Review of the Undulator System of the Linear Coherent Light Source

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At the request of the APS project director for the LCLS, a review was conducted of the LCLS Undulator System. The scope of this review encompassed the entire undulator system, and included the undulator magnet proper, the vacuum system, the diagnostics, the controls, and management/cost/schedule related issues. As such, the basic charge to the committee was:

To review the LCLS undulator system and to provide advice on the overall system and the various subsystem designs and their suitability to meet the performance specifications, on the installation and commissioning plan, and on the overall project management of the LCLS undulator system.

The following specific charge questions were asked to be addressed by the Committee. An initial response follows the question.

Question: *Review and evaluate the complete system design. Is the maturity of the design known to the level of detail to justify setting the cost and schedule performance baseline at this time?*

Response: Not at this time. Many of the subsystems are well prepared to be baselined, but the integrated system has many holes and gaps where uncertainties are quite large and approaches are not even at a concept design level.

Request: *Identify any open design issues that should be addressed prior to setting the baseline.*

Response: The integration of rf BPM, quadrupole, vacuum chamber, the cradle (and its design) are of concern. Additional thought and direction on logistics, installation and handling are necessary as well (see specific section comments).

Question: *Is the management team adequately structured for completing the LCLS design?*

Response: Yes, with one possible absence. Clear responsibility for total system integration, interfaces and engineering was not identified. A strong project engineering/manager would be very useful.

Question *Are there adequate resources and of the correct skill type to meet the needs of the project?*

Response: The present team shows very evident technical and project management strength. However, the dramatic increases in effort required in FY05 are a cause for concern. When resources are augmented so quickly an inevitable transitional period results with decreased productivity and a slowing of progress. It is not clear that this has been adequately anticipated.

Question: *Is the project progressing adequately?*

Response: Yes, with the resources and funding that are available considerable progress has been made. Progress since the November review is particularly noteworthy.

A specific aspect of the charge requires comment as this review is directed towards achieving the Department of Energy (DOE) Critical Decision 2 (CD-2), Preliminary Design Complete and Approval of the Performance Baseline. The charge states: "Note that this is a pre-baseline (conceptual) design review." However the DOE Manual 413.3 state concerning CD-2:

> *Approval of the Performance Baseline marks the beginning of performance tracking. It also authorizes submission of the total project budget request. Key activities that take place leading up to the approval include preliminary design; development of key performance, scope and schedule parameters; risk assessment; establishment of a performance measurement system; identification of project interfaces; and development of the Project Execution Plan.* (Section 2.2.1, page 2-5, emphasis added)

The DOE Manual 413.3 also states Concerning Preliminary Design

> …*Preliminary design initiates the process of converting concepts to a design appropriate for procurement or construction. This stage of the design is complete when it provides sufficient information to support development of the Performance Baseline. The appropriate completion percentage is dependent upon the project. … For complex projects, the percentage of design may not be definitive because these projects may have many subsystems undergoing concurrent designs that may be at various stages of completion. Scientific systems, such as accelerators and detectors, production and manufacturing facilities, spacecraft and other systems, do not follow a linear process in which all subsystems reach the same maturity at the same time. Concurrency in these types of projects increases the risk because each subsystem design is dependent upon the design maturity of other subsystems.* (Section 6.2, page 6-1, emphasis added)

Consequently, in view of the desire of the project, and the undulator system in particular, to achieve DOE CD-2 in such a short time, the Committee felt obligated to assess the undulator system in that context which is more rigorous than would be required of a conceptual design review.

General Remarks

The Committee has found it useful in preparing and pursuing the establishment of a project baseline to ask a simple question when examining the state of the project: *Based on your present knowledge would you be willing to commit to build this for a fixed price at this time?* In examining the undulator system in this way there are some aspects that must be noted:

Even though the undulator magnet is indicated as being on the critical path, there are many very near critical path items that are at a very early their design. This elevates concern of the Committee. Consequently, it is quite possible that very soon the critical path will no longer be through the undulator magnet procurements.

The Committee recommends that a risk registry and issues log be developed and implemented for the entire undulator system. This will help focus the project team on addressing near critical items and reducing all forms of risk to the undulator system.

As cited above, having concurrency in the project where not all of the subsystems are at the same design maturity level does not preclude the undulator system, or project by extension, from receiving CD-2 or being baselined provided that adequate risk, uncertainty is identified with the variance design maturity. In order to mitigate that risk and uncertainty adequate management reserve (contingency) must be allocated.

The Committee recommends that while producing the cost budget estimate, that the undulator system project team also provide a technology maturity, a risk (technical, cost, schedule), and an uncertainty assessment at the same time as providing a *contingent-free* (50% probability percentile) estimate of the WBS element. The uncertainty can be approximated by asking those responsible for WBS element to give an "optimistic" and "pessimistic" estimate of the required cost and schedule. The "optimistic" estimate can be assumed to be the 50^{th} percentile estimate and the "pessimistic" can be assumed to be the 80^{th} - 90^{th} percentile number. If the WBS elements are at a fine enough detail and numerous enough, errors in estimates of individual elements can become compensating (Central Limit Theorem) provided that the design maturity and risk are appreciated and understood by the estimator.

Subsystem Specific Remarks

Undulator Magnet Subsystems

The Committee was pleased to see the assignment of a cost account manager to magnet systems that is also responsible for areas less mature in design development.

There have been many technical developments since the last review of the undulator magnet subsystem that are commendable. In particular, the Use of canted jaw for the adjustment of K_{eff}, the removal of additional complicating mechanical systems, and the

development of a more rigorous schedule and procurement approach are particularly commendable.

Unfortunately the delay in addressing recommendations from previous reviews concerning the choice of NdFeB vs. Sm_2Co_{17} has not resulted in a situation that now precludes any action in this area. The experimental data presented during this review does not strongly support conclusions drawn from them. The operational risks identified in November 2003 review still remain and have not been addressed. Consequently, in this present review, the Committee is not ready to endorse the NdFeB material choice, but understands that the Undulator Systems Team must move forward with NdFeB at this time.

Because of the very tight schedule constraints a two-vendor approach is deemed essential for the assembly of the undulator magnets and ought to be pursued.

The Committee recommends that the strongbacks, magnets, and poles each be procured from single sources for delivery directly to the undulator magnet assemblers. This is needed in order to reduce possible variation between sources and maintain a better quality assurance and control over these critical parts. The Committee notes that the procurement approach being pursued, unfortunately, transfers no risk responsibility to any of the suppliers or assemblers and therefore the Undulator Team must exercise extreme diligence or schedule and cost budgets may be exceeded, or technical performance compromised.

In the same vein the granite for support bases should also be procured from a single source, and in fact, from the same quarry face from that source to minimize variation.

The Committee suggests that the team examine the possibility of employing a dithering capability on the quadrupoles for ease of implementation of beam based alignment and the possible use for synchronous detection excitation during startup commissioning.

There are several areas that require specific design attention. The Cradle requires concentrated effort prior to baseline to fully understand its design requirements and specifications. Likewise the requirements for cradle and/or undulator retraction have not been established. The Committee endorses the concept of manual retraction of undulator magnet as being valuable for commissioning and feels that an automated remotely controlled system may provide additional value as well.

The Committee feels that at this time the Undulator Magnet subsystem has relatively low technical risk at this time. The schedule and cost risk as noted above, however, remain.

One point with respect to the cradle needs to be stressed so that is part of the formal design record: it is important that the approach is to align the BPM and quadrupole to the undulator magnet rather than the undulator magnet to the BPM and quadrupole. Although this may seem obvious, it is a detail that could be lost in the inevitable pressure with the first device and could waste precious energy and time.

The Undulator Magnet Subsystems group should concentrate on resolving design issues and prototyping a complete system even at the expense of delay in delivery of undulator magnet first article as many particular issues may be uncovered that are simply not known at this time.

Magnetic Measurements

The magnetic measurements efforts continue to demonstrate strong technical maturity and insight. The measurement procedures and measurements themselves that were presented are very good. The approaches being pursued are sound and well thought out. The measurement capabilities well understood. The fiducialization method in particular looks good and the use of the Magnetic needles is the right approach. The coordinate measuring machine (CMM) system approach should allow integration of undulator system efficiently and effectively.

While the individual techniques well established and evolved, the effort to fully reduce the approaches to production may need to be revisited as it may not be sufficient. Likewise, the logistics and workflow within the SLAC Magnet Measurement Facility (MMF) need to be carefully studied. It is important to remember that moving an undulator longitudinally is relatively easy, but moving an undulator transversely or rotationally involves more effort and risk.

Interfaces, Support, and Environmental Concerns

The environment evaluation provides important guidance and the Committee commends the Undulator Team and the LCLS project for attacking this problem at this time. The evaluation clearly emphasizes need for beam based alignment, and the requirements on BPM's and potential value of having adjustable quadrupoles.

Given the scare resources, funding limitations, and lack of a complete systems engineering consideration of the environmental and support issues, the Committee suggests that prototype of the granite support could be deferred. Additional trade information is available and should be extensively evaluated. A careful examination of support of granite benches, the size requirements and function should be examined. Access and installation flow must be factored into the design. The Committee is concerned about air flow and induced thermal gradients noting that titanium has thermal characteristics similar to stainless steel and can therefore maintain large thermal gradients for significant periods of time. The total integrated system performance should be modeled to fully understand all of the driving factors and concerns.

Vacuum System

The Committee commends the approach taken on the vacuum chamber trade studies. The trade study presented at the review for the chamber design very well executed, comprehensive and meticulous. These trades should be followed up with prototypes to

fully understand and address fabricability and finish, vacuum performance (voids/leaks), and mechanical performance (alignment stability). Beam physicists should evaluate the transition pieces with respect to impacts on the beam. In particular with regards to shape changes. A careful mechanical engineering evaluation should be performed of the bellows motions. The electrical conductivity/continuity through transitions must also be fully considered. The projected system performance during commissioning needs to be studied and examined, e.g., pumping, gas loading, recovery time. When the system is first commissioned there may be significant out gassing and photo-desorption. This could have a negative effect to commission in a timely manner and an attempt should be made to anticipate what will be the operational constraints.

Diagnostics

The requirements placed on diagnostics by beam based alignment are well described and understood. Although regrettable, the deferring intra-undulator x-ray diagnostics seems to be a sound prudent decision given time and resource constraints. The electron beam position monitors (BPM) are very near the critical path of the undulator system as a whole. Consequently, BPM prototype development should be given very high priority.

The work on optical diagnostics is at a very early stage and there is a significant need to proceed to a more detailed design as quickly as possible and anticipate its uncertainty and risk in the development of the proposed baseline budget. In connection with the diagnostic designs presented the required chamber transitions should be integrated into the FEL physics assessment. Developing a prototype system would be valuable for proving out system integration approach.

Controls

There is a good overall approach on the Controls. The undulator system is being developed as a stand alone control system that should allow rapid integration into the entire controls structure and there is a conscious desire to capitalize on existing platforms/software. The task envelope well described and there is a good knowledge base for detailed development. The Committee had only a few areas of potential concern. Among them is the integration with SLAC controls. This needs early attention as the controls are dispersed throughout the WBS and will therefore require particular care in integration. Another area of concern is the rapid jump in staffing in required in FY05. It is not clear how realistic this may be, nor whether the inefficiencies inherent in such large resource jumps have been properly anticipated.

Concluding Remarks

- The Committee was impressed by the progress made overall and on many of the subsystems since the review in November 2003.

- **Physics Performance** issues appear well understood, including tolerancing and the significance of environmental effects.

- The **Magnet Systems**, particularly the undulator subassembly including procurement of long-lead items, schedule and understanding of cost structure show maturity and are well in-hand. Article 1 procurement of one subassembly appears feasible in the very near term. A remaining concern is the choice of the permanent magnet material NdFeB over $Sm_2 Co_{17}$. The sample size on which the decision appears to be based was not compelling to the Committee, i.e. $Sm_2 Co_{17}$ may have a larger advantage over NdFeB than the factor of ~2.5 conveyed in the presentations.

- The **Vacuum Subsystem**, specifically the undulator vacuum chamber, the bellows and transition profiles in the breaks need much effort before conceptual design work can be considered complete. The engineering survey and trade study of vacuum chamber geometries, materials and fabrication approaches was deemed very thorough. It is a good start for an R&D program which should yield a successful design in several months.

- **Diagnostics** requirements appear to be well understood and solutions exist at the conceptual level. The RF BPM is crucial to successful operation of the undulator system. It is now on a critical path and may have negative float. Significant effort should be devoted to this in FY 04. The reclassification of the X-ray diagnostics program to an R&D effort is, in the Committee's view, a wise decision.

- **Controls** solutions appear to be state of the art and conceptual at this time. APS and SLAC controls efforts need to be integrated at an early time.

- The **Magnetic Measurements** program is state of the art with strong players, both at APS and at SLAC. The Committee recommends that further thought be expended on the logistics of undulator flow through the new SLAC LCLS magnetic measurements lab.

- The **Environmental** and **Mechanical Support** programs have made major progress. The Committee strongly supports the decision to mount the undulators on long granite girders and install these on bedrock in an as yet to be built tunnel in the hill on the east end of the SLAC research yard. The Committee has questions on the wisdom of using forced air convection to achieve the desired temperature stability of the undulator subassembly. Further, placement of the undulator support girder assemblies close to the tunnel wall presents major future maintenance logistics problems and should be re-thought.

- The **Cost Structure** appears quite mature for some subsystems like the undulators, but seems very sketchy at this time for the vacuum subsystem, diagnostics and controls. Particularly the appropriate level of contingency for the various subsystems is missing. Without it there can be no credible cost estimate from which to effectively and successfully manage such a large and complex project.

- Lastly, but not least, the Committee feels strongly that a **Project Engineer/Coordinator** type individual is needed now to integrate all subsystems into one cohesive program.