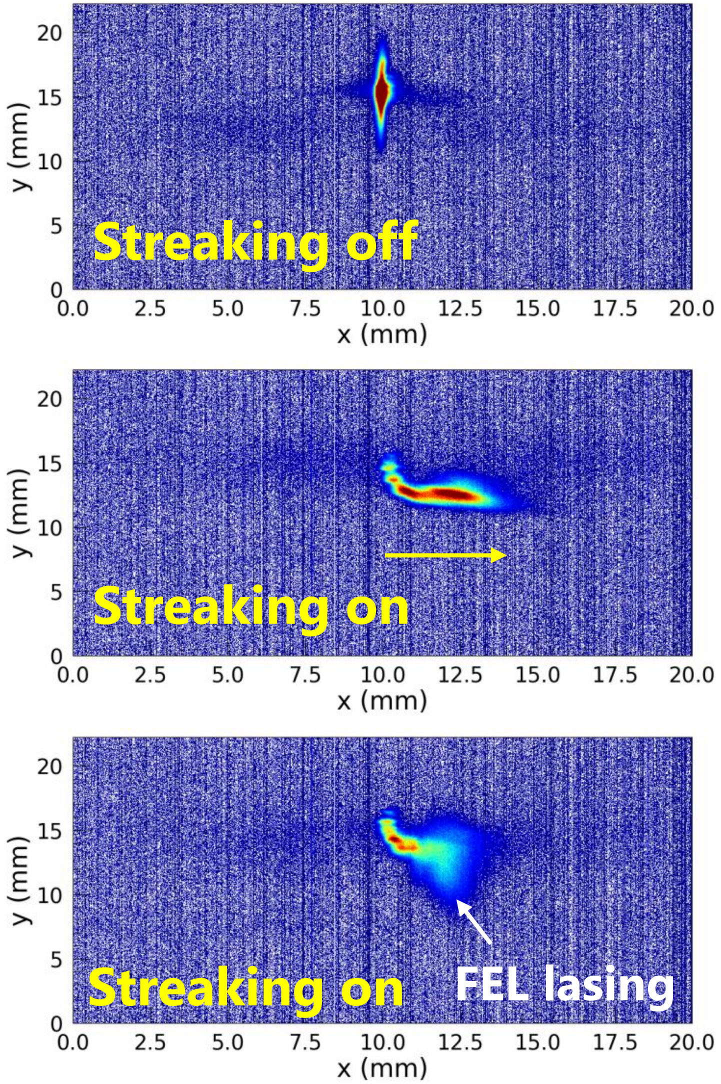


Wake fields in a cavity (fig from *CERN-2017-006-SP, 2017*)



Experimental Results of Reconstruction

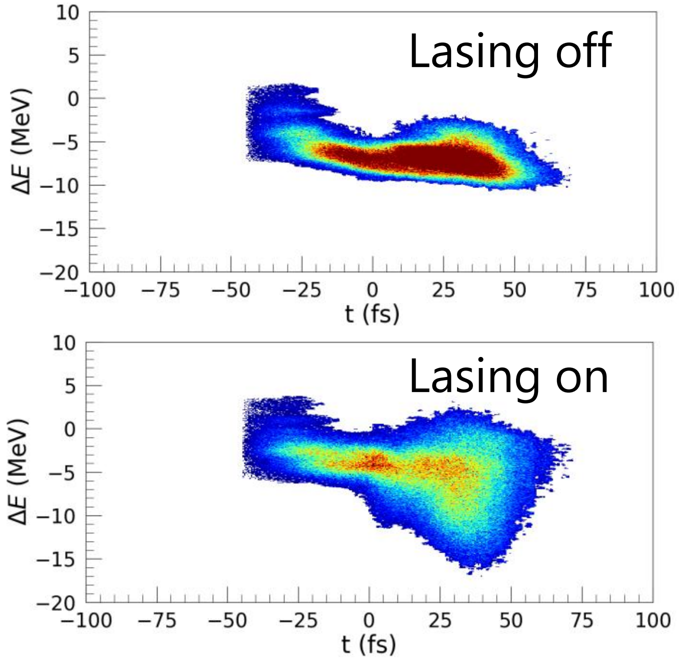
- Verified reconstruction with <u>iterative method</u> in simulation and experiments



➢ Screen image of streaked and dispersed beam at dump

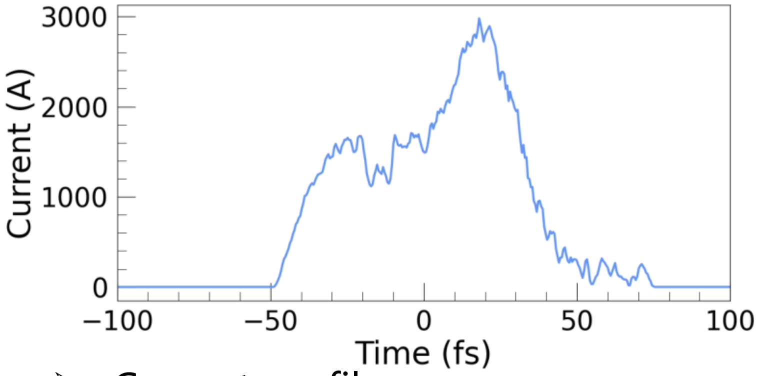
※ Current profile I(t) prediction → calculate wakefield w(t) and momentum kick → Estimate $\rho(x)$ at screen using linear matrix → compare with measurement → New prediction for I(t) and iterate procedure

- Developing reconstruction approach
  - ➢ Reconstruction depends on initial prediction
  - ➢ Low resolution in head due to nonlinearity of wakefield

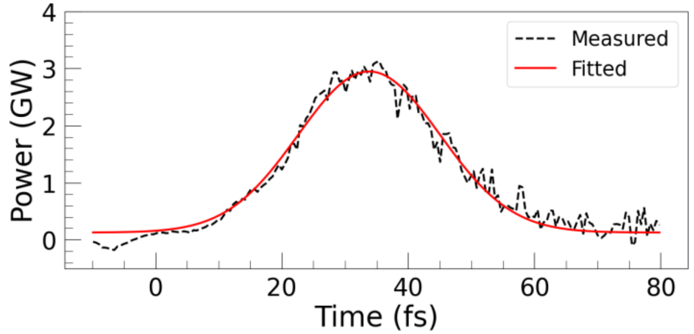


➢ Longitudinal phase space reconstruction

[C. Sung, poster presentation at IBIC'25]



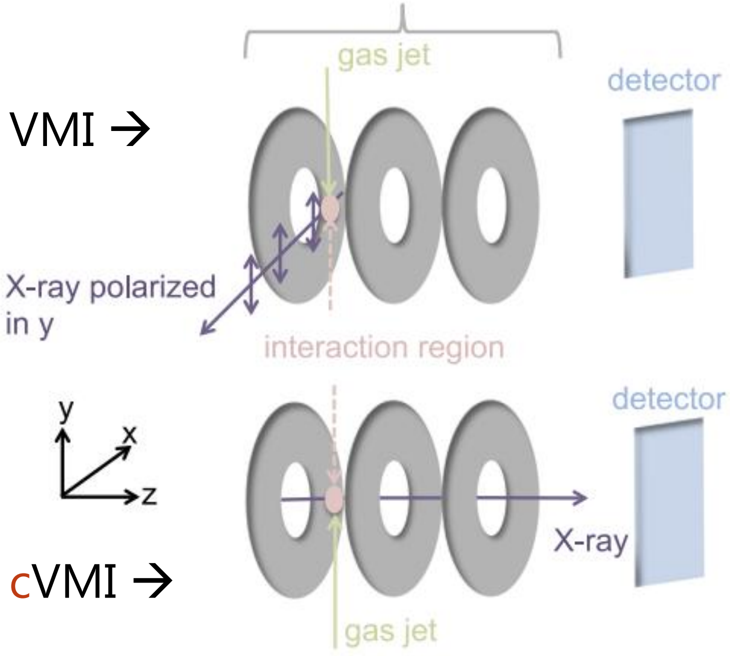
➢ Current profile



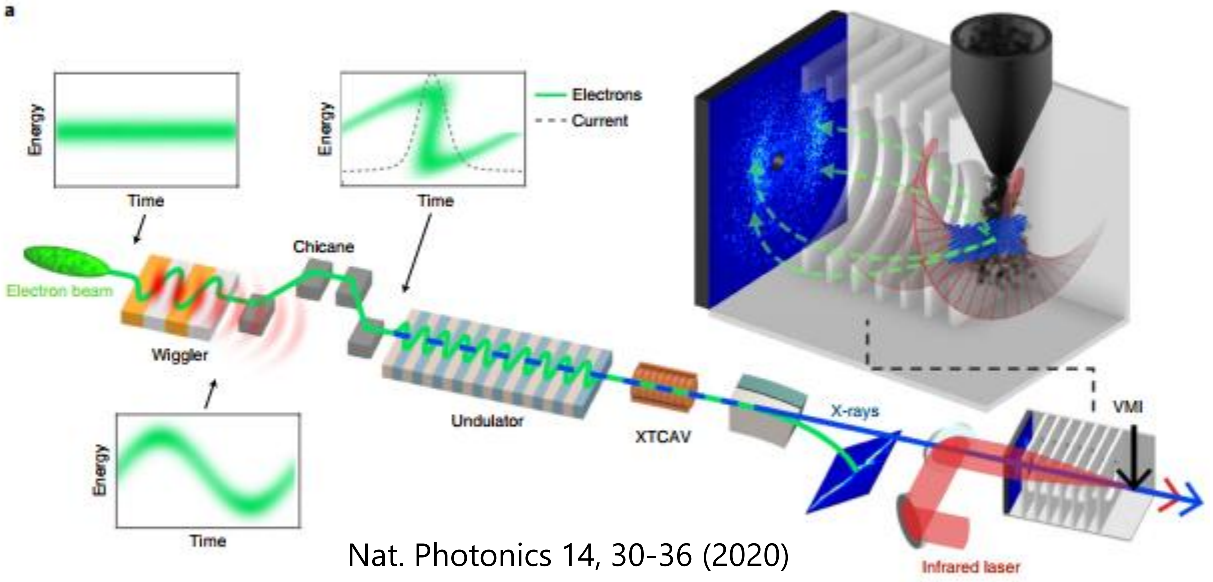
➢ FEL temporal profile

Co-Axial Velocity Map Imaging: X-ray Temporal Diagnostics

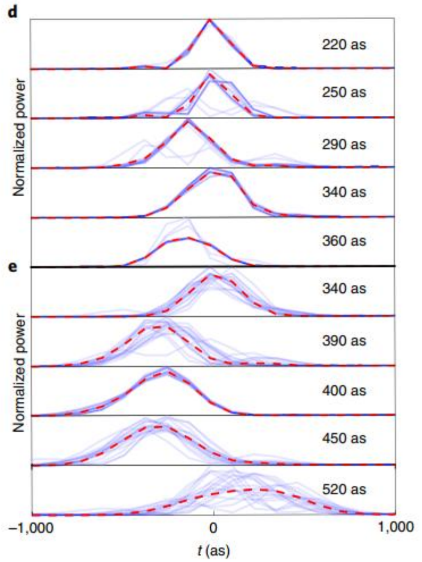
- **Attosecond streak camera**: Directly characterize (as) FEL profile
  - Actively utilized at LCLS to verify attosecond FEL generation
- Working principle:
  1. X-ray pulse ionizes the gas jet in chamber, producing photoelectrons
  2. IR laser co-propagates with X-ray and angularly streaks photoelectrons
  3. Reconstruct temporal profile from angular distribution on the screen

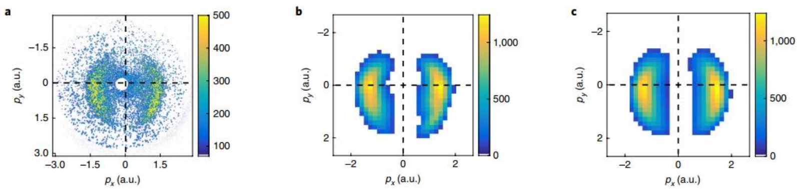


S. Li, et al., AIP advances 8 115308 (2018)



Nat. Photonics 14, 30-36 (2020)





a. Streaked photoelectron momentum distribution

b. Filtered data

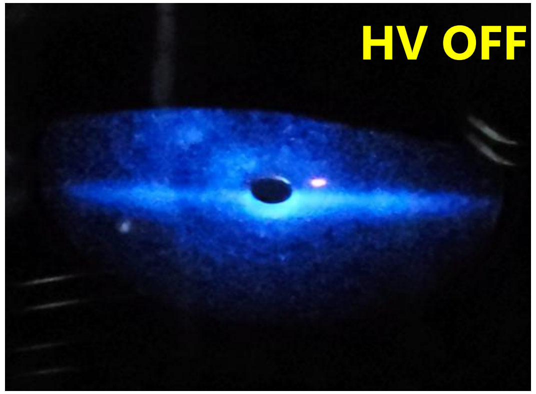
c. Simulated distribution from reconstructed profile

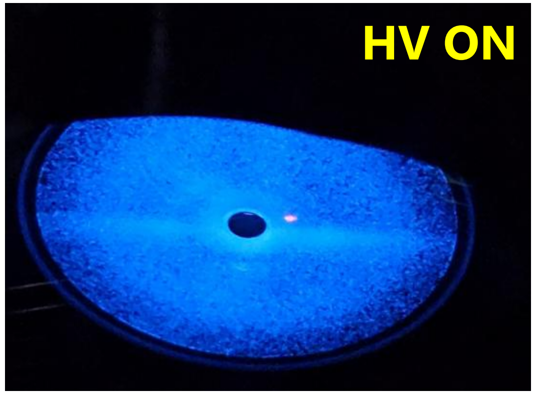
d, e. Pulse reconstructed at 905 eV and 570 eV

cVMI Commissioning at PAL

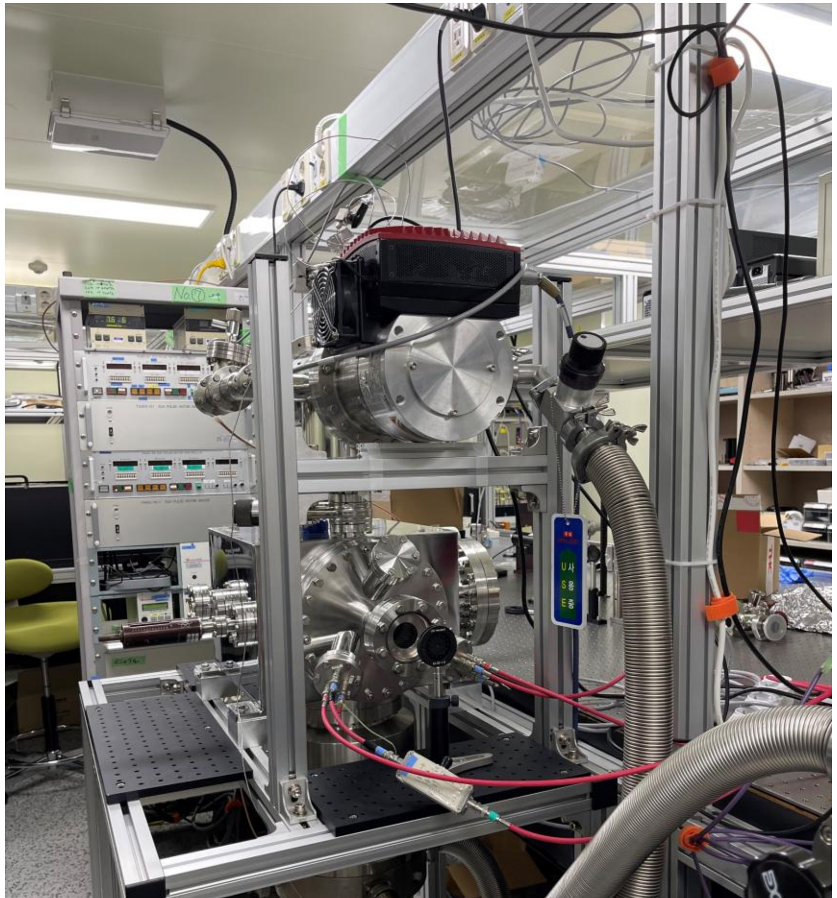
*Collaborative work with Shini Minemoto (Tohoku university)

- Commissioning with UV laser before testing for X-ray laser
  - Ar gas jet for ionization
- Setting up the optics system UV laser for high intensity and gas jet profile measurement system

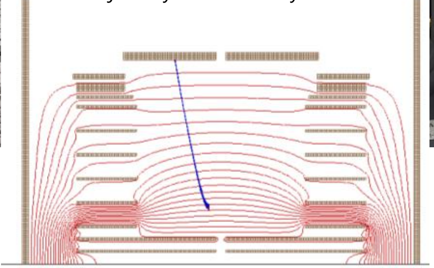




❖ Photoelectrons from residual gas at detector depending on voltages for MCP



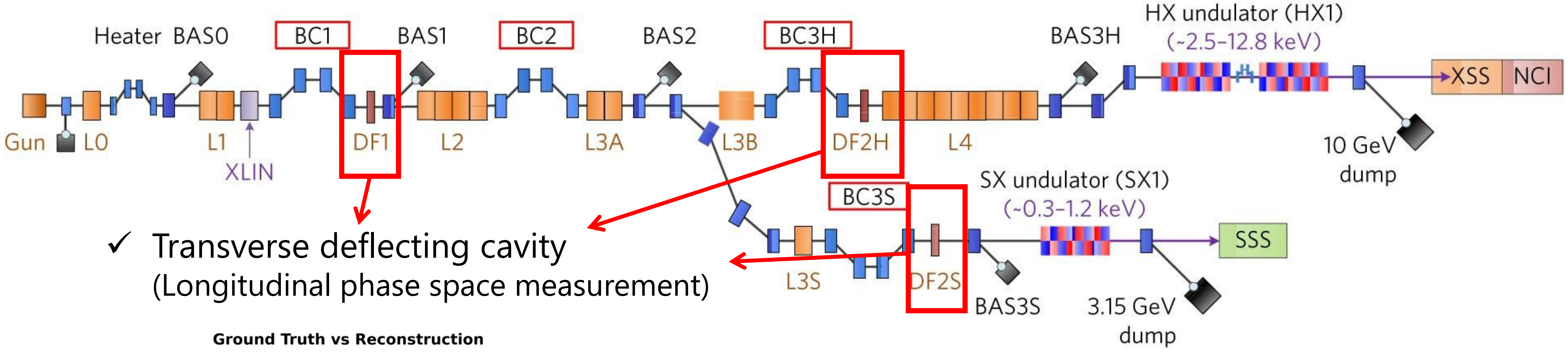
❖ Electric potential and electron trajectory simulated by SIMION



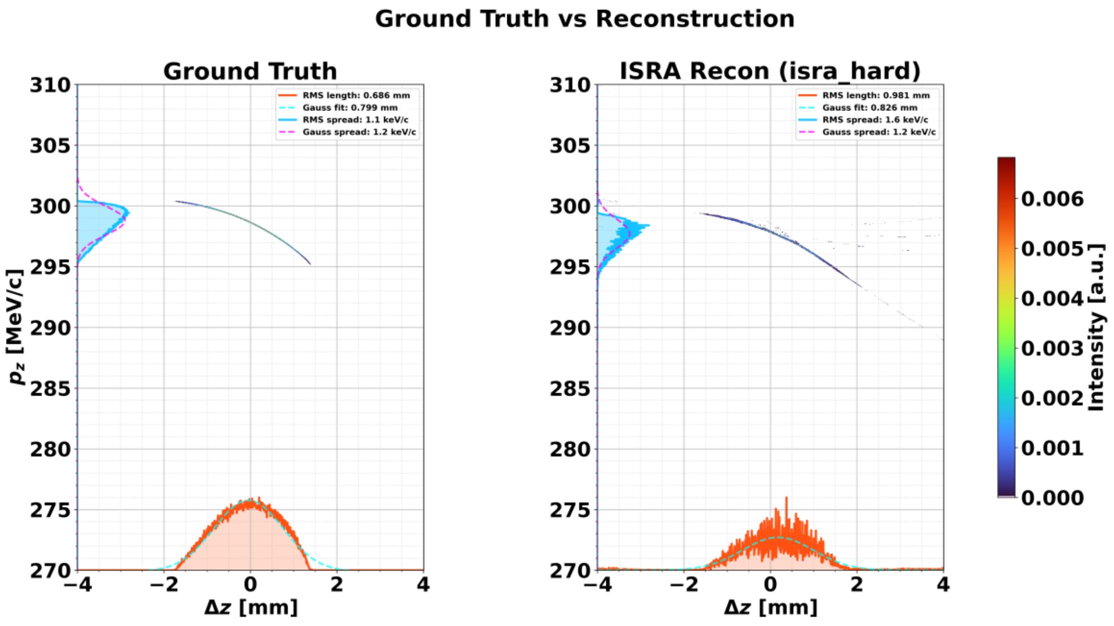
Longitudinal Tomography

*Collaborative work with Geunwoo Kim and Moses Chung (POSTECH)

- Longitudinal phase space measurement where transverse deflecting cavity is not installed (e.g., INJ)



✓ Transverse deflecting cavity
(Longitudinal phase space measurement)

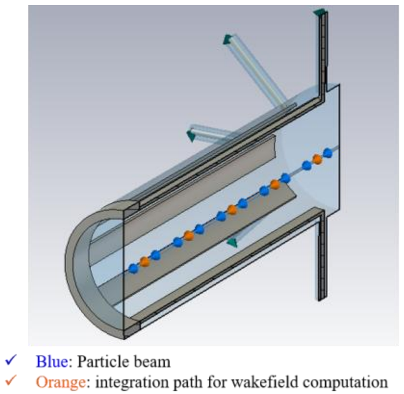


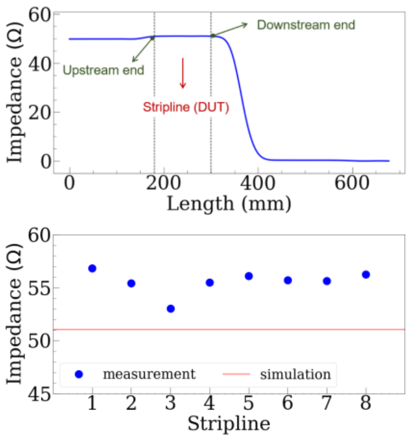
- Demonstration using simulation (with ELEGANT) at L1
- Based on the simulation results, the experimental data were measured and under analysis (by Geunwoo Kim)

Non-destructive Beam Energy Spread Monitor

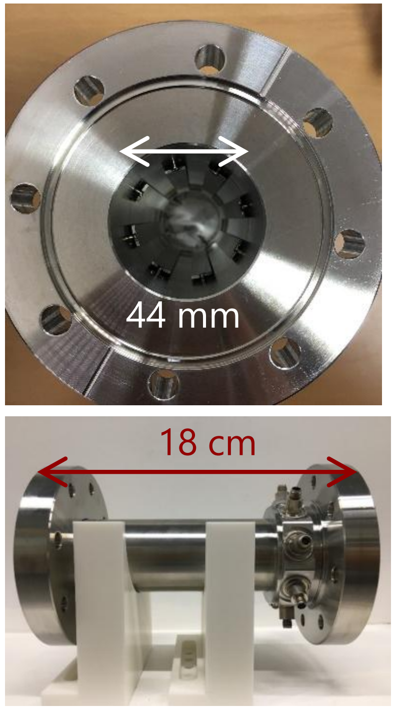
- Non-destructive energy spread measurement at dispersive section (e.g., bunch compressor of XFEL) by means of beam size measurement with 8-stripline pick-up monitor
- Tested with low energy electron beam at test facility of PAL and confirmed its feasibility
- Preparing further test at the test facility of PAL

[C. Sung, et. al., JKPS, **82** 346-355 (2023)]

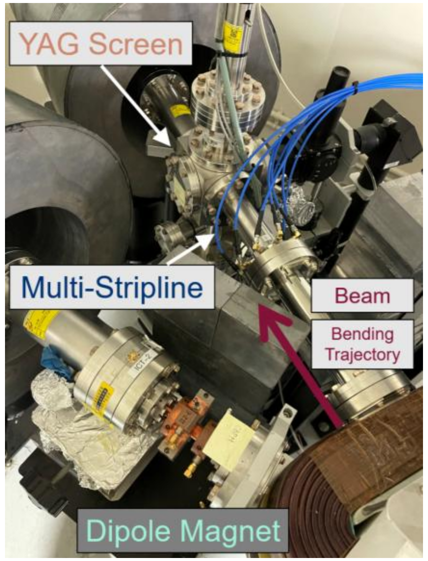


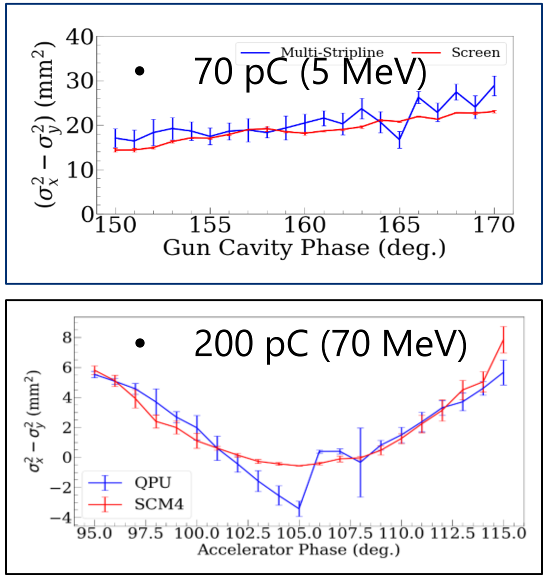


❖ Electromagnetic design with CST and quality test



❖ 8-stripline pick-up monitor





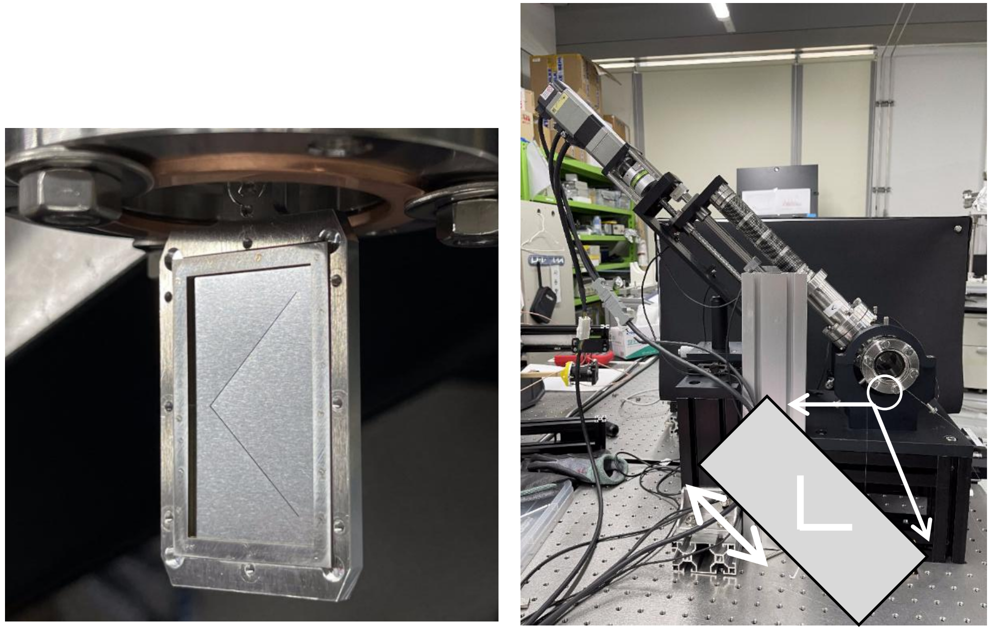
❖ Beam test at test facility of PAL (eLABs)

*[G. Z. Georgiev and M. Krashilnikov, IBIC'19]

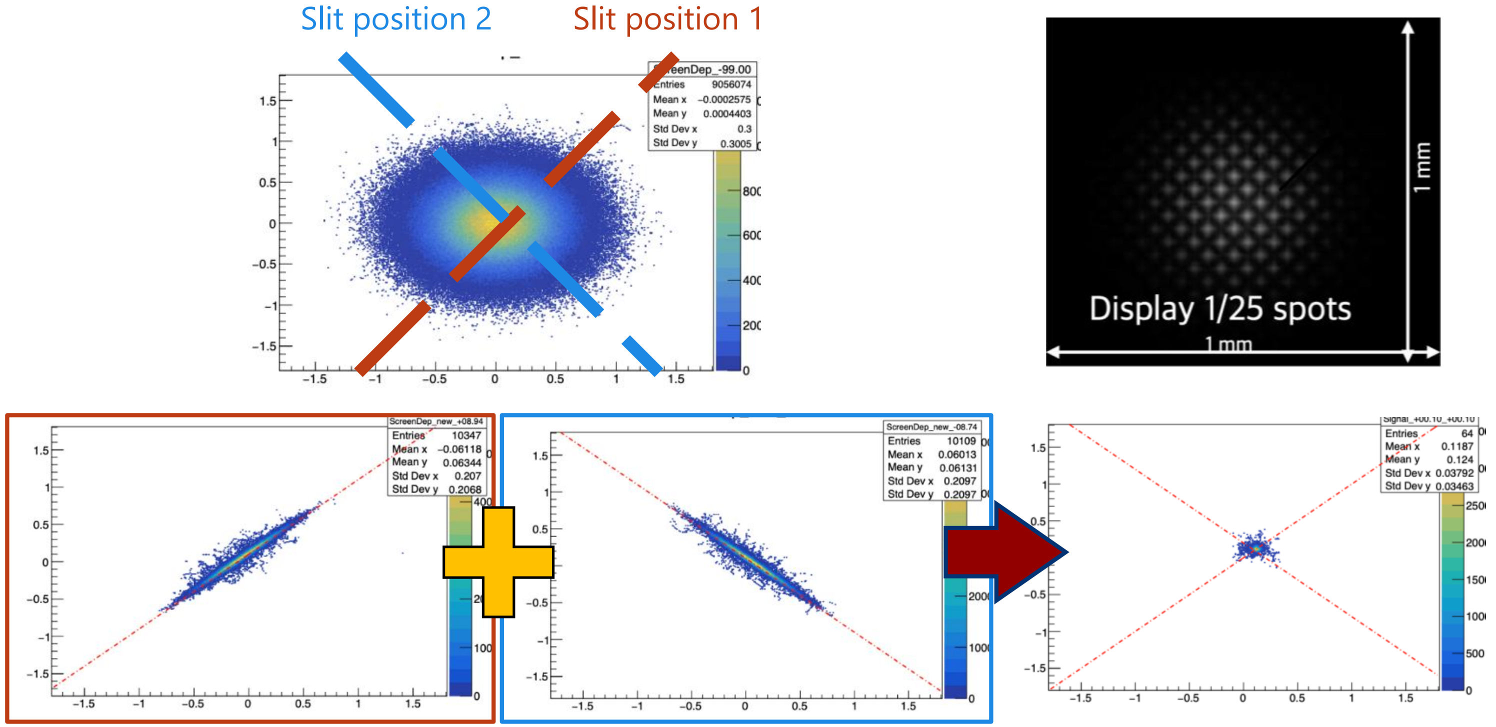
Virtual Pepper-Pot for 4-dimensional Phase Space

❖ Virtual pepper-pot* (VPP): **slit optimization** and **image processing method** for enabling 4D phase space measurement including XY coupling

- 1D slit-scan system with image processing, functioning as pepper-pot device (➔ *Virtual* pepper-pot)
- Preparing experimental demonstration at the test facility of PAL



❖ Slit-scanning system for virtual pepper-pot. Slit designed with 100 um width and 100 um thickness and fabricated with stainless steel



❖ Obtaining pepper-pot-like data for XY coupling analysis from 1D slit scan with image processing method

Summary

- World's highest brightness XFEL achieved with high-resolution beam diagnostics at PAL-XFEL (and beam diagnostics-based feedback and control system for stable long-term operation)

- Various beam diagnostic methods are being studied for next-generation FEL

- Machine learning-based beam diagnostics are underway