Short Prototype Magnetic Measurements

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LCLS-II - UNDULATORS

SXR-HE SHORT MAGNETIC PROTOTYPE

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1 REVISION HISTORY

Rev.	CM Number	Description of Change
A		Baseline

2 APPROVALS

The following individual(s) shall approve this document:

Approver	Project Role
Matthew Williamson	CAM
Windchill Approved / Concurred By	

3 ABBREVIATIONS AND ACRONYMS

LCLS-II	Linac Coherent Light Source
LCLC-II-HE	LCLS-II High Energy Upgrade
LBNL	Lawrence Berkeley National Laboratory
SXR	Soft X-Ray
SXU	Soft X-Ray Undulator

4 INTRODUCTION

For the high-energy upgrade of the LCLS-II, the existing SXR undulator will be reconfigured to have a longer period length due to the increase in electron energy from 4 to 8 GeV. The period length of the undulator will be changed from 39 mm for the original SXR undulators to 56 mm for the new SXR undulators. This requires that new magnetic modules be designed, assembled, and tested. This note describes the magnetic measurements that were performed on a short prototype (14 pole) of the LCLS-II-HE SXU magnet modules. The magnetic design for the LCLS-II-HE SXR undulators is covered in LBNL document number LC-1006-1957. The mechanical design of the magnet modules is covered in LC-1006-2180. The assembly process and mechanical measurements for the short prototype, that is the topic of this note, are covered in LC-1006-2727.

5 REQUIREMENTS

In this section the LCLS-II-HE SXU requirements that are relevant to the short prototype are described. The listed requirements are the relevant subset from the LCLS-II-HE Undulator Physics Requirement Document (LCLSII-HE-1.3-PR-0049-R1). The undulator has been designed with a period length of 56 mm. This is verified through mechanical and magnetic measurements. The undulator is of planar hybrid permanent magnet type (soft magnetic poles and NdFeB permanent magnets) and produces horizontally polarized radiation (vertical field orientation). The operational gap range is 7.2 mm to 33 mm, and the effective magnetic field requirement at minimum gap (7.2 mm) is 1.76 T. The effective field requirement (PRD0049.4026) can be fully verified on the short prototype [1]. The K value requirement at minimum gap (PRD0049.4027) is redundant since the period length is specified separately. For the horizontal field roll-off, two equivalent / redundant requirements are specified (PRD0049.4034, PRD0049.4035). These can also be fully verified on the short prototype. The final requirements listed are related to field quality: phase shake, x/y field integrals, and x/y second field integrals. For these requirements, the short prototype is used for partial verification of requirements since the short length is not representative of a full-length undulator. The partial verification is done through demonstration that requirements are satisfied over the short length.

[1] The effective field strength depends strongly on the as received permanent magnet and pole properties. For production, the properties are specified in documents LC-1006-1866 and LC-1006-1820. For the short prototype, manufacturer material catalog grades, with similar properties as for the production specification, were specified.

Table 1. Undulator requirements as specified in document LCLSII-HE-1.3-PR-0049-R1.

Requirement #	Parameter	unit	Value	Verif. Method
PRD0049.4014	Undulator period length	mm	56	Test
PRD0049.4018	Undulator type	-	Planar	Inspection
PRD0049.4019	Undulator magnet type	-	PM Hybrid	Inspection
PRD0049.4020	Gap type	-	Variable	Inspection
PRD0049.4021	Magnet material	-	$Nd_2Fe_{14}B$	Inspection
PRD0049.4022	Linear polarization direction of the x-ray radiation	-	Horizontal	Inspection
PRD0049.4023	Magnetic Field Symmetry	-	Antisymmetric	Inspection
PRD0049.4024	Minimum operational magnetic gap	mm	7.2	Inspection
PRD0049.4025	Maximum operational magnetic gap	mm	33	Inspection
PRD0049.4026	On-axis vertical effective field at min. oper. gap	T	>1.76	Test/ Analysis
PRD0049.4027	Keff at minimum operational gap		>9.21	Test/ Analysis
PRD0049.4029	Minimum operational K values	T	1.51	Test/ Analysis
PRD0049.4034	Horizontal K sextupole $\left\lvert\frac{1}{2}(1/K_{eff})\,\partial^2 K_{eff}/\partial x^2\right\rvert$	$1/mm^2$	$<5\times10^{-4}$	Test/ Analysis
PRD0049.4035	Equivalent $\Delta K/K$@ x = ±0.4 mm		$<0.8\times10^{-4}$	Test/ Analysis
PRD0049.4038	Phase shake (rms) over Lcell	deg Xray	<5.0	Test/ Analysis
PRD0049.4040	First field integral of By per cell (abs) 10	µTm	<50	Test/ Analysis
PRD0049.4041	Second field integral of By per cell (abs)	μTm^2	<200	Test/ Analysis
PRD0049.4042	First field integral of Bx per cell (abs)	µTm	<50	Test/ Analysis
PRD0049.4043	Second field integral of Bx per cell (abs)	μTm^2	<200	Test/ Analysis

6 MEASUREMENT RESULTS

The short prototype magnet modules were assembled at LBNL and sent to SLAC for magnetic characterization (measurement performed by Y. Levashov). Figure 1 shows the hall probe measurement setup at SLAC, including the magnet modules mounted on the short test frame.

Figure 1. Hall probe measurement setup for the short prototype. The short magnet modules are mounted on the 1 m short frame from the LCLS-II project.

Figure 2 shows the vertical magnetic field measured at the minimum gap of 7.2 mm. Note that the antisymmetric field symmetry (req. # **PRD0049.4023**) is demonstrated here. The measured period length, based on the peak field at the poles, is 56.004 mm (req. # **PRD0049.4014**). Figure 3 shows the measured effective field requirement. The measured effective field value is 1.85 T at minimum gap, which corresponds to a Keff value of 9.69. This is approximately 5% above the requirement (**PRD0049.4026, PRD0049.4027**).

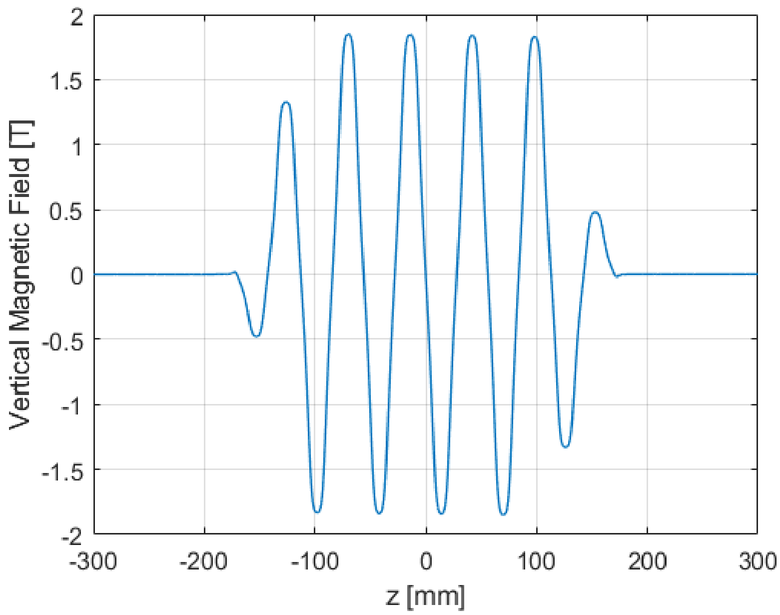

Figure 2. Vertical magnetic field along the short prototype length.

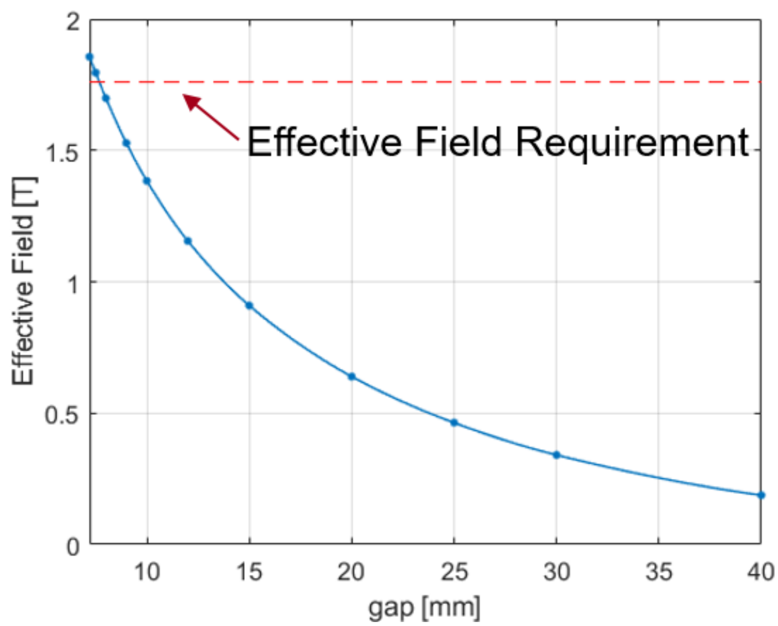

Figure 3. Measured effective field magnetic field as a function of gap. At the minimum gap, the short prototype exceeds the required effective magnetic field strength by approximately 5% above the requirement.

Figure 4 shows the measured and calculated magnetic field roll-off at the maximum gap of 33 mm. The measured roll-off, based on a quadratic fit of the data, is 3.5×10^{-4} 1/mm2, which satisfies the required value of 5.0×10^{-4} 1/mm2 (**PRD0049.4034**). This also satisfies the redundant requirement, **PRD0049.4035**, with a $\Delta K/K@$ x = ±0.4 mm of 5.6×10^{-5}.

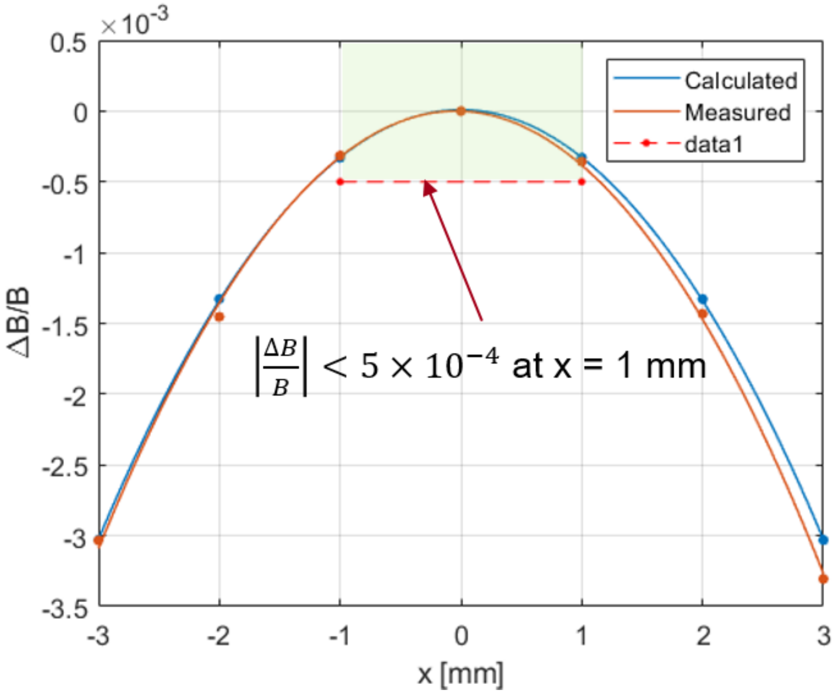

Figure 4. Magnetic field roll-off measurement at maximum gap (33 mm) and calculation comparison. The measured magnetic field roll-off is 3.5×10^{-4} 1/mm^2, which satisfies the requirement of 5.0×10^{-4} 1/mm^2.

In the remainder of this section, the field quality requirements are considered: RMS phase error (i.e. phase shake), vertical and horizontal first field integral, vertical and horizontal second field integrals. As it relates to a full length undulator, only partial satisfaction of these requirements is claimed due to the short length of the prototype. The following phase error results that are presented are without undulator tuning. Figure 5 shows the calculated phase error at the peak field locations (left) and the resulting RMS phase error (phase shake) as a function of the undulator gap (right). The RMS phase error for this short prototype is largest at 10 mm gap with a value of 2.4^0, this is below the full length undulator requirement of 5^0 (**PRD0049.4038**).

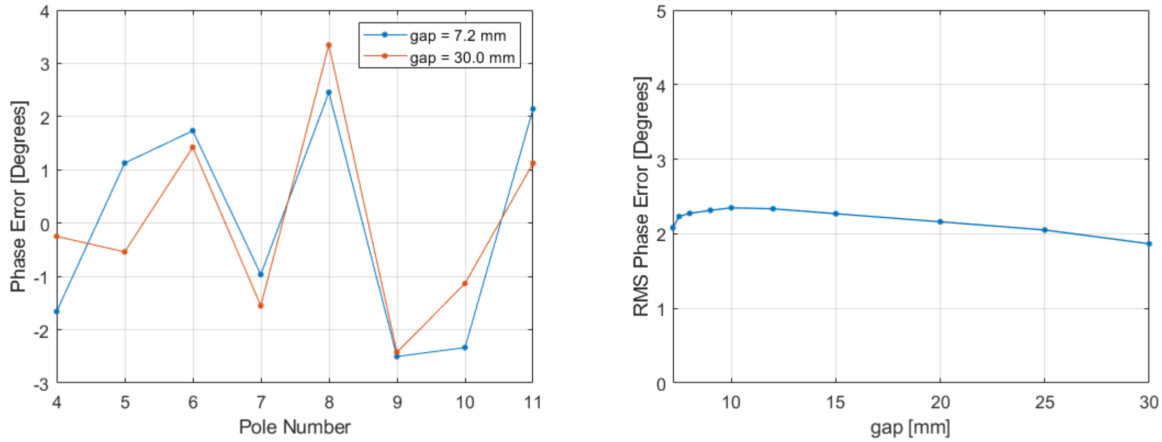

Figure 5. Calculated phase error at the poles from measurement data at 7.2 mm gap (left). Calculated RMS phase error for gap range between 7.2 mm and 30 mm (right). The results presented are without tuning.

Figure 6 and Figure 7 show the first and second field integral measurements before tuning in the vertical and horizontal directions. The un-tuned field integrals are slightly above the required value of 50 μTm. The vertical field integral Figure 6 (left) shows a fast change below approximately 10 mm gap. Tuning methods to correct these fast changing errors were developed at SLAC by combining pole adjustments with ferromagnetic shims. The resulting field integrals after tuning are shown in Figure 8. Within the operational gap range, the absolute value resulting field integrals in x and y is below 12 μTm, which satisfies the full length undulator requirement of 50 μTm (**PRD0049.4040, PRD0049.4042**). The measured second field integrals (before tuning) are below 50 μTm^2 for the vertical direction (right plot on Figure 6) and below 20 μTm^2 for the horizontal direction (right plot of Figure 7). Both of these satisfy the full length undulator vertical and horizontal second field integral requirement of 200 μTm^2 (**PRD0049.4041, PRD0049.4043**). Figure 9 shows the measured and calculated vertical second field integral along the length of the undulator. As can be seen from the plot, there is a "jump" in the second field integral at each end of the undulator of approximately 20 μTm^2. Based on the simulation results from OPERA3D, this "jump" is expected to be lower for the full length undulator as is shown in Figure 10, and it should only consume a small amount of the overall margin for the second integral requirement.

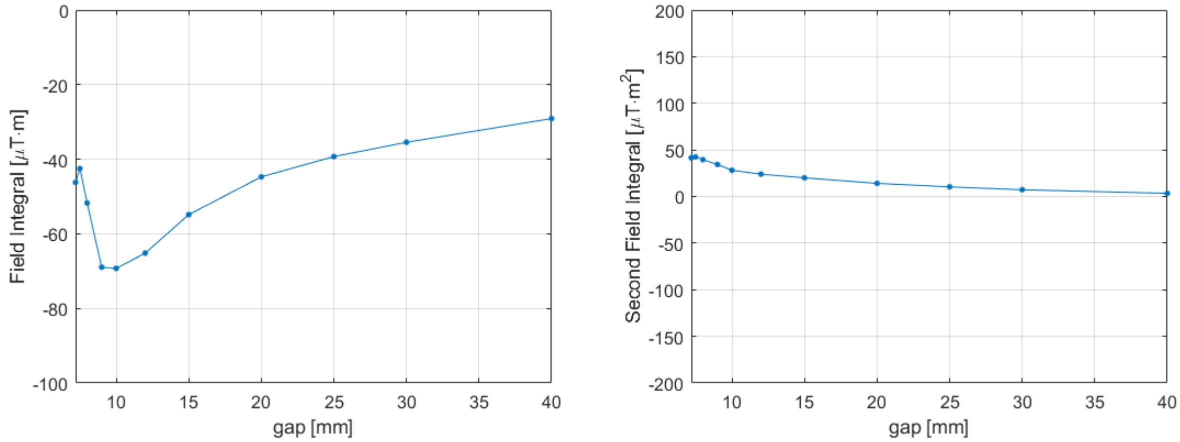

Figure 6. Vertical field integral (left) and vertical second field integral (right).

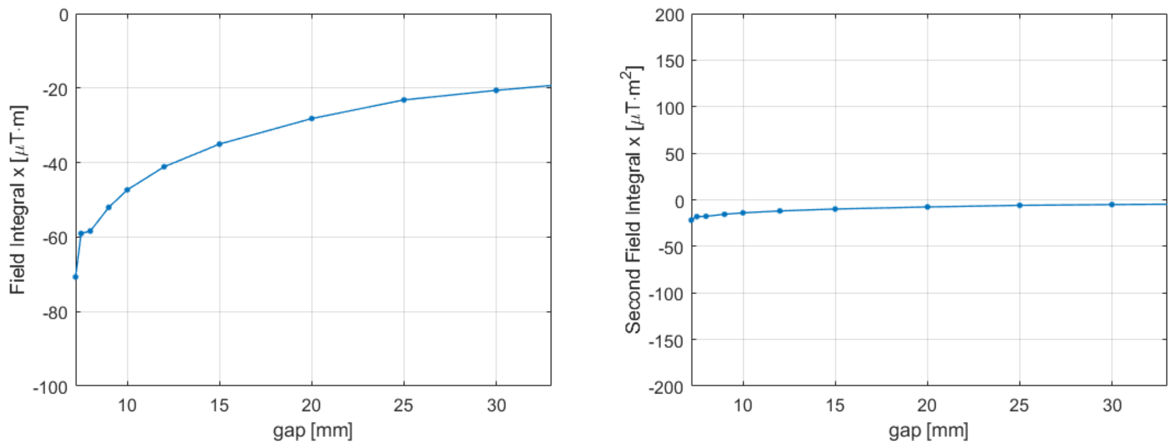

Figure 7. Horizontal field integral (left) and horizontal second field integral (right).

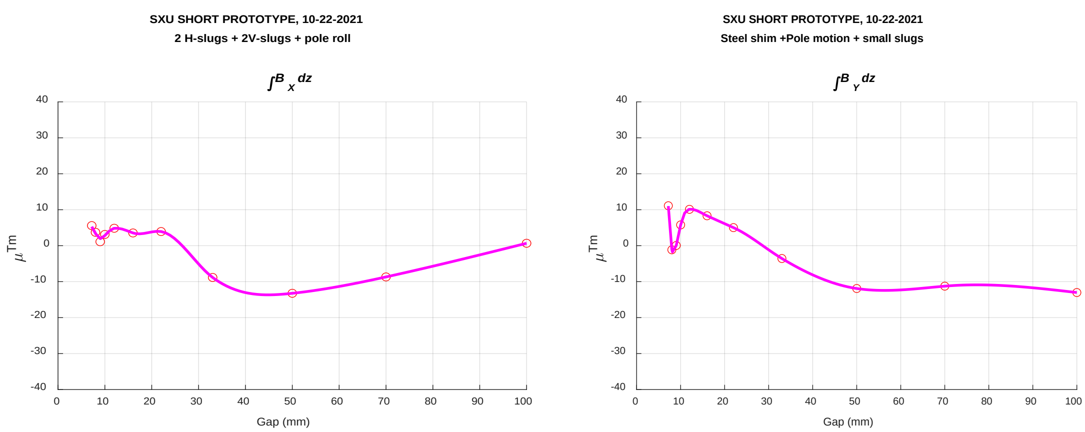

Figure 8. Measured x and y field integral after tuning (courtesy of Y. Levashov).

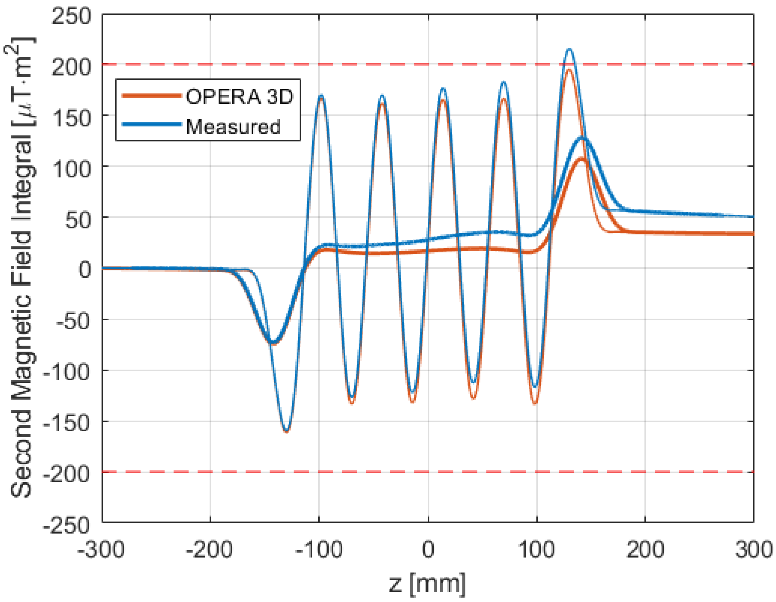

Figure 9. Second field integral as a function of z. Good agreement between the measurements and calculations is seen in the “jump” of the second field integral at the entrance and exit of the undulator.

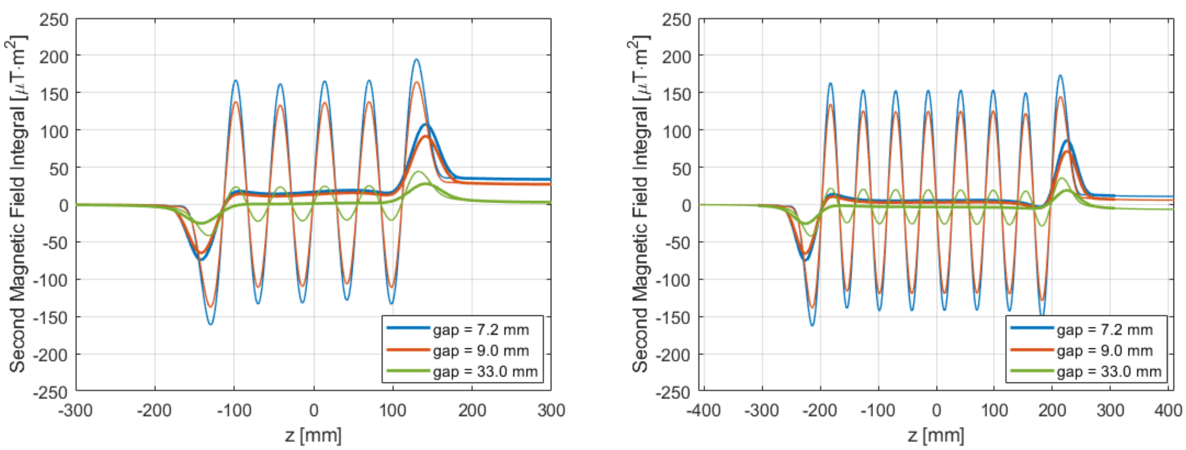

Figure 10. Calculated second field integral as a function of z for various gaps. The left plot shows the calculation for the short prototype, while the right plot shows the calculation that is representative of a long undulator. The second field integral “jump” error at the ends is expected to decrease for the full length undulators when compared to the short prototype.

7 DISCUSSION OF REQUIREMENT SATISFACTION

Table 2 shows the list of requirements along with the values achieved for the short prototype. The cells that are highlighted in green are ones where the length of the short prototype is sufficient to demonstrate full satisfaction of the requirement. For the orange cells, the measured values are reported; however, the short prototype is not fully representative of a production undulators, since the accumulation of random errors is limited by the short device length.

Table 2. Undulator requirements as specified in document LCLSII-HE-1.3-PR-0049-R1.

Requirement #	Parameter	unit	Req. Value	Meas. Value
PRD0049.4014	Undulator period length	mm	56	56.004
PRD0049.4018	Undulator type	-	Planar	Planar
PRD0049.4019	Undulator magnet type	-	PM Hybrid	PM Hybrid
PRD0049.4020	Gap type	-	Variable	Variable
PRD0049.4021	Magnet material	-	$Nd_2Fe_{14}B$	$Nd_2Fe_{14}B$
PRD0049.4022	Linear polarization direction of the x-ray radiation	-	Horizontal	Horizontal
PRD0049.4023	Magnetic Field Symmetry	-	Antisymmetric	Antisymmetric
PRD0049.4024	Minimum operational magnetic gap	mm	7.2	7.2
PRD0049.4025	Maximum operational magnetic gap	mm	33	33
PRD0049.4026	On-axis vertical effective field at min. oper. gap	T	>1.76	1.85
PRD0049.4027	Keff at minimum operational gap		>9.21	9.69
PRD0049.4029	Minimum operational K values	T	1.51	1.51
PRD0049.4034	Horizontal K sextupole $\left\|\frac{1}{2}(1/K_{eff})\,\partial^2 K_{eff}/\partial x^2\right\|$	1/mm^2	<5×10^{-4}	3.5×10^{-4}
PRD0049.4035	Equivalent $\Delta K/K$@ x = ±0.4 mm		<0.8×10^{-4}	0.56×10^{-4}
PRD0049.4038	Phase shake (rms) over Lcell	deg Xray	<5.0	2.4
PRD0049.4040	First field integral of By per cell (abs) 10	μTm	<50	12
PRD0049.4041	Second field integral of By per cell (abs)	μTm^2	<200	50
PRD0049.4042	First field integral of Bx per cell (abs)	μTm	<50	12
PRD0049.4043	Second field integral of Bx per cell (abs)	μTm^2	<200	20

8 REFERENCE DOCUMENTS

Document Number	Title
LCLSII-HE-1.3-PR-0049-R1	LCLS-II-HE SXR Undulator System PRD
LC-1006-1957	HE-SXR Undulator Magnetic Design
LC-1006-2180	HE-SXR Magnet Module Design
LC-1006-2727	Short Prototype Fabrication and Mechanical Measurements