

RESULTS OF MAGNETIC MEASUREMENTS OF 2.8 m LONG VERTICALLY POLARIZING UNDULATOR WITH THE DYNAMIC COMPENSATION OF MAGNETIC FORCES*

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Abstract

A novel undulator prototype with a horizontal magnetic field and dynamic compensation of magnetic forces has recently been developed at the Advanced Photon Source (APS) as a part of the LCLS-II R&D program. This undulator should meet stringent requirements for any LCLS-II insertion device. These requirements include limits on the field integrals and phase errors for all operational gaps, and the reproducibility and accuracy of the gap settings. Extensive mechanical testing has resulted in a performance that meets the requirements on the undulator gap setting. The magnetic tuning has been accomplished by applying a set of magnetic shims. As a result, the satisfactory performance of the undulator prototype has been demonstrated.

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 synchrotron radiation. Although e-beam in FELs is quite symmetric in the transverse plane, ID designers have not taken real advantage of it thus far. This status quo could soon be changed because of recent advancements in the design of ultra-small emittance storage rings. Such machines promise to operate with round e-beams and execute on-axis injection. Therefore, the development of novel planar IDs with horizontal magnetic fields becomes a practical matter.

There are at least two major advantages of rotating ID geometry by 90 degrees. 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 mechanical system. When such a design is combined with the magnetic force compensation system, the ID gap drive mechanism could

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 in the design of ID gap drive mechanisms, regardless of the type of IDs: out of vacuum, in-vacuum, APPLE-type, etc. 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 control of the ID magnetic gap value at a micron level. Typically the fabrication of such devices requires unique machine tools that can process several meter beams within a few microns of precision. Recently, after more than a decade of developments, European XFEL successfully constructed several dozen 5-m long IDs with a very sophisticated ID drive system that meets XFEL specifications [1]. SACLA XFEL in Japan has followed the design of in-vacuum IDs developed for the Spring-8 storage ring [2], and FERMI FEL in Trieste, Italy [3] is using APPLE-type IDs for its soft x-ray FEL. Newly built XFEL in Pohang, South Korea is adopting European XFEL ID design [4], and Swiss FEL follows SACLA’s footsteps by choosing in-vacuum IDs [5]. The alternative ID design based on the “gravity neutral” concept with the dynamic compensation of magnetic forces has recently been developed at the APS.

First, a short prototype (847-mm-long) of an ID with the dynamic compensation of magnetic forces was designed, built and tested at the APS of the Argonne National Laboratory. The ID magnetic forces were compensated by the set of conical springs with exponential force change placed along the ID strong back [6]. Based on the magnetic measurements of the ID effective magnetic field (B_{eff}), it has been demonstrated that the magnetic gaps within an operating range were controlled accurately and reproducibly within ± 1 micron. Successful tests of this ID prototype led to the design of a 2.8-m long device based on the same concept. Schematics of the 2.8-meter long prototype are shown in Fig. 1. There were load cells attached to the actuators to control the uncompensated force remaining due to preload and errors in matching the magnetic force and spring force.

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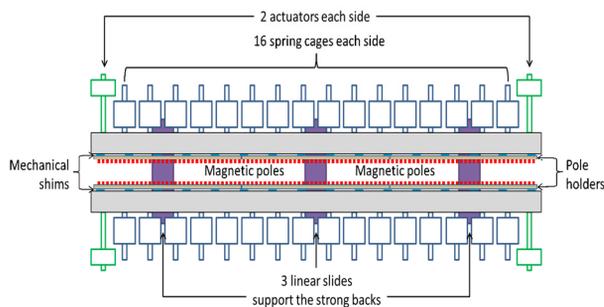


Figure 1: Top view of undulator prototype schematics. Magnetic force dynamic compensation is provided by 16 spring cages for both strong backs.

MAGNETIC AND MECHANICAL PERFORMANCE OF THE PROTOTYPE

Tuning of the device was done in the following order: 1) mechanical shimming of the gap; 2) magnetic tuning of the straightness of trajectory; for all gaps, 3) magnetic tuning of field integrals for all gaps.

Initial mechanical tuning of the gap was done for 20 mm gap by adjusting the thickness of shims between the magnet/poles holders and the strong back. Final tuning of the gap was done by tuning the spring settings at the gap 11 mm.

Magnetic performance results have been obtained at the APS magnetic measurement facility [7] by using the Senis 2-axis Hall probe and a rotating stretched coil. Taper during measurements was controlled with accuracy of better than 0.5 μm .

STRAIGHTNESS OF TRAJECTORIES

Straightness of trajectory is an important parameter for free electron laser (FEL) devices in both horizontal and vertical directions. A typical requirement for LCLS undulators is $\pm 2 \mu\text{m}$. Figure 2 shows trajectories before and after magnetic tuning.

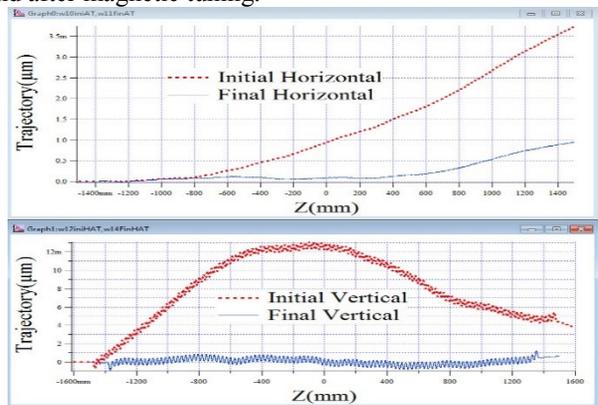


Figure 2: Horizontal trajectory (top) and vertical trajectory (bottom) before and after tuning (energy 14 GeV), gap 7.2 mm.

PHASE ERRORS AND FIELD INTEGRALS GAP DEPENDENCE

Data related to the performance of the device for all gap ranges are shown in Table 1.

Table 1: LCLS-2 Prototype Tuning Results

Gap	RMS phase error	B(effective)
7.2	5.63	10051
8.0	5.78	9145
9.0	6.34	7962
11.0	4.46	6156
13.0	6.03	4727
15.0	5.35	3666
20	2.99	1983

The results slightly exceed the specification value of 5 degree rms phase errors. That is due to the fact that compensation of the force is not perfect. It can be seen from Figure 3 that gap at 11 mm is very consistent. It is not the case for gap 15 mm where close to 0.1 mm bow in the middle can be seen. Local gap distortions together with bow indicate that this design has to be improved to provide more rigid strong backs to be sure that bow stays as small as needed for all gap ranges.

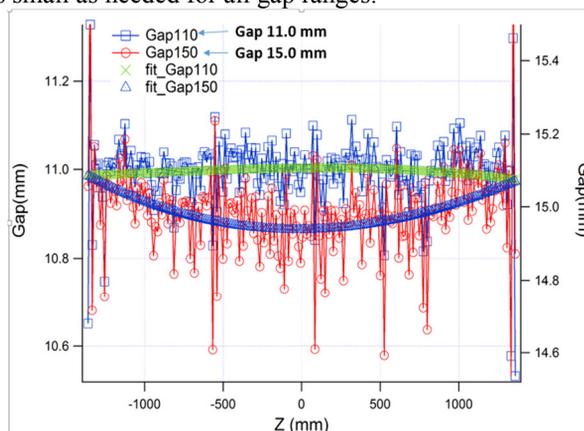


Figure 3: Gap vs. Z for 11 mm (squares, left scale) and 15 mm (circles, right scale). Solid lines –fitting. Bow and local gap distortions can be observed.

RMS phase error is very sensitive to the bow of strong backs. In order to get some idea of how the bow affects RMS phase error, a numerical simulation was done. It was performed by means of Radia code.

The bow itself has a parabolic profile for this configuration of the device. It is very small and, thus, the second order differential equation is used to describe the bending of the beam [8]. As a result of the simulation, main field distribution along the device and corresponding phase errors were calculated. The phase error in the case of the 30 μm bow is 6.18 degree, which is 50% more than the required 4 degree (see Fig. 4).

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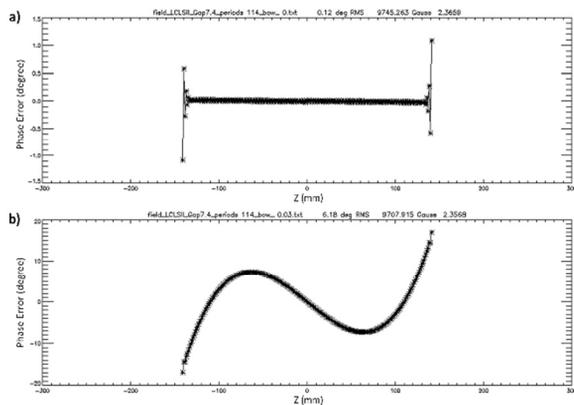


Figure 4: Calculated phase error behaviour for gap 7.2 mm: a) no bow-rms phase error 0.12°, b) parabolic bow of the gap with 30 μm error magnitude-rms phase error 6.18°.

After the trajectory straightness and phase errors tuning, the magnetic tuning of field integrals has been accomplished. Requirements for first ($J_{1x,y}$) and second ($J_{2x,y}$) field integrals are: ± 40 G-cm and ± 15 kG-cm². [9] They met according to results shown below in Table 2.

Table 2: LCLS-2 Field Integrals

Gap	J_{1x} (G-cm)	J_{2x} (kG-cm ²)	J_{1y} (G-cm)	J_{2y} (kG-cm ²)
7.2	22	-1.2	-28	3.9
8.0	-7	-4.6	-32	2.5
9.0	-25	0.2	-33	1
11.0	-22	5.5	-31	-0.2
13.0	0	3.7	-27	-0.8
15.0	23	2.2	-18	2.1
20	22	-5	-5	6.2

A very important requirement for the FEL performance is stability of the effective field, which requires stability of the undulator parameter K at fixed gap $\Delta K/K$ with accuracy of $2.3 \cdot 10^{-4}$. Results of the test are shown in Fig. 4.

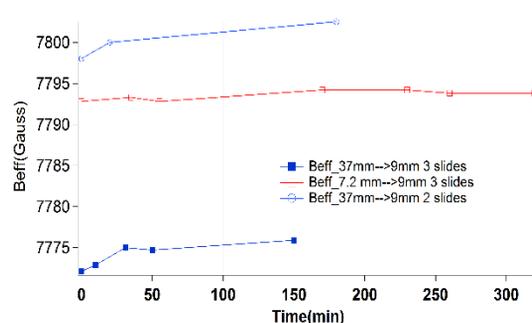


Figure 5: Effective field time dependence for gap 9 mm. Top curve-2 slides, bottom curve-3 slides, and middle curve- released friction. Requirements are ± 1.8 Gauss.

There is a clear dependence of the gap stability on the history of gap motion (see Fig. 5). Initial design was done with 3 linear slides (see Fig. 1). The main source of this instability is torque created by friction force in the slides around the actuator support point. With released friction, gap is very stable. Slides and actuators for future devices will be located at the same axis to avoid this problem.

Design of the full-length 3.4 m prototype device took into account all of the lessons learned to satisfy all the requirements for the LCLS-II device.

LESSONS LEARNED

Magnetic measurements and tuning revealed issues that have to be addressed during design of the next, 3.4-m-prototype:

1. The main challenge is strong back deflection, which is the primary source of phase errors. Device is very sensitive to it. At gap 7.2 mm, bow less than 0.01mm is required to achieve RMS phase error 4.0°.
2. Location of actuators has to be optimized. Putting actuators and slides on the same axis decreases deflection of strong backs.
3. More reliable design of spring cages setup providing easier tuning of them during installation and providing the same conditions during calibration and operation to avoid mismatch of the spring and magnetic force is required.
4. Even in recent conditions, it is possible to tune device very close to the LCLS-II ID specifications.

CONCLUSION

- A new design of the variable-gap hybrid permanent magnet undulator was introduced and studied 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 2.8-m-long prototype with the dynamic compensation of the magnetic forces was designed, built, tuned and tested at the APS.
- 3.4-m-long prototype is under development.

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