U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Project Assessment
Status Review Report on the

High Luminosity LHC U.S. ATLAS Detector Upgrade (HL-LHC ATLAS) Project

at Brookhaven National Laboratory

February 2024

EXECUTIVE SUMMARY

A Department of Energy/Office of Science (DOE/SC) review of the High Luminosity Large Hadron Collider U.S. A Toroidal LHC Apparatus Detector Upgrade (HL-LHC ATLAS) project, located at the Brookhaven National Laboratory (BNL) was conducted on February 21-23, 2024. The review was conducted by the Office of Project Assessment (OPA) at the request of Michael Procario, Director of Facilities for High Energy Physics, Office of High Energy Physics (HEP). The review was chaired by Kurt Fisher, Director, OPA.

The purpose of this review was to assess the project's status and progress since the October 18-20, 2022, DOE/SC review. The Committee judged that the overall preparation and documentation provided for the review was comprehensive and thorough. The Committee was impressed with the overall progress made by the project despite the fact that the project team had encountered some technical issues that had arisen. However, the Committee felt that while there are some challenges to be overcome, the project team is well experienced and capable of tackling these challenges. The Committee recommended that the US ATLAS project teamwork with the International ATLAS team in order to align schedules to be realistic. Finally, the Committee stated that it would be worthwhile for the US project team to socialize with CERN/International ATLAS the potential consequences of cost increases for schedule advancement to make them an active part of the best eventual baseline solution.

Silicon Strips

The silicon strips have faced two serious technical challenges since the October 2022 review. The first, Cold Noise, has been fully addressed for Long Strip Staves, approximately two-thirds of the total, and is partially mitigated for the remaining Short Strip Staves. The second issue, Sensor Fracturing, has a promising mitigation on paper but is yet to be demonstrated. As a result, the schedule slipped 10.5 months and there is very limited float for the production period. The project has an acceleration plan that regains some of the float at an estimated cost impact of $3-5 million (US dollars). The Committee recommended that the project refresh the forecast and risk analysis once the solution to the second problem is demonstrated and deploy the acceleration in a staged fashion to be flexible should external pressures lead to changes in the international schedule.

Pixel and Global Mechanics

The pixel subproject has made good progress, preparing for module assembly and testing but is currently limited by the availability of components provided by International ATLAS. The Committee noted that if the bump bonding challenges are resolved in the near-term module hybridization campaigns, then the probability of a key risk (RD-06-01-05-003) will be reduced, which will then reduce the time to completion calculated using the Monte Carlo and bring it more in line with the current project plan.

The Committee suggested that the pixel team should work closely with International ATLAS to coordinate the qualification of vendors for sensor/readout chip hybridization by rapidly assembling and testing pre-production modules. The U.S. project will work with their International ATLAS colleagues until these problems are solved.

The Committee urged the project to ensure that the May 2024 ATLAS "Pixel Global Mechanics FDR [Final Design Review] and Pixel Support Tube (PST) PRR[Production Readiness Review]" reviews do indeed occur on the timescale proposed.

Trigger/Data Acquisition

The Committee commended the data acquisition (DAQ) team for the good technical progress made on hardware prototyping, testing, and firmware development. The project has made adequate technical progress since CD-2/3 to ensure that the objective Key Performance Parameters (KPPs) will be met. The KPPs have been further refined since the October 2022 review to specify the number of links and bandwidth rather than the number of cards to allow flexibility in the optimization of board design.

The Committee commended the project team's choice to go through another round of the FELIX pre-production prototype using the VP1522 field programmable gate array (FPGA). This solves the routing failures observed for the previous FPGA and allows for up to twice as many (48 vs 24) fibers to be received by a single board. It also ensures compliance with the PCIe gen5 protocol. The price increase for the new FPGA is still not determined. The Risk Register accommodates a price increase up to 54%.

Liquid Argon (LAr) Calorimeter Electronics

The project team is experienced and has worked successfully together for many years. The preamp/shaper ALFE2 ASIC has passed a Final Design Review and is scheduled for a PRR in April 2024. The system integration seems well planned.

The pre-production ALFE2 ASIC, now in Ball Grid Array (BGA) packaging, has successfully gone through a full set of tests including electrical performance and radiation tolerance. The Committee expects that it will pass the PRR scheduled in April 2024.

Cost and Schedule

The Committee thanked the project team for prompt responses to questions and open engagement.

The Control Account Manager (CAMs) interviewed demonstrated command of their Control Account responsibilities, including schedule logic and variance analysis reports (VARs). The Committee judged that the US schedule float against the CERN dates is not realistic based on forecasted completion dates and Monte Carlo analysis.

The Committee identified that uncosted hours are not included in standard reporting or earned valued (EV) analysis. Increased pressure on research budgets imperil this resource type, particularly as the project is relying on about 100 full-time equivalents (FTEs) for uncosted labor (about 25% of scheduled labor) across all work breakdown structure (WBS) elements. Alternate indices may provide appropriate insight.

Project Management and Environment, Safety and Health

The Committee noted that the preparation and documentation provided for this review was very good. Congratulations to the overall US project team!

The US project team was open and transparent with ongoing issues to which it is attending. These issues include:

- Strips Sensors Fracturing;
- Schedule float insufficiency as demonstrated by Monte Carlo analysis to meet CERN's long shutdown 3 (LS3) need-by dates;
- Downward pressure on research budgets impacting scientific labor;
- Encountered and ongoing risks including pixels (availability of bare quad modules from international partners), strips (sensor fracturing when staves are cooled), Liquid Argon (LAr) FEB2-NSF and LAr Signal Processing (LASP) board; and
- International delays impacting System Integration, and Integration and Installation (I&I); start impacted by delays in deliverables.

Besides these five items, no other significant issues were identified by either the Committee or project team that would require management attention. The project was impacted by a crisis (item above in silicon strips—strip sensors fracturing), which is one major contributing factor in making the schedule incompatible (minimal amounts of float) with the LS3 schedule.

The Committee identified that, in addition to starting production, the project needs to analyze options for improvement to the global production schedule. Schedule advancement potentials ("schedule economies") have been described at a rough level. A more precise estimate needs to be developed.

The Committee judged that it is reasonable to expect that schedule advancements will introduce additional risks and cost increases (additional hardware for productions lines, additional efforts for oversight, and quality assurance/safety activities, etc.) that will push against the Total Project Cost (TPC) ceiling. The US project team possesses the potential to defer I&I activities (rather than reducing hardware scope) if cost increases are pushing against the TPC ceiling. It is worthwhile for the US project team to socialize with CERN/International ATLAS the potential consequences of cost increases for schedule advancement to make them an active part of the best eventual baseline solution.

Key Recommendations

- With resolution of the Fracturing Sensors issue, reassess the remaining risks and update the schedule forecast and float to need-by date, to provide input to the discussion of the LS3 schedule, on the timescale of six months (from the time of the review), or earlier if possible.

- Work with US ATLAS management to deploy the mitigation plan in a staged manner, minimizing unrecoverable cost expenditures while still enabling a potential acceleration if necessary.
- Within six months, the pixel subproject work with their International ATLAS colleagues to develop a plan for handling the various outcomes of hybridization vendor performance. This plan should propose mitigating strategies and decision points that can be acted on when delays reach critical thresholds, and it should take into account potential changes to CERN's LS3 schedule.
- Ensure successful completion of the remaining "Pixel Global Mechanics FDR and PST PRR" within the next six months.
- Identify a consistent mechanism for reporting uncosted labor to ensure accurate earned value. Demonstrate this mechanism at future status reviews.
- Frequently identify and monitor open relationships due to the frequency of SS (Start-Start) relationships in successor planning. Demonstrate this monitoring at future status reviews.
- Formalize and document the process for management reserve reset within the next three months.
- Ensure successful completion of upcoming PRRs (GM and Stave Production) estimated to take place within the next six months.
- Prepare a more detailed schedule and cost estimate for potential improvements to key Production Activities within six months, or earlier if possible.
- Socialize with CERN/International ATLAS the potential consequences of cost increases for schedule advancement if the current LS3 schedule is maintained. Achieve this by the end of calendar year 2024.

CONTENTS

1. INTRODUCTION

The ATLAS (A Toroidal LHC Apparatus) Experiment is a seven-story, 7,000-ton multi-purpose detector system located at the European Organization for Nuclear Research (CERN) laboratory in Geneva, Switzerland. The ATLAS Detector, and the other general-purpose CMS detector, are situated at the Large Hadron Collider (LHC), the world's highest energy accelerator currently in operation. The experiment probes the fundamental forces of nature in proton-proton collisions at the energy frontier of particle physics, a regime that offers unique opportunities for seminal discoveries in basic physics.

The LHC provides access to new physical phenomena, some predicted by promising theoretical models, which would manifest themselves as heretofore unobserved states, including: supersymmetric particles, manifestations of technicolor or extra dimensions, new gauge bosons, or evidence of compositeness of quarks or leptons. The discovery in 2012 of a Higgs boson at CERN was a striking achievement, representing a multi-decade world-wide scientific campaign to understand the basic forces that govern our physical world. Its observation offers the opportunity to further study the origin of electroweak symmetry breaking and other elemental phenomena through precision measurements of the Higgs boson's properties, including its couplings to other particles, self-couplings, and rare decays.

In May 2014, the U.S. HEP program completed its long-term strategic plan through the Particle Physics Project Prioritization Panel (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP). The P5 plan for Energy Frontier recommended that the U.S. actively continue its participation in the LHC program at CERN, and specifically, in the planned High Luminosity LHC (HL-LHC) upgrades, designating it as the "highest-priority near-term large project".

The U.S. participation in the ATLAS experiment has been crucial to its success. The U.S. ATLAS collaboration makes up about 19% of the entire ATLAS collaboration. U.S. groups have made significant contributions to nearly every aspect of the detector throughout all phases including construction, installation, and preparation for data taking. ATLAS personnel is supported as part of the Department of Energy (DOE) High Energy Physics (HEP) research program; the National Science Foundation (NSF) Elementary Particle Physics Program; and the U.S. ATLAS Operations Program, which is jointly funded by DOE and NSF.

The LHC successfully completed its initial three-year run in 2012 at center-of-mass energies of 7 and 8 Tera-electron Volts (TeV), reaching a peak luminosity of 7.7 x 10^{33} $cm^{-2}s^{-1}$, and resumed operations in 2015 at an energy of 13 TeV with planned increases to luminosities of 2-3 x 10^{34} $cm^{-2}s^{-1}$ through 2023. A High Luminosity upgrade of the LHC is planned to begin operations in 2029 with levelled luminosities reaching 5–7.5 x 10^{34} $cm^{-2}s^{-1}$, 5–7.5 times the design luminosity, and corresponding to 140 to 200 interactions per crossing (pile-up) with 25 ns bunch spacing operations. Such pile-up conditions are expected to be factors of five to eight times higher than those presently seen at the LHC. To operate for an additional decade within the challenging environment, the ATLAS detector requires upgrades to an aging tracker system, the calorimeter and muon system readout electronics, and the trigger and data acquisition system. Additionally for the first time in a collider experiment, a timing detector will be added.

The High Luminosity LHC U.S. ATLAS Detector Upgrade (HL-LHC ATLAS) project is designed to enhance the detector capability for the high luminosity data run that is scheduled to begin in 2029.

Upgrades are needed to four detectors where the U.S. played a leadership role in the original construction: replacement of the Inner Detector (ID) by the Inner Tracker (ITk), replacement of the Liquid Argon (LAr) and tile (TILE) calorimeter readout electronics, new muon system chambers and electronics (MUON), and overhaul of the Trigger and Data Acquisition (DAQ) system.

Inner Tracking (ITk) Pixel Detector: The U.S. (DOE) will deliver the Inner Pixel system, comprising the innermost two pixel layers and their services. Inclined Pixel modules will be used in the outer barrel region of the ATLAS detector. However, in the innermost layers (Inner System), this geometry leads to complications in the thermal properties of the system and in the routing of services. U.S. groups proposed an alternative option in the Pixel Technical Design Report (TDR) in which inclined modules are replaced with rings. The design of the local supports is much simplified (making the construction much simpler) and the services can be more efficiently routed outside the volume. Preliminary simulation studies show no physics performance degradation versus the baseline inclined option. A formal choice of the inner system design was be made in summer 2018 after optimization of the alternative layout. Readout data rates for the innermost layers of the pixel system are extremely large, which has led to a design of the pixel front-end readout chip that can transmit data at 5.12 Gb/s. Transferring this data over several meters require the use of special, low mass, radiation hard, data cables. Several potential options were considered, and the U.S.-developed twinax cable solution was chosen as the baseline for the TDR.

ITk Strips Detector: The US (DOE) will deliver half of the barrel strip detector and its services. The strip system consists of four barrel layers and six disks in the forward region. The corresponding area of silicon sensors, at 165 m^2 corresponds to 2.5 times that of the current Inner Detector silicon strip system. The target acceptance has been extended to ± 4 units of pseudo-rapidity and the number of pixel layers, the outer radius of the pixel array and its corresponding area have all increased. The new detector layout results in a lower inactive material in the tracking volume (comprising less than one radiation length up to a pseudo-rapidity of 2.7) and gives a performance that is as good and, in many cases, better than the existing detector, but in a much more difficult tracking environment with up to an average of 200 proton-proton interactions per beam crossing. The ITk has been designed with efficient pattern recognition and track reconstruction in mind to give high track reconstruction efficiency and a low rate of fake tracks (even at HL-LHC pile-up levels). For muons with transverse momentum above 3 GeV this means greater than 99% efficiency; with efficiencies of greater than 85% for pions and electrons above 1 GeV out to a pseudorapidity of 2.7, while keeping fake rates below 1%. In addition, the performance is shown to be robust against a 10% loss of channels or modules that might occur as a worst case over the lifetime of the experiment.

ITk Global Mechanics: The U.S. (DOE) will develop and produce mechanical support structures for the ITk.

DAQ and Data Handling: The U.S. (DOE) will develop and produce the Global Common Module (GCM) electronics board for the Global Trigger and develop elements of the common readout system (FELIX) for the HL-LHC ATLAS project.

LAr Calorimeter Electronics: The U.S. (DOE) will develop the LAr preamp/shaper ASICs (application-specific integrated circuits) and lead LAr electronics integration efforts.

Several alternatives to the current baseline design of the LAr preamp/shaper ASIC have been considered. Initial studies were made that investigated using the SiGe (silicon-germanium) process for the chip, and sufficient progress was made to consider this as a viable backup option. However, the baseline design uses a complementary metal-oxide-semiconductor (CMOS), which requires lower power—a significant issue for front-end electronics cooling. The chip is implemented using the 130 nm Taiwan Semiconductor Manufacturing Company (TSMC) process and is at the final prototype stage.

Project's Current Status

The excellent performance of the LHC so far and the experience gained from ongoing analysis of data taken at lower luminosities, and from special high pile-up runs produced by the LHC machine group, along with studies of simulated data for expected higher luminosities, has helped ATLAS plan for upgrades at the higher luminosity that will be needed to search for new physics with high efficiency. The overall ATLAS physics program can only succeed if the necessary upgrades are implemented; thereby ensuring that high efficiency for expected physics is maintained as energy and luminosity increase beyond current design.

As with the U.S. participation in the construction of the original ATLAS detector, the ATLAS Upgrade will be funded jointly by DOE and the NSF. The scope has been divided between the agencies in a manner that minimizes the inter-agency dependencies. The fractional cost sharing will be approximately 66% from DOE and 33% from NSF. DOE approved Critical Decision (CD) 0, Approve Mission Need, for HL-LHC ATLAS on April 13, 2016; CD-1, Approve Alternative Selection and Cost Range, on September 21, 2018; and CD-3A, Approve Long Lead Procurement of Early Production Components, on October 15, 2019.

In early 2022, an Independent Project Review was conducted by the DOE Office of Project Assessment (OPA) to assess the project's progress in preparation for CD-2/3. On October 18-20, 2022, an Independent Project Review was conducted by the DOE/OPA to assess the project's readiness for CD-2/3. CD-2/3 for the project was obtained in January 2023. This status review of the project was conducted on February 21-23, 2024.

2. TECHNICAL SYSTEMS EVALUATIONS

2.1 Science Case/Silicon Strips

2.1.1 Findings

The ATLAS inner detector (pixels, silicon microstrip (SCT), and transition radiation tracker (TRT)) will be replaced with a full silicon-based tracker including the ITk pixel and the ITk strip detectors ("strips") to cope with the increased radiation level (corresponding to 4000/fb of pp collisions) and instantaneous luminosities (up to 7×10^{34} $1/cm^2s$) expected at the HL-LHC. The sensor and module design, readout, detector layout, cooling, and power scheme are optimized to provide efficient object reconstruction and identification.

The U.S. ATLAS ITk Strips Key Performance Parameter (KPP) is the delivery of 50% of the barrel strip detector, in the form of 196 "staves", which meet the ATLAS performance specifications. A stave is composed of a stave core (a carbon fiber/carbon foam composite with embedded cooling to provide mechanical support and thermal stability), mounted with 28 modules (where a module is a silicon sensor with one or two hybrids carrying readout and control ASICs) and associated power supply and monitoring electronics.

The WBS structure mirrors the assembly of staves, as follows:

- Stave Core (WBS 6.02.01)—this scope of work assembles the stave cores from carbon fiber and carbon foam components, with the embedded bus tapes to provide connection from the end-of-service card to the modules.
- Readout Electronics (WBS 6.02.02)—this scope of work designs and fabricates the module electronic components, in particular the readout ASIC ATLAS Binary Chip (ABCStar), data concentrator Hybrid Controller Chip (HCCStar), slow control chip Autonomous Monitor and Control Chip (AMACStar), high voltage multiplexer chip (HV-mux), and the power board (IPB) to supply low and high voltage to the module, and the coils for the DC-DC conversion.
- Module (WBS 6.02.04)—this scope of work assembles and tests all the hybrids, including loading the ASICs and associated surface mount components and testing the bare hybrid before delivery to module assembly; it also assembles sensors, hybrids, and power boards into modules and performs quality control testing before delivery to stave assembly.
- Stave Assembly (WBS 6.02.05)—this scope of work assembles 28 modules onto staves and performs quality control testing and delivers to CERN.
- US Contributions to CERN (WBS 6.02.07)—this WBS captures the contributions to CERN procurements, chiefly in ASICs, bus tapes, and power conversion components.
- Contributions to Installation and Commissioning (WBS 6.11)—this WBS includes the Installation and Commissioning activities from the entire project, including WBS 6.02 ITk Strips. The budget associated with this work is $2.56 million, which is not included in the strip detector Baseline at Completion (BAC) below.

With the exception of the silicon sensors, the project was deeply embedded in the design process and is now making major contributions to the fabrication of all the components, as well as stave assembly and shipment to CERN. The threshold KPP includes "Fabricate, test and deliver to CERN 156 staves for the barrel of the silicon strip detector, constructed to ATLAS specifications". The objective KPPs add: a) Fabricate, test and deliver to CERN 196 staves for the barrel of the silicon strip detector, constructed to ATLAS specifications; and b) Contribute, in proportion to the US contributions to the barrel strip detector, effort required to install and integrate the silicon strip barrel staves into the ITk and connect and check-out in the ATLAS detector in the pit. Moving from the objective to the threshold KPPs would lead to a potential savings of up to $3 million and up to eight months contraction of schedule. The Integration and Installation (I&I) savings would correspond to up to two years and $1-2 million.

The BAC estimate for the strip detector is $52.5 million, which represents an increase of $4.4 million since CD-2/3, and the largest of the Level 2 areas. It comprises 59% labor, 40% material and supplies, and 1% travel. The breakout at Level 3 is shown in Table 2.1-1.

Table 2.1-1. Level 3 Breakdown of BAC for Strips, by Labor, Material, and Travel

WBS L2	Labor	Material	Travel	Grand Total	Fraction
6.02.01 Stave Core	53.0%	46.7%	0.3%	7,197,548	13.7%
6.02.02 Readout Electronics	48.7%	50.9%	0.4%	7,749,730	14.8%
6.02.03 Hybrid Assembly	47.8%	52.2%	0.0%	1,622,240	3.1%
6.02.04 Modules	77.5%	20.5%	2.0%	22,180,302	42.2%
6.02.05 Stave Assembly	67.5%	32.0%	0.5%	8,361,129	15.9%
6.02.07 US Contributions to CERN Procurements-BNL	0.0%	100.0%	0.0%	5,388,002	10.3%
Grand Total	**59%**	**40%**	**1%**	**52,498,950**	**100%**

The cost and schedule evolution was presented including 12 baseline changes between setting the post-CD-2/3 Performance Measurement Baseline and this review, contributing $2.63 million to the above increase. Significant Baseline Change Requests (BCRs) include supplanting scientific labor ($1.2 million) and additional effort responding to sensor fracturing ($1 million).

The project has two main international partners: the United Kingdom (UK) and China. The UK/China consortium is building the remaining 50% of the strips barrel. Responsibilities for input are split as follows: module hybrids (UK); power boards (US); core locking points, core c-channels and closeouts (UK); carbon fiber and foam (US). The main remaining external dependencies are hybrids, which had some quality issues at first that appear to be resolved as the latest deliveries demonstrate improved quality, and end-of-substructure cards, which are in production. Bus tapes production has also been delayed initially by quality issues, but started in January 2024, with first delivery due in mid-April.

Significant technical progress since CD-2/3 included: completion of stave core pre-production; first batch of 2,000 Power Boards; completion of AMACStar/HCCStar probing; production of 100+ long strip modules with no issues related to "cold noise"(see below); assembly of three additional staves.

The project, however, has been facing two technical issues that have effectively stalled pre-production's completion and final Production Readiness Review (PRR) that launch production. The first, discovered in May 2022, is "cold noise", where strips predominantly under the hybrids show increased levels of noise as the temperature is lowered to the nominal operating point and beyond. Studies of cold noise have progressed and led to a mitigation strategy that is promising. However, a second issue has arisen, where some modules loaded onto staves exhibit HD breakdown at low voltages (~ 100 V) after being cooled down, which lead to the discovery of "sensor fracturing", where stresses concentrated near the hybrid and power board cause the silicon sensor to crack.

These two issues, as well as the bus tape delay, have resulted in significant delays in meeting the international schedule. The current forecast shows the last stave delivery on March 3, 2027, where the need-by date is May 3, 2027, resulting in two months of float over the next three years, a reduction of 10.5 months since the CD-2/3 review. The updated risk analysis shows that the strips project needs at most an additional 15.5 months at the 90% confidence level to complete the project. If the current mitigation plan for the sensor fracturing is effective, this is reduced to about 11 months. As a consequence, the project team developed a proposal to accelerate stave cores, module, and stave assembly. If implemented, the plan adds the needed float of 11.5 months at the 90% confidence level and a forecast with seven to ten months of float. The estimated impact is 15-18 staff years and a total of $3-5 million.

2.1.2 Comments

The Committee thanked the review team for well-prepared presentations and candid and open discussion of the issues facing the strips at this time. Even more so, they are to be commended for the impressive response to two separate significant challenges that have evolved since the October 2022 review.

Historically, SC-1 has also been responsible for the review of the science case. The science case has not changed, and the importance of the ATLAS Upgrade was re-confirmed by the 2023 P5 Report (Recommendation 1a).

The continuing erosion of the research budgets for laboratories and universities represents an existential threat to the successful completion of the ATLAS strip detector upgrade. A total of 25% of the budgetary increase comes from the need to supplant research labor due to eroding research budgets. Project mitigations exist but will only go so far in ensuring there is sufficient labor to successfully complete the project.

The vendor selection situation regarding bus tapes was resolved during the October 2022 review, but subsequent issues with quality has delayed the bus tape production by about a year. Latest deliveries show the quality issues have been resolved but this should be monitored closely to keep stave cores off the critical path.

Similarly, the cold noise issue, which was just emerging at the time of the October 2022 review, has been thoroughly investigated and the mitigation for long strips has been demonstrated. The same mitigation is moderately effective for short strips and may be sufficient. As short strip production does not start until after long strip production (about two years), there is sufficient time to develop further mitigation, should that be necessary. The sensor fracturing issue, which appeared about nine months ago, has also been thoroughly investigated, with many avenues of possible mitigation developed. The current proposed changes, with maximum effect for minimum design change, are being tested in the next two to three months, and if they are effective, would allow resumption of production of long strips.

Given that there have been two subtle yet serious issues emerging only after designs were finalized, it may be worth considering an extended operational test of a small number of modules/staves in parallel with standard burn-in quality control, to provide experience with many more thermal cycles and hours of operation without hindering module production and subsequent stave assembly.

The project has a complete set of risks that provide adequate coverage and have plausible probabilities and impacts. Once the sensor fracturing issue is resolved (one way or the other) it would be worthwhile to update all risks and reassess the aggregate schedule impact.

As an outcome of the risk analysis and the two serious technical issues faced by the project, it is abundantly clear that the current schedule is not compatible with the current need-by dates.

With the aggregate KPP delay of 10.5 months since CD-2/3, the project has a proposal to accelerate stave cores, module assembly, and stave assembly. The plan is rational, and can be deployed in a staged fashion, with early procurements of additional infrastructure, which are also risk mitigations against future delays, and additional labor brought on when it is clear the acceleration is required to meet the international commitment.

Regardless of the mitigations and meticulous planning of the US project proponents, success at the end of the day also depends on international partners pursuing similar avenues to deliver a fully functional detector and subsequent LHC physics program in a timely fashion. Although not within the purview of this review, US ATLAS should continue the strong engagement with the international collaboration to guarantee the investment in this upgrade results in the expected excellent science program.

2.1.3 Recommendations

1. With resolution of the fracturing sensors issue, reassess the remaining risks and update the schedule forecast and float to need-by date, to provide input to the discussion of the long shutdown 3 (LS3) schedule, on the timescale of the next six months, or earlier if possible.

2. Work with US ATLAS management to deploy the mitigation plan in a staged manner, minimizing unrecoverable cost expenditures while still enabling a potential acceleration if necessary.

2.2 Pixels

2.2.1 Findings

The U.S. deliverable for the HL-LHC ATLAS pixel upgrade is the fully integrated standalone inner system made of 12 independent quadrants that include all active detectors, are fully loaded and tested, and shipped to CERN with all electrical and optical services and power supplies. This will be delivered by 2026.

In total, the U.S. will deliver 800 modules for instrumenting layer 1, which comprises 69% of the total number of layer 1 modules needed to build the detector.

Hybridized sensors are provided by International ATLAS, but vendors are still struggling to produce high-quality bare modules.

The Monte Carlo analysis suggests that at the 90% confidence level, the pixel subproject needs an additional five months to complete compared to the current project plan.

2.2.2 Comments

The Committee thanked the project team for their excellent preparation for this review and recognize the important technical progress they have made since the October 2022 CD-2/3 review.

The pixel subproject has made good progress preparing for module assembly and testing but is currently limited by the availability of components provided by International ATLAS.

If the bump bonding challenges are resolved in near-term module hybridization campaigns, then the probability of a key risk (RD-06-01-05-003) will be reduced, which will then reduce the time to completion calculated using the Monte Carlo and bring it more in line with the current project plan.

The pixel subproject commented on the loss of several key personnel. However, the Committee noted that for future work, there is redundancy built into the module assembly and testing plan, and that any short-term loss of capabilities at one site could be absorbed by others.

The pixel subproject proposed ways to speed-up the module loading processes that will compensate for delays in module delivery. The project does not incur standing army costs in the event of delays delivering components for assembly.

The pixel subproject team should work closely with International ATLAS to coordinate the qualification of vendors for sensor/readout chip hybridization by rapidly assembling and testing pre-production modules. The U.S. project will work with their International ATLAS colleagues until these problems are solved.

2.2.3 Recommendation

3. Within the time scale of six months, the pixel subproject work with International ATLAS colleagues to develop a plan for handling the various outcomes of hybridization vendor performance. This plan should propose mitigating strategies and decision points that can be acted on when delays reach critical thresholds, and it should take into account potential changes to CERN's LS3 schedule.

2.3 Global Mechanics

2.3.1 Findings

The Committee reviewed Global Mechanics with the following subprojects:

- Integration System Testing (WBS 6.3.1)
- Outer Cylinder (WBS 6.3.2)
- Pixel Support Tube (WBS 6.3.3)
- Structural Bulkhead (WBS 6.3.4)
- Strip Shells (WBS 6.3.5)
- Infrastructure (WBS 6.3.6)
- Internal Support Tubes (WBS 6.3.7)

The majority of subprojects (WBS 6.3.1, 6.3.2, 6.3.4, 6.3.5, 6.3.6) are completed, and consequently the review breakout session focused on the Pixel Support Tube (WBS 6.3.3) and The Internal Support Tube (WBS 6.3.7) with short update related on the Outer Cylinder (WBS 6.3.2) and the Strip Shells (WBS 6.3.5), which have been finished since the October 2022 review.

For the Outer Cylinder and Strip Shells, the project team reported on progress since the October 2022 CD-2/3 review, which is summarized here briefly:

- The L3 shell was assembled with an out-of-spec flange; the part is usable and fully functional.
- The Outer Cylinder structures separate into two forward and one barrel sections with different need-by and delivery dates.

  - The barrel section of the Outer Cylinder had developed a defect (crack) during the manufacturing process, which was not handled as specified to the vendor, but eventually successfully addressed by modifying other assembly parts.
  - The barrel Outer Cylinder structure was delivered together with all parts in May 2023 and is complete from the US scope point of view.
  - For the forward and backward Outer Cylinder's there was an issue at the vendor that led to the cylinder flanges being bonded inaccurately. Flanges on either side of one forward Outer Cylinder and on one side of the other Outer Cylinder needed a custom repair due to the flanges bonded 5mm off the intended positions. The project team was able to address these wrong flange positions successfully without any impact on

functionality. To achieve required flatness tolerances on the flanges the final surfaces were sanded down and forward Outer Cylinder structures are ready to be provided for international partners.

The Pixel Support Tube design is mature and awaits a final PRR prior to manufacturing, which is dependent on a Final Design Review (FDR) of the International ATLAS common mechanics. Finite Element Analysis (FEA) with expected deformation at the level of 250 micron was discussed during the breakout session from earlier CD-2/3 review material. The locations of the "hat" stiffeners are still somewhat flexible to mitigate deformations as best as possible according to the outcome of the FDR of common mechanics. The order for the final manufacturing is placed and delivery of the mandrel for PST (and L1) is either imminent (L1) or in the next two months (PST). A reasonable amount of time is budgeted for manufacturing of these structures in September 2024 (L3) and March 2025 (barrel PST) ahead of the CERN need-by date, providing seven months and twelve months of float, respectively. It needs to be pointed out that this level of float is to the current CERN schedule with the forward PST being further relaxed in terms of schedule since installation of these two forward PST structures requires the barrel PST and their detectors to be fully integrated and cabled up.

Final manufacturing is on hold until the PRR is finished, which explains a low level of Schedule Performance Index (SPI) due to prepreg orders not being placed, and labor expenses being delayed. The project expects the SPI metric to catch-up rapidly once prepreg orders are placed and work can commence.

The Internal Support Tubes (IST) includes manufacturing of IST and Inner Pixel Tube (IPT), both projects are on hold until after the common mechanics FDR and subsequent PRR to determine final length of these structures. Manufacturing is intentionally delayed but relevant deformation studies including effect of dynamic loads during installation (using 70kg of weight) are completed. These studies demonstrate to maintain an IST envelope of 2mm provided a 650 micron thick IST under load deforms less than ~700 micron. Once the PRR approval is received, the manufacturing of IST commences and sub-structures will be transitioned to CERN. Tube section assembly for IST and IPT is scheduled to take place at CERN and will most likely be moved from WBS 6.3.7 to 6.11, to allow closing of WBS 6.3.7. Allowing the final assembly being done at CERN eases transportation and reduces risk of damage during "storage" at CERN—the same applies also to the IPT.

Since the October 2022 review, new scope (small) was added, the IST end flange. This part is non-load bearing and serves to connect a conical environmental seal between the IST and the PP1 bulkhead. The design will closely follow examples used elsewhere in the ITk structure.

2.3.2 Comments

There is one subsystem FDR and two subsystem PRRs that are not yet completed. At the time of the CD-2/3 review these were scheduled for March 2023, and are currently scheduled to be completed in May 2024 ATLAS "Pixel Global Mechanics FDR and Pixel Support Tube (PST) PRR". The Committee urged the project team to ensure that this review does indeed occur on the timescale proposed.

The remaining tasks from the Pixel Support Tube and Layer 1 Tube and the IST and IPT, and as recently added scope the IST end flange are waiting for completion of the above mentioned FDR/PRR before material and some of the tooling can be ordered. While all tasks still have comfortable levels of float (more than one year), the float is being reduced while waiting for the review.

The SPI 'nosedives' observed for WBS 6.3.3 and WBS 6.3.7 are satisfactorily explained by the ordering and work delays incurred due to the FDR/PRR holdup.

The problems at the external vendor encountered during assembly of WBS 6.3.5 L3, L2 and WBS 6.3.2 (Outer Cylinder) are worrisome, in particular because they occurred despite the fine-grained detailed controls written into the contracts, but these problems are in the past and were successfully dealt with.

It is reassuring that for both the PST and Layer 1 tube, and the IST and IPT, most of the critical work (carbon fiber layup, bonding of stiffeners and attachment parts) is done in-house at Lawrence Berkeley National Laboratory (LBNL) and Seattle respectively, which eliminates potential issues that could be associated with vendor oversight and communication.

The design of the IST end flange is very similar to other flanges in the WBS 6.3 Global Mechanics scope and seems well under control.

Particular attention should be paid to Integration and Installation of the various structures delivered by the US project team (PST, IST, IPT), which is carried out by the international partners of the ATLAS collaboration especially CERN.

2.3.3 Recommendation

4. Ensure successful completion of the remaining PRR within the next six months.

2.4 Trigger and Data Acquisition

2.4.1 Findings

The scope of the DOE ATLAS HL-LHC Trigger and DAQ (WBS 6.7) is to provide a system able to generate a L0 trigger decision using the full granularity of the calorimeter and muon inputs at a rate of 40 MHz, sustain readout rates of all detector systems at 1 MHz, and facilitate event reconstruction, including preparation of tracking data, in the Event Filter (EF) with output rates at 10 kHz and an average raw output event size of 6 MB.

It comprises three deliverables:

- hardware and firmware design of the Global Common Module (GCM; WBS 6.7.1)
- hardware and firmware design of the Front End LInk Exchange module (FELIX; WBS 6.7.3)

- Readout Interface Firmware for the GCM-to-FELIX interface, and firmware for the EF Tracking data provider readout (WBS 6.7.4)

The deliverables are under the responsibility of BNL (6.7.1 and 6.7.3 hardware) and Argonne National Laboratory (ANL; 6.7.3 firmware and 6.7.4) and rely on the expertise built by these two groups during the design of ATLAS Phase I upgrades. The fraction of deliverables within the US vs. international partners is 70% for the hardware design and between 25% to 100% for the firmware responsibilities.

GCM is an ATCA [Advanced Telecommunication Computing Architecture] blade servicing > 100 optical links with speed between 9.6 to 25 Gbps, connected to an external optical switch. Two on-board field programmable gate arrays (FPGAs) are used to control data aggregation/time multiplexing (MUX), and global event processing/trigger algorithms (GEP), respectively. Firmware for MUX and for data formatting in GEP are also included in this deliverable. The objective/threshold KPP specifies that DOE ATLAS will deliver to CERN GCM boards capable of delivering 16.5/9 Tbps to the rest of the DAQ.

FELIX is a PCIe card designed to interface the ATLAS frontend detectors to the DAQ system. It must provide 24 optical links with bandwidth up to 25 Gbps. Firmware for the clock and busy signal distribution and for control of the I/O [input/output] protocol of up and down-link connections are also included in this deliverable. The objective/threshold KPP specifies that DOE ATLAS will deliver to CERN FELIX boards capable of receiving 4800/2520 of the 10 Gbps links needed in the system. The threshold KPP relies on usage of some Phase-1 FELIX cards to meet ATLAS needs.

The Readout Interface Firmware deliverables are the firmware for transmitting outputs, and monitoring and control data between GCM and FELIX (WBS 6.7.4.2); and the firmware for receiving and preparing data needed by the tracking algorithms inside the Event Filter (WBS 6.7.4.1).

A GCM/FELIX integration test using the v2b GCM prototype and the v2a FELIX prototype was performed at BNL in February 2023. It showed reliable fiber eye and BER $< 10^{-14}$. It also successfully tested the 9.6 Gbps link between GCM and the LT1 trigger module, and the 25.6 Gpbs Interlachen protocol between GCM and FELIX.

The GCM v3 prototype was redesigned around two Xilinx Versal Premium 1802 FPGAs per board, after a layout optimization informed by cooling and airflow tests performed at CERN in September 2022. It passed the Preliminary Design Review (PDR) in October 2023. This v3 prototype arrived at BNL in January 2024 and is currently under test. Five boards will be needed for integration tests at the CERN 10% vertical slice test, which aim at evaluating the on-board firmware and the dataflow between external systems. The FDR for the GCM hardware is anticipated to take place before the end of 2024.

The FELIX v2b prototype, using the VP1552 Versal Premium FPGA, is in progress with the layout nearly complete. The Versal FPGA will alleviate a resource limitation, accommodate an increase in the number of input channels from 24 to 48, and allow the possibility of using PCIe

Gen. 5 interconnect. The PDR was conducted in February 2024 for this latest FELIX design. The FDR is anticipated in fall 2024.

The GCM readout links are required to pass data to FELIX (Interlaken at 25 Gb/s) and receive data from FELIX for the TTC links (8b/10b at 9.6 Gb/s). The firmware has been designed and found to meet timing using a Versal FPGA. It was tested in the GCM-FELIX integration test. Progress in the firmware development was delayed due to loss of key personnel. The PDR is now scheduled for August 2024.

Progress toward the EF Tracking Data Provider firmware, which is needed to prepare tracking data for the EF tracking algorithms in the FPGA accelerator option implementation, includes development of firmware blocks to cluster pixel hits and decompress ITk pixel data. This has been verified with behavioral simulations and converted to Vitis kernels.

The up-to-date total cost for the TDAQ DOE project is $14.53 million:

- $4.16 million for WBS 6.7.1,
- $4.73 million for WBS 6.7.2,
- $1.61 million for WBS 6.7.4, and
- $4.04 million for US Contribution to CERN Procurement (WBS 6.7.7).

Engineering plus scientific effort is peaking at about six full-time equivalents (FTEs) in FY 2024 and 2025 and is tapering to about two FTEs in FY 2026 and about 0.2 FTEs in FY 2027. I&I funding will be used to continue the effort in FY 2026 thru the start of ATLAS HL-HLC run.

GCM is on the critical path. Float days with respect to needed-at-CERN dates are 407, 237, and 731 for GCM and FELIX and 6.7.4.2, respectively. The WBS 6.7.4.1 baseline schedule ends at the EF PDR in third quarter FY 2025.

The highest risks are delays in components availability for delays in components availability and loss of key personnel. They are mitigated by handling procurements and board assembly/production via CERN and sharing board design expertise across a large group of engineers. External dependencies coming from hardware and firmware deliverables from international partners are also captured in the Risk Registry.

The TDAQ group has not received any previous review recommendations.

2.4.2 Comments

The Committee commended the DAQ team for the good technical progress made on hardware prototyping, testing, and firmware development. The Committee judged that the project has made adequate technical progress since CD-2/3 to ensure that the objective KPPs will be met. The KPPs have been further refined since the October 2022 review to specify the number of links and bandwidth rather than the number of cards to allow flexibility in the optimization of board design.

The TDAQ project continues to rely very effectively on previous experience in hardware construction and firmware design, including collaboration with international partners, and maintains credible schedule and cost estimates.

Since CD-2/3, both GCM and FELIX teams have designed and started to test final prototype boards that satisfy the project technical requirements of a large number of high-speed serial links, compliance with the ATCA standard, and feasibility of the latest PCIe interface. The choice of larger FPGAs used in such prototypes mitigates the risk of insufficient resources and allows for future development of firmware logic.

The Committee commended the project team's choice to go through another round of the FELIX pre-production prototype using the VP1522 FPGA. This solves the routing failures observed for the previous FPGA and allows for up to twice as many (48 vs 24) fibers to be received by a single board. It also ensures compliance with the PCIe gen5 protocol. The price increase for the new FPGA is still not determined. The Risk Register accommodates a price increase up to 54%.

Both the GCM and FELIX boards are presently using the CERN preferred 12-channel 25 Gbps electro-optical module. This chip has not yet been demonstrated to satisfy specifications according to external groups and the vendor. A new version addressing the remaining problems is expected to be available by the vendor in few months. If this version were to fail, alternative solutions from another vendor have already been tested and found to be acceptable. The GCM and FELIX hardware teams recognize that this decision has to be done before the end of CY 2024 to avoid a negative float for the project.

Ample float to the need-by dates at CERN remains in the schedule for GCM (407 days) and for FELIX (237 days). The reduction in float since CD-2/3 stems from the realization of the risk for the loss of key personnel. The project team is commended for promptly making new hires to minimize the schedule impact. The risk will still be retained for the time being.

The Committee supported the desire to launch the GCM and FELIX productions as soon as possible, even with the ample float to need-by dates or LHC schedule delays, in order to maximize the time for I&I and commissioning activities at the experiment.

The resource loaded schedule for Event Filter Tracking Data Provider runs until third quarter FY 2025, when the choice of technology for the tracking EF will be-made between CPU/GPU or mixed CPU/FPGA accelerator solution. Should the FPGA-accelerator solution be adopted, the Committee supported the allocation of new resources to facilitate the continuation of this task.

2.4.3 Recommendation

None.

2.5 Liquid Argon Calorimeter Electronics

2.5.1 Findings

The Liquid Argon Calorimeter (LAr) involves the full replacement of precision readout electronics. This project shares deliverable responsibilities between NSF and DOE.

The upgrade task encompasses five components, including:

- Frontend Electronics (ADC ASIC and Optical links; WBS 6.4.1)
- Frontend Boards (FEB2) and Layer Sum Boards (LSB; WBS 6.4.2)
- Backend Electronics (WBS 6.4.3)
- System Integration (WBS 6.4.4)
- Preamp/Shaper ASIC (WBS 6.4.5)

System integration (WBS 6.4.4) and preamp/shaper development (WBS 6.4.5) are conducted under DOE scope; all others belong to NSF. All LAr scope is managed together and uniformly at L2. Funding sources are separated at "deliverable level" corresponding to WBS Level 3.

The preamp/shaper ASIC, ALFE2, passed an FDR in November of 2022. Pre-production ALFE2 ASICs were received in February 2023. The parts were packaged as a Ball Grid Array (BGA) device. Benchtop and radiation tests show the packaged ASIC is performing according to specifications with a yield of >95%. The PRR is scheduled for April 2024.

A yield factor of 0.7 has been assumed for ALFE2. A production quantity of ~78K ALFE2 ASICs will be produced to allow for the assembly of all FEB2 boards with 6% spare chips. A robotic system to test production ALFE2 chips has been developed and operated at ICJLab/Omega. A second test system will be shipped to BNL. The two test systems will be used at BNL and IJCLab/OMEGA to process the production chips.

The system integration and testing will include performance/compatibility tests of the FE, BE, DAQ and calibration/timing/trigger components. System integration also covers the QC testing of 50% of the production FEB2 boards. The remaining boards will be tested by French collaborators. A set of test boards has been designed to stand in for production boards until they become available. This will allow system integration to move forward in the absence of any particular board(s).

2.5.2 Comments

The team is experienced and has worked successfully together for many years. The preamp/shaper ALFE2 ASIC has passed a Final Design Review and is scheduled for a Production Readiness Review this April. System integration seems well planned.

The pre-production ALFE2 ASIC, now in BGA packaging, has successfully gone through a full set of tests including electrical performance and radiation tolerance. It is expected to pass the PRR scheduled in April 2024.

A yield factor of 0.7 has been assumed for ALFE2 ASICs. Planned total quantity is ~78K ALFE2 ASICs which will be used to assemble all FEB2 boards (1524 boards required plus 103 spare boards) plus have 6% spares. This seems sufficient based upon prior experience and the fact that the pre-production chips have a yield of >95%.

The design of a robotic ASIC test system has progressed significantly. A full test cycle was demonstrated at IJCLab/OMEGA. An identical test system will be set-up at BNL and chip testing will be evenly split between IJCLab/OMEGA and BNL. This system is expected to speed up and ease chip testing. Parameters for determining ASIC pass/fail criteria must be established and documented. All results will be saved to a database.

System integration tests exercise all board-to-board interfaces and will use final prototype boards or earlier prototype/emulator boards when final boards are not yet available. This will be a dynamic and flexible test stand and configurations will change as final boards become available. It will be important to make sure that sufficient resources are allocated to keep up with hardware, firmware and software changes.

The power distribution to the LAr Calorimeter Front End Crate has changed and delivery of the FEB2 is delayed due to having to finalize and test a new 48 Volt down-conversion circuit - problems have arisen with radiation tolerance. This has led to a 3 to 6 month delay in system integration testing. The team believes they understand the required changes but are still in the process of testing a new rad tolerant design. A sufficient group effort should be able to overcome this unexpected technical issue.
The LASP board, a component provided by international collaborators, is likewise delayed by 3 to 6 months. The integration team should make sure they have sufficient resources in place to be successful with a reduced time period. Plans exist to have international collaborators come to BNL to expedite system testing.

When all components become available, a Frontend Crate System Test, including 14 FEB2 (1792 channels), will take place. This represents a sufficient slice of the experiment to validate the full electronics chain.

2.5.3 Recommendation

None.

3. COST and SCHEDULE

3.1 Findings

PROJECT STATUS		
Project Type	MIE	
CD-1	Planned: 9/2018	Actual: 9/2018
CD-2	Planned: 10/2019	Actual: 10/2019
CD-3	Planned: 10/2022	Actual: 1/2023
CD-4	Planned: 12/2030	Actual: TBD
TPC Percent Complete	Planned: 60%	Actual: 56%
TPC Cost to Date	$93.4M	
TPC Committed to Date	$107.6M	
TPC	$200M	
TEC	$183.6M	
Contingency Cost (w/Mgmt Reserve)	$32.8M	44% to go
Contingency Schedule on CD-4b	24 months	%
CPI Cumulative	0.99	
SPI Cumulative	0.93	

The project's most recent approval gate was for CD-2/3, which received ESAAB approval January 31, 2023, enabling the project to move forward with full scope execution.

The project is jointly funded by an NSF Major Research Equipment and Facilities Construction (MREFC) for $75 million and DOE support for U.S. ATLAS HL-LHC of $200 million with the following CD completion dates:

- CD-0, approved April 13, 2016,
- CD-1, approved September 23, 2018,
- CD-3A, approved October 16, 2019
- CD-2/3, approved January 31, 2023.
- CD-4, planned for first quarter FY 2031, which includes two years of float

DOE FY 2022 Inflation Reduction Act funding ($32.8 million) supported efficient execution and softening the impact from Continuing Resolutions, Federal government shutdowns, and contracting challenges. However, an appropriation is needed to fully fund FY 2025 scope.

Based on December 2023 data, deliverables have a 50% contingency on cost-to-go and I&I has a 30% top-down contingency on cost-to-go.

The US ATLAS HL-LHC schedule is driven by the CERN LHC LS3 schedule, starting in January 2026 with three-year duration. ATLAS need-by dates for project deliverables are available and used to compute subsystem schedule contingency. Each Level 2 system has its own independent critical path to deliverable completion.

BNL EVMS has been certified; ATLAS participated in the most recent DOE recertification (surveillance) review in August 2023. Specific actions are summarized in the FY23 EVMS Corrective Action Plan.

The project management team, Level 2 and Control Account Managers (CAMs) have taken two-day Earned Value Management System (EVMS) training and are required to take a refresher course every year.

The Monte Carlo analysis is run on technical maturity scores and risks using Safran, excluding I&I.

The resource loaded schedule is technically driven.

There are eight separate projects, each with their own schedule file, for the DOE scope. All projects can be loaded simultaneously into the scheduling software to provide the full scope schedule. There are no inter-project dependencies or links. Note that the LAr (WBS 6.04) contains both DOE and NSF funds.

The resource loaded schedule resources have a base year of FY $19 million to align with the baselined NSF scope.

The schedules contain approximately 10,500 activities with each separate project schedule containing 400-4,000 activities.

The Project Management Baseline was set in February 2023.

The non-PM project level of effort percent ranges from 0-46%.

The Cost and Schedule Performance Indices (CPI/SPI) are at .99 and .93, respectively, through December 2023 with the project at 56% completion.

Nominal float to the "needed at CERN" dates range from two months (Strips) to 20 months (DAQ).

The baseline project includes uncosted scientific labor.

I&I (WBS 6.11) is planned with activities in FY 2024 with future remaining activities deemed planning packages.

The project had 11 Variance Analysis Reports (VARs) in December 2023.

The Project's Monte Carlo indicates that the plan supports full US deliverable completion within budget and the CD-4 bound, independent of the LS3 schedule.

No costs are quantified for identified risk mitigation(s).

The project performs a series of quality checks as part of its monthly statusing process.

3.2 Comments

The Committee thanked the project team for prompt responses to questions and open engagement. Interviewed CAMs demonstrated the ability to efficiently navigate the project's financial reporting tools, as well as awareness of the earned value processes and Control Account responsibilities. Further, The VAR "explanation of variances" exhibited examples of best practices with root cause analysis and traceable variance detail.

The resource loaded schedules provide an adequate plan for executing the project's scope of work so that it can serve as the cost and schedule part of the performance baseline.

There are a number of instances where the WBS naming is inconsistent, including where WBS numbering system drops "zero" in WBS dictionary and in the Project Management Plan, though Primavera (P6) and the Work Authorization Documents (WADs) contain the "zero". In addition, the WBS Dictionary and P6 WBS names and WAD names do not always match (WBS 6.x.7, 6.3.1, and 6.3.7). Finally, the WBS dictionary does not contain references to WBS 6.x.90, which houses Project Management support for each Level 2.

The December Contractor Project Report includes current period actuals of $147,000 for WBS 6.02.07 with no performance in the current period, indicating a potential misalignment with accruals.

A detailed schedule is not available for I&I and it is not part of the Monte Carlo simulation. A top-down contingency of 30% has been assumed for I&I. The Committee concurred with the project's intention to develop WBS 6.11 I&I Risks.

Uncosted hours are not included in standard reporting or earned value analysis. Increased pressure on research budgets imperils this resource type, particularly as the project is relying on about 100 FTE for uncosted labor (about 25% of scheduled labor) across all WBS elements. Alternate indices may provide appropriate insight.

The project's Lessons Learned is aged (dated November 2021)

Contingency tracking includes a management reserve reset without a Baseline Change Proposal (BCP; November 15, 2023). The project provided a description of an informal process that is an agreement between the project office and Federal Project Director (FPD).

An error in the Change Control Log in which "Schedule Impact (Months)" for BCPs 119, 120, 121, and 122 each indicated a "40 days delay" was corrected by the project after identification by the Committee.

Quantifiable Backup Data (QBD) need to be generated consistently for activities greater than 60 days. Generating QBD quarterly overlooks expanded activities.

The project utilizes a user-defined field to identify "SVT" activities for activities without any resources, rather than in the activity name. This requires additional attention when working to determine whether resources are missing or uncosted. The August 2023 EVMS surveillance also made note of the ambiguity associated with not labelling SVTs in the activity name.

Project is utilizing Start-to-Start (SS) successors relationships in the baseline where the only successors are SS. Without non-SS successor relationships, the relationship is deemed an "open-end" and the activity finish will not drive any successive work. On paper, the activity could never complete and the problem in the logic would not be evident. A similar practice is deployed in the status schedules to resolve out-of-sequence events. The use of SS scenarios are typical in situations where planning is attempting to recover time and schedule work concurrently. Simply adding another non-SS successor or additional work detail will allow logical sequencing and resolve the open-end problem. Updating quality checks to identify and resolve an only SS-successors situation is needed. The August 2023 EVMS surveillance also made note of the ambiguity associated with open ends.

3.3 Recommendations

9. Identify a consistent mechanism for reporting uncosted labor to ensure accurate earned value. Demonstrate this mechanism at future status reviews.

10. Frequently identify and monitor open relationships due to the frequency of SS relationships in successor planning. Demonstrate this monitoring at future status reviews.

11. Formalize and document the process for a management reserve reset within the next three months.

12. Develop the Risk Register for WBS 6.11 I&I prior to the next status review.

4. PROJECT MANAGEMENT and ENVIRONMENT, SAFETY and HEALTH

4.1 Findings

The project Total Project Cost (TPC) includes $200 million for DOE scope and about $83 million for NSF scope. The deliverables for each funding type are clearly delineated within the project's WBS. The project's scope includes deliverables for inner tracker detectors (pixels and strips), LAr electronics, Global Mechanics (for Tracker), and TDAQ; and is achieved through multiple laboratories (ANL, BNL, LBNL, and SLAC National Accelerator Laboratory) and universities involvement. There are 28 DOE deliverables and 13 NSF deliverables.

The KPPs in the finalized Project Execution Plan (PEP) at CD-2/3 include design, fabrication testing, and delivery of project deliverables. Objective KPPs include extending the deliverables to the full desired detector coverage and include I&I. The project plan is designed to include objective KPPs.

Memoranda of Understanding (MOUs) between the project and all participant institutions have been executed, identifying scope, personnel, cost, schedule safety and quality assurance oversight, reporting, etc. In addition, the US-CERN HL-LHC agreement was executed in April 2023, outlining US commitments to HL-LHC ATLAS.

The total funding disbursement to the project amounted to $147.3 million to the end of FY 2023. A total of $5.8 million (expected FY 2024 disbursement) of $16.2 million have been allocated in FY 2024. Carry-over is used to provide funding to institutions and the project is not funding limited currently in FY 2024, but an appropriation will be needed to fully fund FY 2025 activities. The project is 56% complete with a contingency on cost-to-go of about 45-50% at about $31 million. While funding supports the baseline plan, there is insufficient schedule float between the US deliverable and CERN need-by date when executing the base plan.

The baseline schedule presented was the December 2023, with a working schedule reflecting updates status since December and used for the Monte Carlo analysis. The CD-4 date includes two years of built-in float and the US schedule to CD-4 is not in jeopardy at this point, but the schedule to the "CERN need-by dates" has several shortcomings.

Specifically, the project's reports that numerous WBS elements currently have insufficient float to meet CERN LS3 need-by dates. The WBS elements and the amount of float deficit as demonstrated by Monte Carlo analysis are:

- Strips – 14 months
- Pixels – 5 months
- LAr – 2 months

The reduction in schedule float is at odds with the LS3 "CERN need-by dates" and the project reported that several other international contributors have utilized schedule float. A presentation from International ATLAS would have been beneficial to set the US schedule delay in the background of overall HL ATLAS schedule.

The project holds quarterly risk workshops to update the Risk Register. The Monte Carlo risk analysis is updated annually. The overall risk has decreased at a rate that is commensurate with the progress of the project since CD-2/3 and with contingency spend totals. COVID impacts have largely disappeared from the project currently, though minor COVID-related supply chain risks are still encountered.

The project appears to have all necessary safety and health related documentation in place (e.g., an Integrated Safety Management System Plan and Construction Safety and Health Plan) for work being done for the project. BNL employs a decentralized approach to the management of ESH requirements for each of its outside partners and collaborators, including other DOE National Laboratories. Considering the number of partners and collaborators, this approach appears to make sense. For these outside collaborators and partners, the ESH policies applicable at their respective site are followed for all work under this project. The Committee was told that there was a huge effort to put into place MOUs at all of the off-site locations documenting this arrangement. It is recognized by the US ATLAS project team, via their Project Management Plan, that the MOUs are useful instruments but do have limitations.

4.2 Comments

The preparation and documentation provided for this review was very good and the project has adequately addressed recommendations from prior reviews. Congratulations to the overall US ATLAS project team!

The project has benefited from approximately $32 million additional funding from the Inflation Reduction Act in FY 2022. Currently, the project budget is in good shape with respect to funding; however, an appropriation will be needed in FY 2025 to ensure that the project has enough funding to continue efficiently.

The project demonstrated progress since CD-2/3, including significant progress on CD-3A scope. Photographs included in the presentations are a helpful tool to help reviewers visually identify progress toward significant project milestones.

Total project procurements are 67% complete, including 87% complete for pixels and 75% complete for strips. Major procurements were adequately identified and largely completed via CD-3A scope, which has allowed the project to progress relatively unhindered by procurement delays. The project also derives significant benefit from CERN's sophisticated procurement mechanism, as indicated in presentations by multiple Level 2 managers.

The project cost contingency levels appear to be adequate based on Monte Carlo analysis including the inclusion of recent crises (more on this later). If needed, I&I objective KPP scope may also be deferred, but the project is optimistic that will not be necessary.

The US Project team was open and transparent with ongoing issues to which it is attending.

These issues include:

- Strips Sensors Fracturing
- Schedule float insufficiency, as demonstrated by Monte Carlo analysis, to meet CERN LS3 need-by dates
- Downward pressure on research budgets impacting scientific labor
- Encountered and ongoing risks and external dependencies including Pixels (availability of bare quad modules from international partners), Strips (sensor fracturing when staves are cooled), LAr (FEB2-NSF and LASP-international delays impacting System Integration) and I&I (start impacted by delays in deliverables)

Besides these four items, no other significant issues were identified by either the Committee or project team that would require management attention.

The project was impacted by a crisis (Item 1 above, Strip Sensors Fracturing), which is one major contributing factor in making the schedule *incompatible* with the LS3 schedule and CERN need-by dates. Management of the crisis was appropriate. Actions, such as a call for "all hands on deck", open communication, capture of new risks to be managed going forward and rapid decision making (i.e., use of Hysol as a new bonding element), were appropriate. The same approach needs to be maintained through the testing of the new 3+3 staves in case a second failure is lurking around the corner.

The risk for a second failure in the stave assemblies is captured by the Risk Register and is mostly at the basis for the approximately 12-month schedule delay (to set the scale) advertised by the US project team. The project indicated that alternative solutions have been considered, but the team would not develop them until the initial solution based on Hysol bonding element is tested.

Some major "final deliverable" productions activity in the US (i.e., pixel shells or strip staves) have not achieved full PRR approval to move ahead. This is potentially troublesome only about one year after CD-2/3 approval. It is bestowed on the project office to follow closely the preparation for the most critical PRRs coming up in the near future.

- Global Mechanics is supposed to achieve PRR in approximately three months
- The Strips Staves tests and resolution of sensors fracturing issue is expected in the next three months with full PRR approval shortly thereafter.

In addition to start production, the project needs to analyze options for improvement to the global production schedule. Schedule advancement potentials (or "schedule economies", as called by the project) have been described at a rough level. A more precise estimate needs to be developed.

It is reasonable to expect that schedule advancements will introduce additional risks and cost increases (additional hardware for productions lines, additional efforts for oversight and quality assurance/safety activities, etc.) that will push against the TPC ceiling. The US ATLAS project team possesses the potential to defer I&I activities (rather than reducing "hardware scope") if cost increases are pushing against the TPC ceiling. It is worthwhile for the US project team to socialize and discuss with CERN/International ATLAS the potential consequences of cost increases for schedule advancement to make them an active part of the best eventual baseline solution.

The project concisely summarized dependencies on outside resources at WBS Level 2. The list of main dependencies covers Pixels, Strips, LAr, DAQ, and I&I with potential impacts captured in the Risk Register and ranging from one to twelve months in the schedule. GM has no significant remaining external dependencies.

There is a significant contribution of uncosted scientific labor to the project, about 100 FTE-years going forward. These are funded from the DOE and NSF research programs, which have seen flat-flat funding at best. If groups participating in the upgrade project were to fare at the average level, this effectively means about 10% reduction in available FTEs every three years. A risk has been introduced to cover for the potential replacement of these resource with technical personnel with minimal schedule impact.

In 2018, the project scope was reviewed and determined to be within the scope of an existing National Environmental Protection Act (NEPA) Categorical Exclusion (CX). This review was documented in a letter from the BNL NEPA subject matter expert to the BNL Project Manager. However it was not clear, based upon the documentation provided, whether the cognizant DOE NEPA Compliance Officer (NCO) agreed with the determination. As such, the US ATLAS Project Team should confirm that the cognizant DOE NCO agrees that the determination outlined April 17, 2018, letter, entitled "NEPA Review of Proposal HL-LHC ATLAS Upgrade – Phase II", meets the NEPA requirements applicable to the project.

Project documentation provided to the Committee states that a security and vulnerability risk review was performed in 2018 and that the project did not require a Security Vulnerability Assessment Report (SVAR) in reference to DOE Order 413.3B. This review was documented in a BNL letter (from the BNL Manager of Safeguards and Security Division to the BNL Project Manager) dated April 24, 2018. Nonetheless, considering the large number of seismic shifts that have occurred in the safeguards and security arena since 2018, it would be prudent for the US ATLAS Project Team to evaluate whether this April 24, 2018, letter requires a refresh to ensure that all pertinent DOE security requirements have been met and are acceptable to cognizant DOE security official.

US ATLAS Project Team ESH representatives should continue to monitor and visit, when possible, the worksites of these partners and collaborators as part of their continued oversight.

4.3 Recommendations

13. Ensure successful completion of upcoming PRRs (Global Mechanics and Stave Production) estimated to take place within the next six months.

14. Prepare a more detailed schedule and cost estimate for potential improvements to key Production Activities within six months, or earlier if possible.

15. Socialize with CERN/International ATLAS the potential consequences of cost increases for schedule advancement if the current LS3 schedule is maintained. Achieve this by the end of CY 2024.

Appendix A Charge Memo

Department of Energy
Office of Science
Washington, DC 20585

MEMORANDUM FOR KURT FISHER
DIRECTOR
OFFICE OF PROJECT ASSESSMENT

FROM: MICHAEL PROCARIO
DIRECTOR, FACILITIES DIVISION
OFFICE OF HIGH ENERGY PHYSICS

Michael P. Procario
Digitally signed by Michael P. Procario
Date: 2024.01.08 13:22:10 -05'00'

SUBJECT: Request to conduct an Independent Project Review of the HL-LHC ATLAS Detector Upgrade Project

I request that your office conduct an Independent Project Review of the High Luminosity-Large Hadron Collider (HL-LHC) A Toroidal LHC Apparatus (ATLAS) Detector Upgrade Project at Brookhaven National Laboratory (BNL). The purpose of the review is to assess the project's status and progress since the last Department of Energy review, held on October 18-20, 2022, at BNL. This status review will be held on February 21-23, 2024, at BNL with Zoom video access available.

Your review committee is requested to perform a general assessment of the project’s progress, status, the identification of potential issues and address the following questions:

1. Is the project making adequate technical progress to ensure that the completed project will perform as planned and the key performance parameters will be met?
2. Are the resource-loaded schedule and the estimate-to-complete up-to-date, accurate, and credible?
3. Does the project understand its dependencies on outside resources such as international collaborators, funding from other agencies, and participation by researchers with other funding sources?
4. Are the major procurements being managed successfully?
5. Is Environmental Safety and Health being handled appropriately?
6. Has the risk analysis been updated to reflect the real risks of completing the project and are the contingencies acceptable?
7. Has the project satisfactorily responded to the recommendations from previous reviews?
8. Are there any other significant issues that require management attention?

As Program Manager for the HL-LHC ATLAS Detector Upgrade, Dr. Athanasios Hatzikoutelis will serve as the contact person for the Office of High Energy Physics for this review.

We appreciate your assistance in this matter. As you know, these reviews play an important role in our program. I look forward to receiving your committee's report.

cc: Harriet Kung, DDSP
Juston Fontaine, DDO
Athanasios Hatzikoutelis, DDSP/HEP
Kurt Fisher, OPA
Robert Caradonna, BHSO
J. Kotcher, BNL
Dmitri Denisov, BNL

Appendix B Review Committee

DOE/SC Status Review of the
High Luminosity LHC ATLAS Detector (HL-LHC ATLAS) Project at BNL
February 21-23, 2024

Kurt Fisher, DOE/SC/OPA, Chairperson

SC1 Silicon Strips	SC2 Pixel	SC3 Global Mechanics	SC4 Trigger/DAQ
* Steve Nahn, FNAL	* Matthew Jones, Purdue	* Andreas Jung, Purdue	* Monica Tecchio, U of Michigan
Anadi Canepa, FNAL	Petra Merkel, FNAL	Stefan Gruenendahl, retired FNAL	Darin Acosta, Rice University

SC5 LAr Calorimeter Electronics	SC6 Cost and Schedule	SC7 Project Management and ES&H
* Terri Shaw, FNAL	* Jolie Macier, FNAL	* Giorgio Apollinari, FNAL
Sergey Los, FNAL	Kathy Bailey, ORNL	Jon Cisek, ANL
	Christopher Hart, ORNL	*Kevin Hartnett, DOE/BSO*
	Katherine Southworth, ORNL	

Observers

Regina Rameika, DOE/HEP	Robert Caradonna, DOE/BHSO
Mike Procario, DOE/HEP	Cheuk Kwok, DOE/BHSO
Athans Hatzikoutelis, DOE HEP	James Shank, NSF
Joseph Diehl, DOE/HEP	
Abid Patwa, DOE/HEP	

LEGEND

SC Subcommittee
* Chairperson
[ ] Part-time Subcom. Member
ITA Will participate remotely
Count: 18 (excluding observers)

Appendix C Review Agenda

DOE/SC Status Review of the
High Luminosity LHC ATLAS Detector (HL-LHC ATLAS) Project at BNL
February 21-23, 2024

Agenda

Wednesday, February 21, 2024 (EDT): Plenary (includes 7' for questions), Berkner B

8:30 am	Full Committee Executive Session	Kurt Fisher
9:30 am	Welcome	Dmitri Denisov
9:35 am	Project Status and Overview	Jonathan Kotcher
10:20 am	Technical Status, I&I	Hal Evans
10:55 am	Break	
11:10 am	Baseline Cost & Schedule, EVMS	Penka Novakova
11:45 am	Maturity & Risk, Monte Carlo	Gustaaf Brooijmans
12:20 pm	Lunch	
1:20 pm	Pixels	Philippe Grenier
1:55 pm	Strips	Tony Affolder
2:30 pm	Global Mechanics	Eric Anderssen
3:05 pm	Break	
3:20 pm	Liquid Argon	John Parsons
3:50 pm	Trigger & Data Acquisition	Stephanie Majewski
4:20 pm	Full Committee Executive Session	Kurt Fisher
6:00 pm	Adjourn	
6:30 pm	Dinner (TBA)	

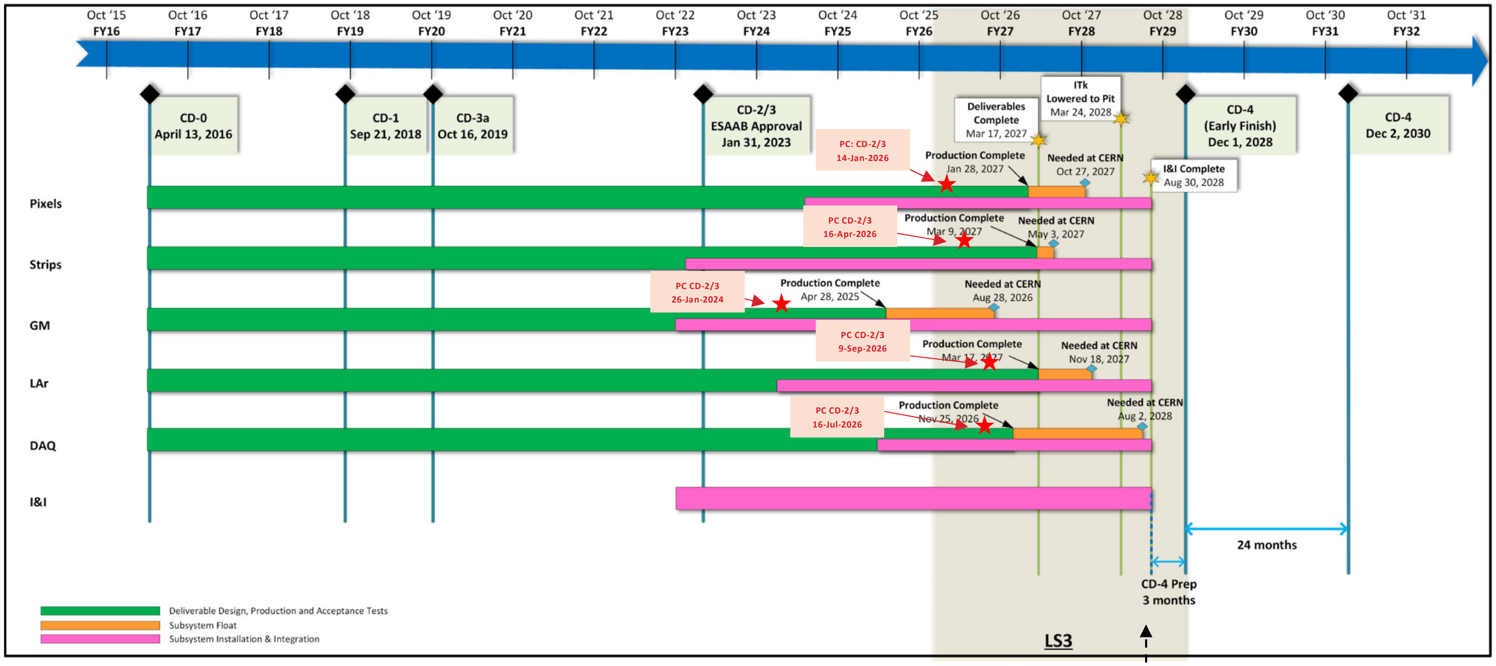
Thursday, February 22, 2024: Breakout Sessions

8:30 am	Subcommittee Breakout Sessions	Sub. Chairs
10:15 am	Break (timing TBD by each subcommittee)	
10:30 am	Subcommittee Breakout Sessions *Includes CAM interviews, if/as required*	Sub. Chairs
12:30 pm	Lunch	
1:30 pm	Responses to Questions	Full Committee & Project Team
2:30 pm	Subcommittee Executive Sessions	Sub. Chairs
4:00 pm	Executive Session, report writing	Kurt Fisher
6:00 pm	Adjourn	

Friday, February 23, 2024: Final Report Preparation & Closeout, Berkner B

8:30 am	Executive Session/Report Writing
10:00 am	Closeout Dry Run
11:30 am	Break, fact checking with project team
12:30 pm	Closeout Presentation
1:30 pm	Adjourn

Appendix D HL-LHC ATLAS Schedule Chart



- Based on the working schedule (no MC).
- Min. deliverable base float to CERN need-by date = 2 mo. (strips)
- Given its scale and pit access requirements, ITk will drive the HL-LHC schedule.

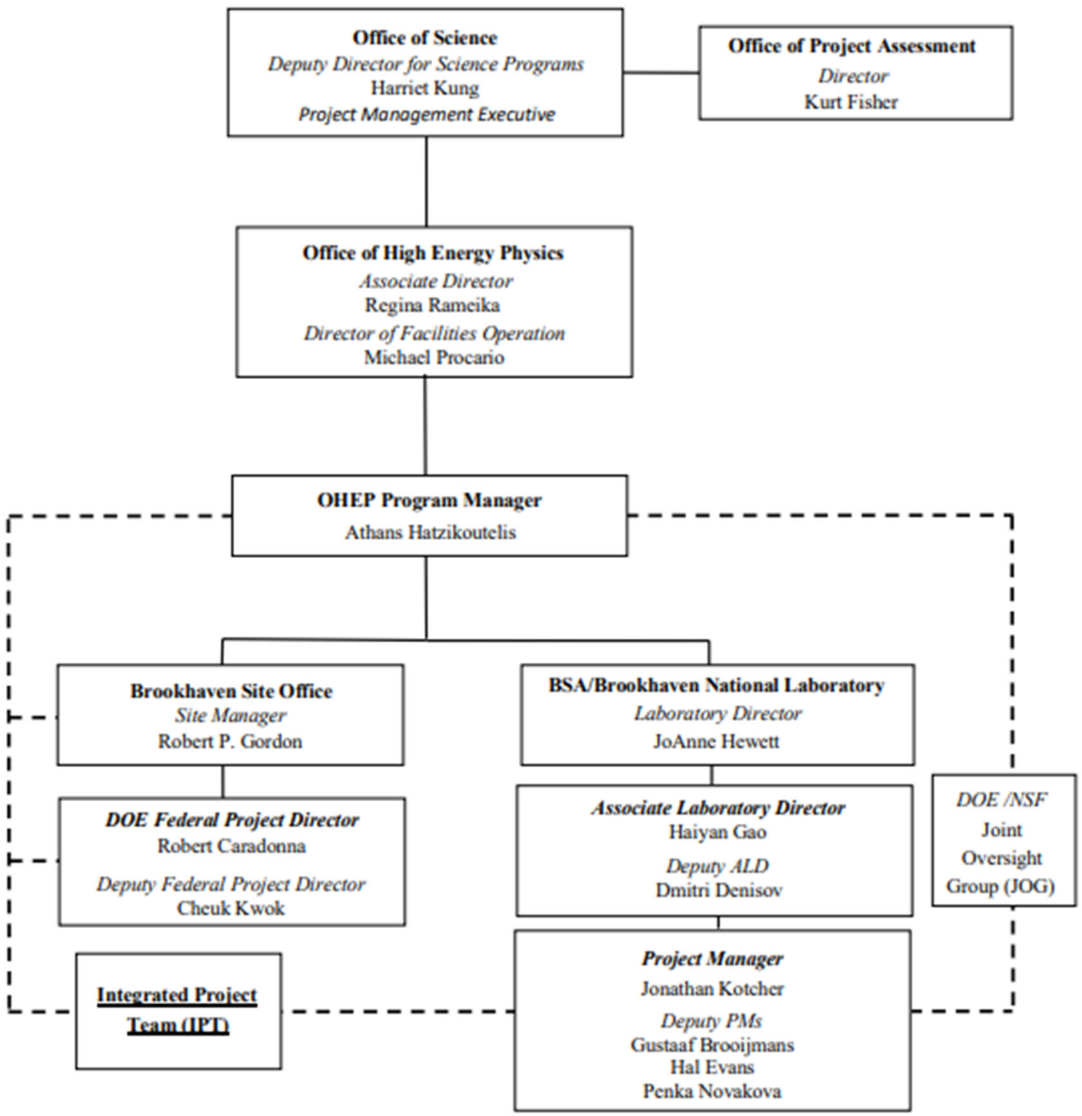
Objective KPPs

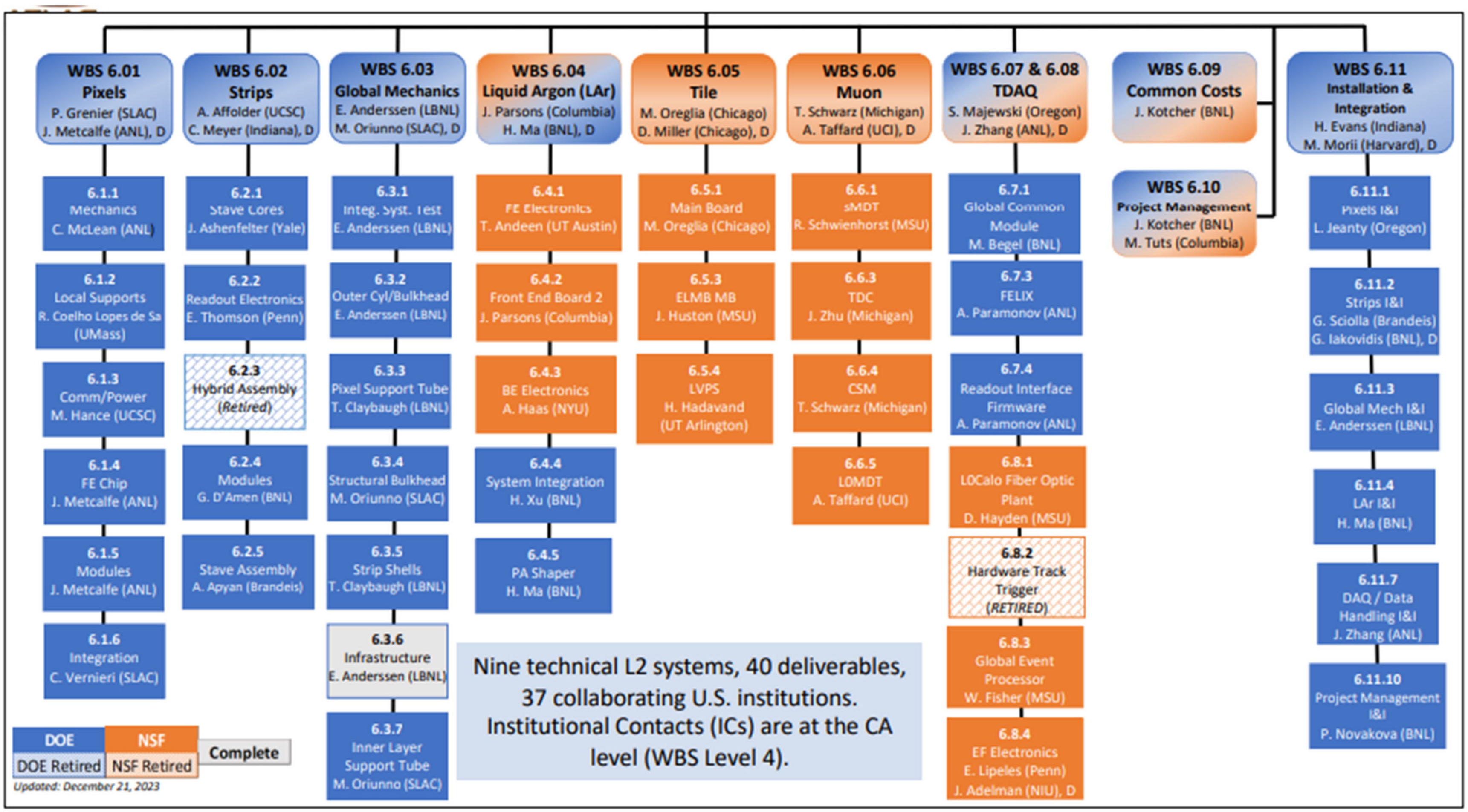
J. Kotcher, Project Manager US ATLAS HL-LHC DOE IPR Review, Feb 21-23, 2024 1

Appendix E HL-LHC ATLAS Funding Table

DOE Funding Guidance Jan 2024 (AY$k)		**FY21 & Prior**	**FY 2022**			**FY 2023**	**FY 2024**	**FY 2025**	**FY 2026**	**FY 2027**	**FY 2028**	**Total**
			Approp.	***IRA***	***TOTAL***							
	TPC	**84,515**	**20,000**	**32,785**	**52,785**	**10,000**	**16,200**	**16,200**	**14,000**	**6,300**	**-**	**200,000**
	TEC	68,000	20,000	32,785	52,785	10,000	16,200	16,200	14,000	6,300	-	**183,485**
	OPC	16,515	-			-	-	-	-	-	-	**16,515**

Appendix F HL-LHC ATLAS Management Chart




WBS 6.01 Pixels P. Grenier (SLAC) J. Metcalfe (ANL), D
WBS 6.02 Strips A. Affolder (UCSC) C. Meyer (Indiana), D
WBS 6.03 Global Mechanics E. Anderssen (LBNL) M. Oriunno (SLAC), D
WBS 6.04 Liquid Argon (LAr) J. Parsons (Columbia) H. Ma (BNL), D
WBS 6.05 Tile M. Oreglia (Chicago) D. Miller (Chicago), D
WBS 6.06 Muon T. Schwarz (Michigan) A. Taffard (UCI), D
WBS 6.07 & 6.08 TDAQ S. Majewski (Oregon) J. Zhang (ANL), D
WBS 6.09 Common Costs J. Kotcher (BNL)
WBS 6.10 Project Management J. Kotcher (BNL) M. Tuts (Columbia)
WBS 6.11 Installation & Integration H. Evans (Indiana) M. Morii (Harvard), D
6.1.1 Mechanics C. McLean (ANL)
6.1.2 Local Supports R. Coelho Lopes de Sa (UMass)
6.1.3 Comm/Power M. Hance (UCSC)
6.1.4 FE Chip J. Metcalfe (ANL)
6.1.5 Modules J. Metcalfe (ANL)
6.1.6 Integration C. Vernieri (SLAC)
6.2.1 Stave Cores J. Ashenfelter (Yale)
6.2.2 Readout Electronics E. Thomson (Penn)
6.2.3 Hybrid Assembly (Retired)
6.2.4 Modules G. D'Amen (BNL)
6.2.5 Stave Assembly A. Apyan (Brandeis)
6.3.1 Integ. Syst. Test E. Anderssen (LBNL)
6.3.2 Outer Cyl/Bulkhead E. Anderssen (LBNL)
6.3.3 Pixel Support Tube T. Claybaugh (LBNL)
6.3.4 Structural Bulkhead M. Oriunno (SLAC)
6.3.5 Strip Shells T. Claybaugh (LBNL)
6.3.6 Infrastructure E. Anderssen (LBNL)
6.3.7 Inner Layer Support Tube M. Oriunno (SLAC)
6.4.1 FE Electronics T. Andeen (UT Austin)
6.4.2 Front End Board 2 J. Parsons (Columbia)
6.4.3 BE Electronics A. Haas (NYU)
6.4.4 System Integration H. Xu (BNL)
6.4.5 PA Shaper H. Ma (BNL)
6.5.1 Main Board M. Oreglia (Chicago)
6.5.3 ELMB MB J. Huston (MSU)
6.5.4 LVPS H. Hadavand (UT Arlington)
6.6.1 sMDT R. Schwienhorst (MSU)
6.6.3 TDC J. Zhu (Michigan)
6.6.4 CSM T. Schwarz (Michigan)
6.6.5 L0MDT A. Taffard (UCI)
6.7.1 Global Common Module M. Begel (BNL)
6.7.3 FELIX A. Paramonov (ANL)
6.7.4 Readout Interface Firmware A. Paramonov (ANL)
6.8.1 L0Calo Fiber Optic Plant D. Hayden (MSU)
6.8.2 Hardware Track Trigger (RETIRED)
6.8.3 Global Event Processor W. Fisher (MSU)
6.8.4 EF Electronics E. Lipeles (Penn) J. Adelman (NIU), D
6.11.1 Pixels I&I L. Jeanty (Oregon)
6.11.2 Strips I&I G. Sciolla (Brandeis) G. Iakovidis (BNL), D
6.11.3 Global Mech I&I E. Anderssen (LBNL)
6.11.4 LAr I&I H. Ma (BNL)
6.11.7 DAQ / Data Handling I&I J. Zhang (ANL)
6.11.10 Project Management I&I P. Novakova (BNL)
Nine technical L2 systems, 40 deliverables, 37 collaborating U.S. institutions. Institutional Contacts (ICs) are at the CA level (WBS Level 4).
DOE
NSF
Complete
DOE Retired
NSF Retired
Updated: December 21, 2023