Operation Status of PAL-XFEL

2021. 3. 18

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on behalf of PAL-XFEL
Pohang Accelerator Laboratory

Contents

PAL-XFEL

Apr. 2011: PAL-XFEL project started
(Total Budget: 400 M$)

Apr. 2016: Commissioning started

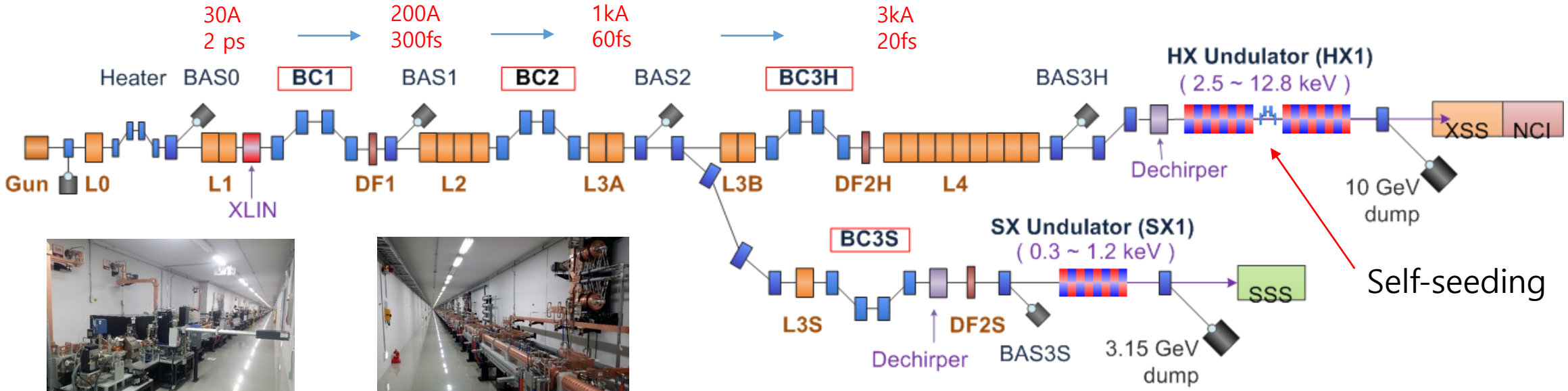
Jun. 2017: User-service started
- 120 days for user (>95% of availability)

Achieved in 2018
- 140 days for user (>95% of availability)
- HX self-seeding commissioning

Achieved in 2019
- 160 days for user (96.8% of availability)
- 60 Hz operation started

Achieved in 2020
- 170 days for user (96.9% of availability)
- HX self-seeding user service started

PAL-XFEL Parameters

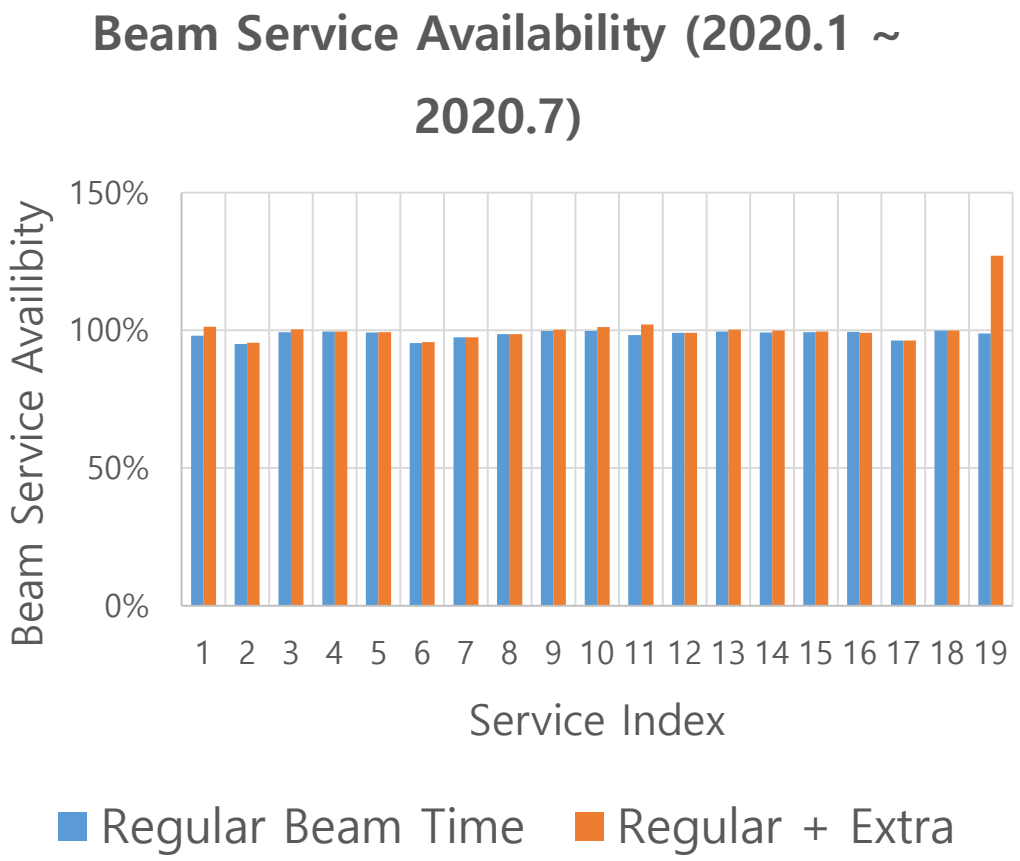


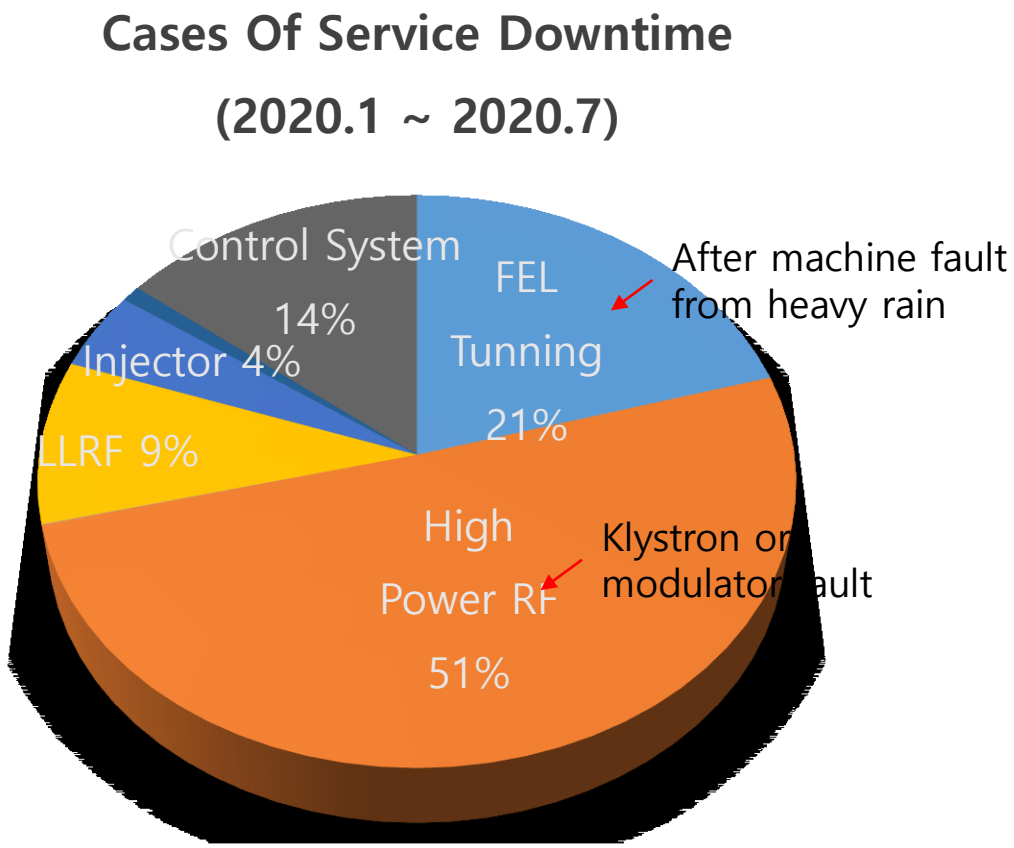
Main parameters

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

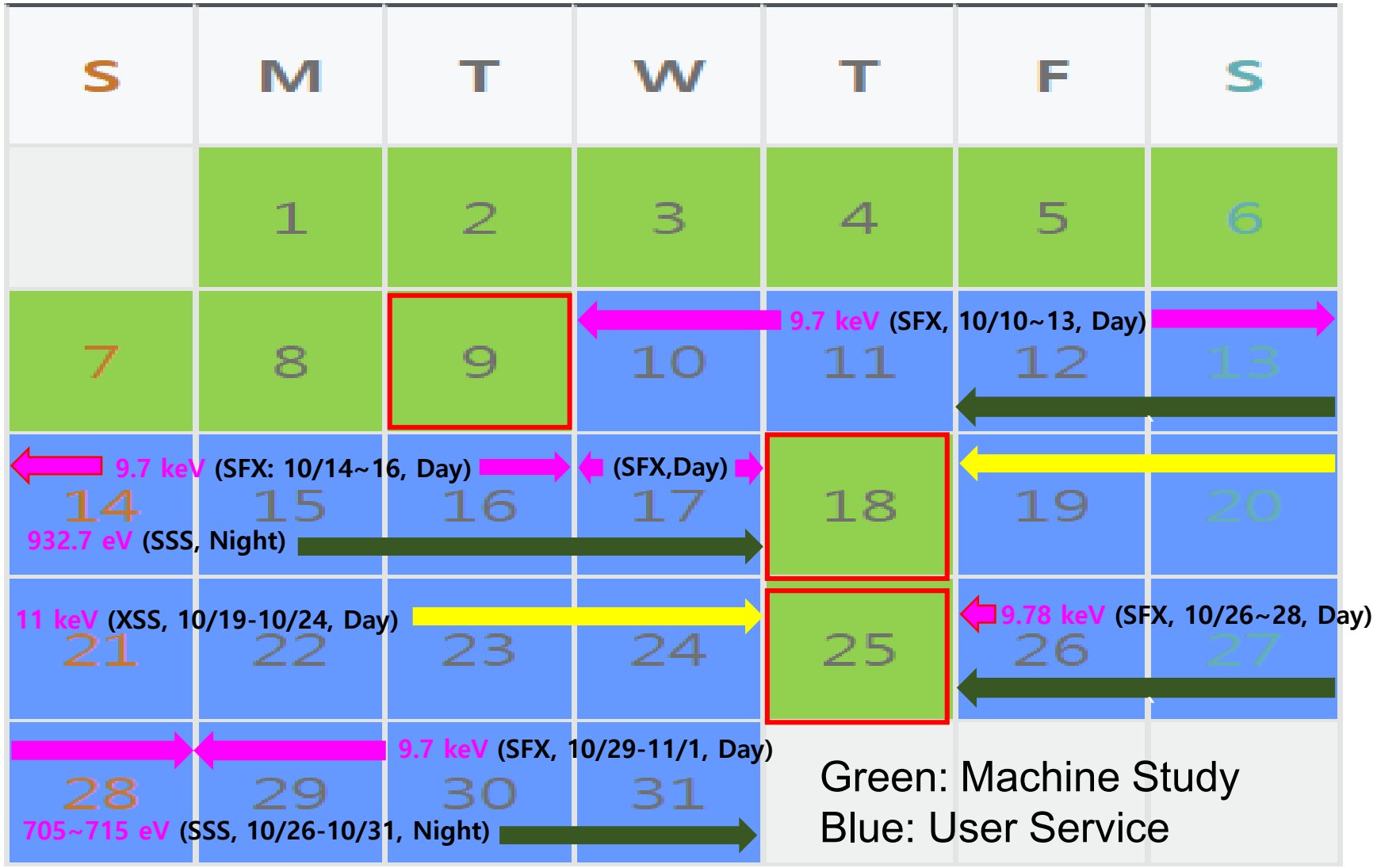
Undulator Line	HX	SX
Photon energy [keV]	2.4 ~ 15	0.28 ~ 1.0
Beam Energy [GeV]	4 ~ 11	3.0
Wavelength Tuning	Energy	Gap
Undulator Type	Planar	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 9.0

Beam Service Statistics

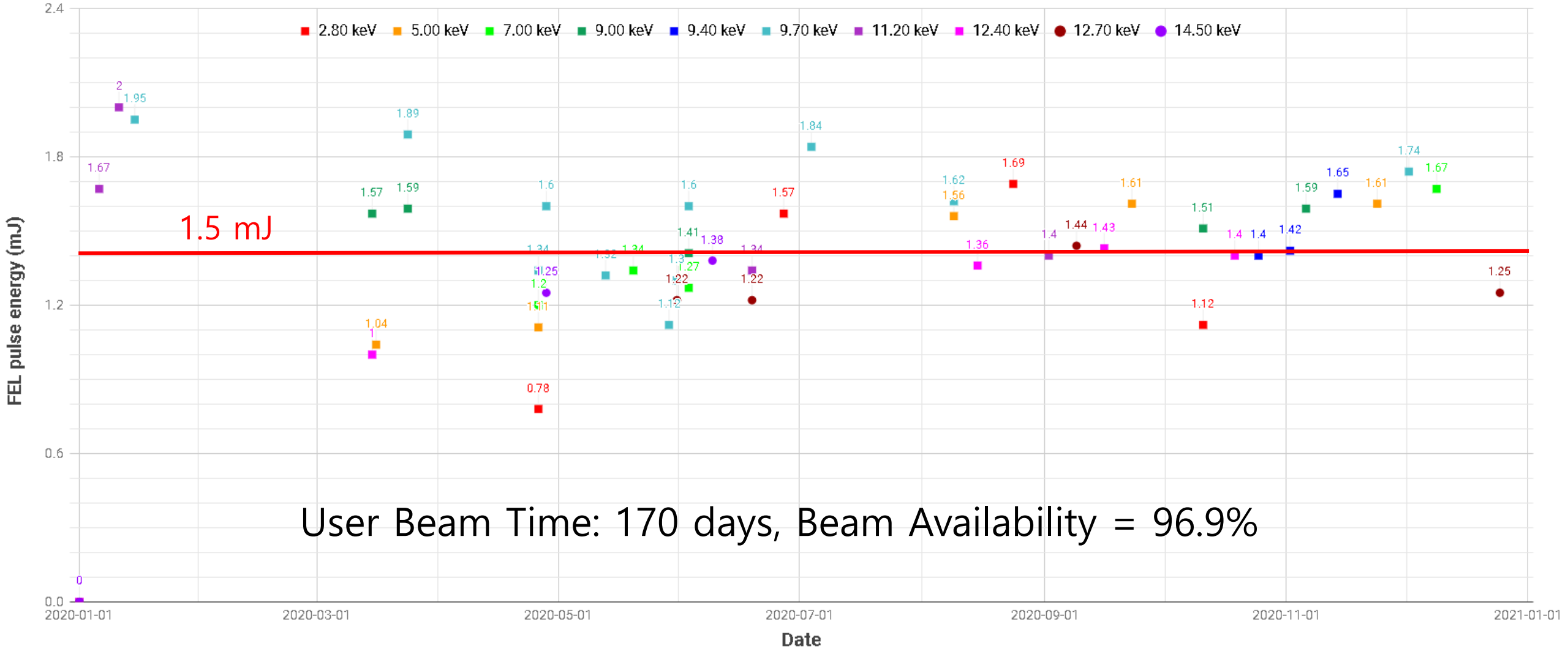




User Service Schedule



FEL Energy in 2020



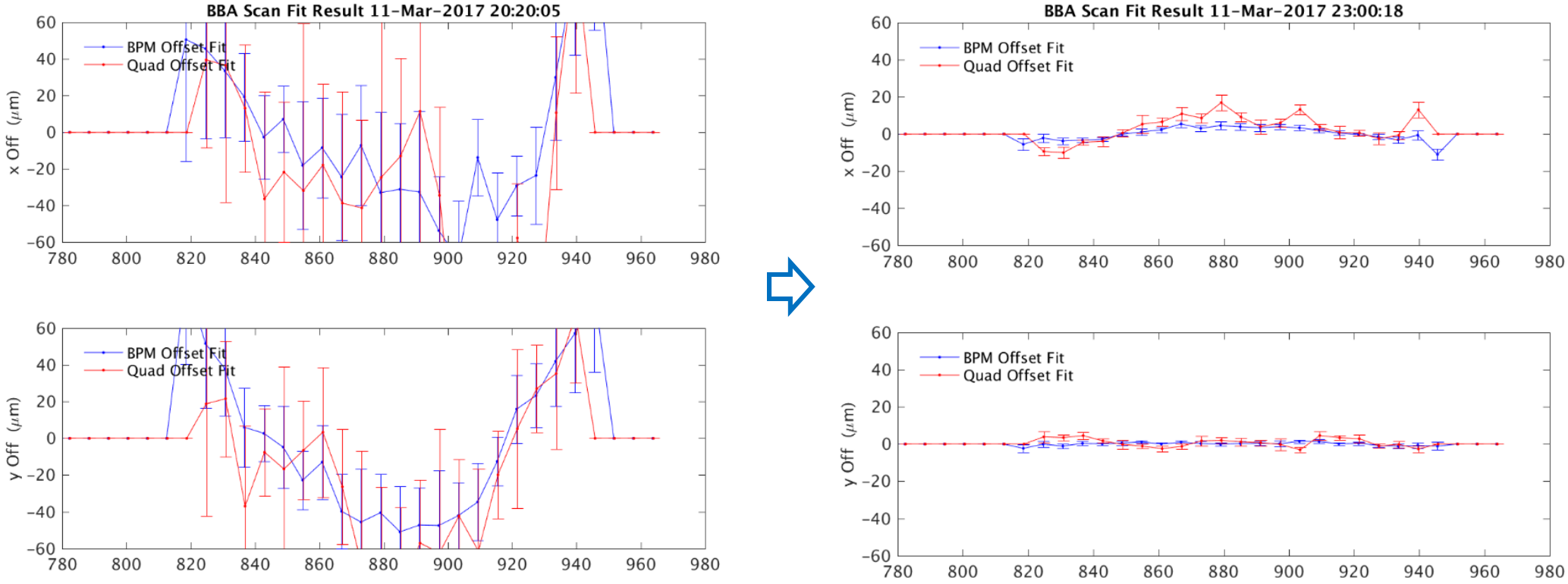
User Beam Time: 170 days, Beam Availability = 96.9%

FEL Optimization Process

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

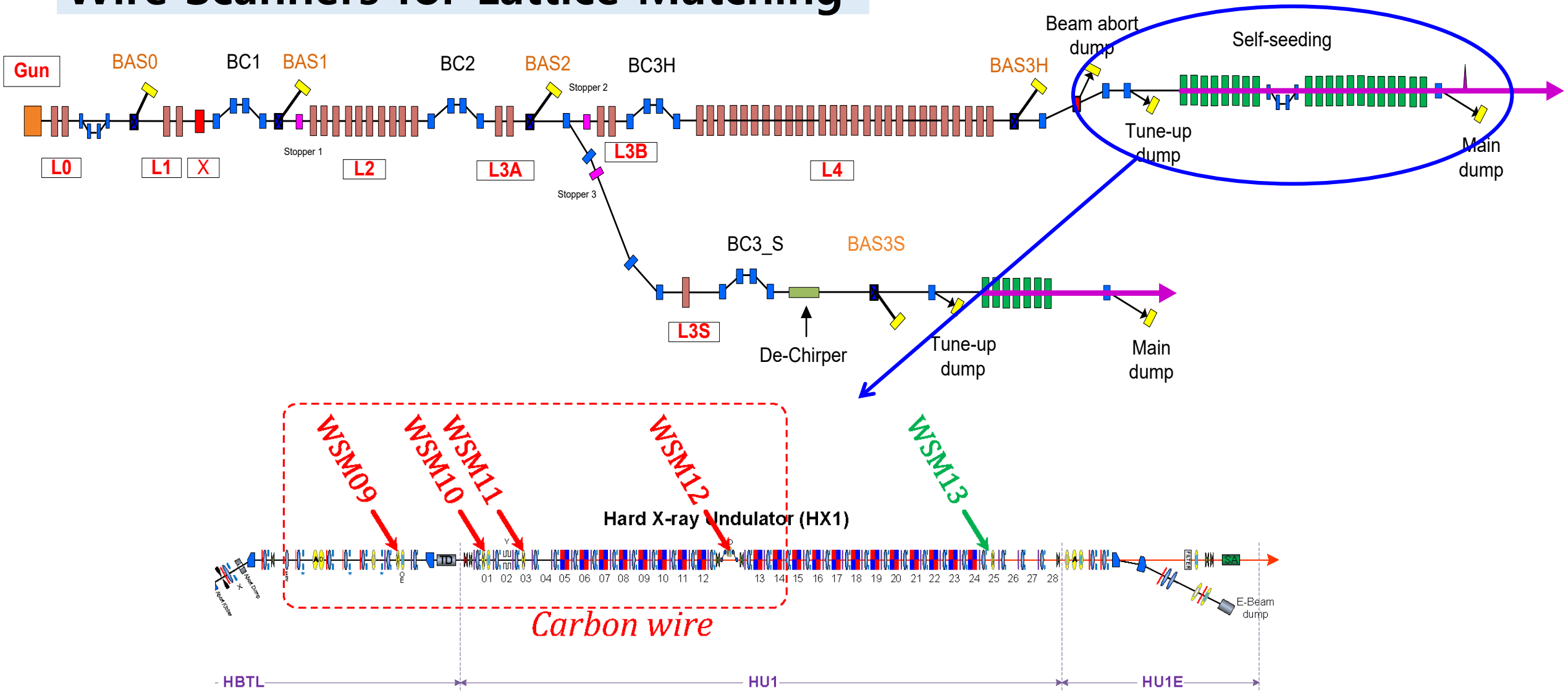
Undulator BBA

- 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 its own mover which can move up to +/-1 mm with precision of 1 um for horizontal and vertical directions

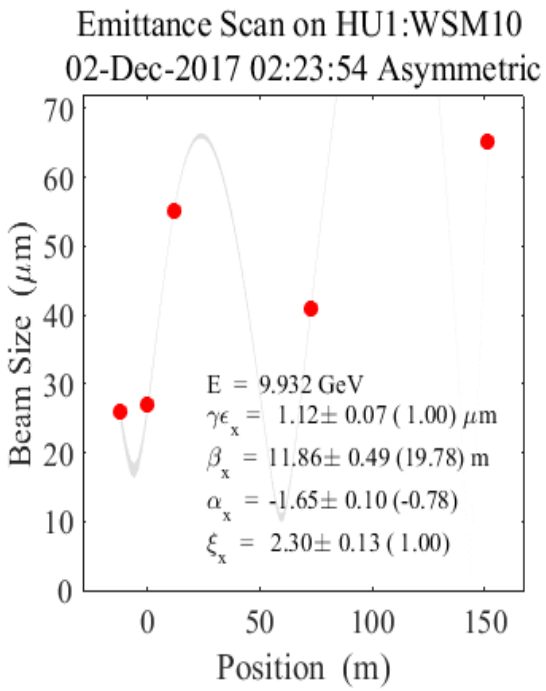


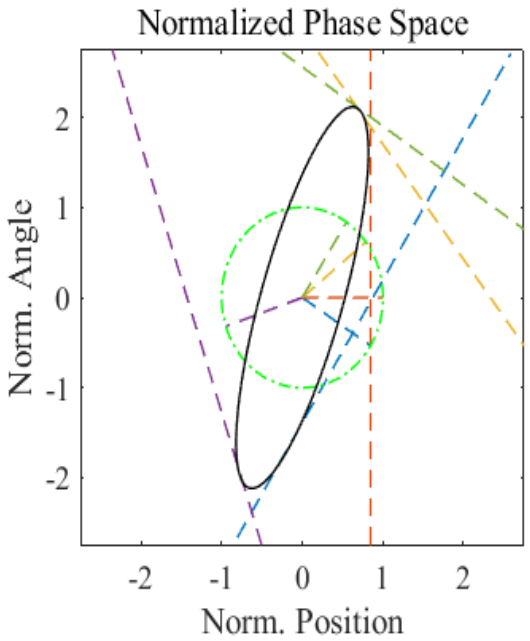
Henrik Loos, LCLS FAC (2009), P. Emma *et al.*, *NIM A* **429**, 407-413 (1999)

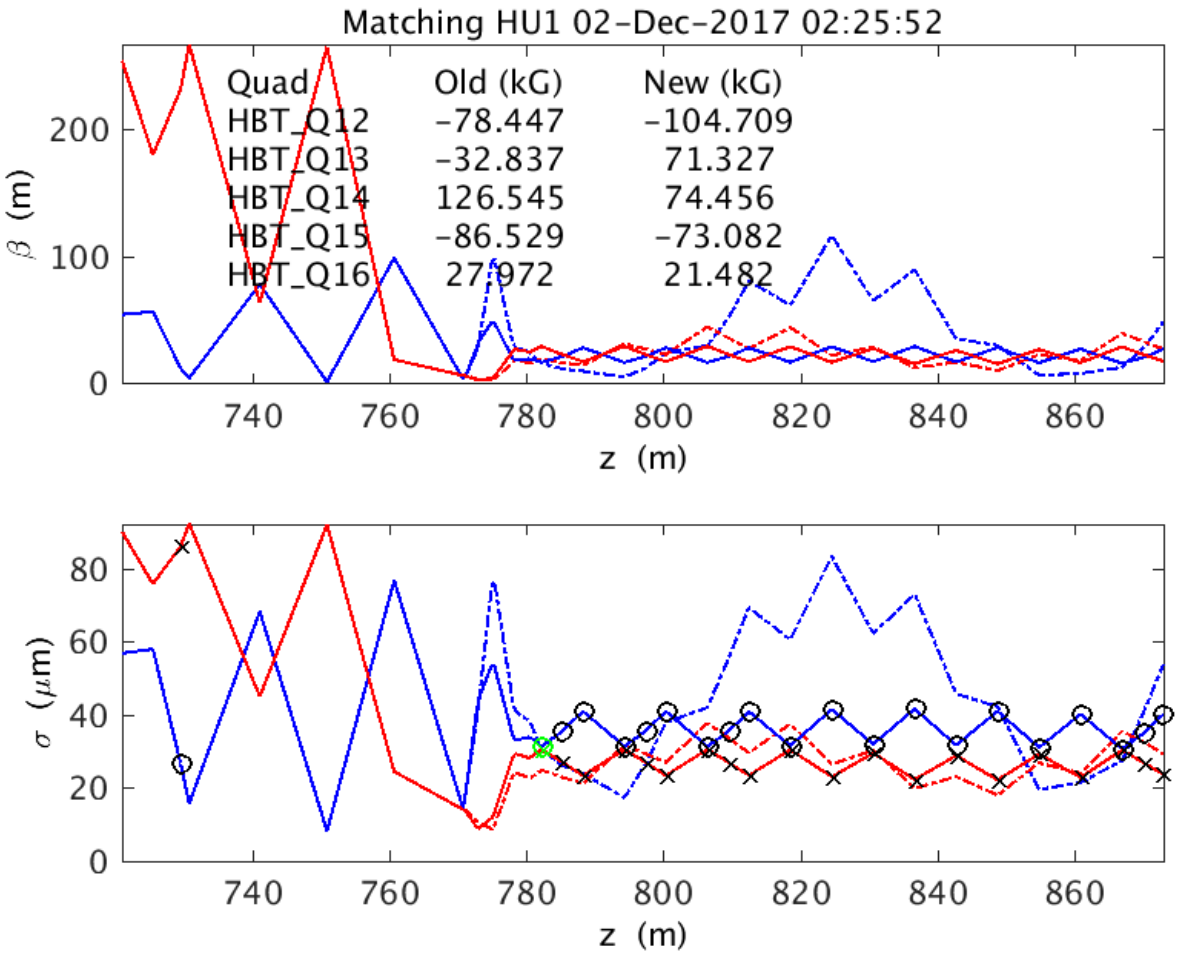
Wire Scanners for Lattice Matching



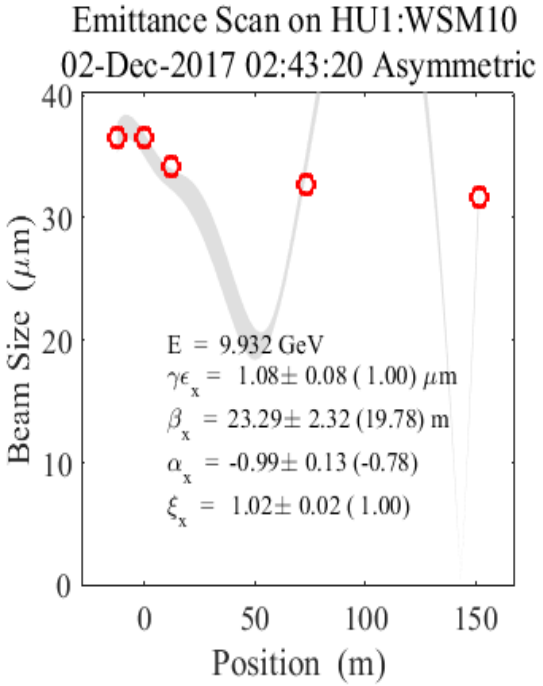
Before Lattice Matching in Undulator

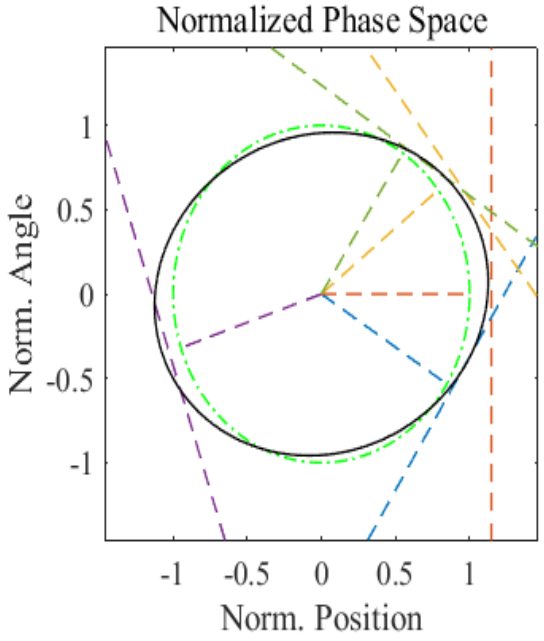


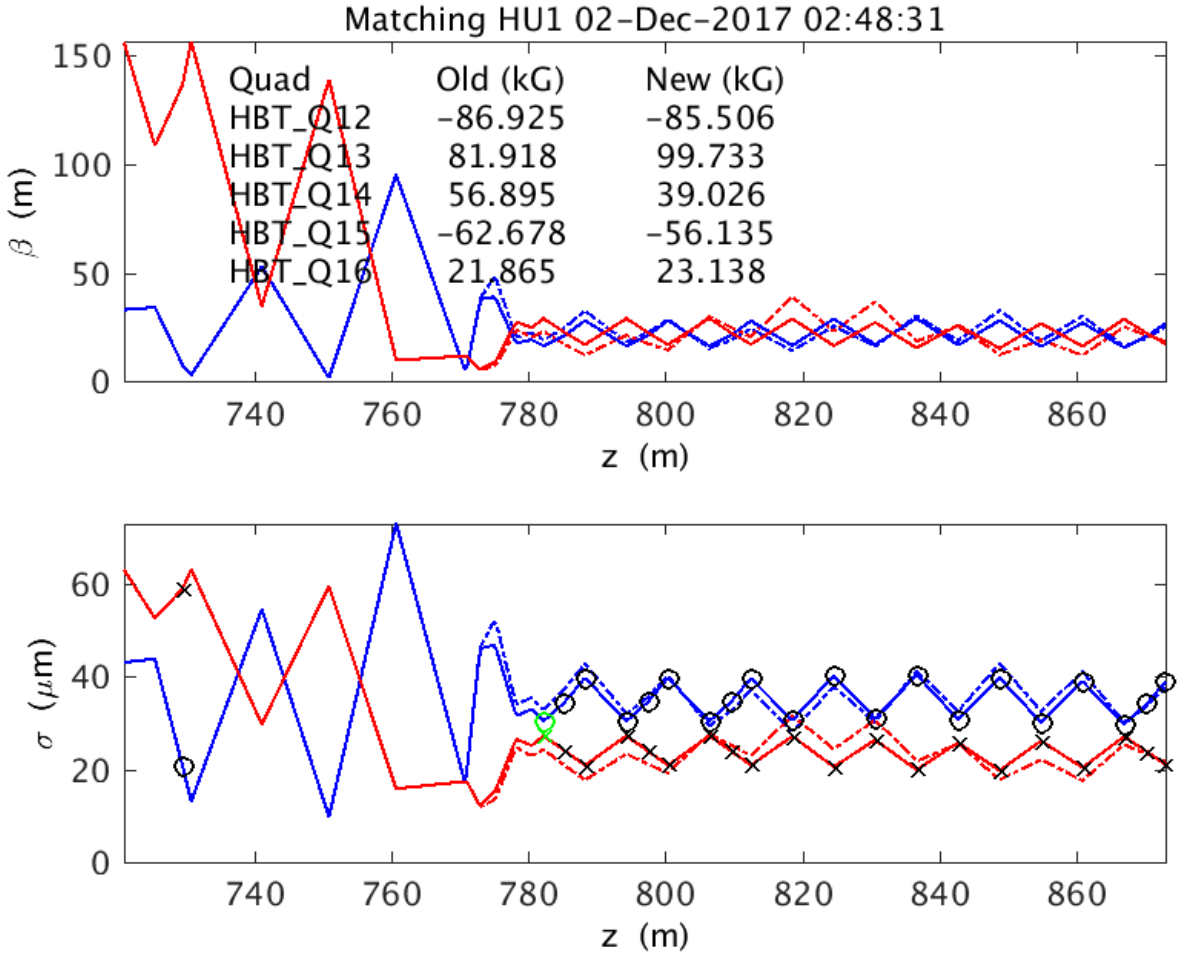




After Lattice Matching in Undulator

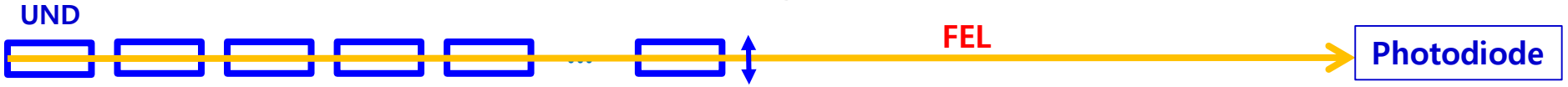


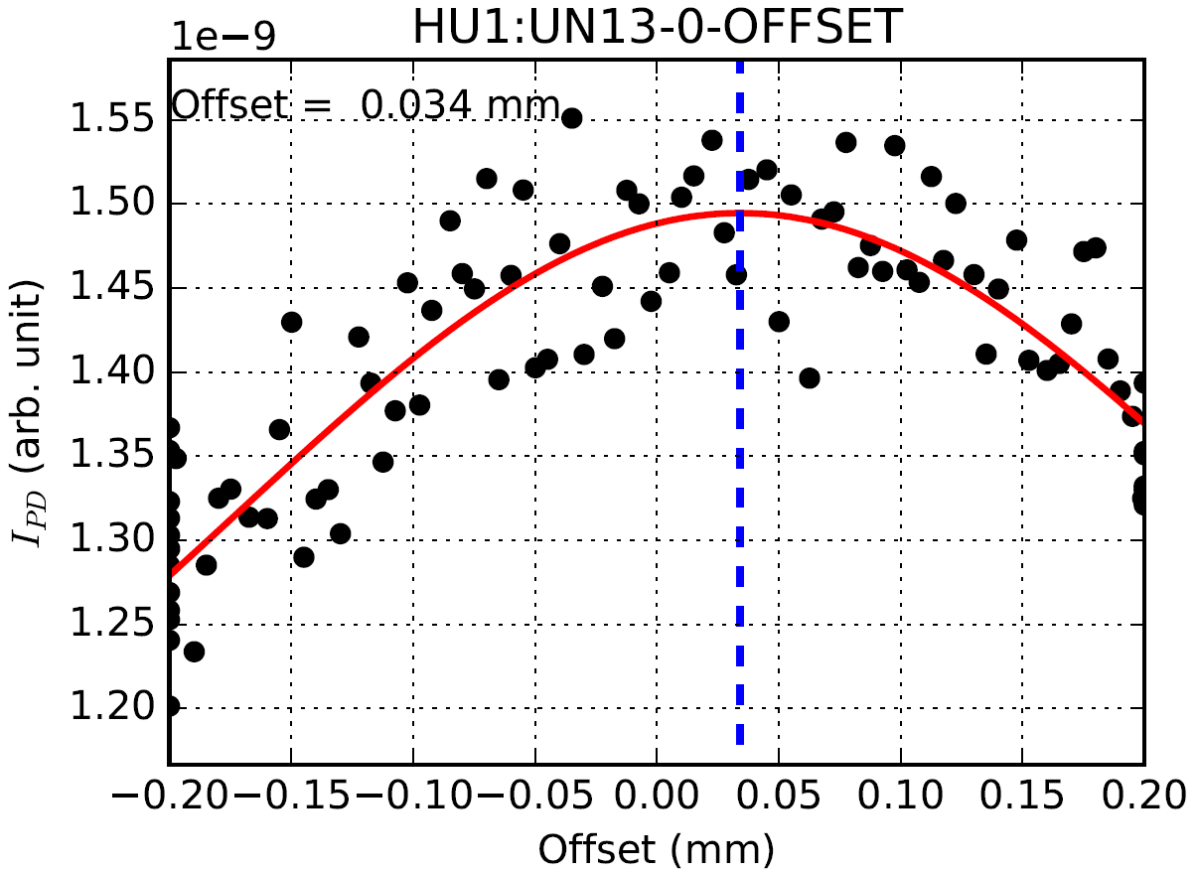




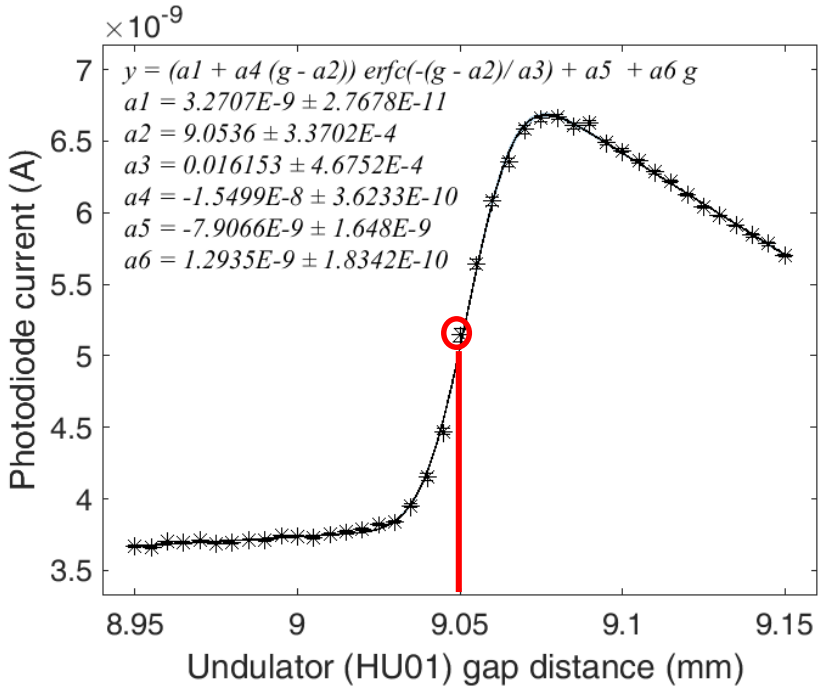
Undulator Offset Tuning

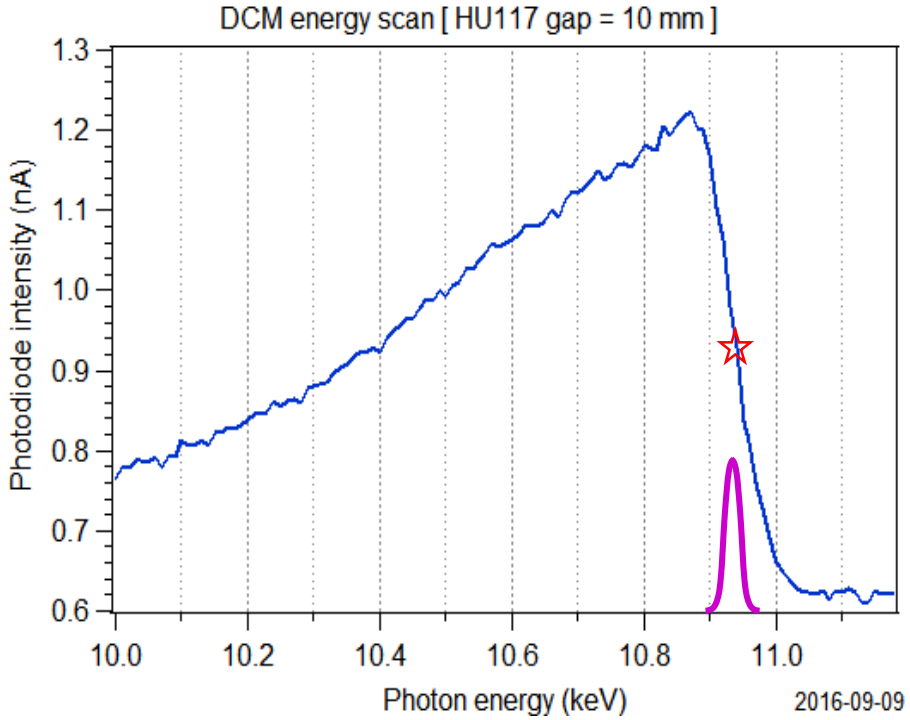
- Finding of an undulator mid-plane by vertical offset scan
- To use the optimum field region in an undulator



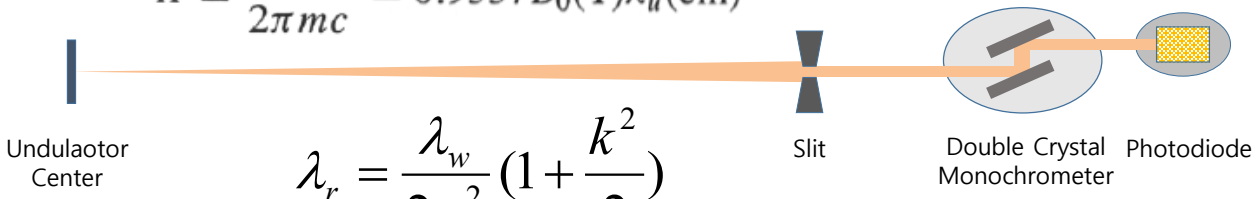


Undulator Gap Tuning





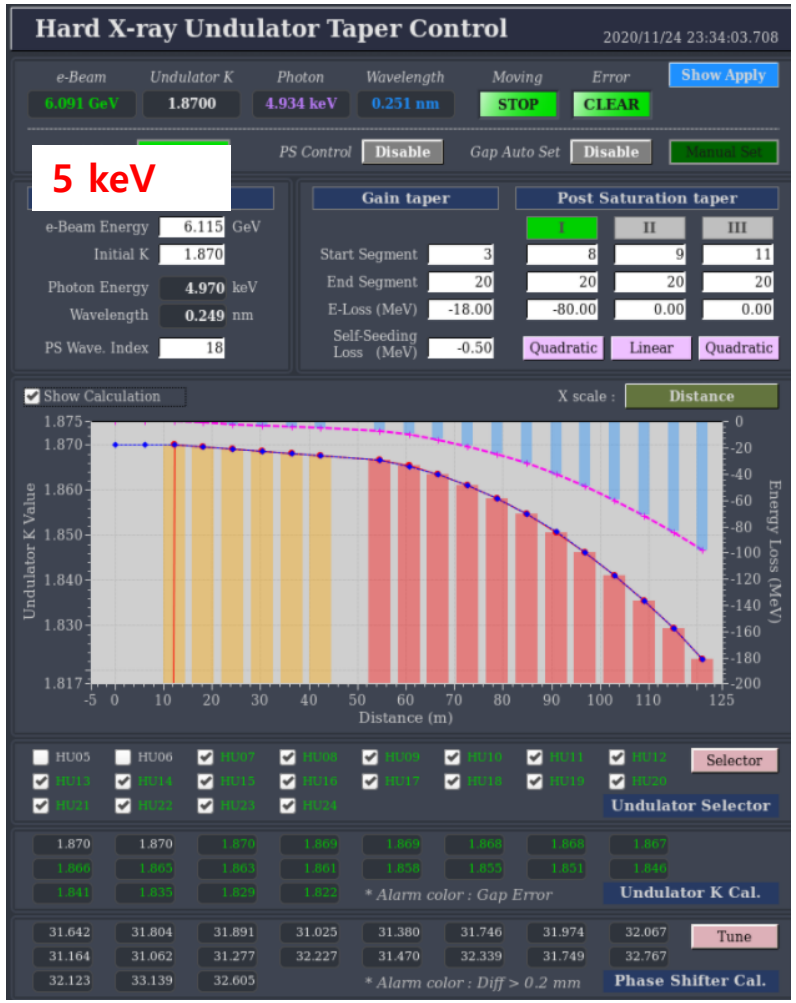
$$K \equiv \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0(\mathrm{T})\lambda_u(\mathrm{cm})$$



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

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

Undulator Tapering Tuning



Phase Shifter

Phase shifter delays the path of electron beams compared to FEL radiation.

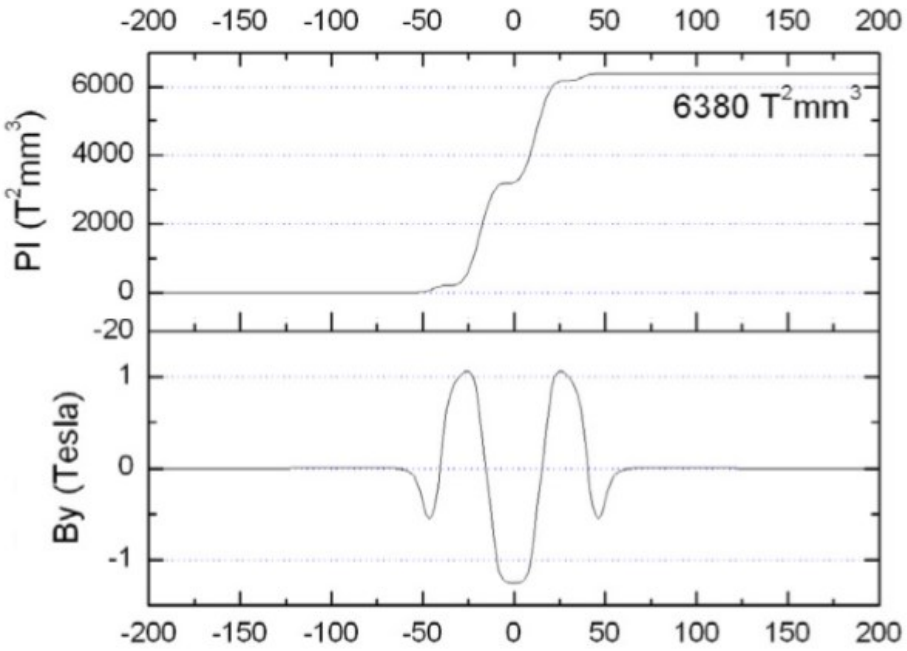
Scanning the phase shifter is a control option for phase delays of electron beams.

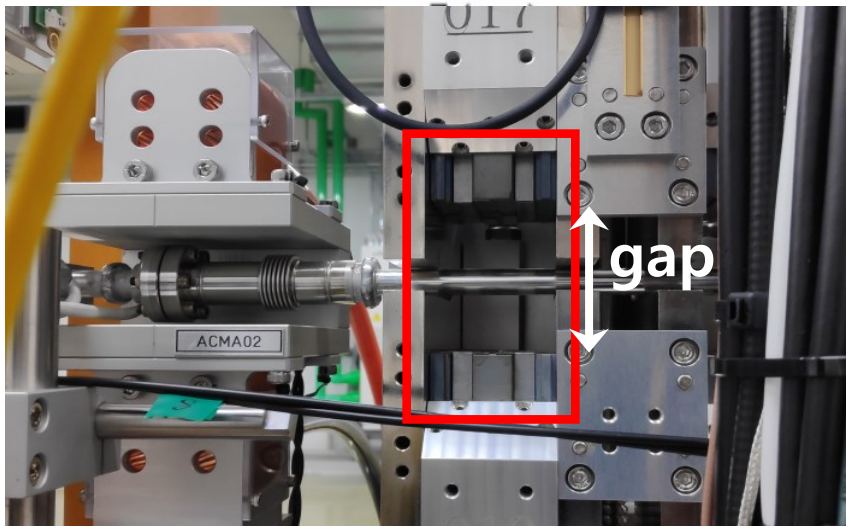
$$PI_{\mathrm{PS}} = \int_{-\infty}^{\infty} \left(\int_{-\infty}^{z''} B_{\mathrm{y}}(z')dz' \right)^2 dz''$$

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

PI_{PS} : the phase integral

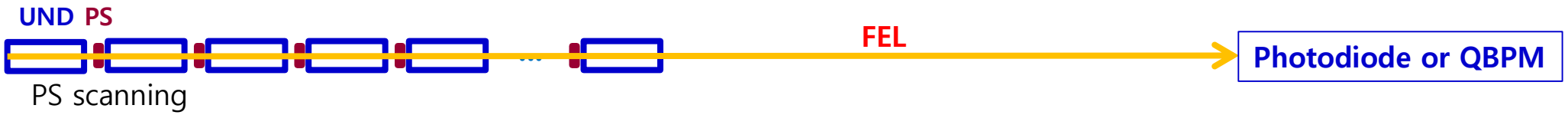
s : the delayed distance

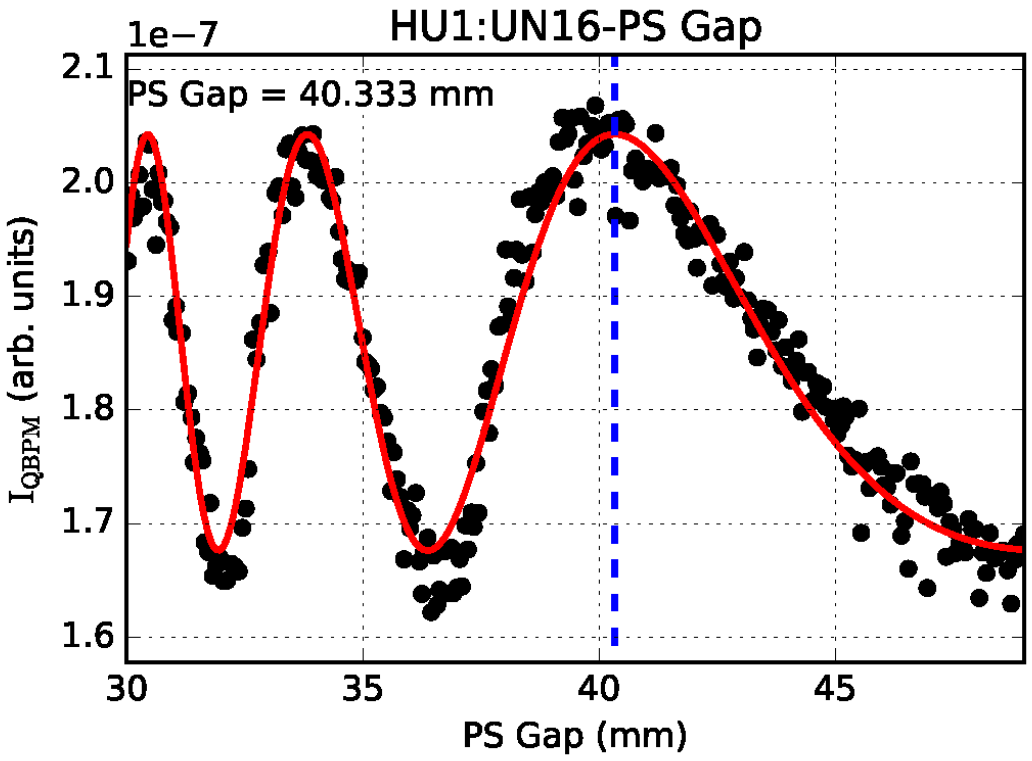




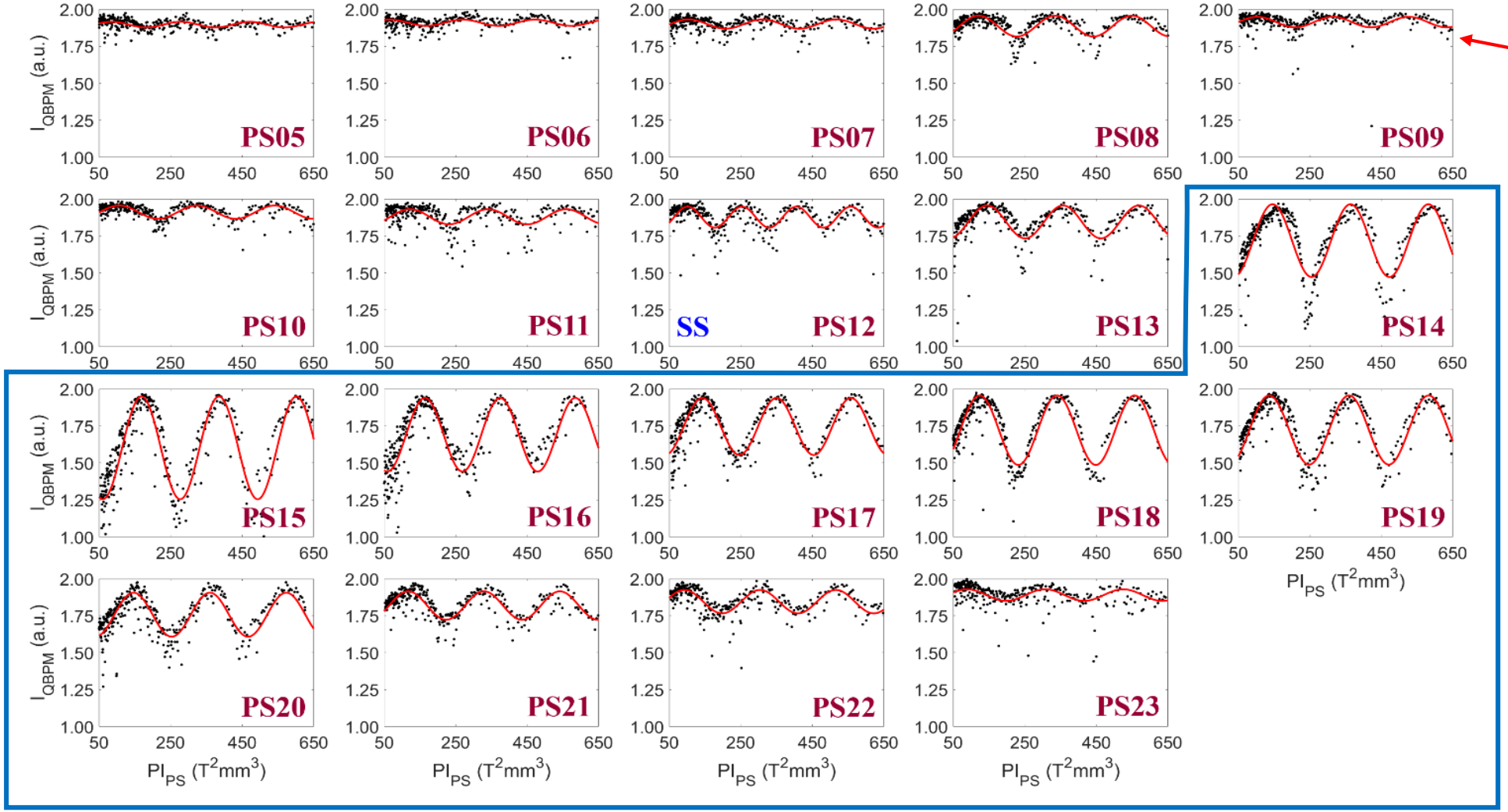
Phase Shifter Gap Tuning

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





Phase Shifter Scan

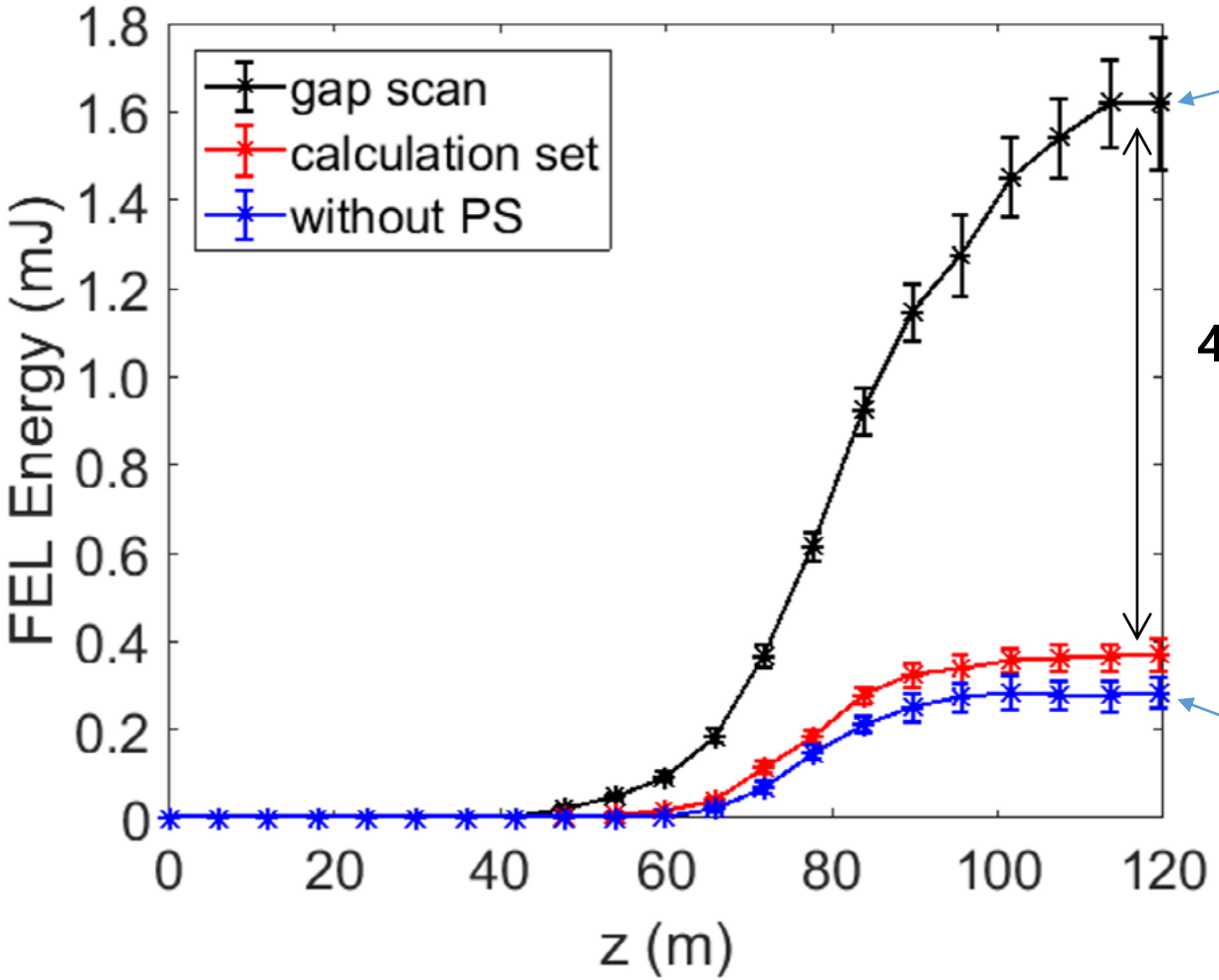


Sinusoidal fitting

Saturation region

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

FEL Optimization using Phase Shifters



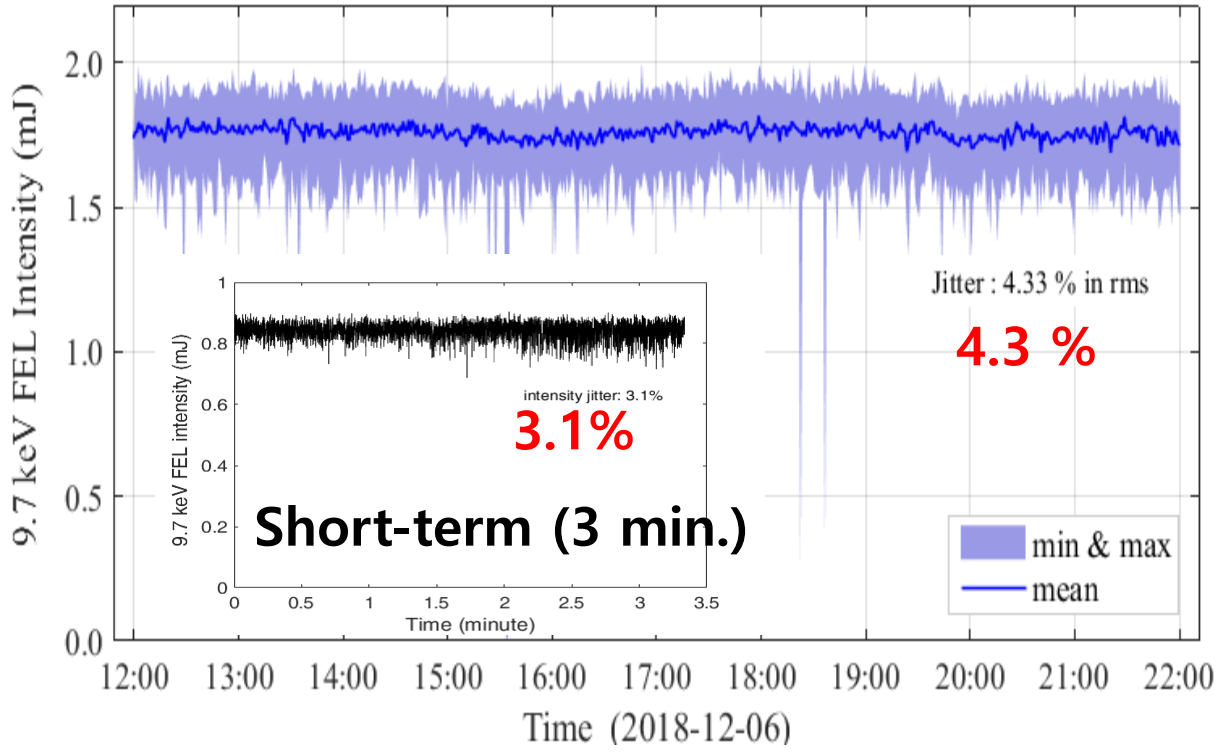
Phase shifter scan

4 times enhancement

Phase shifters are fully opened.

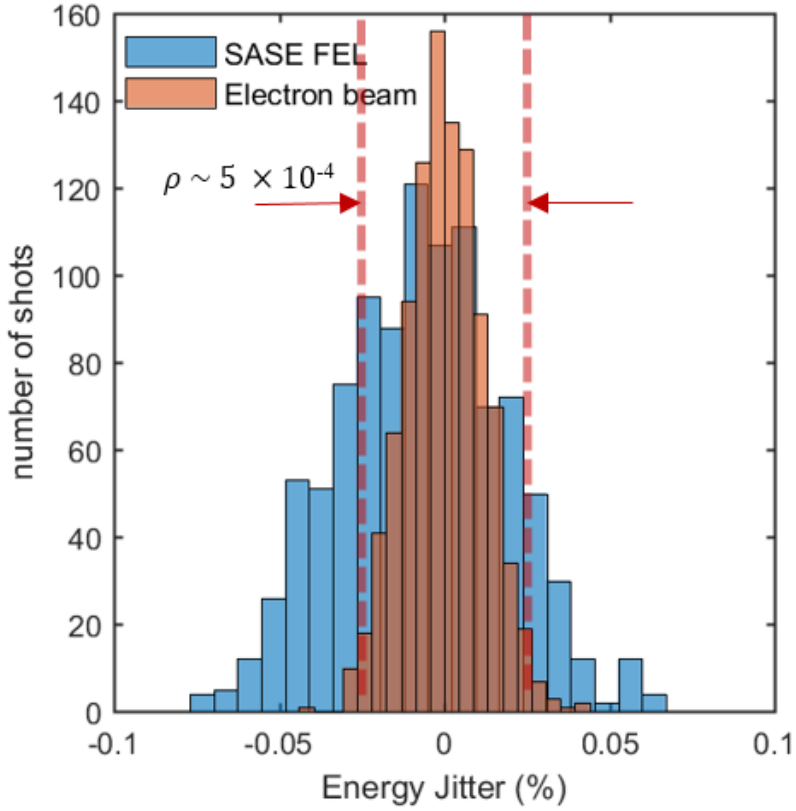
Pulse Energy Statistics

Long-term (10 hour)



- FEL beam pulse duration 24.7±0.7 fs (FWHM)
- M_L ($\approx {}^{24.7}/_{0.22}$) 112
- Fluctuations after saturation 3.2%

Photon and electron energy jitter



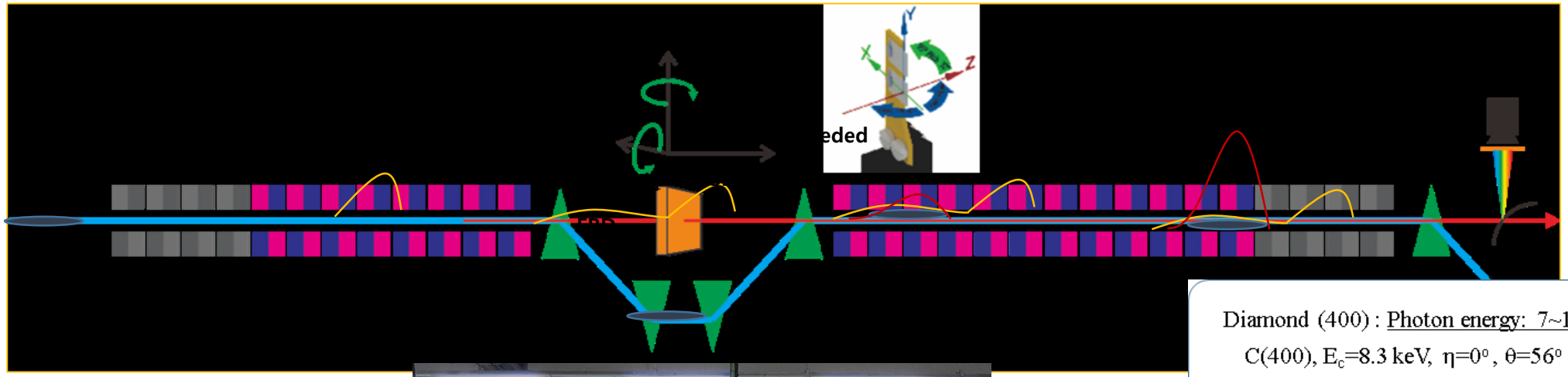
Electron jitter: 0.012% rms
Photon jitter: 0.025% rms

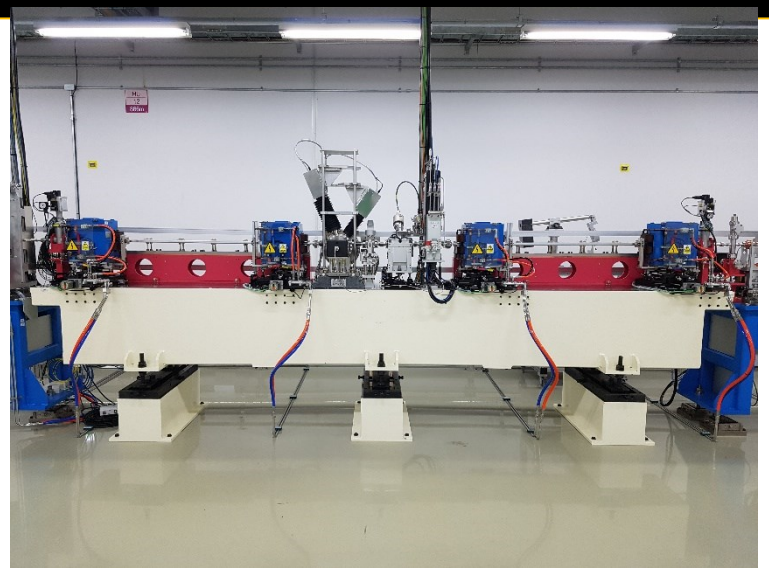
Self-Seeding Project History

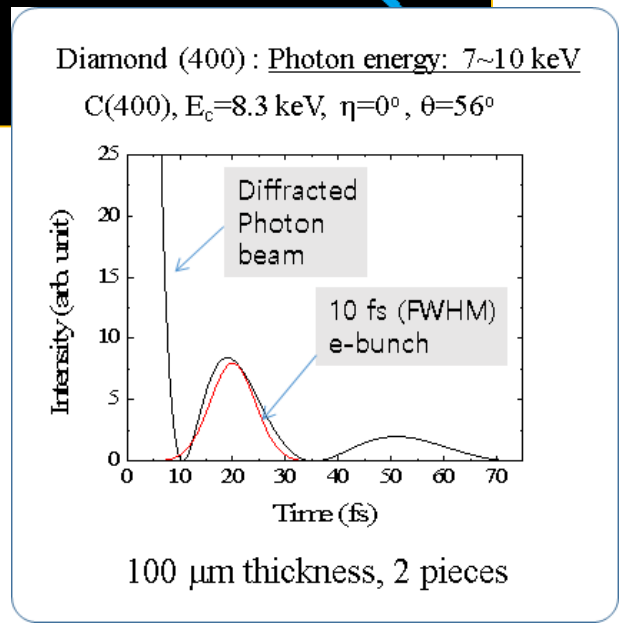
- Collaboration with APS/USA, LCLS and TISNCM/Russia
  - Design of Diamond crystal monochromator by APS
  - Diamond crystals fabricated by TISNCM, Russia are checked at APS for its property
  - Engineering design by PAL staff and fabrication by Korean company
  - Feb. 2018: Installation of HXSS
- Commissioning 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

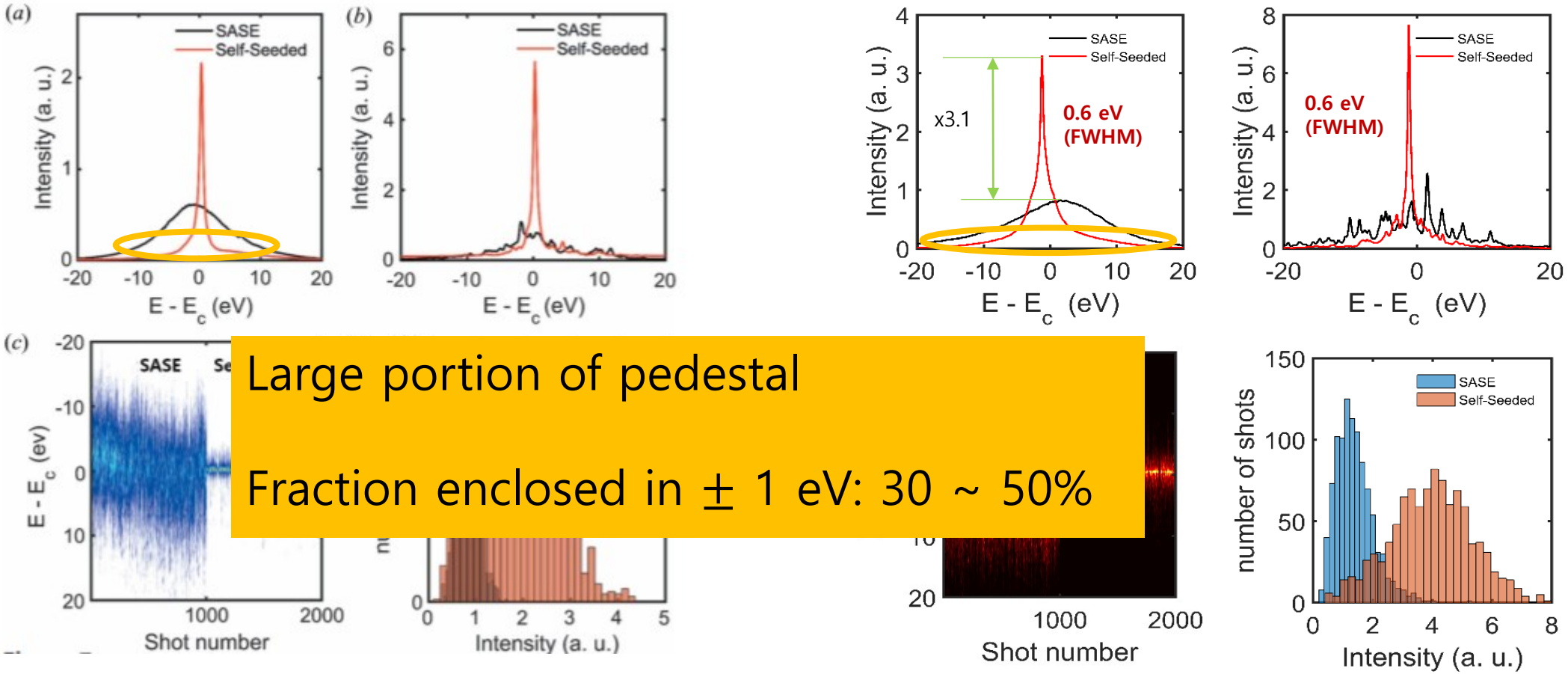
- Schematic of hard x-ray self-seeding with a diamond crystal







Previous Results (Nov. 2018)



Large portion of pedestal

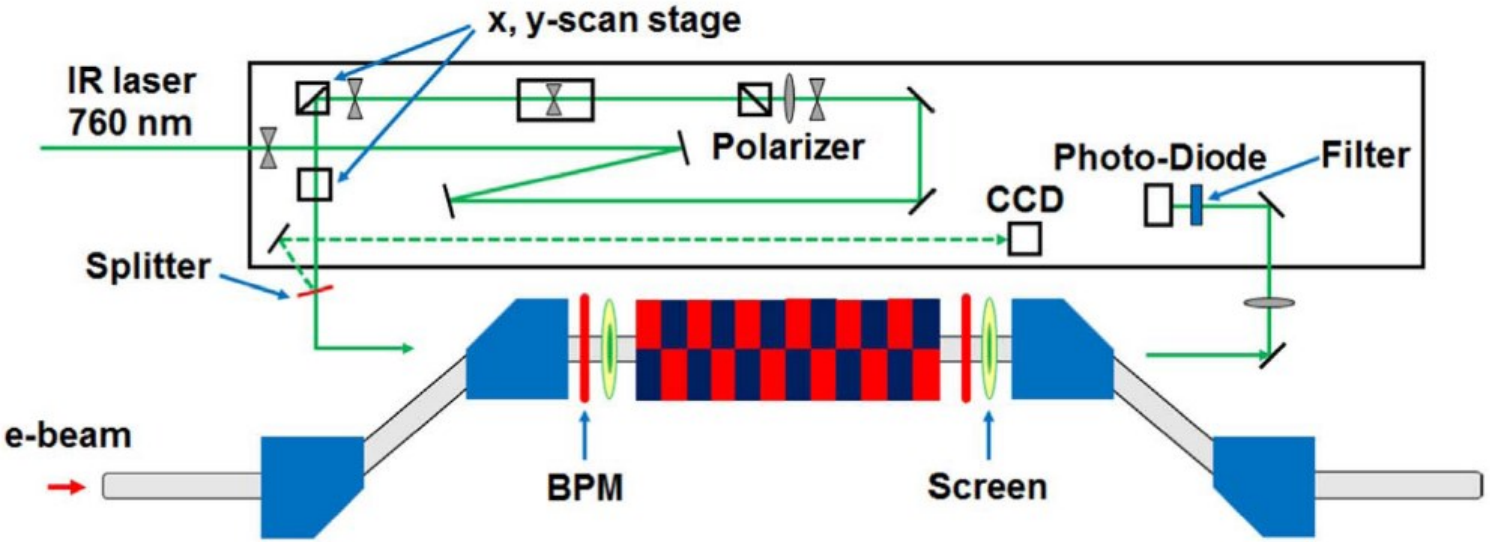
Fraction enclosed in ± 1 eV: 30 ~ 50%

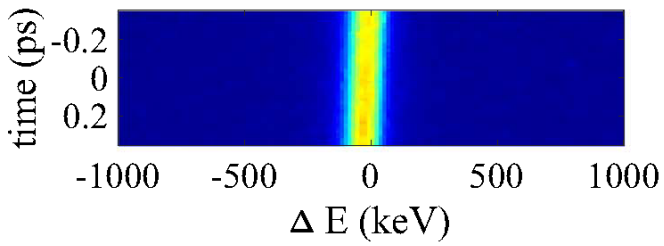
Ec = 7 keV

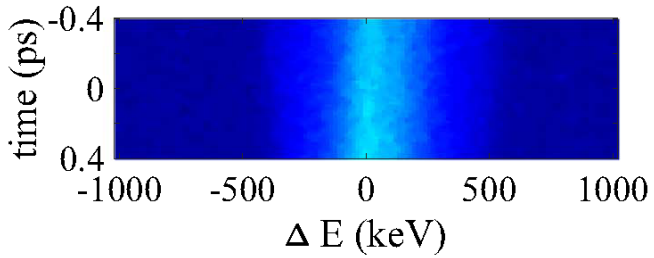
Ec = 14.4 keV

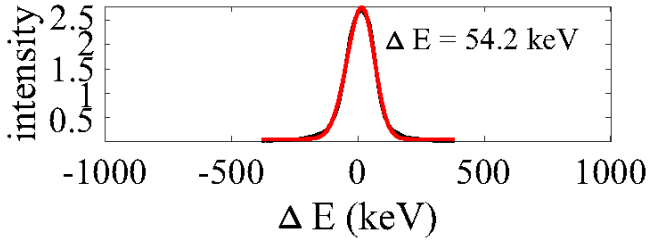
C. K. Min *et. el., J. Synchrotron Rad.* **26**, 1101 (2019)

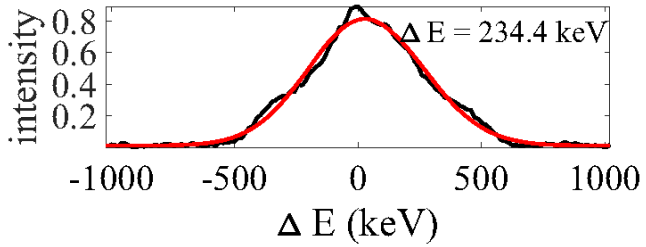
Laser Heater

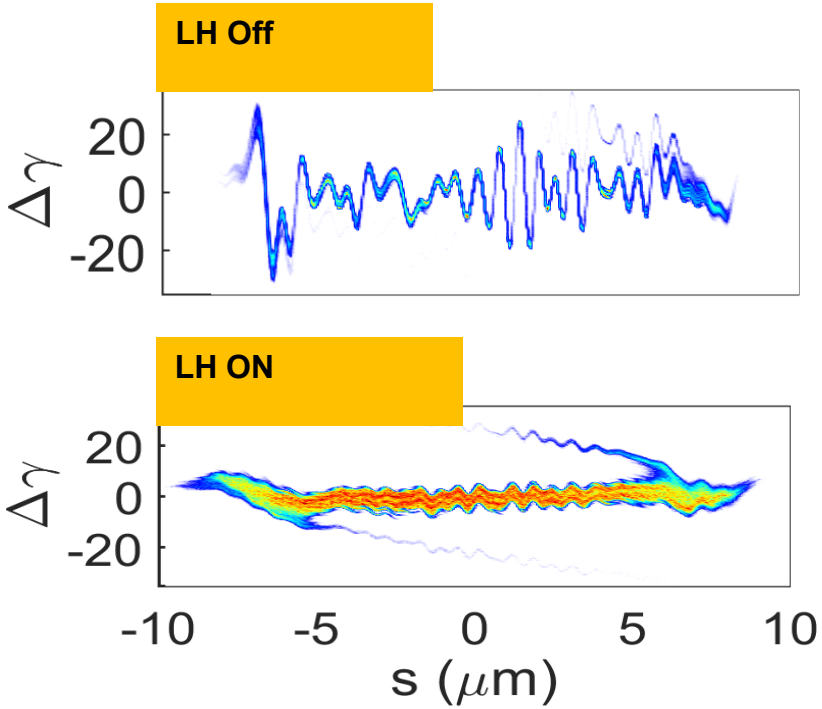






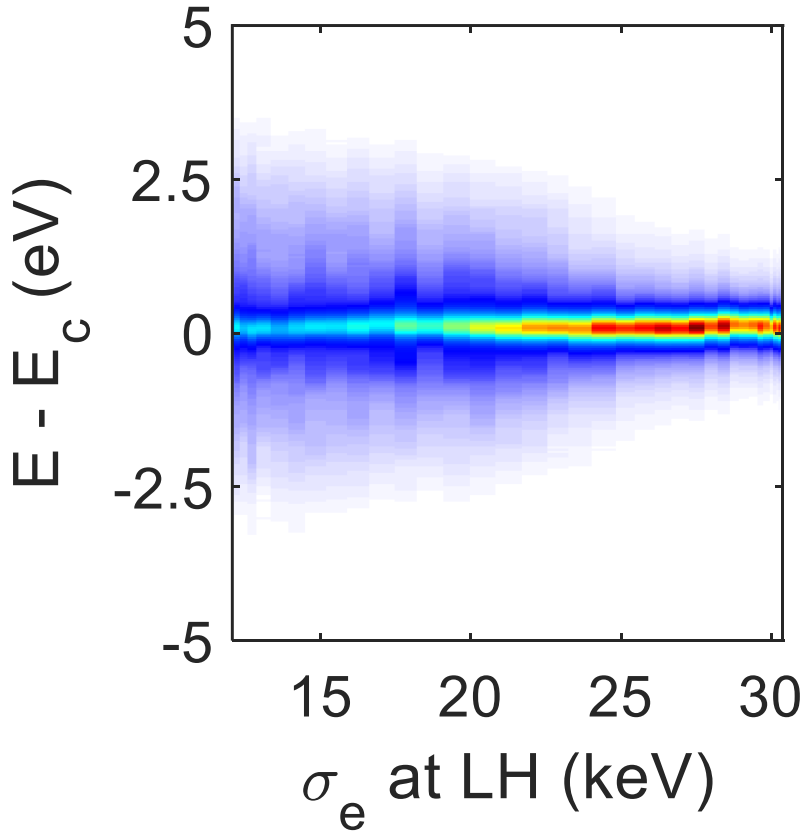


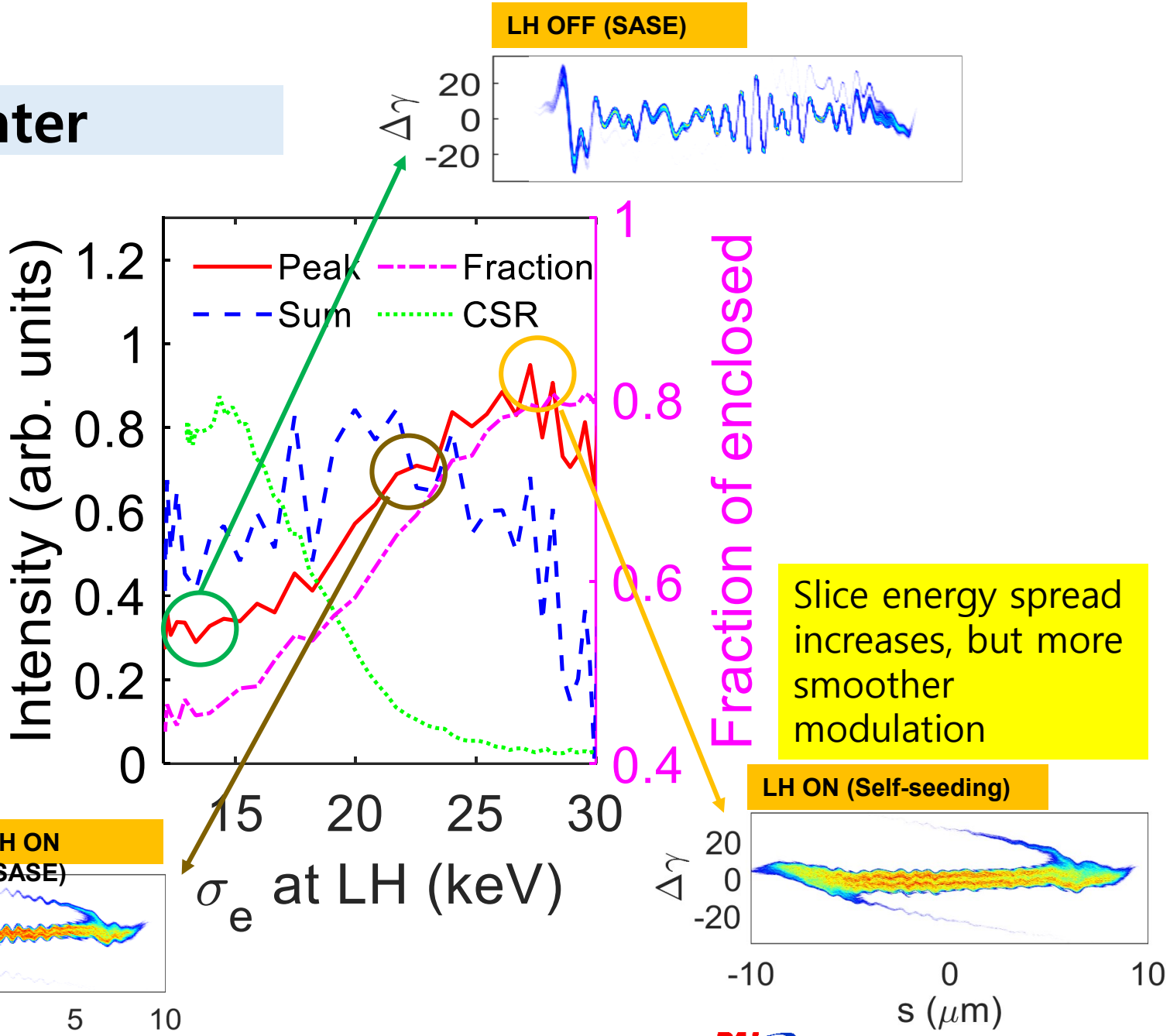




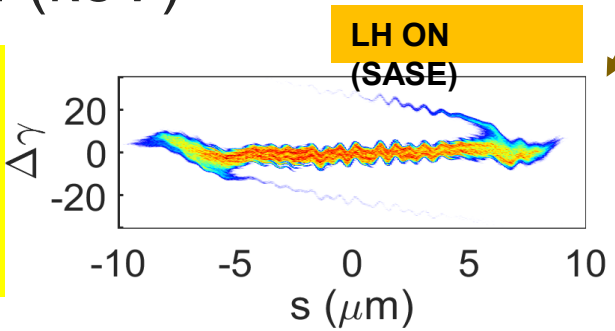
J. Lee *et al.*, *NIM A*, **843**, 39 (2017)

Seeded Peak vs Laser Heater





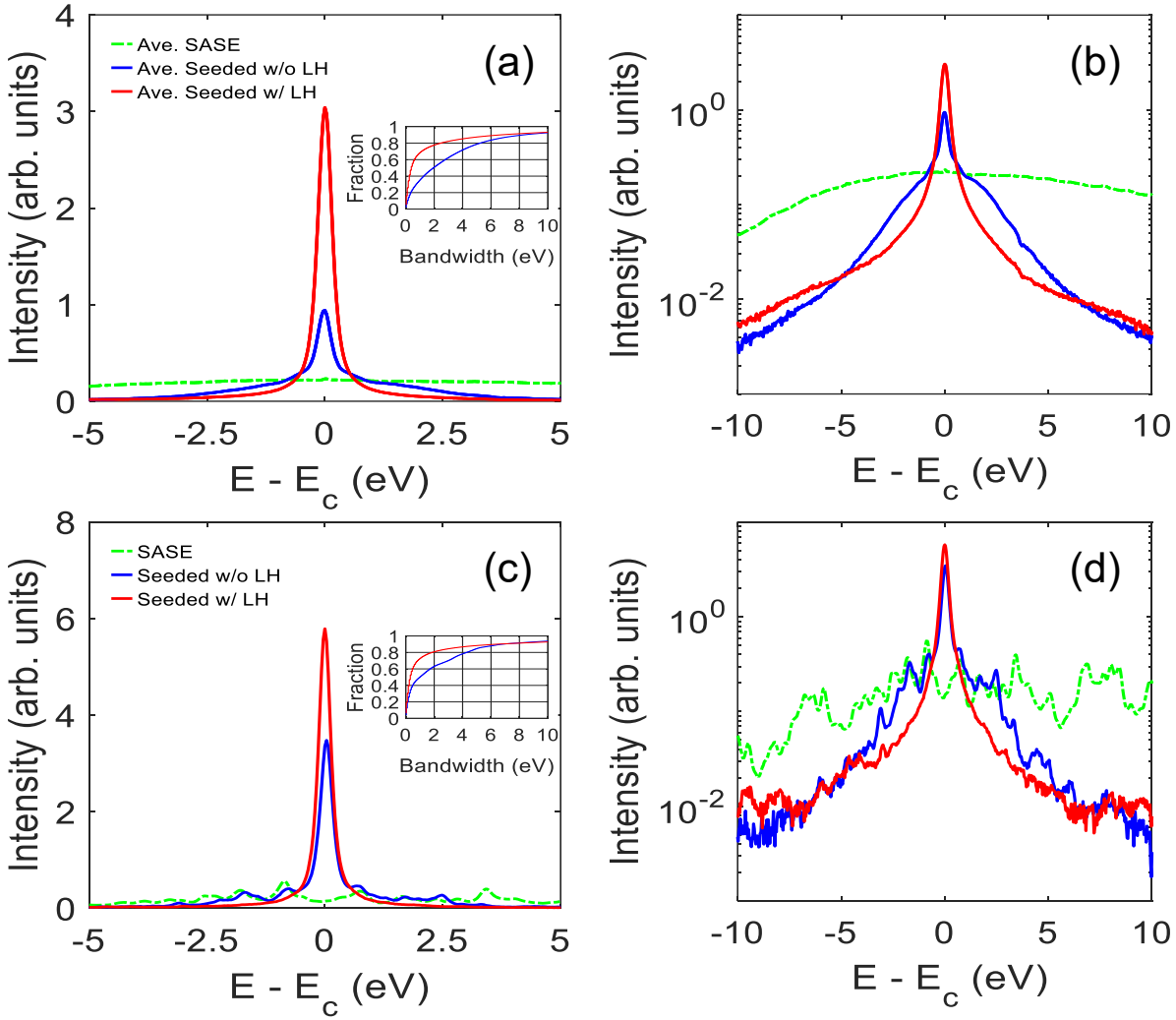
Slice energy spread increases, but more smoother modulation



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

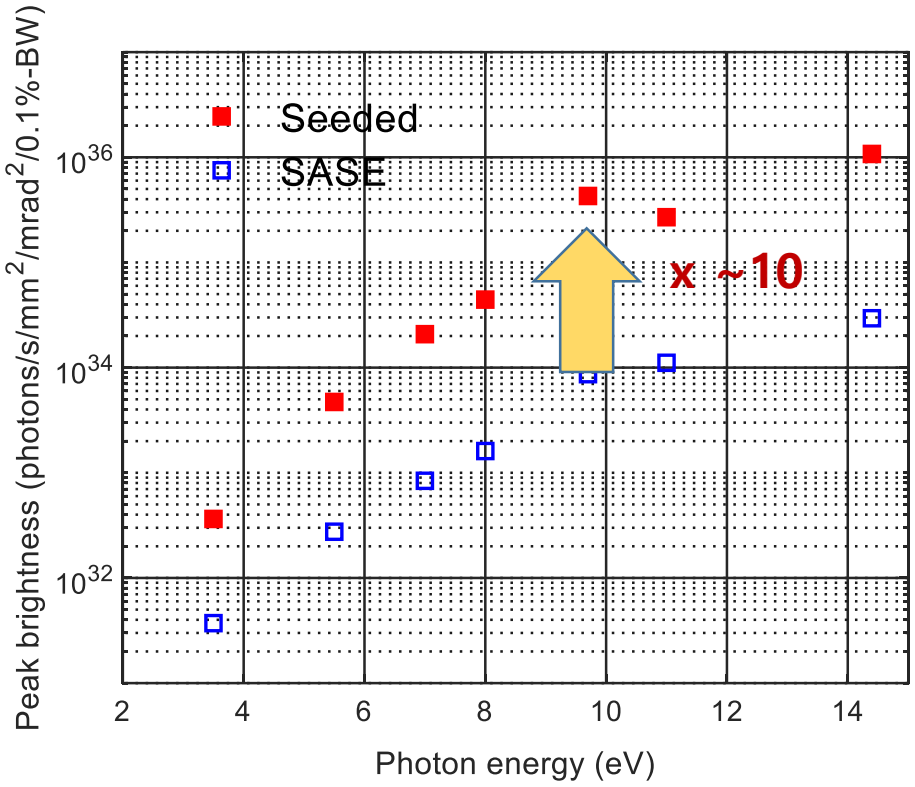
Results for Self-Seeded FEL at 9.7 keV

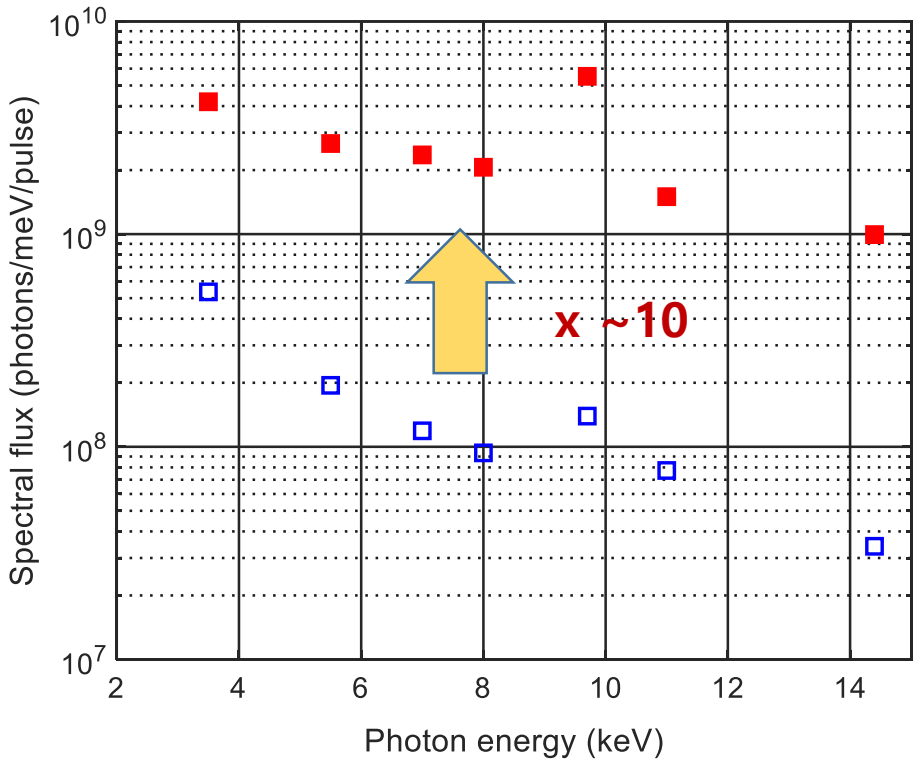
- Photon Energy Ec = 9.7 keV
- Averaged FEL energy: **~850 μJ (~1.5 mJ for single shot)**
- SASE bandwidth (FWHM) = 27 eV
- Measured bandwidth = 0.35 eV (Resolution = 0.26 eV)
- De-convoluted bandwidth (FWHM) = **0.22 eV**
- FEL Pulse duration = ~ 20 fs
- Chicane time delay = 30 fs
- Bragg orientation = [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

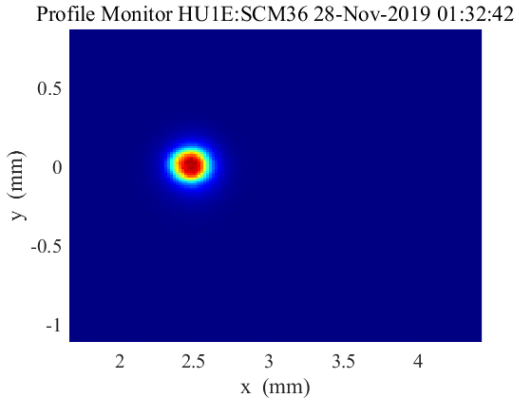




- **For self-seeded FEL, almost one order of magnitude of the peak brightness and spectral flux is enhanced compared to that of the SASE mode**

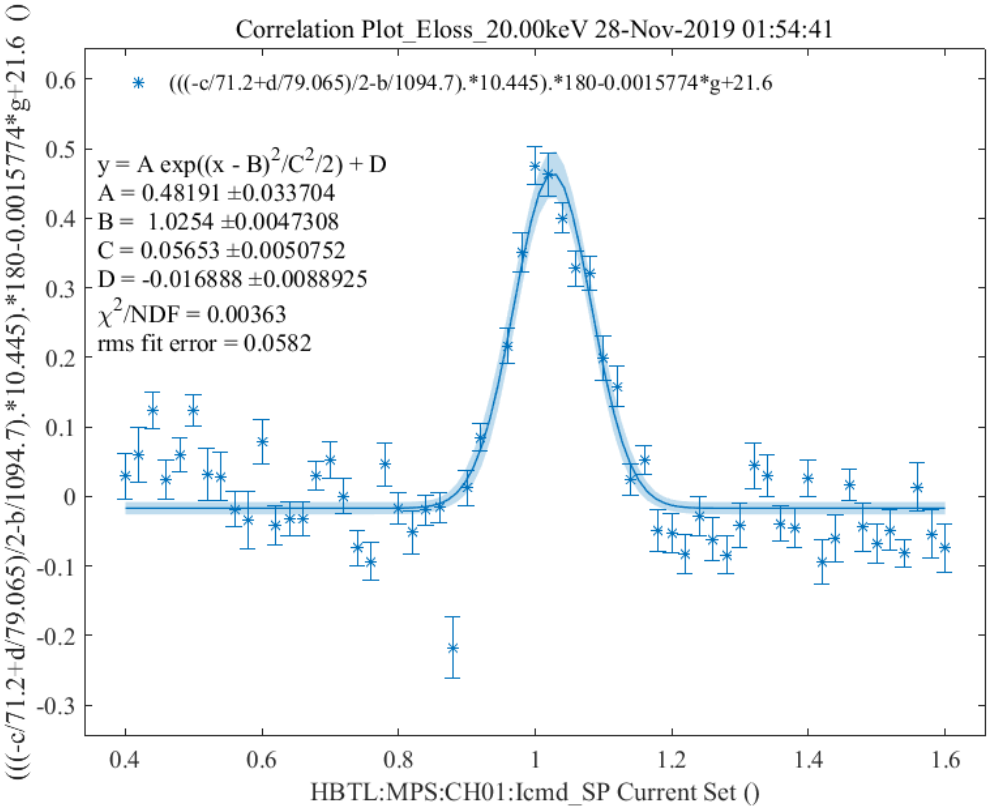
I. Nam *et al., Nature Photonics* (2021)

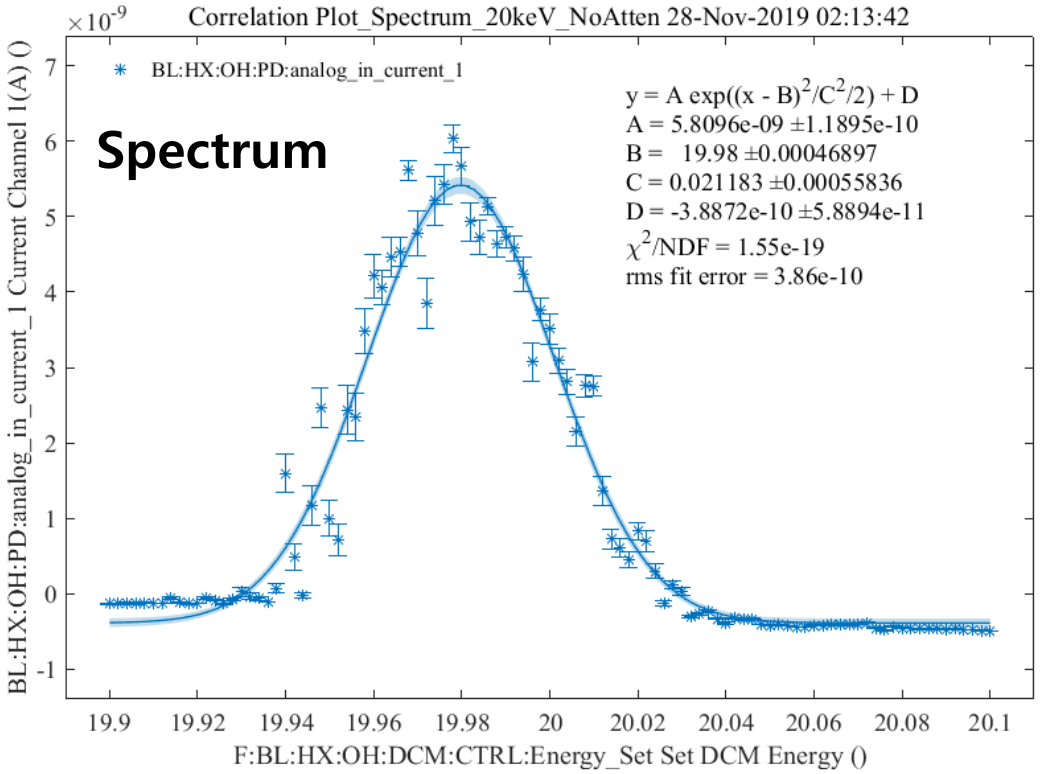
Extending FEL Range up to 20 keV



(YAG) screen monitor located 42m downstream from the last undulator

E-loss measurement



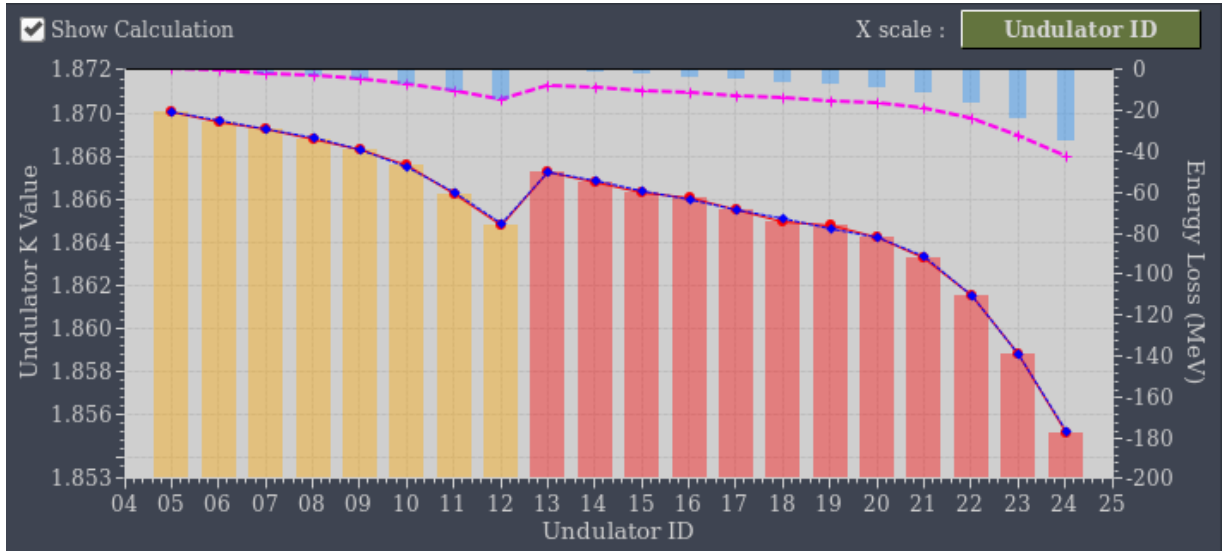


FEL Pulse Energy: ~0.48 mJ
Undulator K = 1.409
E-beam energy: 10.446 GeV (K=1.87 for 14.5 keV)

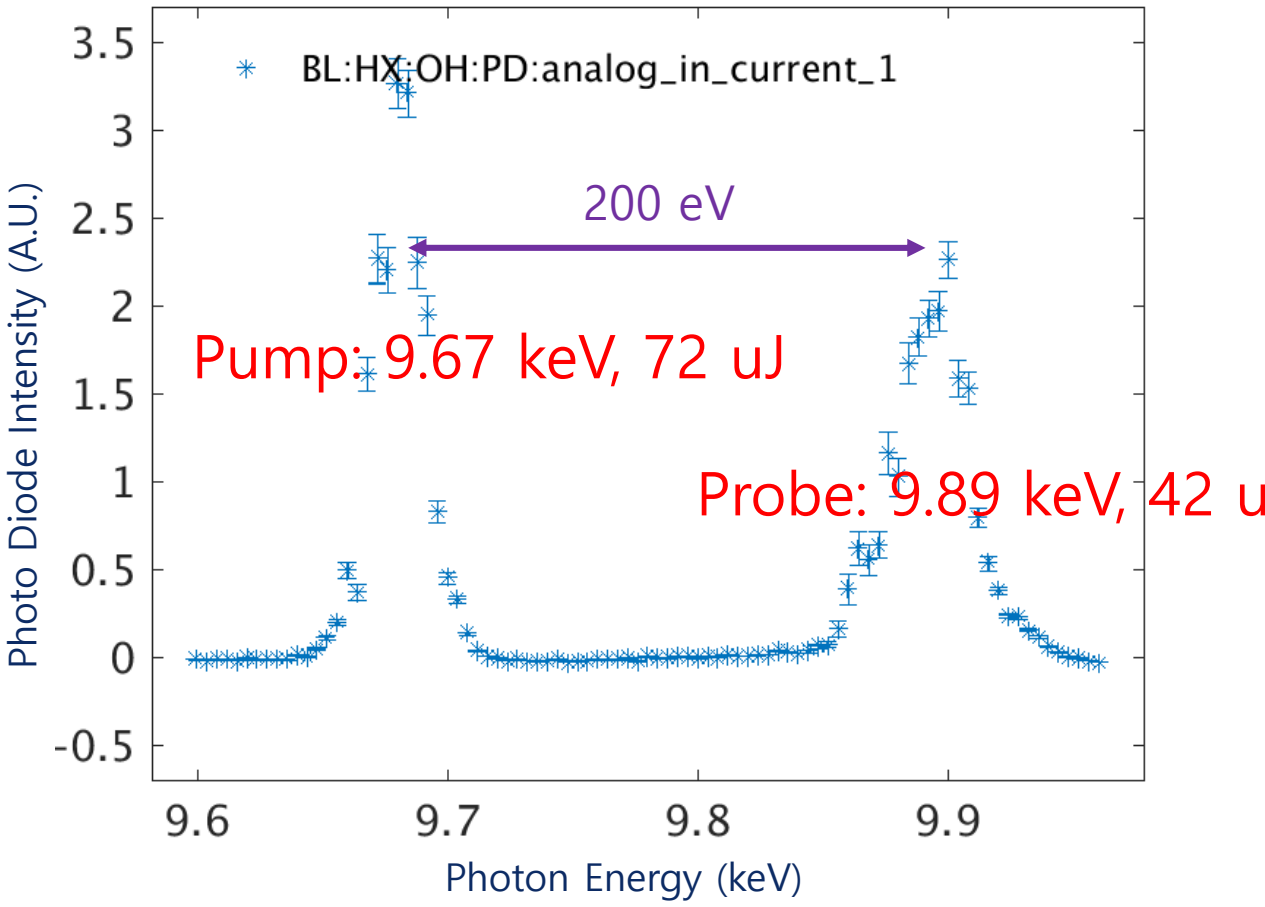
Bandwidth: ~ 21.2 eV (rms)

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

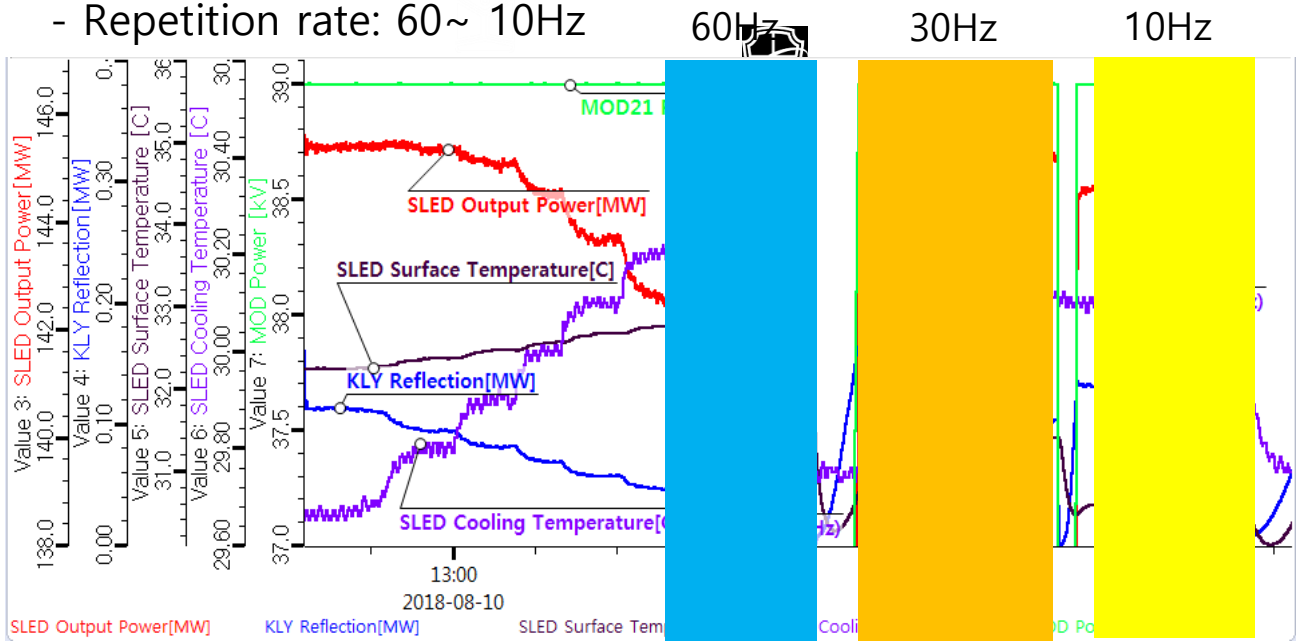


Photon Energy Measurement Result of Two-Color FEL

Energy Doubler (SLED) Tuning for 10, 30, 60 Hz Operation

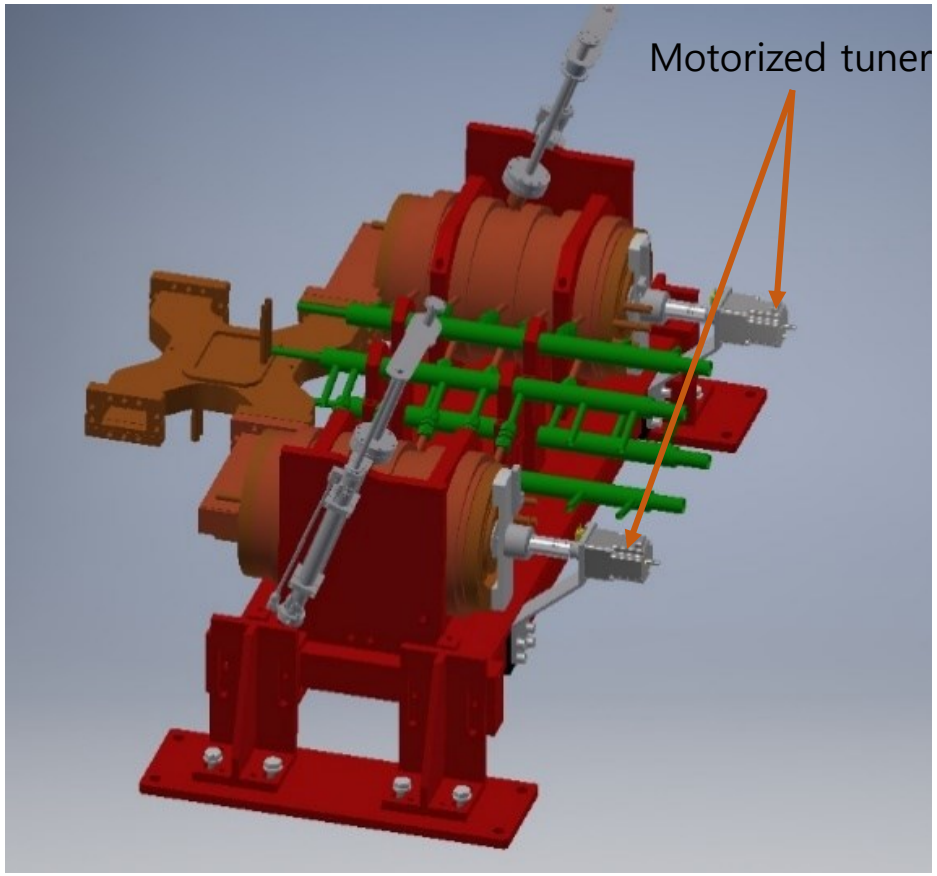
❖ **Cooling water temperature control of energy doubler (SLED)**

- Repetition rate: 60~ 10Hz



- SLED can be simply tuned from 10 Hz to 60Hz by water temperature control after one time mechanical tuning.

  1. 60Hz: SLED temperature 0℃ (27.75 ℃)
  2. 30Hz: SLED temperature 0.4 ℃ ↑ (30.15 ℃)
  3. 10Hz: SLED temperature 0.55 ℃ ↑ (30.30 ℃)



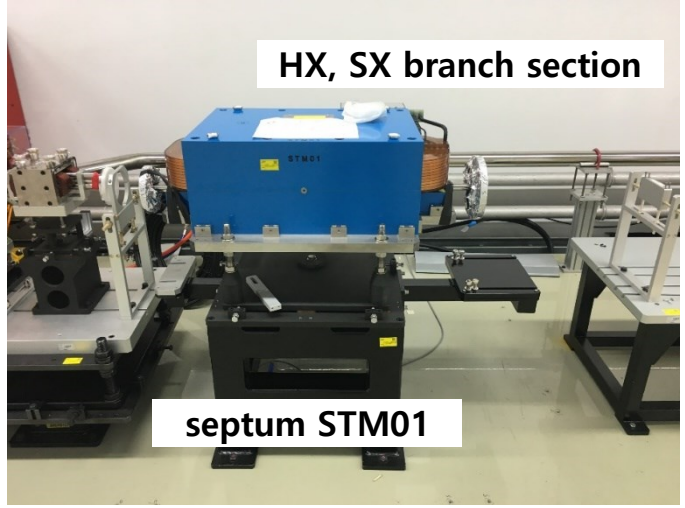
3D Design of Energy Doubler

Simultaneous Operation of HX and SX

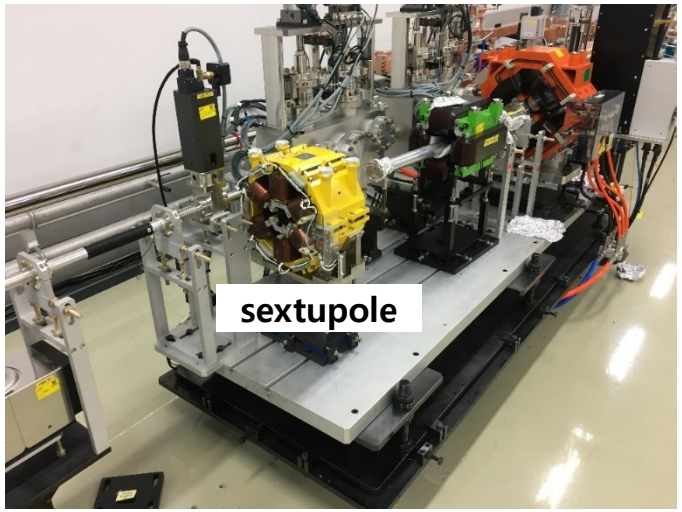
- We have completed modifying SX branch line during Feb. 2020.
- The optics of the new kicker-SX branch line was confirmed by using a DC kicker magnet power supply.
- The pulsed switching FEL operation at a low repetition rate (2 Hz) with an AC kicker power supply was succeeded on August 2020.
- The preparation of the HX-SX sharing mode operation by using a 60 Hz pulsed kicker is ongoing.

Magnets for HX-SX Parallel Operation (Continued)

Magnets ready for field measurements



Magnet measurements with Hall probe



User Beamtime Operation Status

2020 Beamtime summary

- User beamtimes between Mar 25 through May 12 were moved to Jun 28 through Aug 30.
- Maintenance schedules in summer shut-down were minimized.
- 170 days of user beamtime was maintained.
- Remote experimental supports (so called “mail-in service”) were provided for foreign users.

2021 Beamtime operation

- From 2021, remote experimental support (so called “mail-in service”) is no longer available.
- At least two users are mandated to participate for sample handling and conducting experiments.
- User beamtime will resume in March after one month of regular maintenance period.

Thank you for your attention!