DESIGN AND CONSTRUCTION OF THE LINAC COHERENT LIGHT SOURCE (LCLS) UNDULATOR SYSTEM*

James L. Bailey, Thomas Barsz, William Berg, Jeffrey Todd Collins, Patric Den Hartog, Horst Walter Friedsam, §Geoffrey Pile, Mark Jaski, Soon-Hong Lee, Robert M. Lill, Elizabeth Rahm Moog, James Morgan, Shigemi Sasaki, Steven Shoaf, Laura Skubal, S. Joshua Stein, William F. Toter, Emil Trakhtenberg, Isaac Vasserman, Dean Walters, Marion White, Greg Edward Wiemerslage, Joseph Z. Xu, Bingxin Yang
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, USA
Heinz-Dieter Nuhn, David Schultz
Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, California 94025, USA

Abstract

The Linac Coherent Light Source (LCLS), now under construction at the Stanford Linear Accelerator Center (SLAC) in California, will be the world's first x-ray free-electron laser when it comes online next year. LCLS design and construction are being performed 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 is responsible for design and construction of the high-precision, state-of-the-art undulator system, including the undulators, quadrupoles, sub-micron-precision beam diagnostics, vacuum chambers, ultra-stable and micron-level-settable support and motion system, and computer control and monitoring. An overview of achieved precision and stability results will be presented together with the LCLS construction status.

INTRODUCTION

The LCLS, the world's first x-ray free-electron laser (FEL), is in the final stage of construction at SLAC in California. First light is scheduled in 2009. An overview of the LCLS including the Undulator System is shown in Figure 1.

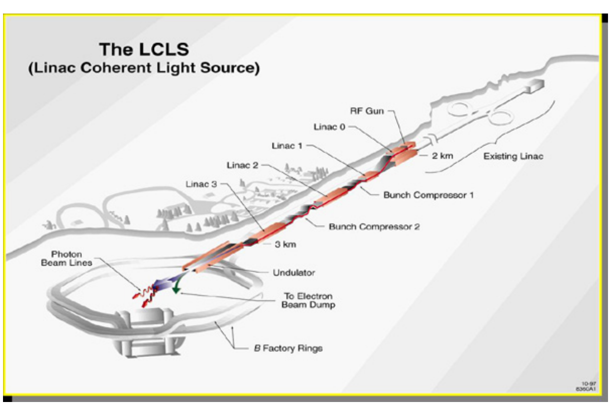

Figure 1: The LCLS with the Undulator System section at the end of Linac 3.

LCLS design and construction has been accomplished primarily via a partnership of three U.S. national laboratories: ANL, LLNL, and SLAC. Because of the Advanced Photon Source team's experience in undulator systems, ANL was chosen to design and construct the high-precision undulator system, including the undulator magnets, quadrupole magnets, beam diagnostics, vacuum system, ultra-stable support and motion system, and undulator computer control and monitoring. The LCLS Undulator System, containing 33 separate undulator segments, is the heart of the FEL and is responsible for the production of spontaneous and FEL x-ray radiation. Major LCLS design parameters are listed in Table 1.

Table 1: LCLS Design Parameters

X-ray wavelength	1.5 to 15 Ångströms (on the scale of atoms)
Ultra-short pulse duration	1 to 230 femtoseconds
Peak brightness	0.8 to 0.06 $x10^{33}$ photons per s-mm^2-$mrad^2$-0.1% bandwidth
X-rays per pulse	1.1 to 29 $x10^{12}$
Electron beam energy	4.5 to 14.3 GeV
Peak current	3.4 kA
Laser properties	Coherent x-rays at same wavelength
Fundamental saturation power at exit	8 to 17 GW
Meters of undulator magnets to generate x-rays from electrons	112

Each undulator module contains one undulator segment, a quadrupole magnet, a vacuum chamber with associated vacuum equipment, a beam position monitor (BPM), various other position monitoring and beam diagnostic systems, all of which are fiducialized, aligned, and installed on a precision support and motion system (SMS), [1-5]. The undulator project was planned using a work breakdown structure (WBS). There are five main areas: (1) Technical Management, (2) Magnets and Supports, (3) Controls, (4) Vacuum Systems, and (5) Diagnostics. This paper describes technical components in the last four areas.

* Work is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.
§pileg@aps.anl.gov

MAGNETS AND SUPPORTS

The LCLS design requires thirty-three installed undulator modules in order to meet its commissioning and operational design goals. A schematic view of an undulator module is shown in Figure 2. In total, 40 undulators were manufactured, including six operational spares and one reference unit. Thirty-seven quadrupole magnets with horizontal and vertical correctors and thirty-eight support and motion systems were constructed as well. These items are described in the following sections.

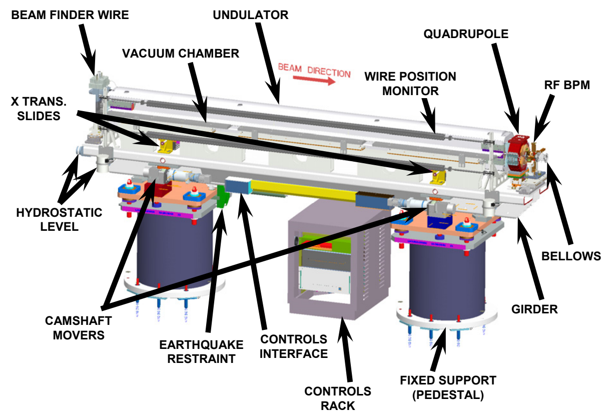

Figure 2: Schematic view of an undulator module.

Undulator Magnets

The LCLS undulators are fixed-gap devices, 3.4 meters long with a 30-mm period and a nominal k-value of 3.71. The magnets are slightly canted with a 4.5-mrad opening angle, allowing for some k tunability. The resulting B_{eff} is 1.325T. Each undulator contains four hundred fifty NdFeB magnets and 452 precision-machined vanadium permendur poles. Magnets and poles are installed in precision aluminum bases, and the resulting magnetic structures are installed into a precision-machined housing, or strongback, made entirely of titanium. Titanium was chosen as it is nonmagnetic, extremely strong, has a low coefficient of thermal expansion, and has excellent long-term stability. Finally, earth-field shielding made of mu-metal was installed around the titanium housings to shield the earth's magnetic field. A prototype undulator, shown in Figure 3, was fabricated at Argonne, and was tested over a period of several years. Magnetic tuning was completed to correct for phase errors and to ensure trajectory straightness. Undulator ends were phased.

Several changes were eventually made to improve the design, and were successfully implemented and tested in the prototype device. After experience fabricating and testing the prototype undulator at Argonne, it seemed reasonable that, with appropriate engineering design, documentation, assembly procedures, safety training, and oversight, the production undulators could be constructed by highly-qualified industrial vendors lacking any prior undulator manufacturing experience. Bid packages were sent to prequalified vendors, some specializing in undulator production and some with absolutely no prior experience in undulators. Two highly-qualified industrial vendors (as a means to mitigate risk) were chosen to do the final assembly. First-article undulators from both vendors were successfully tuned at Argonne, meeting all technical specifications and passing all acceptance tests. This method of manufacture proved extremely successful, and the 40th undulator was produced (ahead of schedule and with cost savings to the project) 27 months after award of the first long-lead item contract.

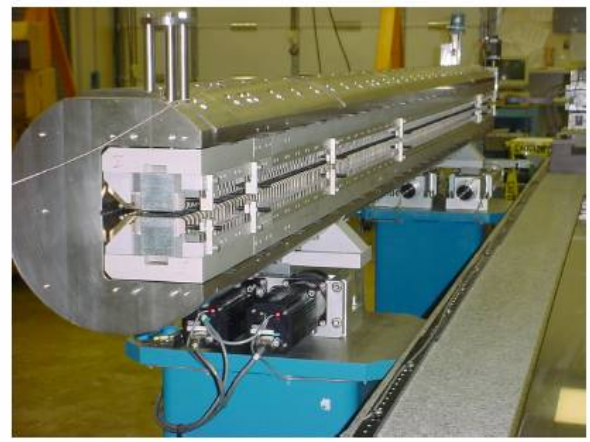

Figure 3: The prototype undulator. The magnetic structure is visible, housed in the titanium strongback.

Support and Motion System

The SMS was designed to support and maintain accurate alignment between the various components that make up an undulator module, and to provide precise positioning of an undulator segment with respect to adjacent segments. The main components of the SMS are: girders, intermediate plates with camshaft movers, and fixed supports. The SMS also provides the capability for an undulator to be remotely retracted from the beamline, leaving the vacuum chamber in place, by 80 mm, and then to be accurately returned to the original position to within ±2 microns. This remote retraction or "roll-away" capability is necessary to enable the beam to pass by without being disturbed by the undulator's magnetic field. Translation stages are attached to and supported by a very stiff girder. The two stages are controlled in tandem, and synchronous motion is achieved through motor control. The girder supports the 1000-kg undulator, quadrupole magnets, vacuum chamber and other vacuum system components, a beam position monitor, and various other beam diagnostic components.

The fixed supports, bolted and grouted to the Undulator Hall floor, provide a rigid mounting platform for the rest of the support and motion system. The fixed support system contains two rigid pedestal bases with adjustment capabilities on the top of each base. Vertical, transverse, and yaw adjustments are provided via a series of precision adjustment screws used for initial alignment of the bases with respect to one another. Each pedestal is filled with sand and is also equipped with an insulating blanket to minimize response to thermal gradients.

Intermediate plates, located on top of each pedestal, serve as the mounting platforms for a five-axis camshaft mover system. A double camshaft mover and a single camshaft mover are located adjacent to each other on the upstream intermediate plate, and two single camshaft movers, acting as a double camshaft mover, are located on the downstream intermediate plate. Hardened-steel wedge blocks are mounted on the bottom of the girder support system and used to contact the camshaft mover bearings. This arrangement provides the equivalent of a three-point kinematic support for the girder support system.

The girder support system moves under the command of the five camshaft movers with five degrees of freedom. If the "z" dimension is defined to be along the path of the beam, the camshaft movers can move the girder support system in the "y" (up and down) and "x" (side to side) directions, and, depending on the relative motions at each end, pitch and yaw motions of the girder support system can be commanded, as described in the next section. The camshaft movers can also provide roll motion control for the girder support system. Camshaft movers offer precision motion control without jeopardizing system rigidity or stiffness.

CONTROLS AND DATA ACQUISITION

The controls and data acquisition system is responsible for micron-accurate positioning of each undulator segment within the Undulator Hall to ensure FEL operation while simultaneously protecting the undulator from over-travel through the use of redundant sets of software and hardware limits. The controls system also monitors temperature in 12 different positions along the module. Commercial off-the-shelf components were selected for the system whenever possible, though some custom hardware was required to achieve the demanding system tolerances. The EPICS-based, wired Ethernet control system was configured into 33 identical subsystems, each with a self-contained rack of control hardware that regulates motion of the five camshaft movers and two translation slides. Argonne designed and assembled all 33 racks and procured 1,800 custom mil-spec connecting cables to facilitate efficient installation of the complete control system in the LCLS tunnel.

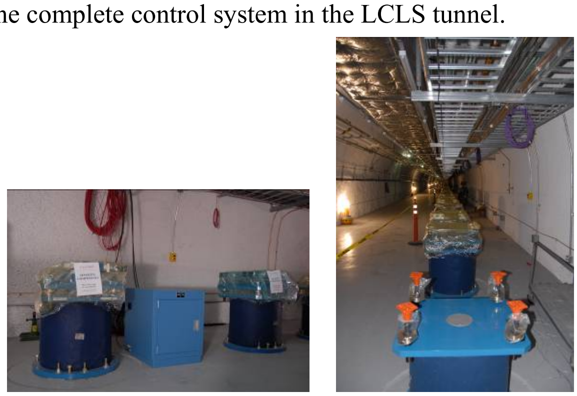

Figure 4: Control racks and fixed bases for the SMS in Undulator Hall.

Cables are fully "connectorized" at both ends, enabling controls for a single undulator module to be connected within four hours. Figure 4 shows a rack installed between fixed support pedestals in the Undulator Hall.

The control system regulates the camshaft mover motion in the x and y directions, and controls system pitch and yaw. One of the problems that had to be solved during remote "roll away" of the undulator was that moving the one-ton undulator by 80 mm caused an unacceptably-large 110-micron shift in the center of the quadrupole magnet relative to the beam center. By modifying the angle of the traditional 45-degree wedge block, the 25-micron requirement for quadrupole-center stability during rollout was met. The final design meets all requirements without any extra active correction systems, significantly simplifies the system control algorithm, and improves system reliability. Figure 5 shows the configuration of the camshaft movers.

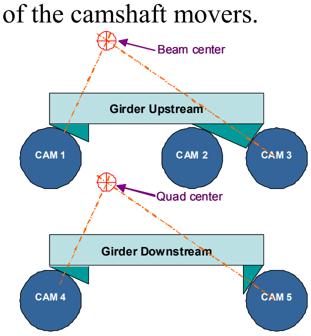

Figure 5: Five-cam girder support system with modified wedge block angles.

Results of precision and repeatability tests of the camshaft system were ±2 μm with a feedback and motion resolution of 0.13 μm. Precision of the transverse travel on linear stages for the slides was ±2 μm; the precision of the k-value adjustment was ±5 μm. In operation, transverse undulator motion is constantly monitored to ensure synchronicity of the two translation stages within 50 μm. All motion control is supported by six spring-loaded potentiometers with a resolution of 2 μm. Four of the potentiometers detail the vertical position while two track horizontal position. The short-term (10-hour) stability of the girder and undulator was verified to be ±3 μm, meeting or exceeding the ±5-μm requirement.

VACUUM SYSTEMS

A separate, 3.4-meter-long, internally-polished vacuum chamber is required in each undulator module, or a total of thirty-three for the entire undulator system. Forty chambers, including seven spares, were manufactured. The surface roughness, electrical surface conductivity, and geometric shape of the chamber all contribute to the impedance of the vacuum chamber. The goal of the system design was to keep the contribution from surface roughness and geometric shape small (<10%) compared to the contribution from electrical surface conductivity. The mechanical aspects of mass-producing this chamber to the demanding tolerances and surface finish required were extremely challenging. Surface finish was more than twice as smooth and wall thickness was half that of any existing vacuum chamber previously manufactured at Argonne. Figure 6 shows a cross section of the vacuum chamber.

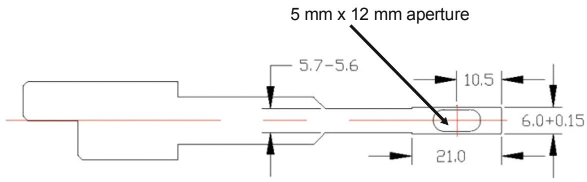

Figure 6: Cross section of the vacuum chamber. Dimensions are in mm.

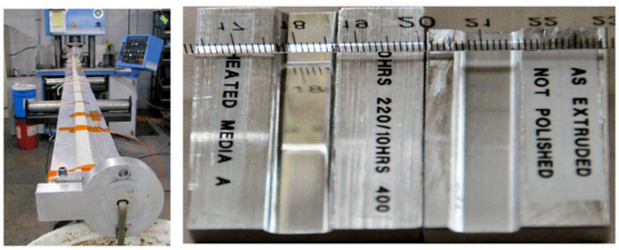

Figure 7: Abrasive flow polishing. The picture on the left shows alumina grit exiting a raw extrusion. The alumina entered the system at 400 psi and 30°C, first from one end and then from the other so that the extrusion was polished from both ends. The picture on the right shows a chamber before and after polishing.

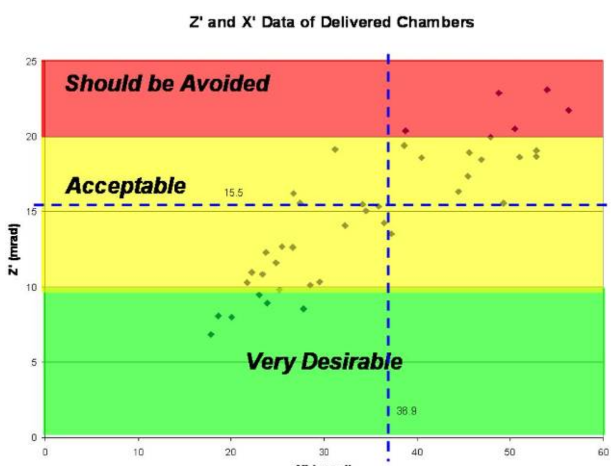

Figure 8: Graphical display of surface finish data from 46 chambers. The average of all vacuum chambers is 14.86 mrad in Z′ and 35.14 mrad in X′. The rms of Z′ is 15.5 mrad and X′ is 36.9 mrad. Selecting the best 33 chambers yields an rms of 13.9 mrad for Z′ and 34.2 mrad for X′. Five chambers were sacrificed to verify the surface finish in the middle of the extrusions.

During production, 46 raw extrusions were subjected to abrasive flow polishing. Five chambers were sacrificed for quality control purposes, so that surface roughness could be measured at various positions along the chamber extrusions. The production process was perfected and surface roughness specifications were met. The remaining raw extrusions were machined to exacting dimensions to allow for an overall flange-to-flange length of 3464.44 mm +0.2/-0.8 mm and a vertical straightness after alignment of ≤ 0.050 mm. Figure 7 shows the polishing process and visual results; Figure 8 shows the surface finish data.

DIAGNOSTICS

The diagnostics system consists of a submicron x-band cavity beam position monitor (BPM), a wire diagnostic for beam location, and a beam loss monitor system. In operation, these components are used to obtain position and current information from the electron beam. The beam loss monitor is designed to protect the undulator from radiation damage.

Beam Finder Wire (BFW)

The BFW allows beam-based alignment of an undulator segment to be accomplished from the control room without the need for tunnel access. The electron beam will be brought into collision with two wires, one at a time, by moving the BFW-undulator/girder arrangement. The amount of beam hitting the wire will be measured by detecting scattered particles downstream of the wire. Argonne designed and manufactured 37 BFWs, 33 of which are installed in the beamline. The quality assurance/quality control during the manufacturing process was rigorous. Each BFW was subjected to a 100-cycle repeatability test after initial adjustments and positioning specifications were met. Figure 9 shows a BFW.

Figure 9: Beam finder wire.

Beam Loss Monitor (BLM)

Five beam loss monitors are being produced by Argonne for the undulator system. The main function of the BLM is to protect the permanent magnets in the undulator from magnetic field degradation. Traditional passive dosimetry also will be utilized to monitor radiation dose to the magnets. The five initially-installed BLM units are designed with electronic dosimetry capability. If initial commissioning results demonstrate positive results of the electronic dosimetry, then up to thirty additional units will be built to protect each individual undulator. Figure 10 shows a graphic of the BLM.

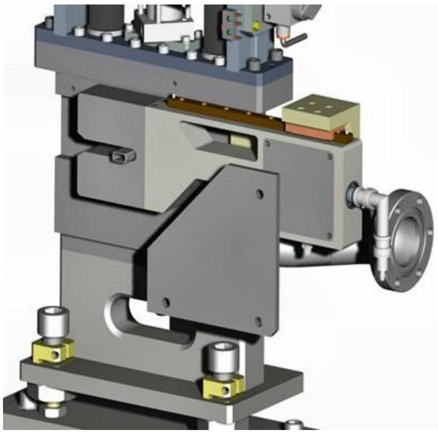

Figure 10: The beam loss monitor.

Beam Position Monitor (BPM)

The purpose of the BPM is to provide high-resolution measurements of the electron beam trajectory on a pulse-to-pulse basis and over many shots. The x-band cavity BPM is a brazed assembly composed of a body, waveguide transitions, end cap rf windows, and EVAC-type vacuum flanges. It potentially has the capability of resolving beam position in the tens of nanometers. Cavity dimensions are machined with a +0.000/-0.015 mm tolerance with a surface finish of 0.1 µm or better.

Performance of the BPM was extensively tested and measured using an electron beam at the APS. During these tests, two additional BPM units were utilized, one on either side of the unit under test, to obtain data and assess BPM performance. Figure 11 shows the BPMs during these tests. The tests showed that the BPM design meets the physics requirements.

Thirty-six rf cavity BPMs were created for LCLS: two are installed in the Linac upstream of the undulator beamline, one is upstream of the first undulator, and 33 are located downstream of each undulator. The BPM manufacturing process has been one of the most challenging processes to date; brazing the BPM requires both a three-step brazing process and a thermal expansion containment process to mitigate problems associated with the fragile windows.

During beam tests, two additional units were utilized to obtain data and assess BPM performance, meet the physics requirements, and measure the full capabilities of the BPM. This extensive series of tests was called 'The Three BPM Tests.' Figure 11 shows the BPMs during these tests.

Table 2 lists the BPM specifications and measured results, and Figure 12 shows a full BPM system installed on a completed LCLS undulator module.

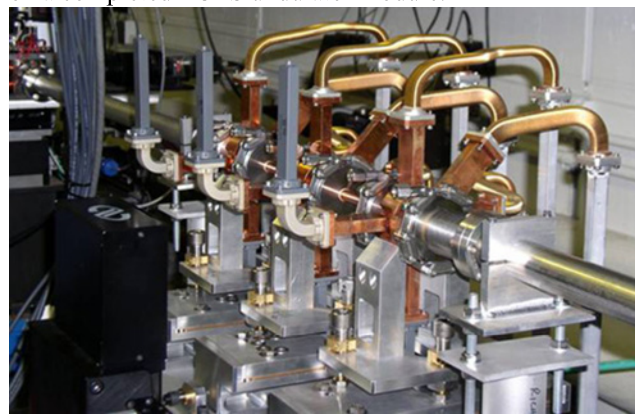

Figure 11: Three BPMs are shown, as installed in the APS linac, during verification testing.

Table 2: BPM Specifications vs. Measured Data

Parameter	Specification Limit	Measured Data (09/27/07)
Resolution	< 1 µm 0.2-1.0 nC ± 1 mm range	< 0.6 µm
Offset Stability	< ±1 µm 1 hour 20.0 ±0.56 Celsius	< ±1 µm
Offset Stability	< ±3 µm 24 hour 20.0 ±0.56 Celsius	< 100 nm electronics test 20.0 ±0.56 Celsius
Gain Error	< ±10% ±1 mm range	< 10% ±1 mm range
Dynamic Range, Position	±1 mm	> ±1 mm
Dynamic Range, Intensity	> 14 dB	> 14 dB

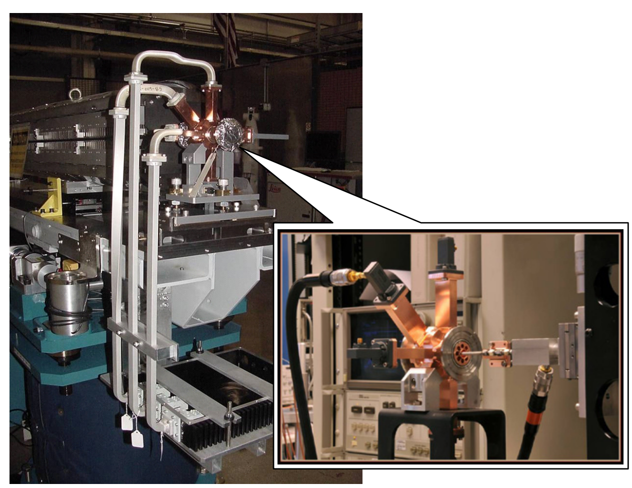

Figure 12: The rf cavity beam position monitor on the left. The inlay shows BPM testing at ANL.

SUMMARY

Prototypes were constructed to prove that all designs met specifications. A long-term-test (LTT) setup was constructed at Argonne utilizing first-article production components. These components were fully integrated, and problems were resolved prior to production. The LTT functions as an integration tool until all 33 undulator systems are commissioned at SLAC. Figure 13 shows the long-term test facility at ANL.

The LCLS Undulator System has been an extremely challenging project from both the theoretical and technical aspects. Organization and mass production of the complete system by Argonne, located 2000 miles from SLAC, required organization, constant communication, and detailed documentation. Argonne-designed project-specific software was created to handle the massive quantities of supporting drawings and documentation. It contains all quality control/quality assurance records, enables components to be tracked en route to SLAC, and delivers this information via a web-based, user-friendly interface that allows all team members to access the information from anywhere.

At the time this paper was written, installation at SLAC was in progress. The majority of the components are at SLAC. All fixed supports and undulator controls racks are installed in the undulator tunnel. Girder assembly is well underway at SLAC: approximately 23 are complete. Figure 14 shows initial installation of the fixed support system at SLAC, and Figure 15 shows the first girder installed in the LCLS undulator tunnel. First spontaneous light is planned for May 2009. The Undulator System is currently on time and within budget.

Figure 13: Long-term test stand. The single undulator system is accurately positioned with respect to a mock tunnel simulating Undulator Hall at SLAC.

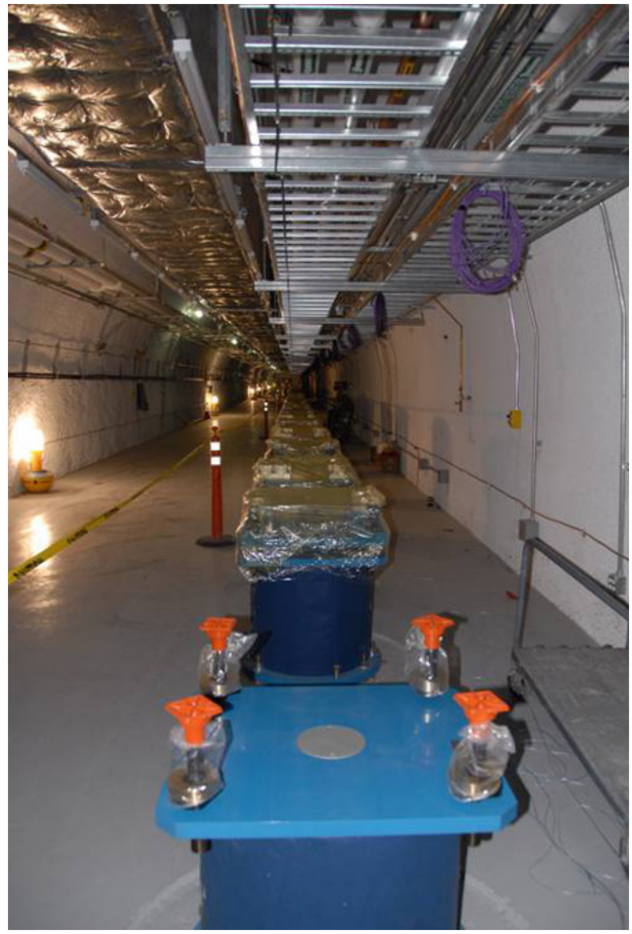

Figure 14: Initial installation of the fixed support systems for the LCLS undulators.

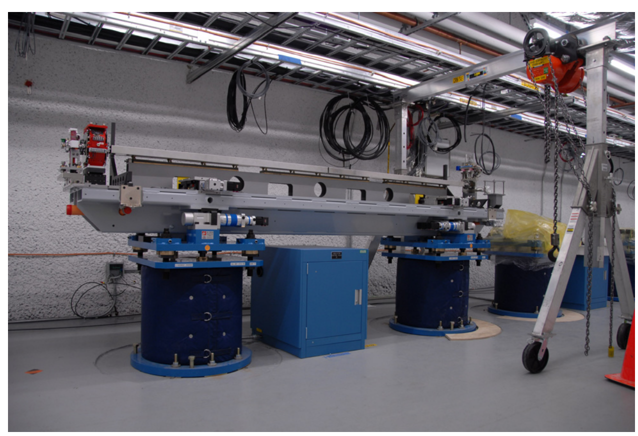

Figure 15: The first girder is shown installed in the LCLS undulator tunnel.

ACKNOWLEDGEMENTS

We gratefully acknowledge the contributions from many other personnel from the Argonne and SLAC teams not listed as authors.

REFERENCES

[1] Linac Coherent Light Source (LCLS) Project homepage: http://www-ssrl.slac.stanford.edu/lcls/
[2] M. White et al., "Magnets, Supports, and Controls for the Linac Coherent Light Source (LCLS) Undulator System," these proceedings.
[3] E. Trakhtenberg et al., "LCLS Undulator Production," Proc. of PAC07, Albuquerque, NM, USA, July 2007, TUPMN100, p. 1148-1150; http://www.JACoW.org.
[4] E. Trakhtenberg et al., Proceedings of the 2008 MEDSI Conference, to be published in NIM-A.
[5] D. Walters et al., "Vacuum and Beam Diagnostics for the Linac Coherent Light Source (LCLS) Undulator System," these proceedings.