U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Project Assessment
Status Review Report on the

Linac Coherent Light Source-II High Energy (LCLS-II-HE) Project

at SLAC National Accelerator Laboratory

March 2022

EXECUTIVE SUMMARY

A Department of Energy/Office of Science (DOE/SC) status review of the Linac Coherent Light Source II High Energy (LCLS-II-HE) project, located at the SLAC National Accelerator Laboratory (SLAC), was conducted remotely, due to the COVID-19 pandemic, on March 22-25, 2022. The review was conducted by the Office of Project Assessment (OPA) at the request of Linda Horton, Associate Director of Science for Office of Basic Energy Sciences (BES). The review was chaired by Kurt Fisher, Director, OPA.

The purpose of the review was to assess the project's overall status and progress, assess the progress of long lead procurements, and determine if the project is appropriately progressing toward a possible combined Critical Decision (CD) 2/3, Approve Performance Baseline and Start of Construction, as early as fourth quarter FY 2023. Prior to the review, the project team had recently made a proposal to the DOE/BES to address cost constraints related to the worldwide economic situation. The Committee determined that the proposed combined CD-2/3 approach is reasonable, facilitates acceleration of time critical elements, as well as delaying baselining during the present uncertain economic period. The project should prioritize design efforts on elements that have the largest technical and cost risks.

Accelerator Physics

The removal of the Low Energy Extraction (LEX) beamline addresses a previous concern regarding significant phase-space degradation. It also provides extra real estate to accommodate three cryomodules (CM) that will provide a further safety margin given uncertainties on the final performance of the installed LCLS-II CMs.

The addition of a separate injector system (gun, bunching system, and one CM) will provide a redundant electron source for improved reliability of the LCLS-II-HE facility and potentially a brighter electron beam without any change to the nominal injector beamline. These changes are welcome—they add flexibility, improve reliability, and reduce complexity of the accelerator.

Cryomodules

There are additions to the project cost in this WBS, as well as deductions that are planned. Completing the baseline changes to evaluate overall project cost and contingency is essential.

Procurements for the final three production CMs and the buncher cavity CM may be adversely affected in both cost and schedule due to the economic climate. The Committee strongly supported starting procurements for the remaining four CMs as soon as possible to avoid standing army concerns at Fermi National Accelerator Laboratory (FNAL).

Plasma processing has a positive impact on multi-pacting in these cavities. Evaluating whether the reduction in testing time versus the time and effort to conduct plasma processing will lead the team to the most efficient testing cycle. Currently, plasma processing is available at FNAL, it will be beneficial to extend the capability to Thomas Jefferson National Accelerator Facility (TJNAF) and as planned.

Cryogenic Distribution System

The Cryogenic Distribution System (CDS) Physics Requirements Document (PRD; LCLSII-HE-1.3-PR-0040-R2) and the CDS Functional Requirements Specifications (FRS; LCLSII-HE-1.3-FR-0054) are both released but have not been updated to show the current L4 CDS configuration. The Committee suggested these be updated at the earliest convenience.

In response to a previous recommendation regarding development of a cryogenic availability analysis, the cryogenic requirements PRD (LCLSII-HE-1.3-PR-0040) was updated to include a section on cryogenic system availability. The Committee suggested that this information be used to update the overall availability analysis to include these cryogenic requirements and the LCLS-II-HE additions at the earliest convenience.

The project's current approach is to deliver cryogens to the L4 string via a feed cap strategically placed to balance the loads between cryoplants 1 and 2 (CP1 and CP2). This arrangement allows for the insertion of a "Tee" later if a rebalance of the L3 and L4 strings is required after the performance of the LCLS-II CMs are known and a final optimization of gradient is determined.

Accelerator Systems

The project team should continue proactively engaging vendors in advance of the procurement with frequent follow-ups and site visits when possible, including addressing and resolving any quality assurance/quality control (QA/QC) issues.

The project team should make it a high priority to have frequent visits to high-power radio frequency (HPRF) waveguide vendors to continue to monitor the quality of the manufacturing processes and components production. The project team should provide more vendor oversight to keep the production of HPRF components on track and be able to resolve any supply chain problems early to minimize any project schedule impacts.

The current installation plan for HPRF appears to be optimistic due to subtle changes between LCLS-II and LCLS-II-HE—this should have a fresh second look.

Flexibility of the modern digital low-level RF (LLRF) system allows adding new features and capabilities that would be beneficial to LCLS-II-HE. The project team was encouraged to pursue adding new features (such as microphonics compensation and machine learning hooks) as needed.

Undulators

During this installation period the new LCLS-II-HE segments can still be operated at 4 GeV together with the old LCLS-II ones.

Evaluation of the experience of the pre-production undulator will provide information about time and schedule issues and will help to organize the exchange and to synchronize de-installation, mechanic modifications, magnetic measurements and tuning, and re-installation etc.

Vacuum chamber cooling is recognized as essential for LCLS-II-HE operation. The responsibility, project scope, and deliverables from LCLS-II and LCLS-II-HE do not appear to be formalized. These roles and responsibilities should be committed to a formal agreement detailing specifically LCLS-II deliverables and LCLS-II-HE responsibilities.

X-Ray Endstations

The current X-Ray Endstations (XES) goal is to provide four instruments (XPP, MFX, CXI, and DXS) to the user community on day one (third quarter FY 2027).

Optics simulation for the Dynamic X-ray Scattering (DXS) is ongoing, and the optics/DXS team has made great progress.

The original XES budget estimate was largely based on the LCLS-II Strategic Instruments (L2S-I) project. The updates needed to accommodate LCLS-II-HE specifications have taken more resources than planned.

Because of the current economy, supply-chain, and COVID-19 situation, the method to baseline the XES tasks can be updated to reflect the more practical cost escalation. The XES team is, therefore, encouraged to verify the effort and materials and supplies budget escalation and develop plans to mitigate any issues caused by the escalation.

The XES team was encouraged to maintain the current momentum and enthusiasm to continue the design of optics and instruments, for example, developing DXS optics specifications, simulation, and evaluation, which is needed for planned technical design reviews.

Controls and Safety Systems

The project, where possible, should use the same control hardware in the Low Emittance Injector (LEI) cryoplant and the main cryoplants. The LEI plant will be procured as a turn-key system, including controls hardware. This method of procurement may reduce cost; however, it may add complexity to the integration of non-standard controls hardware.

The Memorandum of Understanding (MOU) between LCLS-II-HE and SLAC pre-dates the LEI and the partnership with Michigan State University—it needs to be updated.

Long lead procurements are used to reduce risk, something that seems particularly relevant now. The solid-state amplifiers (SSA), field programmable gate arrays (FPGAs), carrier cards, LLRF chassis, motion-control chassis, and motors are all being considered as long lead procurements. The project should continue to add necessary items to the long lead procurements list.

Personnel turnover and low morale of safety systems staff supporting the LCLS-II project were identified as lessons learned that SLAC has since taken serious steps to address. SLAC and LCLS management should continue efforts to mitigate stress and ensure a healthy workforce to support LCLS-II-HE. Management should also determine how best to assess the progress of this effort.

Infrastructure Systems

Work during the long downtime is a schedule risk area and planning to maximize the amount of work that can be accomplished during the long downtime is underway. In addition, as much work as possible is being moved to short downtimes that are scheduled in FY 2024/FY 2025, as well as work that can be potentially accomplished when the beamline is operating.

Coordination with the Matter in Extreme Conditions Upgrade (MEC-U) tunnel project could also be beneficial. A high-level coordination schedule was discussed that includes LCLS operations, the MEC-U project, the Critical Utilities Infrastructure Revitalization (CUIR) project and SLAC activities, and quarterly stakeholder review meetings are planned. This effort will definitely aid in coordinating LCLS-II-HE activities with these external projects and operations.

Leveraging experience and lessons learned from LCLS-II is a best practice, and the project team continues to leverage those lessons learned. In addition, many of the team members are veterans of LCLS-II, which provides a sound experience base.

Injector Systems

The secondary injection tunnel is a large investment, but well justified as it eliminates single point failure and allows a parallel high brightness source development.

Given the recent start of the injector project, the Committee was strongly impressed by how far along the technical work on the gun had moved forward.

Conducting full beam tests of the superconducting RF gun at low energy (2 MeV) is critical as these will answer important questions such as cathode lifetime, cathode-cavity compatibility, and gun performances.

Use of a dog-leg for compression might further ease bunch length and emittance requirements for the injector and presents an opportunity for further risk-reduction.

Cathode studies should proceed as planned in collaboration with SLAC Accelerator Division before the decisions on the cathode material and drive laser specifications are finalized.

Environment, Safety and Health

The current Preliminary Hazard Analysis Report (PHAR) does not have hazards and mitigations relating to a pandemic hazard along with addressing tunnel construction and the LEI.

Project preliminary Oxygen Deficiency Hazard (ODH) analysis has been completed; however, there is a need to complete and add the analysis for the Low Emittance Injector Tunnel (LEIT) once the operating parameters have been finalized.

ESH and QA Manager participation in the system engineering design review process provides direct ESH and QA input, as well as assisting in the ESH/QA integration process.

Radiation protection systems analysis is progressing well, needs are identified, and design is in process. No significant challenges were identified. The project should consider an external review for the LEIT enclosure.

Cost and Schedule

After the decision to defer instruments ($80 million) and considering the increased risk of higher than expected escalation (which could still increase beyond 7% in the first two years and 4% for remainder of the project is captured in Risk Register), options to increase contingency in the future are limited to scope contingency (category 2 and especially category 3 = $53 million), which could have an additional impact to the preliminary Key Performance Parameters (KPPs).

The project presented a definitive list of the scope elements by WBS that are included in the $80 million deferral list, to be presented to DOE/BES and required to maintain the Total Project Cost (TPC). The project has a prioritized scope contingency list that will contribute to maintaining desired levels of contingency. The project team identified other opportunities to support the $710 million TPC including advancing the schedule with a CD-3B long lead procurement package. While this effort is commendable, it is still unclear if it will be successful and seems optimistic.

The judgement factors and design maturity assessments are only being used for cost estimate uncertainty leaving a gap in assessment of schedule uncertainty (e.g., duration validity).

Project Management

The proposed combined CD-2/3 approach is reasonable, facilitates acceleration of time critical elements, as well as delays baselining during the present uncertain economic period. The project should prioritize design efforts on elements that have the largest technical and cost risks.

The project team developed a number of robust management systems including the QA and continued improvement and use of the risk management process.

A well planned, rigorous systems engineering process was presented. There is a substantial body of work to be accomplished to be prepared for CD-2/3. The project is encouraged to prioritize the systems engineering effort to match the needs of a successful CD-2/3.

LCLS-II-HE is dependent on other projects and SLAC funded activities (LCLS operations, LCLS-II commissioning, MEC-U, CUIR, etc.).

The SLAC Memorandum of Understanding (MOU) needs to be updated prior to CD-2/3—this could include not only what the LCLS-II-HE project expects from these other activities, but what these activities expect as interfaces from the project (i.e., make sure it is a two-way MOU).

Key Recommendations

- Maximize the benefit of LCLS-II beam commissioning in mitigating risk and enhancing the design by establishing dedicated beam time for important LCLS-II-HE related studies. Report on progress at the next DOE/SC review.

- Continue studies and simulations on the sensitivity analysis, as well as on important dynamical effects including benchmarking code results against beam data from the normal conducting linac, and also to be taken during LCLS-II commissioning. Report on progress at the next DOE/SC review.
- Finish scope additions and deletions to adequately assess the Total Estimated Cost of the CMs WBS elements by September 30, 2022.
- Proceed with procurements for the remaining three production CMs and one buncher cavity CM as soon as authorized.
- By the end of the calendar year, determine whether the implementation of the CDS "Tee" and new endcap is needed in order to minimize impact on the overall LCLS-II-HE schedule.
- Advance the Accelerator Systems conceptual plan to a more detailed integrated installation schedule/resource plan with interdependencies specific to the Accelerator Systems prior to the next DOE/SC review.
- The project team is encouraged to immediately initiate the procurement for the remaining 7 kW SSAs as soon as authorized.
- Refine and update the plan and schedule when experience with the pre-production undulator is available and evaluated, by the next DOE/SC review.
- Revisit the XES scope based on the revised project budget, by fourth quarter FY 2022.
- Re-evaluate the Risk Registry by using more realistic escalation rates or by the experience with recent quotes, by the next DOE/SC review.
- Prior to the next DOE/SC review, define with more granularity the logic links and milestones in the Primavera schedule between controls activities and mechanical activities.
- Prior to the CD-2 review, ensure a dedicated controls person is assigned to the SLAC team responsible for procuring and commissioning the LEI cryoplant.
- Finalize the tunnel location and construction approach by the 30% design milestone, and continue to analyze tunnel construction costs, schedule duration, and risks, prior to CD-2/3.
- Continue to analyze the planning for the various scopes of work and look for opportunities to improve the schedule, by taking advantage of advance procurement of equipment (e.g., CD-3B), short downtimes, as well as when the beam is in operation, finalizing those plans and schedule prior to CD-2/3.
- Pursue full beam tests of the superconducting RF gun before the injector tunnel is completed.
- Strengthen and formalize plans for the cathode production system in close collaboration with SLAC and LCLS-II programs by the next DOE/SC review.
- Hire a dedicated LCLS-II-HE ESH Manager, as early as possible. Near-term, evaluate the possibility of utilizing interim ESH management support through a consultant.
- By the end of the fiscal year, conduct a full refresh estimate of the project to validate the current cost/schedule estimates to ensure they are updated, current, traceable, and accurately reflect the Estimate at Completion (EAC)/baseline. Ensure available contingency is sufficient to address risks impacts, cost, and schedule estimate uncertainty within the planned TPC.
- Before CD-2/3, revise the KPPs to reflect the decision to defer instrument scope and other scope refinements.
- By the end of the fiscal year, the project should revise the resource loaded schedule that reflects the revised scope and schedule for the project.

- Within four months, the project should revise and update the SLAC MOU (LCLS-II-HE-1.1-PM-0296) for capturing external project dependencies.
- After completing the two immediate recommendations above, conduct a focused status review.

CONTENTS

1. INTRODUCTION

The Linac Coherent Light Source II High Energy (LCLS-II-HE) project will provide a qualitatively new capability, unique in the world, delivering ultrafast atomic resolution at high average power. This project is a natural extension to LCLS-II, adding known technology and using existing infrastructure. It will extend operation of the high-repetition-rate beam into the critically important “hard x-ray” regime (>5 keV) that has been used in more than 75% of LCLS experiments to date, providing a major leap in performance to the broadest cross-section of the user community.

The energy reach of LCLS-II-HE (stretching from 5 keV to at least 13 keV and likely up to 20 keV) will enable the study of atomic-scale dynamics with the penetrating power and pulse structure needed for in situ and operando studies of real-world materials, functioning assemblies, and biological systems.

Background

LCLS is based on the existing normal conducting SLAC National Accelerator Laboratory (SLAC) linear accelerator (linac). The linac was designed to accelerate electrons and positrons to 50 GeV for colliding beam experiments and for nuclear and high energy physics experiments on fixed targets. At present, the last third of the three-kilometer linac is being used to operate the LCLS facility, the first kilometer is being used by LCLS-II to construct a 4 GeV superconducting linac and the second kilometer is being used for advanced accelerator research. When LCLS-II is complete, the first kilometer of the existing linac will have been replaced with a new superconducting linac to provide 4 GeV electron beams to produce high repetition rate x-rays in the 0.2-5 keV range. The LCLS-II-HE will expand the photon energy range out to 12.8 keV in the hard x-ray region by increasing the linac energy to 8 GeV while providing the same high repetition rate and pulse flexibility built into LCLS-II. The project will provide 8 GeV electrons to two undulators, one for hard x-rays (currently provided by LCLS-II) and one for soft x-rays (a new undulator that will replace the soft x-ray undulators for LCLS-II). The last third kilometer of the linac, the LCLS source, will continue to produce 14 GeV electron bunches for hard x-ray production in the 1-25 keV range at a 120 hertz repetition rate. The electron bunches will be sent to the new variable gap undulators provided by LCLS-II to produce two simultaneous x-ray beams. The x-ray beams will span a tunable photon energy range beyond the existing LCLS, or planned LCLS-II facility and they will incorporate “self-seeding” sections to greatly enhance the longitudinal coherence of the x-ray beams. At completion of the LCLS-II and LCLS-II-HE projects, the facility will operate two independent electron linacs and two independent x-ray sources, supporting up to six experiment stations. The middle kilometer of the existing linac (Sectors 11-20) will not be used as part of LCLS-II or LCLS-II-HE but will continue to be used for advanced accelerator research, and it would be available for future expansion of the free electron laser electron source capabilities.

The LCLS-II-HE project is continuing the strategic partnerships with other Office of Science (SC) laboratories for the design, fabrication, installation, and commissioning of the extended energy, superconducting linear accelerator, and the required supporting technical systems.

The project received approval for Critical Decision (CD) 0, Approve Mission Need on December 5, 2016, with a notional range of $260-450 million and a point estimate of $320 million. The project received CD-1, Approve Alternative Selection and Cost Range, on September 21, 2018, establishing a new cost range of $290-480 million based on a new point estimate of $368 million. The project received approval for long lead procurements (CD-3A) in May 2020 in the amount of $98 million with a new point estimate of $428 million.

The project received an appropriation in FY 2018 of $2 million in Other Project Costs (OPC) and $8 million in Total Estimated Costs (TEC) as a line-item construction project. In FY 2019 the project received an appropriation of $6 million in OPC and $28 million in TEC. The FY 2020 appropriation was $4 million in OPC and $50 million in TEC. In FY 2021 the appropriation was $52 million in TEC and $2 million in OPC. In FY 2022 the appropriation is $50 million in TEC and $3 million in OPC.

Charges to the DOE Review Committee

In a February 3, 2022, memorandum (see Appendix A), Dr. Linda L. Horton, Associate Director of Science for the Office of Basic Energy Sciences (BES), requested that Kurt W. Fisher, Director of the Office of Project Assessment (OPA), organize and conduct an independent project review of the LCLS-II-HE project on March 22-25, 2022, virtually via Zoom. The purpose of this review was to assess the project's overall status and progress, address the progress of long-lead procurements, and determine if the project is appropriately progressing toward a possible combined CD-2, Approve Performance Baseline and CD-3, Approve Start of Construction, as early as the fourth quarter of FY 2023.

Membership of the Committee

OPA assembled a Review Committee composed of members (see Appendix B) selected based on their independence from the project, as well as for their technical and management expertise, and experience with building large and complex scientific research facilities. The Committee was organized into twelve subcommittees, each assigned to evaluate a particular aspect of the project corresponding to the subcommittee members' areas of expertise. Kurt W. Fisher, Director of OPA, served as the review chairperson.

The Review Process

The review was conducted virtually via Zoom on March 22-25, 2022. LCLS-II-HE project personnel provided information to the Committee in advance of and during the virtual review. Committee members submitted questions and received responses prior to the review. Representatives from SLAC, Department of Energy (DOE)/BES, DOE/SLAC Site Office (SSO), and DOE/OPA collaboratively developed the review agenda (see Appendix C). Results of the review are contained in this report, which Committee members have individually authored and collectively reviewed.

2. TECHNICAL SYSTEMS EVALUATIONS

2.1 Accelerator Physics

2.1.1 Findings

LCLS-II and LCLS-II-HE will continue the development of LCLS from pulsed operation at 120 Hz to continuous waveform delivery at bunch repetition rates as large as 929 kHZ, with very small electron emittances. The maximum repetition rate increases by almost four orders of magnitude.

LCLS-II commissioning was delayed by about one year due to COVID-19. Cooldown to 4K has begun and is scheduled for completion in April 2022, followed by cooldown to 2K as early as June. Beam commissioning in the superconducting linac is scheduled for completion by September, with first light in November 2022.

The current design uses cryoplant 1 (CP1) for linac modules L1 to L3, CP2 for L4, and a standalone system for the superconducting radio frequency (RF) gun. Options remain open; for example with the possibility of using a "Tee" at the front of L4 to drive a short additional cryomodule (CM).

The Key Performance Parameters (KPPs) may shortly be modified, to match project scope re-tuning. These modifications will have no significant impact on Accelerator Physics activities.

The findings below are distilled from a written Q&A exchange between the Accelerator Physics subcommittee and the LCLS-II-HE Accelerator Physics team.

Benefits of LCLS-II Commissioning

Q: How will LCLS-II-HE planning benefit from LCLS-II commissioning? What cross-communication is there between overlapping communities? Is adequate beam development time foreseen in LCLS-II commissioning?

A: Two issues are important for LCLS-II-HE. The first is to understand the degradation of cavity gradient that happens between partner laboratory measurements and LCLS-II installation, and to understand the performance of the LCLS-II CMs and CPs. The second is to observe and understand LCLS-II beam dynamics, which are expected to be impacted by space charge effects, Coherent Synchrotron Radiation, and micro-bunching instabilities.

It will be important to benchmark beam data taken to explore these effects against the detailed simulations that predict LCLS-II performance. This benchmarking could impact the LCLS-II-HE design. Unexpected issues observed during LCLS-II commissioning could also impact the LCLS-II-HE design.

LCLS-II has already commissioned many systems that verify the LCLS-II and LCLS-II-HE design choices. These include the beam transport systems to the undulators and to the hard x-ray (HXR) and soft x-ray (SXR) undulator systems.

Many members of the LCLS-II beam commissioning team are also engaged in LCLS-II-HE design activities. LCLS-II-HE accelerator physicists are actively proposing studies to verify issues that they feel are important, and which are not necessarily part of the LCLS-II commissioning plan. They are in the process of negotiating beam time for these studies.

Beam Dynamics Studies

Q: Please list and rank the beam dynamics studies that are still required or are still in motion.

A: Beam dynamics studies so far focused on verifying the point designs at 20 pC and 100 pC, using both the Low Emittance Injector (LEI) and the LCLS-II injector. These studies will further enhance confidence in achieving the KPP threshold parameters after benchmarking against data taken during LCLS-II commissioning.

Additional studies will help in design optimization and in achieving the KPP objective parameters. For example, further optimization of the peak current could enhance the performance of lower emittance beams at short free electron laser (FEL) wavelengths.

Intra-Beam Scattering (IBS) is expected to have a significant impact on the beam energy spread. The "low" IBS optics already developed does not preserve the transverse emittance, as well as the nominal optics. Additional studies will identify sources of dilution and quantify the tradeoffs.

FEL performance depends sensitively on the details of the beam distribution. Additional studies will quantify the sensitivities of the distribution on variations in photocathode laser parameters, and on other injector and bunch compressor parameters.

Quadrupole Fields in the Superconducting RF Gun

Q: Lower emittances enhance sensitivity to quadrupole components in the superconducting RF gun. Are there simple mitigation strategies?

A: Although the gun cavity itself is essentially axial-symmetric, the surrounding emittance compensation solenoid may generate a small quadrupole component. Quadrupole and skew-quadrupole trim windings added to this solenoid (and to downstream solenoids) will allow residual quadrupole components to be cancelled.

Relative Performance of the Normal Conducting LCLS-II Gun

Q: The "complex" layout shows good performance even when the superconducting RF gun runs at a low gradient. How well would it work with the normal conducting LCLS-II gun? Would it give similar performance at a reasonable gun gradient?"

A: The shorter anode-cathode gap length in the LCLS-II gun (4 cm vs 7 cm in the superconducting RF gun) makes it difficult to match SRF gun performance with a cathode gradient of 20 MV/m. Using the LCLS-II gun as is, in a complex layout, would also not be optimal as the distance between the gun and solenoid cannot be further reduced.

FEL Radiation Protection

Q: 200 W of FEL power is the current radiation protection limit, but 2 kW is possible. How does the project plan to address this?

A: A significant effort went into understanding damage limits as a function of photon energy between 200 eV and well above 5,000 eV, during the LCLS-II design. The x-ray power decreases, and the attenuation length increases as the photon energy increases, but the incoming spot size decreases. Those studies raised a concern around 7 keV, where the energy density is highest. Although all safety devices were believed to be robust at an X-ray power of 200 W, LCLS-II can produce more power. The conclusion was to develop a "boot-strapping" approach to commissioning these systems.

The project team has not yet tried to understand the expected damage limits for LCLS-II-HE over the full spectral range. However, it is expected to be able to exceed the limits calculated by LCLS-II if x-ray power is maximized from the highest-power incoming electron beam.

The project team has not yet determined a path forward. Although the most restrictive approach would be to limit the incoming electron beam power, there are many operating configurations that extract x-rays from only a small fraction of the incoming electron beam. These modes would be severely impacted by such a restrictive approach.

The project team has sought to develop accurate ways of quantifying the x-ray beam power and wavelength in a manner that includes safety system accreditation.

Radiation Protection Systems

Q: Please list on a single page the radiation protection systems.

A: Response times were originally determined in LCLS-II when the scope of that project still included 250 kW electrons beams. Thus the response times are applicable to LCLS-II-HE. Several detectors are required to be much faster than traditional equipment. New technologies have been applied and are currently being commissioned with LCLS-II. (See Table 2.1-1.)

2.1.2 Comments

The Committee thanked the entire Accelerator Physics team for their thoughtful and clear presentations. This is a world-class team. Keep up the excellent work!

Commissioning and Benchmarking Against Reality

LCLS-II commissioning has begun, following a detailed plan laid out for 2022 activities, ending with first light in November. This plan may prove to be success oriented and may suffer from real-world challenges.

Table 2.1-1.

Name	New / Modified	Category	Response Time	Status
Safety Devices for LEI				
Bulk & local shielding	New	Shielding	n.a.	Preliminary design
Dump	New	BCS	n.a.	Conceptual design
Stoppers	New	PPS	t.b.d.	Conceptual design
Safety System for remaining e^--lines				
Shielding except S7-10 penetrations	LCLS-II	Shielding	n.a.	Commissioning stage
S7-10 penetration shielding	Missing	Shielding	n.a.	Designed
Average Current Monitors	Modified	BCS	200 us	Re-use LCLS-II design
Point Beam Loss Monitors (solid state)	LCLS-II	BCS & MPS	200 us	Commissioning stage
Long Beam Loss Monitors (fibers)	LCLS-II	BCS & MPS	200 us, 4 s for S0-10	Commissioning stage
Water Flow Switches	LCLS-II	BCS	1 s	Commissioning stage
Rastering for dump protection	New	BCS	200 ms	Conceptual
EBD quad interlock (dump protection)	LCLS-II	BCS	4.5 s	Commissioning stage
BPM Orbit and Charge	LCLS-II	MPS	100 us	Commissioning stage
Mechanical Safety Devices for FEL Beams				
Shielding for FEE and hutches	Existing	Shielding	n.a.	Need analysis
Shielding for new devices in accessible areas	New	Shielding	n.a.	Need analysis
Photon stoppers	Modified	PPS	n.a.	Needs analysis
Photon collimators	Modified	BCS	n.a.	Re-use LCLS-II design. Need analysis
Photon beam dumps	New	BCS	n.a.	Conceptual design
FEL ray trace	New	BCS	n.a.	Need analysis
Radiation Safety Interlocks for FEL Beams				
FEL power limit	New	BCS	TBD	Conceptual design
Vacuum interlock for FEL containment	Modified	BCS	<1 s	Re-use LCLS-II design Need analysis
Traditional burn-through monitors for FEL containment	Modified	PPS	~5 s	Re-use SLAC design Need analysis
Fast burn-through monitors for photon beam dump	New	BCS	TBD (ms-level)	Conceptual design
Cooling water flow interlock	Modified	BCS	~4 s	Re-use SLAC design Need analysis
Hutch Protection System (HPS)	Modified	PPS	~5 s	Minor changes from existing HPS
BSOICs	Modified	PPS	~7 s	Re-use existing BSOICs, may relocate

While LCLS-II experimental measurements, for the most part, show good agreement with simulations, there is a need to better understand observed discrepancies, including the somewhat larger energy spread that is measured under certain machine parameters. This would help to ensure that the expected performance of LCLS-II-HE is reached for the hardest x-rays, and for all the "special" operating modes.

Energy spread growth due to IBS is a particular concern, since the model used to predict this effect is only approximate and is not self-consistent. The project team should benchmark the IBS model, by finding simple situations for which it may be compared to more accurate physics simulations, and/or by comparing it to beam measurements.

Safety Systems

Safety systems became part of the critical path for LCLS-II. They are still being defined for LCLS-II-HE, at this relatively early stage in the project timeline. The Committee supported the vigorous continuation of these efforts, particularly in view of the potential need for a more rigorous and/or more layered Machine Protection System (MPS) that does not simply limit electron beam power to achieve safe operation.

The present understanding is that the x-ray power must be limited to 200 W, although powers in excess of 1 kW are possible. The project team proposed a bootstrapping procedure to slowly increase x-ray power and determine whether higher powers are possible. This is a reasonable plan at this stage, but the project should continue to consider how an x-ray power limit can be maintained without overly constraining the electron beam power, particularly in the many operating modes in which the efficiency of converting electron energy to photon energy is small.

Cavities and Cryomodules

The lack of field emission from the verification cryomodule (vCM) is very promising. Nevertheless, field emission is still a concern since simple scaling from the LCLS-II CMs implies an expected current of about 10 or 30 microamps. The project would greatly benefit by understanding this inconsistency, so that similarly good performance may be repeated more confidently with subsequent CMs.

Plasma processing is not part of the current plan for cavity processing, but it has been shown to significantly reduce the number of quenches necessary to bring a cavity to its operating gradient. The project should consider adding plasma processing to the standard processing.

Beam Distribution

The LCLS-II-HE beam distribution system is an extension of the LCLS-II design. While it is relatively low-risk, the project should monitor LCLS-II progress to ensure a smooth transition to 8 GeV beams.

The complex layout for the LEI shows remarkable flexibility and promises to be able to achieve suitable beam quality for a wide range of electron gun parameters. The project team should first work to understand the simulated benefits since some of them run counter to simple scaling laws and expectations. Assuming the results hold, the project team should investigate to what extent the complex layout may relax gun requirements, including whether it may enable a backup solution with a normal conducting gun. This could mitigate risk associated with the superconducting RF gun.

Producing and transporting an electron beam with sufficient brightness is critical for lasing at 20 keV. Nevertheless, there are some tradeoffs regarding energy spread, emittance, final energy, and peak current. The Committee encouraged the continued study of how various design choices impact these parameters, with a focus on optimal FEL performance. This may become critical if the project seeks to reduce cost or scope, or if various systems (e.g., the LEI) perform at the lower end of projections.

Communications

It is imperative to deliberately maintain and enhance good communications between the Accelerator Physics efforts at the multiple laboratories in a relatively complicated collaboration.

2.1.3 Recommendations

1. Maximize the benefit of LCLS-II beam commissioning in mitigating risk and enhancing the design by establishing dedicated beam time for important LCLS-II-HE related studies. Report on progress at the next DOE/SC review.

2. Continue studies and simulations on the sensitivity analysis, as well as on important dynamical effects including benchmarking code results against beam data from the normal conducting linac, and also to be taken during LCLS-II commissioning. Report on progress at the next DOE/SC review.

2.2 Cryomodules

2.2.1 Findings

The scope is to fabricate test and install 23 new high-energy (HE) CMs in L4, one HE CM to serve as the “L0” for the new injector, and one buncher cavity cryomodule (BCC) downstream of the injector. This is an increase from 20 CMs previously.

Design maturity is 92% in 1.02 and 100% in 1.2. This is not inclusive of the BCC.

The plan is to descope the J11 cryomodule and use the validation cryomodule (vCM) as a production cryomodule.

L3 will remain as is so no moving of LCLS-II CMs is required.

A new distribution box and transfer line will be installed to support L4.

Inflation did not strongly affect CD-3A CM components since the long-lead procurements were placed before the increase of prices.

Cavity production is on the CD-3A critical path but there is margin in the overall project schedule.

The HE average gradient and Q specification are 20.8 MV/m and 2.7 X 10^{10}, respectively.

TJNAF and FNAL were chosen as partner laboratories.

FNAL's scope is bulletized below.

- CM Engineer of Record
- R&D to enhance higher cavity performance
- Fabricate, test, and deliver the vCM
- Fabricate, test, and deliver first article (FA)
- Fabricate, test, and deliver nine production CMs
- Provide three additional production CMs
- One superconducting RF Buncher Cavity CM for the new injector

There have been some supply chain issues that required the project to requalify some vendors such as; the vacuum vessel, and Beam Position Monitor (BPM) vendors.

The project team has strong continuity from LCLS-II to HE with improvements in QA.

There is a dedicated facility and infrastructure for LCLS-II-HE CM production at FNAL.

FNAL is sharing resources between HE and the Proton Improvement Project II (PIP-II).

The superconducting RF buncher cavity CM CDR is complete with the Preliminary Design Review (PDR) scheduled for August.

TJNAF has three projects ongoing in parallel—TJNAF scope includes:

- Fabricate, test, and deliver FA
- Fabricate, test, and deliver nine production CMs
    - Will implement new purge system
    - Vertical Test Dewar configured to test three cavities at once

The FA fundamental power coupler (FPC) copper plating issue has been resolved.

The first assembly at TJNAF has been delayed due to cavity delivery but is underway now.

There is a dedicated assembly line for HE and other lines for the other projects at TJNAF. Testing will take place in the TJNAF Low Energy Recirculatory Facility (LERF), which is dedicated to HE.

A verification CM was built with very impressive results—25 MV/m and 3 X 10^{10} Q.

Plasma processing was applied to four of eight cavities in the vCM, which proved useful in reducing multi-pacting.

CD-3A procurements are 100% awarded and 69% complete. This covers 18 CMs in 1.2 and the two FAs in 1.02.

Procurements have not started for the additional four CMs. These procurements will be made after the project is authorized to do so.

There are no spare HE CMs planned.

Cost performance of CD-3A procurements is very good (CPI is 1.09). The schedule is more of a concern, but SPI is increasing (0.87).

There are no high or medium risks in WBS 1.02.

There are three moderate risks in WBS 1.2. The top two are CM rework and inappropriate vendor QA/QC procedures.

The project team is utilizing lessons learned from LCLS-II but it is still ongoing, and lessons were communicated from the vCM effort.

The project is still working on previous recommendations, including long-term storage of CMs and back-up power to control cabinets.

The storage of production CMs at SLAC is being organized. Several different locations are being prepared for the storage. Each of these locations is being equipped to actively pump the stored CMs. The pumping equipment has already been procured, which will mitigate potential delays.

The 12-month look ahead was presented as follows.

- TJNAF first article CM assembly underway, March 2022
- FNAL FA CM assy/test complete, May 2022
- Complete production cavity contract, December 2022
- Receive and store CMs F-1 through F-3, December 2022
- Complete all partner laboratory CM long lead procurements, January 2023
- TJNAF J-2 CM testing underway, February 2023

SLAC’s procurement scope includes:

- Cavities
- Beam line absorbers
- Cryomodule Interconnect parts
- Cryomodule stands

Cavity production is having some quality problems. A great deal of work is being done at SLAC to try to reduce delays and increase quality.

An incentive program is being leveraged to improve the performance of the cavity vendor. This has been unsuccessful to date.

The re-rinse rate is currently 35% after vertical test. Efforts are being made to lower this further.

There was some damage to helium vessel/cavity bellows that require repair at the cavity vendor. A root cause analysis was performed.

Based on January data, 20 cavities have been delivered, and 12 qualified after their first test. Five cavities with field emission (FE) on first test. Three have been cleaned, two needed a second re-rinse. Present day numbers are 31 delivered (21 have been tested) with 15 qualified after their first test.

The total cost of this WBS is expected to increase despite the elimination of one CM (see Table 2.2-1 showing scope additions and deductions proposed).

Table 2.2-1. Proposed Additions and Deductions to Project Scope

Proposed additions and deductions to project scope					
Change #	Change Description	ROM ($K)	Mgmt EAC ($K)	Status	Expected Update
Pend#134	Descope 24th CM (J-11) and associated cavities	-$3,350	-$3,350	2. Proceed Integ.	Mar-22
Pend#117	Cryomodule Storage Support at SLAC	$2,020	$1,825	2. Proceed Integ.	Apr-22
Pend#115	Additional Cavity Procurement	$2,310		1. Pending	May-22
Pend#118	Installation Component Receive/Inspection Support	$500	$500	2. Proceed Integ.	Jun-22
Pend#170	Bellows Rework for 5 Remediation Cavities	$155	$155	CANCELED	Mar-22
Pend#119	SLAC Property and Equipment Return from PLs	$500		6. Postponed	Apr-23

2.2.2 Comments

The Committee commended the project team for incorporating lessons learned from both LCLS-II and the vCM efforts.

There are additions to the project cost in this WBS, as well as deductions that are planned. Completing the baseline changes to evaluate overall project cost and contingency is essential.

Procurements for the final three production CMs and the buncher cavity CM may be adversely affected in both cost and schedule due to the economic climate. The Committee strongly supported starting procurements for the remaining four CMs as soon as possible to avoid FNAL standing army concerns.

The added CMs provide risk mitigation to the LCLS-II cavity performance, as well as benefits in the cryoplant margin without re-distributing LCLS-II CMs to CP2. The Committee supported the addition of the added CMs. Based on XFEL experience, installing the additional CMs even if the LCLS-II cavities exceed expectations is necessary.

The cavity procurement is behind schedule. The Committee strongly supported the increased on-site presence of project personnel at the cavity vendor.

FNAL and TJNAF have many on-going projects. It is necessary to monitor if there are any future coordination problems during the production assembly and testing.

Long-term storage of CMs is necessary and off-project costs are planned to prepare this space. However, the availability of those spaces in some cases is only one month prior to arrival of the CM to be stored. Careful management and oversight of that effort should be maintained by the project.

Plasma processing has a positive impact on multi-pacting in these cavities. Evaluating whether the reduction in testing time versus the time and effort to conduct plasma processing will lead the project team to the most efficient testing cycle. Currently plasma processing is available at FNAL, it will be beneficial to extend the capability to TJNAF and SLAC as planned.

The Committee congratulated the project team for the strong vCM performance.

Transferring relevant information and data from the LCLS-II cooldown and initial operation can have a significant impact on LCLS-II-HE.

2.2.3 Recommendations

3. Finish scope additions and deletions to adequately assess the Total Estimated Cost of the CM WBS elements by September 30, 2022.

4. Proceed with procurements for the remaining three production CMs and one Buncher Cavity CM as soon as authorized.

2.3 Cryogenic Distribution Systems

2.3.1 Findings

Accelerator System Overview

The superconducting linac, cryogenic distribution system, beam transfer line, and undulators are all under the same WBS 1.03.

Deputy System Manager and Linac/CDS CAM is currently a dual role. LCLS-II-HE relies on matrixing of resources from line organizations and require close communication with Division Heads and established Service Level Agreements. Staffing is prioritized based on LCLS-II milestones.

The CDS is currently at 67% cost-weighted design maturity. Overall Accelerator Systems is at 75%. CDS completed the overall reference design review in August 2021. Design maturity is on track to be at 85% by fourth quarter FY 2023 in order to meet CD-2/3.

The project team completed the design of cross-connection between CP1 and CP2.

The project team released multiple RFIs on CDS components, and Request for Proposals (RFP) for the distribution box in September 2021.

Several moderate risks are defined for the CDS including the L3/L4 break point location—CP heat load balance, and the CDS L3 fast cooldown failure.

COVID-19 impacts during the design layout phase limited availability of engineering personnel for HE due to extended LCLS-II installations.

Lessons learned were implemented for improved maintainability and installation sequencing of the distribution box, which includes development of a lifting system to facilitate relief valve and discharge piping installation and procurement of long lead items that are external to the design such as vacuum pumps.

There were three recommendations from the December 2020 DOE/SC Status Review, all of which have been closed.

CDS is finalizing component specifications to support contract design, which is expected in third quarter FY 2022.

Installation and Integration Strategy

Installation activities are very similar to those just completed for LCLS-II. Installation access to the accelerator housing is only available when the superconducting linac is off. Two ten-week summer downtimes and one 12-month long shutdown are planned.

The superconducting linac installation must be completed in significantly less time than was performed by LCLS-II. The 12-month superconducting linac downtime duration was selected to minimize impact to LCLS-II science program.

The project team will partner with a design integrator to produce and maintain a Building Information Modeling (BIM)-based integrated model of accelerator, controls, and infrastructure systems. An RFI for this service went to suppliers and the project is reviewing responses.

Cryogenic Distribution System

Five out twelve component design reviews have been completed.

Lessons learned include improved maintainability and installation sequencing of the distribution box.

Another lesson learned is the added risks and workload to SLAC of having a third party install a cryogenic system manufactured by others. Mitigation is to include design, procurement, and critical installation activities in the procurement contract.

The distribution box procurement started and RFIs for all components except the interface box have been issued.

All CDS referenced general arrangement drawings have been completed.

Location of the CDS L3/L4 was reassessed in lieu of different cryogenic load demands on CP1 due to the shift of the LEI load to a dedicated cryoplant.

The interface box was configured to require cross-connection of plants without the warming-up of sections.

The CDS SLAC reference design is scheduled for completion at the end of third quarter FY 2022. The CDS detailed design contract is out and expected to be completed in fourth quarter FY 2023 for CD-2/3. The CDS installation is largely independent from the long downtime because it mostly involves surface level installations. The project team plans to finalize the CDS component specifications for design-build contracts in third quarter FY 2022. The CDS reference design FDR is in third quarter FY 2022. The project team plans to award CDS components to vendors in first quarter FY 2023; and to award the distribution box in second quarter FY 2022.

CDS Design Statistics and Installation Plan

The relief system design has been optimized.

The distribution box Technical Package Readiness Review (TPRR) was completed in August 2021 and procurement documents were issued.

RFIs have been issued for the surface transfer line, vertical transfer line, feed cap, and end cap.

The interface box allows operation of the entire linac from either CP1 or CP2 and allows isolation from the cryoplant without removal of U-tubes. Requirements are listed in the CDS FRS (LCLSII-HE-1.3-FR-0054).

LCLS-II lessons learned for the distribution box, vertical transfer line, end cap, and vacuum break are being applied to the LCLS-II-HE designs. The vertical transfer line and feed cap preliminary design is in progress. The Vacuum Break (VBB) preliminary design has been completed and the technical specification is in progress.

Many of the CDS installation tasks can be performed during linac operation. Tasks that require tunnel access will be performed during the short downtime #2 period (summer 2025) and the long shutdown (starting April 2026).

Leveraging LCLS-II equipment installation experience using the same processes and procedures and incorporating lessons learned.

The project team developed standards for CDS component manufacturing and handling that build on LCLS-II experience and facilitate the upcoming CDS procurements substantially.

The installation plan and preliminary schedule appears to be well thought through and feasible for the CDS scope.

Accelerator Systems Procurement Strategy

In order to mitigate supply chain issues, front-end acquisition planning consisting of Advanced Procurement Plans (APP), Acquisition Strategy Panel (ASP) Sourcing Plans RFIs, TPRRs, and Source Selection Plans have been put in place with the goal to develop acquisition strategies and complete procurement packages well in advance of the requirement need.

Supply chain issues are still a concern with continued COVID-19 impacts and inflation with supplier estimates 26% higher than current project budget estimates. Previous LCLS-II suppliers are reporting loss of profits from previous procurements and raw material cost increases.

A lesson learned for complex components is to focus on quality and minimize the number of separate contracts. This is critical for components that involve design, manufacturing, and installation. Consolidating contracts minimizes interface discrepancies and optimizes project resources.

2.3.2 Comments

The cryogenic team should be commended for advancing the project. The large amount of work that has been completed is impressive.

A new cryogenic engineer position was established in December 2020, but after ten months of interviewing candidates it remains unfilled. The resource shortfall was mitigated by collaborating with the SLAC AD/Mechanical Technical Support Department who supplied a lead engineer. The Committee supported continued involvement with support departments to identify and share skilled resources and outsourcing partial scope to partner laboratories to mitigate these shortfalls.

The CDS PRD (LCLSII-HE-1.3-PR-0040-R2) and the CDS FRS (LCLSII-HE-1.3-FR-0054) are both released but have not been updated to show the current L4 CDS configuration. The Committee suggested these be updated at the earliest convenience.

The Committee supported the use of component vendors for installation work where appropriate. Direct component vendor involvement and/or guidance during installation is encouraged to ensure proper installation and minimization of delays.

Installation of the LCLS-II-HE scope in the accelerator housing during the summer downtimes and long downtime seems very challenging. Earlier linac designs incorporated a T-junction box "Tee" that would allow for supplying L3 CMs from CP2 for balancing cryoplant loads (addressing another risk of insufficient cooling power). However, this would mean major additional installation efforts in the tunnel, including on the already commissioned L3. In order to mitigate both the insufficient cooling power risk and the short installation window risk (with regard to CDS and CMs) the project has decided to de-couple the injector/superconducting RF gun refrigeration from the linac by adding a smaller third standalone cryoplant. The Committee endorsed this choice.

In response to a previous recommendation regarding development of a cryogenic availability analysis, the cryogenic requirements PRD (LCLSII-HE-1.3-PR-0040) was updated to include a section on cryogenic system availability. The Committee suggested that this information be used to update the overall availability analysis to include these cryogenic requirements and the LCLS-II-HE additions at the earliest convenience.

Lessons learned from LCLS-II CDS procurements indicate that minimizing the number of separate contracts has benefits by minimizing interface discrepancies and optimizing the use of project resources. The Committee encouraged this philosophy but noted that this must be balanced with the potential impacts of lengthening fabrication and delivery schedules due to vendors reaching shop capacity limits and other factors.

The hydraulic calculation, as noted in LCLSII-HE-1.3-EN-0324, provides a rational for the line B increase in size to 12 inches and the limiting of acceptable flow to 191 g/s. The capacity is reduced to 189 g/s to ensure 2K in the tunnel following final location of the distribution box (refer to the document LCLSII-HE-1.3-PM-0431-R1 and references). Theoretical operational margins are 15.4% for CP1 and 12.4% for CP2, respectively. The Committee commended this line size optimization and suggested an updated calculation of the operational margins, based on real data from recent CP1 operational experience at the earliest convenience.

Even though the overall LCLS-II-HE installation effort in the downtime periods seems ambitious, the installation plan and preliminary schedule for the currently foreseen CDS scope appear to be well thought through and feasible.

The project's current approach is to deliver cryogens to the L4 string via a feed cap strategically placed to balance the loads between the CP1 and CP2 cryoplants. This arrangement allows for the insertion of a "T" later if a rebalance of the L3 and L4 strings is required after the performance of the LCLS-II CMs are known and a final optimization of gradient is determined.

2.3.3 Recommendation

5. By the end of the calendar year, determine whether the implementation of the "T" and new end cap is needed in order to minimize impact on the overall LCLS-II-HE schedule.

2.4 Accelerator Systems

The Accelerator Systems Subcommittee evaluated the design and status of the accelerator systems for the LCLS-II-HE project. The Accelerator Systems team made substantial progress in all areas since the December 2020 DOE/SC status review. The project team has a good understanding of the performance requirements, their scope and the deliverables, and the team is keenly aware of the technical, schedule, procurement, and skilled resource challenges ahead of CD-2/3. The design of the Accelerator Systems capitalizes on LCLS-II experiences and has implementing lessons learned in its planning and practice.

2.4.1 Findings

The LCLS-II-HE project scope is to design and construct an extension of the LCLS-II superconducting RF linac to increase electron beam energy from 4 to 8 GeV beam energy. The Accelerator Systems (WBS 1.03) scope consists of the following:

- Project Management and Integration (WBS 1.03.01)
- Superconducting Linac (WBS 1.03.03)
- Accelerator Linac – CDS (WBS 1.03.04)
- Beam Transfer Line (WBS 1.03.05)
- SXR Undulator (WBS 1.03.06)
- SXR Undulator (Lawrence Berkeley National Laboratory (LBNL) scope; WBS 1.03.07)

The scope of the superconducting linac includes the installation of 23 1.3 GHz CMs and of the associated RF systems. This will form the L4 segment of the linac.

The beam transfer lines (BTL) scope includes installing the BTLs to transport the LCLS-II-HE 8 GeV electron beam to the undulator hall and the electron beam dumps, the addition of six kicker magnets in each linac-to-undulator hall beamline, and the design, fabrication, and installation of the beam rastering system to the beam switchyard and the Electron Beam Dump (EBD) area.

LCLS-II-HE relies on the matrixing of resources from the line organizations. This requires close communication with division heads, group leaders, and establishing service level agreements with the resource organization.

The accelerator systems cost/schedule estimate is under development and will be completed in the next 12 months.

The accelerator systems requirements documents release process flows from KPPs/global requirements to physics requirements and then to functional and engineering/technical specifications, and interface requirements. Requirement documents are incrementally and iteratively produced as the technical designs mature.

Design maturity is evaluated by the project team using uniform metrics based on successful Conceptual Design Reviews (CDRs), PDRs, and FDRs.

For accelerator systems, the design maturity is expected to be at 85 % by fourth quarter FY 2023 in line to meet the CD-2/3 date. As presented at the review, the cost-weighted design maturity is currently at 75% with superconducting linac at 71% and BTL at 68%.

Overall accelerator risks are responsible for 2.5% of risk impact in model. One moderate risk is reported, related to the installation window being too short to complete the work. The remaining risks are considered to have low impact. Mitigation plans are developed.

Specific accelerator systems hazards are captured in Preliminary Hazard Analysis Report (PHAR) documents.

The technical scope of the high-power RF (HPRF) systems is the design, procurement, and installation of the HPRF plants for the 23 new CMs that will be configured in L4.

For LCLS-II-HE, the responsibility for Non-Ionizing Radiation Protection (NIRP) engineering control will be shared between HPRF and Controls. An Interface Control Document (ICD) is pending.

Due to the similarities, the LCLS-II-HE HPRF significantly leverages LCLS-II experiences and lessons learned. Although revised LCLS-II documentations and specifications will be generally applicable to LCLS-II-HE, it should be noted that the RF power requirement for the HE CMs is specified to be 7 kW compared to 3.8 kW for the LCLS-II.

The specified output power of the solid-state amplifiers (SSA) is based on the expected cavity performance. The 7 kW units will allow to operate at the required accelerating gradient for LCLS-II-HE. The verification CM tests at FNAL showed excellent gradient performance (25.0 MV/m versus requirement of 20.8 MV/m), meeting Q_0 requirement and with no measurable field emission, which could be critical for high gradient operation.

The HPRF amplifier systems are similar to LCLS-II 3.8 kW units. They have same real-estate footprints as LCLS-II, which make it possible to be fitted inside the same size racks, thus preserving the current layout, power distribution, and interfaces.

Eighteen 7 kW SSAs were received and tested as first articles with additional 166 units to be procured. The first articles were long-term tested at SLAC. Eight SSAs each are at TJNAF and FNAL for CMs testing.

WR650 waveguide (WG) runs will connect each SSA to the corresponding powered cavity. Each WG run is composed of several components: directional couplers, isolators, E and H bends, and WG straights. The WG runs for four RF plants will be using the same penetration from gallery to tunnel, so 46 penetrations will be required to complete all connections. The layout of the RF plant is similar to LCLS-II with modifications to account for the different position of the penetrations with respect to SSAs and cavities. The project team developed WG runs for all 46 locations reusing LCLS-II components design.

The original LCLS-II isolators were designed to handle 7 kW, which also meets HE requirement.

The first article 7 kW isolator should be high-power tested to 7 kW with an available RF source.

The accelerator systems team has adopted lessons learned from LCLS-II regarding the quality control issues of WG components provided by the vendor. The project team plans to conduct leak-test of the WG subassemblies before releasing them for installation and will provide additional oversight with visits to the vendor.

The scope of the low-level RF (LLRF) is to update and install the RF hardware as needed for the high gradient cavities. One LLRF system serves four cavities, therefore for each CM, two LLRF systems are needed. The total of 48 additional LLRF systems for the 23 additional CMs (plus one) are needed. The LLRF for LCLS-II-HE is based on the LCLS-II with only small system changes. The LLRF team recognizes that it must be prepared for components updates due to obsolescence.

The LLRF controls system software and firmware are very mature, benefiting from LCLS-II LLRF and the tests at the TJNAF LERF and FNAL Cryomodule Test Facility (CMTF).

The project team keeps developing flexible software patches, as well as transferring software knowledge to other members of the team. Adding new features and functionalities to the LLRF will be beneficial.

The LLRF LCLS-II-HE PDR is planned for September 2022.

Design and engineering of the BTLs is progressing. Mechanical engineering and integration are complete for most areas except shielding for CEDOG (collimator) and a differential pumping station. Currently, the mechanical systems engineering design is in its preliminary phase. The main technical focus is towards the completion of the mechanical system documentation focusing on the beam rastering design and the final design of the BTL. The BTL PDR review is planned for April 2022 and the FDR is planned for October 2022.

The installation strategy is to utilize LCLS-II maintenance downtime periods as efficiently as possible and perform installation in the gallery and the cryoplant as much as possible during linac operation.

Access to the accelerator housing is allowed only when the superconducting linac is not in operation. Two ten-week summer downtimes are planned in 2024 and 2025 and a 12-month long downtime is planned from April 2026 to March 2027.

Work in the gallery may continue while the superconducting linac is supplying beam to LCLS. The superconducting linac installation must be completed in significantly less time than was used by LCLS-II, so it requires careful planning.

The project will partner with a design integrator to produce and maintain a BIM-based integrated model of accelerator, controls, and infrastructure systems. An RFI for this service went to suppliers and the project team is reviewing the responses.

2.4.2 Comments

The Committee appreciated the accelerator team prompt response to the Committee's requests for information and providing additional materials and answering questions before and throughout the review. The Committee commended the Accelerator Systems team for the well-prepared, detailed, and informative presentations at this review.

Since the December 2020 DOE/SC review, the project team has made substantial progress advancing the design of the LCLS-II-HE accelerator system and is congratulated for this work. The project team has done an excellent job identifying main technical challenges that need focused attention to be completed ahead of CD-2/3.

The collective experience of LCLS-II has provided valuable practical knowledge on best practices to LCLS-II-HE. The Committee commended the project team for incorporating relevant lessons learned from the LCLS-II experiences and encouraged the team to continue this process as needed.

The Committee was concerned about two high-priority projects (LCLS-II and LCLS-II-HE) with notable overlaps plus other planned SLAC projects. Unpredicted events and/or other laboratory's priorities could further complicate resource availability. The project team should make it a high priority to provide appropriate resources to complete the remaining final designs and conduct FDRs of the Accelerator Systems. This requires close coordination within the entire LCLS-II-HE project.

The Committee judged the current Accelerator Systems installation plan is highly optimistic and it was noted that it does not currently have an overall integrated schedule. LCLS-II-HE complex installation activities require close supervision and careful coordination during the execution phase.

The Committee learned that responsibility for NIRP engineering control will be shared between HPRF and Controls. The Committee emphasized that the ICD should clearly define roles and responsibilities.

The 7 kW HPRF isolators have not been tested to full power yet. The Committee encouraged the project team to test the RF isolators to 7 kW at SLAC as soon as possible using the available SSAs.

The Committee encouraged the project team to continue to proactively engage vendors in advance of procurements with frequent follow-ups and site visits when possible, including addressing and resolving any QA/QC issues. This becomes more important for the procurement of WG components, which resulted in QA/QC issues for the LCLS-II. A combination of incorporating the relevant LCLS-II lessons learned and frequent vendor visits to closely monitor workmanship of components and the quality of the vendor manufacturing processes and practices will greatly benefit the project.

Supply chain disruptions are among the major risks for successful on-time/on-budget implementation of large projects in current worldwide situation. Mitigating these issues requires additional vendors oversight to keep the production of HPRF components on track and be able to resolve any supply chain problems early on to minimize any schedule impacts on the project.

The current installation plan for the LCLS-II-HE HPRF appears to be optimistic. Although the HPRF shares many common design features and the project team relies on the recent LCLS-II experience, it is prudent to pay especial attention to the subtle changes between the LCLS-II and LCLS-II-HE. The Committee judged that the Accelerator Systems current plan needs a fresh, second look to develop a more realistic executable plan before CD-2/3.

Scheduling and installation coordination of LCLS-II-HE high power RF systems will be challenging and should be carefully planned and choreographed, due to the high number of groups involved. Resource availability and sharing issues should be addressed accordingly.

Flexibility of modern digital LLRF system allows adding new features and capabilities that would be beneficial to LCLS-II-HE. This could be a strategic asset for operation and performance optimization. The project team is encouraged to pursue adding new features (such as microphonics compensation and machine learning hooks) as needed.

The LLRF collaboration has been a key to the development of the LLRF system of LCLS-II in partnership with other laboratories. The Committee appreciated that the collaboration remains strong and is ongoing. Nevertheless, the SLAC team should work closely with LBNL to transfer firmware/software knowledge and train SLAC staff in a timely fashion. Full ownership of the system at SLAC will be an important asset to both LCLS-II and LCLS-II-HE Accelerator Systems.

The Committee supported continuing the CM tests at the partner laboratories with the 7 kW SSAs. The Committee encouraged continued monitoring, collecting, and analyzing the RF performance of the amplifiers since this will allow to qualify and flesh out problems early on and put in place performance enhancements and improvements if needed.

Obsolescence is a major concern for the LLRF system due to the rapid technology advancement in the electronic components field. The Committee noted that the LLRF team is aware of it. The Committee suggested that the project team implement its plan to deal with obsolescence issues related to LLRF components.

The Committee concurred with the project team about using an integrated model of accelerator, controls, and infrastructure systems. This approach could help to flag any interferences in advance.

2.4.3 Recommendations

6. Advance the Accelerator Systems conceptual plan to a more detailed integrated installation schedule/resource plan with interdependencies specific to the Accelerator Systems prior to next DOE/SC review.

7. The project is encouraged to immediately initiate the procurement for the remaining 7 kW SSAs as soon as authorized.

2.5 Undulators

2.5.1 Findings

At 8 GeV now 30 soft x-ray (SXR) undulator segments are required. The 21 existing SXR undulators will be reused but need reconstruction in the way of increased period length from 39mm to 56mm. This requires new magnet structures for these devices.

The existing gap separation drive systems will be re-used with moderate modifications such as force compensation springs and absolute linear encoders.

Nine new SXR undulators are needed in addition. They will be purchased through LBNL. Finally, the SXR will comprise 30 undulator segments.

All redesign work of the SXR undulators, as well as the procurement of the new magnet structures will be handled through LBNL taking advantage of the LCLS-II experience.
A total of 81% of design work is completed.

The magnet structures will be delivered to and mounted by LCLS-II-HE.

LCLS-II-HE scope for SXR modifications includes:

- Exchange of the old magnet structures ($\lambda = 39mm$) against the new ones with $\lambda = 56mm$
- Exchange of compensation springs
- Installation of new absolute encoders to monitor the centerline of the magnet structures
- Magnetic measurements and tuning in the Magnetic Measurement Facility at SLAC

A total of 29 phase shifters with increased phase integral are needed to match the modified undulators. The already existing 20 phase shifters will be modified and equipped with new magnet structures. Nine new phase shifters need to be purchased in addition. All phase shifter work is covered by LCLS-ll-HE/SLAC.

The SXR self seeding (SXRSS) chicane needs to be modified with stronger magnets and a new vacuum chamber with cryogenic crystal cooling. A first preliminary design already exists.

There are delays to the LCLS-II-HE project, which affect undulator installation.

The exchange of the old vs. modified undulator segments will be done in Planned Machine Maintenance Access (PMMA) breaks of three to four days during operation. It now exends from fourth quarter 2024 to third quarter 2026. The plan is to exchange two undulators in one PMMA access.

The presented time schedule is still a logistic challenge. De-installation, mechanic refurbisment, magnetic measurement and tuning, and re-installation, as well as commissioning in the linac are closely entangled.

A detailed schedule analysis has shown that about seven months of schedule float can be generated by using the existing Kugler Bench together with an upgrade of the existing the Dover Bench.

Water cooling of undulator chambers is already available for the installed 21 segments and is planned for the extension in SXR CELLS 17-25. The cooling water temperature in the vacuum chambers needs to be controlled and adjusted to the local environmental air temperature in the tunnel individually for each undulator.

A first test for vacuum chamber cooling under realistic conditions have been have performed in the laboratory.

2.5.2 Comments

The SXR undulators closely follow the plan presented in the December 2020 review. This plan is executed and makes heavy use of LCLS-II experience.

Undulator controls should be included in following reviews.

Delays in the project are due to COVID-19, inflation, price increases, delays in supply chains, etc.

The plan for exchanging undulator segments (including phase shifter) in PMMA days has been adopted and modified:

- The start has shifted from first to fourth quarter FY 2024.
- The end has shifted from second to third quarter FY 2026.
- Exchanges will be done in PMMA days in lots of about two segments.
- Four days will be required for deinstallation, reinstallation, and commissioning.

Only the quadrupole lattice needs alignment with beam-based alignment requiring several shifts. This can be done after quadrupole installation but prior to undulator installation. Undulators and phase shifters are quasi transparent to the beam. This reduces commissioning time.

The exchange of undulator segments with $\lambda = 39mm$ against ones with $\lambda = 56mm$ with only minimum or no impact on FEL operation has been investigated. It was confirmed that it can be done in the scheduled installation time (fourth quarter FY 2024 to third quarter FY 2026).

During this installation period the new LCLS-II-HE segments can still be operated at 4GeV together with the old LCLS-II ones.

Evaluation of the experience of the pre-production undulator will give information on time and schedule issues and will help to organize the exchange and to synchronize de-installation, mechanic modifications, magnetic measurements and tuning, and re-installation etc.

Vacuum chamber cooling is recognized as essential for LCLS-II-HE operation. The responsibility, project scope, and deliverables from LCLS-II and LCLS-II-HE do not appear to be formalized. These roles and responsibilities should be committed to in a formal agreement detailing specifically LCLS-II deliverables and LCLS-II-HE responsibilities.

2.5.3 Recommendations

8. For the LCLS-II-HE water cooling define the scope, deliverables, responsibilities in a formal agreement between LCLS-II and LCLS-II-HE and more parties if needed by the next DOE/SC review.

9. Refine and update the plan and schedule when experience with the pre-production undulator is available and evaluated by the next DOE/SC review.

2.6 X-Ray End Stations

2.6.1 Findings

LCLS-II-HE delivers 100 kHz (up to 1 MHz) and photon energy up to 25 keV. The present X-ray End Stations (XES) scope includes four instruments, XPP in the Near Experimental Hall (NEH), MFX, CXI, and DXS in the Far Experimental Hall (FEH), beamline systems, HXR optics, laser systems, and a laser hutch in FEH, data systems, and fast-framing imaging and spectroscopy detectors.

End stations/instruments, lasers, detectors, data systems, and common components are designed based on LCLS and LCLS-II experience.

Since the December 2020 review (after an XES scope broadening), significant advances have been made in designing the four HXR instruments.

- XPP: high-repetition-rate upgrades to optics, diagnostics, end station, including a new, large offset double crystal monochromator LODCM that monochromatizes the FEL beam and enables multiplexing;
- MFX: high-repetition-rate upgrades to optics, diagnostics, and diagnostics, new KB focusing mirrors replacing transfocators;
- CXI: high-repetition-rate upgrades to optics, diagnostics, and end station, including a new KB-based zoom focusing system with 1 micron and 100-nm focus capabilities at a common interaction point;
- DXS: a new instrument and major alteration to incorporate high-resolution inelastic x-ray scattering capability with a high energy resolution of 1 meV, while preserving capabilities of the XCS instrument (XPCS, x-ray split-and-delay apparatus).

All instruments are planned to be day-one (third quarter FY 2027) ready for high-rate experiments.

The new laser systems in NEH serving XPP are procurement stage supported LCLS-II discretionary funds. New laser systems in FEH and infrastructure are included in the XES scope, as most of the components are similar to the existing ones in the NEH and replicas of the L2S-I design to serve DXS, CXI, and MFX. A Memorandum of Understanding (MOU) between LCLS-II-HE and SLAC is signed to facilitate the plans of using Hutch 6 (current Matter in Extreme Conditions Upgrade (MEC-U) project hutch) for housing the new FEH laser system.

Significant advances have been achieved in coherent optics simulation and design in the transfer-limited regime. The DXS optics include three major components: periscope mirrors, high heat load monochromator (HHLM), and high-resolution monochromator (HRM). The CDR of the HHLM was performed, while the CDR of HRM is scheduled for April 2022.

The ePix-based new detector systems are planned for all four instruments: ePixHR 25kHz for XPP, CXI, and MFX and SparkPix-S for MFX, DXS, and CXI. The R&D of the detector systems are supported by LCLS-II, while the LCLS-II-HE project supports the fabrication of these detector systems.

LCLS-II data system (through L2S-I) is scalable to LCLS-II-HE data rates to support an average throughput of 100 GB/s and a peak of 310 GB/s in 2025. The system includes components such as data acquisition, data reduction pipeline, data management, and offline analysis.

The XES common components matrixed team was newly created to deliver components devices used in all instruments with a minimum upgrade, some upgrades, and more extensive design modifications.

2.6.2 Comments

The XES team is commended for their significant progress in designing instruments (and associated diagnostics, optics, beam defining devices, etc.) and diligent preparation for this review.

The present XES goal is to provide four upgraded and new instruments, XPP, MFX, CXI, and DXS, to the user community, aiming to take advantage of the LCLS-II-HE photon beam to address the science needs, from day one (third quarter FY 2027).

The optics team responded to the December 2020 review comments satisfactorily. As a result, optics simulation for DXS is ongoing and significant progress has been made, which demonstrated the feasibility of the novel design concepts to achieve meV photon energy resolution with orders-of-magnitude higher photon flux than other facilities.

The original XES budget estimate was largely based on the L2S-I project. The budget would have been accurate if only replicates were built for the HE project. However, the updates needed to accommodate the LCLS-II-HE specifications have taken more resources than planned.

In addition, because of the current economy, supply-chain, and COVID-19 situation, the method to baseline the XES tasks can be updated to reflect the more current and realistic cost escalation. The project team has used an across-board 3%-escalation rate defined by the project, which is very low at the time of this review. Therefore, the XES team was encouraged to verify the effort and M&S budget escalation and develop plans to mitigate any issues caused by the escalation.

The XES team has shown strong momentum and high enthusiasm in all the activities performed including this review. The team is encouraged to maintain the momentum to continue the design of optics and instruments, for example, developing DXS optics specifications, simulation, and evaluation, which is needed for planned technical design reviews.

The project is encouraged to work with SLAC management to explore the alternative path for delivering world-class instruments in a timely manner so that the user community can take advantage of LCLS-II-HE on day one.

Although XPCS is still part of the present DXS instrumentation scope, the project team did not focus on the XPCS instrument in the presentations, which is appropriate.

2.6.3 Recommendations

10. Rescope the XES project based on the revised project budget, by Q4 FY2022.

11. Reevaluate the baseline budget and risk registry by using more realistic escalation rates or by the experience with recent quotes, by the next status review.

2.7 Controls and Safety Systems

2.7.1 Findings

The Controls subsystems include design, procurement, installation and checkout.

- The linac will be added to support the relocated EXT/DOG to accommodate L4; approximately 300 meters downstream.
- Installation of new L3-L4 controls in the warm beamline section of the linac.
- Controls for 23 new CMs in L4 and a new distribution box for L4.
- Reconfigure LCLS-II Sector 7-10 (gallery racks, cables, and trays).
- Add controls for nine new SXR undulators with phase shifters. Retrofit and retune 21 existing SXR undulators with longer period and add additional encoders.
- Modify LCLS-II Beam Containment System (BCS) for increased e-beam power.
- Extend ODH in Sector 7-10.
- Extend MPS to support all new/relocated devices and new injector.
- Reconfigure Sector 7-10 Personal Protection System (PPS) to support L4 RF and additional areas of refuges
- Upgrades HXR instruments and x-ray transport controls to support high-rate operations.
- LCLS-II Sectors 7-10 warm beam line racks configuration to be transformed to typical RF support configuration. This requires demolition of some LCLS-II racks and trays in gallery and tunnel.

The controls groups are in the process of identify additional resources that can execute HE without disruptions. The groups is working on establishing Service Level Agreements with resource organizations and are holding regular meetings with resource managers.

The LEI CM 00 helium distribution will be supplied by a new vendor supplied cryoplant. The total Controls' cost for LEI is $17 million, with design maturity on track to be 85% by fourth quarter FY 2023.

Controls Current Design Maturity:

- RF and Power Systems (WBS 1.05.02) 50%
- High Performance Systems (WBS 1.05.03) 50%
- Industrial and Infrastructure Systems (WBS 1.05.04) 50%
- Safety Systems (WBS 1.05.05) 40%
- Rack and Cable Plan (WBS 1.05.06) 50%
- Experimental System (WBS 1.05.07) 50%

2.7.2 Comments

Approximately $17 million of Controls cost was added for the LEI, scaled from LCLS-II actual costs, which may be considerably higher, particularly since some of the procurement costs used were pre-COVID-19 and pre-inflation.

The Committee was pleased to see the Controls team utilizing a re-use design review path where relevant. This should streamline some of the design review process by reducing the number of reviews and by re-using applicable analyses and component validations.

The LEI Controls effort is distributed across multiple WBS areas, potentially making it more difficult to accurately track progress of the LEI Controls. The Controls team should consider organizing the schedule for the LEI controls activities in a sequence that shows a singular completion for the LEI Controls effort.

Many of the team members have multiple assignments with presumably various priorities and schedules. It is desirable to have, where possible, dedicated resources with minimal potentially-conflicting responsibilities.

Electrical equipment must meet SLAC's Electrical Equipment Inspection Program (EEIP) requirements to be allowed to be energized at SLAC. The equipment must be Nationally Recognized Testing Laboratory (NRTL) listed or inspected to comply with SLAC policy. SLAC requirements should be made known to other providers at the start of the partnership. Electrical equipment provided by others, for example MSU, should be inspected while the equipment is at the Michigan State University (MSU) facility so that any corrective action can be taken before arrival at SLAC. Early interactions with the MSU team can prevent unpleasant surprises after equipment is delivered (see Recommendation #3).

Some skillsets are understood in the shop codes captured in P6, and others are captured by naming specific people. Subsystem leads, resource managers, and the project team work together to identify resources. The project team should consider breaking out critical non-generic skillsets such as field programmable gate array (FPGA) programmers separately.

The project, where possible, should use the same control hardware in the LEI cryoplant and the main cryoplants. The LEI plant will be procured as a turn-key system, including controls hardware. This method of procurement may reduce cost; however; it may add complexity in integration of non-standard controls hardware.

The LEI cryoplant spares should be determined in collaboration with the main cryo group, maximizing sharing of items where possible.

Use of the same installation and verification procedures for the LEI cryo transfer lines as for the others should be strongly considered if not already planned.

The Committee did not get detailed information regarding responsibility for installation and commissioning of the LEI cryoplant. Assigning some form of oversight responsibility to the main cryo group for the LEI plant would add a level of comfort.

Operations funds will be used to procure spares when operational funds become available, and the project will include yield in the procurement of materials that could eventually become spares. Creation of a list of critical spares not in the "yield" category seems essential for one-of-a-kind components such as the gun, if that has not already been done.

The MOU between LCLS-II-HE and SLAC pre-dates the LEI and the partnership with MSU. It needs to be updated.

The project and SLAC should create and maintain a joint "gap" list to catch items and tasks that are needed but not in scope anywhere.

Long-lead procurements are used to reduce risk, something that seems particularly relevant now. The SSA amplifiers, FPGAs, carrier cards, LLRF chassis, motion-control chassis and motors are all being considered as long lead procurements. The project team should continue to add necessary items to the long lead procurements list.

The 6kW dump and rastering magnet is not fully designed yet, but the Committee understood that these are not needed to demonstrate threshold KPPs. Design should continue to ensure these are ready on time.

Personnel turnover and low morale of safety systems staff supporting LCLS-II were identified as a lessons learned, which SLAC has since taken serious steps to address. SLAC and LCLS management should continue their efforts to mitigate stress and ensure a healthy workforce to support the LCLS-II-HE project. Management should also determine how best to assess the progress of this effort.

2.7.3 Recommendations

12. Prior to the next DOE/SC review, clarify, optimize, and communicate the electrical inspection process for electrical equipment that is provided by other institutions.

13. Prior to the next DOE/SC review, define with more granularity the logic links and milestones in the P6 schedule between controls activities and mechanical activities.

14. Prior to the next DOE/SC review, update the MOU to reflect the current scope of the project.

15. Prior to the CD-2 review, ensure a dedicated Controls person is assigned to the SLAC team responsible for procuring and commissioning the LEI cryoplant.

2.8 Infrastructure Systems

2.8.1 Findings

Infrastructure Systems (WBS 1.06) scope includes the following:

- Linac and Photon Infrastructure (LPI; WBS1.06.02)
- Low Emittance Injector Tunnel (LEIT; WBS1.06.03)
- Experimental Infrastructure (EI; WBS1.06.04)

The current Estimate at Completion (EAC) for infrastructure is $60.180 million, an increase from $48.9 million at the December 2020 review. The architect/engineer (A/E) cost estimates will be received at major design milestones (30%, 60%, 90%, etc.) and then reconciled with an independent cost estimating firm. EACs for the various WBS elements are LPI at $24.1 million, LEIT at $29.7 million, and EI at $3.2 million.

Infrastructure systems is currently in the design phase and is planned to be about 95% design at CD-2/3.

Gordon Prill, the A/E for the LPI, has been contracted and submitted the 30% Design Report in December 2021. It has been reviewed internally including by the SLAC Building Inspection Office (BIO). The A/E's 30% cost estimate is undergoing review and reconciliation by an Independent Cost Estimating firm (TBD).

Current LPI design progress was reported to be 37% complete (based on cost-to-date and progress against contract schedule of values). The 60% design submittal is planned to be received in April 2022, and the 90% design submittal in August 2022. The 100% design submittal/construction documents are expected in November 2022.

Mott MacDonald, the A/E for the LEIT design, was contracted in February 2022 and was reported to be at about 19% complete, also based on cost-to-date. The 30% design is due in May 2022, 60% in September 2022, the 90% in January 2023, and 100% in April 2023.

Overall design completion for installation systems was stated at 25% complete (December 2021).

A geotechnical study was completed in May 2021 by Rutherford + Chekene to aid in down-selection to the final tunnel configuration. Additional geotechnical analysis is in progress.

Option 2 for the tunnel design approach was stated during the review as the preferred approach at this time; however, Option 4 is also stated as still under consideration. The final location decision is planned to be made at the 30% design milestone.

Injector tunnel construction was previously planned to coincide with downtime for the LCLS-II from third quarter FY 2025 through second quarter FY 2026. The long downtime is now planned for mid FY 2026 (April) through mid FY 2027 (March) due to the delays experienced since the December 2020 review.

A MOU (LCLS-II-HE-1.1-M-0296 Rev. 0) was approved and released on July 8, 2021. This MOUs purpose is to describe, in sufficient detail, the project's requirements for the use of SLAC resources and/or existing facilities, or any modifications to existing infrastructure to ensure the successful delivery of the project. This includes: 1) equipment removal/disposal, 2) storage facilities, and 3) infrastructure upgrades.

An important off-project scope of work, the Critical Utilities and Infrastructure Revitalization (CUIR) project, received CD-1 in January 2022. This project scope includes the K5B Substation Installation, which is a critical interface with the LCLS-II-HE project.

BIM is planned for the major infrastructure work to avoid interferences, using existing SLAC data and incorporating new design information and is a best practice.

2.8.2 Comments

Adequate resources to perform the work according to the project's schedule is a critical need, and the project has responded by recently bringing on two additional CAMs, one for the LEIT scope and one for the EI scope. A Service Level Agreement with SLAC Facilities and Operations for matrixed support has also been drafted and recently approved.

Tunnel location and construction method decisions are upcoming and will be supported by the additional workshops and the 30% design. All risks need to be thoroughly analyzed and not over simplified. The final tunnel location may not be the simplest or least costly from a conventional facilities perspective, but the balancing of scientific requirements with tunnel construction is key.

A communications strategy and plan for new tunnel construction is planned and will be very important for working with stakeholders including non-SLAC neighbors.

Room Data Sheets (a total of 12) have been completed and approved for the x-ray tunnel, undulator hall, cryomodule storage room, various hutches, FEH laser room, injector tunnel and others. An additional Room Data Sheet is anticipated for the new cryoplant. It is very important that this information is kept up to date and under change control and having a technical review board to vet and approve changes to those requirements is noteworthy and a great lessons learned from LCLS-II.

Work during the long downtime is a schedule risk area and planning to maximize the amount of work that can be accomplished during the long downtime is underway. In addition, as much work as possible is being moved to short downtimes that are scheduled in FY 2024 and FY 2025, as well as work that can be potentially accomplished when the beamline is operating.

Coordination with the MEC-U project could also be beneficial. A high-level coordination schedule was discussed that includes LCLS operations, the MEC-U project, the CUIR project and SLAC activities, and quarterly stakeholder review meetings are planned. This effort will definitely aid in coordinating HE activities with these external projects and operations.

Leveraging experience and lessons learned from LCLS-II is a best practice, and the project team continues to leverage those lessons learned. In addition, many of the team members are veterans of LCLS-II, which provides a sound experience base.

Continuing to engage stakeholders including Facilities and Operations (F&O) in design reviews and owner, architect, contractor (OAC) meetings will greatly aid in transition-to-operations planning and execution and minimize surprises.

The project team and the SLAC F&O Director (who is also the CUIR project director) provided a good discussion of interface/dependency projects between SLAC and the LCLS-II-HE project, including the K5B substation, the CUIR project, and LCLS-II-HE CM storage.

The MOU LCLS-II-HE-1.1-M-0296, approved and released on July 8, 2021, will be annually reviewed and signed. With the large amount of interdependency between projects, this is a critical item that the project team is encouraged to continually review and communicate.

Additional detail needs to be added to the schedule as design matures, specifically for the short downtime and long downtime construction periods. The upcoming hiring of a Construction Manager firm should be very beneficial and their knowledge and expertise will be critical to establishing feasible construction sequencing, logistics, and durations.

Risks discussed included the following moderate ranked risks: K5B substation, Bay Area construction market, and unreliable power infrastructure. The risks for the Low Emittance Injector Tunnel were only ranked as low, and the Committee suggested a close examination of risks for that scope as the project progresses.

2.8.3 Recommendations

16. Finalize the tunnel location and construction approach by the 30% design milestone, and then continue to analyze tunnel construction costs, schedule duration and risks, prior to CD-2/3.

17. Continue to analyze the planning for the various scopes of work and look for opportunities to improve the schedule, by taking advantage of advance procurement of equipment, short downtimes, as well as when the beam is in operation, finalizing those plans and schedule prior to CD-2/3.

18. Continue to reevaluate the risks of each scope of work, specifically the tunneling scope and dependency on off-project work, updating the Risk Register accordingly prior to CD-2/3.

2.9 Injector Systems

The decision to include an ultralow emittance injector installed in a secondary injection line in the project baseline is on solid footing. The design process is well underway and computer modeling shows that the performance goals necessary to achieve the 20 keV photon energy range are achievable. The design should be sufficiently developed for the planned CD-2/3 in FY 2023. Collaborations with other national laboratories have brought to bear significant expertise in critical areas. Of special note is the addition of the Facility for Rare Isotope Beams (FRIB) superconducting RF team, which offers significant expertise in quarter-wave superconducting RF structures, key to development of the electron gun. The use of an ultralow emittance injector is by far the most cost effective way to extend the photon energy reach of the LCLS-II-HE to the 20 keV photon energy range.

The development of a superconducting RF injector is not without risk, especially considering that the project requirements significantly extend the state-of-the-art of this technology. However, modeling suggests that there is a larger safety margin with the addition of the so-called "complex" transport line, which eases the requirement to achieve 30 MV/m field on the cathode. Of course, the primary issue remains the cathode assembly (load lock, stalk, and cathode proper). The project team and especially the FRIB collaboration are encouraged to continue to involve experts in superconducting RF electron guns and cathode assemblies such as Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in the ongoing development.

2.9.1 Findings

The scientific case for 20 keV photons is clear, and the only cost-effective way to achieve this performance is the addition of an ultralow emittance injector, with a normalized emittance of 0.1 microns at 100 pC bunch current. Given space limitations for added CMs, higher beam energy is not a viable alternative.

The design and performance specifications of the proposed superconducting RF gun injector fully supports the project's objective KPP and ultimate performance. The maturing design, together with extensive modeling, justify the decision to move forward with the superconducting RF option.

Achieving technical progress leading to production of the SRF gun injection system is based on establishing strong inter-laboratory collaborations (FRIB, Argonne National Laboratory (ANL), and HZDR). This process is converging with solid communication and management links among the parties.

Extensive preliminary design and beam dynamics studies of the superconducting RF gun injector have identified a new "complex" injector configuration that appears to ease requirements on the superconducting RF gun, including achievable gradient and mean transverse energy at the cathode.

Photocathode development is leveraged with ongoing LCLS-II efforts, and there are well established channels to access information and results effectively.

Cathode and beam tests of the electron gun are being planned to allow confirmation of crucial performance goals before installation of the full injector tunnel, acceleration, and transport beamline. A Baseline Change Request (BCR) is to be submitted shortly for $4-8 million.

2.9.2 Comments

The secondary injection tunnel is a large investment, but well justified as it eliminates single point failure and allows parallel high brightness source development. Clearly, further work is necessary to fix the design, location, and cost, but in no case should the secondary injector be a candidate for descoping of the overall project.

Given the recent start of the superconducting RF injector project, the Committee was strongly impressed by how far along the technical work on the gun has moved forward. There has been extensive modeling with state-of-the-art simulations with considerable effort using optimization techniques. The cavity shape has been modified to reduce peak surface fields and to limit multi-pacting. Design efforts are proceeding nicely on the doublet-winding solenoid, CM, and cryoplant. Magnets, beam diagnostic, vacuum hardware, controls, safety systems, and many other subsystems will be using existing SLAC and LCLS-II designs and will have similar Experimental Physics and Industrial Control System (EPICS) interfaces to what is in use.

The project team is commended for planning a well-defined sequence of separate testing of the cathode stalk, "dummy" cavity, and full gun, which will allow addressing separately the issues in design and fabrication. Maximizing the testing that can be done before finalization of the production gun design is very important. Given that the superconducting RF gun will certainly expand the state-of-the-art, it is crucial that testing of each subsystem be performed as soon as possible.

FRIB is doing remarkable work in leading the gun cavity design, which has progressed quite well and at a fast pace since the contract was awarded. Given the importance and relevance of the experimental tasks assigned to ANL for the test at cryogenic temperatures and to HZDR for designing the photocathode stalk and the photocathode system, it would have been nice to have them involved into the presentation and discussion to hear more details on the planned activities, on the rationale behind the technical choices, and on the anticipated challenges.

The superconducting RF gun planned for the LCLS-II-HE project will push the state-of-the-art by operating in an unprecedented parameter regime in terms of gun gradient and photocathode performances, such as quantum efficiency and thermal emittance. Even though lots of progress has been made in the last two decades, no existing superconducting RF gun has demonstrated gradients of 30 MV/m when operating with high QE cathodes. For this reason, it will be extremely important to plan and carry-out a full beam test even before the injector tunnel is ready. While some photocathode down-selection can take place before the gun is ready, testing the photocathode in the LCLS-II-HE operating regime can only be done once the gun being fabricated by FRIB is available. At that point, only a relatively modest investment will be needed in order to measure key parameters like QE and thermal emittance. This will allow answering critical questions such as cathode lifetime and long-time cathode-cavity compatibility, which would otherwise remain unaddressed in the current development plans.

The results from numerical simulation on the performances of the "complex" beamline appear to offer a scenario with increased safety margins should the gradient of the gun not reach the 30 MV/m due to the presence of the photocathode stalk, field emission, or incompatibility with photocathode material. This solution offers further knobs for the optimization of the design for a minimal increase in the injector design complexity.

The observed leveling of the emittance performance between 20 MV/m and 30 MV/m in simulations deserves further investigation. Theoretical scaling suggests that additional optimization at 30 MV/m might yield even better results. Earlier studies had shown the 30 MV/m gradients offered upward of a factor of two improvement in normalized emittance, and it would be prudent to have a firm qualitative understanding of what parameter changes led to the softening of the impact of the higher gradient. For example, it is noted that the 2 MeV output energy of the current gun design was reduced from the WiFEL gun 3 MeV. Is the assumed that multi-turn extraction (MTE) used in the numerical studies reasonable since it becomes dominant at 30 MV/m as opposed to space charge, which the "complex" beamline controls in the 20 MV/m case.

The current plan to bring the beam from the secondary injection tunnel to the main linac is to use a dog-leg beamline after the CM at ~100 MeV beam energy. This section contains dipoles and quadrupoles, and it might be interesting to include it in the optimization loop as it could easily be used to help compressing the beam and ease some of the requirements on the injector. The Committee strongly encouraged the project team to look at this option using the numerical tools already developed by the injector group, as it might offer another opportunity for risk reduction in the design.

Most of the semiconductor photocathodes share similarities in how the MTE depends on the excess energy with respect to the emission threshold, and similar properties on electron beams can be obtained with a proper tune of laser drive wavelength. The choice of S-20 photocathode, while well justified based on reported experimental data, appears for now premature as the reported characterizations were performed at one order of magnitude lower gradient. The S-20 photocathode is designed to be capable of emission at longer wavelengths and has a reduced work function if compared to other alkali antimonides. Field emission properties at the highest gradient could represent an issue and should be considered as well. The design of a dedicated growth chamber should start as soon as a preliminary design of the cathode plug is available. The time required to develop a particle-free photocathode growth chamber and delivery system should not be underestimated.

At the Photocathode Physics for Photoinjector workshop held in November at SLAC, DESY Photo Injector Test Facility at Zeuthen (PITZ) presented the first results of the tests of the alkali antimonide cathodes grown at INFN-MI in the L-band XFEL injector. The gradient in this gun can reach up to 45 MV/m, but at these field levels unacceptable amounts of dark current were observed when the new cathode plugs were used. To give a useful comparison, the dark current was found to be orders of magnitude larger than CsTe at similar gradients. While these results are still preliminary, they are worrisome and should be considered during the team discussions. Dark current mitigation strategies using apertures or even deflectors should be investigated to limit the impact of this issue in LCLS-II-HE.

As the transverse emittance from the injector improves, the spot size during transport decreases. This causes higher beam densities in the beamline and correspondingly increased intra-beam scattering at the level to make an impact in the final FEL performances according to existing models. The Committee noted here that these models have been benchmarked in storage rings, but not in high brightness FEL beamlines. This is mainly due to the challenges associated with measuring IBS contributions to the energy spread. Still, this suggests that a dedicated plan to measure this contribution and benchmark the models would be extremely useful. This could be performed in-house or by leveraging existing collaborations with interested parties.

The design of the superconducting RF injector system is moving along well. Since it is early in its development, one cannot expect the maturity offered by other subsystems. It is expected that the design will be sufficient for CD-2/3 as planned based on the rate of progress demonstrated in developing the superconducting RF injector concept to date. In particular, the design and specification of the gun has rapidly progressed thanks to the newly formed collaboration with FRIB, which brings strong technical expertise in superconducting RF quarter-wave cavity development. The LCLS-II-HE injector team has addressed well the issues presented by the Committee during the December 2020 review.

2.9.3 Recommendations

19. Pursue full beam tests of the superconducting RF gun before the injector tunnel is completed.

20. Strengthen and formalize plans for the cathode production system in close collaboration with SLAC and LCLS-II programs by the next DOE/SC review.

21. Improve understanding of the limits and tradeoffs in the beam dynamics in the new "complex" injector program for the full-range gun performances (e.g., gradient, MTE) by the next DOE/SC review.

3. ENVIRONMENT, SAFETY and HEALTH

3.1 Findings

The project is in the process of hiring a full-time ESH Manager to support the project team. The ESH and QA Managers are incorporated into the systems engineering design review process. In addition, the ESH and QA managers are members of the risk management and the technical change control boards.

The Project Preliminary Hazard Analysis Report (PHAR) is in the process of being updated to reflect the hazards associated with the construction of the tunnel and low emittance injector. A draft Supplemental Analysis (SA) to the LCLS-II Environmental Assessment addressing new injector tunnel has been reviewed by SLAC subject matter experts and DOE/Stanford Site Office (SSO). A LCLS-II-HE Memorandum of Agreement (MOA) is in place between SLAC and their four partner laboratories.

The project is planning to implement the SLAC Human Performance Improvement (HPI) training program for the construction and installation phases of work activities. As part of the LCLS-II-HE Work Planning and Controls (WPC) program, the project developed an enhanced work planning process that was utilized to coordinate the handling of the first CM delivery.

The QA team is focusing on design development for CD-2/3 scope and production oversight for CD-3A scope. LCLS-II-HE QA has a non-conformance/action item dashboard that is reviewed with the management team monthly. The Project and Partner Laboratory Quality Assurance representatives (SLAC, FNAL, TJNAF) meet on a monthly basis—and the QA Manager is currently working with LBNL and FRIB to incorporate them into the project team.

A comprehensive radiation protection design, including shielding, PPS, BCS, and monitoring has been developed and documented. The PPS and ODH systems are extensions of existing LCLS-II systems. The systems for rastering on the dumps are the only completely new component.

The systems engineering design review process is maturing with 43 design reviews in 2021 and 106 design reviews scheduled for 2022. The Visure requirements management system is used to capture, organize, analyze, and track all LCLS-II-HE project technical requirements.

All partner laboratories are operating under local COVID-19 protocols and have experienced minor impacts to HE activities.

3.2 Comments

The project has experienced ESH and QA Managers. The ESH Manager is interim and part time. The project needs an experienced full-time ESH Manager. This position should part of the project's senior management team and not matrixed through a support organization. The ESH and QA Manager's participation in the system engineering design review process provides direct ESH and QA input, as well as, assisting in the ESH/QA integration process.

All required DOE Order 413.3B document requirements are identified and in place. The current PHAR does not include the hazards and mitigations relating to a pandemic hazard along with addressing tunnel construction and the LEI. The project preliminary ODH analysis has been completed; however, there is a need to add the analysis for the LEIT once the operating parameters have been finalized.

The project is well positioned to implement the enhanced SLAC WPC and HPI programs. There is a clear commitment to emphasize and apply lessons learned within the project team.

The project's MOU details safety expectations; however, the QA expectations are not addressed within the document. The multi-laboratory coordination and communication challenges are acknowledged, and the project understands the importance of communication, which was stressed consistently through the project team's presentations.

COVID-19 has been well managed by the project, as well as, at the partner laboratories; however, COVID-19 travel restriction severely impacted the ability for project QA to provide oversight to partner laboratories and at vendor sites.

The radiation protection systems analysis is progressing well, and needs are identified. The design is in process with no significant challenges identified. The project should consider use of external review for the LEIT enclosure.

Additional formality to the safety system development is a needed and positive improvement.

There are many design reviews planned over the next two years. Attention needs to be given so as not to lose quality in the performance of those reviews.

3.3 Recommendations

22. Hire a dedicated LCLS-II-HE ESH Manager, as early as possible. Near-term, evaluate the possibility of utilizing interim ESH management support through a consultant.

23. Complete the update to the Preliminary Hazard Analysis Report by June 2022.

4. COST and SCHEDULE

4.1 Findings

PROJECT STATUS January 2022		
Project Type	Line Item	
CD-1	Planned: 4Q FY 2019	Actual: 09/21/18
CD-3A	Planned: Feb 2020	Actual: 05/12/20
CD-2/3	Planned: 4Q FY 2023	Actual:
CD-4	Planned: June 2031	Actual:
TPC Percent Complete	Planned: 20%	Actual: 18%
TPC Cost to Date	$101M	
TPC Committed to Date (Actuals + Commits)	$119M	
TPC	$710M	
TEC	$678M	
Contingency Cost (w/Mgmt Reserve)	$97M*	19% to go*
Contingency Schedule on CD-4	22 months	24%
CPI Cumulative (LLP)	1.05	
SPI Cumulative (LLP)	0.91	

The current TPC for the point estimate is $710 million, derived from an EAC of $613 million and inclusive of $35 million worth of pending BCRs. The remaining contingency is $97 million, which is 19% on work remaining. Work complete on the current point estimate is 18% of the EAC. The pending BCR Log value totals $45.9 million, with $35 million approved for inclusion in the EAC value. The largest item is the Level of Effort (LOE) BCR which totals $29 million.

The current Critical Decision schedule is to hold a CD-2/3 in fourth quarter FY 2023 with a 12-month long downtime to begin third quarter FY 2026 and CD-4 scheduled for third quarter FY 2031 with approximately 22 months of remaining float.

All procurements are awarded for the CD-3A long lead procurement scope with eight of the 20 long lead procurements completed, which is about 52% complete. The remaining contingency for the CD-3A scope is 45%. The schedule performance for the long lead procurement items as of January 31, 2022, is SPI=0.87 (variance primarily due to FNAL/TJNAF vendor delays) and the cost performance CPI=1.09 (most of the variance due to lower than planned travel and management costs). COVID-19 delays resulted in late cavity deliveries, which will impact CM installation (on critical path). The project is proposing a $80.6 million CD-3B long lead procurement package with a Level-1 approval milestone in December 2022.

As requested by DOE/BES the project added additional scope including three additional CMs, a new injector, and five fully upgraded end stations in 2020. This additional scope increased the project TPC by $232 million (for a total of $660 million) in 2020.

Due to inflation uncertainty and COVID-19 impacts, the proposed TPC has increased to $710 million, just below the 150% upper limit ($720 million) of the high end of the CD-1 cost range of $290 million to $480 million. The current BAC/EAC being proposed is planned to the objective KPPs.

The project presented two options to DOE/BES to address the low contingency amount to either: 1) defer $80 million of instrument scope to alternative funding sources, or 2) increase TPC to approximately $850 million to maintain full scope. DOE/BES's chose the first option to defer $80 million of instrument scope. Per DOE/BES direction, the project developed a detailed deferral list to increase contingency by $80 million.

The current project cost estimates have approximately 15% factor applied related to design maturity and judgement factor totaling $86 million. The BOE assessment for the project indicated 64% of the estimates were based on engineering judgement estimates.

The cost contingency assessment of risk impacts and estimate uncertainty together indicates a greater than 40% need but only 19% of work to go cost contingency is currently available. Cost contingency assessment based on Monte Carlo analysis of the risks and an estimate uncertainty contingency need totals $228.5 million; with existing available contingency of $97 million, there is a shortfall of $131 million.

Additional cost drivers include COVID-19 delays, supply chain issues, and increased escalation above the SLAC Chief Financial Officer provided 3%. Since 2021, vendor quotes averaged 26% higher than LCLS-II actuals.

The project modeled increased inflation by varying the calculated escalation rates in COBRA assuming FY 2023 and FY 2024 were increased to 7% and FY 2025 and beyond escalation was increased to 4%. The cost impact of this increase is $60 million for the full project. Until the project receives updated escalation rates from SLAC, this risk has been added to registry. The risk has a $60 million likely impact with 85% probability. There was an increase in active risks from $37 million to $126 million due to scope additions, maturing design and cost estimates, and COVID-19 impacts. The Risk Board meets monthly and the risks are updated bi-weekly.

LCLS-II installation schedule delays have limited the availability of engineering personnel for HE, which has extended the CD-2/3 readiness for LCLS-II-HE by one year. The schedule has two critical paths, one through the accelerator installation and commissioning and the second through the injector tunnel construction, installation, and commissioning. With the decision to descope instruments (specifically in the end hall), changes in the MEC-U project schedule will no longer impact LCLS-II-HE. The long downtime for LCLS-II in FY 2026/FY 2027 is a key driver in overall project schedule. COVID-19, off-project dependencies, installation, and staffing shortages risks are 69% of the total risk impact.

Vendor supply chain and shipping delays, plant shutdowns, and travel restrictions that limit the ability to address quality issues are cost drivers in the increased TPC. Mitigation has been defined through increased onsite presence, negotiated cost sharing, and contract incentives (both quality and schedule).

4.2 Comments

The Integrated Project Team (IPT) should closely monitor the cost/schedule performance to stay under the $720 million triggers for a CD-1 Refresh as the current plan is optimistic as noted below.

The Committee analyzed the TPC taking into account the numbers provided by the project. It appears the total TPC is closer to $761 million even with the $80 million deferred scope decision. The project has determined the current project EAC is at $613 million with all pending BCR, which total $35 million. With the reduced scope of $80 million and the additional of risk impact of $142 million and $86 million for estimate uncertainty, the TPC is $761 million. The project is hoping to stay within the $710 million TPC resulting in a deficit of $51 million (see below):

- EAC with pending BCRs of $35 million ($613 million)
- Less deferred scope ($80 million)
- EAC/baseline ($533 million)
- Add risk impact at 85% confidence ($142 million)
- Add estimate uncertainty impacts ($86 million)
- TPC total ($761 million)
- TPC goal ($710 million)
- TPC delta to goal ($51 million)

The project identified two opportunities to reduce costs to stay within the $710 million goal, described below:

- $27 million reductions in risk/estimate uncertainty (33% of $80 million) and
- $13-25 million opportunities to advance schedule, assumes CD-3B is authorized.

The project has presented a definitive list of the scope elements by WBS that are included in the $80 million deferral list, to be presented to the program and required to maintain the TPC. The project has a prioritized scope contingency list that will contribute to maintaining desired levels of contingency. The project identified other opportunities to support the $710 million TPC including advancing the schedule with a CD-3B long lead procurement package. While this effort is commendable, it is still unclear if it will be successful and seems optimistic in the Committee's view.

The risk of increased escalation over the SLAC Chief Financial Officer guidance of 3% should be incorporated into the baseline due to the 85% probability that it will occur. The escalation rate assumptions in the what-if analysis may be somewhat conservative for the regional area and their experience with recent quotes (some 26% higher than previous experience).

After the decision to descope instruments ($80 million) and considering the increased risk of higher-than-expected escalation (which could still increase beyond 7% in the first two years and 4% for the remainder is captured in Risk Register), options to increase contingency in the future are limited to scope contingency (category 2 and especially category 3 = $53 million), which could have an additional impact to the preliminary KPPs.

The project stated they are "resource limited", which implies staffing delays and concerns regarding maintaining project schedule. They are planning to have Level 2 managers dedicated by April, which indicates effort to address this staffing issue.

The project appears to be actively assessing how lessons learned from LCLS-II can be incorporated into the LCLS-II-HE project. An example provided is the need for the project team to have increased collaboration with internal (SLAC) stakeholders, which indicates a healthy "learning" mindset. The project is making good use of procurement information from LCLS-II, e.g., using actual cost values for their estimates with scaling factors applied.

The project schedule appears to be well developed, incorporating the long downtime, and off-project dependencies with the intent to maximize the opportunity for early science. Fuse analysis indicated a generally healthy schedule.

The WBS drilldown exercise revealed the following:

- Most estimates are in a stage of being refreshed from the CD-1 and/or original state. Quotes were older and some estimates were based on older estimates from other projects, e.g., LCLS-II (2018) and then escalated to 2021.
- LCLS-II actuals or lessons learned were observed informing both the refinement of the cost and identifying gaps missed in the initial cost estimate.
- Escalation followed the 3%/year guidance provided by SLAC in the samples reviewed.
- In the WBS 1.06.02 drilldown, the Committee was pleased to see comprehensive and high-quality BOEs. The construction estimate is in the process of being reconciled with both an A/E and Independent Cost Estimates (ICE) estimates at the 30% design stage.
- In WBS 1.05.02, gaps in the CD-1 estimate have been filled from lessons learned on LCLS-II-HE. One example is the addition of approximately 26,000 hours for SLAC technicians to re-do cable work not performed correctly on the LCLS-II. project. Unfortunately, this was considered a gap and not an offset to contractor pricing.
- WBS 1.02.02.10 drilldown indicated that much of the cost breakdown was from CD-1 and has not been fully refreshed to date (as would be expected at this stage of the project). The CAM addressed the delta in a "what-if" file that is intended to add to the "pending list" for the baseline. However, deriving an accurate confidence level seems difficult until the estimate has been fully refreshed. This could be an indicator that required contingency is still somewhat uncertain and is dependent on how representative this example is throughout the entire project estimate.

The ongoing refresh of the estimate is expected for this stage of the project but could impact the confidence level in the total cost. Supply chain issues and escalation are being addressed as a risk that adds $60 million at an 85% probability but determining the right uncertainty and escalation rates for this risk is a challenge for the project to support the development of an accurate cost estimate.

BOE categories indicate 64% of the estimates are a type of engineering judgement, 23% are existing liens and cataloged items, and 13% is undetermined. Based on this, the design maturity and judgement factors being applied to calculate the uncertainty estimate seem understated for the project and should be reviewed and reconciled.

The judgement factors and design maturity assessments are only being used for cost estimate uncertainty leaving a gap in assessment of schedule uncertainty, e.g., duration validity. The project team should evaluate risk and estimate uncertainty similarly and consider adding an assessment of schedule estimate uncertainty as part of the overall project risk/estimate uncertainty analysis.

The risk program is systematic with robust procedures and appears to be part of the project culture. However, the Committee judged that improvements can be made on the analysis related to the inclusion of schedule estimate uncertainty.

The project team should consider preparing an assessment of project progress on developing the CD-2 baseline against the Government Accounting Office (GAO) cost and schedule checklist, this is critical for a successful ICE review.

4.3 Recommendations

24. By the end of the fiscal year, conduct a full refresh estimate of the project to validate the current cost/schedule estimates to ensure they are updated, current, traceable, and accurately reflect EAC/baseline. Ensure available contingency is sufficient to address risks impacts, cost, and schedule estimate uncertainty within the planned TPC.

25. After completing the first recommendation, schedule a cost and schedule estimate review including the project's assessment against the GAO checklist for cost/schedule.

26. Before CD-2/3, revise KPPs to reflect the decision to defer instrument scope and other scope refinements.

5. PROJECT MANAGEMENT

5.1 Findings

Since the December 2020 review, the project has proposed a combined CD-2/3 in August 2023. Under the current schedule, the linac would resume operations in January 2028, with an early finish in August 2029, and a CD-4 in June 2031.

The project developed and matured processes around QA, and risk and systems engineering that were described in some detail during the review. Currently the project shows 198 active risks valued at $142 million, up from 149 active risks valued at $37 million at the December 2020 review, with the most significant new risk being (COVID-19 Excessive Annual Inflation) for COVID-19 driven inflation exposure. The total value of the rolled-up risks attributed to COVID-19, including inflation is approximately $63 million.

In the domain of systems engineering and design basis documents, 2,204, of an anticipated 4,000-5,000 technical requirements have been captured, and 43 design reviews of the approximately 200 needed for CD-2/3 have been completed. The project stated that the design is approximately 61% complete and that the target completion for baseline is 85%.

LCLS-II-HE has a number of significant external activities upon which it depends. These include LCLS and LCLS-II operations, and the MEC-U and CUIR projects. One component of CUIR is to provide power for the new linac equipment. These dependencies are captured in the SLAC MOU with the project.

A deputy director role has been established to manage dependencies external to the project and a standalone high-level schedule was created to manage the external dependencies of ongoing efforts at SLAC.

5.2 Comments

The proposed combined CD-2/3 approach is reasonable, and facilitates acceleration of time critical elements, as well as delaying baselining during the present uncertain economic period. The project should prioritize design efforts on elements that have the largest technical and cost risks.

The project is nominally at 61% design complete based on the dollar weighted value of completed design work. But this is heavily weighted by the CMs, which have a large dollar value and were highly evolved at the start of the HE project.

The sum of the forecast cost exposures (including design uncertainty and risk) may exceed the proposed TPC, which is a cause for concern.

The project developed a number of robust management systems including the QA and continued improvement and use of the risk management process. Project risks, including COVID-19 and supply chain disruptions are being appropriately identified and managed.

A well planned, rigorous systems engineering process was presented. There is a substantial body of work to be accomplished to prepare for CD-2/3. The project is encouraged to prioritize the systems engineering effort to match the needs of a successful CD-2/3.

The Committee judged that the project has the necessary resources and support from SLAC and the partner laboratories to deliver the project, but that care will be needed to assure they are available when needed. Kudos to the project for its extensive mining and use of lessons learned from LCLS-II and HE itself.

LCLS-II-HE is dependent on other projects and SLAC funded activities (LCLS operations, LCLS-II commissioning, MEC-U, CUIR, etc.). The project has been diligent in identifying and tracking off-project activities that could negatively impact the project if not completed on schedule. Those activities controlled by SLAC are captured in an MOU with the project. This document needs to be updated in preparation for CD-2/3. These revisions could include not only what the HE project expects from these other activities, but what these activities expect as interfaces from the HE project (i.e., ensure a two-way MOU).

Overall, the Committee judged the project is being planned, staffed, and managed to successfully deliver the scope and KPPs within the preliminary cost and schedule, but that adjustments will be needed to stay within the project TPC ceiling.

5.3 Recommendations

27. By the end of the fiscal year, the project should revise the resource loaded schedule that reflects the revised scope and schedule for the project.

28. Within four months, the project should revise and update the SLAC MOU (LCLS-II-HE-1.1-PM-0296) for capturing external project dependencies.

29. After completing recommendation 27, conduct a cost/schedule focused status review.

Appendix A Charge Memo

Department of Energy
Office of Science
Washington, DC 20585

February 3, 2022

MEMORANDUM FOR: KURT W. FISHER
DIRECTOR, OFFICE OF PROJECT ASSESSMENT
OFFICE OF SCIENCE

FROM: LINDA L. HORTON Linda L Horton
ASSOCIATE DIRECTOR OF SCIENCE
FOR BASIC ENERGY SCIENCES
OFFICE OF SCIENCE

Digitally signed by Linda L Horton
Date: 2022.02.03 11:50:18 -05'00'

SUBJECT: DEPARTMENT OF ENERGY (DOE) REVIEW OF THE LINAC COHERENT LIGHT SOURCE II HIGH ENERGY (LCLS-II-HE) PROJECT

With this memo, the Office of Basic Energy Sciences (BES) requests that your office organize and conduct an Independent Project Review (IPR) of the LCLS-II-HE project at SLAC National Accelerator Laboratory on March 22-25, 2022, by videoconference. The purpose of the review is to assess the project's overall status and progress. The review should address the progress of long lead procurements (LLPs) and determine if the project is appropriately progressing toward a possible combined Critical Decision-2 (CD-2), *Approve Performance Baseline*, and CD-3, *Approve Start of Construction*, as early as 4Q FY 2023.

The LCLS-II-HE project received CD-1, *Approve Alternative Selection and Cost Range*, on September 21, 2018, establishing a revised cost range of $290M to $480M based on a point estimate of $368M. The project received CD-3A, *Approve Long Lead Procurements*, on May 12, 2020, with an authorization of $98M. The current project point estimate is $660M. The estimated CD-4 completion date is 3Q FY 2031.

The objective of the LCLS-II-HE project is to increase the LCLS-II superconducting electron linac energy from 4 GeV to 8 GeV. This energy increase will extend the x-ray energy range to 12.8 keV and beyond as required in the Mission Need Statement.

In carrying out this charge, the review committee should respond to the following questions:

1. <u>Design Maturity:</u> Are the designs, specifications, and interfaces sufficiently mature, for this stage of the project, to meet the project goals? Is the design on track for a combined CD-2/3 in 4Q FY 2023?

2. <u>Technical:</u> Are the designs, specifications, and interfaces appropriately defined to achieve the technical performance requirements as defined by the preliminary KPPs and the mission need? Are the appropriate technical resources and expertise available? Are the

technical risks and opportunities for risk reduction being appropriately identified and addressed? Is the technical progress to date appropriate for this stage of the project, considering COVID and supply chain disruptions, and on a good trajectory for CD-2/3 in 4Q FY 2023?

3. ES&H/QA: Are Environment, Safety, and Health and Quality Assurance (ES&H/QA) requirements and plans, including COVID-19 protections and safety measures, being properly implemented?

4. Cost and Schedule: Are the cost and schedule estimates, including contingency, credible for completing the defined scope? Is the LLP cost and schedule performance, including contingency utilization, reasonable? Are major cost and schedule drivers, including increased material supply costs and delivery times, supply chain constraints, and other COVID impacts, being adequately addressed?

5. Management: Is the project being planned, staffed, and managed to successfully deliver the scope and KPPs within the preliminary cost and schedule? Is the strategy to combine CD-2/3 sound and achievable? Does the project have the necessary resources and support from SLAC and the partner labs? Are project risks, including COVID and supply chain disruptions, being appropriately identified and managed? Is the project identifying and tracking off-project activities that could negatively impact the project if not completed on schedule?

6. Overall: Have prior DOE IPR review recommendations been appropriately addressed?

Ed Stevens, the LCLS-II-HE Program Manager, will serve as the BES point of contact for this review. We would appreciate receiving the committee's report **within 60 days** of the review's conclusion.

cc: P. Golan, SSO
H. Lee, SSO
W. Swasdibutra, SSO
C-C. Kao, SLAC
N. Holtkamp, SLAC
G. Hays, SLAC
J. Fitzpatrick, SLAC
K. Chao, SC-23
C. Clark, SC-23
E. Stevens, SC-32.3
H. Joma, SC-32.3
E. Lessner, SC-32.3
V. Nguyen, SC-32.3
T. Russell, SC-32.3
R. Meneses, SC-32.3
P. Hudson, ORISE
L. Severs, ORISE

Appendix B Review Committee

DOE/SC Status Review of the
Linac Coherent Light Source-II High Energy (LCLS-II-HE) Project at SLAC
March 22-25, 2022

Kurt Fisher, DOE/OPA, Chairperson

SC1 Accelerator Physics	SC2 Cryomodules	SC3 Cryogenic Distribution System (CDS)	SC4 Accelerator Systems
* Steve Peggs, BNL	* Matt Howell, ORNL	* Alex Martinez, FNAL	* Ali Nassiri, ANL
Ryan Lindberg, ANL	Serena Barbanotti, DESY	Philipp Arnold, ESS	Alessandro Fabris, Elettra
Dan Wang, LBNL	Catherine Madec, CEA		

SC5 Undulators	SC6 X-ray Endstations	SC7 Controls and Safety Systems	SC8 Infrastructure Systems
* Joachim Pflueger , DESY retired	* Jin Wang, ANL	* Aaron Coleman, ORNL	* Jeff Pittman, retired PNNL
Dean Hidas, BNL	Wah-Keat Lee, BNL	Marion White, ANL	Wenbo Yuan, LLNL

SC9 Injector Systems	SC10 ESH&Q	SC11 Cost and Schedule	SC12 Project Management
* Joseph Bisognano, retired U of Wisc	* Mike Andrews, FNAL	* Cathy Lavelle, BNL	* Erik Johnson, BNL
Luca Cultrera, BNL	Andrew Ackerman, BNL	Jennifer Fortner, ANL	John Galambos, ORNL
Pietro Musumeci, UCLA		Frank Gines, DOE/ASO	
		Jeff Thomas, DOE/FES	

Observers

Linda Horton, DOE/BES	Yiping Feng, DOE/BES
Ed Stevens, DOE/BES	Joe Lebbie, DOE/SLI
Hannibal Joma, DOE/BES	Hanley Lee, DOE/SSO
Eliane Lessner, DOE/BES	Walter Swasdibutra, DOE/SSO
Van Nguyen, DOE/BES	Sheri Alexander, BNL
Tom Russell, DOE/BES	

LEGEND

SC Subcommittee
* Chairperson
[ ] Part-time Subcom. Member

Count: 30 (excluding observers)

Appendix C Review Agenda

DOE/SC Status Review of the
Linac Coherent Light Source-II High Energy (LCLS-II-HE) Project at SLAC
March 22-25, 2022

AGENDA

Tuesday, March 22, 2022 Via Zoom (All times listed are in PST, EST, and CET)

PST	EST	CET	Topic	Presenter
7:00 AM	10:00 AM	3:00 PM	Executive Session	K. Fisher
8:00 AM	11:00 AM	4:00 PM	Welcome	Lab Directors
8:10 AM	11:10 AM	4:10 PM	LCLS Science	M. Dunne
8:30 AM	11:30 AM	4:30 PM	Project Overview	G. Hays
9:20 AM	12:20 PM	5:20 PM	Project Management	J. Fitzpatrick
9:45 AM	12:45 PM	5:45 PM	Path to CD-2/3	D. Fritz
10:15 AM	1:15 PM	6:15 PM	Break/Lunch	
10:35 AM	1:35 PM	6:35 PM	FEL Design Development	T. Raubenheimer
10:55 AM	1:55 PM	6:55 PM	Environmental Health & Safety	I. Evans
11:15 AM	2:15 PM	7:15 PM	FNAL STL	T. Arkan
11:30 AM	2:30 PM	7:30 PM	JLab STL	J. Hogan
11:45 AM	2:45 PM	7:45 PM	LBNL STL	D. Arbelaez
12:00 PM	3:00 PM	8:00 PM	Full Committee Executive Session	
1:00 PM	4:00 PM	9:00 PM	Adjourn	

Wednesday, March 23, 2022 and Thursday, March 24, 2022

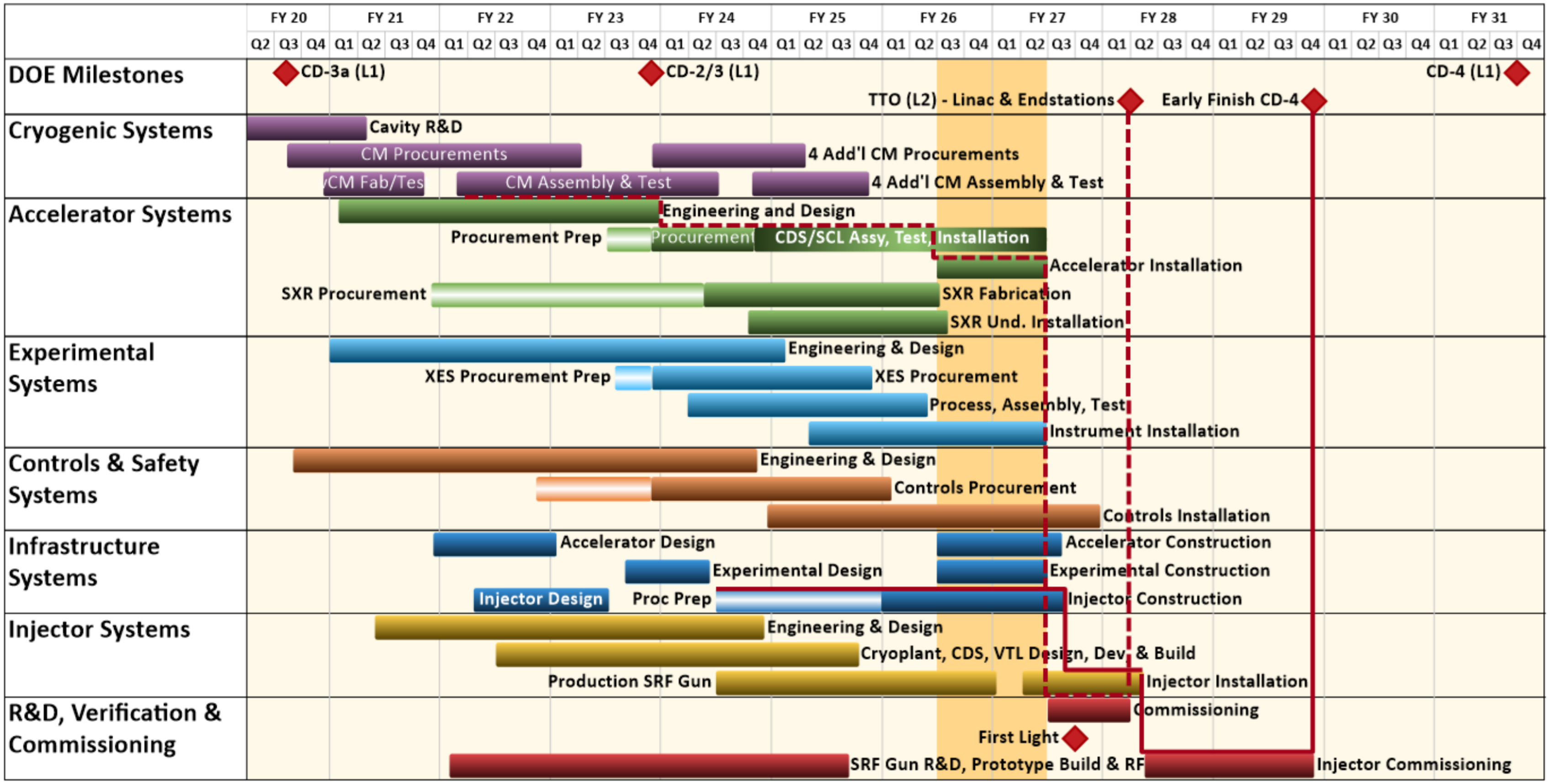
Via Zoom (All times listed are in PST, EST, and CET)

PST	EST	CET	Topic	
7:00 AM	10:00 AM	3:00 PM	Subcommittee Breakout Sessions	
10:00 AM	1:00 PM	6:00 PM	Subcommittee Executive Session	
11:00 AM	2:00 PM	7:00 PM	Full Committee Executive Session	
12:00 PM	3:00 PM	8:00 PM	Adjourn	

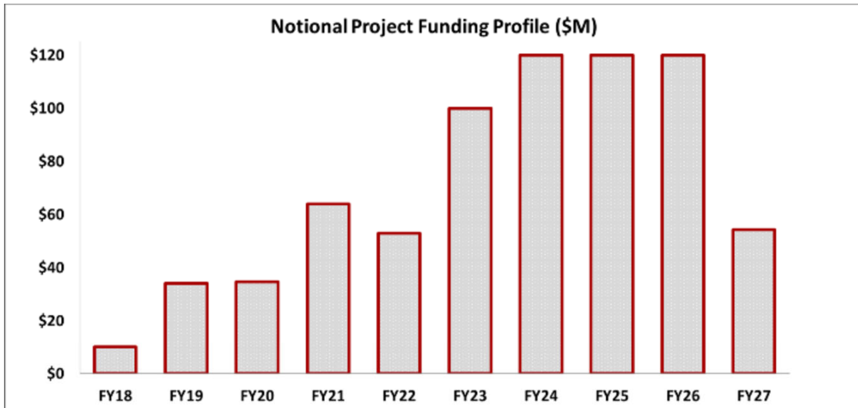
Friday, March 25, 2022 Via Zoom (All times listed are in PST, EST, and CET)

PST	EST	CET	Topic	
7:00 AM	10:00 AM	3:00 PM	Full Committee Executive Session	
9:00 AM	12:00 AM	5:00 PM	Closeout Presentation	
10:00 AM	1:00 PM	6:00 PM	Adjourn	

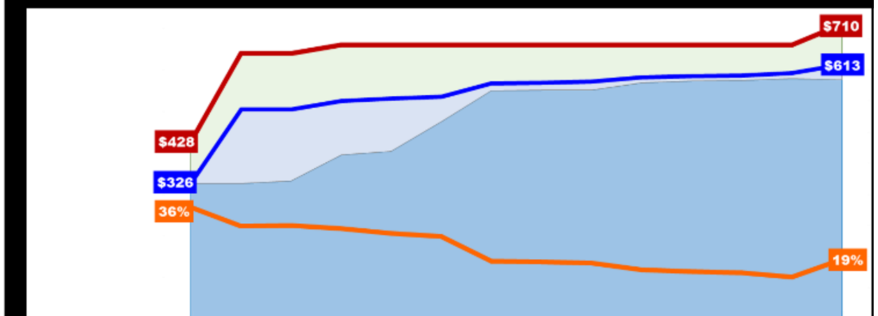
Appendix D LCLS-II-HE Schedule Chart



Appendix E LCLS-II-HE Funding Table

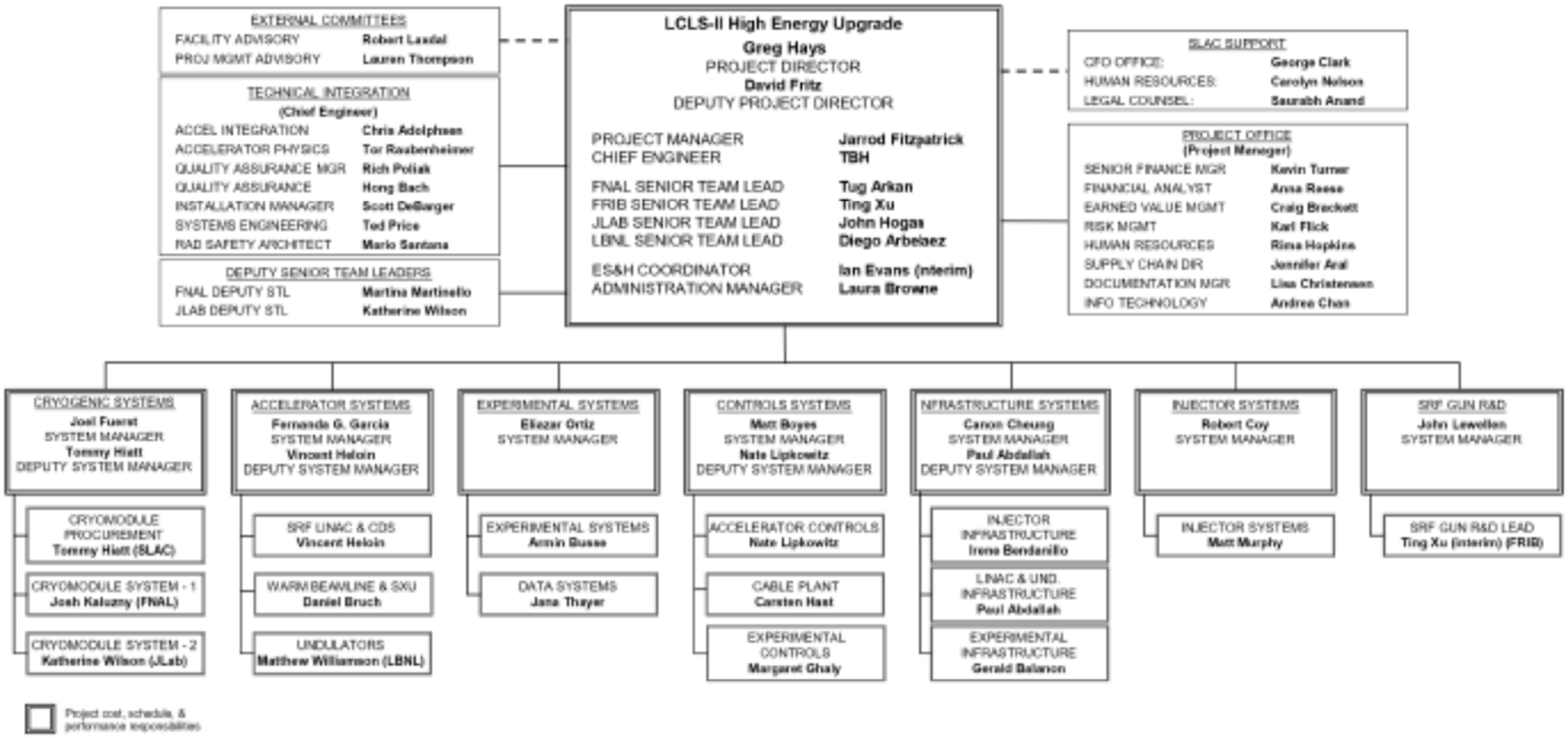


	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	Total
[redacted]	$ 2.0	$ 6.0	$ 4.0	$ 2.0	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	$ 8.0	$ 28.0	$ 30.7	$ 62.0	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	$ 10.0	$ 34.0	$ 34.7	$ 64.0	$ 53.0	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]



	Dec 2020	Jan 2021	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan 2022
Contingency	$102	$135	$135	$135	$129	$124	$92	$90	$88	$78	$75	$73	$67	$97
Pend BCRs	$0	$178	$172	$130	$128	$60	$17	$18	$20	$12	$12	$12	$14	$35
EAC	$326	$327	$333	$395	$404	$476	$551	$552	$552	$570	$573	$575	$579	$577
TPC	$428	$640	$640	$660	$660	$660	$660	$660	$660	$660	$660	$660	$660	$710
EAC+Pend	$326	$505	$505	$525	$531	$536	$568	$570	$572	$582	$585	$587	$593	$613
Contin. (Rem Work)	36%	30%	30%	29%	28%	27%	19%	18%	18%	16%	15%	15%	13%	19%

Appendix F LCLS-II-HE Management Chart



Updated: 2 March 2022

Jarrod Fitzpatrick — Jarrod Fitzpatrick (reviewer)

David Fritz (reviewer)

Greg Hays (approver)