Progress of PAL-XFEL Undulator Program

Dong-Eon Kim, Y. G. Jung, W. W. Lee, S. J. Lee, H. S. Kang, H. G. Lee, S. B. Lee, H. S. Suh*

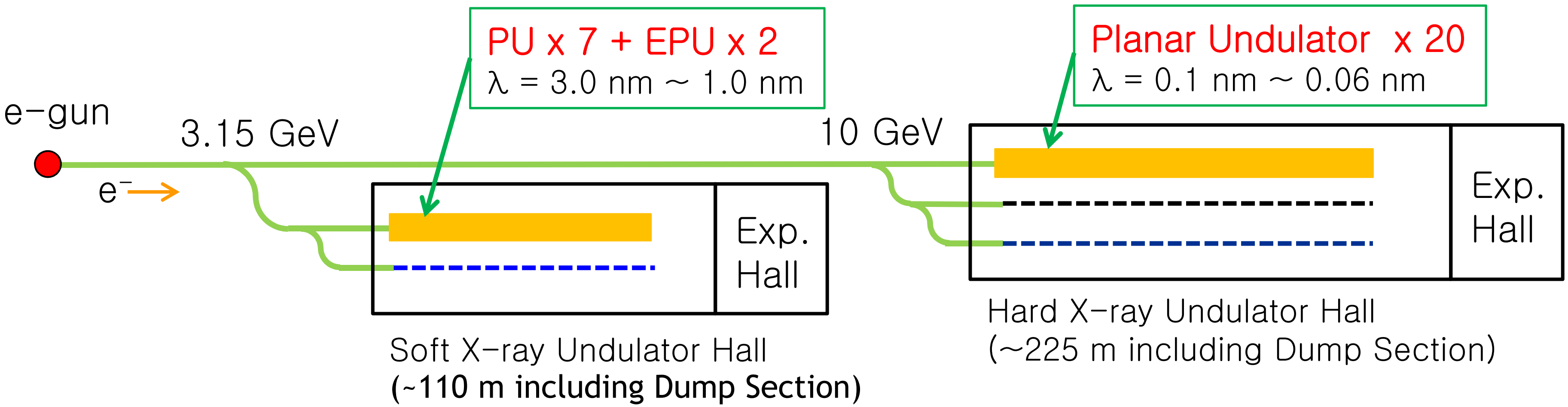
Pohang Accelerator Laboratory , POSTECH, Korea

Aug 23 2017
FEL2017, Santa Fe, NM, USA

Contents

- Introduction of PAL-XFEL undulator system
- Undulator structure/magnet system general.
- Pole height tuning
- Background field compensation.
- Selected magnetic measurement results.
- Midplane moving modifications.
- Undulator cell matching, analysis of the measurement results.
- Upgraded landmark magnet.
- Summary

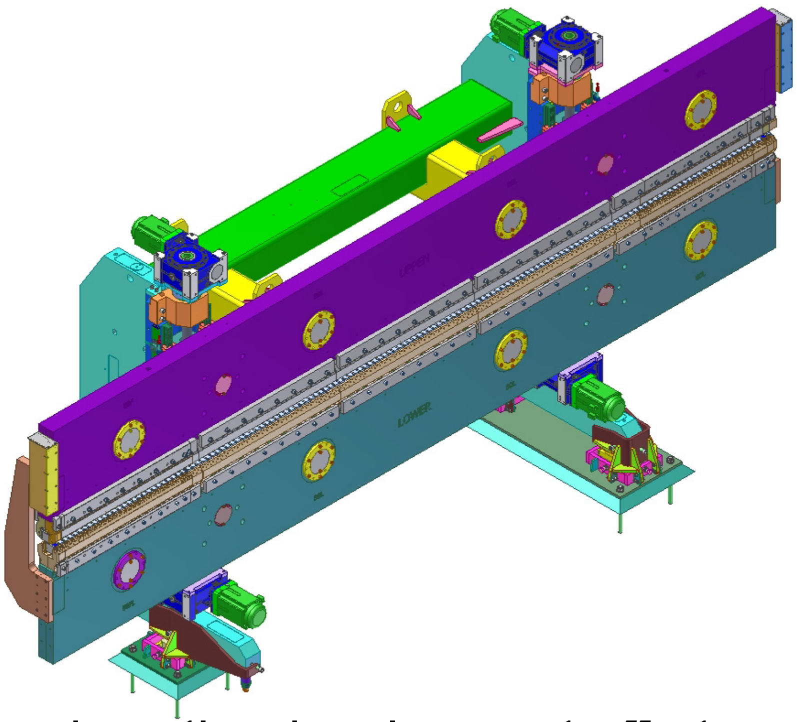
PAL-XFEL Undulator Layout (Schematic)

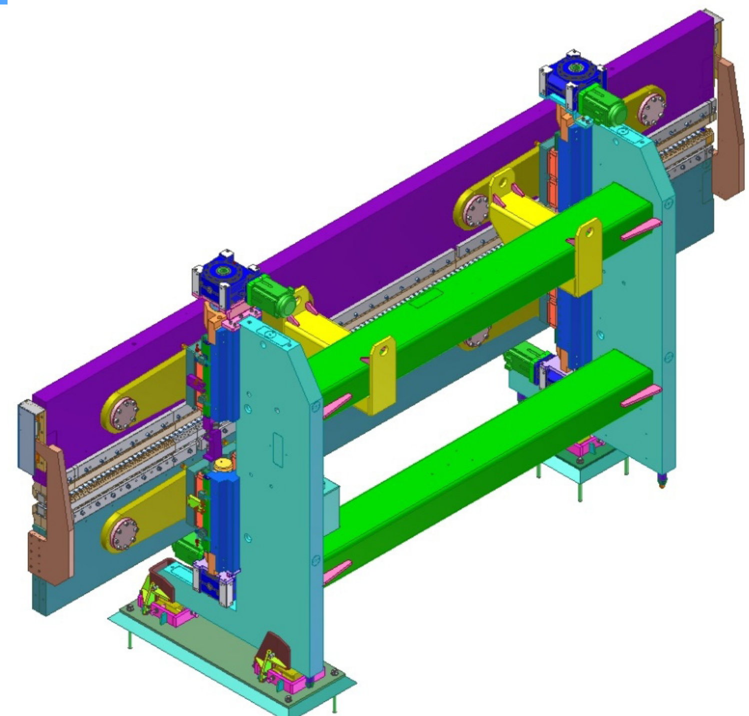


- Two FEL beamlines in the first phase: one soft X-ray (SXFEL1) and one hard X-ray (HXFEL1)
- **Planar Undulator + EPUs** in soft x-ray FEL provides the capability of **full polarization control**

XFEL	HXFEL1	SXFEL1
Beam Energy [GeV]	10.0	3.15
Wavelength [nm]	0.7 ~ 0.06	3.0 ~ 1 .0
Wavelength tuning	Beam energy: 0.7 ~ 0.1 Gap change : 0.1 ~ 0.06	Undulator gap
Undulator type	Planar	Planar+EPUs
Undulator period [mm]	26.0	35.0
Undulator gap [mm]	8.3	8.3

PAL-XFEL General





- To reduce the development efforts and period, EU-XFEL undulator design is benchmarked. A MOU to use the EU-XFEL design is agreed on 2011 June between PAL and EU-XFEL.
- The design is proved in FLASH, and PETRA, and it's cost effective and adapted for mass serial production.
- PAL modification includes, new magnetic design, EPICS control, updated tolerances reflecting new parameters.
- Application of tilt-meter for extra safety, "local" touch screen for easy maintenance. Midplane moving capability is implemented.

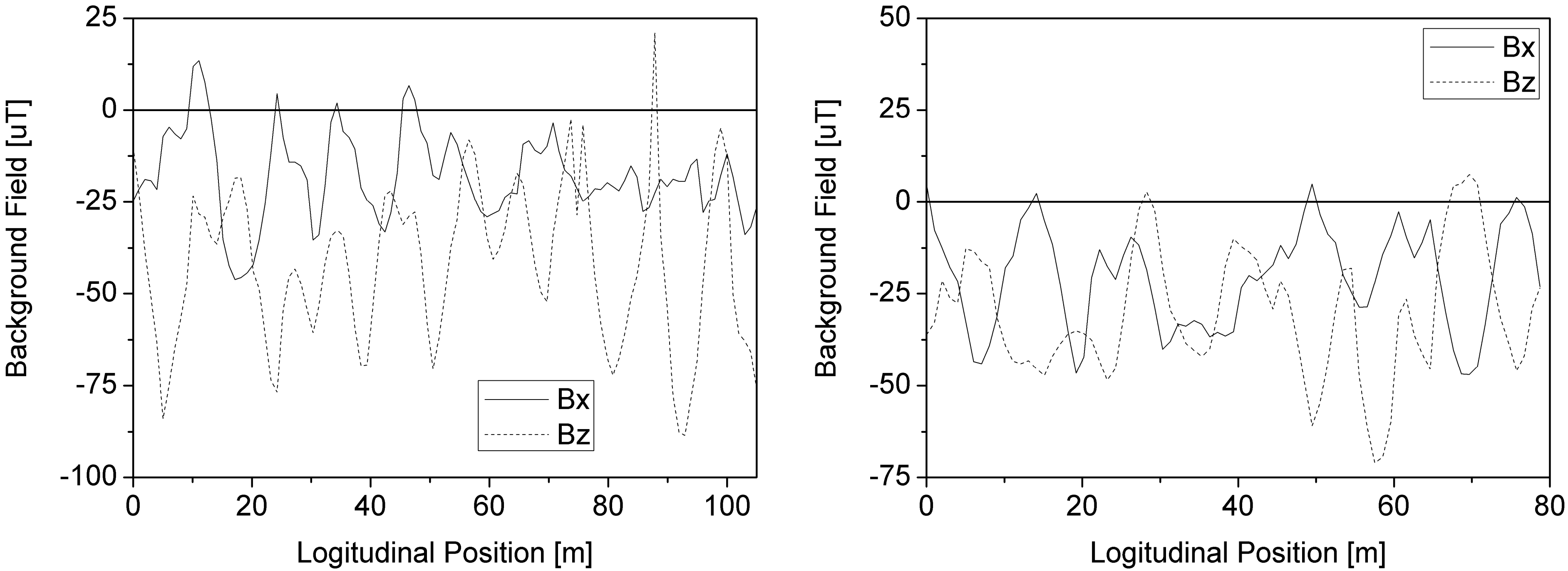
Basic Undulator Parameters of PAL-XFEL

	Unit	HX min gap	HX max gap	SX min gap	SX max gap
E	GeV	10.000	10.000	3.150	3.150
g	mm	8.30	11.39	8.3	15.0
λ_u	mm	26.0	26.0	35.0	35.0
I_p	A	3000	3000	2500	2500
λ_r	nm	0.1000	0.0600	3.0000	1.0000
ε_n	mm mrad	0.5	0.5	0.5	0.5
β_X	m	20.0	20.0	12.0	12.0
β_Y	m	20.0	20.0	12.0	12.0
σ_e	Unitless	1.00E-04	1.00E-04	3.17E-04	3.17E-04
Lg	m	3.14	5.69	1.03	1.63
Lg/Lg1D	Unitless	1.32	1.85	1.22	1.24
Pbeam	TWatt	30.0	30.0	7.9	7.9
Psat	GWatt	13.8	5.5	17.0	10.6
Lsat	m	58.0	99.6	21.1	32.2
K	Unitless	1.9727	1.2390	3.3209	1.5306
B_{eff}	Tesla	0.8124	0.5102	1.0159	0.4682

Measurement Benches

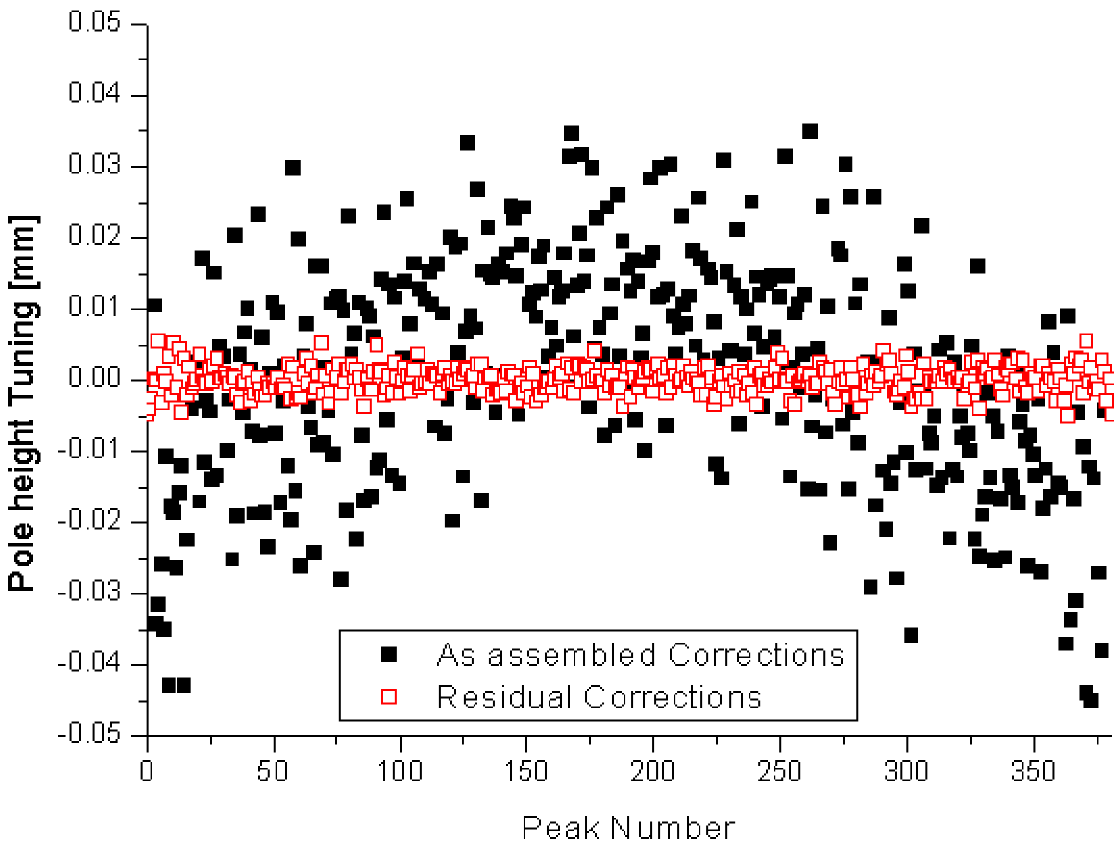
- Purchased 2 measurement benches expecting 3 bench week to process 1 undulators.
- 2 temperature controlled (±0.1 K) measurement rooms are set up. Helmholtz coils are setup to simulate the background field.
- Different Hall probes has a slight different scaling. (about 4 X 10^{-4}). Another 3rd party Hall probes (known to have better accuracy) are purchased and used for calibrating the existing hall probes.
- The company supplied "Moving wire" system which uses direct integration was not precise enough. We had to modify it to use analogue integrator for better accuracy and reproducibility.
- The stretched wire system is calibrated using a small "standard magnet" with known field integral with broad "good field region".
- The field integral data from Hall probe was not precise enough (planar hall effect, impact of even order calibration error), and stretched wire integral measurement is used to tune the Hall scan data.

Background Earth Field



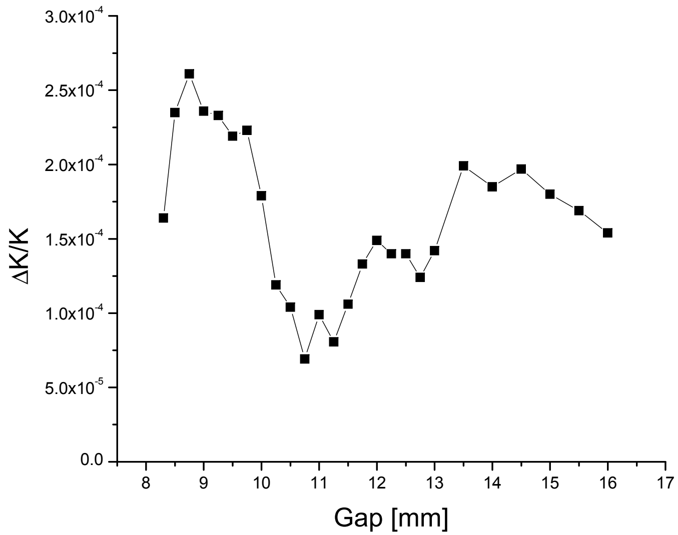
- Background Bz, Bx fields are measured for each undulator position. The average is about -25 uT (Bx), -40 uT (Bz). Oscillatory structure reflects the building structures.
- The measured field is averaged and reproduced at the measurement bench using coil fields.
- Any mismatch between the measurement environment and the real field can be compensated using the “two-wire” corrector which is built into the vacuum chamber.

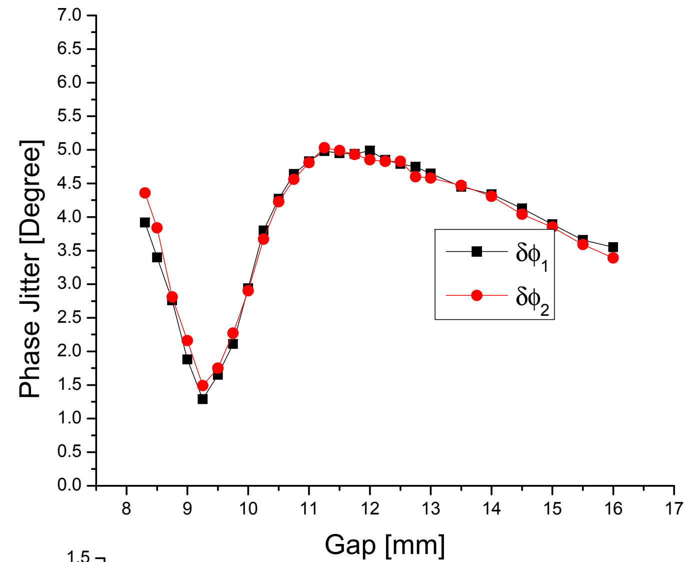
Example of Calculated Corrections

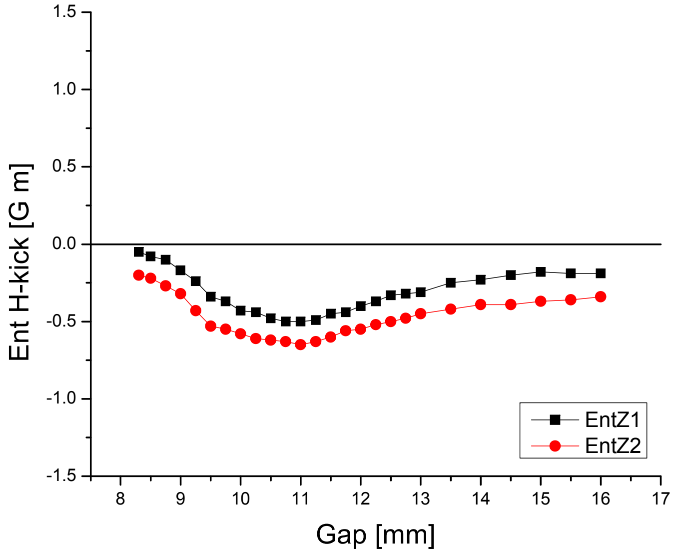


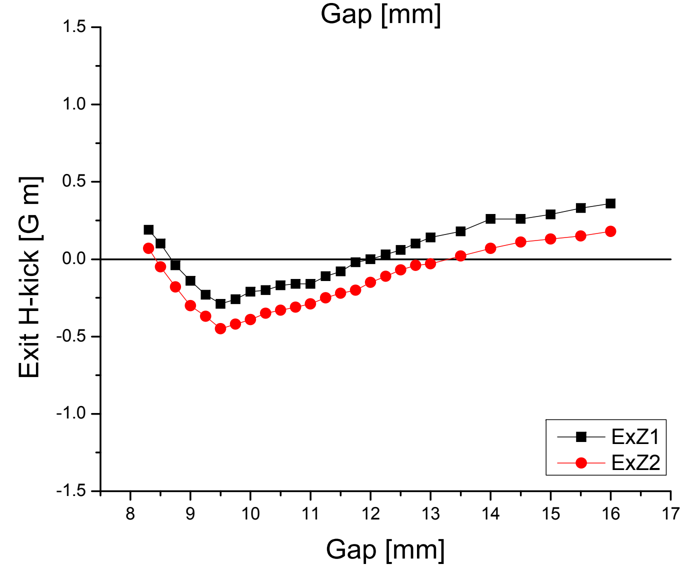
- Black square are required corrections based on the magnetic measurement just after delivery. Phase jitter as delivered is between 10-13 degree
- Red circles are required corrections based on the magnetic measurement after the 1st pole height tuning. After 1st pole height tuning, phase jitter reduces to 1-2 degrees.

SN110 Install, Deinstall Impact on K, Phase jitter, Entrance Exit kicks



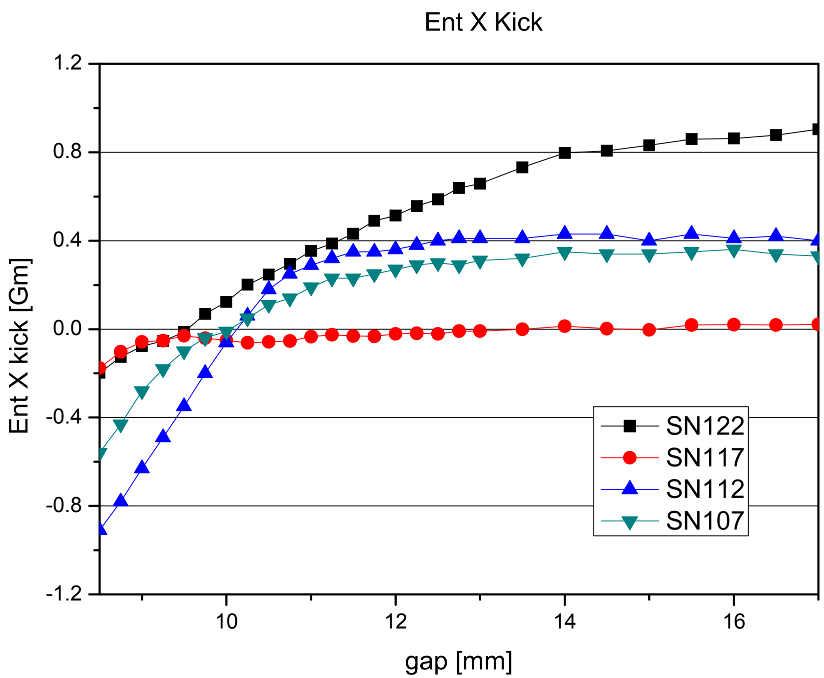


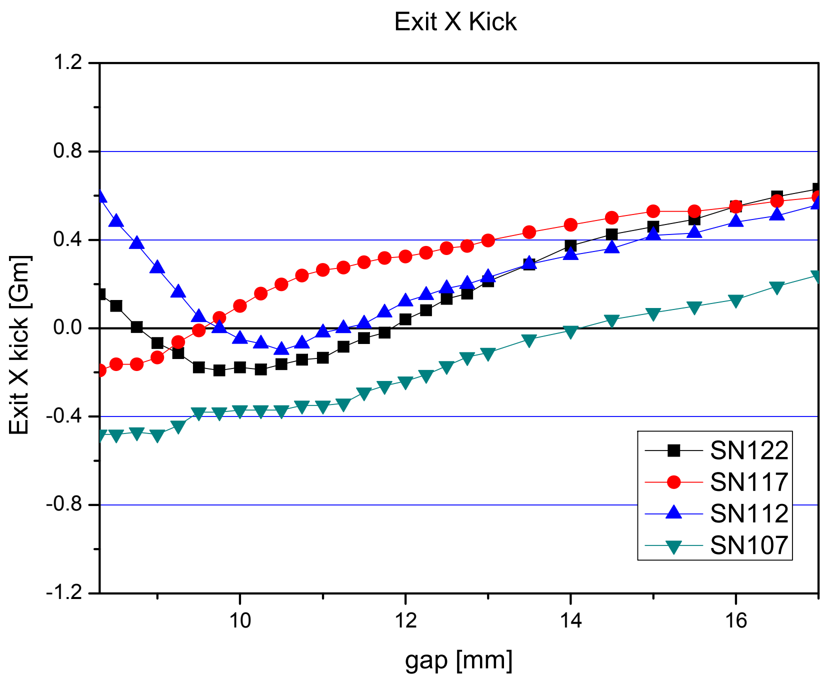




For Phase jitters, and entrance, exit kicks, the graph range is allowed specifications.

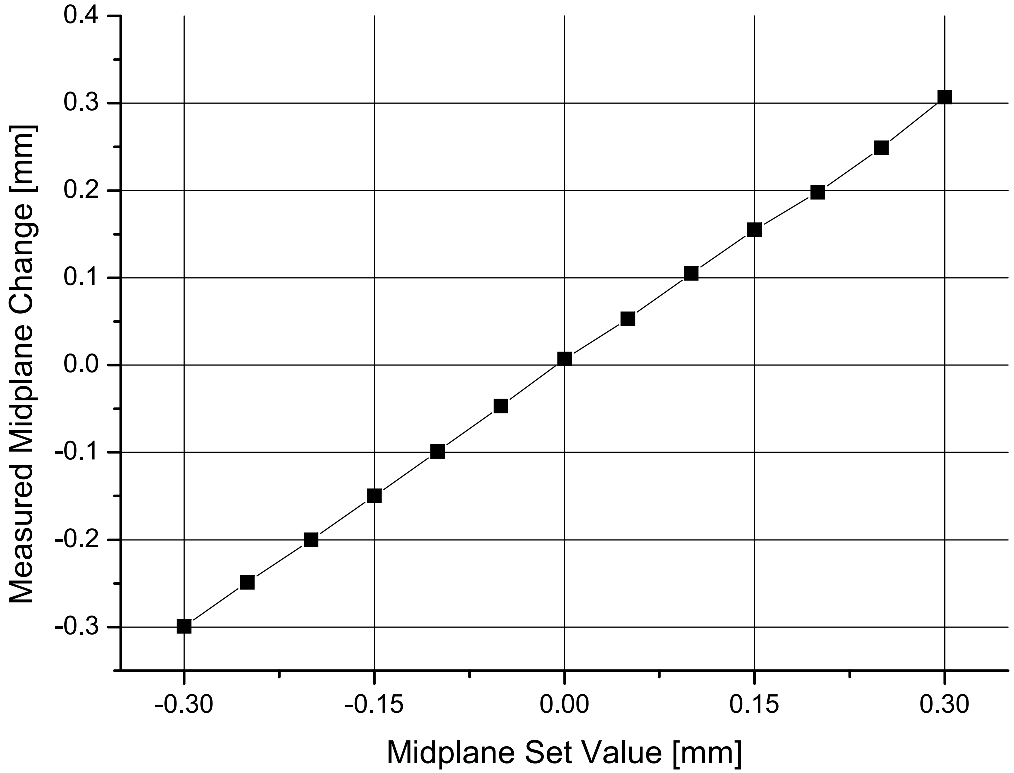
Gap Dep Ent/Exit Kicks





- Ent Horizontal Kicks are calculated to straighten the orbit.
- Exit Horizontal Kicks are calculated to compensate the residual integral.
- The results are calculated by combining the Hall scanning results and the moving wire integral measurements.
- All are within the requirements of 1.5 Gm.
- Required V-kicks are far less than the H-kick and not shown here.

Midplane Moving Experiment

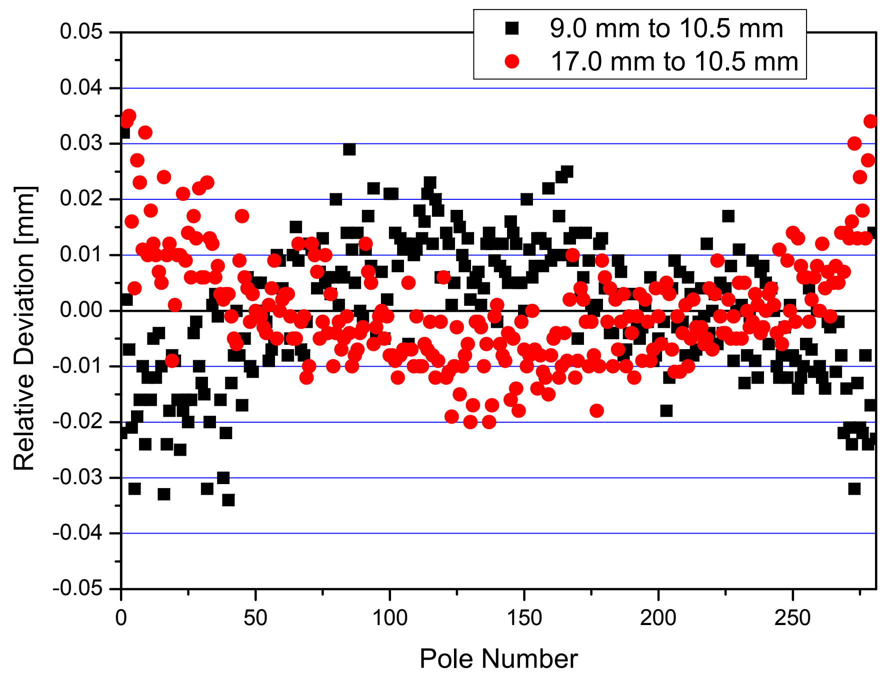


- Undulator midplane is shifted from -0.3 mm to +0.3 mm mechanically, and the magnetic measurement is carried out to confirm the impact.
- The results shows excellent agreement between the mechanical offset and the measured magnetic offset.
- Midplane moving feature is used for undulator commissioning. TUP021, T. Tanaka et al., PRSTAB **15**, p110701.

Installed Photograph

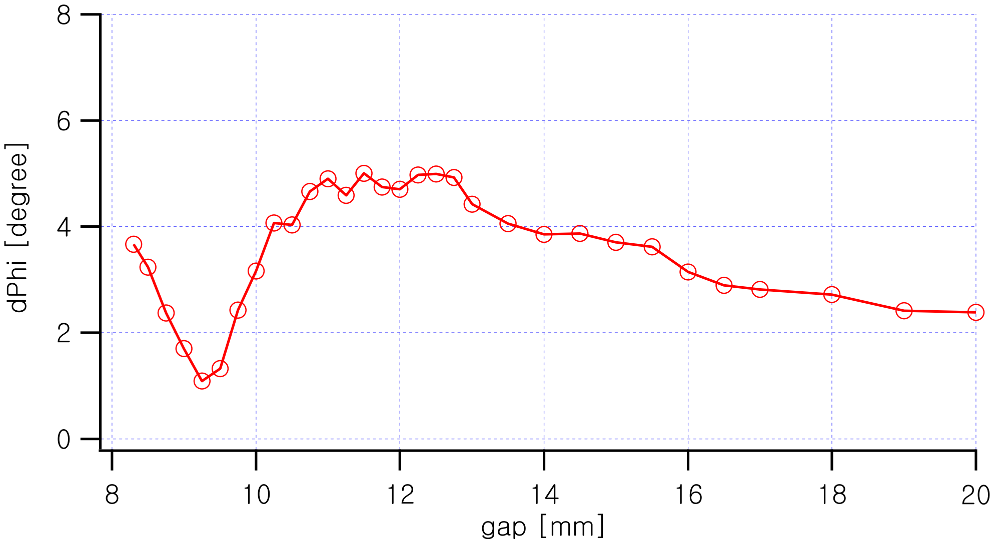
- 20 HXU Undulators, and 7 SXU Undulators are installed at the undulator Hall.

Girder Deformation



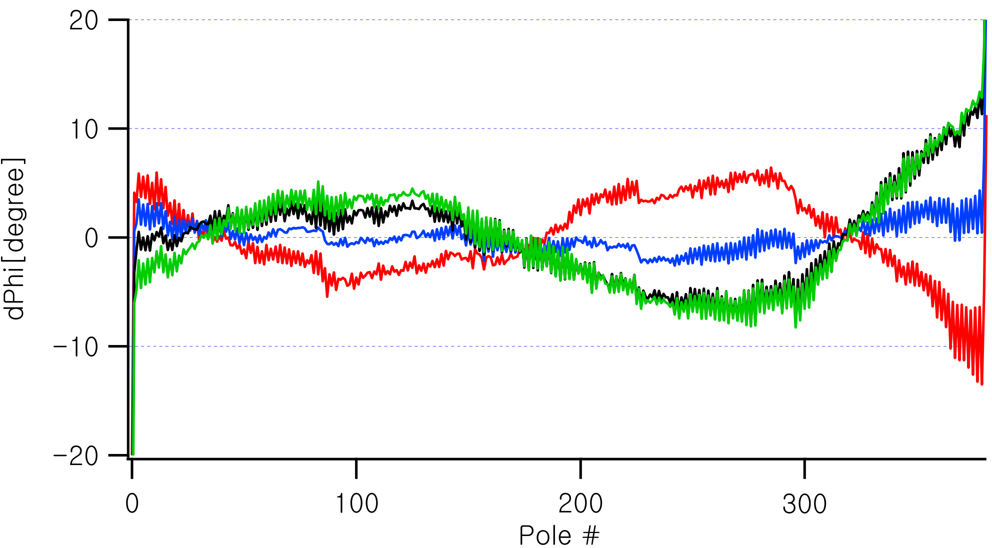
- Al girder deformations are estimated for working gap range.
- Required pole height tuning are calculated for several gaps.
- The difference in the required correction represents the girder deformation.
- Assuming a flat girder at the tuning gap, the girder deformations is about ±30 μ m for working gap range.

Gap Dependent Phase Jitters

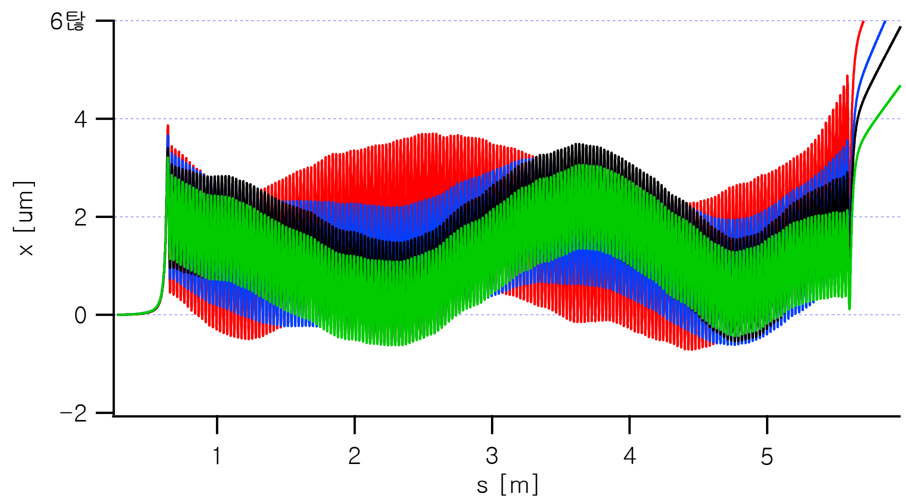


Gap dep phase jitter

When we move away from the "tuning gap", the phase jitter shows typical signature of the small girder bending.



Phase jitter profiles for several gaps



E-orbit for several gaps

Phase Matching of an Undulator Cell

- Slippage of an undulator cell (undulator+drift) should be integer multiple of the radiation wavelength (Or the phase advance should be integer multiple of 2pi)
- Slippage coming from the (1) slower electron speed (less than the speed of light) (2) electron wiggling should be added.

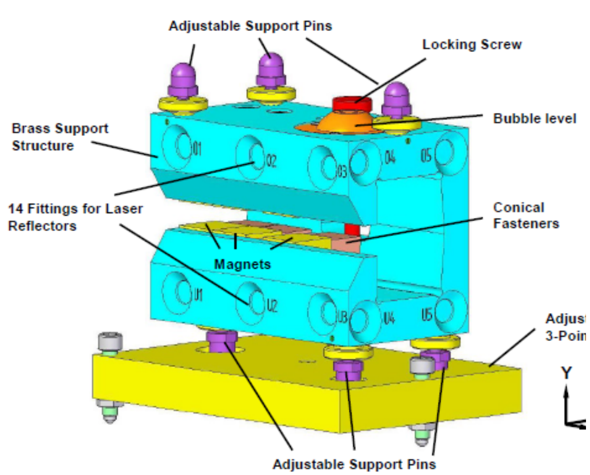
$$s = \frac{1}{2\gamma^2} L + \frac{1}{2\gamma^2}\left(\frac{e}{mc}\right)^2 PIu(gap) + \frac{1}{2\gamma^2}\left(\frac{e}{mc}\right)^2 PI_{PS}(gap) = n \times \lambda_R$$

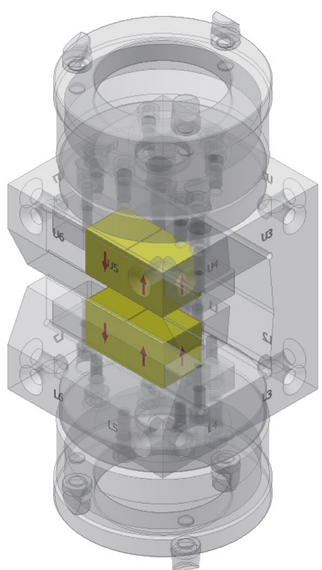
- L is the length of an undulator cell: 6.05m
- Undulator gap is determined from the radiation wavelength and e-beam energy therefore determining K.
- Phase shifter gap is calculated to meet the matching condition.

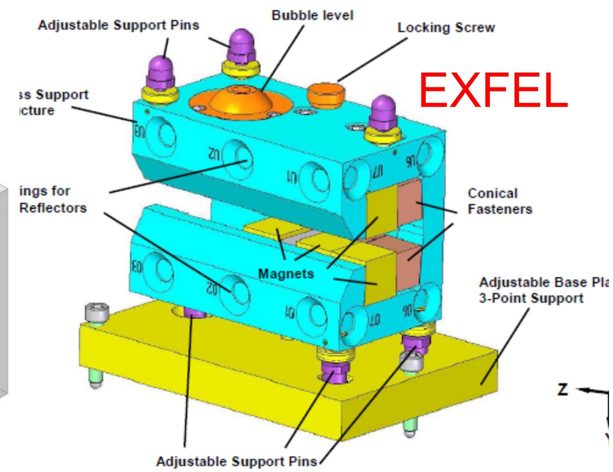
Data processing of the measurement results

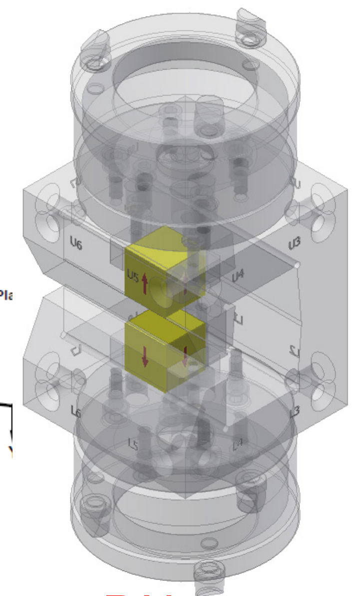
- Interpolate gap vs K in evenly spaced gap using piece-wise continuous polynomial (cubic spline).
- Use the table (linear interpolation) to calculate the required gap for specific K.
- Interpolate gap vs $(PI)_U$ in evenly spaced gap using piece-wise continuous polynomial (cubic spline).
- Calculate the phase integral for drift, undulator using the tables.
- Calculate the nearest integer meeting the matching requirements.
- Interpolate gap vs (PI)PS in evenly spaced gap using piece-wise continuous polynomial (cubic spline).
- Calculate the required (PI)PS for the matching. Invert the table to calculate the 1st estimation of the PS gap.
- Tune the PS gap for [–pi, pi] scan for accurate matching.

Landmark Magnet









EXFEL

Normal Position

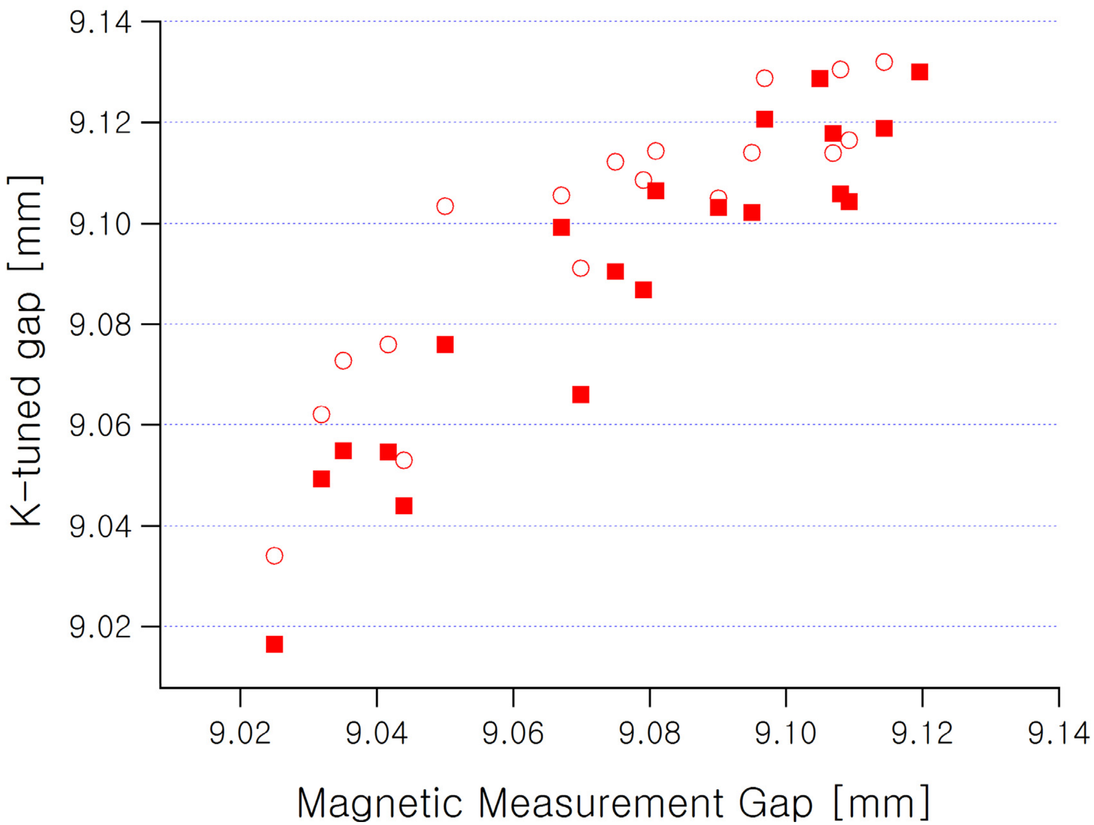
PAL

Flipped Position

PAL

- Benchmark magnets to be used to transfer the measurement coordinates, to mechanical coordinates are being redesigned following EU-XFEL benchmark magnet.
- X landmark is in normal Quad, Z landmark is in Skew Quad configuration.
- X (Horizontal), Z (vertical) landmark magnet is splatted because of limited transverse scanning range. Worked better.
- Normal and Flipped measurement (magnetic, SA) determines the offset between the mechanical center and the magnetic center.
- It’s an upgrade of the “wedge” magnet used in other lab.

Some Results of K-tuning



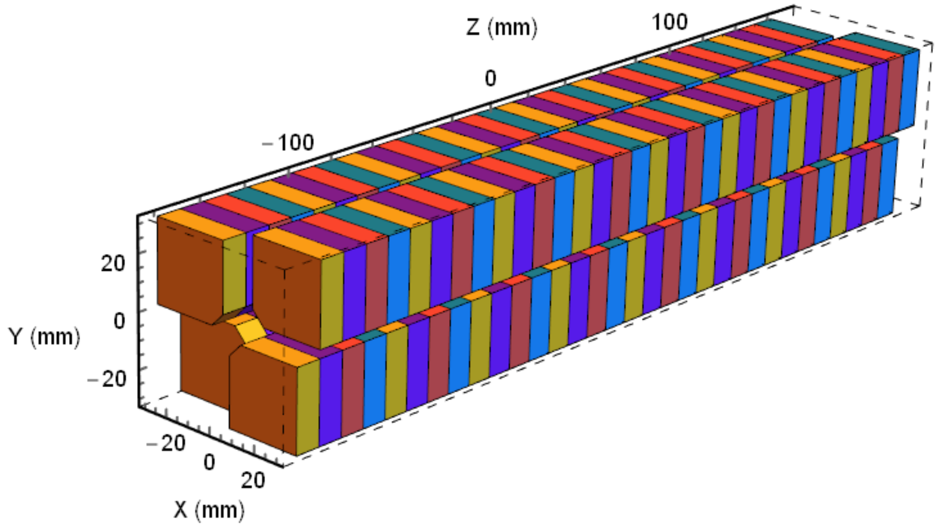
- Plotted two independent K-tune results vs the magnetic measurements.
- Compare linearly with measurement although not perfect (max 40 um difference)
- K-tuning has also reproducibility errors.
- The difference can be explained by offset in midplane, or temperature errors.

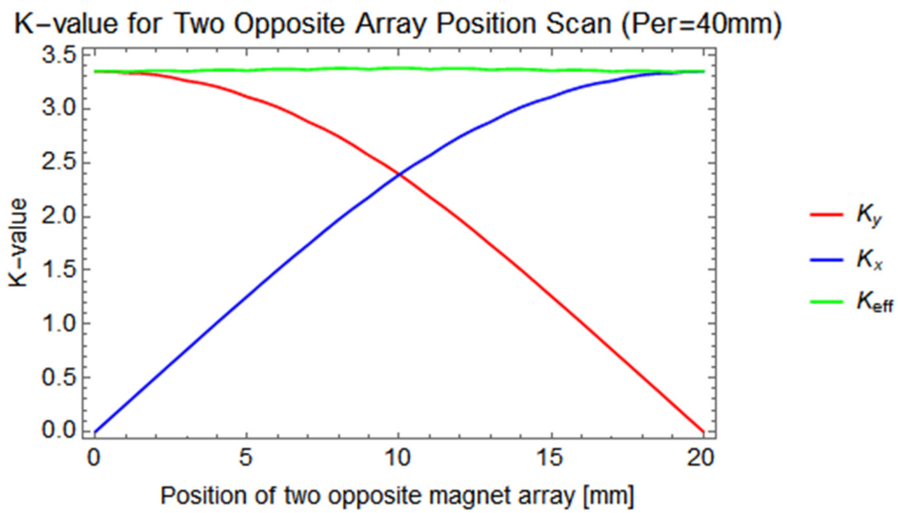
Near term (a few years) Plan

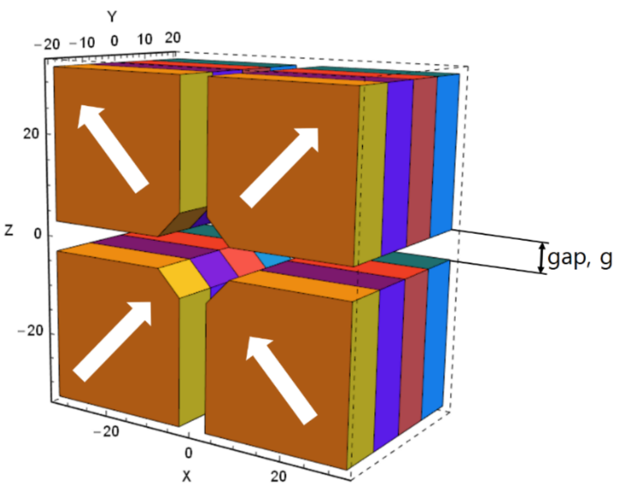
- Need to add more SXU undulators to reach 1.0 nm saturation. (with 7 undulators, saturation upto 1.5 nm is reached).
- Need to add EPUs for SXU afterburner polarization.

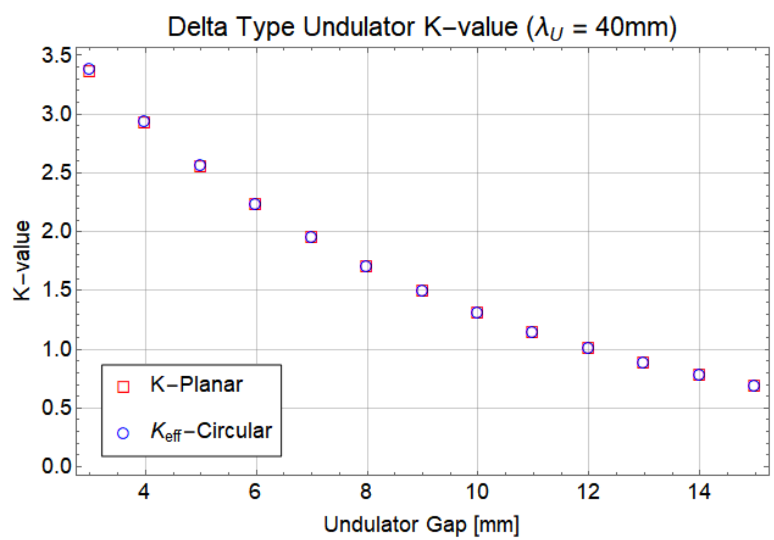
Radia Model of Apple-X type EPU

For polarization control of the SXU lines, Applex-X typ EPUs afterburners are being considered following PSI.









Discussions and Summary

- 20 HXU undulators with 19 phase shifters installed at the end of 2015.
- 7 SXU undulators with 6 phase shifters are installed by May 2015.
- All measurements data are analyzed and implemented to the control system and commissioned successfully.
- BBA was very important for early lazing. For HXU, compression optimization resulted initial lazing with measured undulator phase shifter settings. For SXU, first lazing happened while BBA iteration is converging with measured gap settings for undulators and phase shifters.

- Need to install a few more planar undulators, and EPUs for SXU BL for saturation in 1.0nm and polarization control.

- Thank you so much for your attention!

Acknowledgements

- Special thanks to EU-XFEL Undulator team for kindly allowing us to use their design, and sharing their valuable experiences. Their help contributed a lot to save efforts, costs and the project schedules.
- Particular thanks to Drs. Joahim Pflueger, Yuhui Li, Suren Karabekyan and many others.