PERFORMANCE OF THE 3.4-METER LONG VERTICAL POLARIZING UNDULATOR PROTOTYPE FOR LCLS-II*

N.Strelnikov[1], I.Vasserman, J.Xu, and E.Gluskin, Advanced Photon Source,
Argonne National Laboratory, Argonne, Illinois 60439, USA
[1]also at Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

Abstract

As part of the LCLS-II R&D program, a novel 3.4-meter long undulator prototype with a horizontal main magnetic field and dynamic force compensation — called the horizontal gap vertical polarization undulator (HGVPU) — has recently been developed at the Advanced Photon Source (APS). Initial steps of the project included designing, building, and testing a 0.8-meter long prototype [1]. Extensive mechanical testing of the HGVPU has been carried out. The magnetic tuning was accomplished by applying a set of magnetic shims. As a result, the performance of the HGVPU meets all the stringent requirements for the LCLS-II insertion device [2], which includes limits on the field integrals and phase errors for all operational gaps, as well as the reproducibility and accuracy of the gap settings. The HGVPU has been included in the baseline of the LCLS-II project for the hard x-ray undulator line.

INTRODUCTION

The absolute majority of synchrotron radiation (SR) sources, including free electron lasers (FEL), utilize insertion devices (IDs) with a vertically-oriented magnetic field. This preferential direction is the result of the strong asymmetry – the horizontal size is much larger than the vertical one – of the electron beam cross-section in the storage rings, which is the main source of SR. Although electron beams in FELs are quite symmetric in the transverse plane, ID designers have not yet taken real advantage of this. The status quo (even that of SR sources) will soon be changed because of the recent advancements in the design of ultra-small emittance storage rings. Such machines promise to operate with round electron beams and execute on-axis injection. Therefore, developments of novel planar IDs with horizontal magnetic fields will become a practical matter.

There are at least two major advantages for horizontal magnetic field IDs. One is related to the rotation of the polarization plane of emitted radiation, which results in the transformation of monochromators and experimental set-ups to the “gravity neutral” systems. In many cases it would significantly simplify the construction and operation of these set-ups. The second advantage is also related to the “gravity neutral” design, but now applies to the undulator’s mechanical system. When such a design is combined with the magnetic force compensation system, the ID gap drive mechanisms become quite compact without sacrificing stringent requirements on the accuracy and reproducibility of the ID gap control.

Currently all FELs around the world utilize the traditional approach as to the design of the ID gap drive mechanisms, regardless of the type of IDs. These designs are loaded with very strong, often bulky, beams that are able to withstand tremendous magnetic forces without noticeable distortions, and with very precise mechanical components that permit the control of the ID magnetic gap value at the micron level. Typically, the fabrication of such devices requires unique machine tools that can process several meter beams within a few microns of precision [3, 4, 5, 6, 7].

The alternative ID design based on the “gravity neutral” concept with the dynamic compensation of magnetic forces has recently been developed at the APS. The undulator’s 2.6-cm period magnetic structures are supported by two 3.4-m long, 15-cm thick and 20-cm tall aluminium strongbacks. Each strongback is placed on two linear slides that allow independent horizontal motion. The position of the strongbacks, and therefore the gap of the undulator, is controlled by 4 linear actuators, 2 for each strongback. The linear actuators are preloaded with constant force springs at the linear slides. Special force compensation systems have been designed and constructed to closely match the magnetic force gap dependent function [1]. The HGVPU prototype system is shown in Fig. 1.

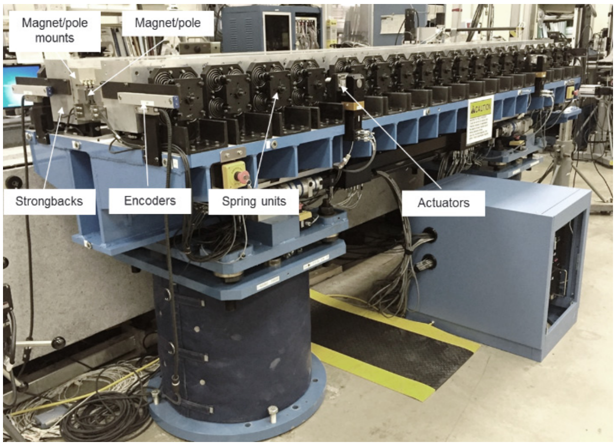

Figure 1. HGVPU at the APS ID magnet measurement facility.

HGVPU ASSEMBLY AND MECHANICAL TUNING PROCESS

The length of the prototype magnetic structure populated with magnets and poles is 3.4 meters long. The

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poles were mounted on the magnet/pole mounts. The magnets were inserted in between the poles according to the sorting sequence and then clamped onto the positions. The mounts were fastened onto the strongbacks by the mounting bolts. There are 3 sections of magnet/pole mounts on each strongback. The mounting bolts were pre-loaded with a set of three belleville washers, arranged in serial, each with a working force of 1,000 lbs, which is 18 times the highest magnetic force on each bolt. The adjustment of the mounting bolts can be accessed from the back of the strongbacks so that the straightness of the poles can be adjusted at the smallest gap to the LCLS-II specifications of ±10 µm.

The strongback assemblies were then placed on the linear slides and gauged to the gap of 30 mm. The spring units were calibrated and locked at the position equivalent to the gap of 30 mm. They were installed one at a time while the gap was monitored to ensure that the position of the spring unit is correct within ±5 microns.

Once the spring units were all mounted, the gap was closed step-by-step while monitoring the forces on the actuators. Since the units were calibrated against the calculated magnetic force, there were offsets that needed to be set by adjusting the spring unit's main shaft lock nut to set the position of the spring compression plate so the real magnetic forces at the smallest gap could be matched within ±30 lbs.

After the assembly of the device, the pole heights were measured with the Capacitec gap measurement system. The system consists of two Capacitec HPS-1x4G-A-200-FX sensors mounted back-to-back with a distance adjuster. The dimension of each sensor is 2.0 mm in the horizontal and 4.0 mm in the vertical direction. Each sensor is calibrated by the vendor to the accuracy of 0.1 microns. Measurement results show no observable lower order deflections of the strongbacks at different operational gap settings.

The heights of the poles were then adjusted by adjusting the pole/magnet mounting bolts at the gap of 7.2 mm as shown in Fig. 2. The height of the poles on each strongback as well as the gap profile was verified at different gap settings to be better than ±10 microns.

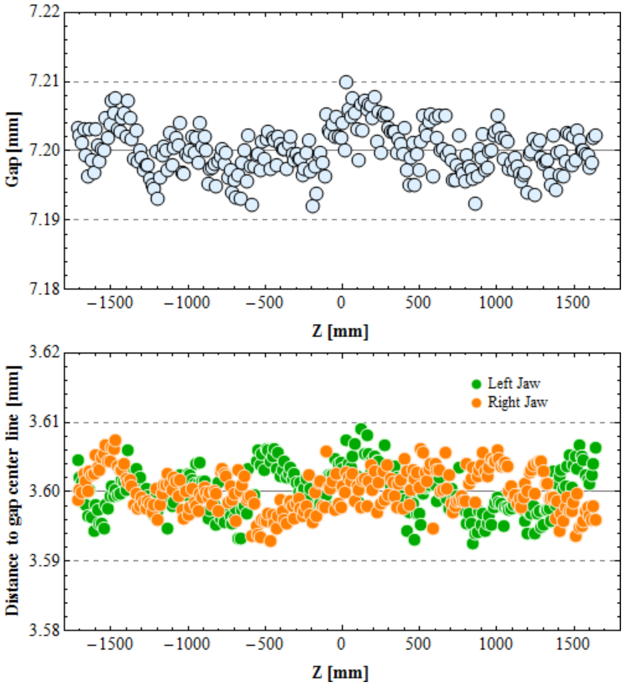

Figure 2: Straightness of the poles (bottom) and gap (top) along the device.

TRAJECTORIES AND PHASE ERRORS

The next step is the magnetic tuning of the HGVPU. It includes tuning of the straightness of the trajectories in both horizontal and vertical directions and bringing RMS phase errors to the level of 4.0 degrees or lower for all operational gaps, as required by LCLS-II undulator specifications. The magnetic tuning of phase errors and trajectory is carried out by applying a special set of magnetic shims, starting at the operational gap of 7.2 mm.

After the trajectory tuning, the trajectory measurements were verified at several operational gaps. That led to the trajectory deviation within ±2.0 microns and the RMS phase errors below 4.0 degrees for all operational gaps (Figure 3 and Table 1). As shown in Figure 3, a corrector has been assumed at the upstream end of the device. In a real scenario, the corrector would be placed farther upstream and the trajectories would be corrected to be even more effective.

The effective field is over 1.06 T at the gap of 7.2 mm, which is better than the LCLS-II requirement of 1.01 T.

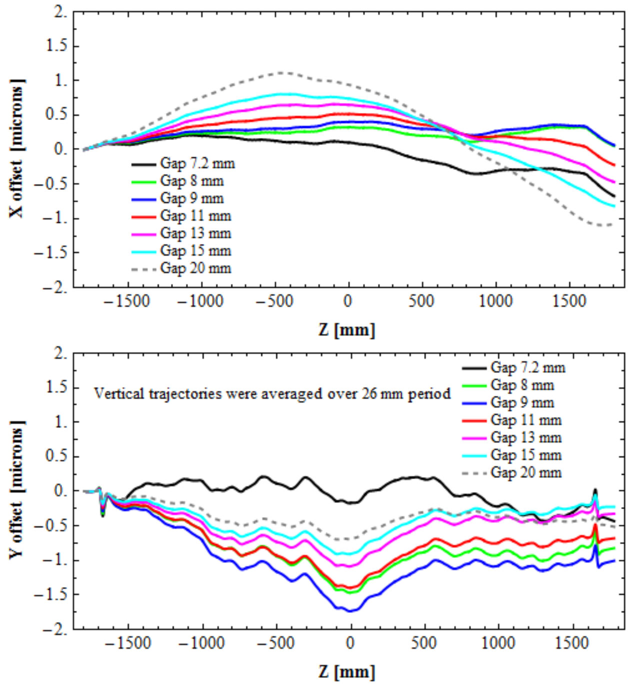

Figure 3: Horizontal trajectories (top) and vertical trajectories (bottom) after tuning (energy 14 GeV).

Table 1: HGVPU Prototype RMS Phase Errors and Effective Field

Gap	RMS phase error (deg.)	B(effective) (G)
7.2	3.34	10604
8.0	2.96	9451
9.0	3.33	8788
11.0	3.09	6217
13.0	2.62	4777
15.0	2.50	3705
20.0	1.44	1997
Req.	<4.0	>10100@7.2

FIELD INTEGRALS AND MULTIPOLES

Another set of magnetic shims is applied to meet the requirements for the 1st (J1x,y) and the 2nd (J2x,y) field integrals as well as the skew and normal quadrupoles (a1, b1), sextupoles (a2, b2), and octupoles (a3, b3). Table 2 shows the 1st and the 2nd integral tuning results. Table 3 shows the multipole tuning results.

Table 2: HGVPU Field Integrals

Gap (mm)	J1x (G-cm)	J2x (kG-cm^2)	J1y (G-cm)	J2y (kG-cm^2)
7.2	15	-0.9	36	2.3
8.0	-37	-4.6	26	0.2
9.0	-33	0.2	22	-0.4
11.0	-17	5.5	22	0.4
13.0	-2	3.7	20	2.5
15.0	10	5.5	13	4.1
20.0	35	8.1	-25	4.7
Req.	±40	±15.0	±40	±15.0

Table 3: HGVPU Multipoles

Gap (mm)	a1 (G)	a2 (G/cm)	a3 (G/cm^2)	b1 (G)	b2 (G/cm)	b3 (G/cm^2)
7.2	-20	-129	270	-26	83	-171
8.0	-36	-89	199	-1	48	-127
9.0	-41	-71	12	-1	42	-151
11.0	-15	12	-82	6	-17	-32
13.0	10	12	-71	6	-4	-32
15.0	24	25	39	59	-16	-50
20.0	68	23	-39	26	25	-18
Req.	±100	±200	±400	±100	±200	±400

A very important requirement for any FEL undulator is the reproducibility of the effective field for any gap setting. LCLS-II undulator specifications call for reproducibility and stability of the undulator parameter K at fixed gap $\Delta K/K$ to the level of $2.3\cdot10^{-4}$.

The long-term stability of the HGVPU has been studied with cycling the undulator gap of the system over 2000 times from maximum to minimum gap. The performance of the device has been measured with a Hall probe scan after every 50 cycles. Change of the effective field at a minimum gap was within $\pm1.1\cdot10^{-4}$. There is no evidence of any long-term drift or degradation of effective field. The standard deviation of the measured data is 0.36 Gauss vs. the requirement of 2.3 Gauss.

CONCLUSION

A full-length 3.4-meter long HGVPU with dynamic compensation of the magnetic forces has been successfully designed, built, tuned, and tested at the APS. The design is “gravity neutral” and uses a novel spring system for the dynamic compensation of the ID magnetic forces. The device delivers vertically polarized radiation. The performance measurement results show that all the LCLS-II requirements have been met. As a result, the HGVPU has been included in the baseline of the LCLS-II project for the hard x-ray undulator line.

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