Beam-based optimization at PAL-XFEL

to maximize FEL intensity

Chi Hyun Shim

on behalf of XFEL Accelerator Department

PAL 포항가속기연구소
POHANG ACCELERATOR LABORATORY

Outline

- Introduction of PAL-XFEL
- Optimization with uncompressed electron beam
  - Beam-based alignment for undulator line
  - Undulator offset alignment / undulator gap alignment
- Optimization with compressed electron beam (~ 3 kA)
  - Lattice matching for linac and undulator line
  - Undulator tapering / phase shifter gap tuning
- Summary

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)

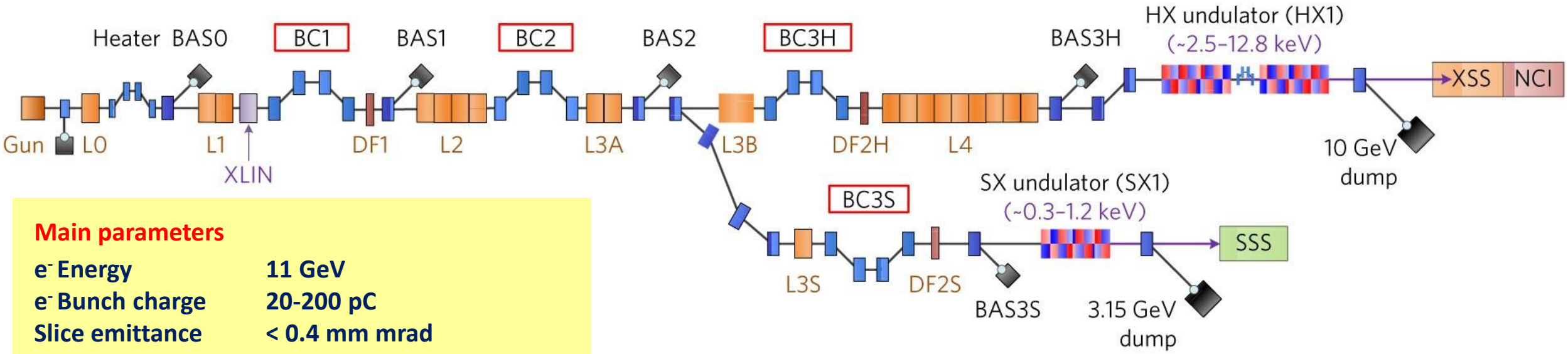
2019: 160 days for user (96.8% of availability)

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)

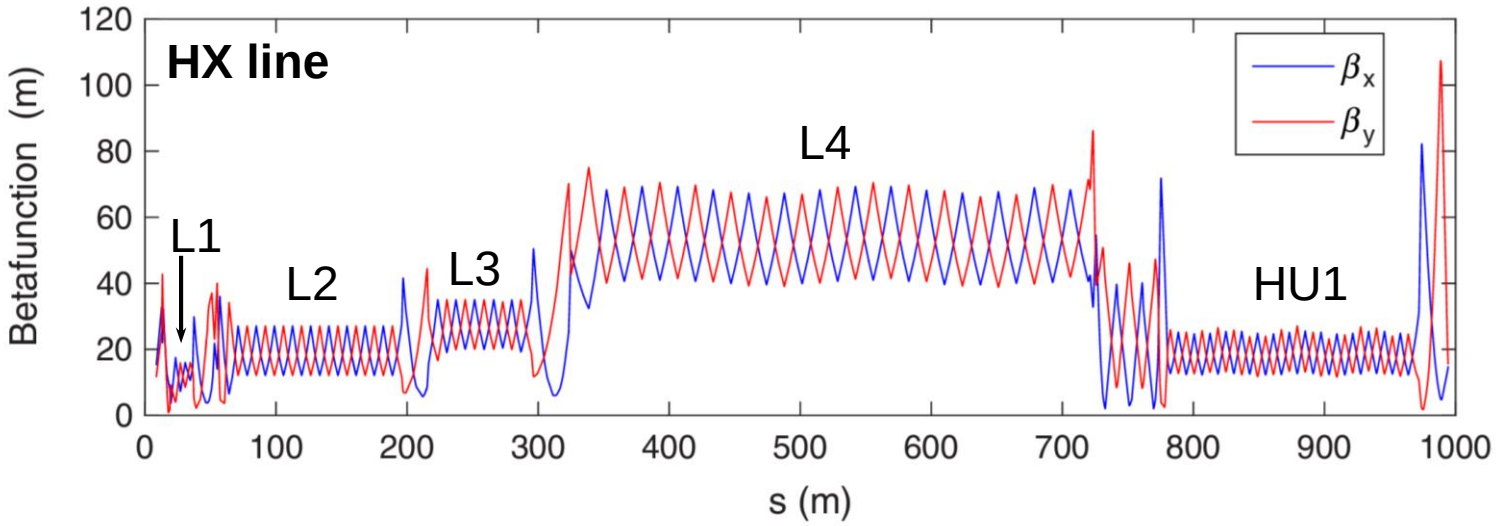
PAL-XFEL Layout & Parameters



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
Und. Period / Gap [mm]	26 / 8.3	35 / 9.0



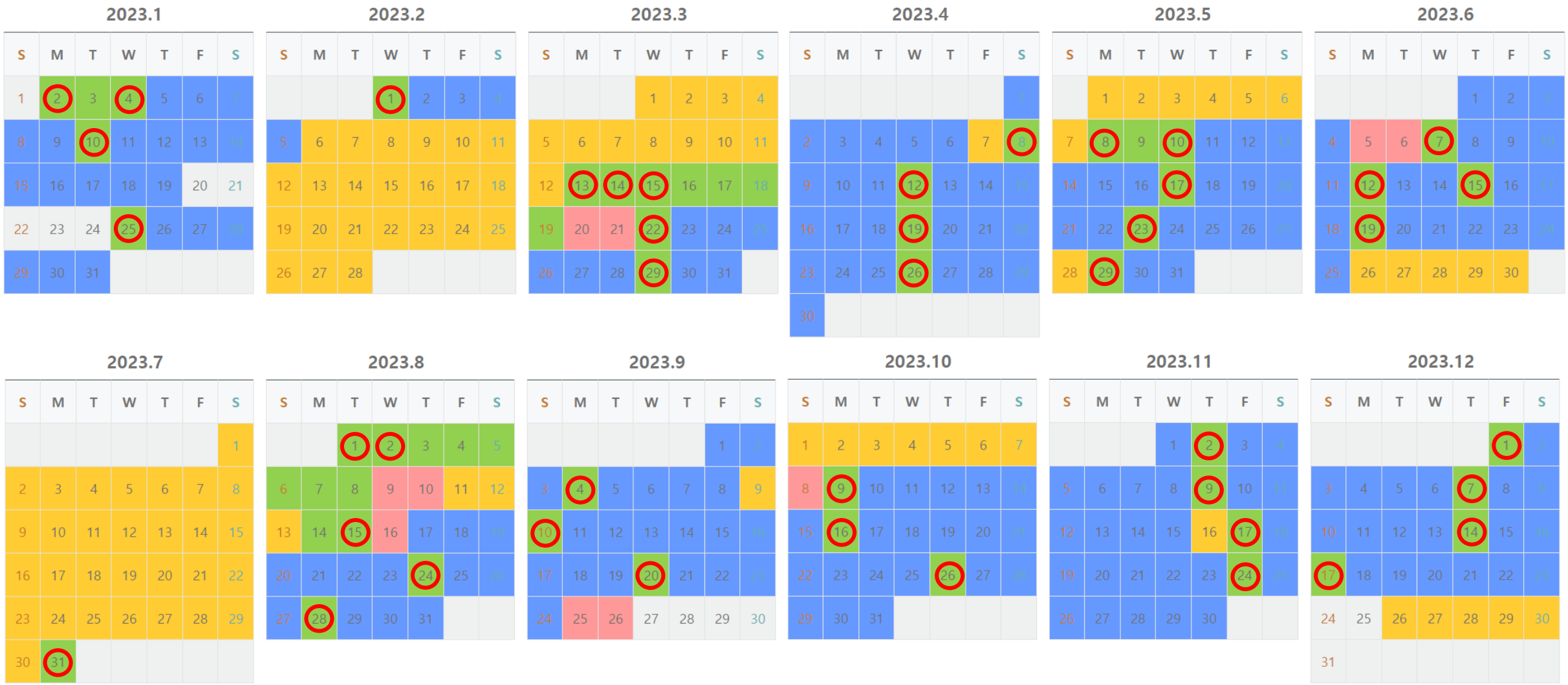
Procedure of beam-based optimization

- ✓ **Uncompressed beam (on-crest acceleration)**
  - ✓ **Undulator beam-based alignment with different beam energies [~2h]**
  - ✓ **Undulator vertical offset alignment (Undulator field center) [~30m]**
  - ✓ **Undulator gap alignment (K tuning) [~30 m]**

- ✓ **Compressed beam (off-crest acceleration)**
  - ✓ Preparing initial setting for specific photon energy [~1h]
    - ✓ Laser for photocathode gun, beam energy, magnet PS, rf phase, BC1 collimator
  - ✓ **Lattice matching for linac and undulator line [~2h]**
  - ✓ **Undulator tapering [~30m]**
  - ✓ **Phase shifter gap tuning [~30m]**

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

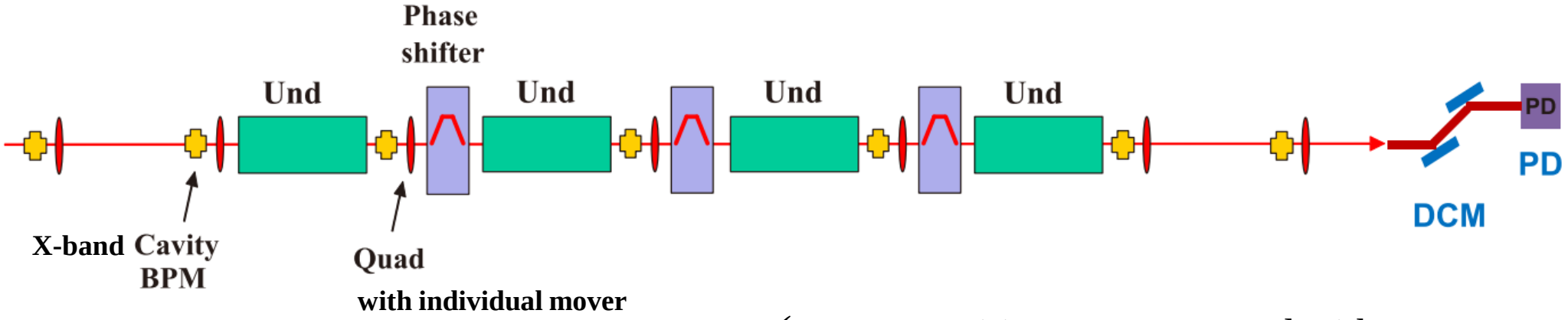
PAL-XFEL operation schedule

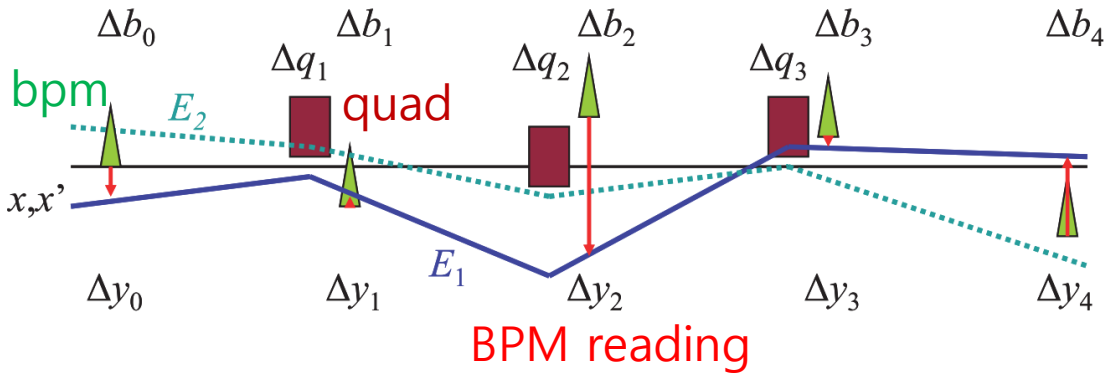


Beam-based optimization process is always performed after the end of maintenance and before the start of user beam time.

Undulator beam-based alignment

P. Emma, R. Carr, and H.-D. Nuhn, NIMA **429**, 407 (1999)
H.-S. Kang, H. Loos, PRAB **22** 060703 (2019)



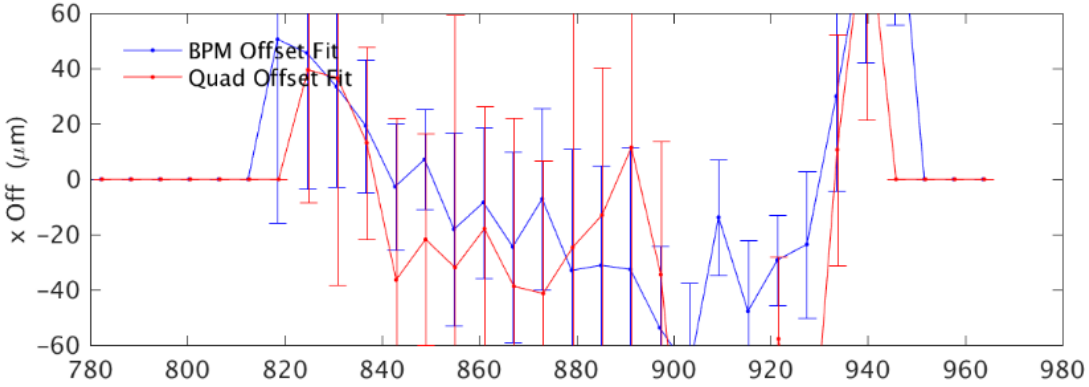


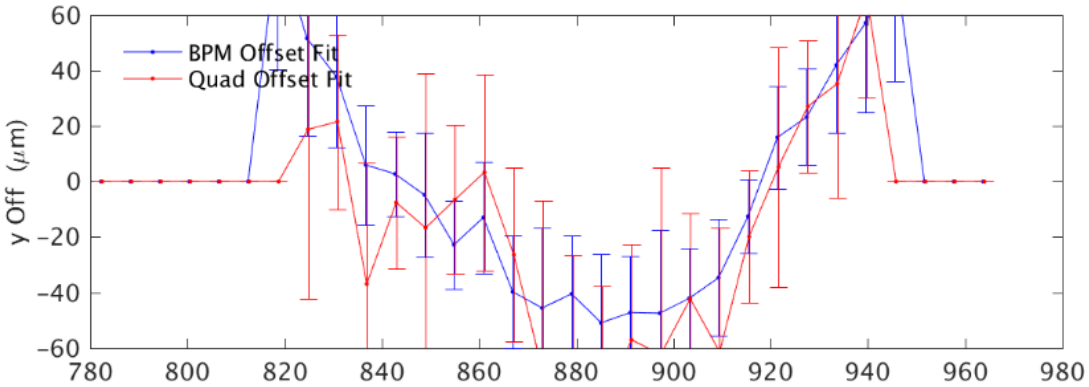
- ✓ Beam positions are measured with BPMs at four different beam energy: 4, 5, 6.6, 10 GeV
- ✓ BPM offsets and quadrupole mover offsets are calculated based on the response matrix of lattice and applied to get dispersion-free straight orbit

- ✓ During undulator BBA, all correctors in HU1 section are turned off, all undulators are closed (minimum gap) and quadrupole strength is fixed for every beam energy

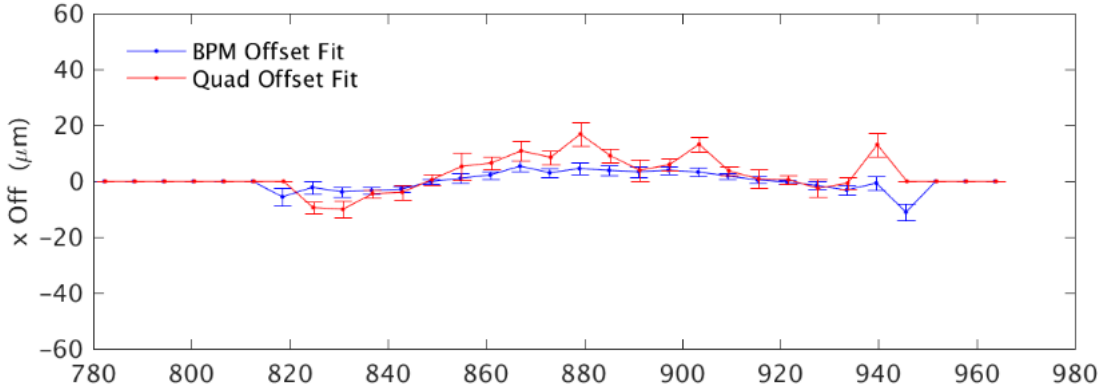
Undulator beam-based alignment

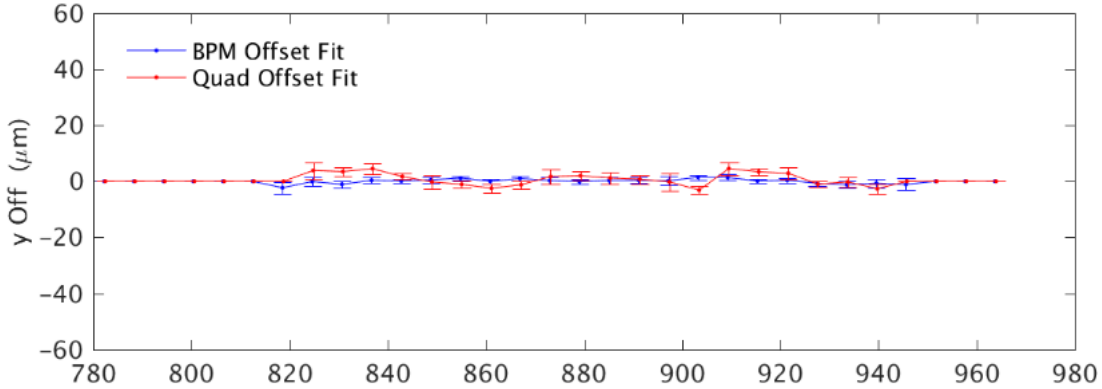
Initial condition





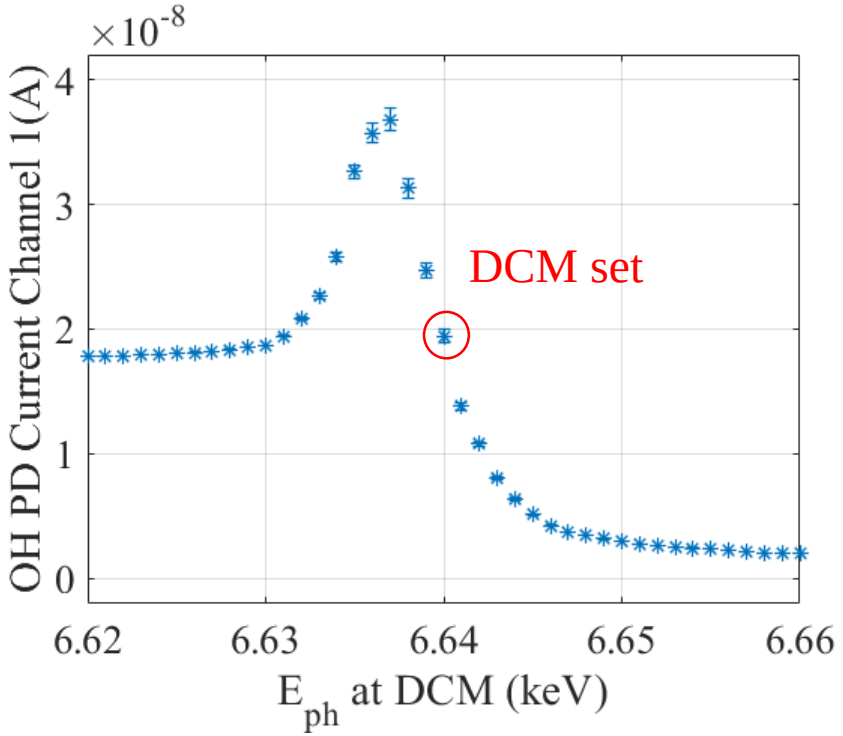
Final condition



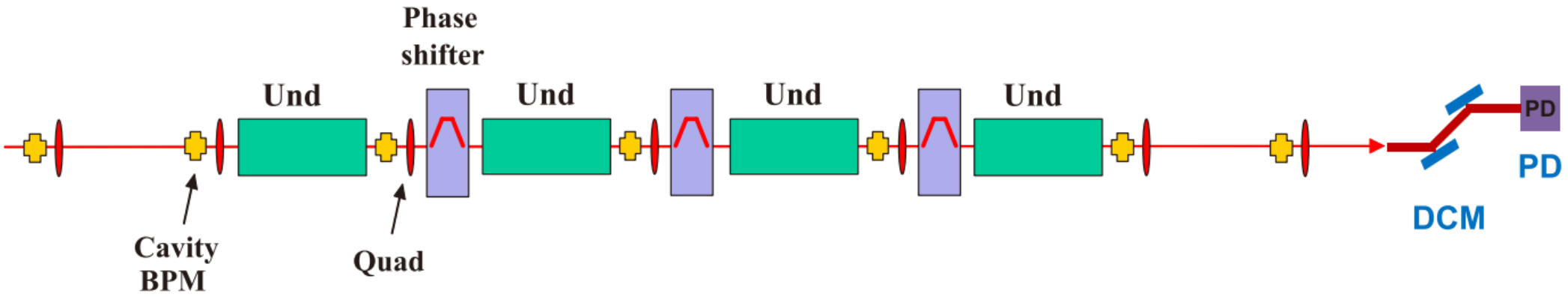


Dispersion-free orbit can be established by changing the BPM offset and QUAD mover offset

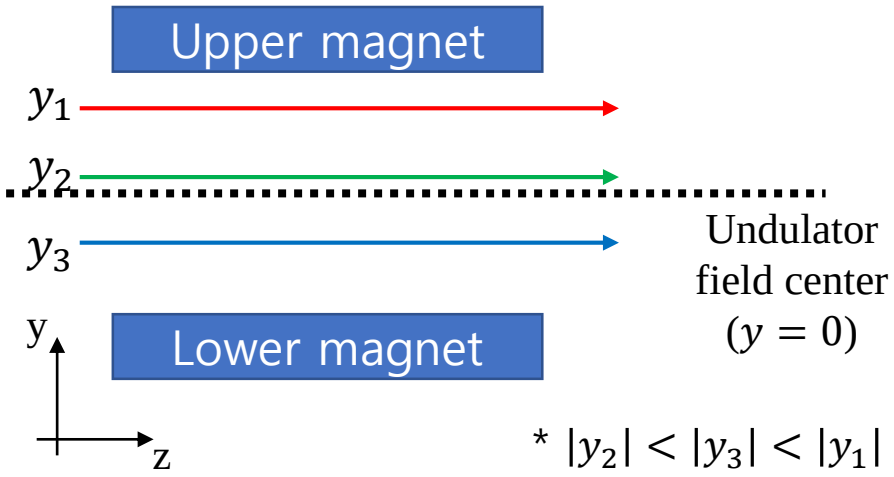
Spectrum of radiation for undulator optimization



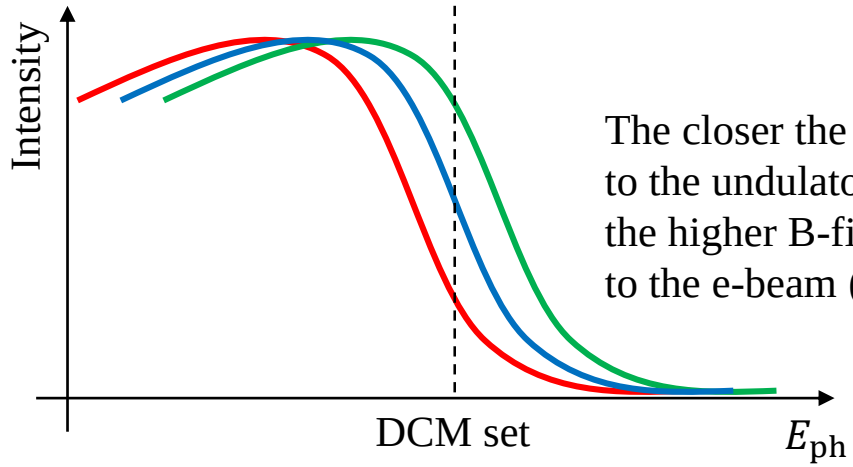
- ✓ Uncompressed electron beam is used to minimize correlated energy spread.
- ✓ Spectrum of the radiation has to be measured to set the photon energy at the monochromator.
- ✓ Photon energy at the monochromator (DCM for HX) is selected at which the signal of detector is sensitively changed.



Undulator vertical offset scan to find B-field center

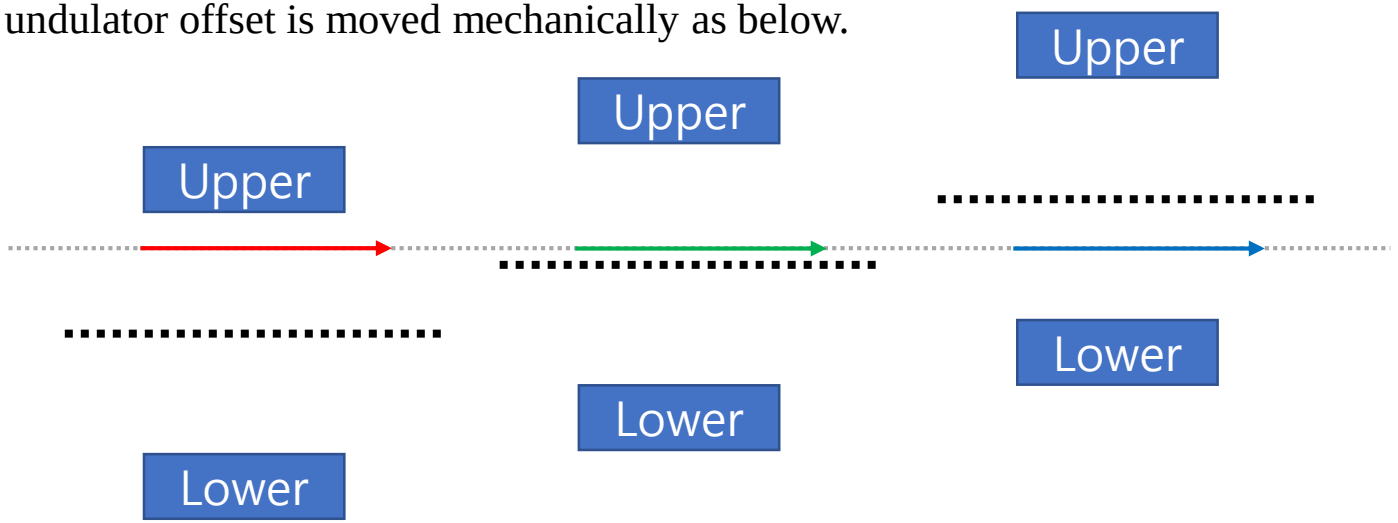


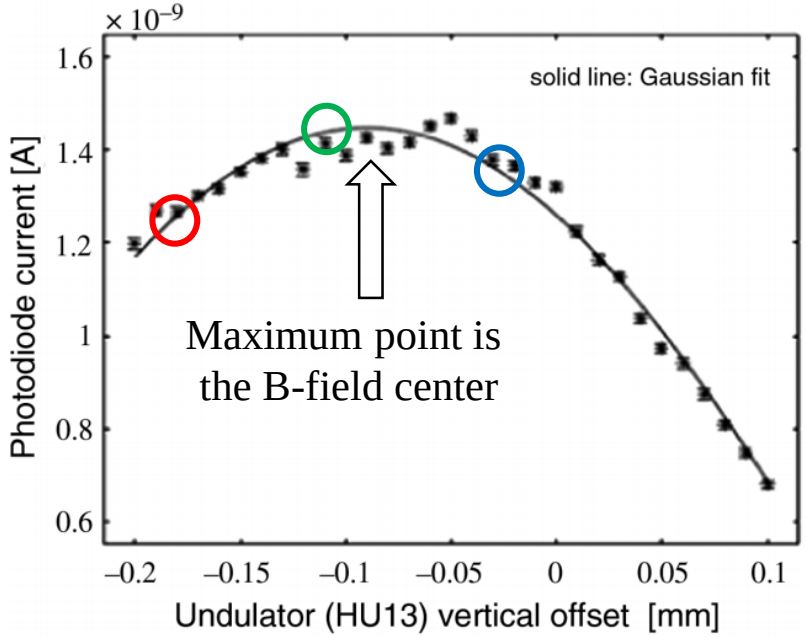
T. Tanaka *et al.*, PRAB **15**, 110701 (2012)
H.-S. Kang, H. Loos, PRAB **22** 060703 (2019)



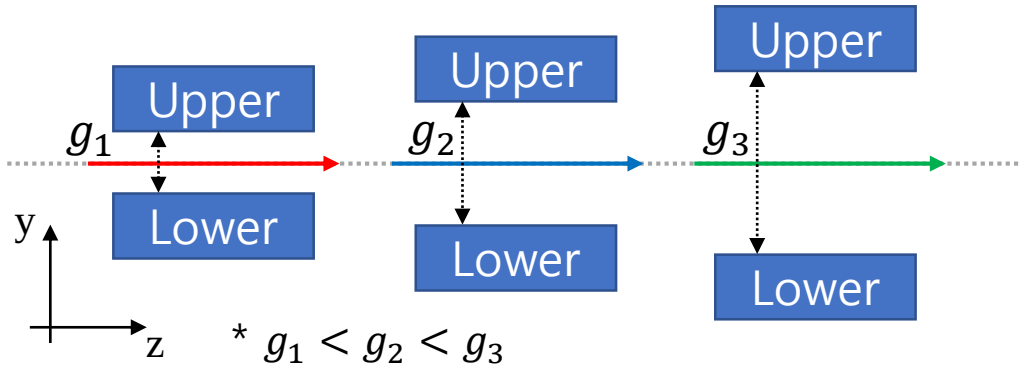
The closer the e-beam path
to the undulator magnet,
the higher B-field is applied
to the e-beam (resonant $E_{ph}\downarrow$)

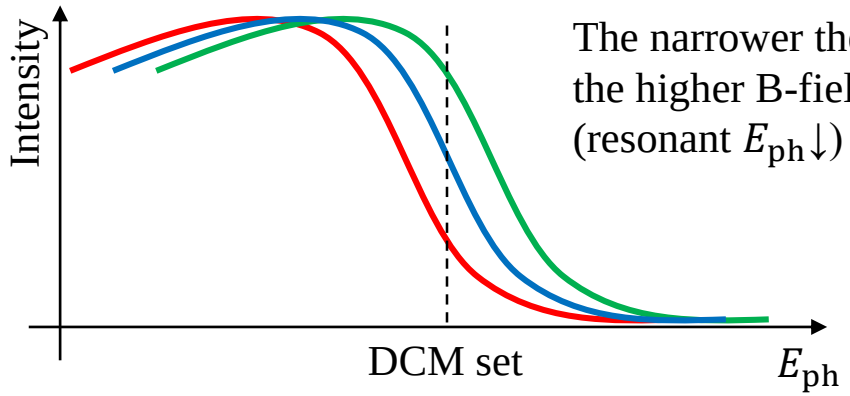
In the Exp. → electron beam path is fixed
and undulator offset is moved mechanically as below.





Undulator K-tuning to match same B-field





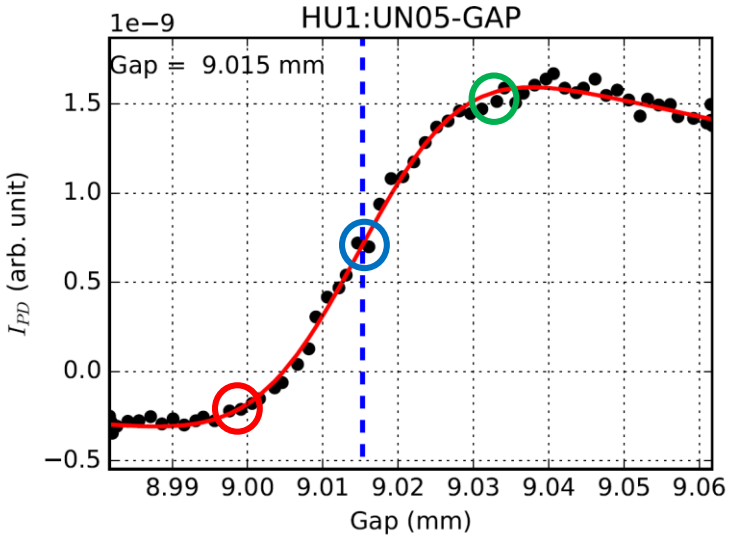
The narrower the undulator gap is,
the higher B-field is applied to the e-beam.
(resonant $E_{ph}\downarrow$)

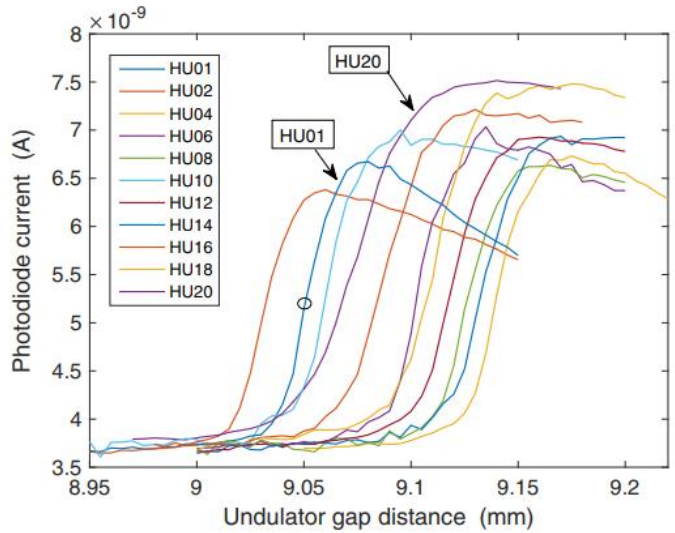
In the Exp.
→ electron beam path is fixed
and undulator gap is moved.

$$f(g) = [a_1 + a_4(g - a_2)]\,\mathrm{erf}\left(-\frac{g - a_2}{a_3}\right) + a_5 + a_6 g$$

a_2 is the determined gap distance

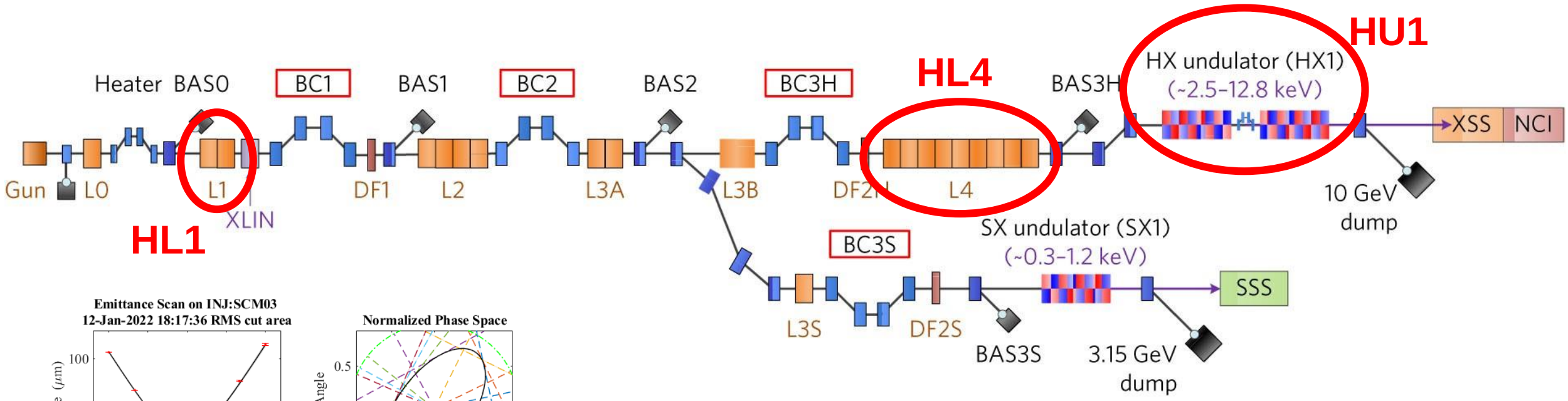
by fitting with the error function

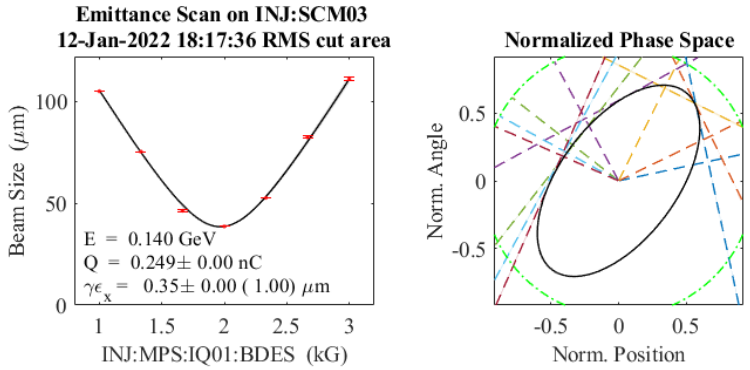


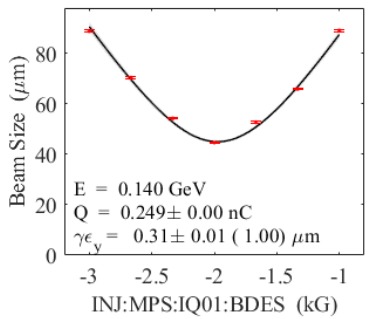


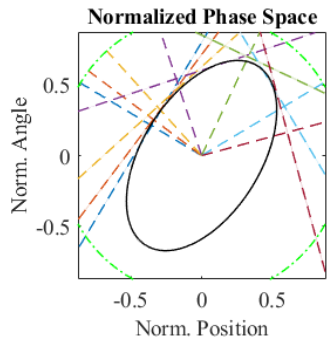
T. Tanaka *et al.*, PRAB **15**, 110701 (2012)
H.-S. Kang, H. Loos, PRAB **22** 060703 (2019)

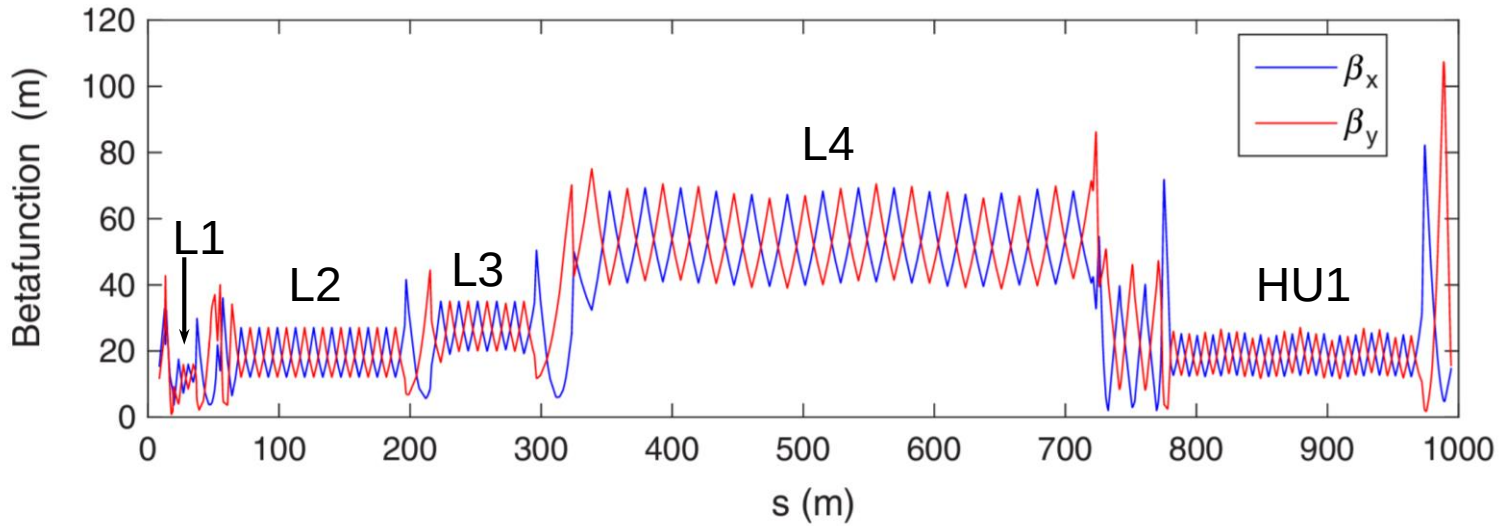
Lattice matching sections at PAL-XFEL





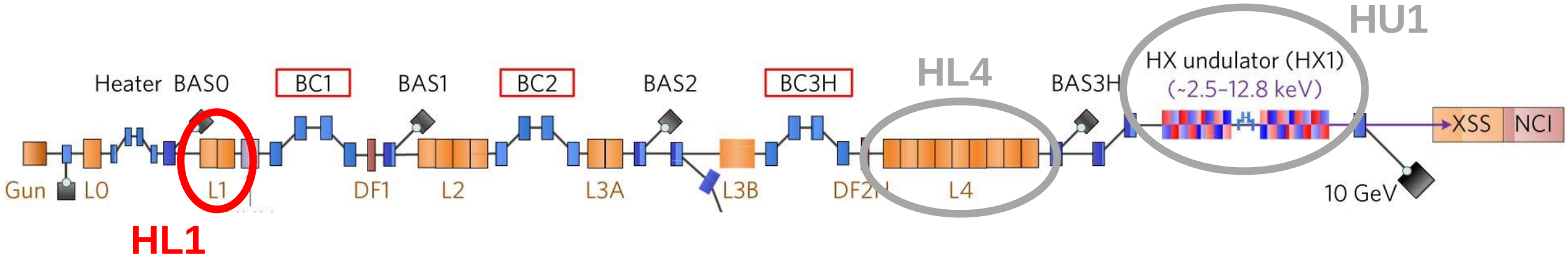


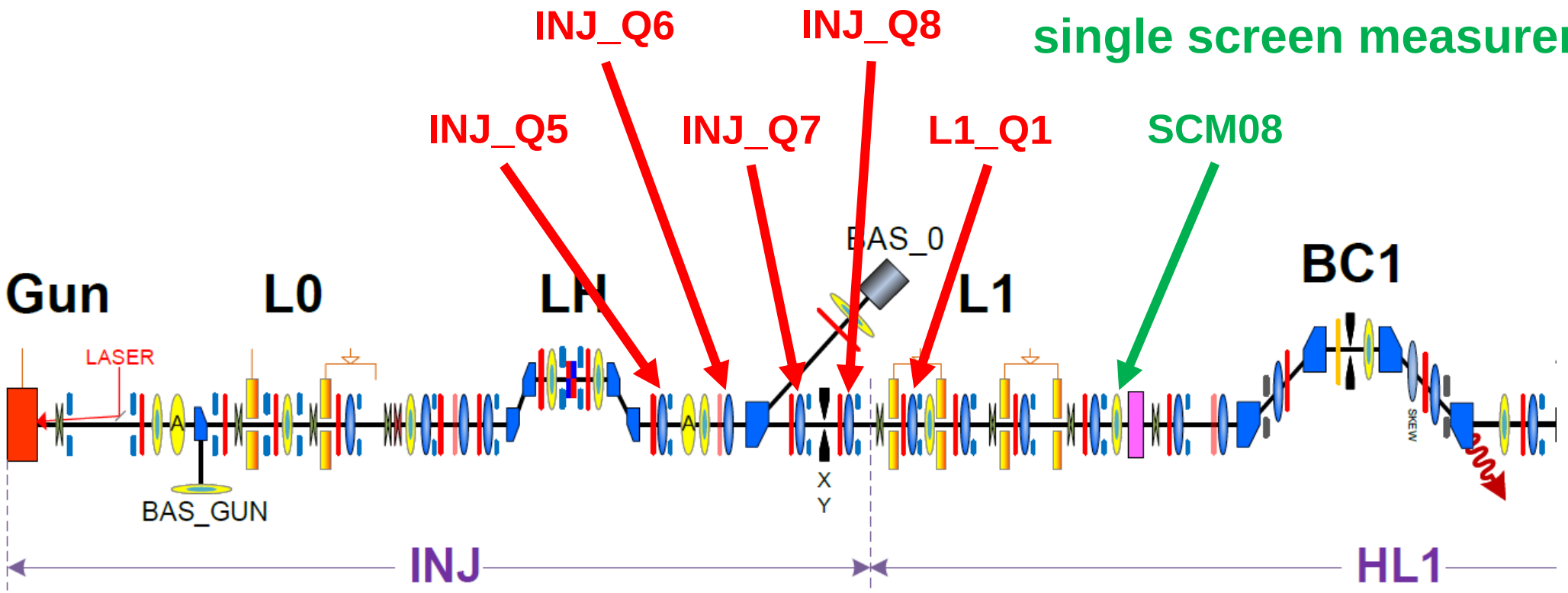




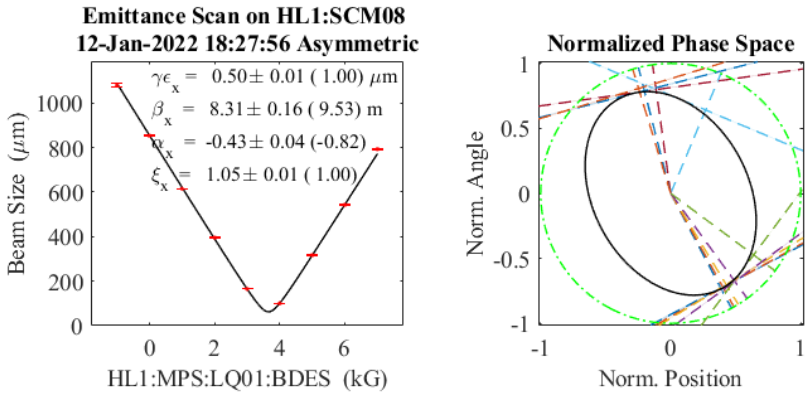
H.-S. Kang *et al.*, Proc. FEL2012, pp. 309–312.

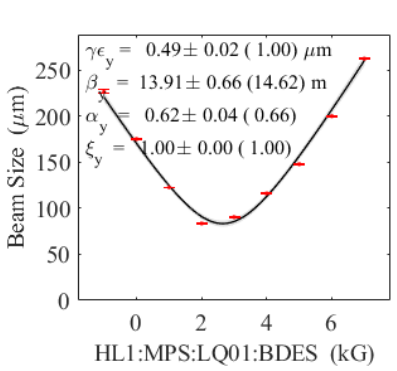
Lattice matching for HL1

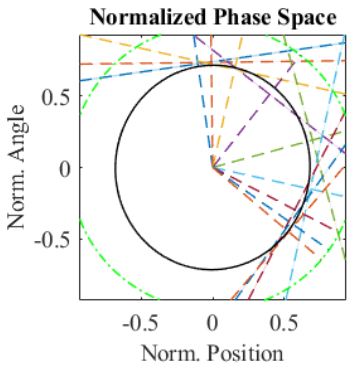




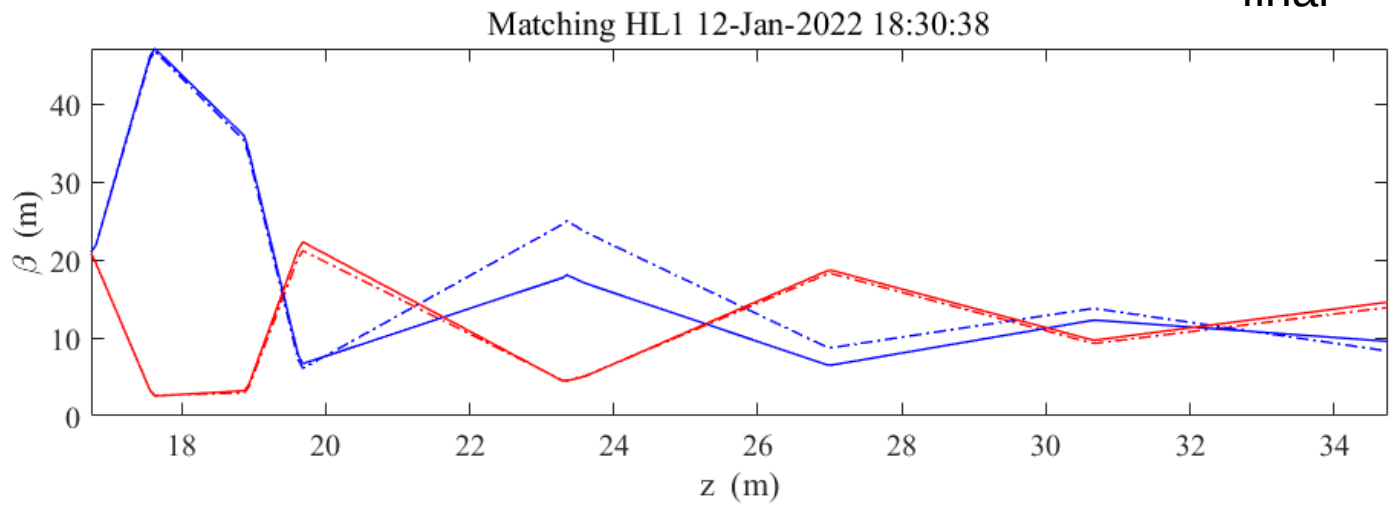
Lattice matching for HL1 (before)





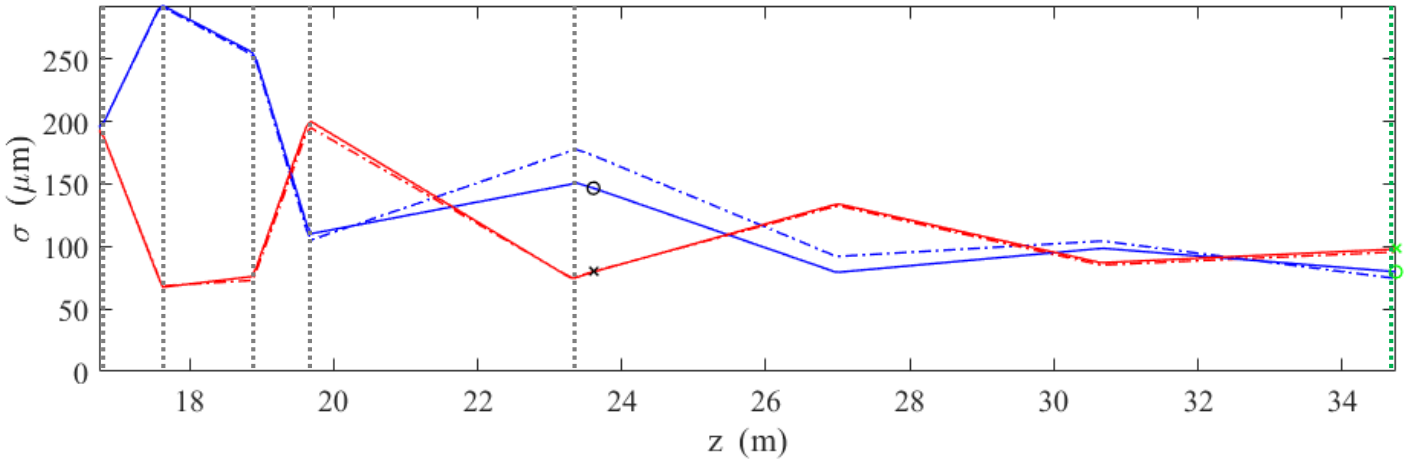


init.
final
X / Y

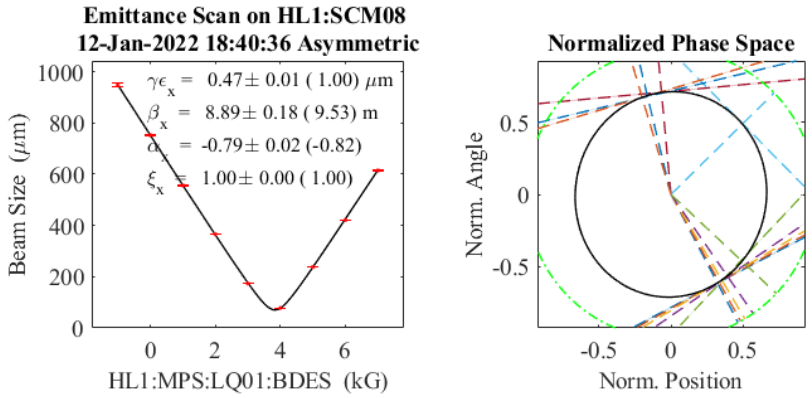


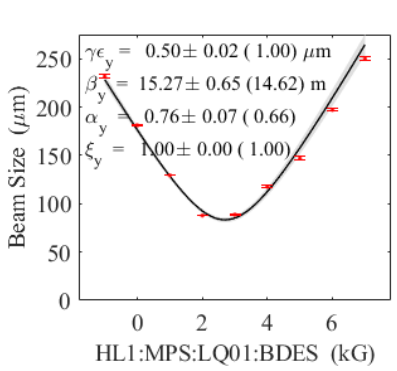
5x matching quads

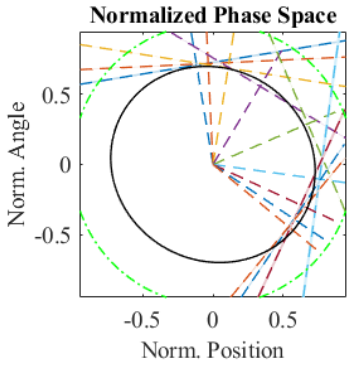
YAG screen



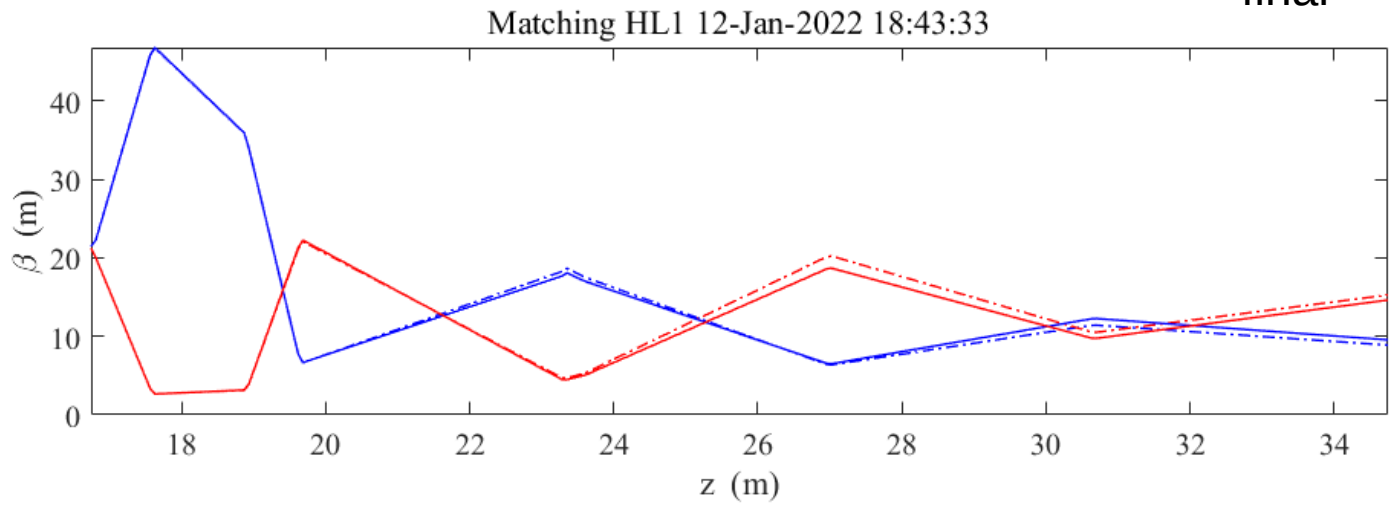
Lattice matching for HL1 (after)





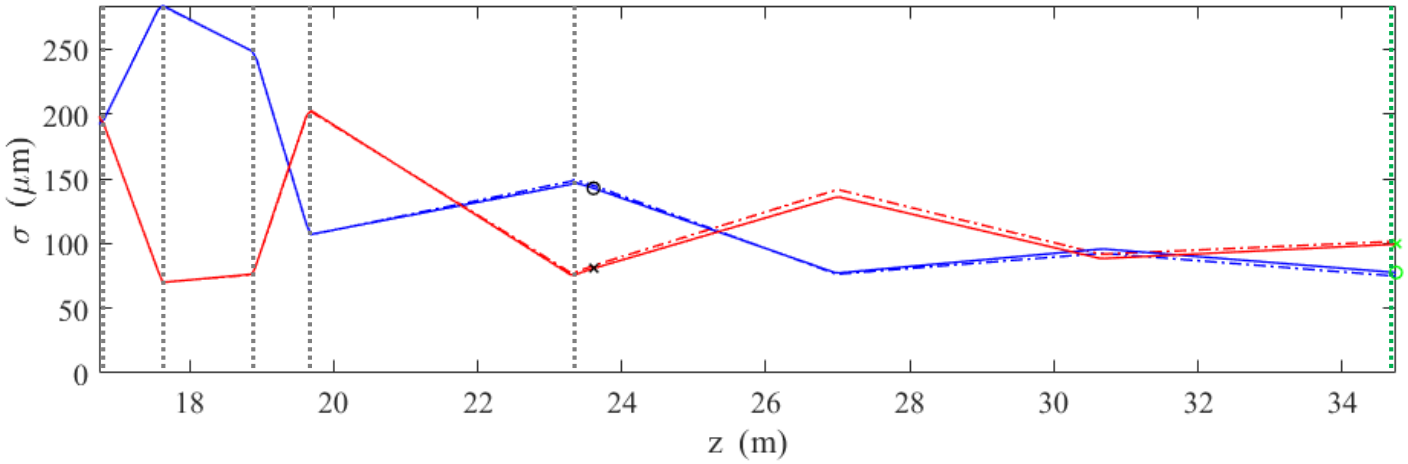


init.
final
X / Y

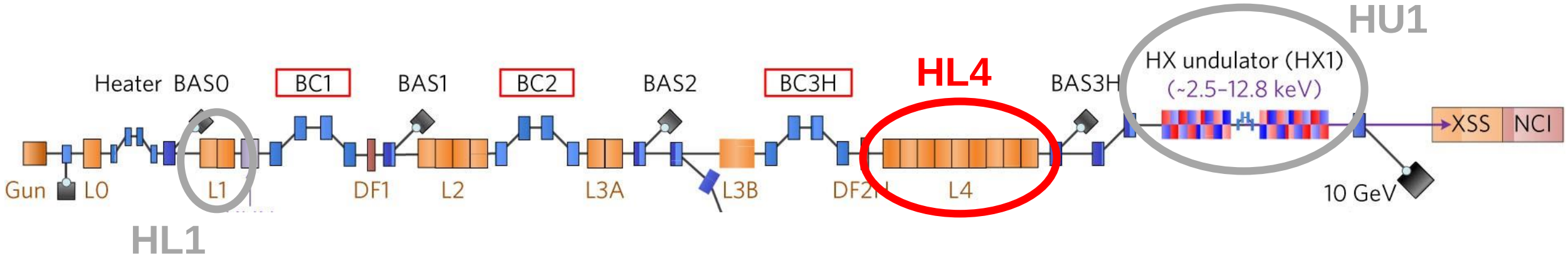


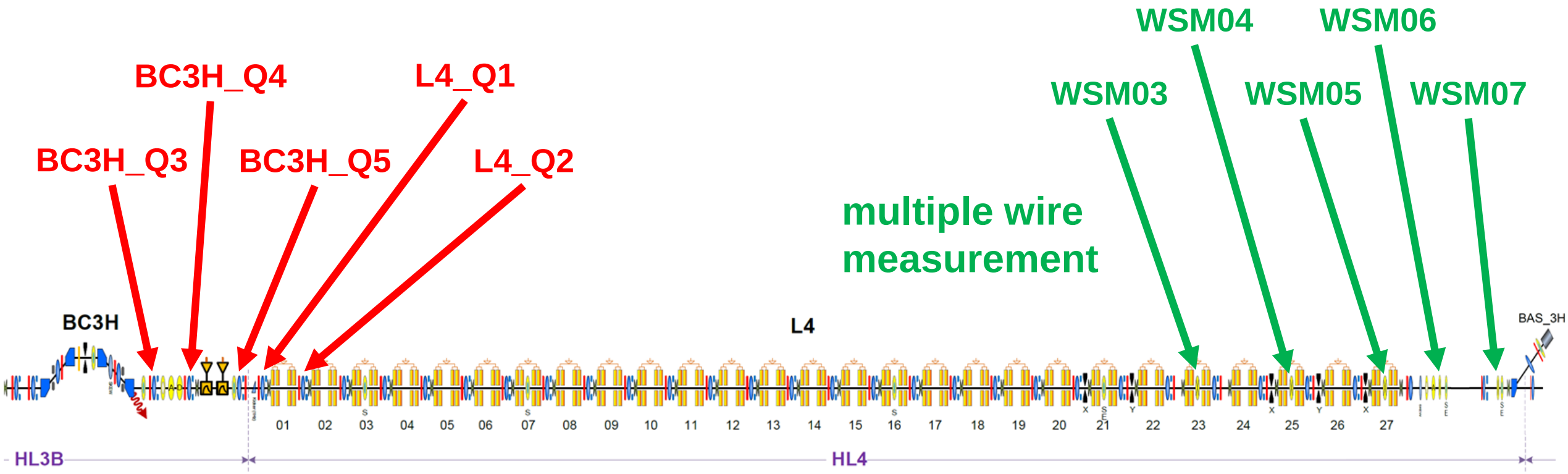
5x matching quads

YAG screen

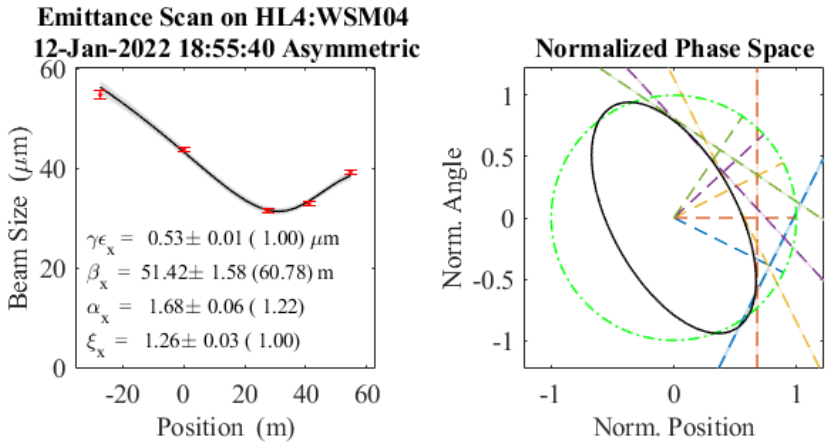


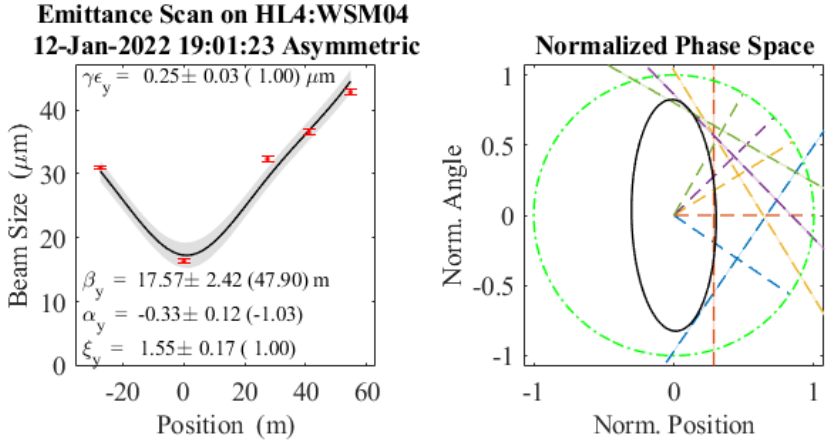
Lattice matching for HL4

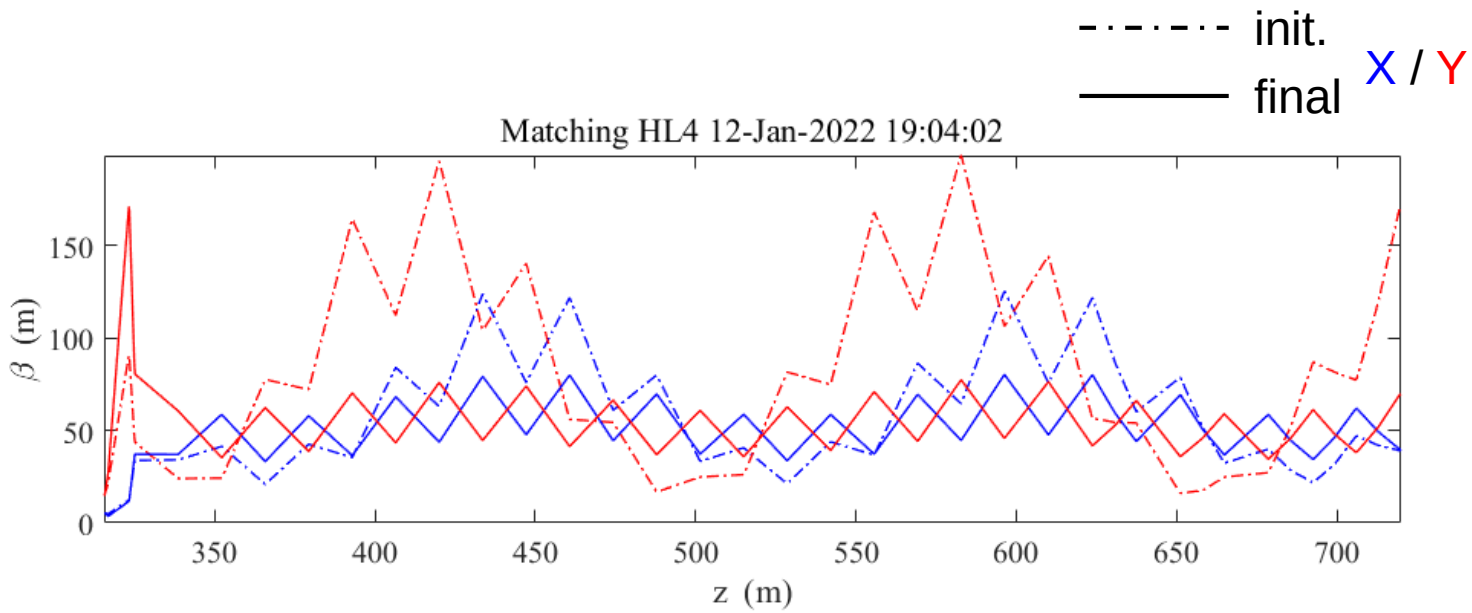


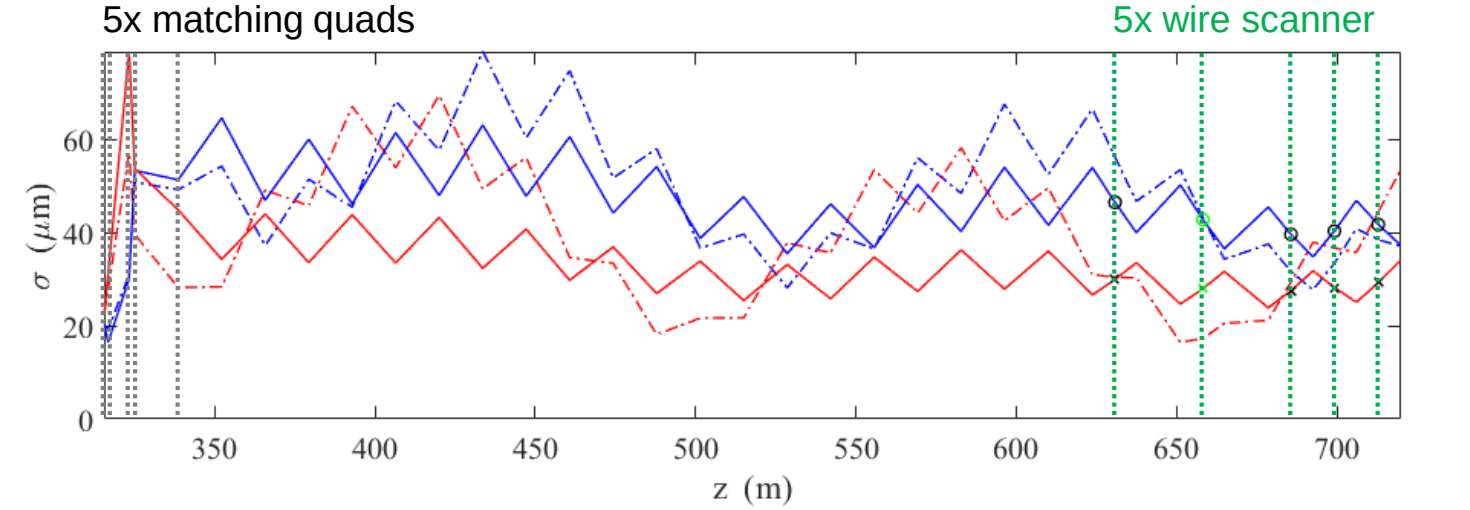


Lattice matching for HL4 (before)

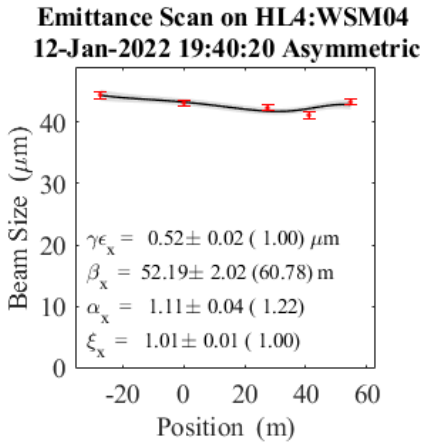


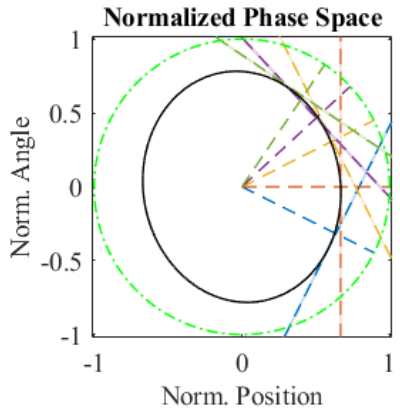


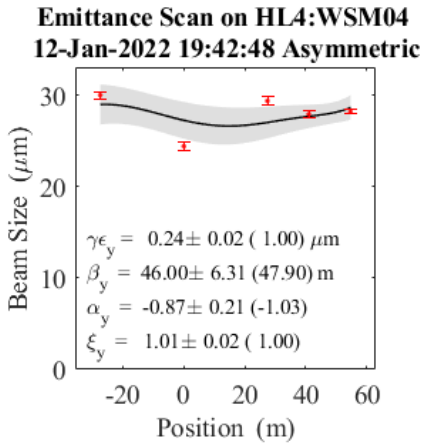


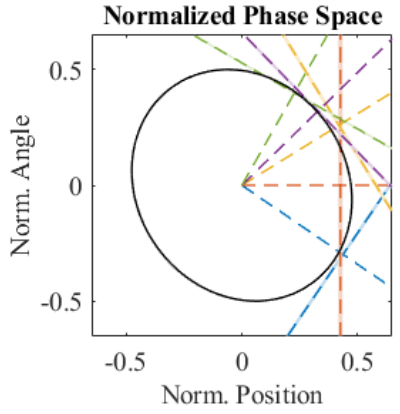


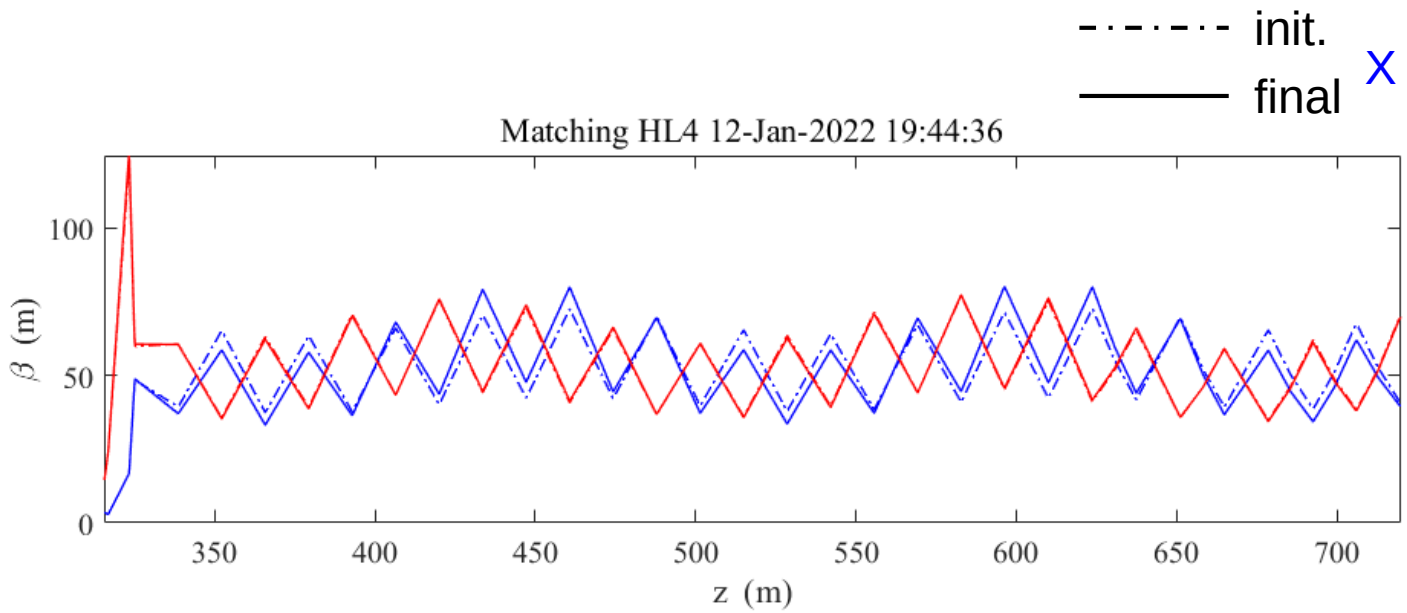
Lattice matching for HL4 (after)

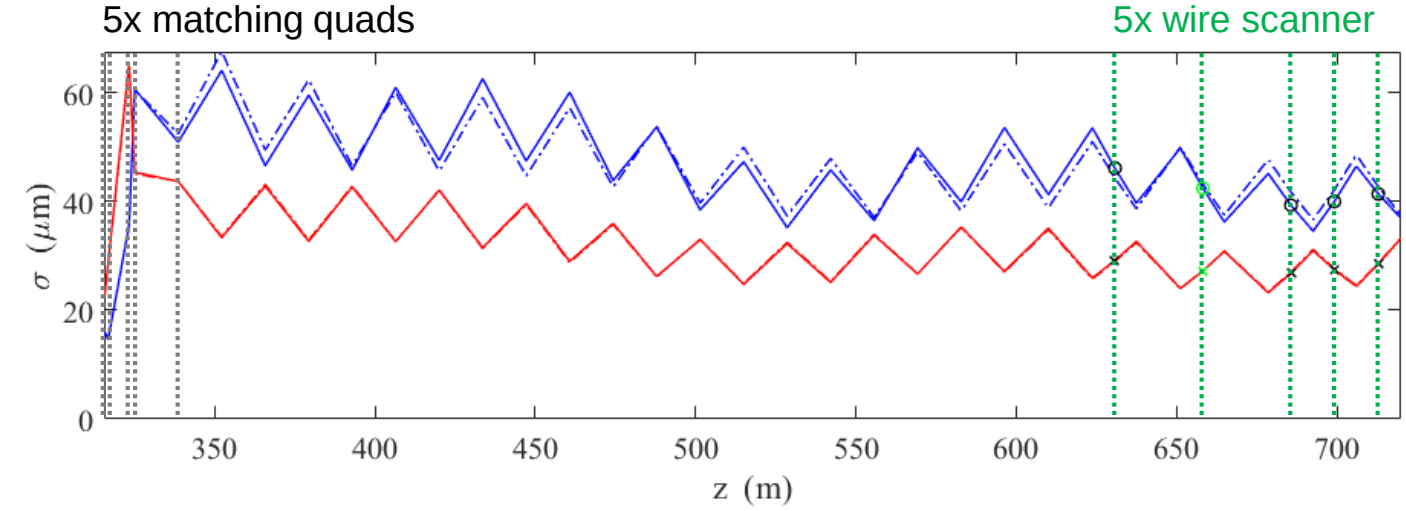




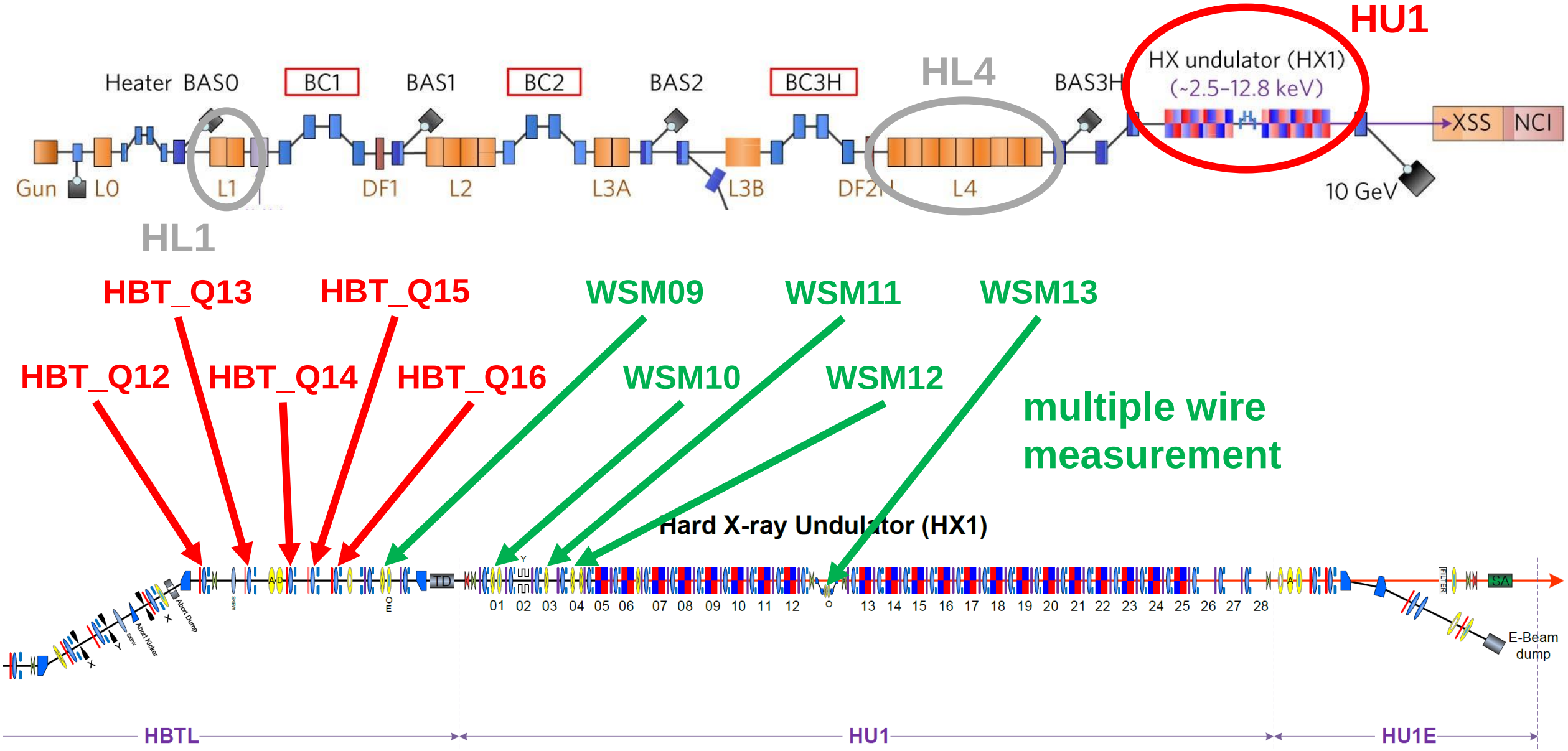




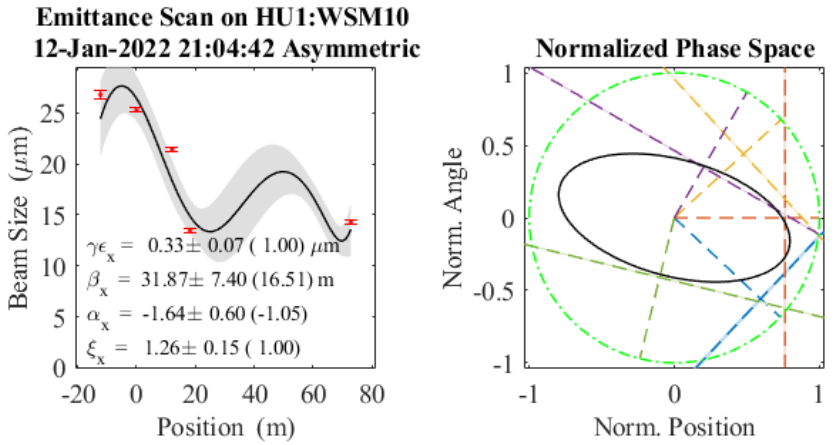


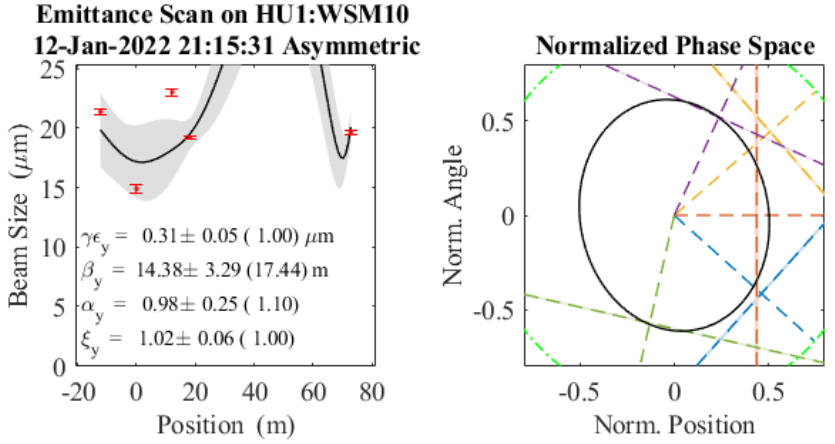


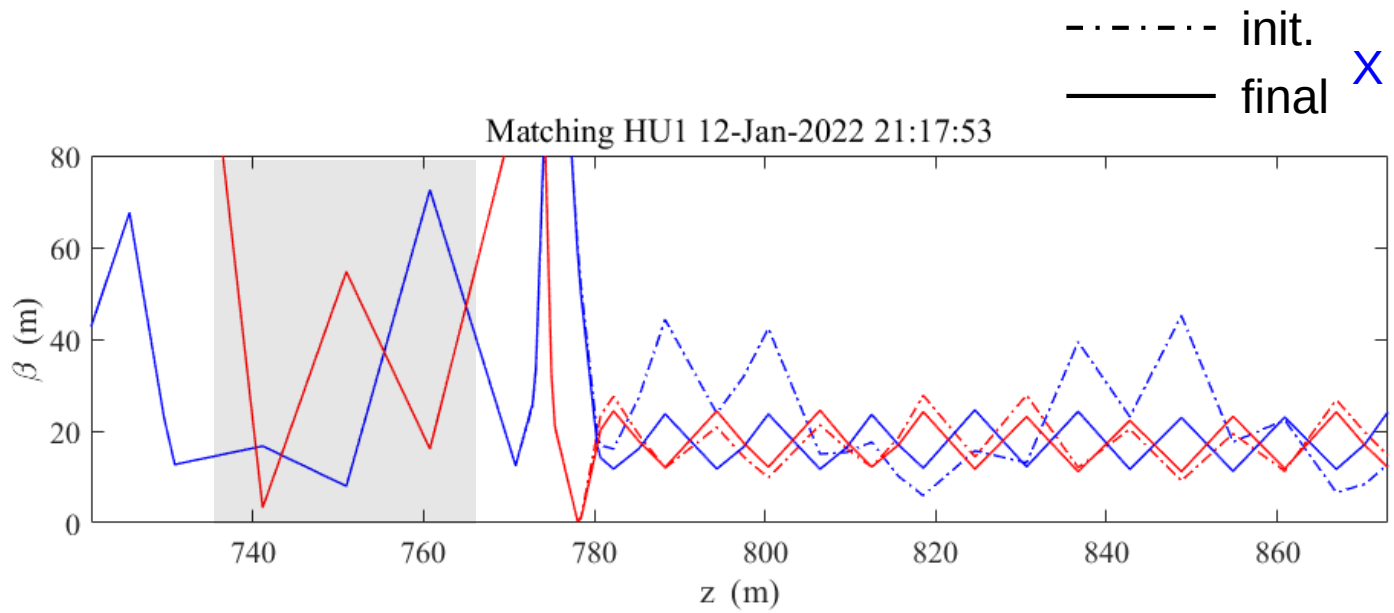
Lattice matching for HU1

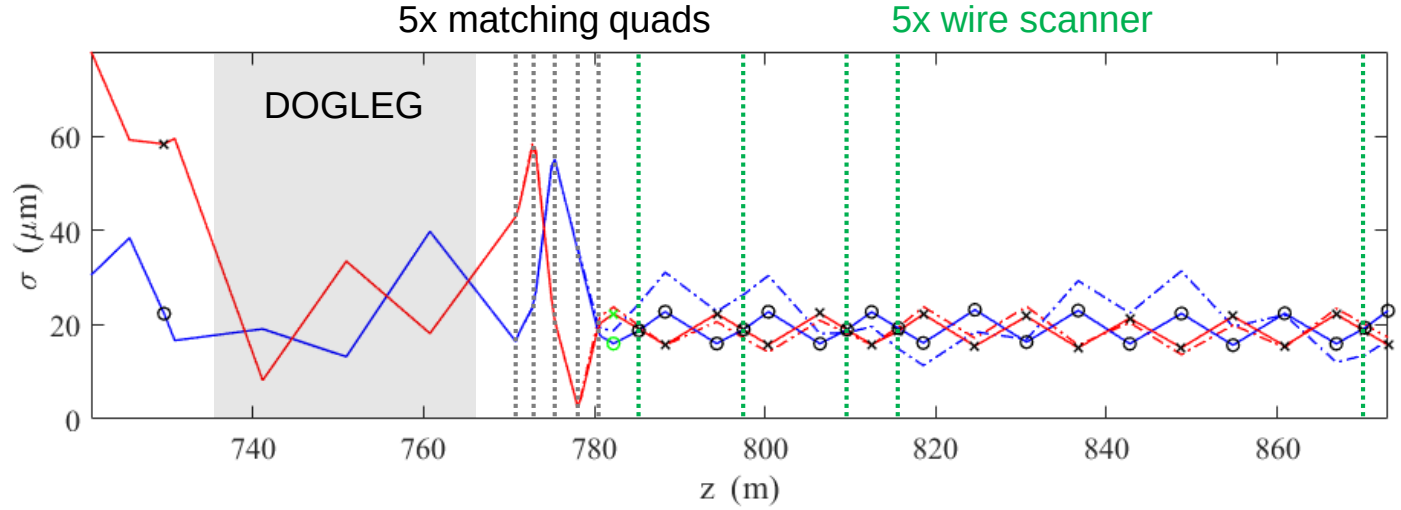


Lattice matching for HU1 (before)

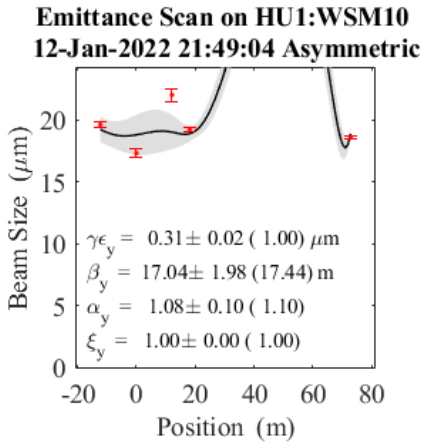


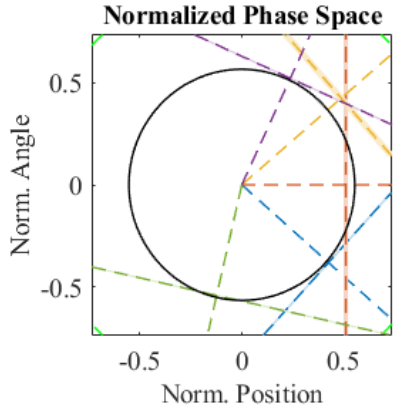


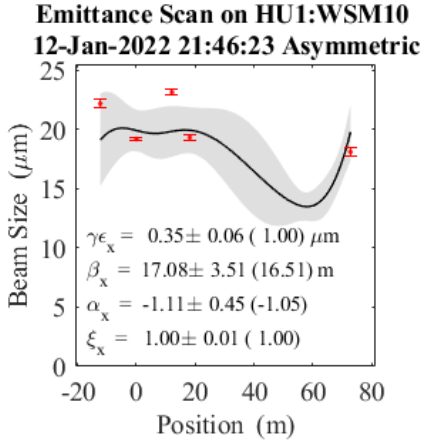


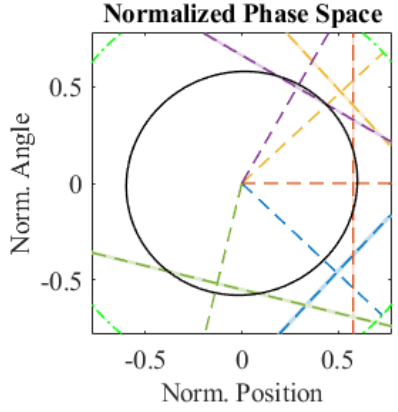


Lattice matching for HU1 (after)

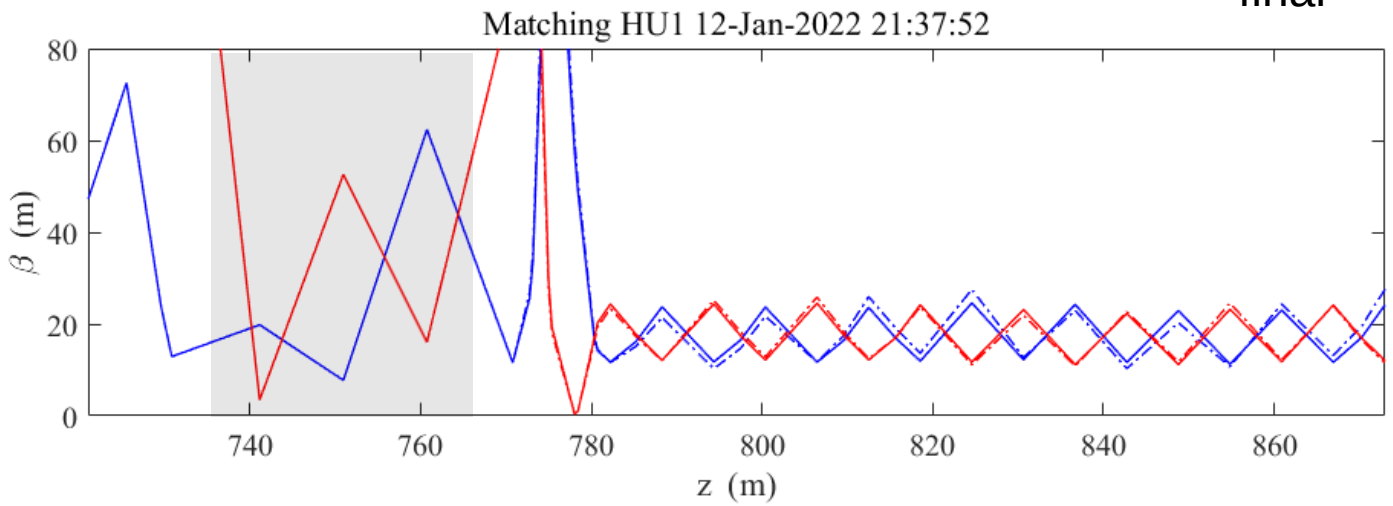




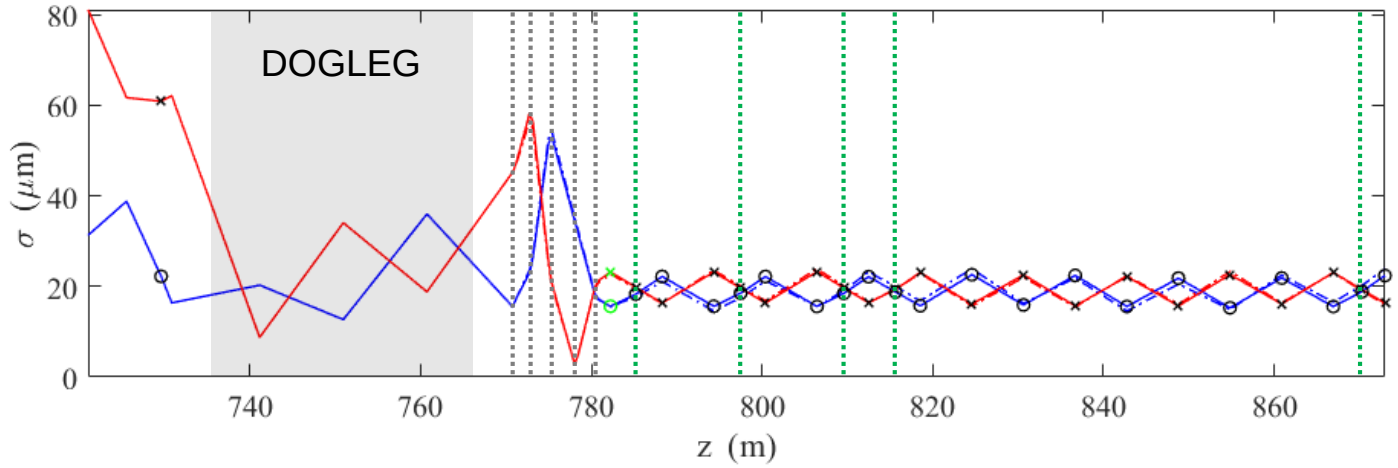




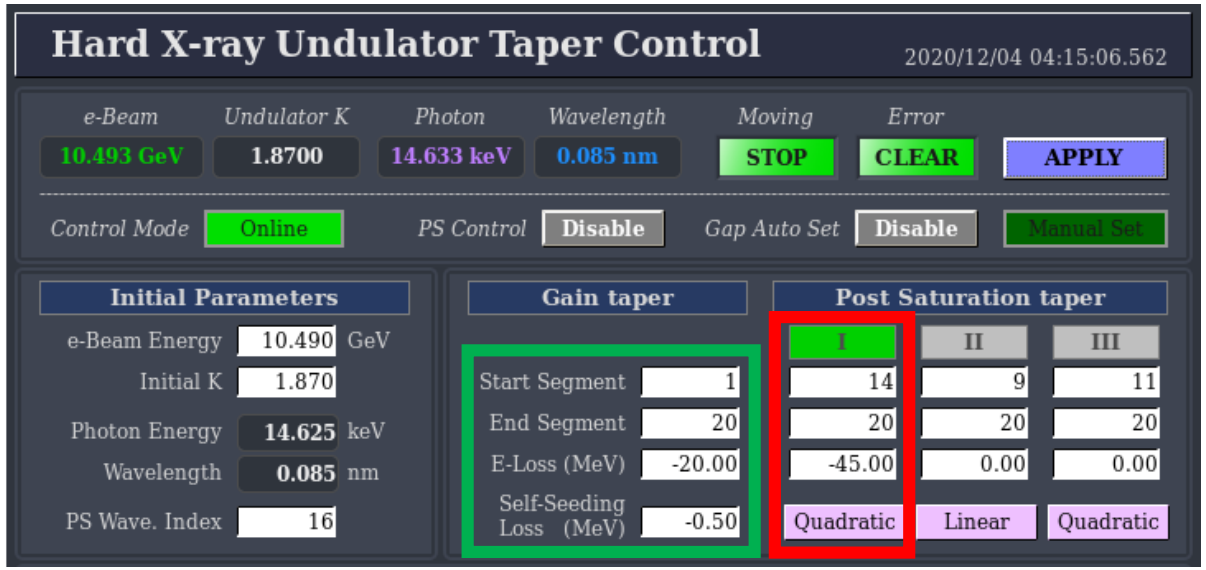
init.
final
X / Y

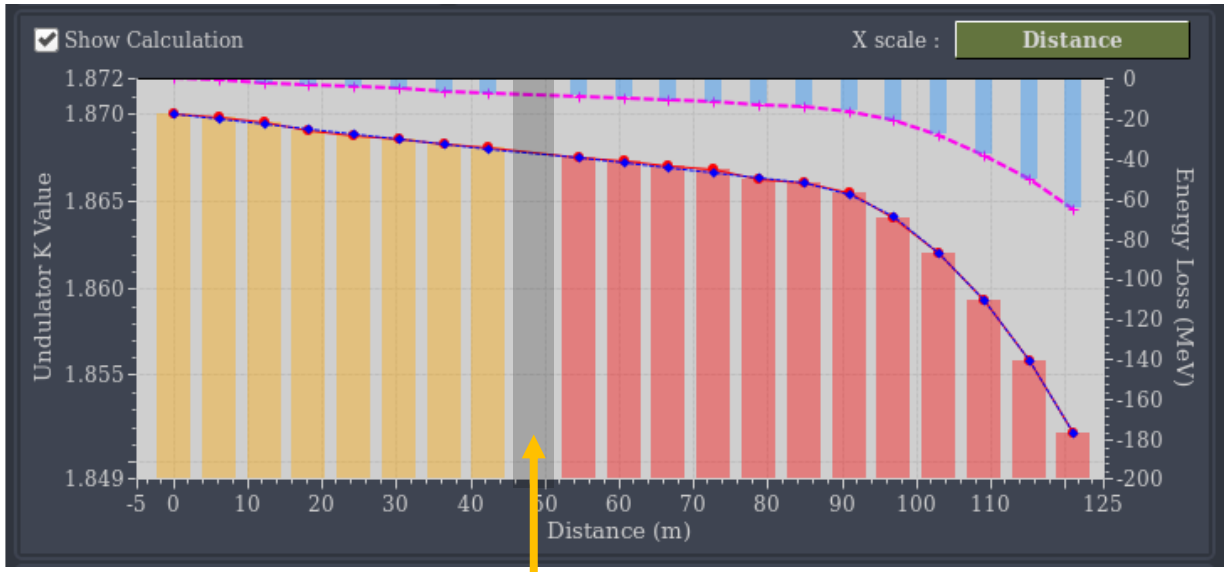


5x matching quads
5x wire scanner



Undulator tapering





energy loss due to the resistive wakefield effect → linear

energy loss due to the FEL lasing → quadratic

self-seeding section

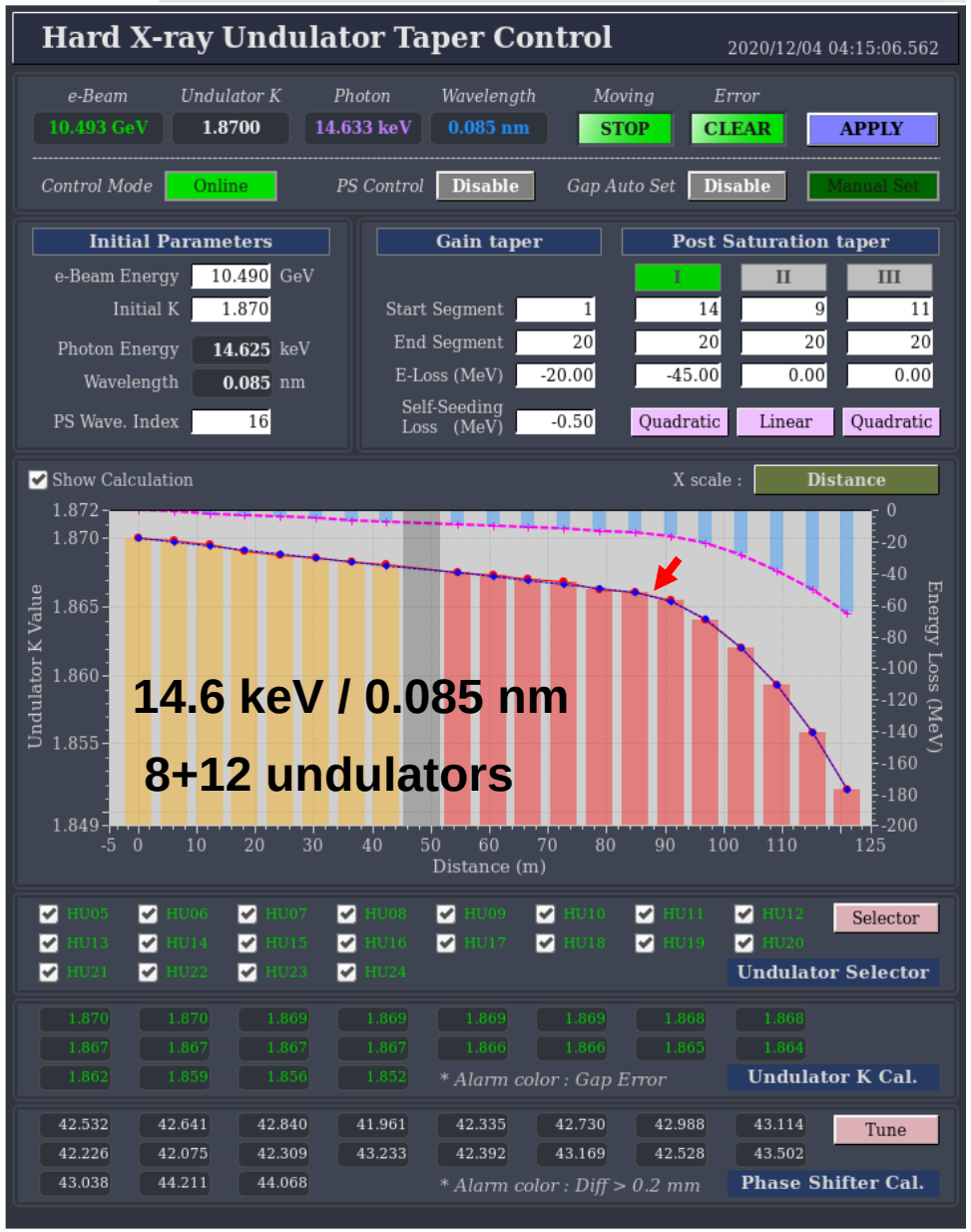
Electron beam energy at the i-th undulator

$$\begin{cases} \mathrm{E_i} = \mathrm{E_{init}} + \dfrac{\Delta E_{linear}}{N_{tot}} \cdot i \quad (i < n_{quad,start}) \\ \mathrm{E_i} = \mathrm{E_{init}} + \dfrac{\Delta E_{linear}}{N_{tot}} \cdot i + \dfrac{\Delta E_{quadratic}}{(N_{tot} - n_{quad,start})^2} \cdot (i - n_{quad,start})^2 \quad (i \geq n_{quad,start}) \end{cases}$$

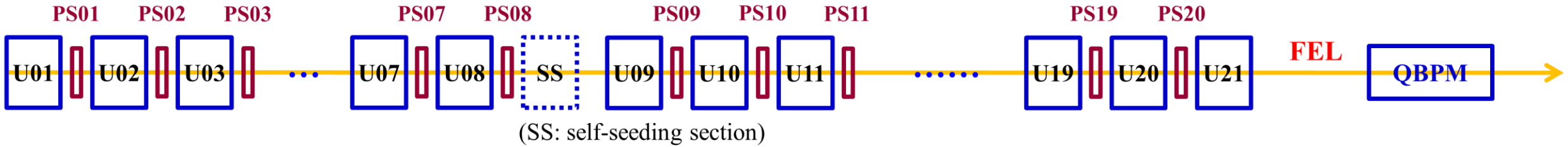
Resonance condition

$$K = \sqrt{2 \cdot \left(\frac{2\gamma^2 \lambda_r}{\lambda_u} - 1 \right)}$$

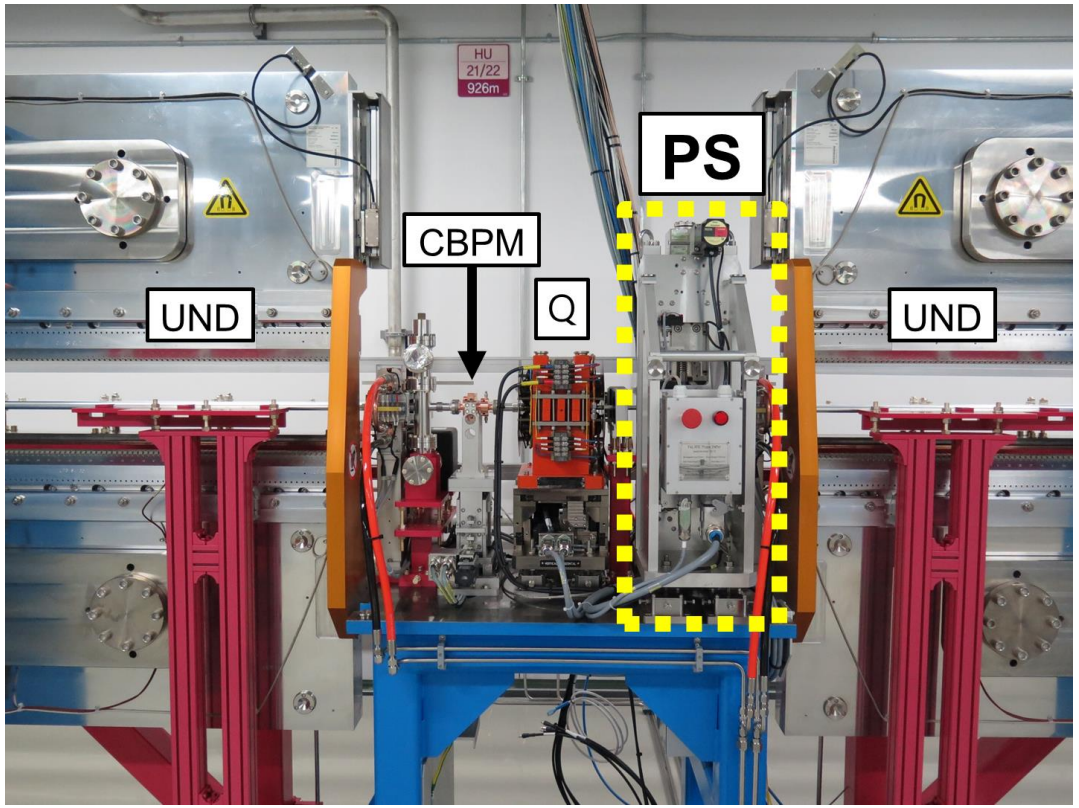
Examples of undulator tapering

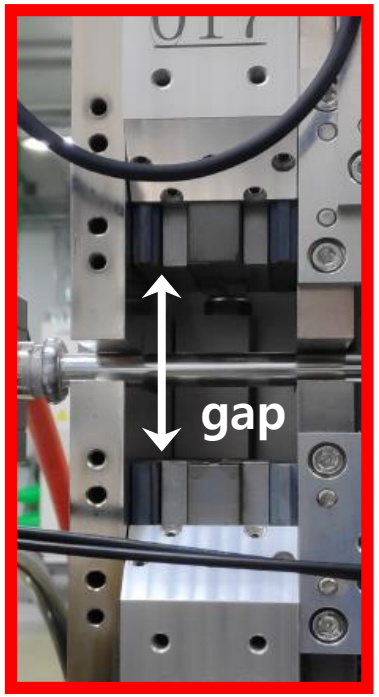


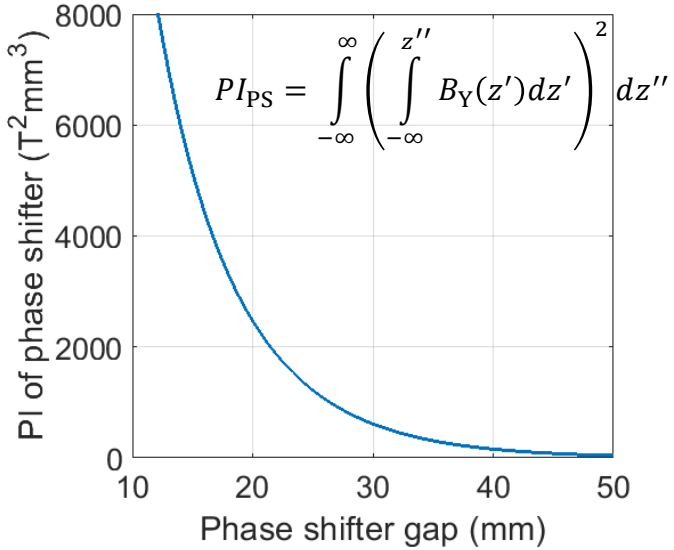
Phase shifter between undulators



(SS: self-seeding section)







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

To match the phase between FEL pulse and electron beam

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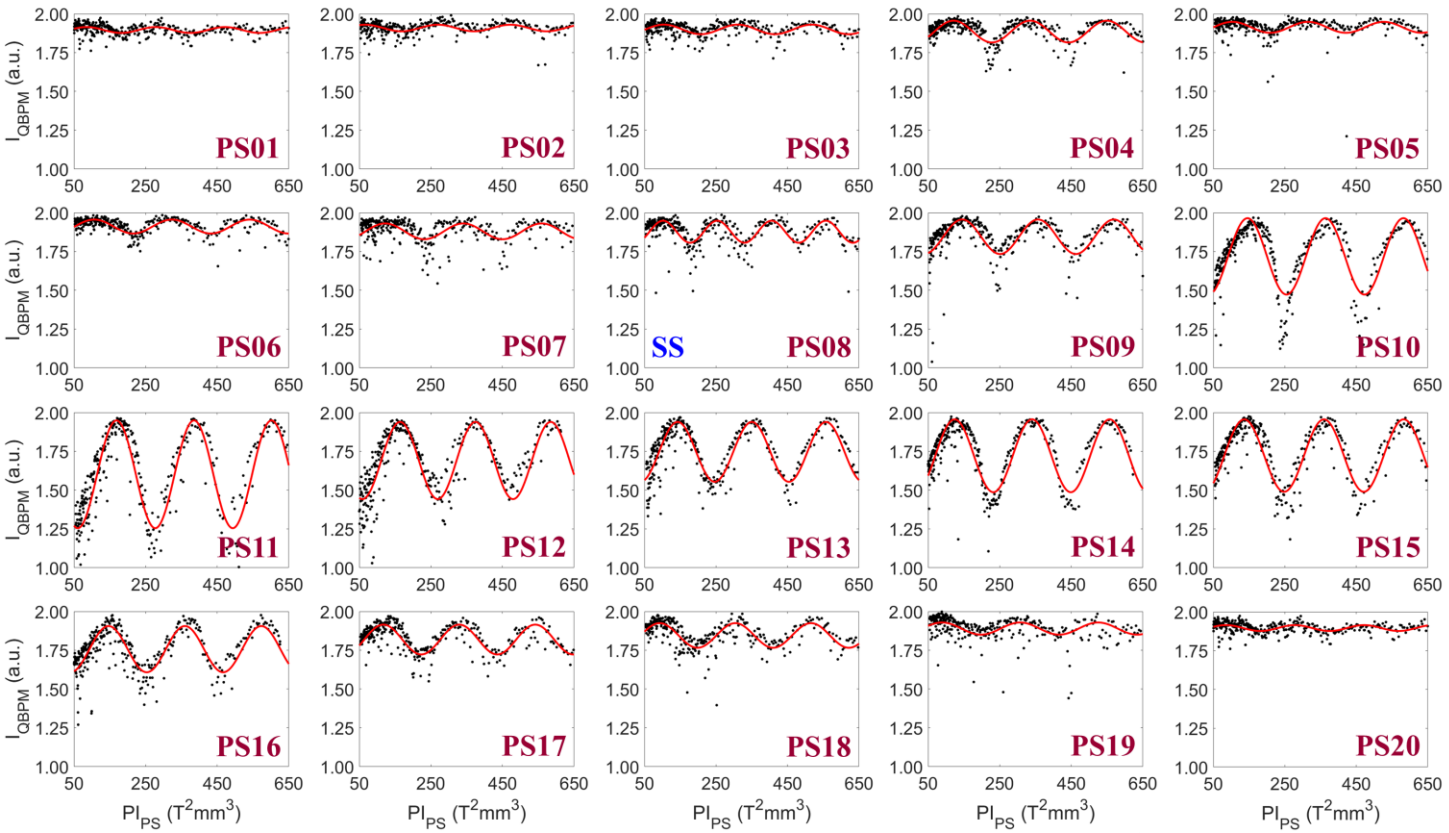
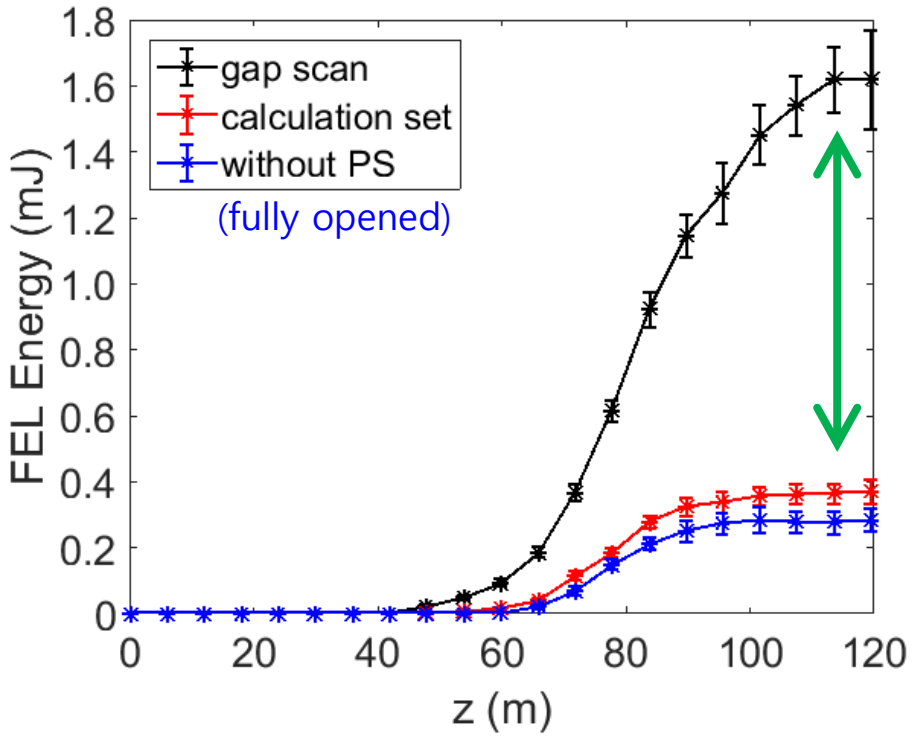
Phase shifter gap tuning results



4 times enhancement



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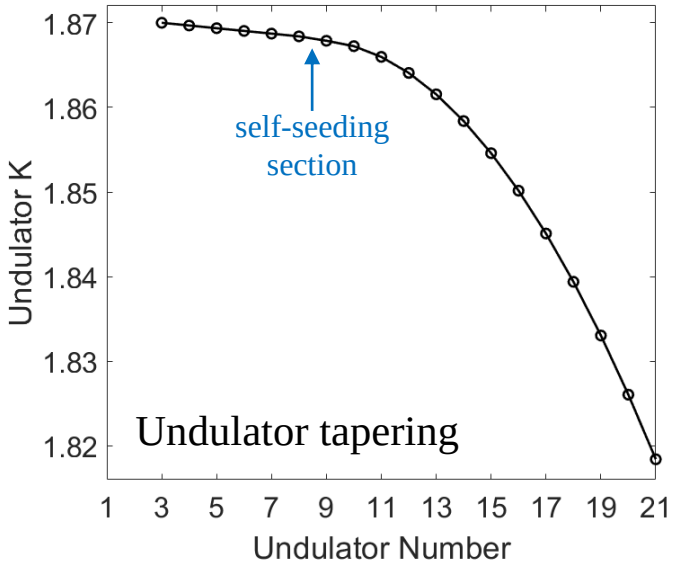
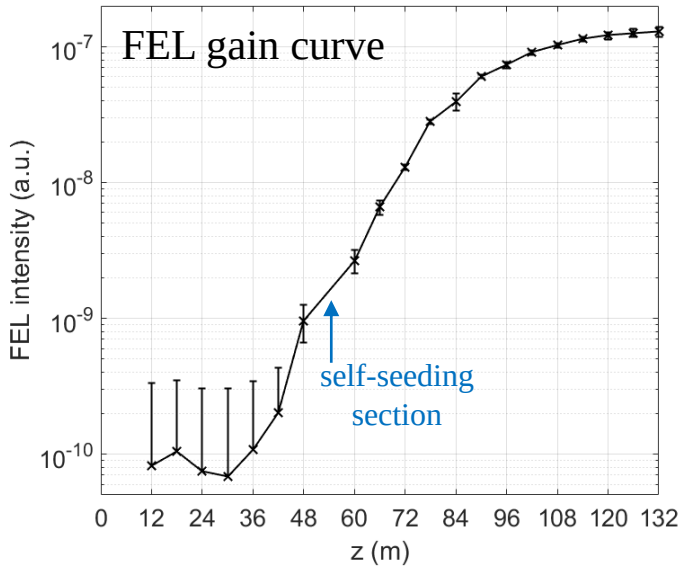
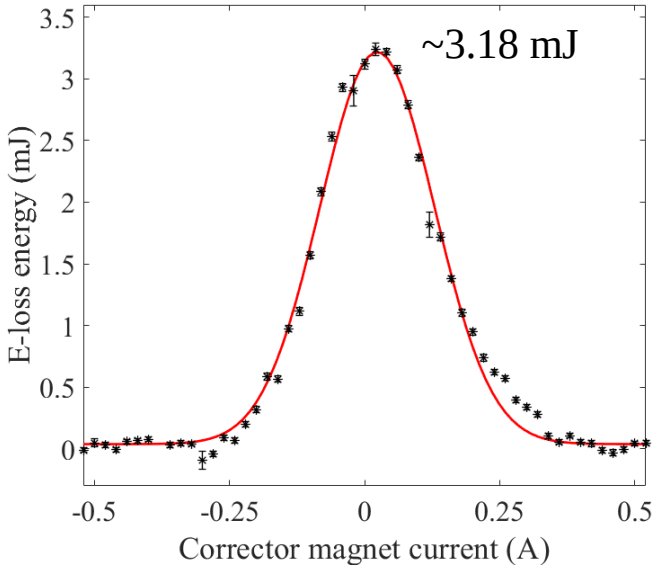
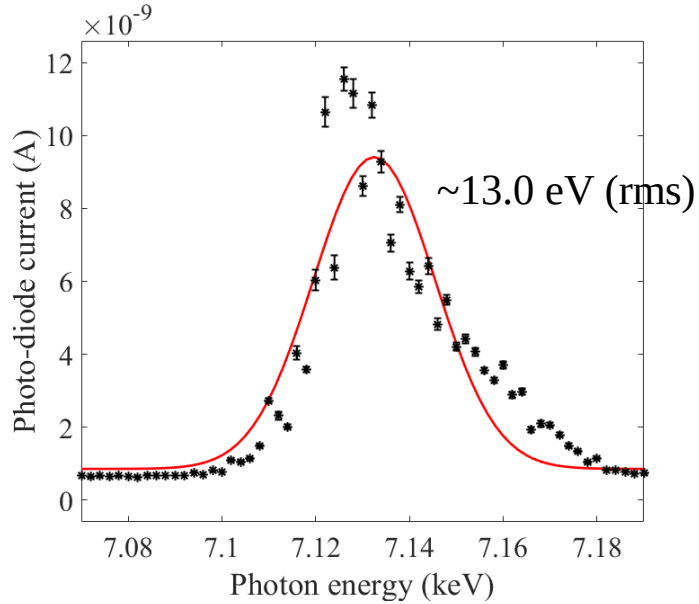
3.2 mJ at 7.13 keV FEL – Record of highest pulse energy at PAL-XFEL

- ✓ 7.13 keV SASE FEL
- ✓ E_{beam}: 7.325 GeV
- ✓ Norm. emittance at injector:
  0.35 μm (hor) / 0.31 μm (ver)
- ✓ Norm. emittance at HU1:
  0.35 μm (hor) / 0.31 μm (ver)
- ✓ Peak current: 2.8 kA
- ✓ 19 (6+13) undulators are used to optimize FEL intensity
- ✓ XFEL pulse duration: 36.0 fs (FWHM)
  measured by using cross-correlation method at self-seeding section









Results of FEL tuning for beamtime (2022. 01. 12)

Summary

- ✓ Beam-based optimization process is performed to maximize the FEL intensity
  after the end of major maintenance in summer/winter and before the start of every user beam time.

- ✓ Alignment process for undulator line
  (quad. mover position, cavity-bpm offset, undulator vertical offset, undulator gap for identical B field)
  is carried out by using un-compressed electron beam

- ✓ Lattice matching, undulator tapering, and phase shifter gap scanning are carried out
  by using compressed electron beam (~ 3 kA)