# CONSTRUCTION OF THE MAGNETS AND SUPPORTS FOR THE LINAC COHERENT LIGHT SOURCE (LCLS) UNDULATOR SYSTEM*

M. White#, J. Collins, M. Jaski, G. Pile, B. Rusthoven, S. Sasaki, S. Shoaf, J. Stein, E. Trakhtenberg, I. Vasserman, and J. Xu, ANL, Argonne, IL 60439, U.S.A.

*Abstract*

The LCLS [1], nearing completion at the Stanford Linear Accelerator Center (SLAC) in California, will be the world's first x-ray free-electron laser when it comes online in mid-2009. Design and production of the undulator system was the responsibility of a team from the Advanced Photon Source (APS) at Argonne National Laboratory. Forty 3.4-m-long precision undulators, 37 laminated quadrupole magnets, and 38 precision support and motion systems with micron-level adjustability and stability were constructed and delivered to SLAC for tuning, fiducialization, final assembly, and installation in the LCLS tunnel. In addition to the magnets and supports, Argonne provided vacuum and diagnostics systems for the undulator line and a computer control and monitoring system that enables undulator girders and all components mounted on them to be accurately positioned [2]. An overview of the magnet and support construction is presented herein.

## INTRODUCTION

The LCLS construction project is nearing completion at the Stanford Linear Accelerator Center (SLAC) in California, and LCLS will be the world's first x-ray free-electron laser when it comes online in mid-2009. LCLS design and construction were accomplished primarily by a partnership of three U. S. national laboratories: Argonne National Laboratory (ANL), Lawrence Livermore National Laboratory (LLNL), and SLAC. A team from Argonne's Advanced Photon Source was responsible for design and construction of the high-precision undulator system, including the undulator and quadrupole magnets, vacuum system, beam diagnostics, ultra-stable support and motion system, and computer control and monitoring of the undulator system. At the time of this paper, the magnets and supports, vacuum system, and undulator controls system are all delivered, and component installation in the LCLS tunnel is well underway.

## MAGNETS AND SUPPORTS

### *Undulators*

Forty planar-hybrid, fixed-gap precision undulators were designed for LCLS by the Argonne team [3,4], and were optimized for efficient, cost-effective industrial mass production. The magnets are made of NdFeB, and poles are vanadium permendur. Magnets and poles are installed on an aluminum structure that defines their precise locations; the aluminum structure is bolted into a strong titanium housing. The most important undulator physics requirements are listed in Table 1. Undulator assembly was accomplished ahead of schedule and with significant cost savings. Bidders on the fabrication and assembly contracts were prequalified to ensure that they were capable of performing the job safely and correctly. The Argonne team devoted time up front to procedure development, vendor safety training, and completion of the necessary documentation. Vendor oversight, communication, and QA were continuous and thorough throughout the duration.

Table 1: Undulator Physics Requirements

| Parameter | Value | Units |
|---|---|---|
| # of 3.4-m-long und. segments | 33 + 7 | |
| Total installed undulator length | 131.520 | m |
| Min. expected undulator sys. life | 20 | years |
| Undulator period length | 30.00±0.05 | mm |
| Undulator gap height | ≥ 6.8 | mm |
| Wiggle plane | horizontal | |
| Horiz. und. seg. good field region | ±5.0 | mm |
| Vert. und. seg. good field region | ±200 | µm |
| Total pole cant angle | 4.5 | mrad |
| Phase slippage distance of 113×2π | 3.656 | m |
| Phase slip. tolerance (@ 1.5 Å) | ±175 | mrad |
| Max. acc. seg. ph. err. (@ 1.5Å) | ±175 | mrad |
| Abs. 1st field int. along und. seg. | $<40\times10^{-6}$ | Tm |
| Abs. 2nd field int. along und. seg. | $<50\times10^{-6}$ | $Tm^2$ |
| Undulator system temp. range | 20.00±0.56 | °C |

The final undulator was ready 27 months after award of the first long-lead contract. The first undulator from each of the assembly vendors [5,6] was magnetically tuned and mechanically verified at Argonne. All other undulators were delivered directly to SLAC for final tuning and fiducialization. Average peak fields of all undulators were measured at factory acceptance using a portable Hall probe. Results for 38 devices are shown in Figure 1.

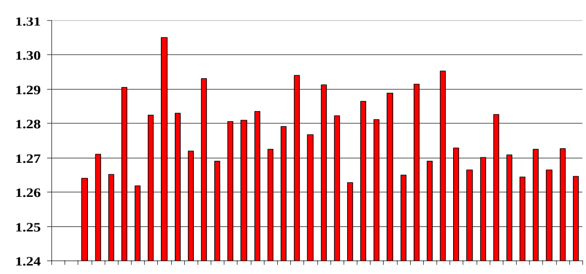


Figure 1: Average peak fields measured during factory acceptance of LCLS undulators.

*Work at Argonne was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-06CH11357.

# mwhite@aps.anl.gov

### *Support and Motion System (SMS)*

The undulator system SMS is shown in Figure 2 [7]. It consists of three main elements: pedestals; intermediate plates with camshaft movers; and a girder with two translation stages onto which the undulator, vacuum chamber, quadrupole, beam position monitors, and various other vacuum and diagnostic components are mounted. Figure 3 is a photo of the girder cross section.

An undulator is ~305 mm in diameter, 3400 mm long, and weighs 1000 kg. The 1000-kg weight of the undulator is transferred through its feet to the translation stages and then directly to the girders. The weight is then transferred to the hardened-steel wedges that are attached to the underside of the girder directly below the stages, and then to the camshaft mover (CSM) bearings, beneath which adjustable screws direct this load to the pedestal. The five camshaft movers, with eccentricity of ~1.5 mm, allow for precise horizontal and vertical positioning and adjustment of the girder. The pedestal's intermediate plate is attached to the pedestal with rods that allow for initial height adjustment. A double CSM and a single CSM are located adjacent to each other on the upstream pedestal. Two single CSMs, acting as a double CSM—where the cams are spread apart for added stability—are located on the intermediate plate of the downstream pedestal, as shown in Figure 4.

Undulators can be remotely retracted out of the beamline by 80 mm using the translation slides. The tolerances on precision, short- and long-term stability, and reproducibility are quite stringent, as shown in Table 2. The complete SMS was tested for many hundreds of hours to ensure that stability, repeatability, and reproducibility met specifications.

Table 2: Major Support and Motion System Requirements

| SMS Requirements | Value | Unit |
|---|---|---|
| Quad. position repeatability | ±7 | µm |
| Short-term BPM & quad stability | ±2 | µm |
| Long-term BPM & quad stability | ±5 | µm |
| Min. quad motion range radius | 1.0 | mm |
| Quad center man. adj. range | ±2 | mm |
| Quad center man. adj. resolution | 2 | µm |
| Quad position change in roll-out | ±25 | µm |
| Quad reproducibility after roll-out | ±2 | µm |
| BPM transverse change in roll-out | ±25 | µm |
| BPM reproducibility after roll-out | ±2 | µm |
| Horiz. und. repeatability in roll-out | ±10 | µm |
| Vert. und. repeatability in roll-out | ±5 | µm |
| Maximum und. roll-out duration | 60 | s |

A complete undulator module was assembled from prototype and first-article components, including pedestals, intermediate plates with camshaft movers, controls rack, cabling, electronic components, a girder with translation stages, a quadrupole, an RF-BPM, a wire position monitor (WPM), and an undulator with mu-metal shield. The module was thoroughly tested for hundreds of hours at the Advanced Photon Source at Argonne in order to demonstrate that the system, as designed, met all specifications. Some adjustments were made to the final production supports to make them even more rigid. Figure 5 is a photograph of the final undulator module and controls system at Argonne, assembled from first-article production components.

### *Control and Monitoring*

The LCLS undulator control system is responsible for micron-accuracy positioning of each undulator segment within the undulator hall. The undulator system controls rack can be seen below the girder in Figure 5.

Each control module controls five camshaft movers and two translation slides. Together, they enable positioning of the girder to micron accuracy with five degrees of freedom, including x and y, pitch, roll and yaw, where the z-axis is oriented along the undulator axis.

Undulators are protected against over-travel by redundant sets of software limits, limit switches, and hard stops. Transverse undulator motion is constantly monitored by software and two long-travel potentiometers to ensure synchronicity of the two translation stages within 50 microns. Motion control is supported by six 0.5-inch-travel spring-loaded potentiometers with a resolution of 0.13 microns. Four potentiometers provide vertical position data and two provide horizontal position data.

The undulator control system is also responsible for monitoring the temperature at 12 points along each undulator and for controlling the beam finder wire diagnostic.

Undulator system installation is progressing extremely well at SLAC and should be complete in the next couple of months.

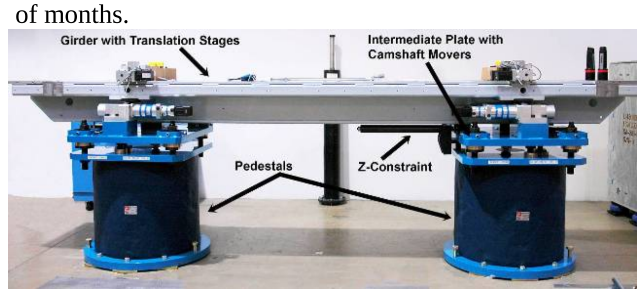


Figure 2: The SMS with pedestals, intermediate plates with camshaft movers, and girder with translation stages.

Figure 3: A cross section of the support girder mounted on the intermediate plate.

Figure 4: The undulator is mounted on a translation slide that is attached to the girder. The double CSM is shown below the girder, mounted on the intermediate plate.


Figure 5: The single-undulator module at Argonne.

### *Quadrupole Magnets*

A quadrupole magnet with horizontal and vertical correctors is installed on each girder. The magnet was designed for excellent field quality and mechanical stability, and is laminated to permit fast beam-based alignment operations. It is air-cooled to avoid the need to supply water in the undulator tunnel. The quadrupole magnet and support parameters are listed in Table 3 and Figure 6 shows the magnet and support stage.

Table 3: Major Quadrupole Magnet Parameters

| Quadrupole Parameter | Value | Unit |
|---|---|---|
| Nominal integrated quad gradient | 3.00±0.03 | T |
| Maximum integrated quad gradient | 4.0 | T |
| Trim strength range | $\pm 3\times10^{-4}$ | Tm |
| Trim stability | $\pm 3\times10^{-7}$ | Tm |
| Trim settability | $\pm 1.5\times10^{-6}$ | Tm |
| Center stability after fiducialization | ±10 | µm |
| Center stability @ ±20% grad. chng | ±3 | µm |
| Center stability - short term (1h) | ±1 | µm |
| Center stability - long term (24h) | ±3 | µm |
| Grad. stability - long term (24h) rms | 0.25 | % |
| Roll tolerance | ±20 | mrad |
| Pitch tolerance | ±15 | mrad |
| Yaw tolerance | ±15 | mrad |

The quadrupole was also designed for low power dissipation, since the total dissipated-power budget from all sources is 50 W/meter, including lighting. The 29.5-kg quadrupole is supported by a stable, compact, rigid stage that provides for vertical and transverse adjustment of the magnet. The stage has a travel range of ±3 mm in both directions and a precision of 2 microns.

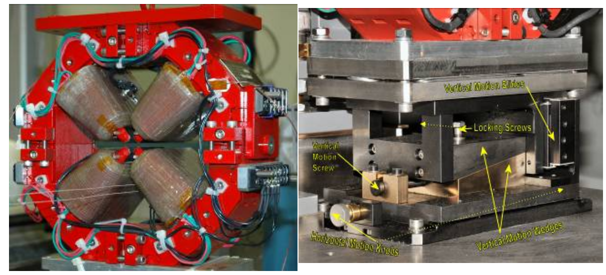


Figure 6: End view of the quadrupole magnet (left) and support and translation stage (right).

## SUMMARY

Forty undulators, 37 laminated quadrupole magnets, 38 precision support and motion systems, and complete undulator system controls were designed, prototyped, tested, and constructed by Argonne. All components were delivered to SLAC. Final undulator tuning and fiducialization are ongoing at SLAC, and component installation in the LCLS tunnel is well underway.

## ACKNOWLEDGEMENTS

We gratefully acknowledge Y. G. Amer, T. Barsz, K. Boerste, D. Capatina, J. Chan, J. Q. Chan, E. Chang, F. Clark, L. Cokeley, R. A. Conley, F. Coose, R. Dejus, P. Den Hartog, F. DePaola, S. Doran, C. Doose, M. Erdmann, C. Eyberger, F. Fisher, H. Friedsam, M. Givens, J. Grimmer, S. Hahn, S. Hanuska, B. S. Hoster, J. Ingraffia, W. Jansma, M. Kasa, R. T. Kmak, K. Knight, J. W. Lang, R. Lanham, G. Lawrence, P. Mast, K. Meitsner, M. Merritt, E. Moog, D. Nocher, H. D. Nuhn, M. Oprondek, T. Powers, C. Rago, D. Schafer, J. Schneider, D. Schultz, L. Skubal, J. TerHaar, R. Voogt, S. Wesling, D. Wilkinson, and J. M. Wozniak for their critical contributions to this effort.

## REFERENCES

[1] Linac Coherent Light Source (LCLS) Project homepage: http://www-ssrl.slac.stanford.edu/lcls/

[2] G. Pile et al., "Design and Production of the Undulator System for the Linac Coherent Light Source (LCLS)," Proc. of FEL08, to be published at http://www.JACoW.org.

[3] E. Trakhtenberg et al., Proc. of PAC07, Albuquerque, NM, USA, July 2007, TUPMN100, p. 1148-1150 (2007); http://www.JACoW.org.

[4] I.B. Vasserman et al., Nucl. Instrum. Methods A575 (2007) 22.

[5] Hi-Tech Mfg., 4637 N 25th Ave, Schiller Park, IL, 60176, USA.

[6] Metalex Mfg., 5750 Cornell Rd., Blue Ash, OH, 45242, USA.

[7] E. Trakhtenberg et al., Proceedings of the 2008 MEDSI Conference, to be published in NIMA.