



## 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 mdwilliamson	

### 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<sup>1</sup>. The K value requirement at minimum gap (PRD0049.4027) is redundant since the period length is specified separately. For the full length undulators, the relative K value must be repeatable to within  $\pm 5.5 \times 10^{-4}$  (PRD0049.4033). This requirement is listed here, but is not considered part of the short undulator prototype test since it is strongly dependent on the undulator mechanical system. The short prototype mechanics do not appropriately represent the anticipated behavior for the full length undulator mechanical system. 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. The short prototype can give useful information in relation to the field quality requirements. However, since these

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<sup>1</sup> 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.



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requirements depend strongly on undulator length, the short prototype results do not directly imply requirement satisfaction for full length undulators.

**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 <sub>2</sub> Fe <sub>14</sub> 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	K <sub>eff</sub> at minimum operational gap	-	>9.21	Test/ Analysis
PRD0049.4029	Minimum operational K values	T	1.51	Test/ Analysis
PRD0049.4033	Undulator parameter tolerance $\Delta K_{eff}/K_{eff}$	-	$\pm 5.5 \times 10^{-4}$	Test/ Analysis
PRD0049.4034	Horizontal K sextupole $ \frac{1}{2}(1/K_{eff})\partial^2 K_{eff}/\partial x^2 $	1/mm <sup>2</sup>	$< 5 \times 10^{-4}$	Test/ Analysis
PRD0049.4035	Equivalent $\Delta K/K$ @ x = $\pm 0.4$ mm	-	$< 0.8 \times 10^{-4}$	Test/ Analysis
PRD0049.4038	Phase shake (rms) over Lcell	deg Xray	<5.0	Test/ Analysis
PRD0049.4040	First field integral of B <sub>y</sub> per cell (abs) 10	$\mu$ Tm	<50	Test/ Analysis
PRD0049.4041	Second field integral of B <sub>y</sub> per cell (abs)	$\mu$ Tm <sup>2</sup>	<200	Test/ Analysis
PRD0049.4042	First field integral of B <sub>x</sub> per cell (abs)	$\mu$ Tm	<50	Test/ Analysis
PRD0049.4043	Second field integral of B <sub>x</sub> per cell (abs)	$\mu$ Tm <sup>2</sup>	<200	Test/ Analysis

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## 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 (left) and short magnet modules after final assembly (right). 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 (first and last three poles are excluded), 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**).



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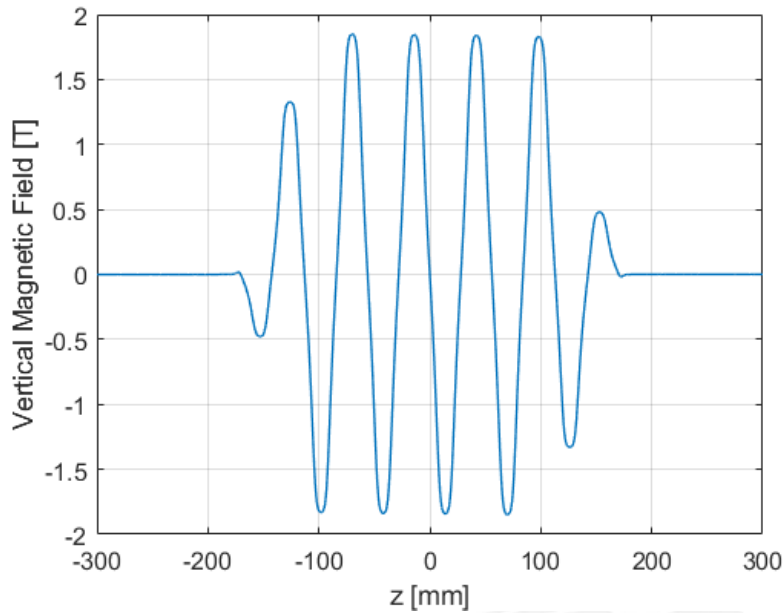


Figure 2. Measured vertical magnetic field along the short prototype length.

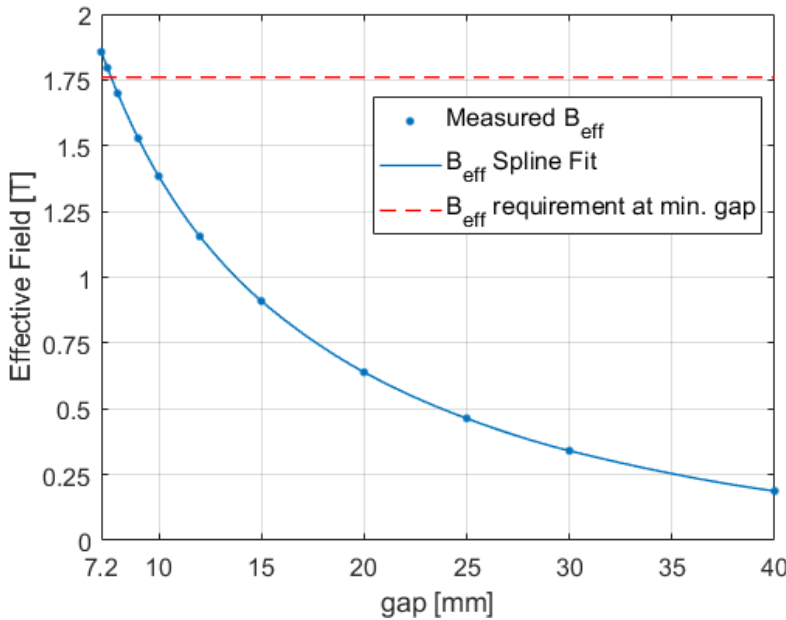


Figure 3. Measured effective field strength as a function of gap. At the minimum gap, the short prototype exceeds the required effective magnetic field strength by approximately 5% above the requirement (PRD0049.4026, PRD0049.4027).



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  $3.5 \times 10^{-4} \text{ 1/mm}^2$ , which satisfies the required value of  $5.0 \times 10^{-4} \text{ 1/mm}^2$  (**PRD0049.4034**). This also satisfies the redundant requirement, **PRD0049.4035**, with a  $\Delta K/K @ x = \pm 0.4 \text{ mm}$  of  $5.6 \times 10^{-5}$ .

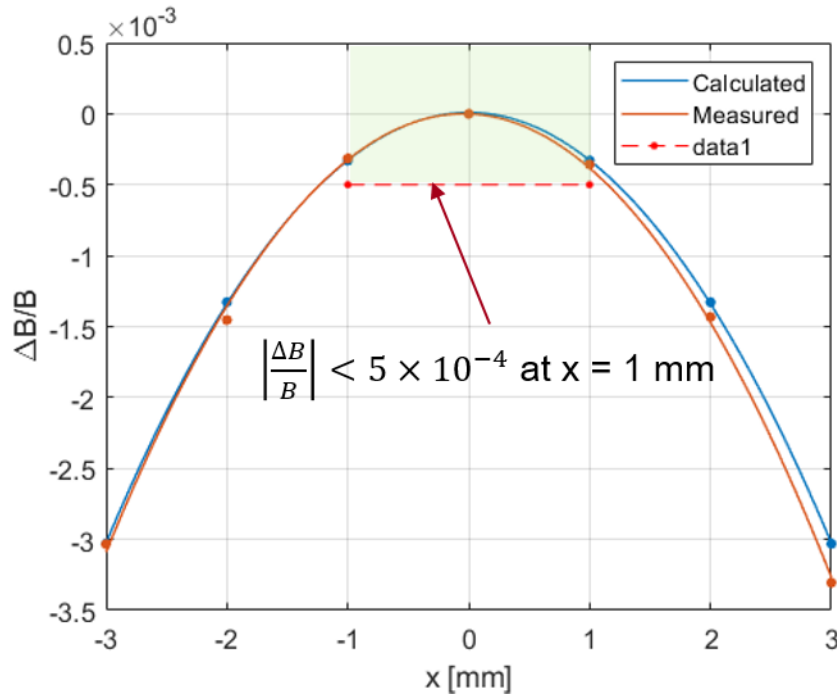


Figure 4. Magnetic field roll-off measurement at maximum gap (33 mm) and calculation comparison. The measured magnetic field roll-off is  $3.5 \times 10^{-4} \text{ 1/mm}^2$ , which satisfies the requirement of  $5.0 \times 10^{-4} \text{ 1/mm}^2$  (**PRD0049.4034**, **PRD0049.4035**).

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, and vertical and horizontal second field integrals. As it relates to a full length undulator, the short prototype results do not imply satisfaction of the requirements; however, they do provide useful feedback on the design. 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). Note that these are the as-built results with no phase tuning. The RMS phase error for this short prototype is largest at 10 mm gap with a value of  $2.4^\circ$ . For reference, this is below the full length undulator requirement of  $5^\circ$  (**PRD0049.4038**).

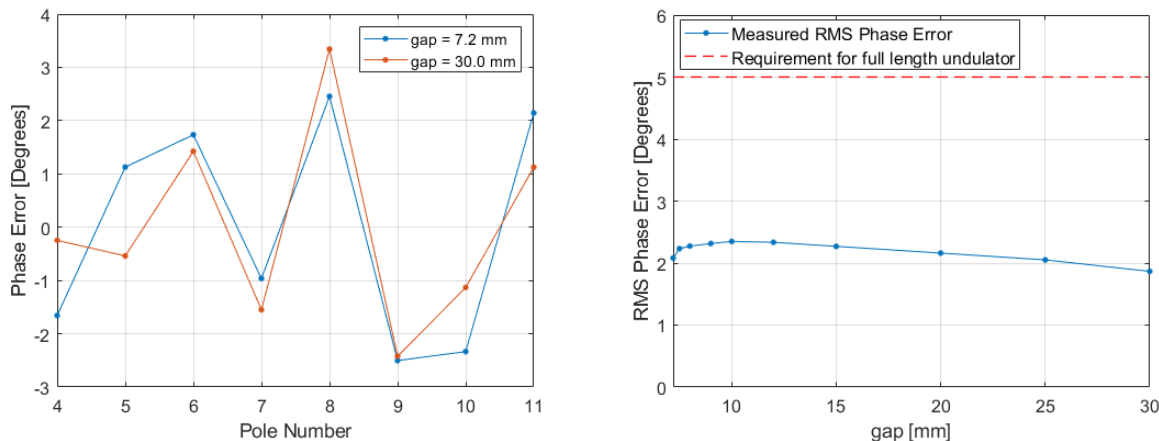


Figure 5. Calculated phase error at the poles from measurement data at 7.2 mm gap (left). Calculated RMS phase error for gap range between 7.2 mm and 30 mm (right). The results presented are without tuning.

Figure 6 and Figure 7 show the first and second field integral measurements in the horizontal and vertical directions. The vertical field integral, Figure 6 (right), 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 also shown in Figure 6. Within the operational gap range, the absolute value resulting field integrals in x and y is below  $18 \mu\text{Tm}$  after tuning. For reference, the full length undulator requirement is  $50 \mu\text{Tm}$  (**PRD0049.4040, PRD0049.4042**). The measured second field integrals are shown in Figure 7. For reference, the bounds of the plots represent the full length undulator requirements (**PRD0049.4041, PRD0049.4043**); however, the results do not imply satisfaction of the full length undulator requirements. This is especially true since the short undulator length leads to small second field integral drift due to first integral errors. Useful information can still be obtained for the end design with respect to the entrance and exit second field integral “jumps”. Figure 8 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  $20 \mu\text{Tm}^2$ . Based on the simulation results from OPERA3D, this “jump” is expected to be lower for the full length undulator as is shown in Figure 9, and it should only consume a small amount of the overall margin for the second integral requirement.



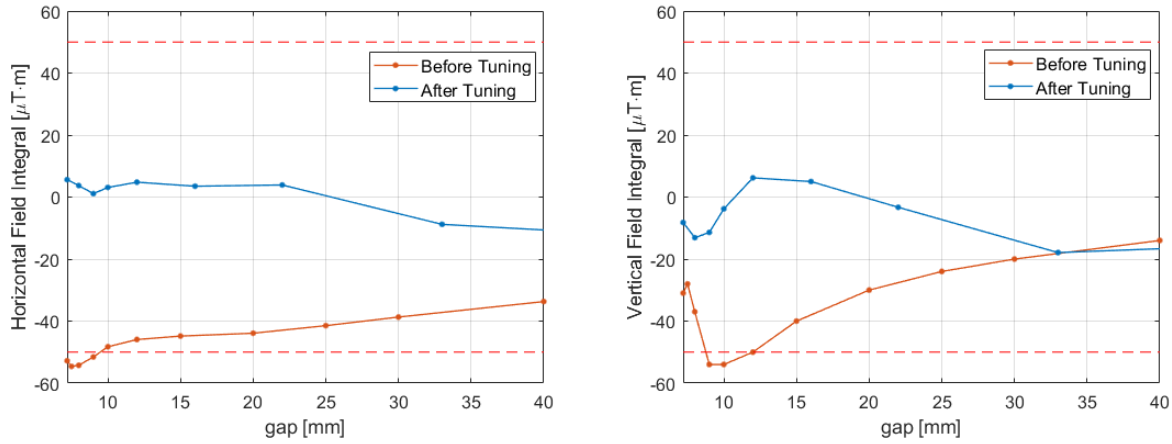


Figure 6. Horizontal field integral (left) and vertical field integral (right) before and after tuning.

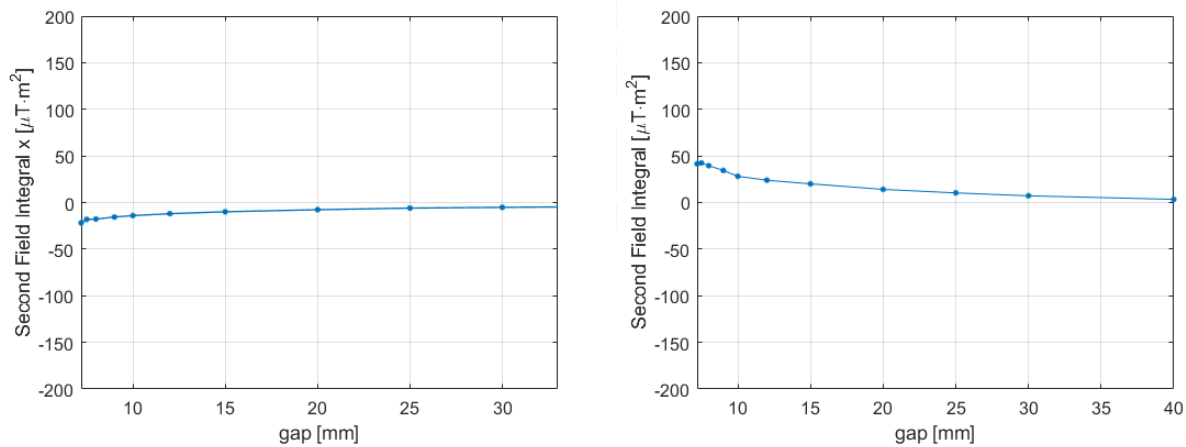


Figure 7. Horizontal second field integral (left) and vertical second field integral (right).



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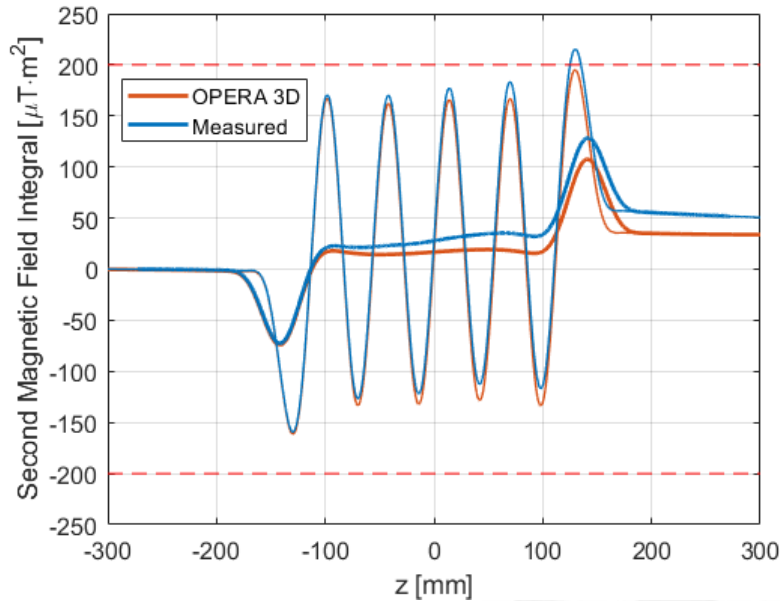


Figure 8. Second field integral as a function of  $z$ . Good agreement between the measurements and calculations is seen in the “jump” of the second field integral at the entrance and exit of the undulator.

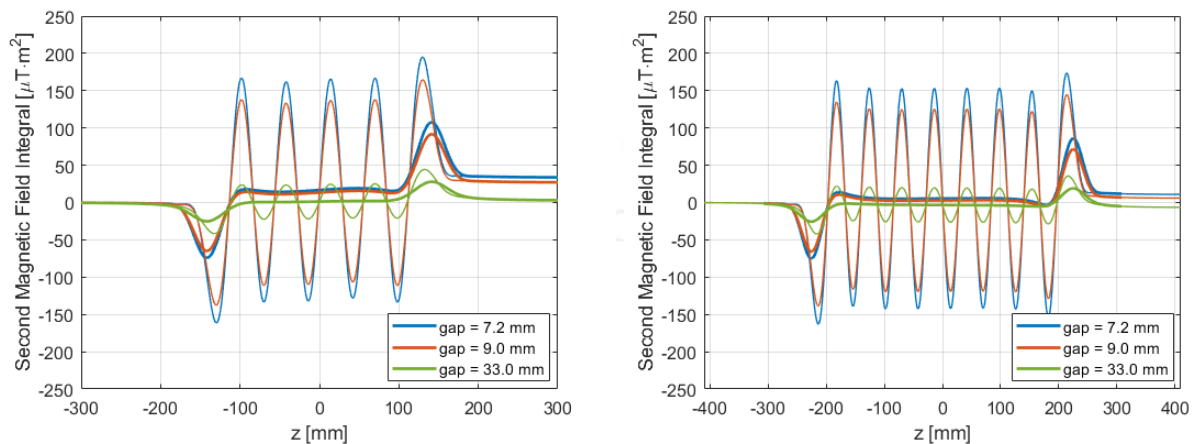


Figure 9. Calculated second field integral as a function of  $z$  for various gaps. The left plot shows the calculation for the short prototype, while the right plot shows the calculation that is representative of a long undulator (minimum of 20 poles are required for convergence). The second field integral “jump” error at the ends is expected to decrease for the full length undulators when compared to the short prototype.



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## 7 DISCUSSION OF REQUIREMENT SATISFACTION

Table 2 shows the list of requirements along with the values achieved for the short prototype. The cells are highlighted in green where the length of the short prototype is sufficient to demonstrate satisfaction of requirements. Table 3 shows the field quality requirements. For these requirements, the short prototype length is not sufficient to imply satisfaction of the full length undulator requirements. For this reason, the measured values are highlighted in orange. The K repeatability requirement is not included here, since it is outside of the scope of the short prototype work.

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

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 <sub>2</sub> Fe <sub>14</sub> B	Nd <sub>2</sub> Fe <sub>14</sub> 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	K <sub>eff</sub> 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 <sup>2</sup>	<5×10 <sup>-4</sup>	3.5×10 <sup>-4</sup>
PRD0049.4035	Equivalent $\Delta K/K$ @ x = ±0.4 mm		<0.8×10 <sup>-4</sup>	0.56×10 <sup>-4</sup>



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Table 3. Undulator requirements where the short length of the prototype does not imply satisfaction of the full length undulator requirement. Measured values are shown for reference.

Requirement #	Parameter	unit	Req. Value	Meas. Value
PRD0049.4038	Phase shake (rms) over Lcell	deg Xray	<5.0	2.4
PRD0049.4040	First field integral of By per cell (abs) 10	$\mu\text{Tm}$	<50	18
PRD0049.4041	Second field integral of By per cell (abs)	$\mu\text{Tm}^2$	<200	50
PRD0049.4042	First field integral of Bx per cell (abs)	$\mu\text{Tm}$	<50	9
PRD0049.4043	Second field integral of Bx per cell (abs)	$\mu\text{Tm}^2$	<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


  
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