Recent Progress of PAL-XFEL Operation

2022. 10. 24

Garam HAHN

on behalf of PAL-XFEL

Pohang Accelerator Laboratory, POSTECH

Contents

- Introduction to PAL & PAL-XFEL
- FEL optimization process
- Hard X-ray Self-seeding FEL generation
- Other improvements

Introduction of PAL

Operation History of PAL-XFEL

Apr. 2011: PAL-XFEL project started

Apr. 2016: Commissioning started

Jun. 2017: User-service started
- 120 days for user (95% of availability)

2018: 140 days for user (95% of availability)

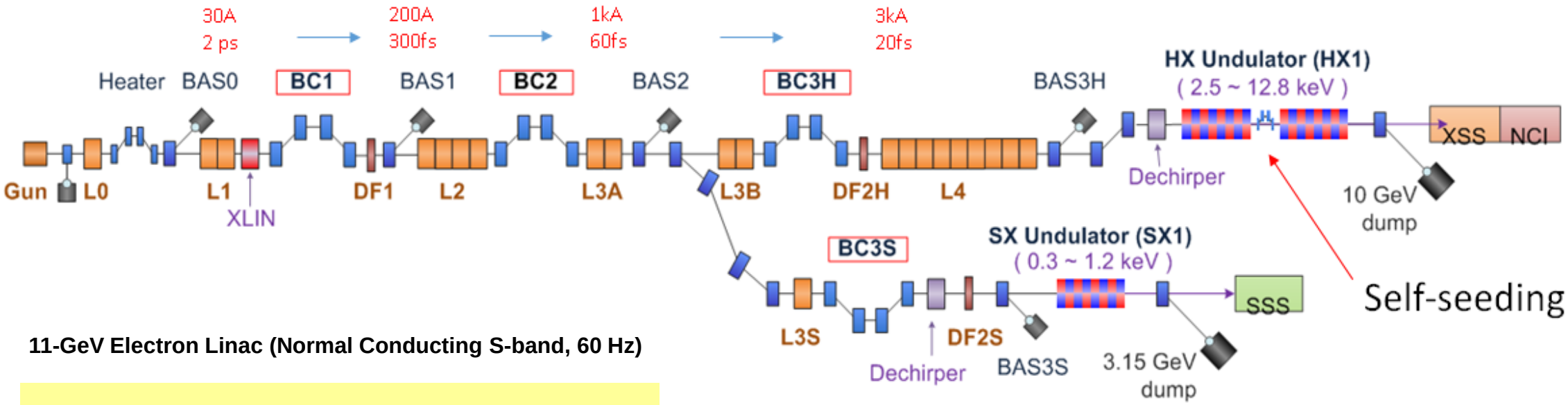
2019: 160 days for user (96.8% of availability)

2020: 170 days for user (96.9% of availability)

2021: 180 days for user (96.9% of availability)

2022: 190 days for user (97.0% of availability)

PAL-XFEL Layout & Parameters



11-GeV Electron Linac (Normal Conducting S-band, 60 Hz)

Main parameters

e^- Energy	11 GeV
e^- Bunch charge	20-200 pC
Slice emittance	< 0.4 mm mrad
Repetition rate	60 Hz
Bunch length	5 fs – 50 fs
Peak current	3 kA
SX line switching	Kicker Magnet

Undulator Line	HX	SX
Photon energy [keV]	2.0 ~ 15.0	0.25 ~ 1.25
Beam Energy [GeV]	4 ~ 11	3.0
Wavelength Tuning	Energy	Gap
Undulator Type	Planar	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

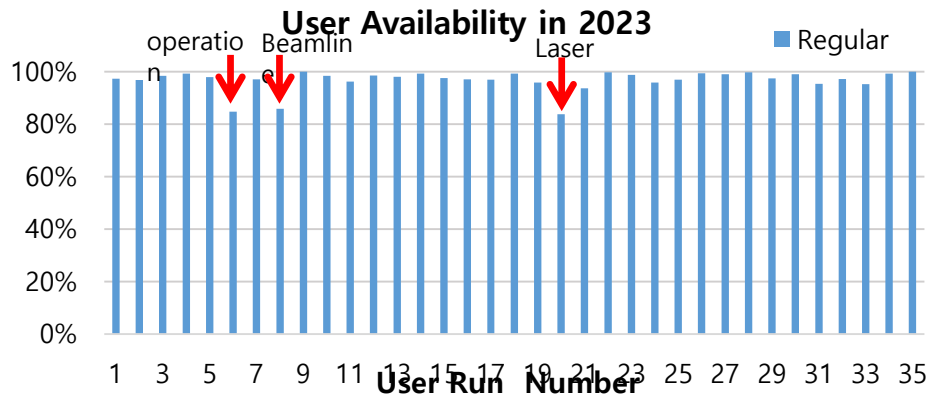
PAL-XFEL Performance

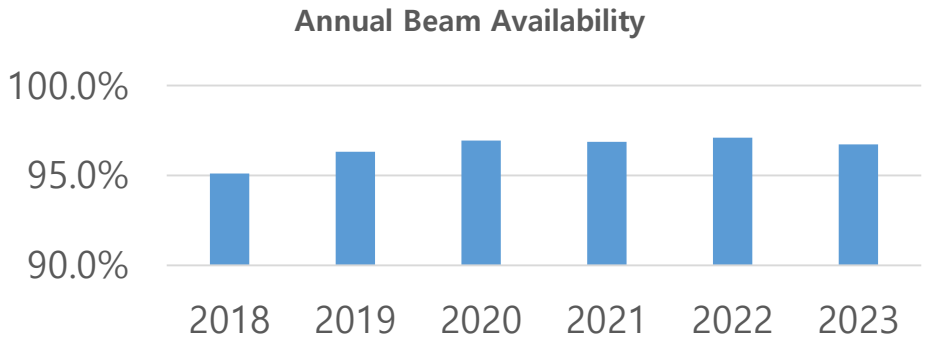
- FEL position stability: < 7% of beam size
- FEL power stability: ~ 3.1% RMS
- E-beam energy jitter: < 0.015 %
- E-beam arrival time jitter: < 15 fs
- FEL pulse energy: ~1.4 mJ at 9.7 KeV
- FEL beam pulse duration: 20 ~ 30 fs (fwhm)
- Saturated FEL up to 14.5 KeV
- FEL beam availability: > 95%

- State of the art technology is implemented for Linac systems such as modulator, LLRF, and timing system
- A best lattice design is implemented using the three bunch compressor configuration
  - High performance of FEL beam stability is achieved by minimizing the CSR effect and beam acceleration with RF phases being closer to crest.

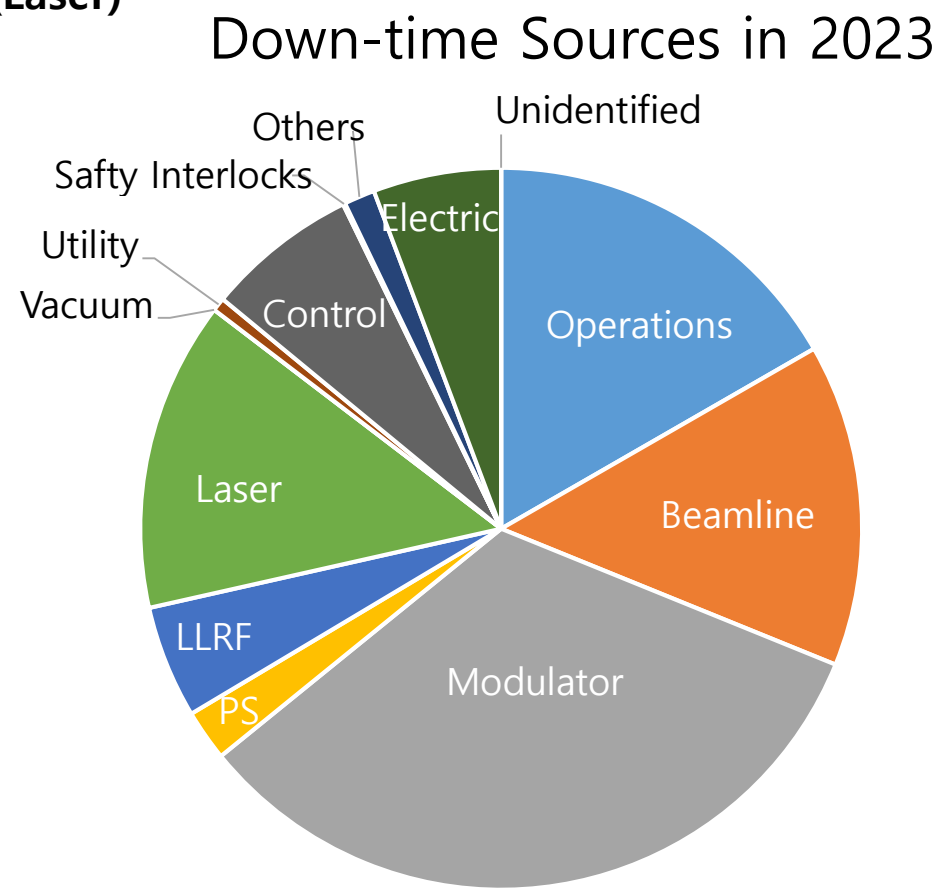
Operation Status : Reliability Summary

- ❖ **Scheduled Hours : 2432 (2023.1.1 ~2023.9.25)**
- ❖ **Delivered Hours : 2352 (> 96%)**
- ❖ **Downtime Hours: 83**



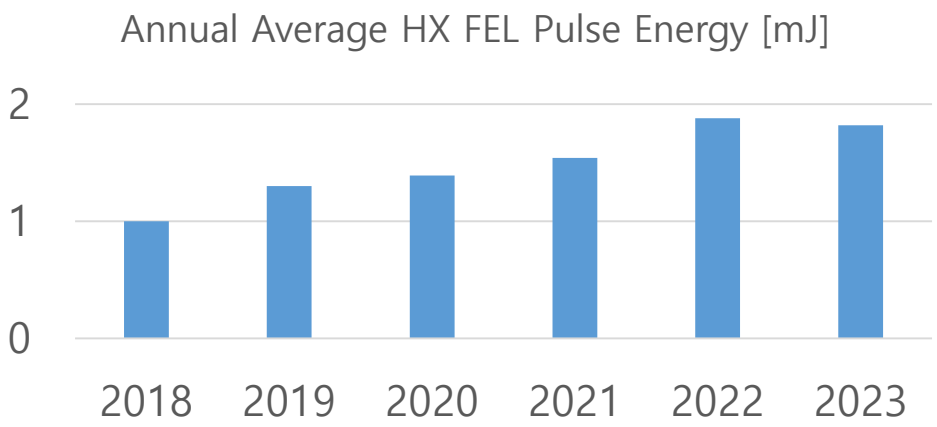


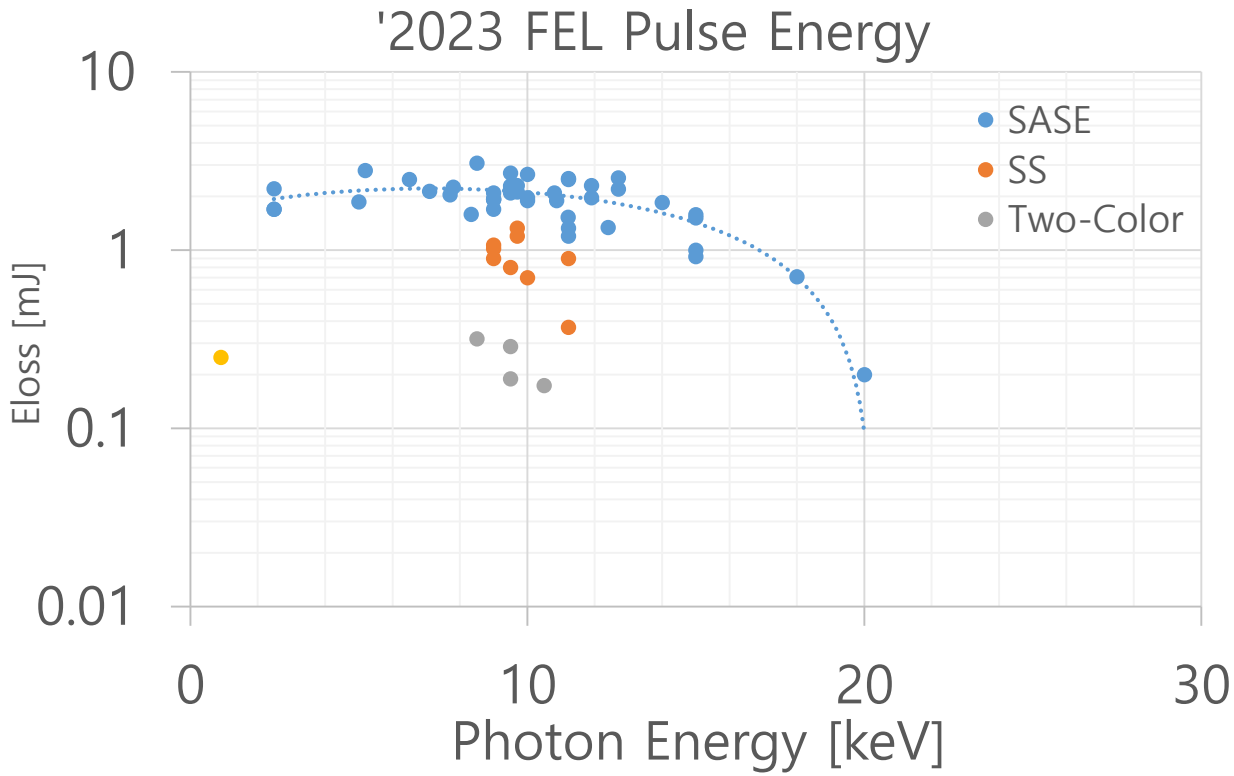
- ❖ **Longest Mean Time to Beam Loss : ~7 Hours (Laser)**



Operation Status : FEL Performance

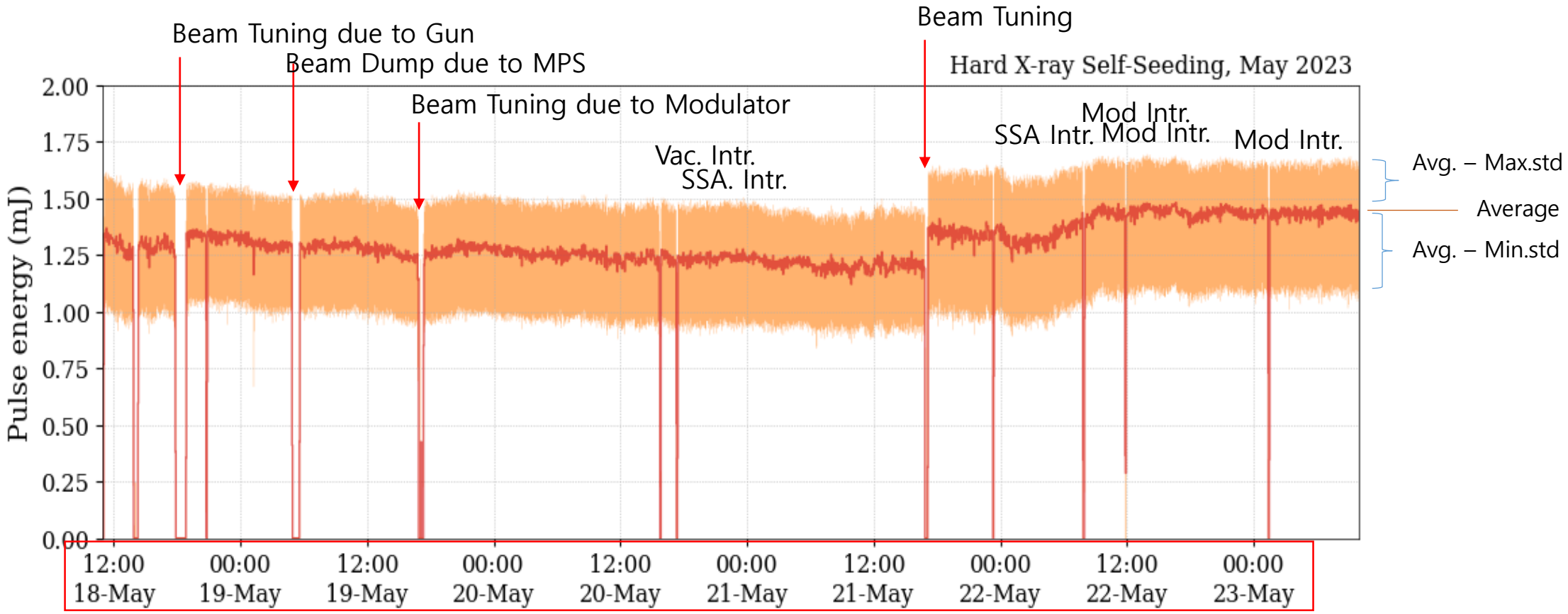
- ❖ More than 1 mJ HX FELs are serviced.
- ❖ Self-seeding HX FEL services increase.
- ❖ Two-colors user service has been started.
- ❖ SX FEL pulse energy is around 250 μJ.
- ❖ From May, RF rate is changed from 60 Hz to 30 Hz due to the electricity bill issue.





Operation Status : Long Period FEL user Service (1)

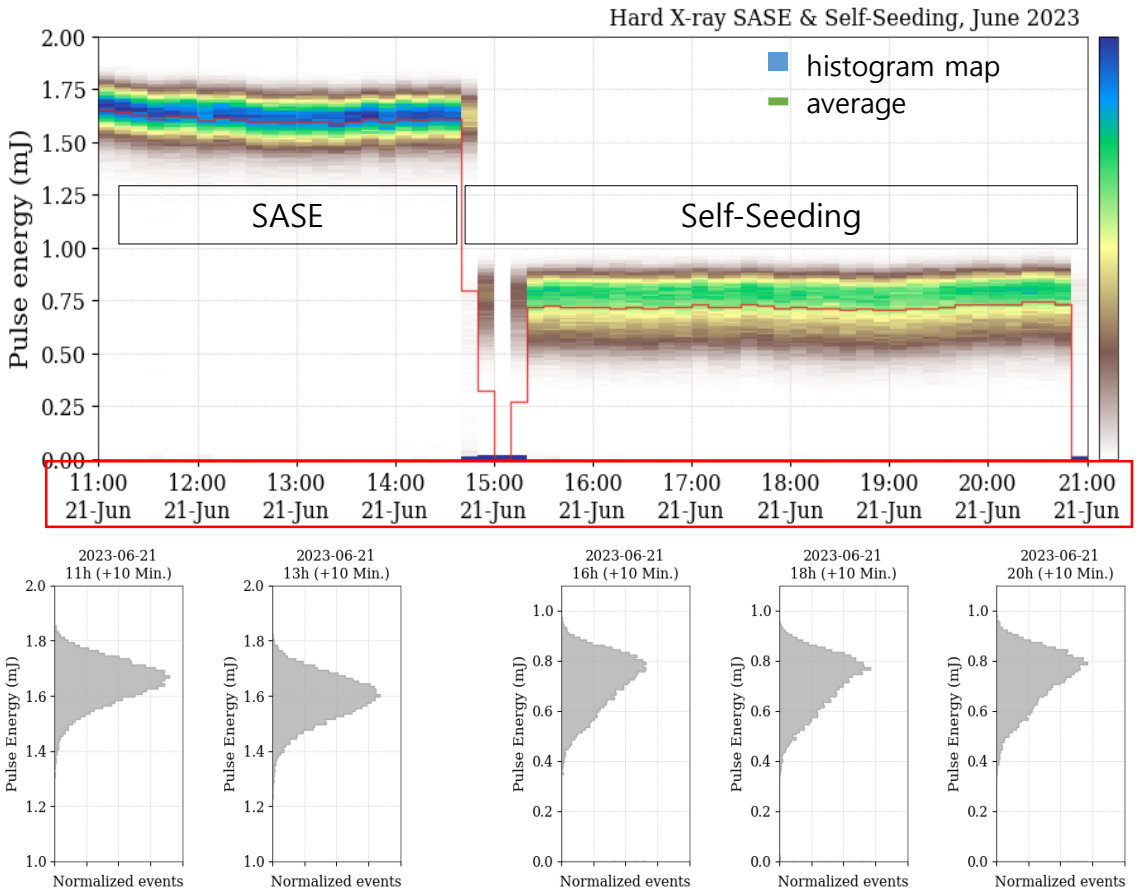
❖ We have serviced stable self-seeding FEL beams.

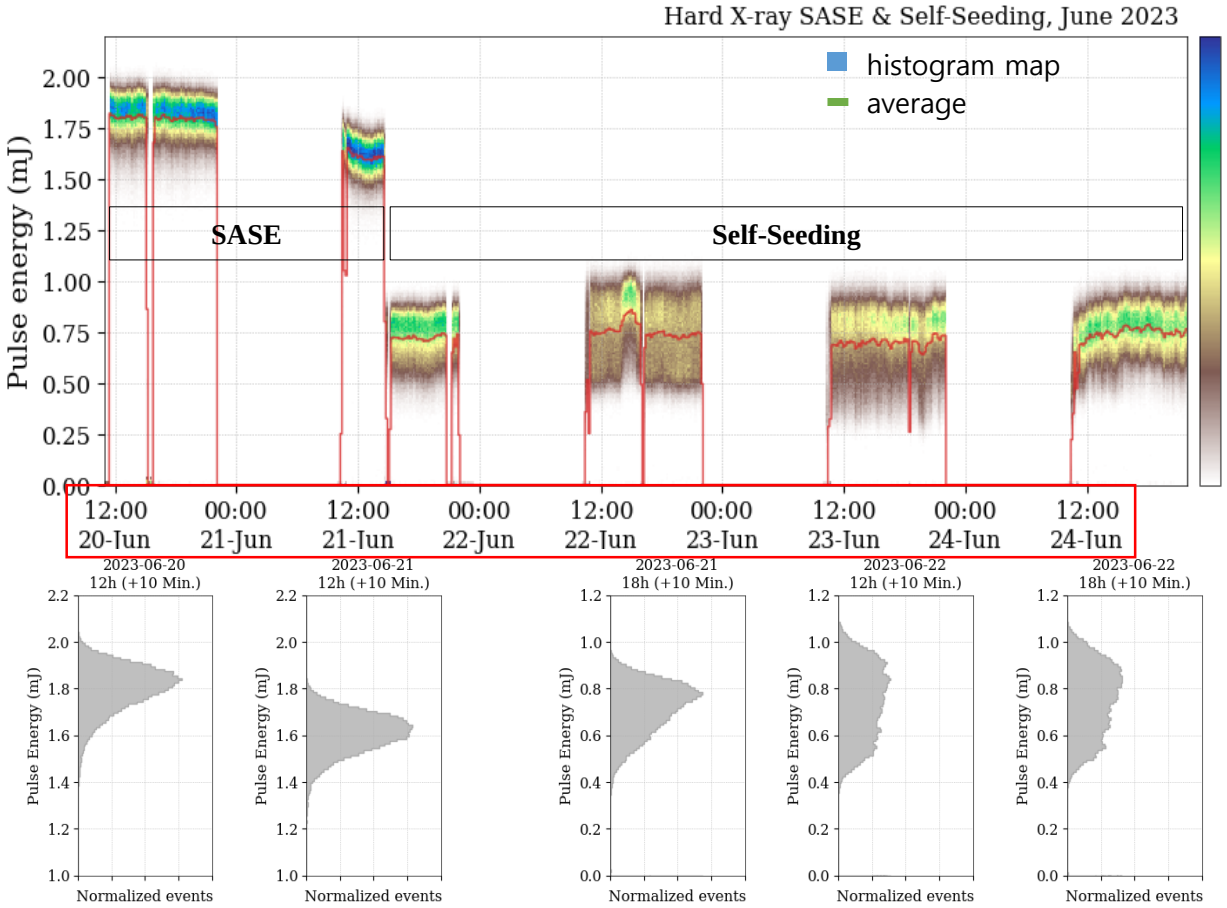


*Pulse energy is calculated by using e-loss factor
*Averaging sampling time is 180 sec

Operation Status : Long Period FEL user Service (2)

❖ **Long term FEL pulse energy drift is reduced.**



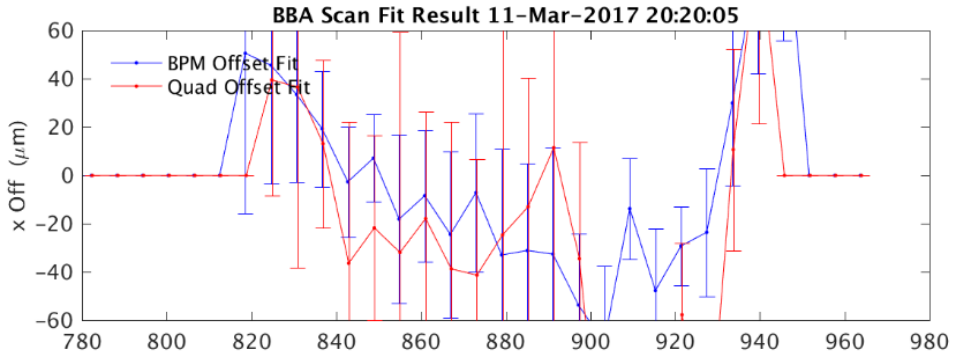


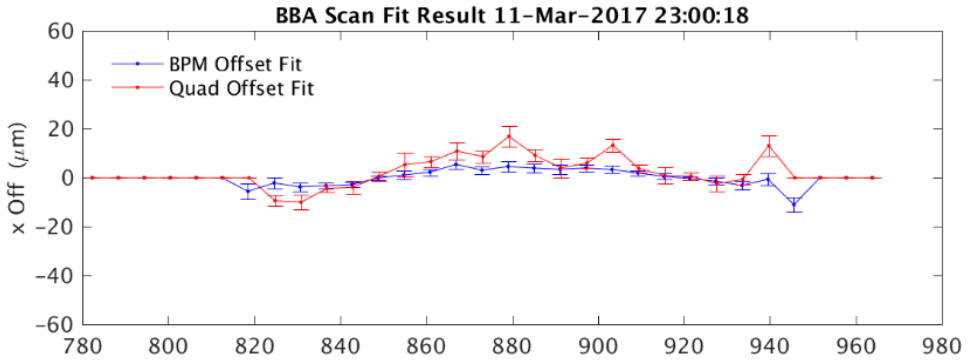
FEL Optimization Process

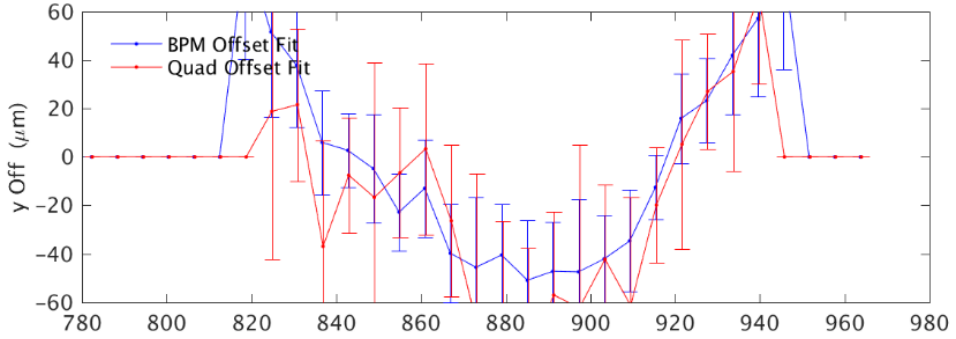
1. Beam based alignment in undulator section
2. Lattice matching in undulator and linac
3. Undulator offset, gap, tapering tuning
4. Phase shifter gap tuning

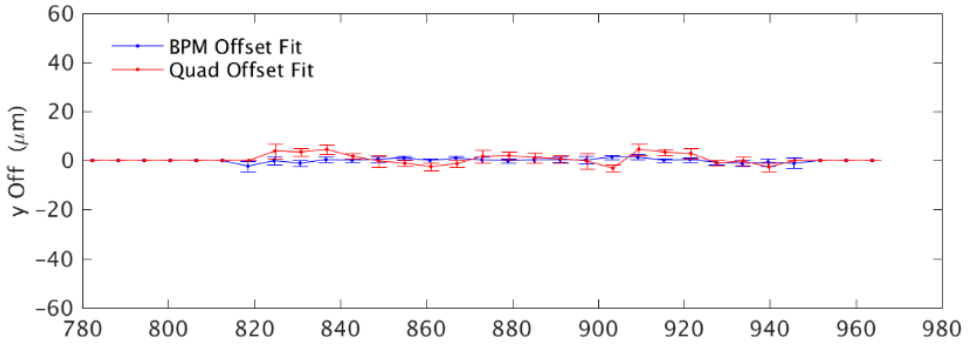
Undulator BBA

- Beam positions are measured at four different beam energy: 4, 5, 7, 10 GeV
- BPM offsets and quad offsets are calculated to get dispersion-free straight orbit
- All cavity BPMs and quads have independent movers which can move up to +/- 1 mm with precision of 1 um for horizontal and vertical directions



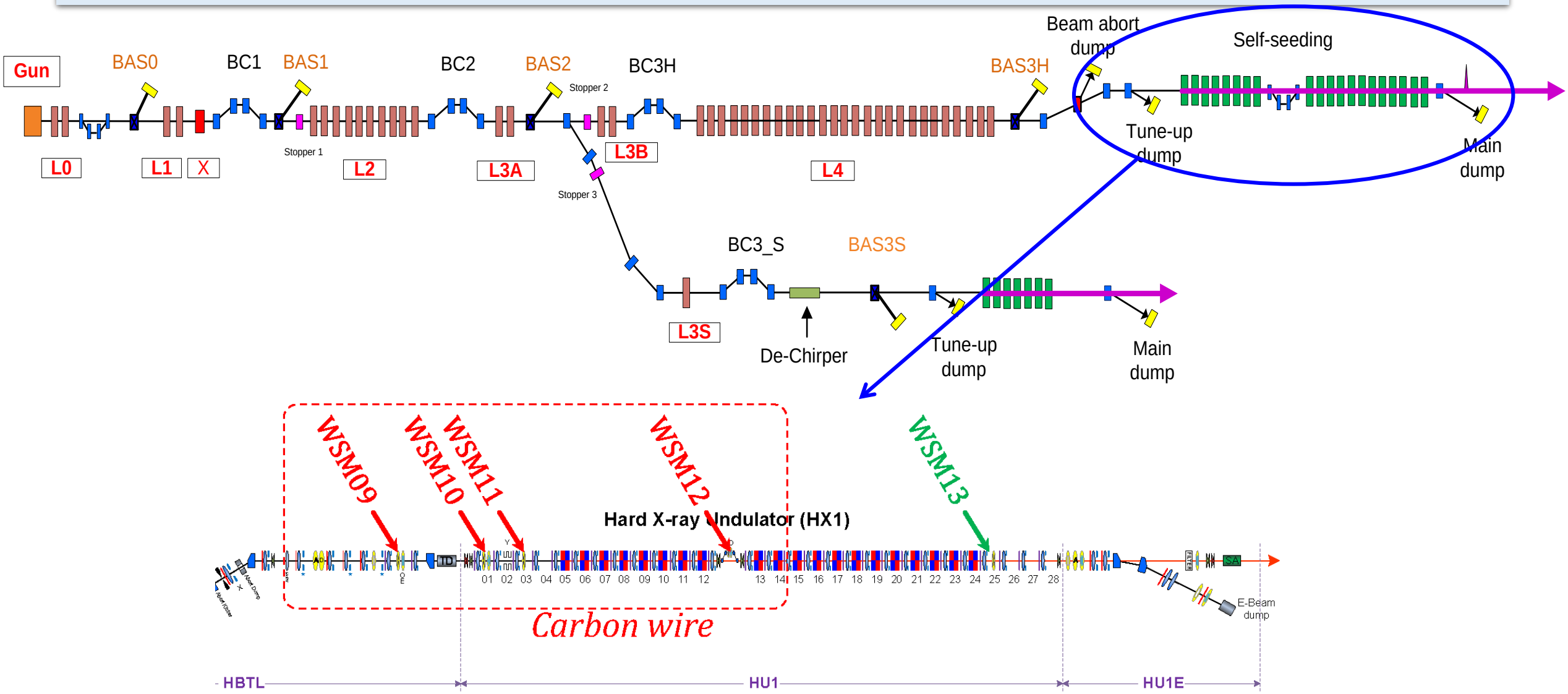




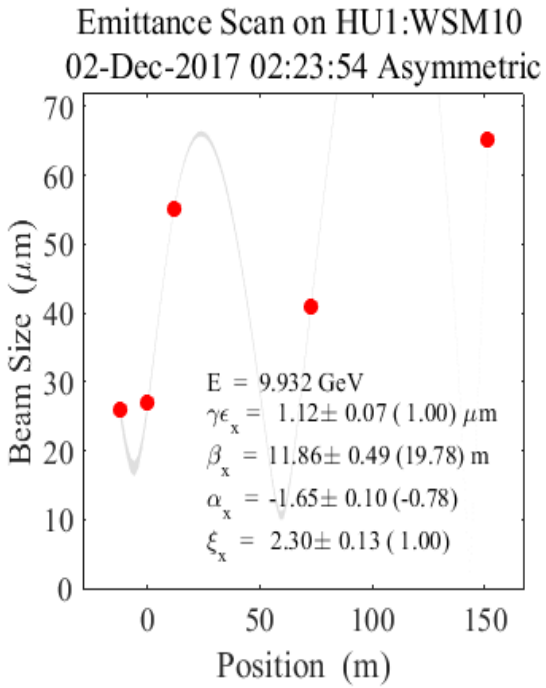


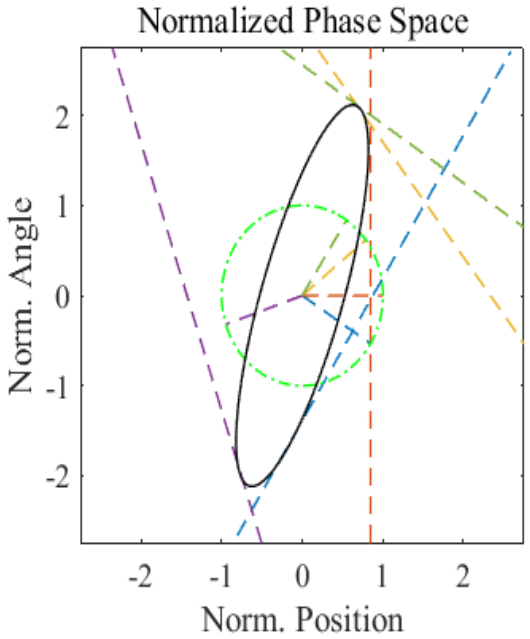
Henrik Loos, LCLS FAC (2009), P. Emma *et al.*, *NIM A* **429**, 407-413 (1999)

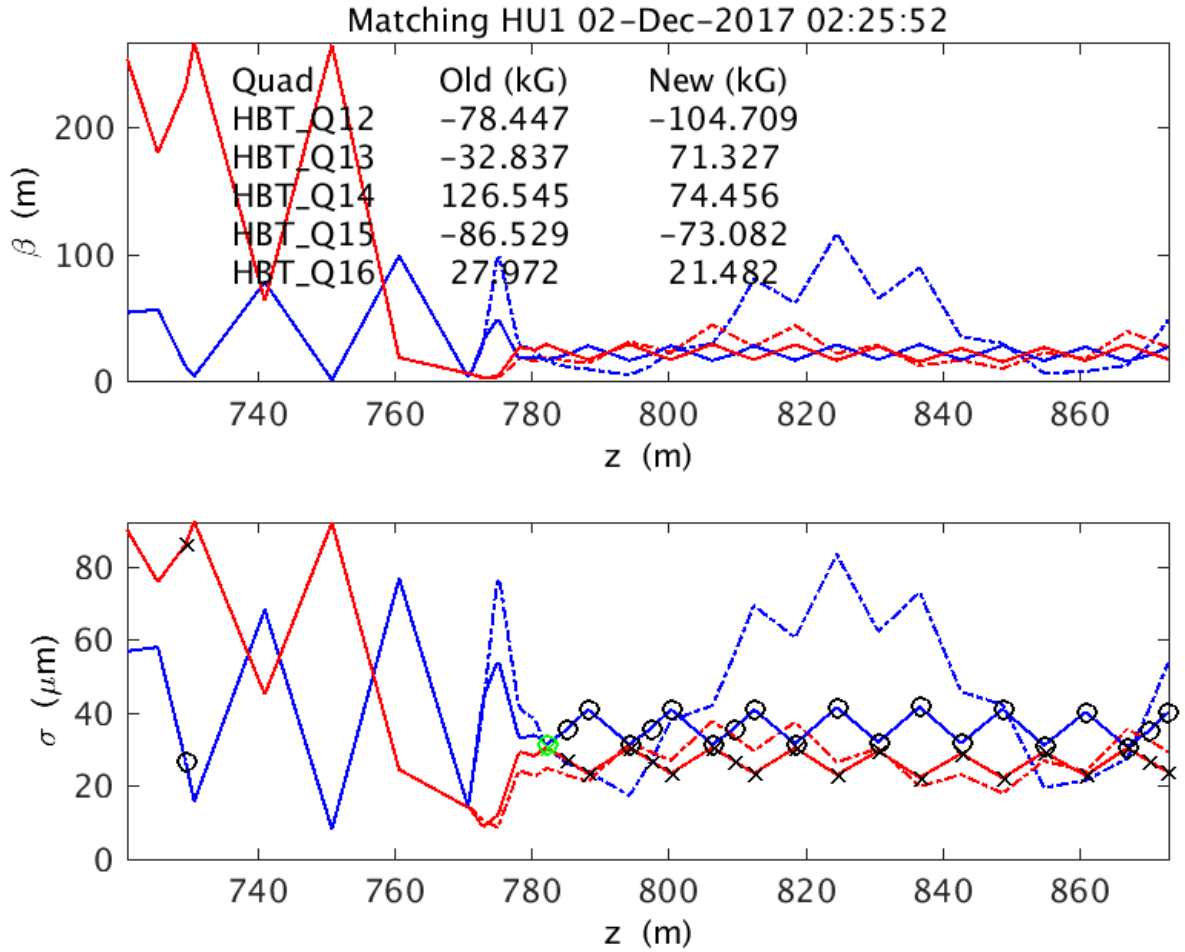
Wire Scanners for Lattice Matching



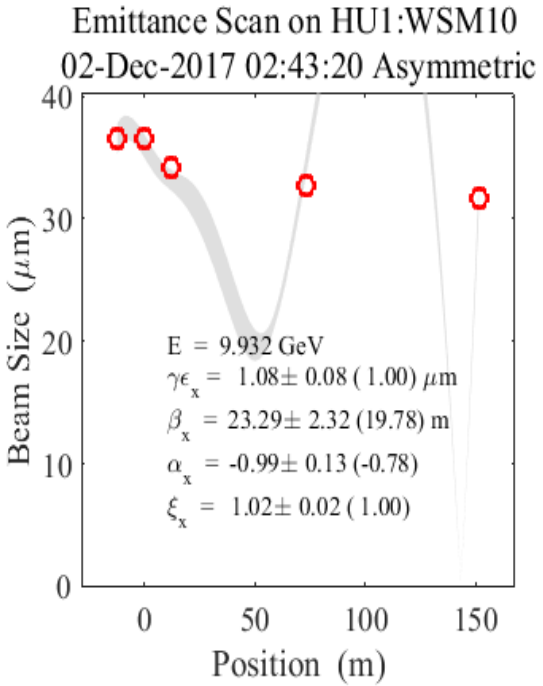
Before Lattice Matching in Undulator

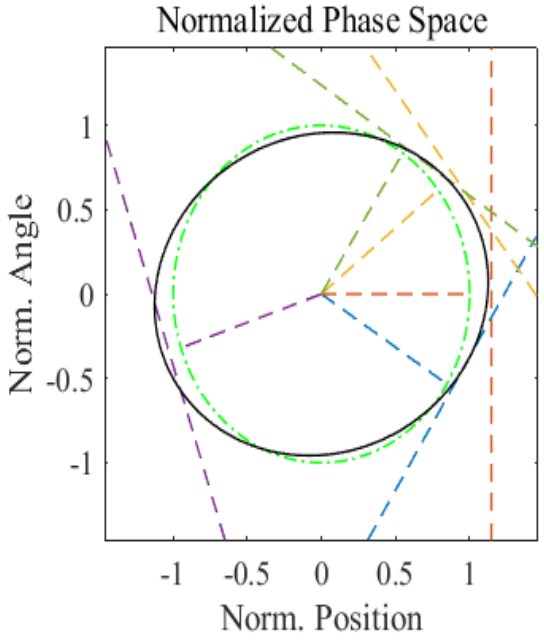


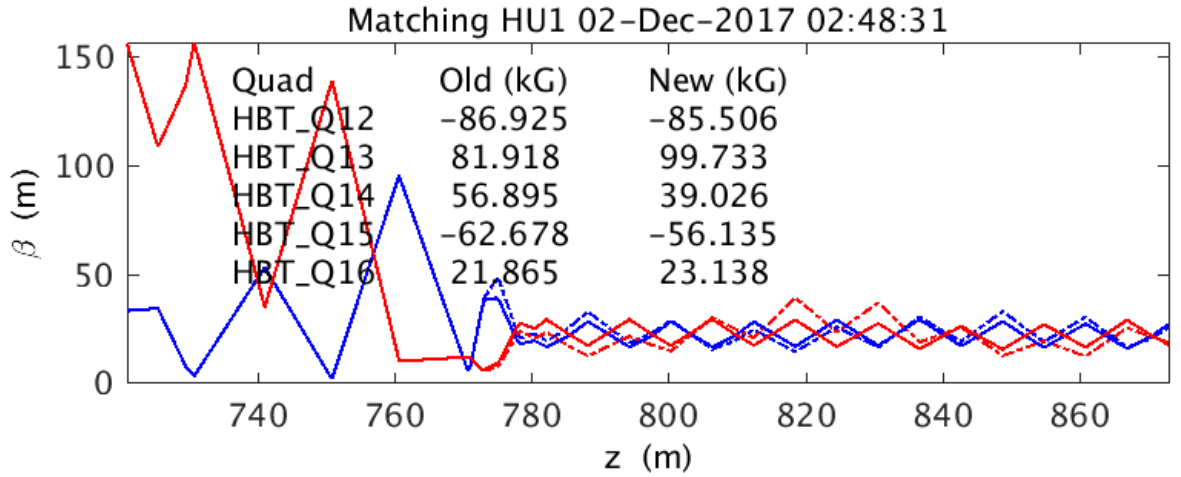


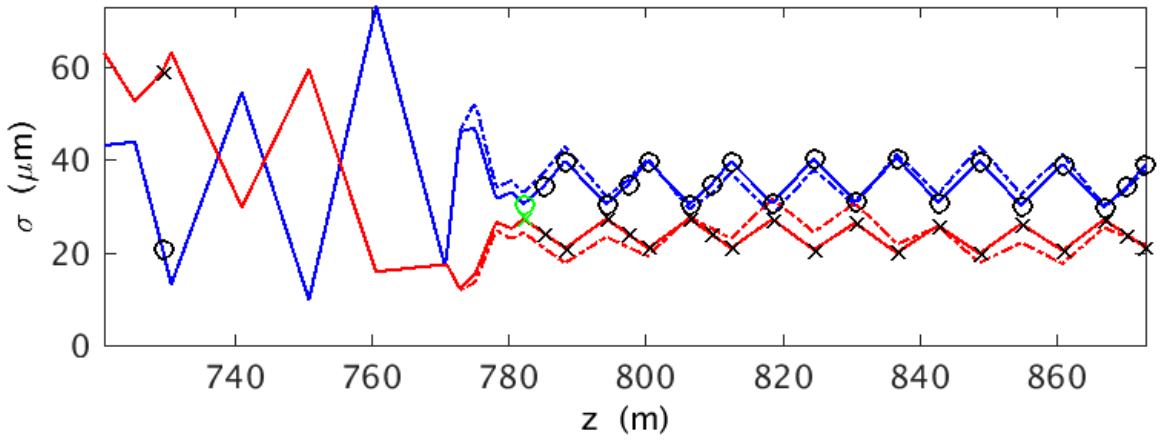


After Lattice Matching in Undulator



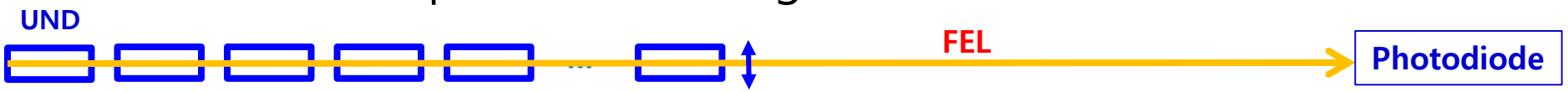


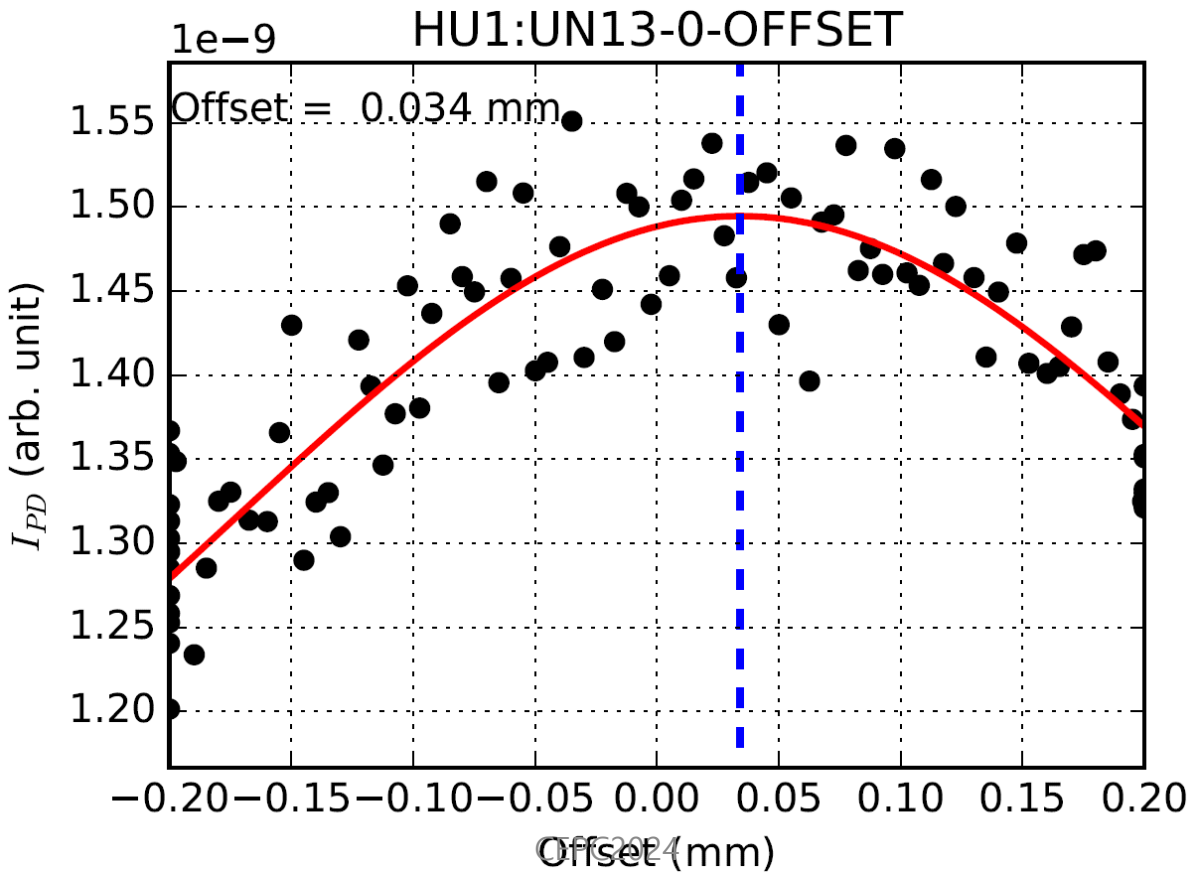




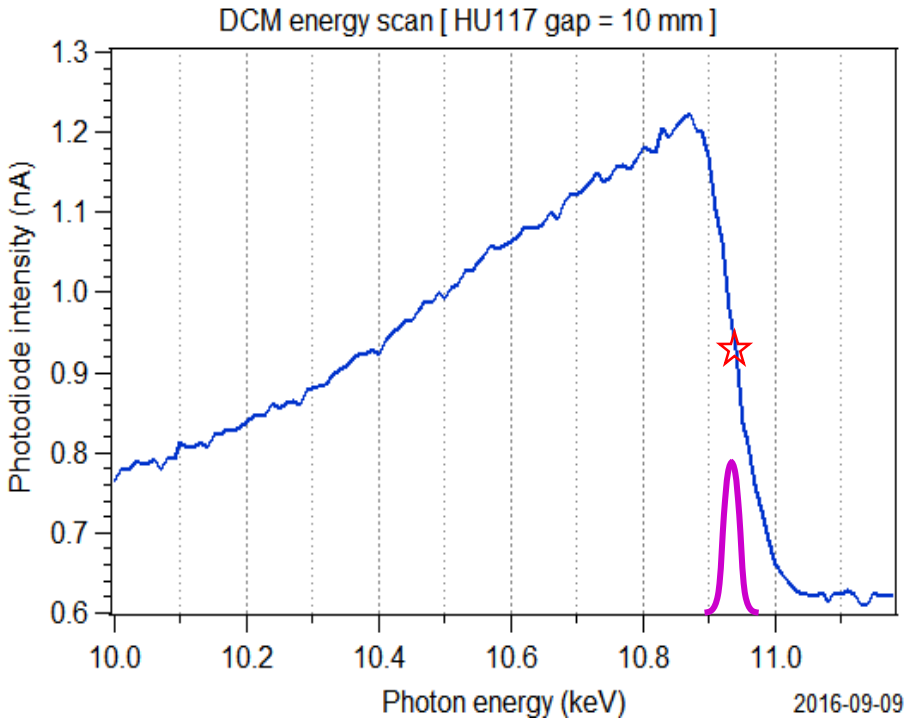
Undulator Offset Tuning

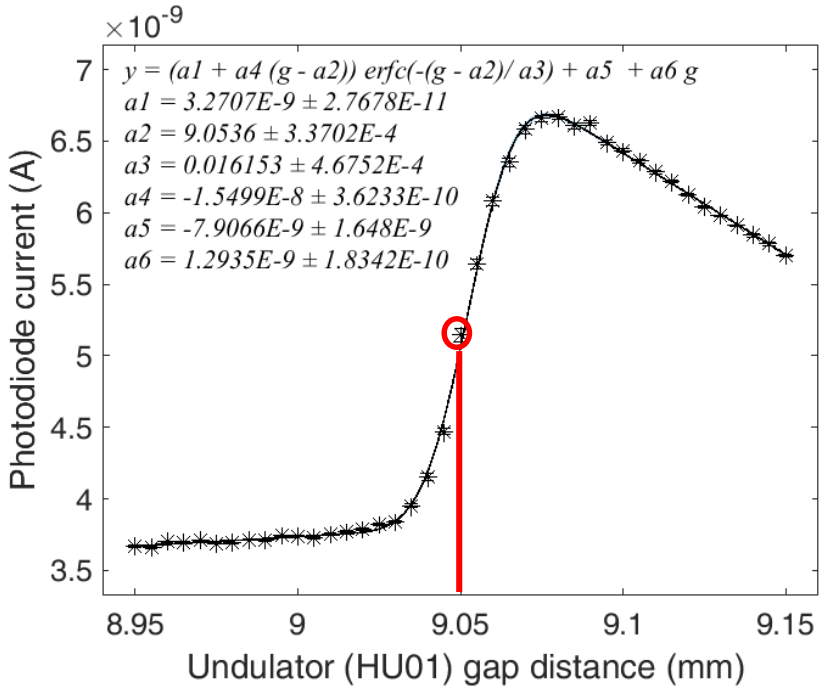
- Finding of an undulator mid-plane by vertical offset scan
- To use the optimum field region in an undulator



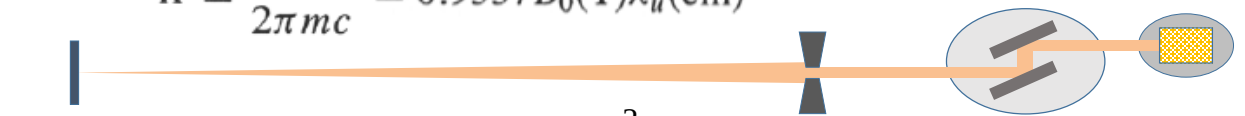


Undulator Gap Tuning





$$K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\mathrm{T})\lambda_u(\mathrm{cm})$$

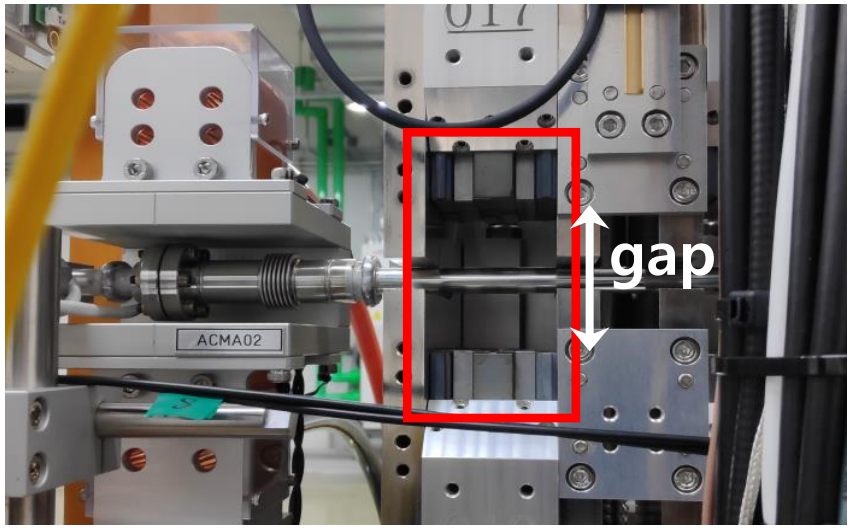


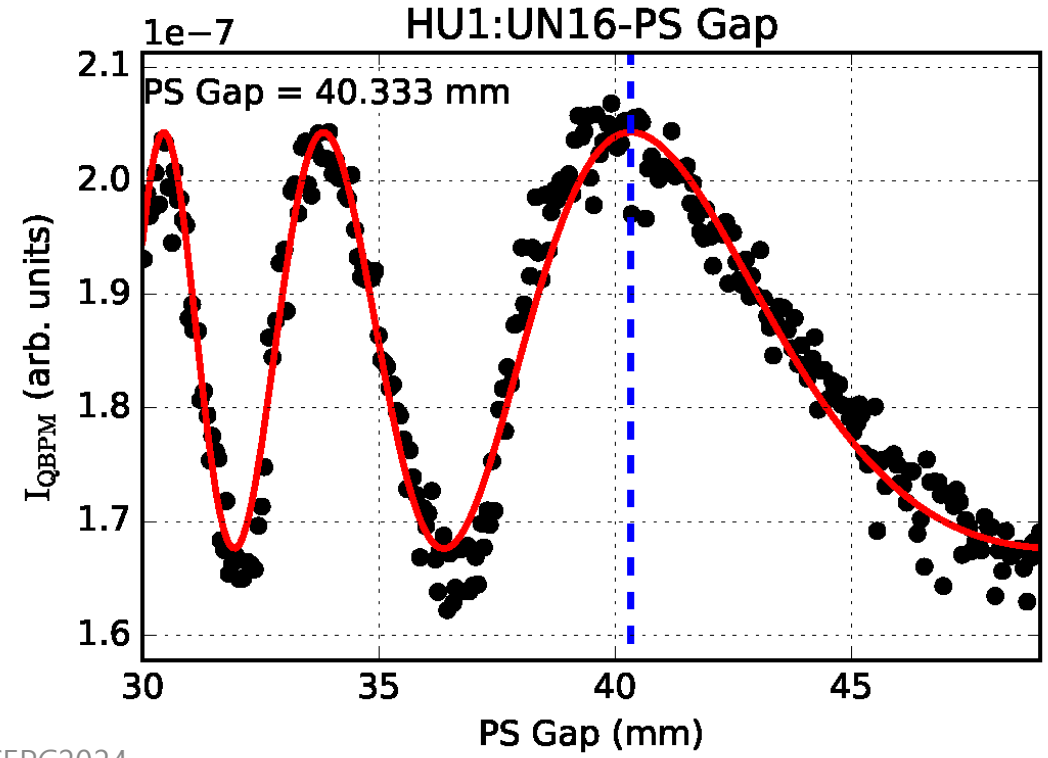
$$\lambda_r = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{k^2}{2}\right)$$

T. Tanaka et al., Phys. Rev. ST Accel. Beam 15, 110701 (2012)

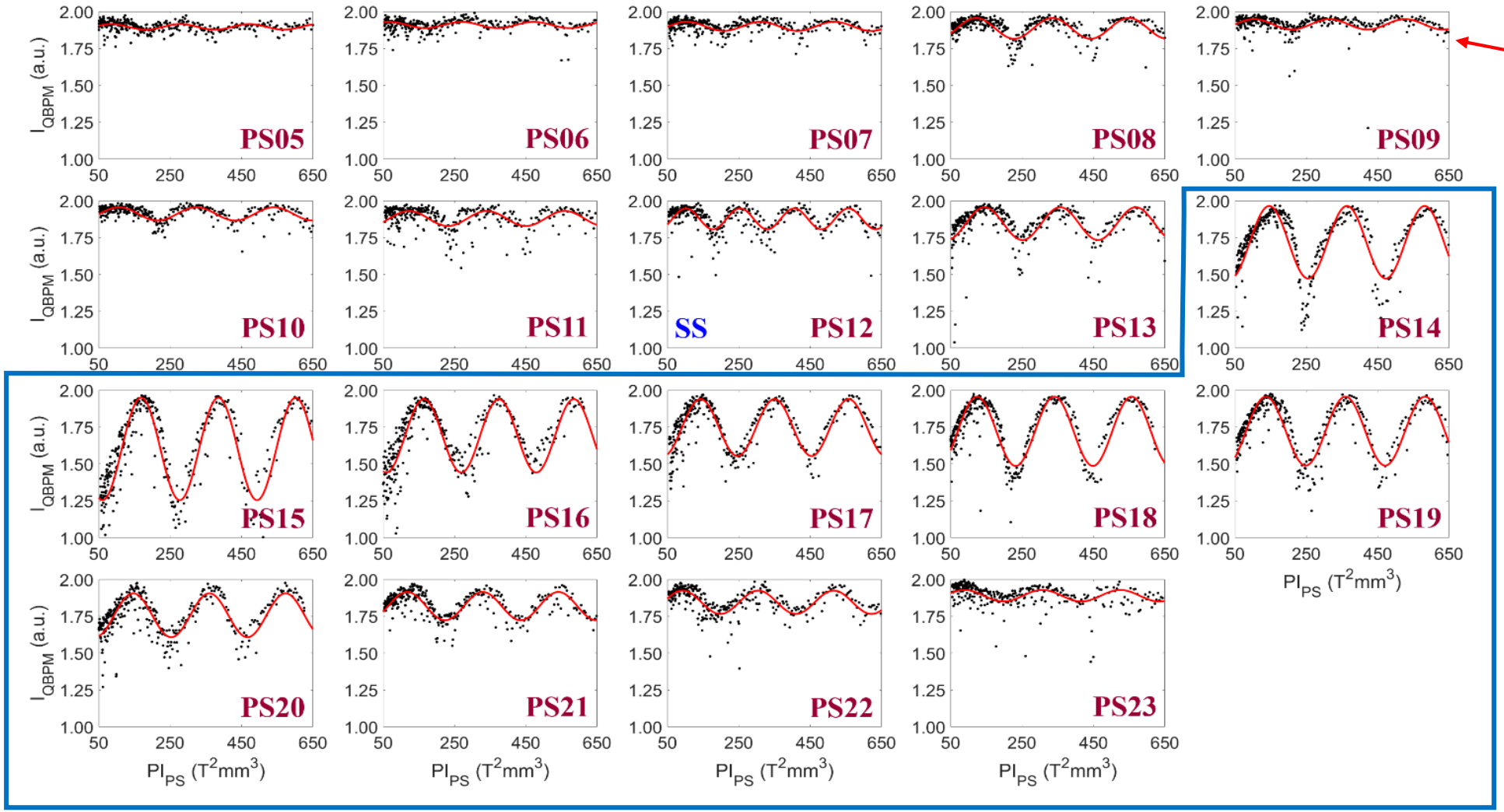
Phase Shifter Gap Tuning

- PS gap scanning with the FEL power measurement
- To find optimum PS gap in the tapering condition





Phase Shifter Scan



Sinusoidal fitting

Saturation region

C. H. Shim *et al., Phys. Rev. ST Accel. Beam* **23,** 090702 (2020)

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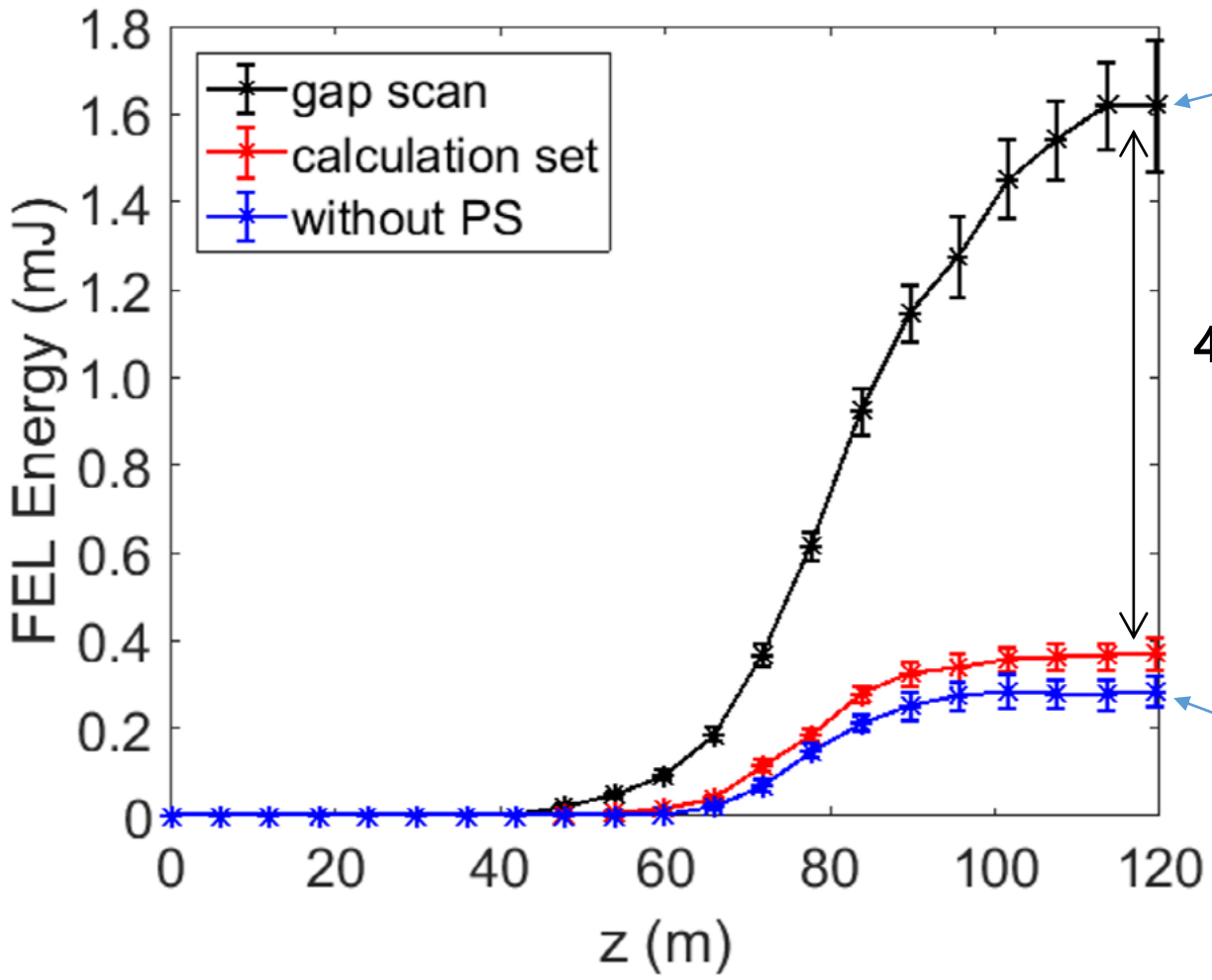
FEL Optimization using Phase Shifters



Phase shifter scan

4 times enhancement

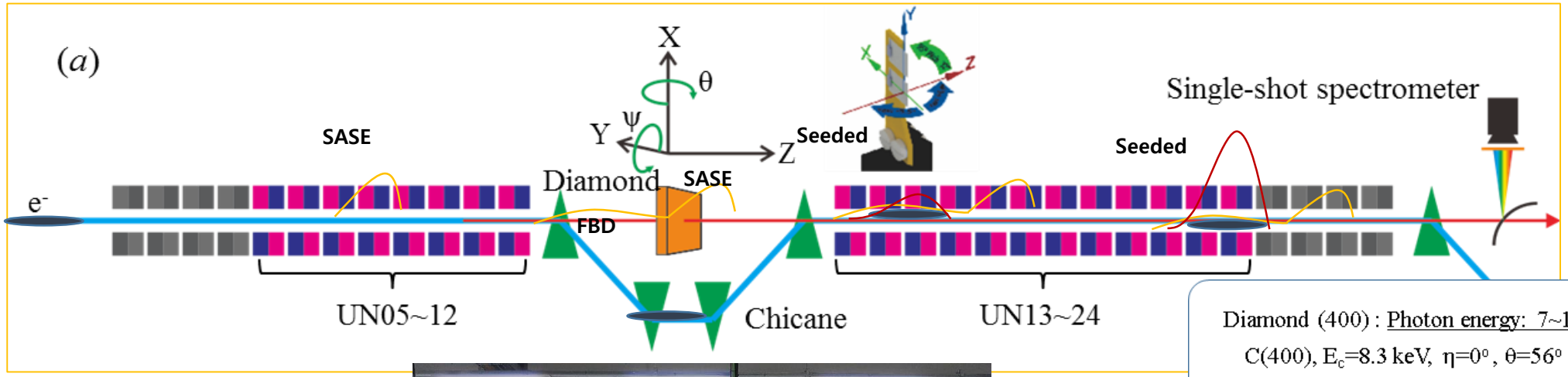
Phase shifters are fully opened.

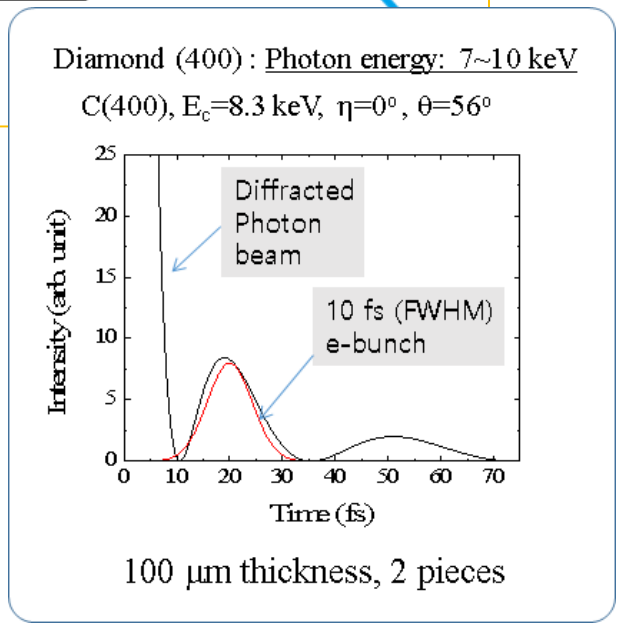
Self-Seeding Project History

- Collaboration with APS/USA, LCLS and TISNCM/Russia
  - Design of Diamond crystal monochromator by APS
  - Diamond crystals fabricated by TISNCM, Russia are checked at APS for its property
  - Engineering design by PAL staff and fabrication by Korean company
  - Feb. 2018: Installation of HXSS
- Commissioning of PAL-XEL HXSS
  - Oct. 2018: Nominal bunch charge 180 pC for 7,8. keV, crystal offset calibration with crossing points of self-seeding (Collaboration with LCLS)
  - Nov. 2018: Seeding for 3.5 keV with 30 um crystal and 14.4 keV (Collaboration with LCLS)
  - Aug. 2019: Seeding performance improved with laser heater
  - Oct. 2019: Optimized peak brightness and bandwidth for seeding at 9.7 keV, 14.4 keV

Hard X-ray Self-seeding

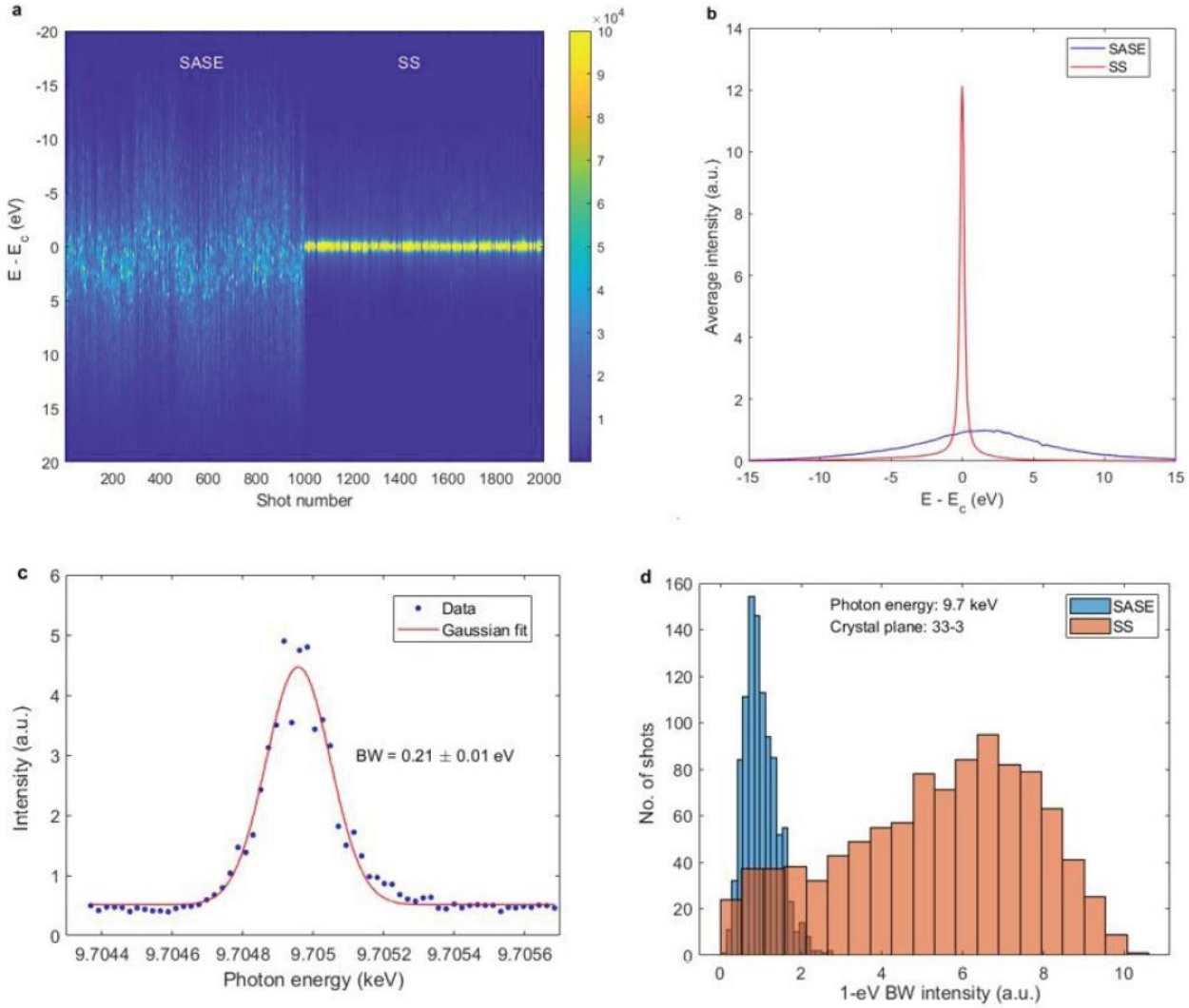
- Schematic of hard x-ray self-seeding with a diamond crystal





Self-Seeded FEL Operation

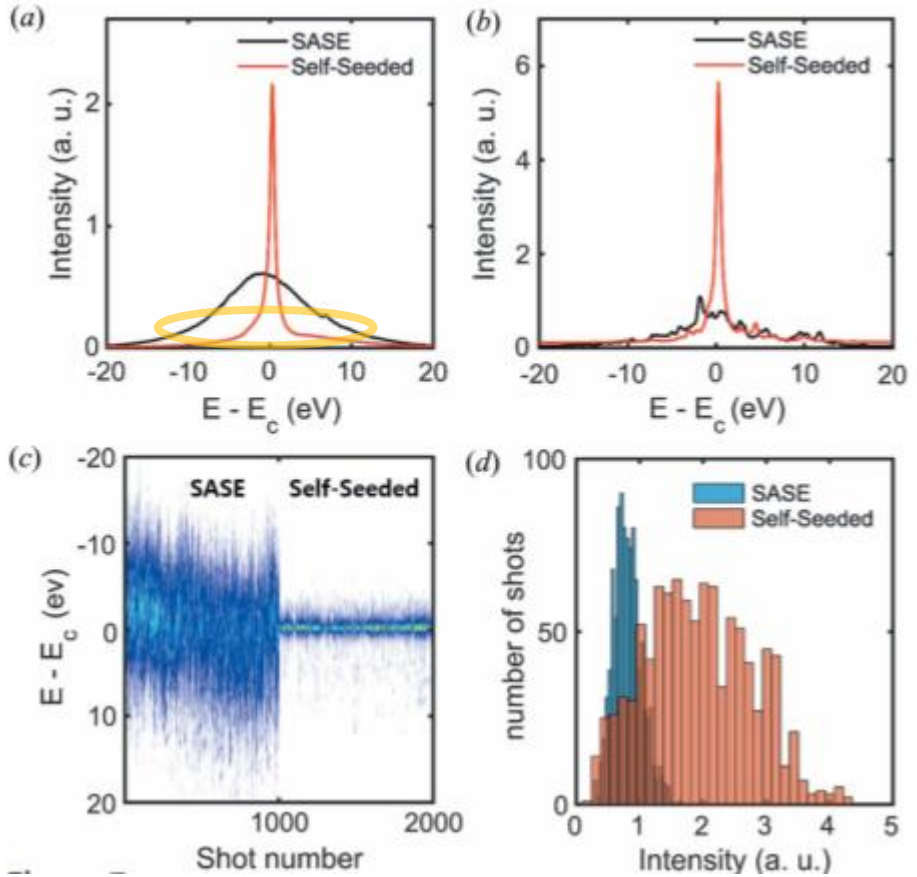
- Two times demo experiments were carried out cooperating with B/L staff
- We are ready to service self-seeded HX FEL since 2022



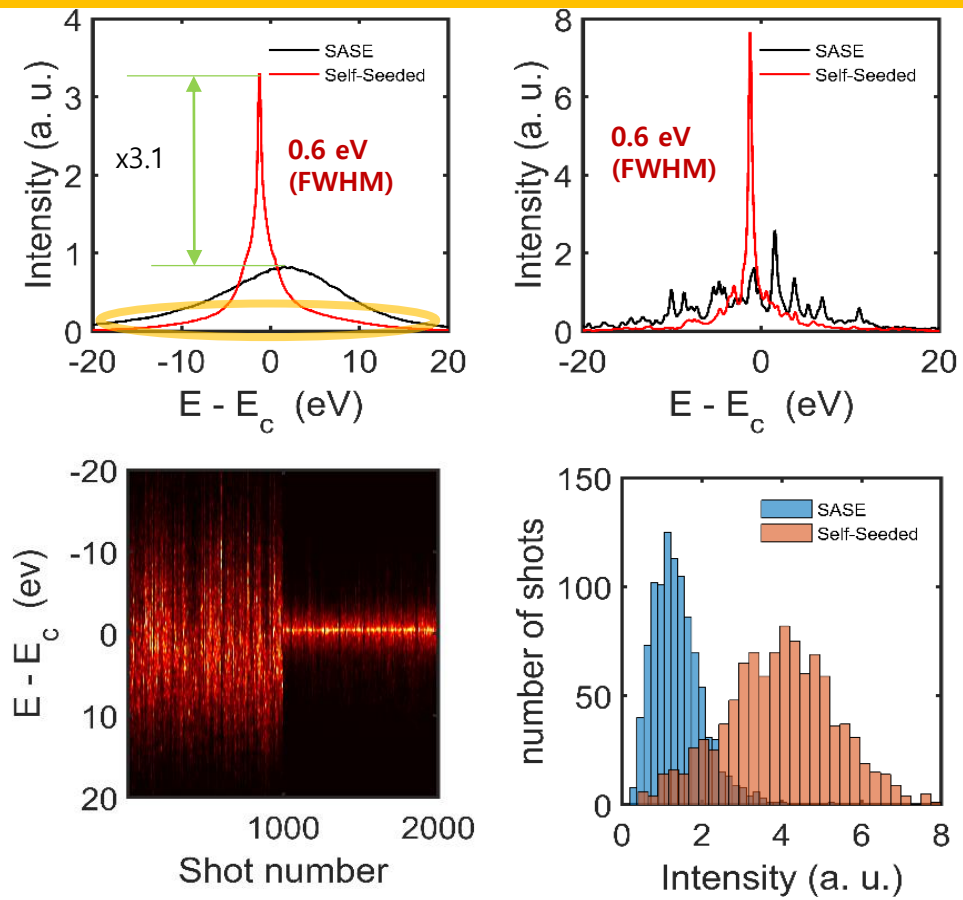
Previous Results (Nov. 2018)

Large portion of pedestal

Fraction enclosed in ± 1 eV: 30 ~ 50%



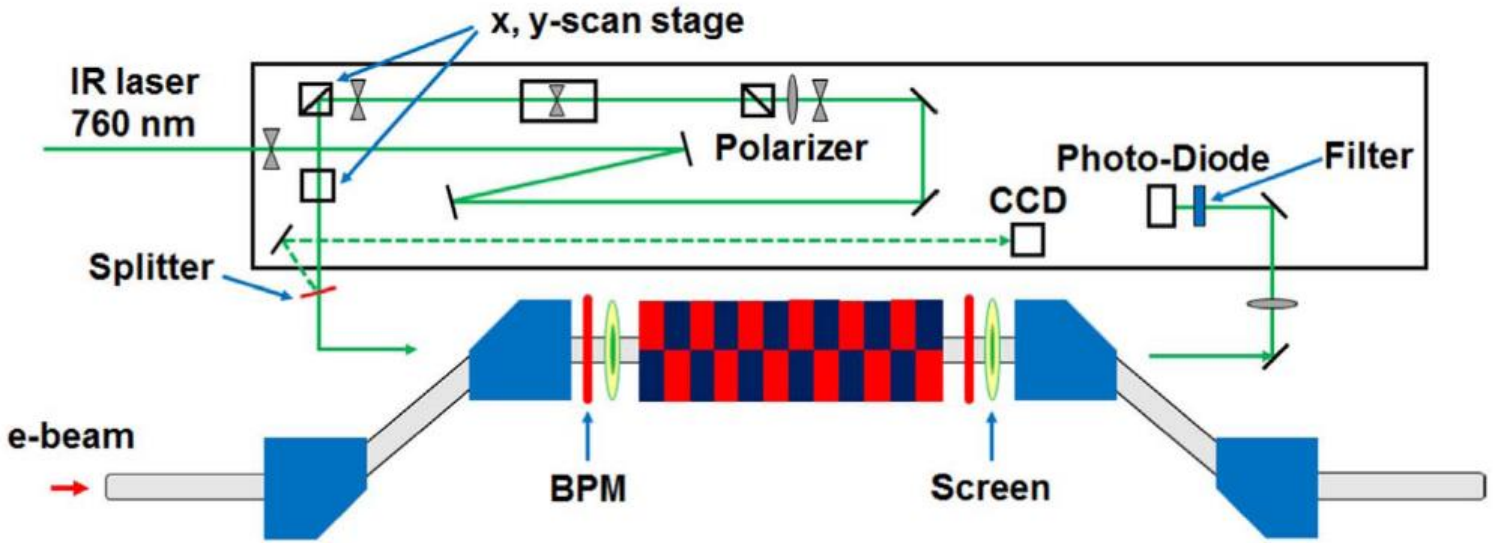
Ec = 7 keV

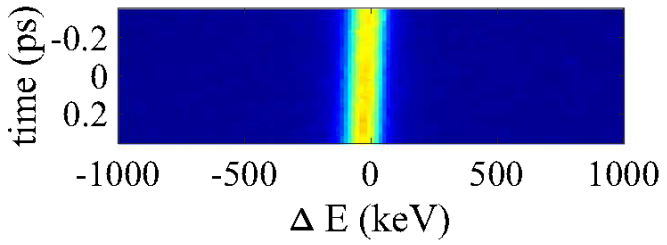


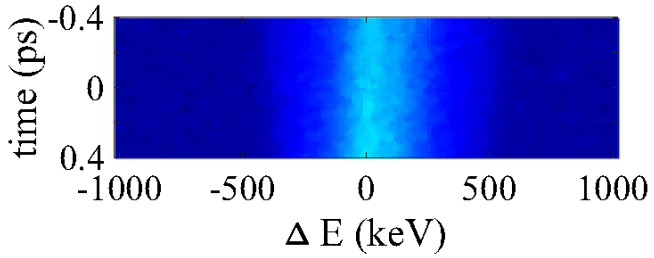
Ec = 14.4 keV

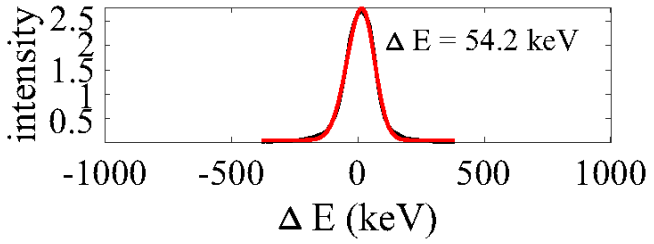
C. K. Min *et. el., J. Synchrotron Rad.* **26**, 1101 (2019)

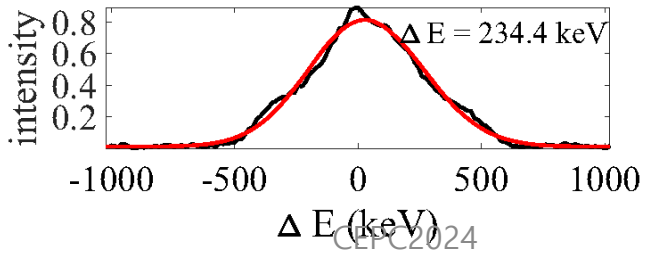
Effect of Laser Heater

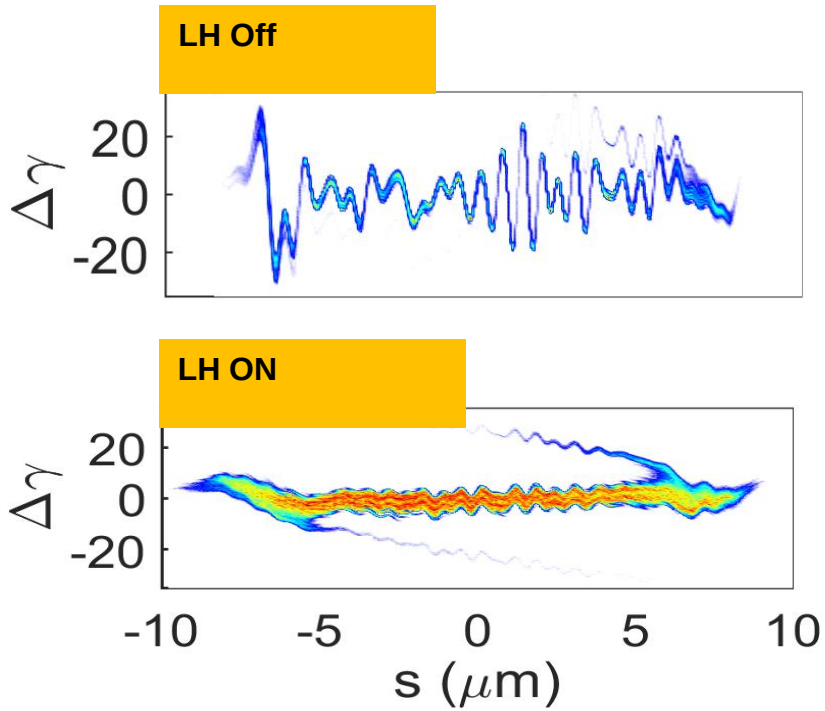






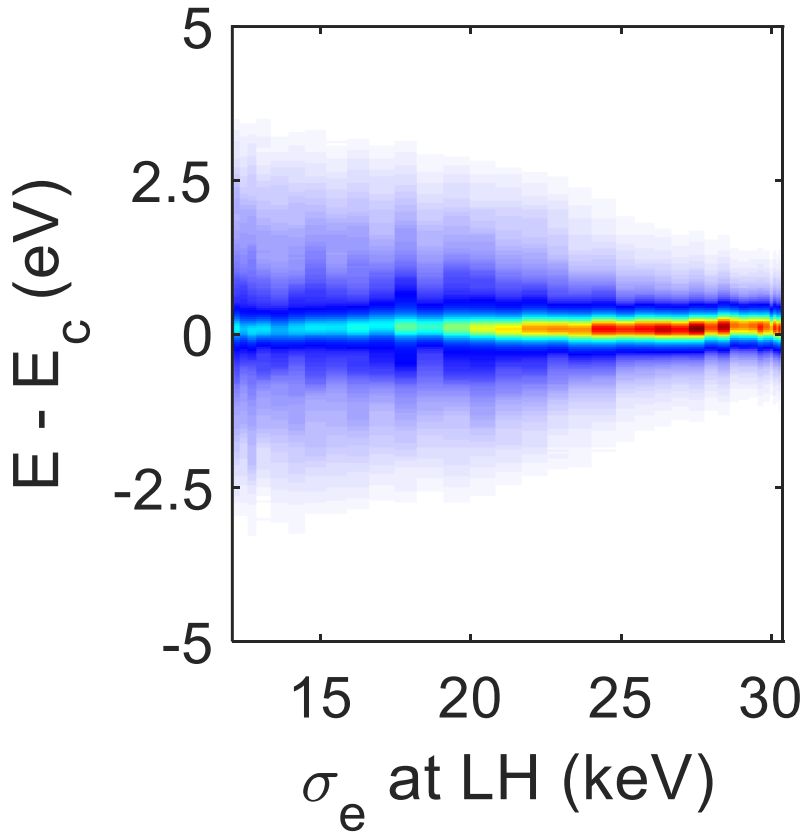


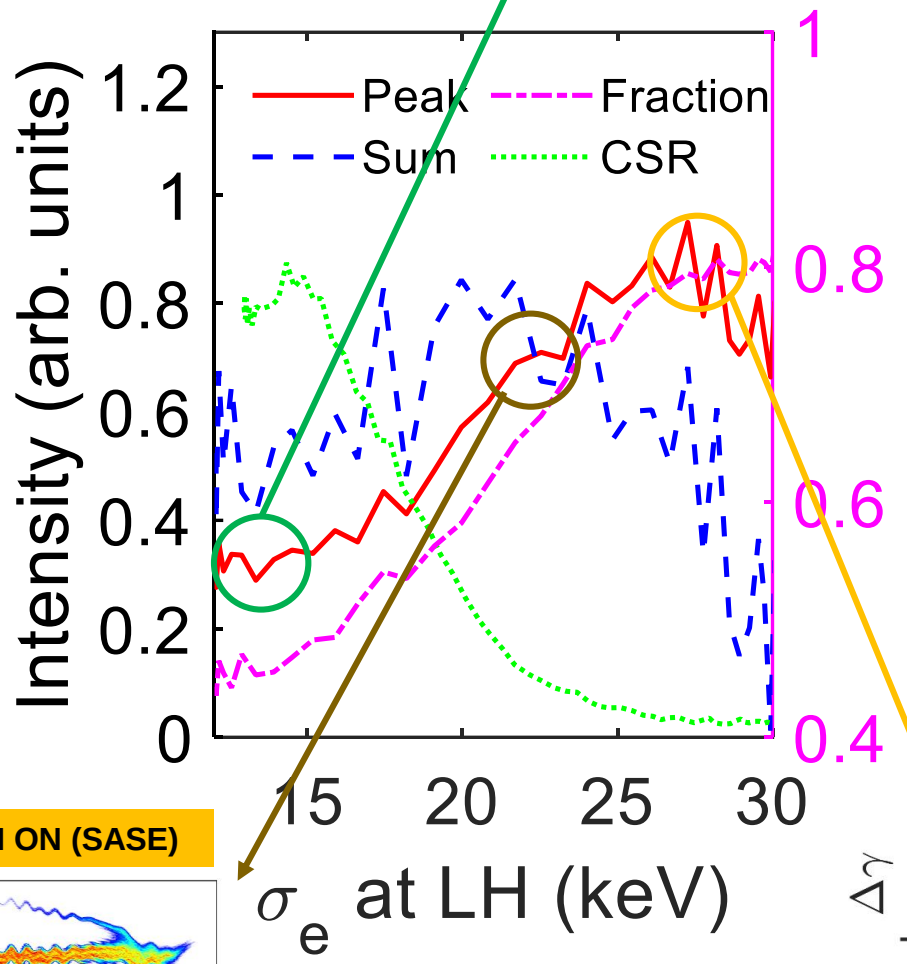




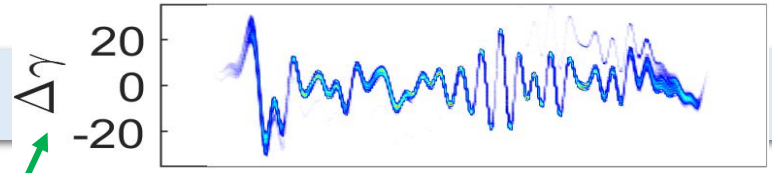
J. Lee *et al.*, *NIM A*, **843**, 39 (2017)

Seeded Peak vs Laser Heater



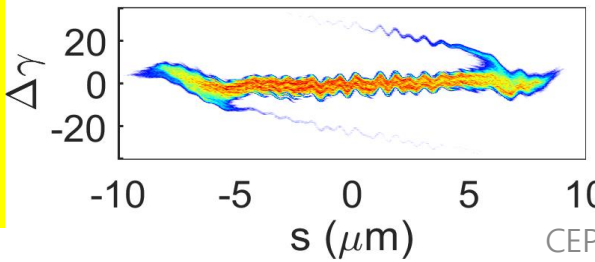


LH OFF (SASE)



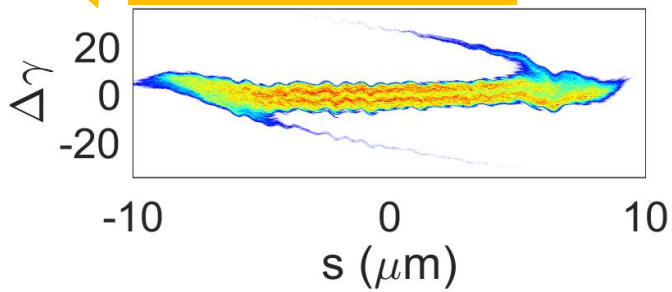
Slice energy spread increases, but more smoother modulation

LH ON (SASE)



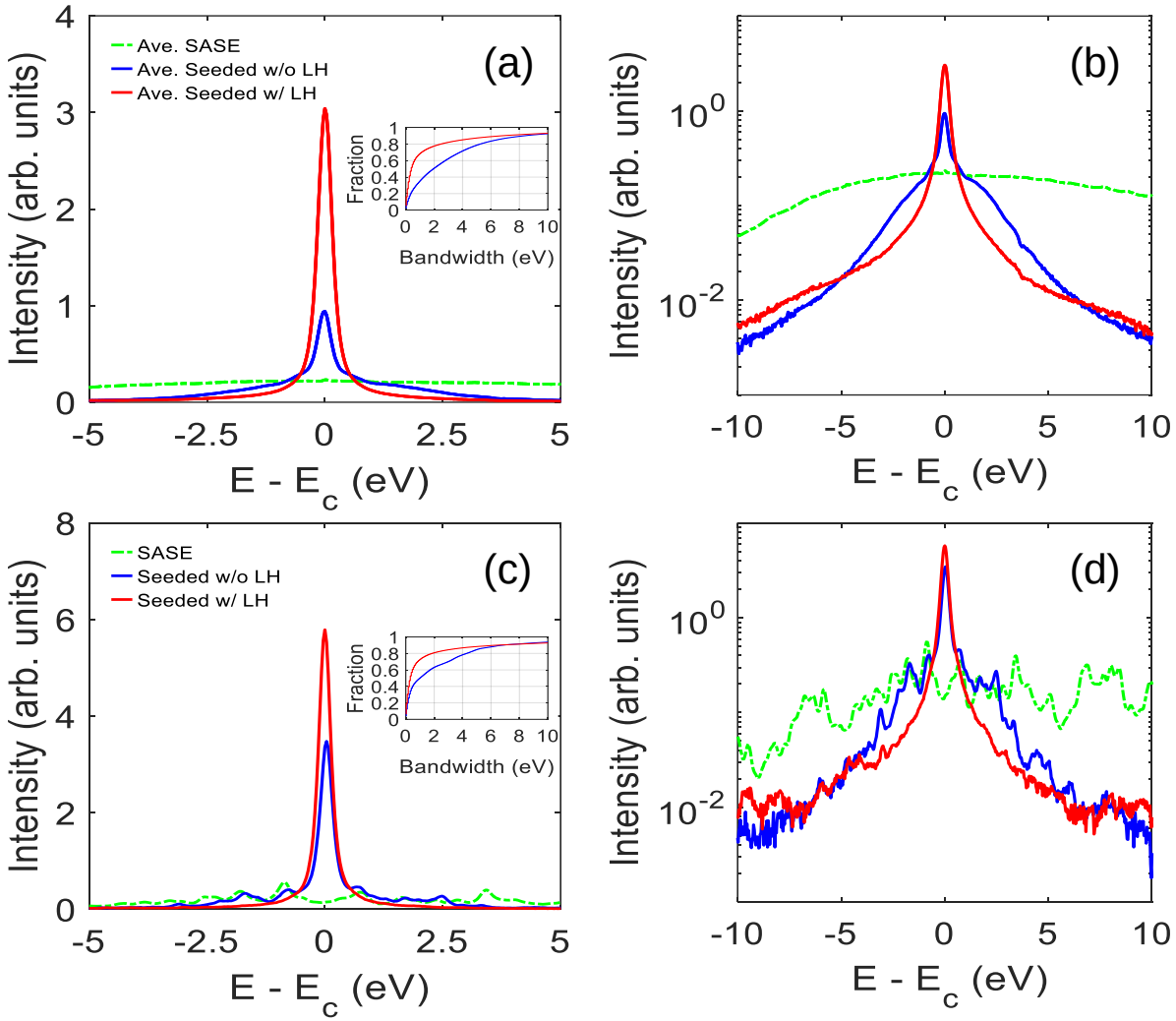
Slice energy spread is minimum but slight modulation is still remained.

LH ON (Self-seeding)



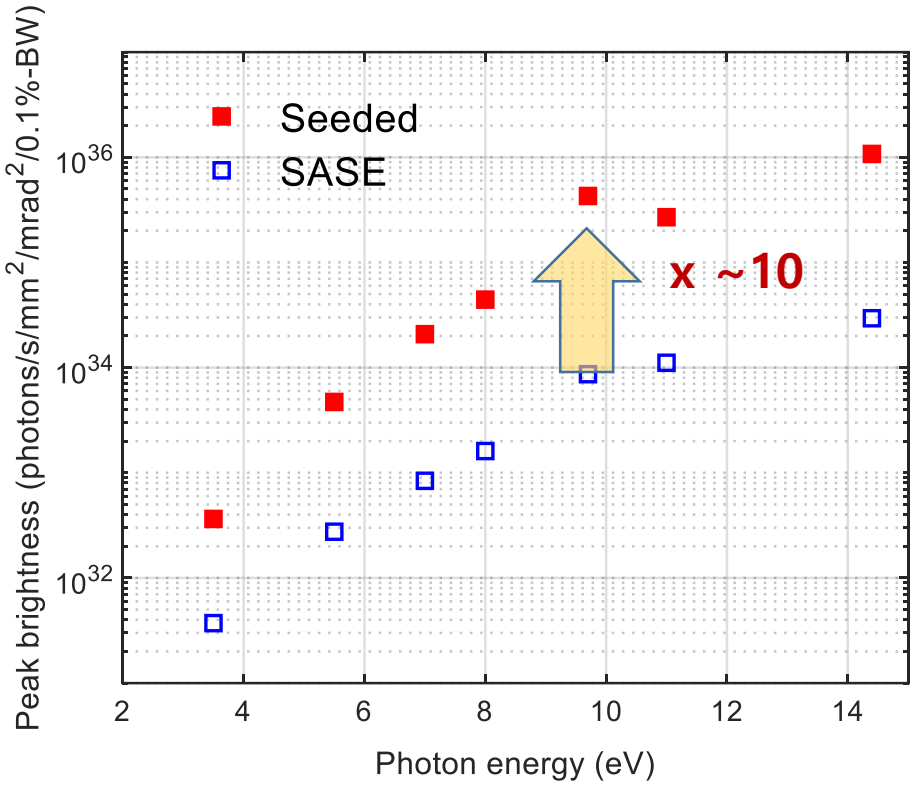
Results for Self-Seeded FEL at 9.7 keV

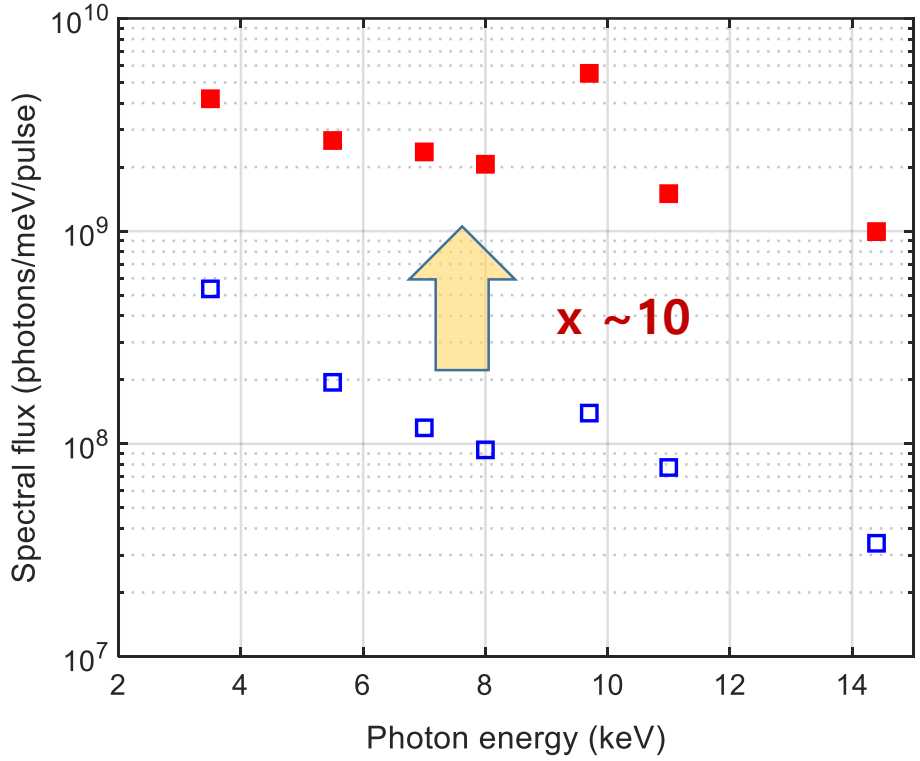
- Photon Energy Ec = 9.7 keV
- Averaged FEL energy: **~850 μJ (~1.5 mJ for single shot)**
- SASE bandwidth (FWHM) = 27 eV
- Measured bandwidth = 0.35 eV (Resolution = 0.26 eV)
- De-convoluted bandwidth (FWHM) = **0.22 eV**
- FEL Pulse duration = ~ **20 fs**
- Chicane time delay = 30 fs
- Bragg orientation = [115]
- Diamond thickness = 100 μm (c100)
- Portion of SASE in seeded FEL: ~6 %
- **Fraction of energy enclosed within ± 1 eV : ~ 80%**



- **Peak brightness (photons/s/ mm² /mrad²/0.1% BW): 5 x 10³⁵**

Peak Brightness and Spectral Flux

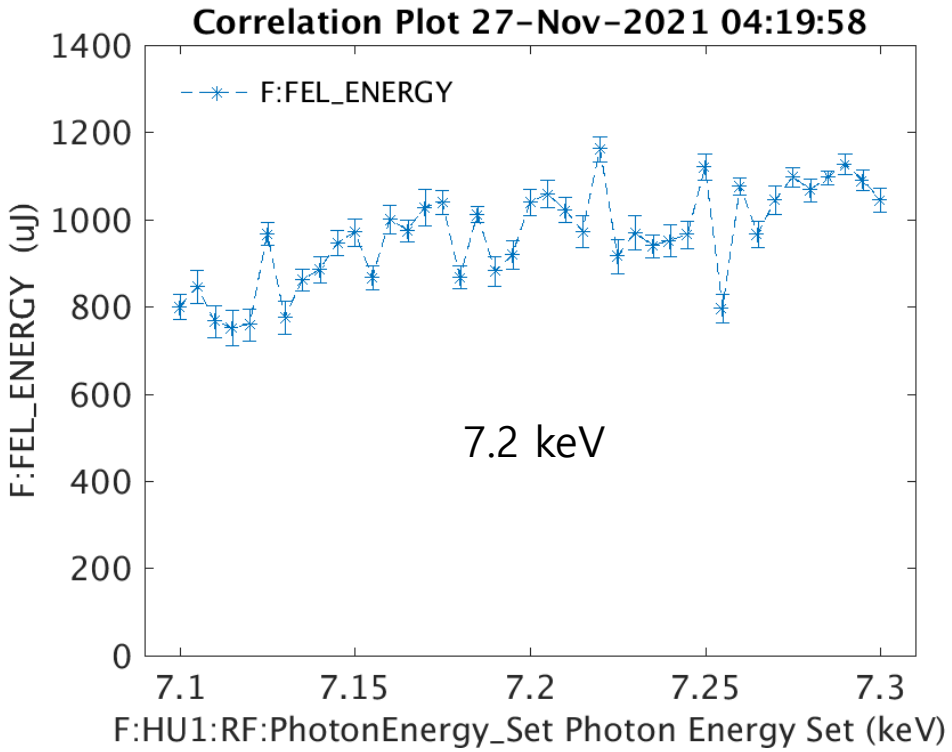




- **For self-seeded FEL, almost one order of magnitude enhancements of the peak brightness and spectral flux were obtained compared to that of the SASE mode**

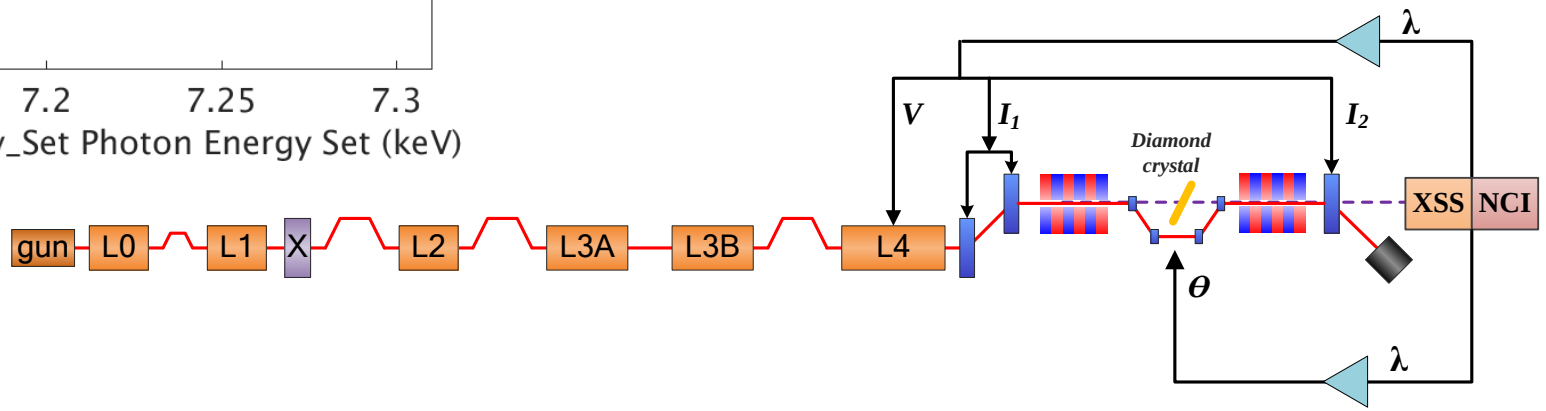
I. Nam *et al., Nature Photonics* (2021)

Energy Scan for Self-Seeding FEL



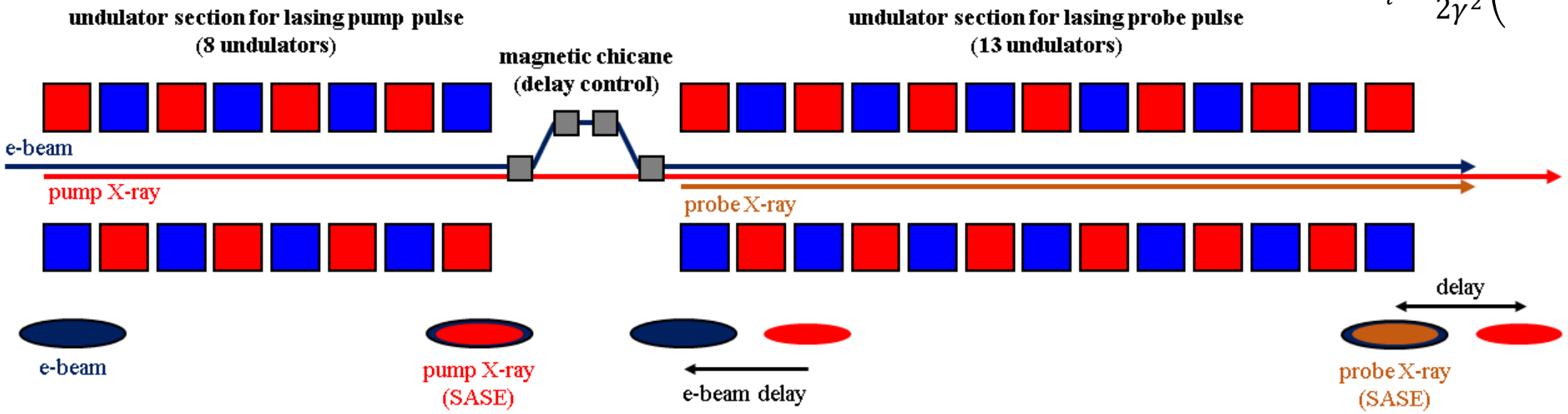
Energy control for Hard X-ray Self-Seeding

- Range : Photon energy ± 1 ~ 1.5 %
- e-Beam energy : Adjustable
- Diamond crystal angle : Adjustable



Two-Color FEL

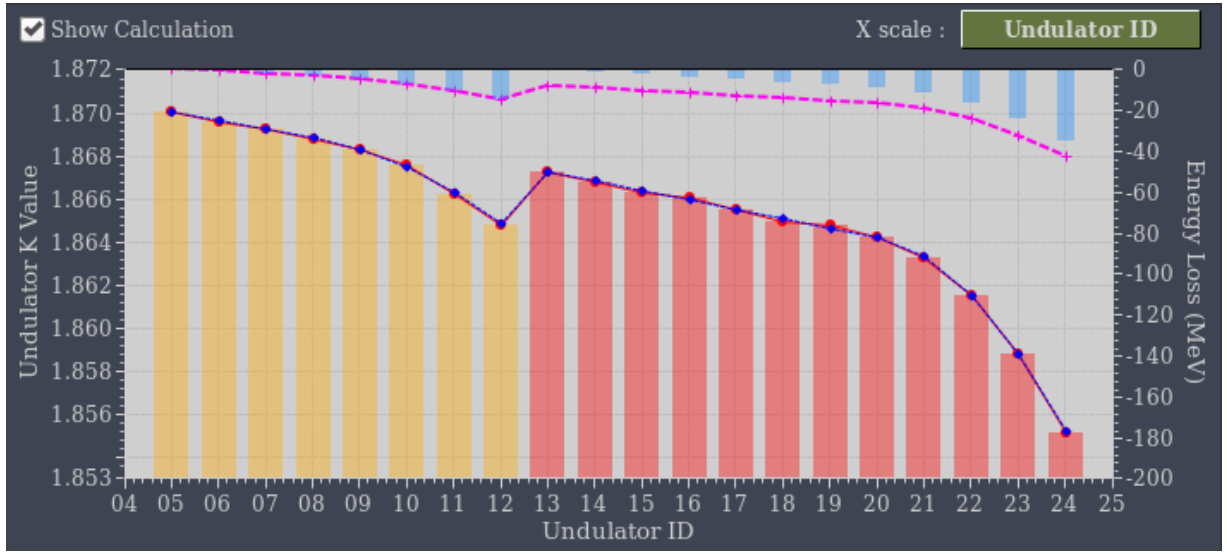
$$\lambda_l = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



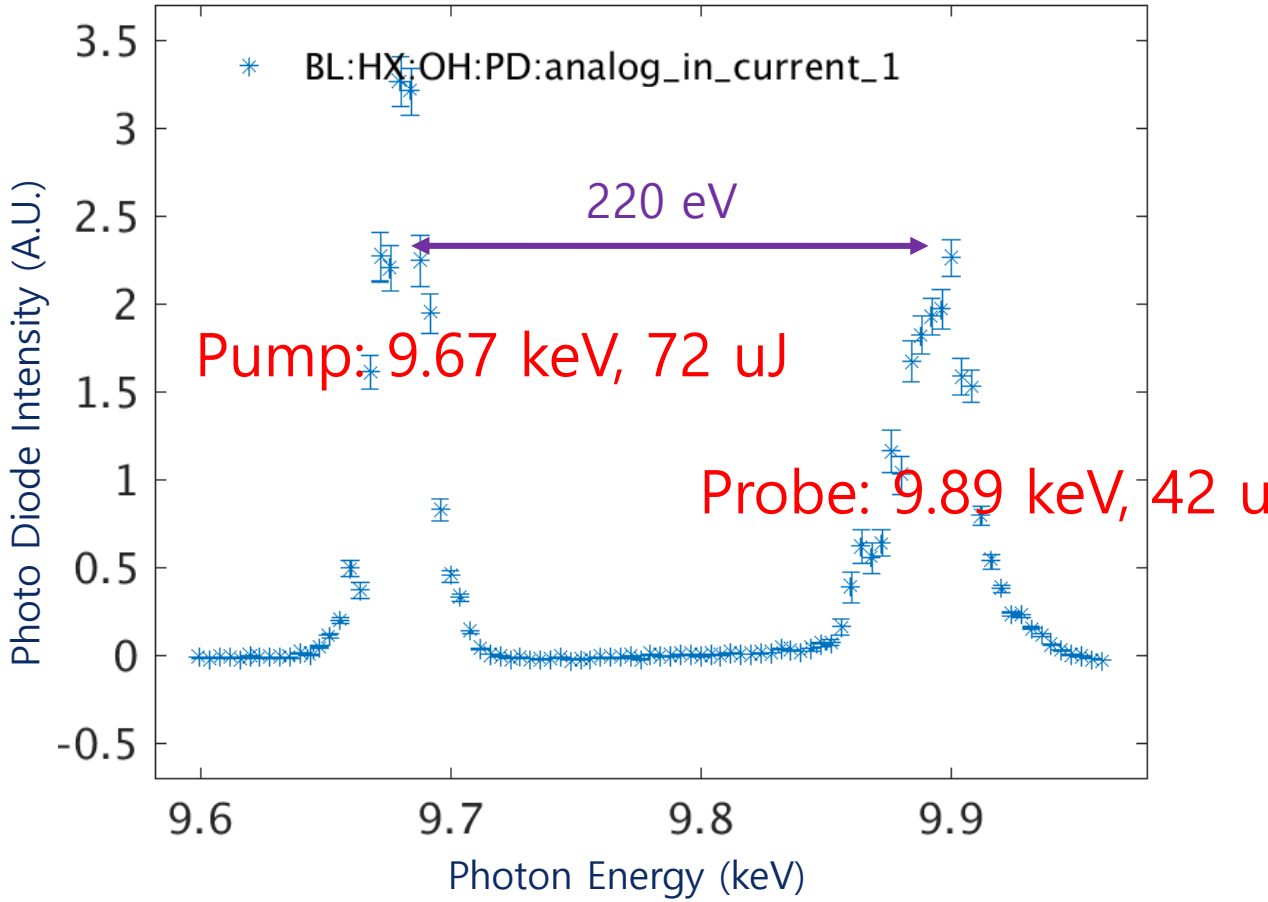
- By utilizing variable gap undulator and dipole magnet for self-seeding section, two-color pump-probe XFEL pulses can be generated from single electron bunch
- 8 undulators located at the upstream of the self-seeding section are used for lasing pump pulse
- 13 undulators located at the downstream of the self-seeding section are used for lasing probe pulse
- Time delay between pump and probe pulse can be controlled by changing the current of the dipole magnet

Two-Color FEL Generation

- Two-color FEL generation was tried in PAL-XFEL for the first time in 2020.
- 8 and 12 undulators were used before and after the self-seeding section.
- 9.67 and 9.89 keV FEL pulses were obtained successfully.



Undulator Gap Setting for Two-Color FEL Generation



Photon Energy Measurement Result of Two-Color FEL

Multi-Beamline Operation of HX and SX

- Kicker and septum magnets were installed in SX branch line on Feb. 2020.
- The optics of the new kicker-SX branch line was confirmed by using a DC kicker magnet power supply.
- The pulsed switching FEL operation at a low repetition rate (2 Hz) with an AC kicker power supply was succeeded on August 2020.
- The preparation of the HX-SX sharing mode operation by using a 60 Hz pulsed kicker is ongoing.

Thank you for your attention!