UNDULATOR COMMISSIONING EXPERIENCE AT PAL-XFEL

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Abstract

Pohang Accelerator Laboratory (PAL) is developing a 0.1 nm SASE based FEL based on 10 GeV S-band linear accelerator named PAL-XFEL. The hard X-ray undulator line requires 20 units of 5 m long hybrid-type conventional planar undulator while soft X-ray line requires 7 units of 5 m long hybrid type planar undulators. All 20 HXU undulator, and 7 SXU undulators are successfully measured, tuned, and installed in the tunnel. Also the control system integration was successful. The measurements results are spline fitted to calculate the required gap of the undulator, and the phase shifters when K, and phase numbers are given. Initial commissioning was based on the magnetic measurement data, and further optimization of the lazing used K-tuning, and the midplane scanning of the undulator. In this report, phase matching scheme of the undulator cell, and the commissioning experiences are summarized.

INTRODUCTION

The Pohang Accelerator Laboratory (PAL) has been developing SASE based light sources since 2011. The target wavelength is 0.1 nm for hard X-ray SASE radiation, with 10 GeV class S-band linear accelerator [1]. For soft X-ray SASE, 3.0 nm FEL radiation using 3.15 GeV electron beam is assumed. To achieve this target, a few key components like low emittance (0.5 μm) photo cathode RF gun, and EU-XFEL style out vacuum undulator system are being developed [2]. For undulator system, there will be 20 undulators for hard X-ray line and 7 planar undulators with additional two EPUs (Elliptically Polarized Undulator) are expected for soft X-ray line. The EPUs will be used for polarization control at the last stages of lasing and are planned to be installed in later phase. The major parameters of the undulator system is summarized in Table 1. And schematic layout of hard X-ray, and soft X-ray undulator lines are shown in Fig .1.
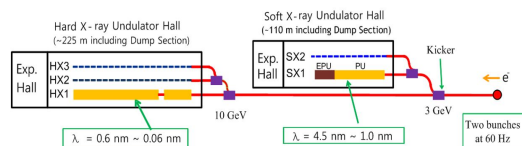

Figure 1: FEL undulator line plan of PAL-XFEL.

UNDULATOR TUNING, MATCHING, COMMISSIONING

For the PAL-XFEL undulators, the EU-XFEL undulator design [3], [4] was adopted and modified for PAL-XFEL.

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Table 1: Major Parameters of the PAL-XFEL Undulator System

Parameter	Unit	Value	Value
Undulator Line		HXU	SXU
Beam energy	GeV	10.0	3.15
Min gap	mm	8.30	9.00
Period	mm	26.0	35.0
Length	m	≃5.0	≃5.0
B_{eff}	T	0.812	1.016
K		1.973	3.321
Phase jitter	deg	< 5.0	< 5.0
Number		20	7

The magnetic gap, and period is changed with new magnetic geometry reflecting PAL-XFEL requirements. Also a precise tilt meter is installed in the magnetic girder to complement the safety feature of the magnetic girder. The control system is adapted to EPICs system for direct integration with other system. EU-XFEL undulator design features a unique pole height tuning mechanism, that enables to move a pole height using locking screws. The pole height tuning scheme is fully utilized to tune all the undulators. It was very essential in speeding up the undulator preparation.

The expected operating gap of the PAL-XFEL hard X-ray undulator (HXU) is between 8.3 mm to 12.5 mm producing 0.1 nm to 0.06 nm SASE radiation at 10 GeV e-beam energy. The undulator tuning gap is decided to be 9.5 mm balancing the errors for both extreme of the operating undulator gaps. Therefore, the HXU undulator is very optimal at the tuning gap, and deviates from the best condition as we move away from the tuning gap. The undulator and phase shifters are measured with 0.25 mm gap steps (0.50 mm gap step for larger gap), up to the maximum expected operating gap of 20.0 mm. The total scanning gap was 35 gaps and 5 independent measurements are carried out for final data collection. The average of the 5 data sets are used a final data. The undulators installed in the tunnel is shown in Fig. 2.

The undulator should be tuned to guarantee a straight orbit inside the undulator to maximize the overlap between the electron path and the photon path. Also, any background field offset error in the undulator measurement can affect the real orbit and can easily result in larger optical phase jitter. Estimation showed that any error in the background vertical field about 20 μT can contribute increases in the phase jitter by 5 degrees. Particularly, the vertical field error affects the orbit, and the phase jitter more seriously than the horizontal background field error. The horizontal field error

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T15 Undulators and Wigglers
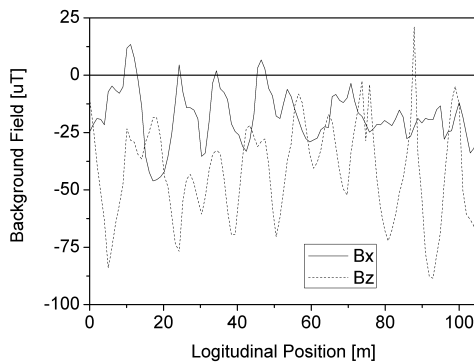
Figure 2: Undulators installed in the tunnel.

Figure 3: Measured background earth magnetic field at the Hard Xray Undulator installation site.

is partially shielded by the poles and the influence on the orbit is limited.

The background earth fields at the undulator installation site are measured using a fluxgate. It showed fluctuating profile that can be attributed to the building steel structures. Average of background field for a undulator site is used to represent the ambient field that was reproduced in the measurement room using Helmholtz coils. As shown in Fig. 3, and Fig. 4 vertical background filed is about 40 μT while the horizontal background field is about -20 μT.
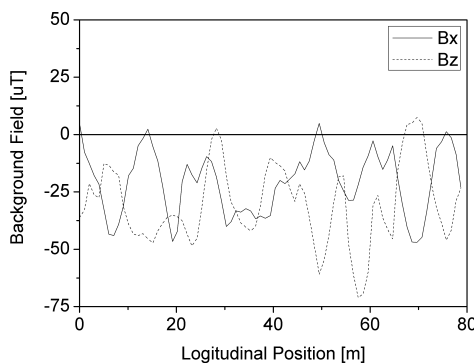

Figure 4: Measured background earth magnetic field at the Soft Xray Undulator installation site.

$$s = \frac{1}{2\gamma^2} L + \frac{1}{2\gamma^2} \left(\frac{e}{mc}\right)^2 PI_u(gap_u)$$
$$+ \frac{1}{2\gamma^2} \left(\frac{e}{mc}\right)^2 PI_{PS}(gap_{PS}) = n\lambda_R$$

As usual, phase integral is defined by following equation.

$$I_1(z) = \int_{-\infty}^{z} B_y(z')dz', \quad PI(z) = \int_{-\infty}^{z} I_1^2(z')dz'$$

In above equations, γ is the usual electron energy, s is the slippage between the photon and electron, e is the electron charge, m, c and L are electron mass, the velocity of light and the period of the undulator cell respectively. Also λ_R is the radiation wavelength, and n is a "phase number" representing the phase advance in multiples of 2π. In principle, the slippge betwen the electron and the light should be integer multiple of the radiation wavelength. The slippage comes from thee contributions. The 1st slippage comes from the difference in speed between the electron and the light, the second term comes from the undulating motion of the electron which effectively slows down the longitudinal speed of the electrons. The third contribution comes from the phase shifter. The purpose of the phase shifter is to match the total slippage to be integer multiple of the radiation wavelength. In this setup, each undulator segment can radiate in phase to act as an long undulator which is critical in SASE amplification.

Each undulator is measured with very fine undulator gap steps with 0.25 mm gap change at smaller gaps and 0.5 mm gap change for larger gaps totaling 35 measured gaps for each undulator. 5 independent measurements sets are carried out for final data collection and the average of 5 measurements are used as a final measurement data. Instead of interpolating the measurement data for whole gaps, local piecewise spline fittings are used to interpolate the K, phase integral of each undulator and phase shifters. For given undulator K and phase number undulator gap is determined from the inverting the cubic-spline data. Given phase number and from the phase integral contribution from the drift and from the undulator, we can decide the phase shifter gaps. For initial operation, low phase numbers ($\simeq 1$) is chosen, to weaken the sensitivity of the slippage with phase shifter gaps. Initial lazing was successful with gaps calculated from the magnetic measurements of the undulator and phase shifters. After initial lazing, K-tunings of each undulator and midplane scannings are carried out to study in detail [5] [6].

In Fig. 5, the calculated gaps from the magnetic measurements, and from the K-tuning results are shown for a specific K=1.87 for 20 HXU undulators. We can notice that (1) the linearity between the measured gap and the measured gap from K-tune is good although not perfect. For a given measurement gap, the K-tuned gap changes maximum ±20 μm. (2) Fig. 5 shows the results of two independent K-tune gaps separated 2 months (open circle, and filled square), although two measurements are showing similar trends, they show

different gaps with maximum difference of 20 μm. (3) The K-tuned gap is always slightly larger than the measurement gap. This can be explained if the undulator is not exactly located at the magnetic midplane. The deflection parameter K increases when one moves away from the midplane. If an undulator has on offset in midplane, the undulator gap should be larger to compensate the increase.
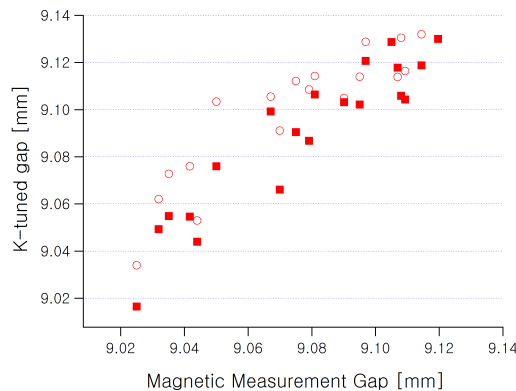

Figure 5: The gap calculated from magnetic measurement, and gap measured using K-tuning.

CONCLUSIONS

All 27 PAL-XFEL undulators are successfully measured and tuned. The local-K pole tuning procedure was developed and tested. For the field corrections the three next nearest neighbors were included into the correction signatures. Tuning was very effective, and a single iteration of pole height tuning could reduce the local-K fluctuations by one order of magnitude. The optical phase error at the tuning gap after pole height tuning is between 1 and 2 degrees. At the tuning gap, the undulator structure is well optimized. However, as we deviate from the tuning gap, the girder deforms in parabolic shape and the phase jitter shows typical S structure which is signature of the parabolic bending. For all operating gap range which is 8.3 mm to 12.5 mm for HXU undulators, the phase jitter meets the specification of 5 degrees. All other undulator properties, like entrance/exit kicks are also calculated from the magnetic measurements. All operation related data are tabulated, and fitted within the tuning gap range.

The background fields at the installation site are pre-measured and reproduced in the measurement bench. The remaining vertical background field errors can be compensated by using the built-in two-wire correctors in the vacuum chamber. But, until now, it's not used since the measurement results are working.

All undulators are installed including 20 HXU (Hard Xray Undulators), and 7 SXU (Soft Xray Undulators) in the tunnel and they are successfully integrated to the control system. The magnetic measurements results of the undulators, and the phase shifters are used for initial commissioning of the SASE lazing. After initial lazing, K-tuning, and vertical midplane scanning [5] are carried out to optimize the SASE lazing [7]. The gap based on the magnetic measurement and the gap from the K-tuning shows good agreement. The difference can be attributed to the (1) the measurement error in K-tuning (2) possible misalignment in the midplane of the undulator. Detailed evaluation of the midplane misalignment, and the accuracy of the K-tuning are being planned.

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