Review of the LCLS Undulator

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At the request of the APS project director for the LCLS, a review was conducted of the LCLS Undulator. Specifically the review committee's opinions of the 1st full-length prototype undulator, its design, magnetic properties, and mechanical/thermal stability were solicited. The review committee was also asked to examine the plans for the 2nd prototype, its additional features, and acquisition plans.

At the review, the APS undulator team presented the 1st LCLS undulator prototype, its design, magnetic measurements, and changes deemed essential to the functioning of that prototype. The changes anticipated to the 2nd prototype and its acquisition plan, as well as that of the production series were also presented. The review committee's charge was in the form of four areas of consideration that follow. The review committee's findings, comments, and recommendations are listed in the context of these four areas of review emphasis, with some concluding global paragraphs and a summary of recommendations.

1. *Review the overall design and design / engineering decisions/solutions used for the 1st prototype undulator magnet and comment on the appropriateness of these decisions with respect to minimizing risk in meeting LCLS performance specifications. In particular, is this a robust design capable of being mass-produced?*

The 1st undulator prototype addresses several critical aspects developed in response to LCLS requirements. The design intent of the 1st prototype was that Ti strongbacks, in connection with Al magnetic structure bases, provide a passive mechanical thermal compensation for the reversible temperature coefficient of the NdFeB magnet residual induction (dB_r/dT = 1.1x10^{-3}/°C). It was reported that the approach was partially successful reducing the thermal dependence of the K_{eff} of the device to dK_{eff}/dT = 5x10^{-4}/°C. Though a significant improvement over the nominal temperature dependence of NdFeB, this level is insufficient for LCLS operation.

The use of mechanical shims to adjust and establish the nominal required K_{eff} was judged to be too difficult and not amenable to mass production. The initial design for the 1st prototype secured the poles on one side only. This proved insufficient and two mechanical clamps per pole have been installed to provide adequate stability and clamping force.

Piezo-driven adjusters at the beginning and end of the prototype provide a means of compensating the phase shake between undulator sections by locally changing the field strength over these end sections. These piezo-adjusted sections can also be used to adjust the total average K_{eff} of the undulator section over a range of 1% for FEL optimization and thermal excursion compensation. Simulations with the RON code show that with the piezo-adjustment sections, FEL performance can be recovered. However, we note that the RON code models the FEL interaction only in the linear regime. The first prototype has demonstrated good long-term mechanical and magnetic stability and it is difficult to imagine a system that could be more stable. The 1st prototype design could be mass-produced provided the thermal stability and an effective means of setting K_{eff} are fully demonstrated.

More exhaustive simulation and analytical checks are needed to provide additional assurance that only the piezo-adjusted sections can adequately compensate for the thermal excursions without loss of FEL performance. Specifically, simulations using codes that properly model the saturation regime, such as GENESIS, are needed. It is important to understand the limits of K_{eff} tuning by means of the end sections so as to clearly establish the design margin of the approach.

2. *Assess the overall quality and appropriateness of the measurements and tuning methods. In particular, has a suitable set of measurements been carried out on the 1st prototype to prove that it has achieved the required specifications without undue difficulty in manufacturing, and has this design been proven to be sufficiently stable over time?*

The approach for the magnetic measurements and field adjustment of the 1st prototype build on the extensive experience, technology, and craftsmanship that APS has developed on previous undulators and wigglers. Carefully calibrated Hall probes and small coils are the technologies used for the magnetic measurements. Phase shims placed on the surface of the magnets are used. In addition, side shims made of soft magnetic material provide direct peak field adjustments. A global approach based on the radiation amplitude rather than a local approach based on the magnetic field is an appropriate way of tuning and optimization undulator sections to ensure FEL performance. Peak field uniformity is difficult to achieve and only indirectly correlated to FEL performance.

The magnetic measurements and tuning approaches presented at the review are suitable and appropriate. The Committee is confident that these measurement techniques are scalable to mass production. Isaac Vasserman has demonstrated that the measurement and tuning can be done in a timeframe that can meet production level of one device every two weeks. Considerable effort will be required however to scale the measurement and adjustment methods to a full production approach that technicians can perform. This should be possible and will provide a means of ensuring a suitable level of quality. The magnetic and mechanical stability of the design has been demonstrated.

Additional measurements of the long-term stability and reliability of the piezo-adjustment sections must be completed. Simple micrometer dial gauges may be used for this purpose, if they have suitable resolution.

3. *Based on the knowledge gained from the 1st prototype, have the appropriate design modifications been made and, in your opinion, will they be successful in a mass produced device?*

As indicated previously, two major items were not successfully demonstrated with the 1st prototype: 1.) thermal stability, and 2.) the ability to set a specific K_{eff} for the undulator section. Other changes made on the 1st prototype were essential such as implementing two pole clamps per pole, and the field clamps added to the ends of the undulator section.

The reliance on the magnet supplier to provide the individual block magnet measurements for quality insurance is acceptable. Further measurements after delivery are not needed. Also sorting, such as simulated annealing, was not considered necessary. It was reported that the main error source comes from pole height fluctuations. As the measurements of the radiation amplitude have shown, these kinds of errors are well under control using the shimming techniques described above.

The approach that the APS LCLS team is pursuing in addressing these shortcomings is the development of a soft-magnetic material comb shunt array. This comb shunt provides an adjustable flux path from the rear of the magnets, thereby reducing the flux on axis of the undulator in predictable fashion. The comb shunt array is being used to address three issues that were not met with the 1st prototype: 1) active thermal adjustment (either in closed-loop control of actual laser performance or measured temperature), 2) the ability to remotely taper undulator sections, and 3) the ability to set K_{eff} to a specific value. The concept as presented to the Committee may use either a single set of comb shunts on one side of the undulator section, or two sets on both halves of the magnetic structure. Six motorized gearboxes provide the remote adjustment capability of the comb shunts.

The decision to pursue comb shunt arrays, either in an automatic or manual configuration, represents a radical departure from the original straightforward elegance and stability of the 1st prototype. Although, there is no question that the comb shunt can adjust the peak field. The application and implementation is presently only at a conceptual level. The inclusion of a complete additional set of active control loops with the shunts and mechanical adjustments adds considerable complexity and issues to the design that are likely not fully appreciated at this point. This increased complexity decreases its amenability to mass production. The relationships between the three goals of the comb shunt array listed in the previous paragraph interfere with each other and indicate an incomplete global LCLS systems thinking with respect to the undulator.

Although the thermal stability of K_{eff} has been measured there seems to have been little effort put in to understanding why it is not as stable as anticipated. Understanding the cause of the imbalance between the change of the magnet gap and block magnetization strength with temperature might lead to a less complex and invasive solution than the proposed comb shunt structure.

Before any additional work is done on the comb shunt arrays, considerably less complex approaches must be investigated to overcome the shortcomings while accomplishing the three goals outlined above. Specifically, the following options must be fully investigated: a) a complete understanding of why the passive thermal compensation scheme was unsuccessful, b) the use of Sm_2Co_{17} for better passive thermal compensation and radiation resistance, c) the use of canted magnetic jaws for setting and tapering K_{eff} through existing transverse adjustment, and d) the use of small enclosures to ensure thermal stability if passive compensation schemes are not successful.

The use of Sm_2Co_{17} should be explored further before additional prototype or production magnets are procured. The variation of magnetization strength with temperature is typically -0.11%/°C for NdFeB and -0.03%/°C for Sm_2Co_{17}. Given the thermal stabilization measurements of the 1st prototype, passive thermal stabilization of K_{eff} for the undulator using Sm_2Co_{17} should be closer to the target specification. The superior radiation resistance of Sm_2Co_{17} would likely have a significant impact on the lifetime of an undulator section during LCLS operation. The applicability of Sm_2Co_{17} can be explored with the 1st prototype by procuring magnets identical to the present NdFeB magnets and installing them into the existing prototype. The effectiveness of the thermal compensation can then be explored. If it is decided to move forward with Sm_2Co_{17}, the magnetic design point may need re-optimization. However, only minor adjustments should be required, before proceeding with the final production procurement.

Though the use of active environmental thermal control was investigated, the Committee feels that additional investigation of this option with small enclosures around the undulators deserves more attention. At the Advanced Light Source (ALS), thermal stability to a level better than the nominal performance of individual components was achieved and the approach may be adapted to the undulator system. A detailed examination is needed to fully establish a definitive cost basis before any further consideration of any active mechanical magnetic compensation approach.

While the comb structure is an interesting R&D activity; it is not considered reasonable to fully design and test comb tuners in time for the 2nd prototype or the production procurement. It is more appropriate to consider, in the time available, the canted magnetic jaw/horizontal field adjustment approach that exploits the existing or enhanced movers necessary for BBA. This canted jaw/horizontal field adjustment scheme can be tested on the 1st prototype with relatively little effort.

4. The 2nd prototype will be constructed in a manner similar to the acquisition plan for the production run. I would like your comments on the acquisition plan and schedule for the 2nd prototype and the production magnets.

As a result of many developments and circumstances in the development of the LCLS undulator system, some of which have been out of the control of the APS team, most of the motivation for the 2nd prototype has been lost at this point in time. The Committee recommends that plans for the 2nd prototype be abandoned and that an approach focusing on a first article with an option to procure the entire production quantity, be pursued. This could be done in such a way that if it is desired to proceed with two vendors, they could be qualified at the same time.

A 2nd prototype with the comb shunt adjuster cannot be considered a mass production prototype at this time. The comb adjuster will undoubtedly need considerable optimization and have a large potential for rework. This could even result in the need for iteration testing, or even an additional complete prototype, to fully demonstrate the viability of the automated comb shunts. Rather than expend scarce resources on the procurement of a second Ti strongback at this time, it appears more appropriate to modify the present strongback to allow the testing of the comb shunt system and to fully test and document its performance.

The goals and constraints of the acquisition plan for the 2nd prototype are incompatible. Given the constraints, it is doubtful that any vendor will provide a meaningful level of value engineering. The vendor will have no opportunity to provide any variations in the major elements of the system. Consequently, in effect, the vendor can, at best, provide only detailing of the design with the possibility of only minor clamp, comb element, and assembly modifications. At this point, the APS team has essentially become locked into the design embodied in the 1st prototype. Consequently, offering procurement to specification would appear disingenuous and may actually result in greater risk to the project and APS. No risk on performance can be transferred to the vendor on any level and it is important that both the APS team and the project as a whole understand this fact and its implications.

The design is essentially frozen. The procurement should consist of a design detailing and then a build to print. Also, it will actually save effort on the part of the APS team if the vendor only executes the most cursory of magnetic measurements to verify the correct orientation of magnets and makes no attempt at tuning. Therefore, the need to restrict the solicitation to only fabricators of complete undulator systems seems unwarranted and may actually be counter productive. It is not at all clear that the required level of assembly optimization and design detailing would be done most cost effectively by fabricators of complete undulator systems which traditionally add significant value from their knowledge of magnetic design, undulator specifications and requirements, and magnetic measurements. The narrowness of the present design choice and approach preclude any significant contribution in these areas.

The approach being followed is similar to that which has been followed at facilities such as ESRF, DESY, and SPring8. In these cases with a fixed design, only detailing, production drawings and subsequent manufacturing was required. Magnet manufacturers such as Sumitomo and Vacuumschmelze have provided such assembled magnet structures. Shin-Etsu also has experience in producing assemblies, though not for undulators. The APS LCLS team may wish to consider how to exploit this demonstrated approach in the production of the undulators.

The schedule for procurement of the 2nd prototype is very optimistic and likely to be unachievable. There is concern on the part of the Committee that the effort necessary to arrive at a fully comprehensive bid package, including QA specifications and controls, the time to process and analyze the resultant bids and make an award, are not realistic. This compounded by the fact that at present, the project and the APS team by extension, continue to operate under a continuing resolution. Uncertainty in the actual dedicated availability of personnel at APS to this effort is another cause of concern to the Committee.

The development of the production plan and an absolutely complete request for proposal package, for the first article and production series, should receive considerably more attention. In addition, a complete risk assessment of the approaches being pursued must be conducted if APS, and the project as a whole, are to have confidence in their ability to meet the schedule and cost of the undulators. Detailed planning, gate points, deadlines, specifications, QA, and control plans must receive additional concerted attention if there is to be some assurance that the request for proposal package will be satisfactorily prepared and released on schedule.

General Comments

In addition to responses to the specific questions of the charge, the Committee had some additional comments concerning the LCLS undulator.

The thermal stability is a crucial requirement of the design and requires a systems approach that examines the impacts on operations, controls, and laser performance. Without such a systems approach the thermal stability represents a risk to the project and is a cause of concern.

Although it is beyond the scope of this review, the Committee suggests that the benefits of a freestanding vacuum chamber be fully investigated. Serious operational consequences likely exist if every undulator section requires breaking and reestablishing a vacuum.

The radiation damage issues are a serious area of concern. If one looks at the scenario that the exchange of some undulator sections on an approximate monthly timescale, because of radiation damage, the tuning and refurbishing efforts associated with the undulator sections nearly equals that during production. It has been established by previous measurements and operational experience that radiation degradation of the magnetic field is reversible and fully recoverable. However, in order to fully recover the original performance of the magnets, re-magnetization and thermal and reverse field stabilizations are essential. This would require either developing capabilities that are not even planned for the production phase, or arranging long-term contracts with magnet suppliers who already have such capabilities. Again, the system implications of radiation damage may be sufficient to justify the use of Sm_2Co_{17}.

The APS undulator team has done much work and demonstrated the viability of the design. The Committee congratulates them on their accomplishments to date. One may argue as to whether or not the design has been properly optimized, but it has progressed to the point that, for the most part, such arguments are mute. Effort should now be focused on preparing for production in the most effective manner possible while perfecting those remaining aspects of the design that have not been resolved.

Summary of Recommendations

1. **1.** Perform more exhaustive simulations and analytical checks to provide additional assurance that the piezo-adjusted sections alone can adequately compensate for the thermal excursions without loss of FEL performance.

2. **2.** Fully test the piezo-controlled end sections for long-term stability and reliability. Simple micrometer dial gauges may be used for this purpose, if they have suitable resolution.

3. **3.** Suspend any additional work on the comb shunt arrays until less complex approaches are investigated in overcoming the shortcomings of the 1st prototype. Specifically, investigate the following: a) a complete understanding of why the passive thermal compensation scheme was unsuccessful, b) the use of Sm_2Co_{17}, c) the use of canted magnetic jaws for setting and tapering K_{eff} using the existing transverse adjustment, and d) the use of small enclosures to ensure thermal stability if passive means are unsuccessful.

4. **4.** Test out the transverse canted jaw K_{eff} adjustment scheme on the 1st prototype.

5. **5.** Procure Sm_2Co_{17} magnets identical to the NdFeB magnets used in the 1st prototype to fully explore possible passive thermal compensation of K_{eff} for the undulator.

6. **6.** Perform a detailed examination of environmental thermal control to fully establish a definitive cost basis.

7. **7.** Abandon plans for the 2nd prototype and focus on a first article with an option to procure the entire production quantity. Do this in such a way that, if desired, two vendors can be qualified at the same time.

8. **8.** Concentrate effort on the development of the production plan and a complete request for proposal package for the first article and production series. In addition, conduct a complete risk assessment of the various design approaches being pursued in order to establish confidence in the schedule and cost of the undulators.