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Office of Science
Washington, DC 20585

SEP 29 2014

MEMORANDUM FOR: JAMES SIEGRIST
ASSOCIATE DIRECTOR
OF THE OFFICE OF SCIENCE
FOR HIGH ENERGY PHYSICS

FROM: STEPHEN W. MEADOR
DIRECTOR
OFFICE OF PROJECT ASSESSMENT

SUBJECT: Final Report on the DOE/SC Review of the LHC CMS Detector Upgrade Project, August 2014

Attached for your consideration and use is the final report on the Department of Energy/Office of Science review of the LHC CMS Detector Upgrade project. The LHC CMS Detector Upgrade review was conducted August 5-7, 2014, at the Fermi National Accelerator Laboratory in Batavia, Illinois.

If you have any questions or would like to discuss the report further, please contact me.

Attachment

cc:
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M. Procario, SC-25
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S. Rolli, SC-25
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SC-25	SC-28	SC-28
See Attached		
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9/26/14	9/29/14	9/29/14

Department of Energy/Office of Science
Review Committee Report

on the

Technical, Cost, Schedule, and
Management Review

of the

LHC CMS DETECTOR UPGRADE PROJECT

August 2014

EXECUTIVE SUMMARY

A Department of Energy/Office of Science (DOE/SC) review of the U.S. Compact Muon Solenoid (CMS) Detector Upgrade project was conducted on August 5-7, 2014, at Fermi National Accelerator Laboratory (FNAL). The review was conducted by the Office of Project Assessment (OPA), and chaired by Kurt Fisher, at the request of Michael Procario, Director, Facilities Division for High Energy Physics. The purpose of the review was to evaluate the CMS project's progress and readiness to proceed to Critical Decision (CD) 2/3, Approve Performance Baseline and Start of Operations, including technical aspects, the overall cost, schedule, and management aspects.

The Committee found that CMS Upgrade design has proceeded well since the August 2013 CD-1 review. The project team has the appropriate skills mix and management experience. The Committee recommended that the project proceed to CD-2/3 after addressing the review recommendations.

Hadron Calorimeter (HCAL)

The Committee noted that the replacement of the present photo-sensors with Silicon photo-multipliers (SiPMs) allows increased granularity the HCAL readout and includes timing information to deal with the higher pile-up. Accompanying "back-end" electronics, provides increased bandwidth to handle the resulting larger volume of information.

All key elements of the design have been tested through prototype; a successful integration test of the readout has been carried out; prototype and some pre-production units of several elements of the boards and crates are in progress. Two vendors capable of meeting the performance specification for the SiPM have been qualified; the QIE10and QIE11 ASICs are being tested in an engineering run.

Forward Pixel Detector (FPIX)

The Committee found that the bump bonding cost estimate is currently based on a quote from the same U.S. vendor (RTI) that produced 60% of the original FPIX modules. It is much lower than a second quote from IZM in Germany. RTI's quote is roughly two times lower than an extrapolation with escalation of the original FPIX production. RTI has been asked for an updated quote. The RTI prototype costs per module were also significantly higher than their quote for final production modules. The assumed contingency in the budget is 60%, based on the U.S. CMS single source rules. Given the issues described above, 60% contingency seems low at this time.

Level 1 Trigger

The proposed design addresses the increase in luminosity, beam energy, and pile-up anticipated in Large Hadron Collider (LHC) Run 2 and Run 3 by expanding the information available to the Level 1 Trigger and by substantially increasing the trigger's processing power. The trigger upgrade will be commissioned "in beam" by operating it in parallel with the existing system.

Experience gained by building and operating the existing CMS trigger system puts the project team in a strong position to complete this sub-project on time and on budget.

Although the flexibility of the system will offer opportunities for ongoing algorithmic improvements as physics needs evolve, it is important to retain a clear baseline against which progress on the trigger upgrade sub-project can be measured.

Cost and Schedule

The Total Project Cost (TPC) is $33.580 million for DOE and $43.364 million when the National Science Foundation (NSF) contribution is included. The total DOE funding profile is $33.25 million. Cost Contingency includes $5.525 million for estimate uncertainty and $1.836 million for risk. This equates to 33% on costs to go. CD-4 is planned for December 2019.

Critical paths are developed for the three subsystems with HCAL driving project completion. The schedule contingency is 13 months from the "HCAL Complete" to CD-4. The FPIX and Level 1 Trigger are completed approximately three years before CD-4.

The DOE TPC slightly exceeds the available funding. Total Estimated Costs (TEC) and Other Project Costs (OPC) estimates differ among documents and presentations.

The cost contingency appears to be reasonable for this stage of the project. It was developed using well-defined methodology. Activities to obtain DOE approval of CD-4 are not included in the schedule and can reduce the advertised schedule contingency.

Project Management

The Committee determined that, given their prior participation on the CMS Project, CMS Operations, and Upgrade preparatory activities, the U.S. CMS Upgrade project staff has extensive background and experience.

The Committee suggested that the project team document and prioritize first articles and pre-production items to ensure maximum flexibility regarding funding modalities.

Laboratory-wide procedures for things like change control need to be properly captured and tailored for specific projects (their size and their needs). The restrictive change control threshold at the "PM level" will require a high-level of interaction with the Program Management Group (PMG). This may force the Program Manager (PM) to "manage up," when in fact the PM would need to be working with the Level 2 managers. The purpose for the PMG interaction is to ensure good access to FNAL resources and oversight, this needs to be balanced against the CMS Upgrade having a large external effort (77% of effort is external to FNAL).

The following recommendations must be addressed prior to CD-2:

- Review data in Basis of Estimate (BOE) text and data to identify and correct errors, and apply consistent contingency rules to all elements of the Work Breakdown Structure (WBS).
- Review the contingency assigned to bump bonding, considering the two differing quotes, and the escalated estimate projected from the original FPIX project involving two vendors.
- Reconcile the TPC with the funding and correct the OPC/TEC split in the project documentation.
- Update and finalize the project documentation.
- The laboratory should quickly finalize procedures (e.g., change control) or establish interim procedures that can be used for the CMS Upgrade Major Item of Equipment. Laboratory procedures or interim procedures should be specified in the Project Management Plan and the Project Execution Plan made consistent with those.

After these recommendations are addressed, the project should proceed to CD-2/3 approval.

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1. INTRODUCTION

The Compact Muon Solenoid (CMS) detector operates at the Large Hadron Collider (LHC) at CERN. The CMS Detector and the other general purpose detector ATLAS, were conceived to study proton-proton (and lead-lead) collisions at a centre-of-mass energy of 14 TeV (5.5 TeV nucleon-nucleon) and at luminosities up to 10^{34} cm^{-2} s^{-1} (10^{27} cm^{-2} s^{-1}). At the core of the CMS detector sits a high-magnetic-field and large-bore superconducting solenoid surrounding an all-silicon pixel and strip tracker, a lead-tungstate scintillating-crystals electromagnetic calorimeter, and a brass-scintillator sampling hadron calorimeter. The iron yoke of the flux-return is instrumented with four stations of muon detectors covering most of the 4π solid angle. Forward sampling calorimeters extend the pseudorapidity coverage to high values ($|\eta| \leq 5$) assuring very good hermeticity. The overall dimensions of the CMS detector are a length of 21.6 m, a diameter of 14.6 m, and a total weight of 12,500 tons.

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-like 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-like boson's properties, including its couplings to other particles, self-couplings, and rare decays.

The U.S. participation in the CMS experiment has been crucial to its success. The U.S. CMS collaboration, with 48 institutions, about 430 Ph.D. physicists, almost 250 graduate students, and nearly 200 engineers, technicians, and computer scientists is the largest national group in the CMS 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. Approximately 700 physicists from U.S. institutions conduct research as collaborators in CMS. They are 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. CMS Operations Program, which is jointly funded by DOE and NSF.

The high energy and luminosity available at the LHC offers the best opportunities for exploration of new physics beyond the Standard Model (SM) and for making precision

measurements of properties of known phenomena. The LHC began operations in 2009 and has delivered over 5 fb^{-1} of data to CMS with luminosities peaking at $3x10^{33}$ cm^{-2} s^{-1} at a center-of-mass energy of 7 TeV. This corresponds to one-third of its design luminosity and half of its design energy. In 2012, the LHC continued its operation at a slightly higher center-of-mass energy of 8 TeV and delivered an additional 20 fb^{-1} to each experiment, which allowed both the CMS and ATLAS experiments to announce the discovery of the Higgs boson in July 2012. The repair of the splices in the LHC is being planned during a long shutdown in 2013-2014. This will allow the LHC to operate at its design parameters with a center of mass energy of approximately 14 TeV and peak luminosities of 10^{34} cm^{-2} s^{-1} when data taking resumes in 2015.

The next long shutdown is being planned for 2018-2019 after which peak luminosities are expected to reach 2-3 x 10^{34} cm^{-2} s^{-1} corresponding to 50 to 80 interactions per crossing (pile-up) with 25 ns bunch spacing operation. In order to preserve adequate detector performance in this high luminosity environment, and hence the discovery potential, significant detector improvements are required. The LHC U.S. CMS Detector Upgrade Project (CMS Upgrade) is designed to enhance the detector capability for the high luminosity data run (Phase I) that is scheduled to begin in 2020. Upgrades to the accelerator during the preceding shutdown will result in delivered instantaneous luminosity that exceeds the original luminosity design specifications of 10^{34} $cm^{-2}s^{-1}$ by a factor of two or three.

Upgrades are needed to three detectors where the U.S. played a leadership role in the original construction: the Pixelated Inner Tracking (Pixel) Detector (FPIX), the Hadron Calorimeter (HCAL) Detector, and the Trigger (L1Trig).

Pixelated Inner Tracking (Pixel) Detector—The Pixel detector plays a key role in the identification of primary vertices, secondary vertices, and secondary tracks. These elements are essential for the efficient identification of long-lived particles, such as *b* quarks, and for the search for new physics at the LHC. The upgrade of the Pixel detector is driven by radiation damage, caused by particles produced at the collision point. The upgraded Pixel detector would replace the degraded present detector while being itself more radiation tolerant to future damage. In addition the upgrade is driven by the data loss at peak luminosity due to the increased number of tracks per crossing at the expected higher luminosities. The new detector and associated electronics greatly reduce the data loss problem and will enable the expanded tracking information to enhance track reconstruction. The implementation of the upgraded Pixel detector would improve all aspects of the CMS tracking.

Hadron Calorimeter (HCAL) Detector—The HCAL upgrade will implement depth segmentation to cope with the higher luminosities. This is achieved by using a new photo-detector, the Silicon Photomultiplier (SiPM), that provides the high gain needed for segmentation; and new electronics, required to read-out the increased data stream and to provide enhanced information to the upgraded Regional Calorimeter Trigger (RCT). In addition, the front-end electronics provides precise timing information that is needed to handle "out-of-time" pile-up that becomes important especially with 25 ns bunch spacing and is also crucial for rejecting various rare background events (from cosmic rays and machine background) in the search for new physics.

Level 1 Trigger (L1 Trig)—The present CMS trigger will need significant modifications to operate at the higher LHC luminosity. Due to the increased occupancy of each crossing the current L1 Trig system will experience degraded performance. Rebuilding the RCT and the Endcap Muon Trigger using new technologies addresses the peak instantaneous luminosity, high pile-up, and overall efficiency.

The excellent performance of the LHC in 2011 and 2012 has demonstrated its ability to deliver luminosity that exceeds expectations and it is therefore prudent to plan for higher than anticipated luminosity and pile-up conditions. 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 CMS plan for upgrades at the higher luminosity that will be needed to search for new physics with high efficiency. The overall CMS 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.

The CMS detector, including U.S. supplied components, were not designed for and are not capable of handling the higher data rates of the LHC expected in 2020 and beyond without the planned upgrades.

As with the U.S. participation in the construction of the original CMS detector, the CMS Upgrade will be funded jointly by DOE and NSF. The scope will be divided between the agencies in a manner that minimizes the inter-agency dependencies. The fractional cost sharing will be approximately 75% DOE and 25% NSF. DOE approved Critical Decision (CD) 0, Approve Mission Need, for the CMS Upgrade on September 18, 2012, and CD-1, Approve Alternative Selection and Cost Range, on October 17, 2013.

In preparation for DOE approval of Critical Decision (CD) 2/3, Approve Performance Baseline and Start of Construction, an independent review was conducted on August 5-7, 2014 at Fermi National Accelerator Laboratory (FNAL), in order to evaluate the proposed technical, cost, schedule, and management baselines, which are needed for CD-2 and the project's readiness for CD-3, which will approve the start of full construction.

The review was conducted by the DOE Office of Project Assessment, with the participation of technical experts.

In carrying out its charge, the Committee was asked to address the following questions:

1. Do the proposed technical design and associated implementation approach satisfy the performance requirements? Are the CD-4 goals well defined?

2. Performance Baseline: Is the cost estimate and schedule consistent with the plan to deliver the technical scope with the stated performance? Is the contingency adequate for the risk?

3. Final Design: Is the design sufficiently mature so that the project can continue with procurement and fabrication? Baseline Cost and Schedule: Are the current project cost and schedule projections consistent with the approved baseline cost and schedule? Is the contingency adequate for the risks?

4. Are the management structure and resources adequate to deliver the proposed final design within the baselines as identified in the PEP?

5. Is the documentation required by DOE Order 413.3B for CD-2 and CD-3 complete?

6. Are ES&H aspects being properly addressed given the project's current stage of development?

2. TECHNICAL STATUS

2.1 Hadron Calorimeter

2.1.1 Findings

The HCAL upgrade project consists of upgrades to the front-end electronics, readout sensors, and back-end electronics to allow the CMS calorimeter system to maintain high performance in the high instantaneous luminosity expected following Long Shutdown 2 of the LHC, and to an integrated luminosity of a few hundred fb^{-1}. Depth granularity is introduced to the HB (barrel) and HE (endcap) calorimeters to mitigate the impact of radiation damage to the plastic scintillator and to improve the performance of the calorimeter for particle flow reconstruction of jets. The implementation takes advantage of the moderate channel cost, small size, and improved quantum efficiency of SiPMs as the readout sensor. In the HF (forward), timing available from the QIE10 application specific integrated circuit (ASIC), together with the use of dual readout of the light signals in multi-anode photomultiplier tubes (PMT) allows rejection of non-prompt background signals that would otherwise be a significant background in triggering on, and measuring, VBF Higgs production. The QIE10 and QIE11 ASIC provide greater dynamic range to maintain the effectiveness of the isolation variable in the detection of prompt leptons such as from W decay. The upgrade plan divides into tasks associated with the HF, scheduled for 2015-2016 for HB/BE, scheduled for LHC LS2, and for the common back-end electronics, which can be installed as soon as available since no access to the CMS detector cavern is required. The findings specific to each of these systems follow.

Forward Calorimeter (HF)

The HCAL project will replace the full front-end electronics for the two forward calorimeters. The schedule calls for delivery of the hardware to CERN in September 2015 for testing and burn-in. Installation on the detector is planned for the winter shutdown of 2016 (January-February). The hardware is needed for improved jet tagging with the forward calorimeter, particularly for the vector boson fusion channel for Higgs production.

The principal items needed are 200 QIE boards using QIE10 custom ASICS, 20 ngCCM clock and control boards and ten calibration modules.

Prototypes of the QIE10 chips have been produced and an engineering run for 5,000 chips was launched in June 2014. This run is expected to supply enough chips to meet the final needs. The other components are largely conventional.

HCAL—HBHE Front-End

The project will replace the photo-detectors and associated front-end electronics for the HB and HE calorimeters. The new hardware will be installed in the existing mechanical enclosures on the detector wedges. These regions are only accessible during a long shutdown and the next one is currently planned to begin in 2018.

The replacements are necessary to cope with decreasing light yield from the calorimeter scintillators, to remove triggering and reconstruction issues coming from Hybrid PhotoDiod (HPD) gain drift and discharges, and to provide better performance at high pile-up.

This part of the upgrade will involve 26K SiPM, 18K QIE11 custom readout chips, and 1,500 QIE readout boards, 375 sets of three SiPM boards, together with supporting hardware.

Two vendors have been qualified for preproduction of the SiPMs and price quotes are available from both. The preproduction order is planned for August 2014 and final device selection for HE in 2015 and HB in 2016.

The QIE11 chip only differs from the QIE10 by the addition of a programmable input current shunt. The final design was submitted as part of the same engineering run as the QIE10 chip. If successful, it will furnish approximately 50% of the required units. The QIE readout boards are relatively low power, low-density boards. A pre-prototype has been constructed and the first full prototype is planned for fall 2014.

For the SiPM mounting boards, eight-channel prototypes have been built and evaluated, while 48-channel prototypes are planned in the fall of 2014.

HCAL—Back-End Electronics

The back-end electronics is common to all calorimeter sections. It receives the digitized data from every bunch crossing over optical links, calculates trigger primitives and transmits them to the calorimeter trigger. It also buffers the data while waiting for the trigger decision.

The system requires optical splitters so the new hardware can be commissioned in parallel with existing data taking, uHTR boards to receive the data, and AMC13 boards for crate management and data storage. Prototype uHTR boards have been built, tested, and approved by CMS. The AMC13 boards have been produced. Prototype optical splitters have been built and tested. Two vendors have been identified.

2.1.2 Comments

Comments arising from material presented at the review and from discussions with the HCAL team follow. The HCAL team is to be complimented on the significant progress since the CD-1 review in 2013:

- The HCAL project has made the decision to adopt the IGLOO2 chip as an alternative to the GigaBit Transceiver Chip (GBTX), thereby removing schedule risk—a concern at CD-1.

- The SiPM packaging issues have been resolved—a concern at CD-1.

- A successful integration test has been carried out; the test of a full readout box in a radiation field is planned for early 2015, prior to the Production Readiness Rreview (PRR)—a concern at CD-1.

- SiPMs from two vendors have been tested and shown to fully meet specification—further development work with vendors may realize devices with Photon Detection Efficiency (PDE) greater than 30%, which could provide greater margin against radiation damage effects. The HCAL team should be prudent in deciding when "good is good enough".

- An engineering run of QIE10/11 ASIC is in progress. The HCAL team is being conservative, but it appears that there is high likelihood of success and the team should plan for this.

- The HF schedule is aggressive but feasible. Prototypes are available for almost all components and test beam studies with the planned hardware have been done. A successful engineering run for the QIE10 chips will be an important milestone.

- During the review a successful drill-down was done for one of the three versions of front-end boards used to readout out the SiPMs, the SiPMs themselves and for their packaging. The documentation and supporting material were found to be in good order and the contingency levels very conservative.

- Basis of Estimate (BOE) element 401.02.04.05 contains a typographical error: (H110890 Fabrication of full chip M&S $26,654K).

- This portion of the CMS Phase 1 Upgrade project contains approximately 20 FTEs of contributed labor. This effort is associated to the project on a year-by-year basis through Statements of Work (SOW) with collaborating institutions and could be vulnerable to changes in the base program funding.

- A drill-down into a number of cost drivers in this part of the project demonstrated that the HCAL management team had good control of the costs and work performed and that the cost uncertainty was generally applied according to the project rules.

- The SiPM procurement is assigned contingency level M4; however, two vendors are capable of meeting the specification for these devices and have provided quotes.

2.1.3 Recommendations

1. Before CD-2, review data in BOE text and data to identify and correct errors. Apply consistent contingency rules to all elements of the WBS. Work with management to ensure accuracy of accrued cost data.

2. Proceed to CD-2/3 approval.

2.2 Forward Pixel Detector

2.2.1 Findings

The current CMS Forward Pixel Detector (FPIX) will continue to lose efficiency after Long Shutdown 1 (LS1) as the LHC luminosity exceeds 10^{34} cm^{-2} s^{-1}, seriously impacting physics performance. Specifically, track seeding, primary and secondary vertex reconstruction, and b-tagging will all be degraded. Upgrades are required to avoid these detrimental effects.

The CMS Collaboration developed an upgrade design to address this degradation, which is documented in the CMS technical proposal for an upgrade pixel system; the U.S. Technical Design Report (TDR) for the FPIX upgrade is based on this document.

The upgraded FPIX system comprises 44 million pixels on 672 modules, mounted on 12 half-disks; the upgrade increases the forward pixel layers from two to three, which increases the typical number of hits per track from three to four for eta<2.5 when combined with the barrel pixel detector. The system is designed to survive an integrated luminosity of 500 fb^{-1}.

The project is budgeted for the Objective Key Performance Parameters (KPPs), which include production of four half cylinders with three disks each and tested components for a spare half disk. The Threshold KPPs specify the four half cylinders, but not the spare half disk components. The components for a spare half disk represent scope contingency.

The FPIX upgrade project involves only U.S. collaborators, no non-U.S. members; however, the project relies on CERN support for aspects that are contributed at no cost to the U.S. Also, the FPIX project relies on digital readout chip (PSI) to supply the Pixel Readout Chip, as well as test setups purchased by the U.S. FPIX project.

The CMS Pixel Collaboration has assigned responsibilities for the various electronics components. The U.S. team is responsible for the Token Bit Managers (TBM) and relies on foreign collaborators for the Readout chips (ROCs), DC/DC (direct current/direct current) Converters, Detector Readout cards (FEDs), and optical receivers.

The latest ROC (PSI46digv2.2) was submitted in July and due back in September. Latest TBM issues have been corrected with 15 specific changes to the TBM08 design in a “Rocket” submission that produced devices in June. Tests of this chip, TBM08b, have proven successful. Irradiation tests are underway and irradiated chips are due back this week for final tests.

Performance and physics studies have been done for the full pixel system upgrade, barrel and forward, and calibrated to test beam data, using the digital readout chip (PSI46dig-v2.1). Significant improvements in signal efficiencies of 50-60% are demonstrated.

The FPIX upgrade project implements significant cost reduction measures compared to the original detector, such as using a single module everywhere, going to six-inch wafers for sensors, and using the same U.S. bump bonding vendor used for 60% of the original FPIX.

In order to complete the needed 672 modules plus 20% qualified spares, the construction plan includes production of 1,000 modules and assumes 85% yield. Sensors have been sole source ordered through a collaborating university (Kansas) with NSF funding.

Modules are being produced in parallel at Purdue and Nebraska. To date, 45 pre-production modules using university setups have been built, demonstrating the collaboration can build working modules.

The FPIX critical path is driven initially by the availability of half disk mechanics. Complete designs and procedures for building the disks and cooling system have been produced

and full prototypes for the disks and cooling are in progress. Both a four-blade prototype and a seventeen-blade outer half disk prototype have been built and demonstrated the required heat transfer resulting in less than 10° C differential from sensor to coolant. The schedule also calls for constructing and testing an eleven blade inner half disk prototype soon.

A pilot system involving eight modules will be installed in the CMS experiment in September 2014 and operated during LHC Run2. The main purpose of this pilot system is to practice aspects of the installation and commissioning, to facilitate conversion of the software and to gain operations experience for the final project.

In addition to the pilot system, a system test is planned at FNAL during January-June 2015, to validate the system performance of the electronics under final realistic conditions (with CO_2 cooling and carbon fiber mechanics).

The planned FPIX installation date in the present LHC schedule drives the U.S. project schedule.

The schedule is designed for delivery to CERN of the last Half Cylinder by August 2016 and handover to CMS operations by September 2016, to meet the installation target during the Extended Technical Stop early in 2017.

Risks are documented in the Risk Register, identifying 23 risks: 20 threats and three opportunities.

2.2.2 Comments

The FPIX team brings a large experience base to the project based on their significant role in the original CMS pixel project and current CMS pixel system.

Given the performance objectives, the scope is appropriate and the design is mature and nearly complete. The upgrade is designed to handle 2×10^{34} $cm^{-2}s^{-1}$ in luminosity with pile-up to 100 interactions per beam crossing and an integrated luminosity of 500 fb^{-1}. The upgrade results in higher efficiencies, lower fake rates, lower dead-time/data-loss and extended lifetime of the detector.

The design is well documented in the technical design report with reasonable cost estimates and documented basis of estimates.

The scope contingency represented by the difference between Objective KPPs and Threshold KPPs is appropriate.

The Risk Register has a thorough collection of risks with analysis of potential impacts. Readout chip and TBM development are nearing completion, thereby reducing risk, but should performance of either chip fall short of success the project will need to react quickly and effectively to protect the schedule.

Even though the number of spares is large, the module yield assumption (85%) is better than the yield from U.S. experience with the FPIX detector for both bump-bonding and assembly of 72% (BOE). The criteria placed on the acceptable dead pixels/ROC and HV requirements have been softened based on experience so the 85% module yield assumption is reasonable at this time.

The mechanical support design is innovative and very low mass. The prototype half disks under development and test will provide critical validation of the concept and implementation. Completion of engineering design of the necessary fixtures needed to fabricate these assemblies is a critical path item.

There are several critical path items needing early procurements, such as the thermal pyrolytic graphite (TPG) blades and the high density interconnects (HDI).

The pilot system will be useful to gain experience operating this system, in particular, on its integration in CMS. Some of the interface issues between the electronics and mechanics performance of the detector need to be validated with studies of modules read out and with mechanics and cooling infrastructure closer to the one implemented in the final system.

The bump bonding cost estimate is currently based on a quote from the same U.S. vendor (RTI) that produced 60% of the original FPIX modules. It is much lower than a second quote from IZM in Germany. RTI's quote is roughly two times lower than an extrapolation with escalation of the original FPIX production. RTI has been asked for an updated quote. The RTI prototype costs per module were also significantly higher than their quote for final production modules. The assumed contingency in the budget is 60%, based on the U.S. CMS single source rules. Given the issues described above, 60% contingency seems low at this time.

RTI is commissioning a new automated flip chip bonding machine, which could reduce cost by accelerating processing. The FPIX project plans to proceed with this approach if it achieves a successful yield. Given the need to continuously monitor the bump bonding via module electrical tests, such an accelerated process introduces risks that could offset any cost savings.

There is currently no electrical testing of diced ROCs prior to flip chip. Depending on the measured yield in prototypes for good chips on module, a new single chip probing step may need to be added.

The funding profile is much healthier than the profile presented for CD-1 and now appears adequate.

2.2.3 Recommendations

3. Prior to CD-2 approval, review the contingency assigned to bump bonding, considering the two differing quotes and the escalated estimate projected from the original FPIX project involving two vendors.

4. Work with management following CD-3 approval to proceed with urgent procurements, such as thermal pyrolytic graphite (TPG) blades and high density interconnects (HDI) for the modules.

5. Proceed to CD-2/3 approval.

2.3 Level 1 Trigger

2.3.1 Findings

The design of the proposed Level 1 Trigger (L1 Trig) upgrade addresses the increase in luminosity, beam energy, and pile-up anticipated in LHC Run 2 and Run 3. It does so by expanding the information available to the L1 Trig and by substantially increasing the trigger's processing power. The result is to improve the momentum resolution of the muon trigger and to increase the processing granularity of the calorimeter trigger.

The upgraded trigger will be commissioned during CMS data-taking with LHC beam by operating the new trigger in parallel with the existing trigger system. This approach allows the new trigger's operation to be verified in-situ without putting the ongoing operation of the CMS experiment at risk.

The key technical goal of the L1 Trig upgrade is clear: to reduce calorimeter and muon trigger rates by a factor of two with respect to the legacy system. The Threshold KPP is to achieve this rate reduction with less than 15% loss of efficiency, while the Objective KPP is to achieve this rate reduction with less than 10% loss of efficiency. Achievement of this goal can be verified using the upgraded trigger's emulation software.

Cost estimates for production runs of upgraded trigger hardware modules are based largely on actual costs of pre-production modules. Estimates of required effort for software and firmware development are based on the designers' past experience in developing the legacy trigger system and are validated with the designers' recent experience in developing the new trigger system.

The milestone completion date for the L1 Trig upgrade is the end of March 2017. The L1 Trig is currently expected to finish in September 2016, six months before the milestone date.

The hardware development is sufficiently advanced that many pre-production articles have already been installed and tested at a system level in the CMS experiment and/or the CERN Electronics Integration Center.

2.3.2 Comments

The technical approach to improved performance is to use high-bandwidth optical links to bring additional information into the trigger and to use powerful modern field programmable gate arrays (FPGAs) to increase processing capability. This approach is sound and leads to a high degree of confidence that the L1 Trig performance requirements will be achieved.

The L1 Trig use of common technical components across sub-systems allows developers to share expertise efficiently between systems. For example, the CTP7 and MTF7 modules use exactly the same Virtex7 FPGA model, which is also used in non-U.S. parts of the CMS L1 Trig upgrade, such as the MP7 module. Another example is the re-use of the MTF7 card, by reprogramming with different firmware, to implement the Muon Sorter function. A third example is the upgrade's reduction in the diversity of optical transceivers, such as the MTF7 optical module's standardization on Avago's AFBR transceivers.

The new trigger will be commissioned in parallel with ongoing CMS operations. This allows for uninterrupted acquisition of physics data with the well-understood legacy trigger system while gaining experience with the upgraded trigger system.

The trigger upgrade's staged commissioning approach allows the CMS physics program to benefit from trigger upgrade efforts well before the completion of the L1 Trig, by providing information used by the legacy trigger system as well as the upgraded system to parts of the upgraded trigger system. The upgrade plan and the hardware design are flexible enough to allow for further improvements.

The trigger upgrade's performance goals, as stated in the KPPs, address the two key features of a digital trigger. It must meet the physics needs of the experiment for a manageable trigger rate while maintaining high efficiency for the physics of interest. And it must operate in a manner that can be reliably modeled via software emulation so the impact of the trigger on physics is well understood. The design and execution of the L1 Trig is well integrated with the activities of the CMS experiment and with the upgrade project as a whole.

The proposed technical design and associated implementation approach satisfy the performance requirements with well-defined CD-4 goals.

System level tests in CMS and/or the CERN Electronics Integration Center have demonstrated that the system design is mature and that the major hardware elements are ready to proceed to production. Software and firmware comprise a large part of the remaining tasks. As these can be more prone to schedule delays, progress towards completing the remaining firmware and software tasks on the L1 Trig should be closely monitored. The cost estimate and schedule are consistent with the plan to deliver the technical scope with the stated performance, and the contingency is adequate for the risk.

The project team has hands-on, as well as leadership experience in building and operating the current CMS trigger system. For example, Smith was the CMS Trigger Project Manager from 1994 to 2007; Acosta has been the CMS Trigger Project Manager since 2012; Furic was responsible for CSC Maintenance and Operations in 2010 and 2011. This experience puts the team in a strong position to complete the L1 Trig on time and on budget.

Using firmware and software to make trigger decisions gives the system flexibility. Algorithms can be readily adapted and improved as beam conditions change and as physics needs evolve. Nevertheless, it is important to retain a clear baseline against which progress on the L1 Trig upgrade sub-project can be measured.

2.3.3 Recommendation

6. Proceed to CD-2/3 approval.

3. COST and SCHEDULE

3.1 Findings

Table 3-1. CMS Project Status

PROJECT STATUS as of June 2014		
Project Type	**MIE**	
CD-1	**Planned: 10/17/2013**	**Actual: 10/17/2013**
CD-2	**Planned: 9/2014**	**Actual:**
CD-3	**Planned: 9/2014**	**Actual:**
CD-4	**Planned: 12/2019**	**Actual:**
TPC Percent Complete	**Planned: 19%**	**Actual: 15%**
TPC Cost to Date	**$4,156K**	
TPC Committed to Date	**$5,173K**	
TPC	**$33,580K**	
TEC	**$19,375K**	
Contingency Cost (w/ Mgmt. Reserve)	**$7,361K**	**33% to go**
Contingency Schedule on CD-4	**13 / 17 months**	**21.70%**
CPI Cumulative	**1.1**	
SPI Cumulative	**0.9**	

Approve Mission Need (CD-0) was obtained on August 28, 2012, and CD-1, Approve Alternative Selection and Cost Range was obtained on October 17, 2013. The project's Total Project Cost (TPC) is $33.580 million, which includes $7.361 million contingency or 33% on the cost to go. The cost contingency is comprised of cost estimate uncertainty ($5.525 million) and risk based contingency ($1.836 million). The project is currently 15% complete of its TPC. The proposed funding profile for the estimated TPC is shown in Table 3-2 below. NSF is providing funding to this project, with this contribution the combined TPC is $43.364 million. The project is making good progress towards submitting a request for CD-2/3 Approve Performance Baseline and Start of Construction, expected in September 2014.

Table 3-2. Funding Profile

Fiscal Year	2013	2014	2015	2016	2017	2018	2019	Total
OPC – Design	1.50	6.25	2.50					10.25
TEC – MIE			5.00	9.50	8.50			23.00
Total DOE	1.50	6.25	7.50	9.50	8.50	0.00	0.00	33.25

The cost estimates were well documented. The project team provided documentation to support the cost estimates including Basis of Estimates, Cost Books, spreadsheets, and vendor/budgetary quotes. Cost estimate uncertainties were developed using a bottom-up approach and applying standard laboratory-wide contingency rules. Qualitative and quantitative risk analyses were performed using Primavera Risk Analysis (PRA) tool. Cost associated with the risks was estimated on a fiscal year basis at a 90% confidence level for the proposed TPC and 80% at the funding level.

Project completion (CD-4) is planned for December 2019. The Resource Loaded Schedule (RLS) was well developed, and critical paths for the project's three subsystems: HCAL, FPIX, and L1 Trig were presented. The HCAL activity is driving the project completion, with 13 months of schedule contingency from the "HCAL Complete" to CD-4. The FPIX and L1 Trig activities are scheduled to be completed approximately three years before CD-4. The RLS has 3,474 activities and 25 constraints, and incorporates the LHC operational schedule constraints and "need-by" dates.

The Primavera (P6) and Cobra system are used to integrate the project's cost and schedule and to monitor the performance measurement baseline (PMB). Three months of earned value reporting (April, May, June 2014) was performed and provided to the Committee. The cumulative cost performance index (CPI) is 1.06 and the schedule performance index (SPI) is 0.9 through June 2014. Variance reports were prepared based on the FNAL default variance thresholds.

3.2 Comments

The DOE TPC slightly exceeds the available funding as shown in Table 3-1 and 3-2 above. The Total Estimated Cost (TEC) and Other Project Cost (OPC) estimates differ from the proposed funding profile and various documents and presentations had discrepancies in the cost

tables between OPC and TEC. The cost contingency was developed using well-defined methodology, and appears reasonable for this stage of the project.

The preparation for obtaining DOE CD-4 approval is not included in the schedule and can potentially reduce the schedule contingency of 13 months. The costs, schedule, and risk analyses were thorough and well-developed. As part of the drill down session, the Control Account Managers (CAM) that were interviewed by the Committee did very well in demonstrating knowledge of the project documentation. They were able to navigate from the BOEs to the cost books and the schedule and provided good traceability of the cost to the vendor quotes or the originating source.

The reported cumulative SPI of 0.9 through June 2014 appears low. Due to the relatively high variance thresholds, this SPI does not require variance analysis reporting that explains the overall delay and potential corrective action. The project should consider lowering thresholds as the FNAL procedure allows. Pending project changes need to be processed and incorporated into the baseline as soon as possible.

Laboratory-wide change control procedures are in flux and should be finalized, with recommended timeframe for processing and implementing Baseline Change Requests, as soon as possible. The Level 3 cost threshold for change requests should be revisited.

3.3 Recommendations

7. Prior to CD-2/3, reconcile the TPC with the funding and correct the OPC/TEC split in the project documentation.

8. Proceed with CD-2/3 approval.

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4. MANAGEMENT

4.1 Findings

The CMS upgrade project is fully staffed. Most of the project team are long-term members of the CMS experiment and were involved in its construction.

There are three principal WBS elements that comprise this project: HCAL, FPIX, and L1 Trig. These three systems areas were also U.S. contributions to the original construction project.

The DOE TPC is $33.58 million, within the CD-1 range, and very close to the CD-1 TPC. The NSF contribution is $11.95 million bringing the combined total project cost to $45.2 million. The contingency for the project is 33% of TPC.

There are 13 months of schedule contingency between project complete and the CD-4 date.

Within the three principal WBS activities, 77% of effort (hours) and 52% of effort (cost) are external to FNAL.

This is a very mature project. The scope is very well defined and there are no remaining technology choices. The project is very far along in terms of their technical design. The project estimates its final design to be 87% complete with at least 77% complete in each of the three project areas.

All of the required documentation for CD-2 and CD-3 were provided to the Committee.

4.2 Comments

Given their prior participation on the CMS Project, CMS Operations, and Upgrade preparatory activities, the U.S. CMS Upgrade Project staff has extensive background and experience.

The Committee has high confidence that this project team can successfully deliver this project.

The new project manager has impressively overseen the transition from CD-1 to CD-2/3, and the implementation of the required project tools.

A number of documents have inconsistencies both within each document and across the documents (e.g., within the Project Execution Plan (PEP), and between the PEP and Project Management Plan (PMP). Some documents require update to final versions (e.g., preliminary reports from CD-1 should formally be designated as final, even if they are unchanged).

Document and prioritize first articles and pre-production items to ensure maximum flexibility regarding funding modalities.

Laboratory-wide procedures for things like change control and variance analyses need to be properly captured and tailored for specific projects (their size and their needs). The restrictive change control threshold at the project manager level will require a high-level of interaction with the PMG. This may force the PM to "manage up", when in fact the PM would need to be working with his Level 2 managers. The purpose for the PMG interaction is to ensure good access to FNAL resources and oversight, this needs to be balanced against the CMS Upgrade having a large external effort (77% of effort is external to FNAL).

It was noted that milestone levels and change control levels use completely separate definitions, which leads to some confusion when evaluating procedures (e.g., see Table 7 of the PEP). For example, use Level 3 WBS or Level 3 milestone vs. Level 3 change control.

Several budget inconsistencies were noted. In particular, OPC and Major Items of Equipment (MIE) profiles must be made to match with the overall budget plan. Also there is a small discrepancy in the total project funding and the planned budget profile.

The KPPs differ in level of detail for the three sub-projects. The largest risk to this project, which happens to be external, has to do with funding profile and how to deal with a potential delayed start of construction.

4.3 Recommendations

9. Update and finalize the project documentation:

    - Update the PEP with the latest information.

- The Committee recommended that the laboratory quickly finalize procedures (e.g., change control) or establish interim procedures that can be used for the CMS.

- Upgrade MIE-laboratory procedures or interim procedures should be specified in the PMP and the PEP made consistent with those.

- Change control description within the PEP is not consistent.

- The change control thresholds for the PM are stringent and should be reexamined.

- Clarify internal project definitions of various levels so that there is no confusion between areas such as change control and milestones.

10. Develop a fallback plan in the event of a FY 2015 continuing resolution.

11. After recommendations are addressed, proceed to CD-2/3 approval.

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APPENDIX A

CHARGE MEMORANDUM

Department of Energy
Office of Science
Washington, DC 20585

JUN 11 2014

MEMORANDUM FOR STEVE MEADOR, DIRECTOR
OFFICE OF PROJECT ASESSMENT

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

SUBJECT: REQUEST TO CONDUCT CD-2/3 REVIEW OF THE LHC-CMS DETECTOR UPGRADE PROJECT

I am writing to request you conduct an Independent Project review for the "LHC-CMS Detector Upgrade" MIE on August 5-7, 2014 at Fermilab. The purpose of this review is to evaluate the proposed technical, cost, schedule and management baselines, which are needed for Critical Decision 2 (Approval of the Performance Baseline) and the project's readiness for Critical Decision 3 which will approve the start of full construction.

In carrying out its charge, the review committee is requested to consider the following questions:

1. Do the proposed technical design and associated implementation approach satisfy the performance requirements? Are the CD-4 goals well defined?
2. Performance Baseline: is the cost estimate and schedule consistent with the plan to deliver the technical scope with the stated performance? Is the contingency adequate for the risk?
3. Final Design: Is the design sufficiently mature so that the project can continue with procurement and fabrication? Baseline Cost and Schedule: Are the current project cost and schedule projections consistent with the approved baseline cost and schedule? Is the contingency adequate for the risks?
4. Are the management structure and resources adequate to deliver the proposed final design within the baselines as identified in the PEP?
5. Is the documentation required by DOE Order 413.3B for CD-2 and CD-3 complete?
6. Are ES&H aspects being properly addressed given the project's current stage of development?

Dr. Simona Rolli is the program manager for the LHC-CMS Detector Upgrade Project in this office and will serve as the OHEP contact person for the 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, within 60 days of the review's conclusion.

Sincerely,

Michael Procario
Director, Facilities Division
for High Energy Physics

APPENDIX B

REVIEW PARTICIPANTS

Department of Energy / Office of Science CD-2/3 Review of the
LHC CMS Upgrade Project
August 5-7, 2014

Kurt Fisher, DOE/SC, Chairperson

SC1
HCal—Hadron Calorimeter (WBS 1.2)

* Jim Proudfoot, ANL
Jim Pilcher, U of Chicago

SC2
Forward Pixel Detector (WBS 1.3)

* Jim Brau, Oregon
Marina Artuso, Syracuse
Maurice Garcia-Sciveres, LBNL

SC3
Level 1 Trigger (WBS 1.4)

* Charlie Young, SLAC
Kevin Pitts, U of Illinois
Bill Ashmanskas, U of Penn

SC4
Cost and Schedule

* Frank Gines, DOE/ASO
Penka Novakova, BNL
Gail Penny, DOE/BHSO

SC5
Project Management (WBS 1.1)

* Michael Levi, LBNL
Mark Palmer, FNAL
Rob Roser, FNAL

Observers

Jim Siegrist, DOE/SC
Mike Procario, DOE/SC
Simona Rolli, DOE/SC
Pepin Carolan, DOE/FSO

LEGEND

SC Subcommittee
* Chairperson

Count: 15 (excluding observers)

APPENDIX C

REVIEW AGENDA

Department of Energy / Office of Science Review (CD-2/3) of the
LHC CMS Detector Upgrade Project
August 5-7, 2014

AGENDA

Tuesday, August 5, 2014—Wilson Hall, in the Comitium

8:00 am	DOE Executive Session	K. Fisher
9:00 am	Welcome	TBD
9:10 am	Project Overview and Conceptual Design (WBS 1.1)	TBD
10:00 am	Break	
10:20 am	HCAL Project (WBS 1.2)	TBD
11:00 am	Pixel Project (WBS 1.3)	TBD
11:40 am	Trigger Project (WBS 1.4)	TBD
12:20 pm	Lunch	
1:00 pm	Subcommittee Breakout Sessions —Management —HCAL —Pixel —Trigger	
3:30 pm	Break	
4:00 pm	Subcommittee Executive Session	
5:00 pm	DOE Full Committee Executive Session	K. Fisher
6:30 pm	Adjourn	

Wednesday, August 6, 2014

8:00 am	Subcommittee Breakout Sessions	
10:15 am	Drill Downs and CAM Interviews	
12:15 pm	Lunch	
1:00 pm	Drill Downs and CAM Interviews (cont'd)	
2:00 pm	Response to Questions	
3:30 pm	Subcommittee Executive Session/Report Writing	
4:30 pm	DOE Full Committee Executive Session	K. Fisher
6:00 pm	Adjourn	

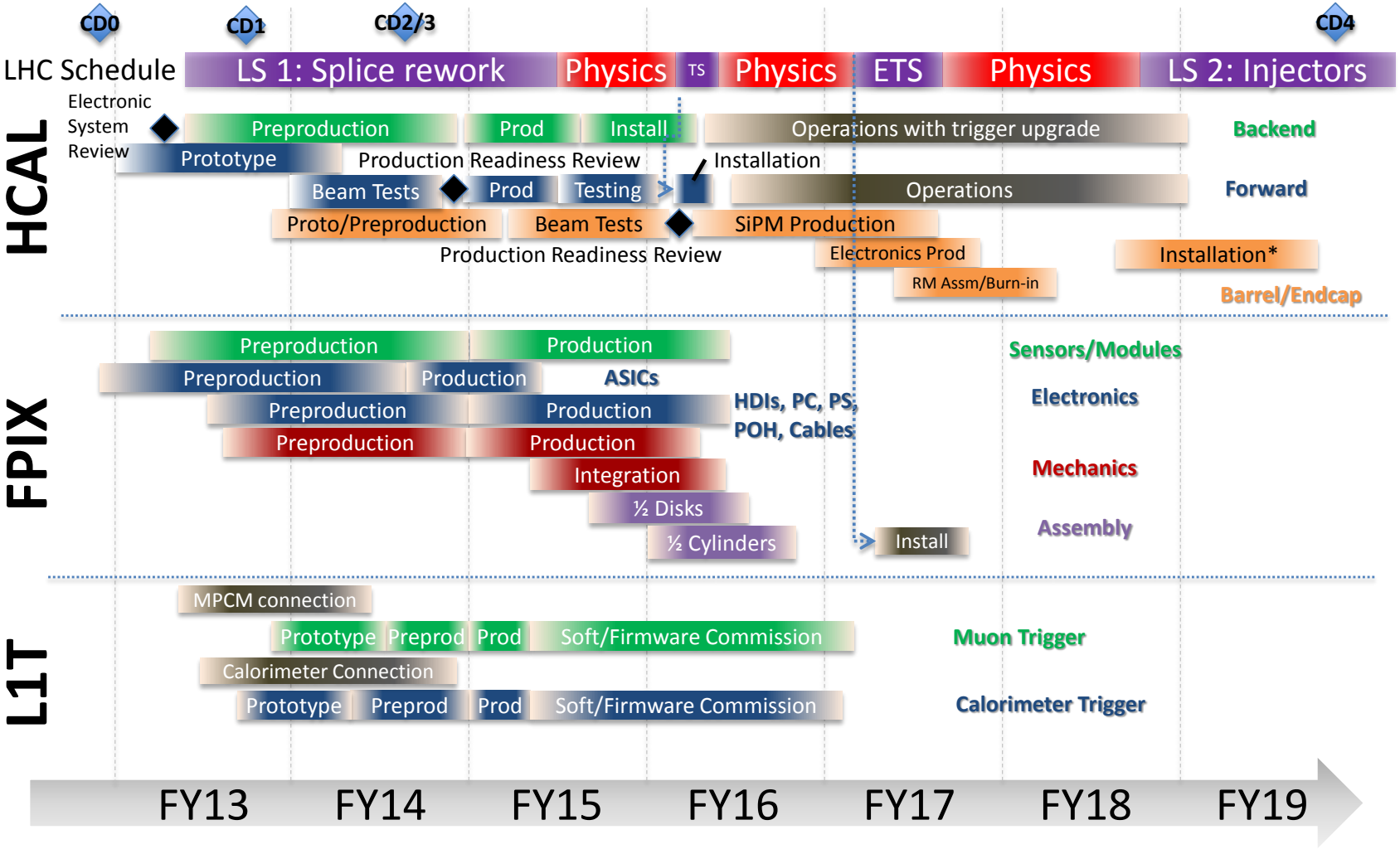
Thursday, August 7, 2014

8:00 am	Committee Report Writing	
10:30 am	DOE Full Committee Executive Session Dry Run	K. Fisher
12:30 pm	Lunch	
1:30 pm	Closeout Presentation	
2:30 pm	Adjourn	

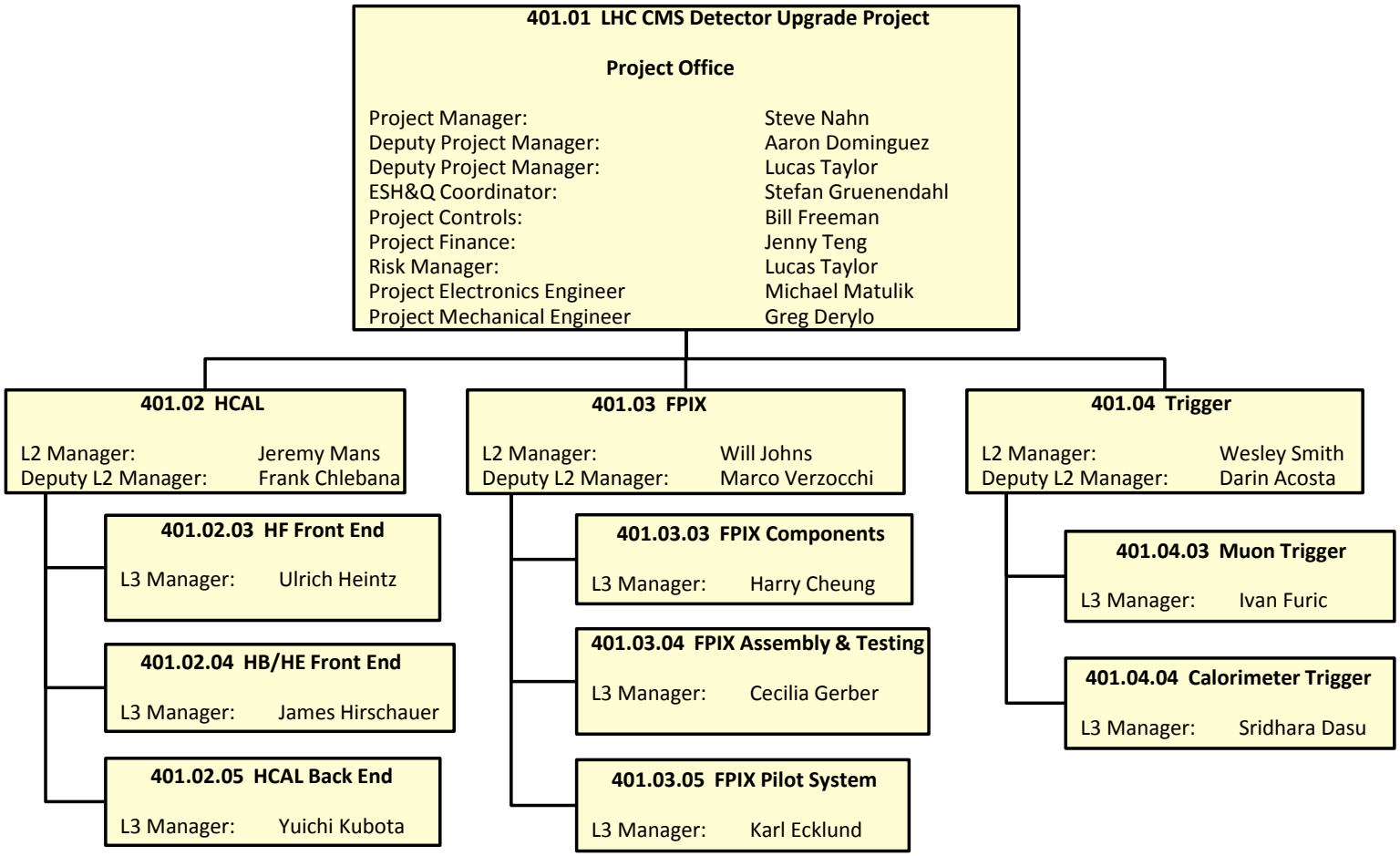
APPENDIX D

SCHEDULE CHART

U.S. CMS Project Schedule



APPENDIX E

MANAGEMENT CHART

CMS Upgrade Organization