MAGNETIC MEASUREMENTS, TUNING AND FIDUCIALIZATION OF LCLS UNDULATORS AT SLAC*

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Abstract

A new Magnetic Measurement Facility (MMF) has been built at Stanford Linear Accelerator Center (SLAC) to measure, tune and fiducialize LCLS undulators. The climate controlled MMF utilizes two magnetic measurement benches and a large Coordinate Measurement Machine (CMM) to provide a throughput of one undulator per week. Magnetic measurement, tuning and fiducialization processes are presented and first tuning results are discussed.

INTRODUCTION

The Linac Coherent Light Source (LCLS) based on a Self-Amplified Spontaneous Emission Free-Electron Laser (SASE-FEL), is being built at Stanford Linear Accelerator Center (SLAC) by a collaboration of four US-DOE laboratories. A new injector and a part of the existing SLAC linac will be used as an electron source at energy of 13.64 GeV. The 120 m long LCLS undulator line consists of 33 segments. Each segment is a fixed-gap planar undulator assembled of permanent NdFeB magnets and canted poles. The undulator period is 3cm, gap at the beam line is 6.8mm, effective K value varies from 3.500 to 3.485 to account for beam energy loss, and the radiation wavelength will be 1.5A. A prototype of the segment and the first two undulators have been measured and tuned at the Advanced Photon Source (APS) in Argonne National Laboratory (ANL) [1],[2].

Requirements for LCLS undulator tuning and fiducialization are specified in a Physics Requirement Document [3]. The requirements must be met for all beam positions within ±2 mm horizontally and ±200μm vertically of the nominal beam axis. Trajectory excursions for one segment should be less than 2μm, r.m.s. phase errors and particle-wave slippage <10°, first field integrals $<40\times10^{-6}$Tm, second field integrals $<50\times10^{-6}$Tm², and K should be set to 1.5×10^{-4}. The position of the undulator magnetic axis, and the beam trajectory at the nominal K value should be known relative to external mechanical references to 50μm horizontally and 40μm vertically.

Because of their low electrical noise and small planar Hall effects, Sentron XZM12-3-0.6-2T Hall probes are used to sample magnetic fields along an undulator for beam trajectories and K calculations. Field integrals are measured by 3.6m long coils. Additional measurements are made with one period long λ -coils.

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The semi-automated process of LCLS undulator tuning allows for a throughput of one undulator per week, which is required to meet the tight project schedule.

MAGNETIC MEASUREMENT LABORATORY

The main concern taken into consideration during construction of the MMF was the temperature. The remnant field of permanent magnet material typically changes by about 0.1% per degree Celsius, which requires the temperature to be constant at ±0.1C° level to meet the tolerance on the K. A high quality air conditioning system keeps the air temperature in the MMF within tolerance, as shown in figure1.

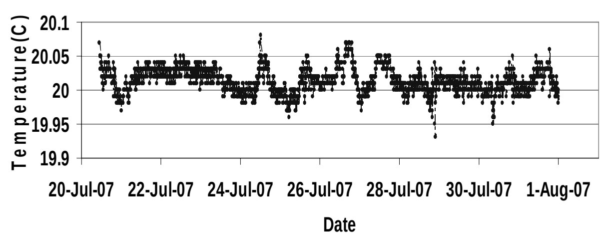

Figure 1. Ambient temperature in MMF

Each undulator stays inside the temperature controlled room for one week prior to the start of measurements to reach thermal equilibrium with the room temperature. During magnetic measurements and tuning, the undulator temperature is monitored by 5 sensors distributed along the length of the device. The difference between the background magnetic field in the laboratory and the magnetic field in the undulator hall at different LCLS tunnel locations was measured to be 0.1G. Many other metal objects, which could affect the ambient magnetic field components, should be taken into account during the tuning process. For that reason all undulators are covered by a μ-metal shield, shown in figure 2, which reduces the ambient magnetic field by a factor of 6. Also they are set in the same orientation in which the segments will be installed in the tunnel, and measured on the same steel support structure.

Initial mechanical acceptance checks and fiducialization measurements of an undulator are made on the 4 meter long CMM. Undulators are tuned on two separate magnetic measurement benches, which allow work to proceed in parallel. The measurement devices are mounted on precision x, y, z - stages with Heidenhain scales and encoders. The instruments are triggered by a National Instruments FPGA in a PXI-1031 chassis. Probe positioning accuracy w.r.t. reference indexes on the scales is better than 5 micrometers. The benches are equipped with cam mover and capacitive sensor systems, which allow alignment of an undulator to the bench in 5 degrees of freedom, with the remaining longitudinal position being only measured. The process of alignment to the bench is completed in approximately 15 minutes to a few micrometers/microradians.

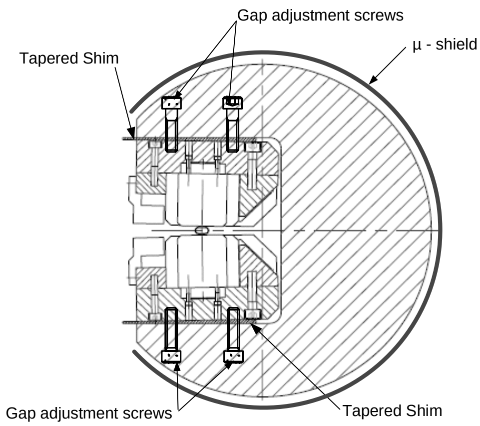

Figure 2. Each undulator is wrapped in a mu-shield, which reduces the ambient magnetic field effect by a factor of 6.

Hall probes are calibrated periodically relative to a Metrolab PT2025 NMR teslameter on a calibration stand. The calibration stand has a special chiller set to 20°C to keep the Hall probe at the same temperature it will have when in use. This increases the accuracy and repeatability of the calibration to 0.3G. The difference between two calibrations is shown in figure 3.

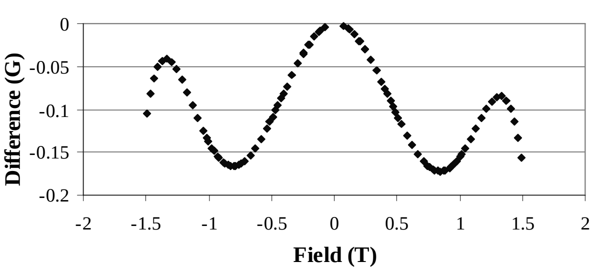

Figure 3. A polynomial fit is made for each Hall probe calibration. The polynomial coefficients are applied to measured data to calculate the corrected field. The difference between two Hall probe calibrations is shown.

Additionally, measurements of a 3.7kG reference magnet are made periodically, right before taking a final set of measurements, to check if the probe calibration has changed.

UNDULATOR TUNING

Undulator tuning is performed in accordance with a plan, in which all steps of tuning and fiducialization are enumerated. On the 4.5m long "rough tuning" bench, trajectories, phases, and K are set to the tolerances. Then a magnetic shield is installed and the undulator is moved to the 7.5m long "fine tuning" bench where a more extensive set of equipment allows field integral measurements, final trajectories, phases, K adjustments and checks to be performed. The undulator support has a steel girder and steel pedestals as will be used in the tunnel to simulate the tunnel conditions. After completion of the tuning process, a final dataset of measurements is made. The fiducialization process also begins on the fine tuning bench and is completed on the CMM.

Tuning trajectories, phases and K

The tuning procedure starts with alignment of a Hall probe to the undulator. Horizontal and vertical scans are made at poles periodically down the undulator. The symmetry point horizontally and the minimum field vertically define the magnetic center at each pole. A fit to the magnetic centers is made to find the axis location. Any magnetic pitch and yaw angles are corrected using the cam mover system. Upon finishing the alignment, scans of the magnetic field, sampling the field every 0.2mm, are made. The Hall probe is moving along the undulator at high speed (80mm/s) which reduces the effect of the probe zero drift. Only a single measurement is required for reproducibility of $2 \cdot 10^{-5}$ which is enough to set K and tune trajectories to better than 1μm. Each Hall probe measurement starts and ends inside zero field chambers located at both ends of the bench. The probe zero offsets and zero drifts are calculated and corrections are made to the measurements. The Hall probe is not used to measure field integrals, since a small DC offset from the probe, when integrated over the segment length, can exceed the required tolerances.

Beam trajectories, phase errors and K are calculated using a special computer program, which also specifies locations and strengths of the shims to be applied to make trajectories straight and to bring phases and K within the tolerances.

Since the magnetic shield blocks access to the gap adjustment screws, as shown in figure 2, an undulator is tuned on the "rough tuning" bench without it and corrections anticipating the shield are made to the measurements. Beam trajectories and phases are tuned by applying special shims, developed at ANL [1]. The K value is set by changing the gap size. All gap adjustment screws should be torqued to the same value to obtain gap adjustment accuracy better than 2μm. After beam trajectories and phases are corrected and K is set, the shield is installed and the undulator is moved onto the "fine tuning" bench.

Measuring and tuning field integrals

Accurate measurements of the small field integrals are made by a 3.6m long integrating coil with 150 turns, wound on a G10 strongback and aligned straight to ±0.1mm. It allows measurement of field integrals in both directions in a small gap by the same coil. The measurements are challenging because the coil is only allowed to move by a half a millimeter due to a small gap, and to minimize averaging over a significant volume of

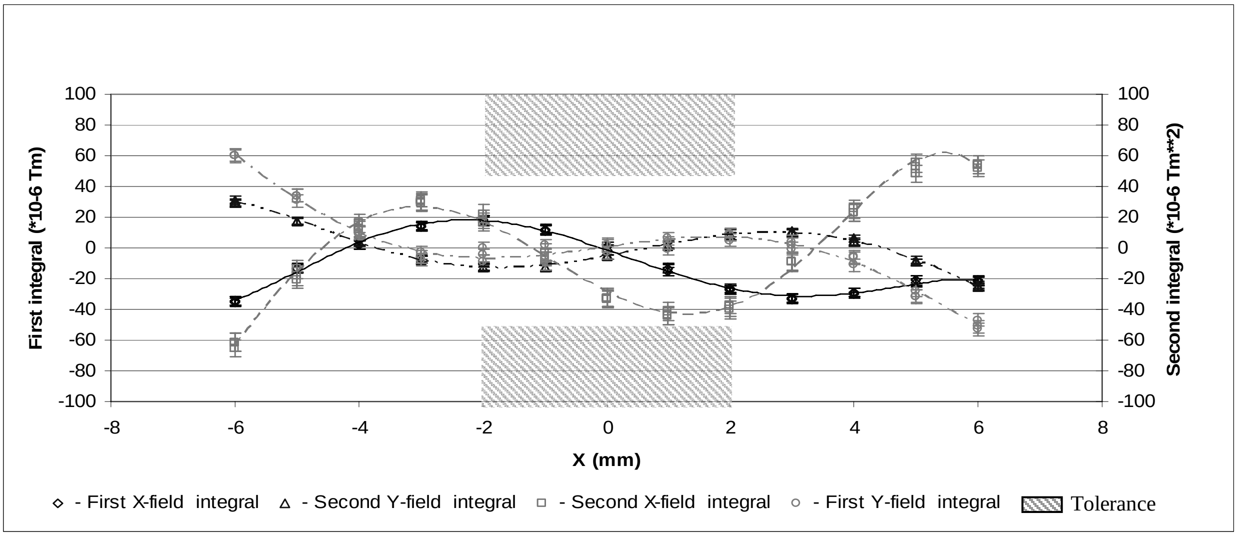

Figure 4. An example of X-dependence of horizontal and vertical field integrals measured by the moving coil. The polynomial fit is of fifth order.

field. Offsets are dealt with by measuring as the coil moves both forward and back. The first integral is measured by fixing return path wires of the coil on the girder and translating both ends of the coil parallel to itself inside the gap by stages. The voltage induced in the coil is sent to a Metrolab PDI-5025 integrator.

The second field integral is measured by holding the exit end of the coil fixed and moving the entrance end, as proposed by P.Vobly [4]. The second field integral has a weighing factor equal to the distance to the end point of the integration.

Heavy filtering is applied to the coil output signal to reduce the electrical noise. The X -dependence of the first and second field integrals in both horizontal and vertical directions is measured and corrected to the tolerances, as shown in figure 4, by applying different types of shims, developed at ANL.

Special tests were done to check the sensitivity and accuracy of the field integral measurement system. The long coil measurements of the small background field integrals were compared to field integrals calculated from fluxgate measurements and to the known field integrals of small magnets placed at various positions. The magnet's strengths were measured by independent means. The tests showed a good 10% agreement between the coil and the fluxgate and 6% level of accuracy in measuring the first and second field integrals by the coil.

Final dataset

When all the measurements are made and the undulator is tuned within the tolerances, the shims are glued in place. Then, the trajectories and the K value are checked and a final dataset of results is made. A map of field integrals is measured in a range of ±6mm with 1mm steps horizontally and ±0.2mm with 0.1mm steps vertically. In addition, Hall probe scans are made in the horizontal direction ±6mm from the magnetic axis location with a step size of 1mm. Small corrections of order of 0.1G are applied to the Hall probe measurements to match the field integrals measured by the long coil.

During the LCLS operation, it is planned to roll an undulator out of the beam line by 80mm. Field integrals are measured by the coil and the magnetic fields are sampled by the Hall probe at the undulator retracted position to have data for future beam trajectory corrections. Since it is outside the magnetic shield, the background field components are measured and taken into account.

To check repeatability of the measurements, a reference undulator is sent through the laboratory for measurements after every 4^{-th} undulator. Results of the reference magnet measurements are shown in table 1.

Table 1

Reference undulator measurement results

		May 2007	**June 2007**	**July 2007**
$\mathbf{I^1_x}$ (10^{-6} T·m)		+30	+20	+44
$\mathbf{I^2_x}$ (10^{-6} T·m^2)		-20	+4	-20
$\mathbf{I^1_y}$ (10^{-6} T·m)		+16	+19	+8
$\mathbf{I^2_y}$ (10^{-6} T·m^2)		+15	+21	+20
Phase Errors (°)	**r.m.s.**	3.7	3.7	3.7
	Entr.	-1.0	-1.5	-1.3
	Exit	-4.4	-4.4	-4.3
	Cell	-5.3	-5.9	-6.0
$\mathbf{K_{corrected}}$		3.498635	3.498567	3.498483
(ΔK/K$_{nom}$)		$2\cdot10^{-5}$	$-2\cdot10^{-5}$	$-4\cdot10^{-5}$

$I^1_{x,y}$ – first field integrals; $I^2_{x,y}$ – second field integrals; $K_{corrected}$ – effective K, corrected for different magnetic axis x-positions; $\Delta K/K_{nom}$ – relative K error w.r.t. nominal.

FIDUCIALIZATION

Fiducialization is the process of finding how the ideal beam axis, determined magnetically, relates to tangible objects on an undulator, in our case tooling balls. Special pointed magnets (PM) are used as an intermediate reference [5]. These magnets have a well defined field pattern. The location of the PM centers w.r.t. the PM tooling balls have been found in advance from a calibration. Upon completion of undulator tuning, two magnets are bolted to each end of the undulator and Hall probe scans are made to locate their centers, as shown in figure 5. Horizontal and vertical offsets of the undulator magnetic axis w.r.t. the PM tooling balls are calculated. Then the undulator with the PMs attached to it is moved to the CMM. On the CMM distances between all tooling balls are measured and the fiducialization data calculated.

A number of additional measurements are made to check fiducialization data for possible errors. Two extra PMs are fixed permanently on pedestals next to the bench and measured as references. Horizontal and vertical distances between all tooling balls are measured by optical tools and compared with the CMM data. Additionally, a direct optical measurement of the Hall probe enclosure is made. The accuracy of the optical measurements is about 50μm, but it is a good check of fiducialization data for large errors.

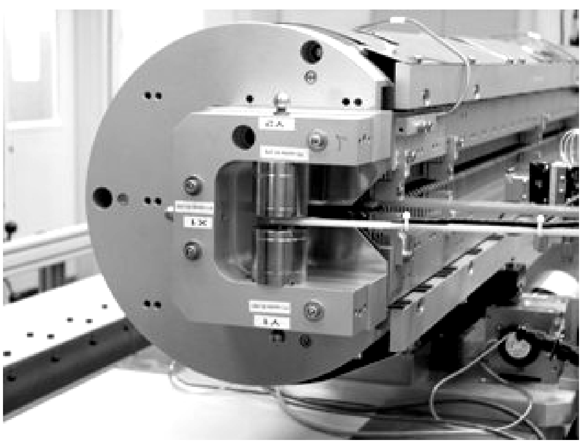

Figure 5. Pointed magnets are attached to the undulator segment for fiducialization.

CONCLUSION

By August 2007, 11 undulator segments have been successfully measured and tuned to specifications in the new climate controlled laboratory at SLAC. All measurement systems are thoroughly calibrated and tested. LCLS undulator measurement and tuning techniques and procedures proved to be adequate to meet the strict tuning requirements. All tuning steps are well documented in a number of technical notes and available online.[†] Raw data and analysis results are saved in a directory structure and available from the SLAC web site[‡].

[†] LCLS Technical Notes are available at www-ssrl.slac.stanford.edu/lcls/technotes.
[‡] At www-group.slac.stanford.edu/met/MagMeas/MAGDATA/LCLS/Undulator/.

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