LCLS UNDULATOR PRODUCTION*

Emil Trakhtenberg, Tom Barsz, Patric Den Hartog, Glen Lawrence, Elizabeth Moog, Shigemi Sasaki, Isaac Vasserman, Marion White, Gregory Goldfarb†, Sergey Lagonsky†, Nikolai Lagonsky†, Simon Sorsher†, Thomas Becker#, Scott Dufresne#, Werner Kummerle#, Rob Schuermann#
Argonne National Laboratory 9700 S. Cass Ave, Lemont, IL, 60439, USA,
†Hi-Tech Manufacturing, 4637 N. 25th Ave, Schiller Park, IL, 60176, USA,
#Metalex Manufacturing, 5750 Cornell Rd., Blue Ash, OH, 45242, USA

Abstract

Design and construction of the undulators for the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center (SLAC) is the responsibility of Argonne National Laboratory (ANL). A full-scale prototype undulator was constructed in-house and extensively tested [1] at Argonne's Advanced Photon Source (APS). The device was tunable to well within the LCLS requirements and was stable for five years. Experience constructing the prototype undulator led us to conclude that with appropriate engineering design and detailed assembly procedures, precision undulators can be constructed by highly-qualified industrial vendors without undulator-construction experience. Argonne's detailed technological knowledge and experience were transferred to the successful bidders who produced outstanding undulators. Our production concept for the 3.4-m-long, fixed-gap, planar-hybrid undulators with a 30-mm period is discussed. Manufacturing, quality assurance, and acceptance testing details are also presented.

INTRODUCTION

Design and construction of the undulators for the Linac Coherent Light Source (LCLS) was the responsibility of ANL. A prototype LCLS undulator was designed and produced in-house at Argonne from 1999 to 2001 by scientists and engineers at the APS, together with visiting scientists from the Budker Institute of Nuclear Physics in Russia. Long-term stability was a critical performance requirement for this undulator, and a key design approach was to make the undulator as rigid as possible. Production of the prototype was followed by an extended period of testing and observation, during which the undulator's performance was verified, and a significant number of design improvements were made [2]. The improvements were incorporated into the final design of the LCLS undulator, together with many new concepts to simplify the construction and assembly of these precision devices.

CONSTRUCTION

Procurement of long-lead items – the magnets, poles, and strongbacks – began in 2005 in order to expedite the entire production process. The undulator strongbacks are large, high-precision objects made from titanium forgings. The number of qualified vendors capable of performing this job was limited; however, there were several candidates. The strongback machining was awarded in Spring 2005, with half of the units going to each of two vendors. The split award was a risk-mitigation strategy. If one vendor could not meet the demanding technical requirements or could not accomplish the task on schedule, the second company should complete the job. Metalex Manufacturing finished its strongbacks flawlessly and ahead of schedule, and therefore was able to manufacture five additional units, maintaining the overall LCLS assembly schedule. Figure 1 is a photograph of the first strongback on the Coordinate Measurement Machine (CMM) after final inspection at Metalex. Hi-Tech Manufacturing manufactured all poles, and all NdFeB magnets were supplied by Shin-Etsu Magnetics.

Figure 1: Titanium strongback on the CMM at Metalex after final inspection and acceptance.

After the long-lead contracts were in place, solicitation for the undulator assembly began. The above-mentioned construction simplifications now enabled highly-qualified machine shops to bid on the undulator-assembly contract. The solicitation was issued to traditional vendors with world-recognized expertise as well as to a few non-traditional ones with no previous experience in undulator technology. It was clear that if a non-traditional vendor won the bid, Argonne would transfer its technology and experience to them. What was not completely foreseen at the outset was that these vendors could also transfer their technology and experience to Argonne and that the resulting undulators would be far better for it. This process evolved and become the foundation for some excellent working relationships.

Two highly-qualified, but non-traditional undulator vendors, Metalex Manufacturing and Hi-Tech

*Work supported by the U.S. Dept. of Energy, Office of Science, Office of Basic Energy Sciences, under contract numbers DE AC02-06CH11357 and DE AC03-76SF00515.

Manufacturing, won the bid to perform final assembly of the LCLS undulators. Lean business practices, efficiency, and attention to detail enabled them to be competitive. Both vendors immediately began preparing work areas and fabricating sub-components and assembly fixtures.

First-article undulators from both vendors were completed and delivered to Argonne for tuning on schedule in March of 2006. Figure 2 shows the Hi-Tech's first-article undulator after acceptance. Both first-article undulators were successfully tuned by Argonne scientists on the 6-m-long bench at APS's magnet measurement laboratory, results of one are shown in Figure 3. After acceptance of the device and all of the associated documentation, both vendors began full-scale production.

Figure 2: First-article undulator acceptance at Hi-Tech.

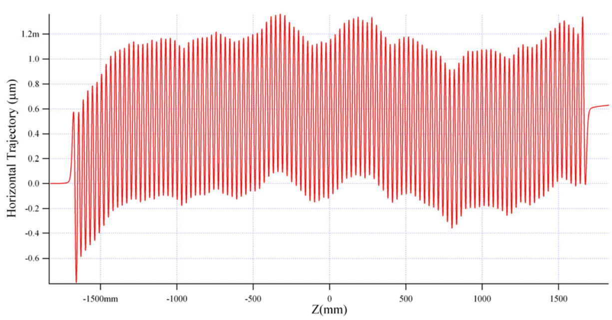

Figure 3: Trajectory in Hi-Tech's first-article undulator after tuning. The trajectory is straight to within 2 microns over the entire 3.4-m-long device.

QA and Documentation

The logistics and quality of all operations, furnished long-lead components, and assembly procedures were of concern to APS and the vendors. Several measures were taken to address these issues:

- All 19,200 precision-machined poles were individually serialized, inspected on a CMM, and documented. The documentation was in the QA package for each undulator.
- Magnets were randomly selected for verification measurements. Shin-Etsu measured each magnet, and provided a complete list of measurements for every lot. Five magnets from each lot were selected from the vendor's list. Those magnets were shipped to Argonne for dimensional and magnetic inspection. After acceptance of the sample magnets for each undulator, Shin-Etsu was granted permission to ship that lot of magnets to one of the assembly vendors. Verification measurement data for all 40 magnet lots are shown in Figure 4, together with the final factory measurements. The offset between the two sets of measurements is understood, resulting from different geometric factors assumed in each system. All magnets are within the required tolerance.

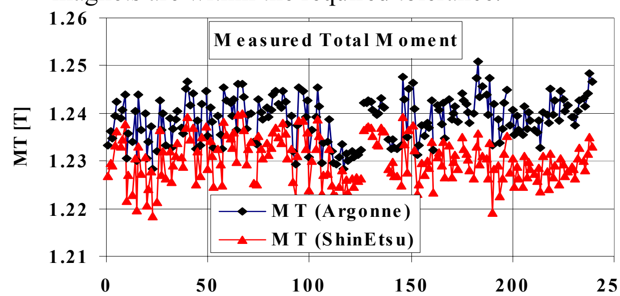

Figure 4: Total moment of the verification magnets.

- The sorting list and a magnet installation map for each undulator were prepared by APS physicists [3] and provided to the assembly vendors. Damaged magnets were replaced by appropriately-chosen spare magnets after consultation with Argonne physicists.

After installation of the magnets into the magnet bases, assembly vendors made photographs of assembled structures and emailed them to APS. Slot numbers were stamped into the aluminum bases and magnet numbers and orientations were inked onto the magnets. Slot number, magnet number, and magnet orientation had to be clearly visible in the photos. The complete set of photographs for each undulator was independently verified by two persons at the APS. After verification that the bases exactly matched the sorting list, the vendor was granted permission to install the magnet bases into the titanium strongbacks using a specialized set of fixtures designed and prepared for that purpose. One of the verification photos is shown in Figure 5.

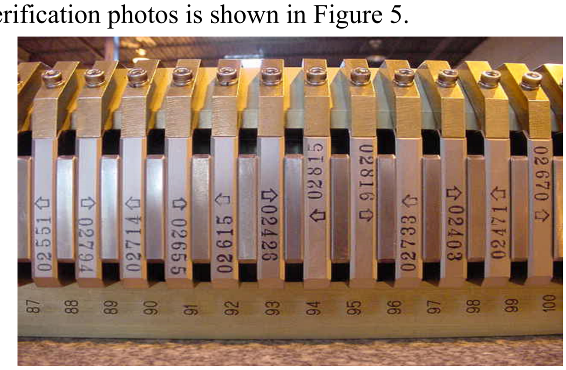

Figure 5: Verification photo from Metalex, showing slot numbers, magnet numbers, and magnet orientations.

Safety Considerations

Although each of the vendors has a strong in-house safety program, personnel safety during the assembly procedure was crucial, particularly since inexperienced personnel would be working with extremely strong magnets. Technicians and engineers from both vendors received initial hands-on training at Argonne to supplement the installation and safety videos that had accompanied the original bid package. Hi-Tech developed safe, efficient, and ingenious tooling for magnet installation and extraction; they shared this tooling with Metalex. In both shops, assembly was done in clean, isolated areas, accessed only by personnel essential to the assembly process.

Each of the 19,200 magnets was packaged by Shin-Etsu in its own clearly-labeled Styrofoam box. Boxes were properly sorted and shelved to facilitate efficient installation of magnets into the bases. If an individual magnet box was opened for inspection or any other reason except installation, the removed magnet was replaced securely back in its box. The box was immediately re-sealed with tape to prevent accidental escape of the magnet and subsequent injury or damage.

Acceptance

Each assembled undulator was individually accepted by the APS team. The acceptance procedure included a visual inspection, verification of the dimension and uniformity of the pole gap by means of “Go” and “No-Go” gauges, and a thorough inspection of all required documentation. We measured the magnitude and direction of the peak field at each pole in every undulator at the factory, facilitated by a portable Hall probe with special fixturing prepared for that purpose. Average peak fields for all devices are shown in Figure 6. Measured data were recorded, together with time and temperature, and incorporated into the final documentation packages.

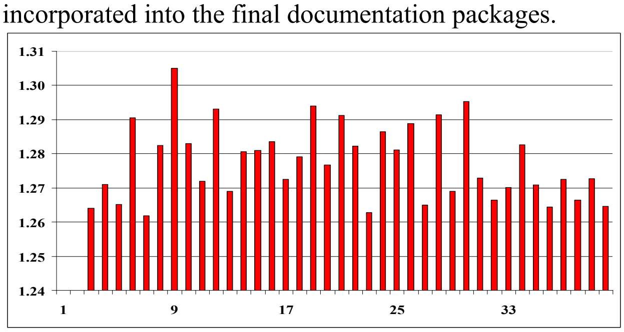

Figure 6: Measured average peak field for each undulator (3-40) at factory acceptance. All undulators will be tuned in the LCLS magnet measurement facility.

Shipment

Shipment of the undulators to the Stanford Linear Accelerator Center (SLAC) required very careful packaging and shipping procedures. Several different methods were tried with varying degrees of satisfaction; however, in all cases the undulators arrived safely at SLAC. Metalex engineers proposed an ingenious cushioning method that resulted in the smoothest ride of all methods tried. The undulator was inserted into a set of deflated tractor-tire inner tubes, and then lowered into its crate. The inner tubes were carefully inflated, then the crate was closed. Because of varying air pressure and temperature during the trip from the Midwest to California, the number of tubes and initial tube pressure were important. Each undulator was individually equipped with a ShockLog device [4] that recorded shocks, temperature, and pressure during the entire shipment, from loading to unloading. Air-ride trucks were specified for the shipment. The temperature was not to exceed 50° C, requiring refrigeration in the summer; the first undulator sent from Argonne to SLAC was transported by a frozen-dessert delivery truck. Although the requirement for shipping was that a single truck and driver would make the entire journey, one shipper chose to re-load the crates onto a different truck in the middle of the night. Photos of the truck before departure and upon arrival, together with ShockLog data, enabled us to know this occurred and at what time. After that experience, loaded trucks were sealed using single-use locks, and complete photographic documentation of all departing and arriving shipments was made.

CONCLUSIONS

Both of these vendors, with no undulator experience at the outset, produced excellent undulators. They developed a good working relationship with Argonne and with each other. All 40 undulators were produced within 15 months of first-article acceptance, limited mostly by magnet delivery. Many innovative ideas and improvements to “how it’s traditionally done” were provided by the vendors. The combined team of Argonne and vendors gained a great deal from this experience.

This project should be viewed as a highly successful model for high-quality, cost-effective mass-production of future accelerator and technical components.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of M. Erdmann, M. Merritt, and T. Powers in procedure development, and D. Capatina, S. Doran, T. Grabinski, and R. Kmak for design and drafting. We also sincerely thank the employees of Hi-Tech and Metalex whose hard work and dedication helped bring this effort to a successful conclusion.

REFERENCES

[1] R. Dejus, Ed., LCLS Prototype Undulator Report, Argonne National Laboratory Report ANL/APS/TB-48, January 2004.

[2] E. Trakhtenberg, V. Tcheskidov, I. Vasserman, M. Erdmann, N. Vinokurov, and J. Pflueger, “Undulator for the LCLS Project – from the Prototype to the Full-Scale Manufacturing,” NIM A543, 42 (2005).

[3] I. B. Vasserman et al., “Magnetic Measurement and Tuning of the LCLS Prototype Undulator,” NIM A507, 191 (2003).

[4] http://www.shocklog.com/product.html#shocklog

