HARD X-RAY AND SOFT X-RAY UNDULATOR SEGMENTS FOR THE LINEAR COHERENT LIGHT SOURCE UPGRADE (LCLS-II) PROJECT*

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Abstract

Stanford Linear Accelerator Laboratory is currently constructing the Linear Coherent Light Source II (LCLS-II), a free-electron laser (FEL) which will deliver x-rays at an energy range between 0.2 keV and 5 keV at high repetition rate of up to ~1 MHz using a new 4 GeV superconducting RF linac, and at and an energy range between 1 keV and 25 keV when driven by an existing copper linac at up to 120 Hz repetition rate. To cover the full photon energy range, LCLS-II includes two variable-gap, hybrid-permanent-magnet undulator lines: A soft x-ray undulator (SXR) line with 21 undulator segments optimized for a photon energy range from 0.2 keV to 1.3 keV plus a hard x-ray undulator (HXR) line with 32 undulator segments designed for a photon energy range from 1.0 keV to 25.0 keV. Lawrence Berkeley National Laboratory is responsible for fabricating the 53 undulator segments. This paper summarizes the main parameters and design attributes for both LCLS-II undulator segment types.

INTRODUCTION

Lawrence Berkeley National Laboratory (LBNL) is presently manufacturing 32 hard x-ray and 21 soft x-ray undulator segments for two variable-gap, hybrid-permanent-magnet undulator lines to be installed at the Linear Coherent Light Source II (LCLS-II) project [1] at Stanford Linear Accelerator Laboratory (SLAC). Figures 1 and 2 show the individual undulator segments. Figure 3 shows the overall LCLS-II facility layout. Table 1 summarizes the main LCLS-II undulator segment and magnetic field tuning parameters [2].

SOFT X-RAY UNDULATORS

The LCLS-II soft x-ray undulator line is based on the European XFEL undulator design [3] and uses hybrid, permanent-magnet (PM) undulator segments with neodymium (NeFeB) magnets plus soft iron (FeCoV) poles, see Fig. 1. The undulator period is 39 mm with a peak magnetic field of > 1.5 T. This necessitates the use of fairly large magnet blocks which exhibit significant forces during assembly. Likewise, the magnet structure has to be carefully optimized to minimize pole saturation effects [5].

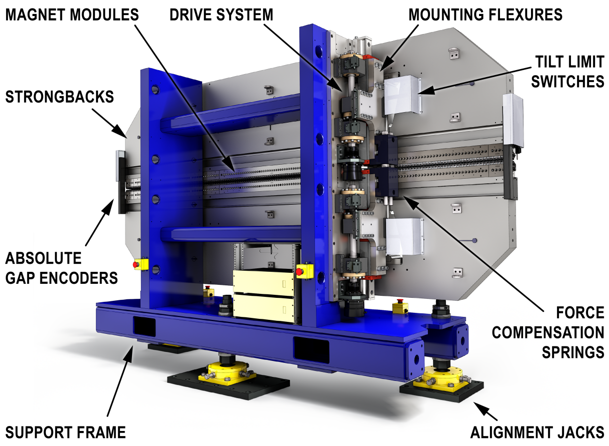

Figure 1: The 3.4 m long LCLS-II soft x-ray undulator is based on a conventional undulator design optimized for minimized tuning time and excellent field reproducibility with minimal gap hysteresis.

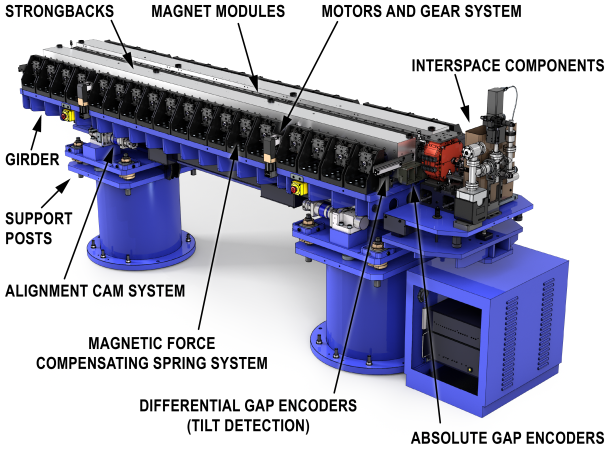

Figure 2: The 3.4 m long LCLS-II hard x-ray undulator incorporates a novel spring magnetic-force compensation system [4]. The compact design reduces cost and allows operating the undulator rotated by 90° generating vertically polarized x-rays.

The NeFeB magnet blocks are enhanced by a Terbium (Tb) grain boundary diffusion process which is well suited

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Table 1: Main LCLS-II Undulator Segment and Magnetic Field Tuning Parameters [2]

Parameter	Soft X-Ray Line (SXR)	Hard X-Ray Line (HXR)
Undulator Period Length (λ_u)	39 mm	26 mm
Photon Energy Range	0.2 - 1.3 keV	1 - 25 keV
Individual Undulator Segment Length	3.4 m	3.4 m
Number of Periods per Segment	87	130
Undulator Type	Planar PM Hybrid	Planar PM Hybrid
Gap Type	Variable	Variable
X-Ray Polarization Direction	Horizontal	Vertical
Magnetic Field Symmetry	Anti-Symmetric	Anti-Symmetric
Magnet Material	NdFeB (Diffusion Treated)	NdFeB (Diffusion Treated)
Minimum Operational Magnet Gap	7.2 mm	7.2 mm
Maximum Operational Magnetic Gap	22 mm	20 mm
On-Axis Vertical Effective Field B_{eff} at Min. Gap	> 1.49 T	> 1.01 T
Undulator Parameter K_{eff} at Min. Gap	> 5.43	> 2.44
Minimum Operational Undulator Parameter K	1.24	0.44
Undulator Parameter Tolerance $\Delta K_{eff}/K_{eff}$	$\pm$ 3.0×10^{-4}	$\pm$ 2.3×10^{-4}
Horizontal K Sextupole $\lvert{}^1\!/_2\,(1/K_{\mathrm{eff}})\,\partial^2 K_{eff}/\partial x^2\rvert$	< 10×10^{-4} 1/mm^2	< 6.8×10^{-4} 1/mm^2
Equivalent $\Delta K/K$ at x = ± 0.4 mm	< 1.6×10^{-4}	< 1.1×10^{-4}
Tuning Good Field Radius	1 mm	1 mm
RMS Phase Shake	± 5.0°	± 4.0°
Phase Error	± 10.0°	± 5.0°
First Field Integral (B_y, B_x)	< 40 μTm	< 40 μTm
Second Field Integral (B_y, B_x)	< 150 μTm^2	< 150 μTm^2

for FEL applications to increase magnet coercitivity specifically on the magnet surface facing the pole corners. Therefore, the magnet structure has a significant margin against demagnetization which is important for long-term FEL operation.

The SXR undulators utilize a C-shaped support structure to allow insertion of the undulator vacuum chamber. Such a support configuration introduces strongback roll which changes with undulator gap opening and must be minimized. The SXR magnet forces reach 5 tons at the smallest gap and decrease approximately exponentially with no significant force exerted at the largest gaps. At the same time the magnet module distortion has to be limited to within μm accuracy. During the prototyping phase the structure, the drive system, as well as the absolute gap encoder assemblies have been optimized to minimize distortion [6]. As a result, the undulator displays excellent gap repeatability $\Delta K_{eff}/K_{eff}$ of less than ±1.0×10^{-4} approaching the gap from either direction or from a fully opened gap condition.

HARD X-RAY UNDULATORS

The LCLS-II hard x-ray undulator period is 26 mm with a peak magnetic field of > 1.01 T. The device is based on a novel undulator prototype [4] recently built at Argonne National Laboratory (ANL) which accomplishes magnetic force compensation by incorporating a custom-designed conical spring system, see Fig. 2. Such a design eliminates the need for large structural beams (as for instance implemented in the SXR undulators) therefore resulting in a significant reduction in overall undulator size. For FELs which utilize a round electron beam cross section this size reduction allows

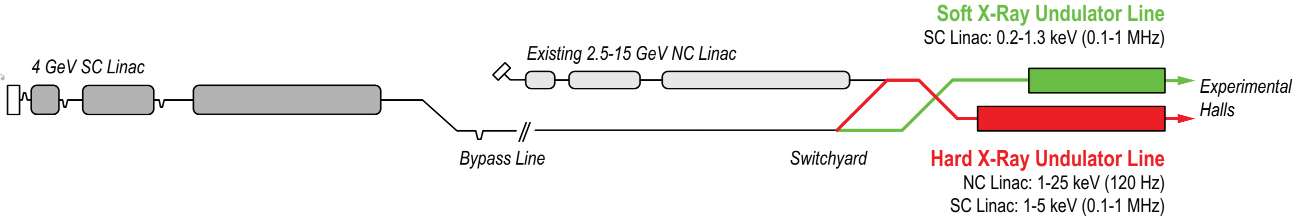

Figure 3: Schematic layout of the LCLS-II facility. A new 4 GeV, superconducting (SC), high-repetition-rate (up to ~1 MHz) linac can feed two variable-gap hybrid permanent-magnet undulator lines: *(a)* A hard x-ray undulator which covers a photon range of 1 to 5 keV; *(b)* A soft x-ray undulator which covers a photon range of 0.2 to 1.3 keV. The hard x-ray undulator can also be fed by an existing, 2.5-15 GeV, normal-conducting (NC), low-repetition-rate (100 Hz) linac generating 1 to 25 keV photons.

operating the undulator rotated by 90° producing vertically polarized x-rays. This polarization plane is advantageous for switching beams to different experiments in the horizontal plane while preserving a higher photon flux - a significant advantage for FELs with only a few undulator lines.

LBNL refined the ANL undulator design to enable reliable industrial production at external vendors. Primarily, the spring system design was enhanced to allow a reproducible assembly workflow from the initial calibration of individual springs to the final assembly on the undulator girder. In addition, LBNL incorporated an advanced magnet module design [7] similar to the SXR undulators (including diffusion-treated magnets). This design was further optimized to reduce fabrication costs while maintaining the efficient gap-dependent tuning capabilities as explained in the next section and illustrated in Fig. 4.

UNDULATOR MAGNET MODULES

A unique feature of the LCLS-II undulators are their advanced tuning capabilities. The LCLS-II undulators operate across a large magnetic gap range from 7.2 to 22 mm. Achieving the required field quality for all gaps was of concern in the early design phase. Different magnet structure errors display individual, gap-dependent error signatures which have to be canceled by independent tuning features.

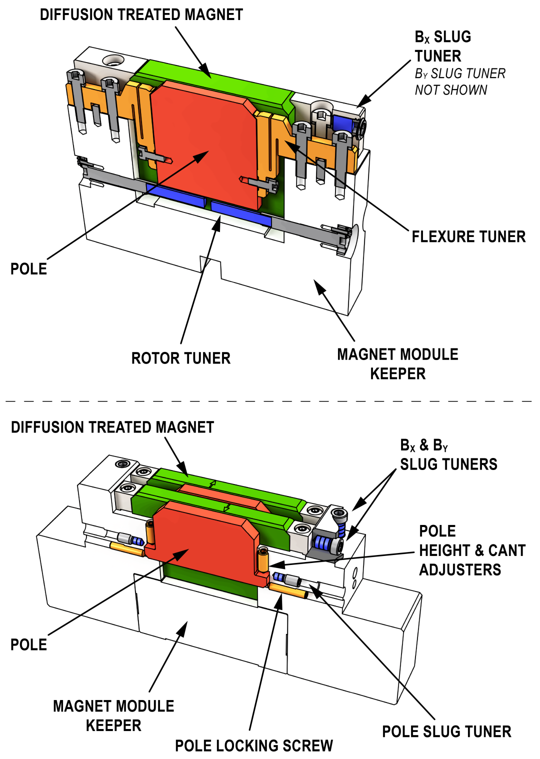

Figure 4: The LCLS-II undulator magnet modules incorporate features allowing efficient tuning of gap-dependent field errors. The SXR magnet module (top graphic) incorporates pole flexures to allow pole height as well as cant adjustments. The HXR magnet module (bottom graphic) provides equivalent tuning options. To reduce cost the flexures have been substituted with set screws. Both magnet modules incorporate rotor and slug tuners for additional gap-dependent error correction using magnetic material (see also Fig. 5).

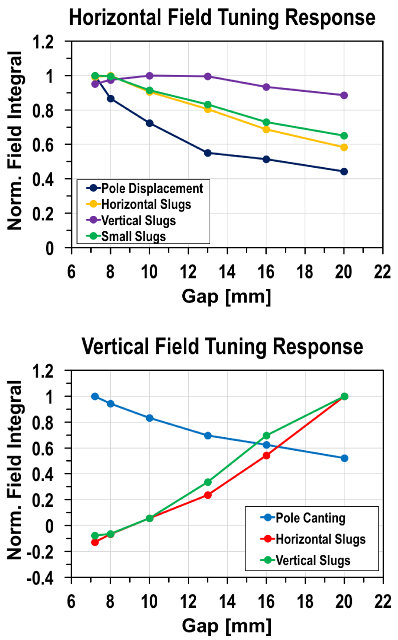

Figure 5: Experimentally measured, gap-dependent field signatures of the HXR tuning elements described in Fig. 4.

Due to the large number of undulators required for LCLS-II the magnet module design has to facilitate efficient and expedient tuning. As shown in Fig. 4, the undulators incorporate either pole flexures (SXR) or set screws (HXR) to allow pole height adjustment as well as pole canting. Extra magnetic material inserted in form of pole rotor tuners (SXR) or pole slug tuners (HXR) as well as B_x and B_y magnet slug tuners provide additional error correction capabilities. For instance, Fig. 5 displays the tuning signatures for each of the mentioned error correction elements for the HXR case. The availability of efficient tuning methods in combination with stringent mechanical fabrication tolerances reduces the amount of tuning interventions required for the LCLS-II undulators. Overall undulator tuning time during production can be reduced to less than a week. Detailed undulator tuning results are shown in [8].

PRODUCTION SCHEDULE

Production for both undulator lines is underway. Fully assembled magnet modules are procured from specialized magnet system suppliers (Vacuumschmelze and Neorem Magnets) which are shipped to our mechanical system suppliers (Keller Technology and Motion Solutions) for full integration into final undulator segments. The completed units are delivered to either SLAC or LBNL for final tuning. SXR deliveries to the project have already started and will continue from April 2017 to Aug 2018. HXR deliveries are planned from Aug 2017 to Sep 2018. Stringent quality assurance and manufacturing processes as described in [9] plus close relationships with our industrial partners ensure successful undulator production for LCLS-II.

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