Upgrade Cost Group Review of the CMS MIP Timing Detector

M. van Beuzekom, W. Christie, H. Danielsson, M. Demarteau, D. Denisov, C. Joram, E. Kajfasz, A. Kuzmin, M. Raymond, H. Sandaker, F. Simon, S. Smith, M. Vos, D. Waters

Process

The review began with a kickoff meeting in June, at which CMS guided us through the cost package and other appendices to the TDR. We then sent CMS a large number of questions, which were discussed in an interim Vidyo meeting on July 9, and followed up with a few additional questions. On September 9 at CERN we heard 3 hours of presentations from the MTD group and an afternoon of breakout sessions.

Overview

The MTD project consists of two independent detectors served by a set of common items. The Barrel Timing Layer (BTL) is based on LYSO scintillators viewed by SiPMs; the Endcap Timing Layer (ETL) is based on Low Gain Avalanche Diodes (LGADs). The common items include cooling, power, clock system, DSS, DCS, and DAQ.

The CMS MTD team produced a detailed responsive cost package for the review, and addressed the nearly 100 UCG questions completely and accurately, both in writing and at the July 9 vidyo meeting. The presentations at the September 9 review were carefully prepared. It was clear that CMS took the review seriously and did its best to profit from the exercise. The project is well organized, with strong leadership, management and technical personnel. The cost estimates, manpower and schedule are credible, with "8-month float everywhere."

Risks are identified and quantified, with reasonable mitigation plans. That said, we are concerned by the 1-yr delay in the lpGBT v2 schedule and its impact on the MTD (as well as on other upgrade projects in CMS and ATLAS). For the short term, prototyping can proceed with v1, but validations with v1 will have to be repeated with v2 when it becomes available, delaying part of the MTD project by ~3 months, within the internal slack of the project. More seriously, further delays will translate directly into delays for the MTD. The project is working on a backup solution to mitigate this risk, but implementing it would result in significantly increased cost and complexity. The CERN microelectronics group must give the lpGBT sufficient priority to deliver on the current schedule, and may need to be strengthened to accomplish this along with all the other critical projects for which it is responsible.

We are also concerned that the current schedule appears marginal to carry out sufficient radiation testing before orders are placed (also applies to the tracker). CMS should take what time is necessary to complete these tests! It is also important to reserve the 4 slots/year for MTD-related efforts in test beams so slippages in individual test beam efforts don't cause significant delays to the schedule.

Cost Situation

The total cost of the MIP Timing Detector is 20.65M CHF, including 900KCHF for the backup "pure clock" system to mitigate the risk of significant further delays in the lpGBT. The costs can be broken down by subsystem into BTL: 8.7M; ETL:10.9M; Common Items: 1.1 M. The largest cost items are the sensor modules (BTL 4.8M + ETL 4.9M = 9.7M), followed by the front-end electronics (4.1M total). The quality factors have been conservatively assigned and have reached a reasonable level for this phase of the project. Currently ~9M of the costs have QF 1 or 2; 10M have QF=3; and 1.3M have QF=4. The risk of a significant increase seems low because

most of the estimates are for reasonably standard and available components, with multiple vendors competing for the order.

The confidential preliminary "money matrix" was reviewed by the UCG and LHCC chairs and the lead CMS referee. Already >85% of the funding has been identified with a good match to the needs, and there are promising opportunities to marshal the remainder. The funding profile fits well with the overall Phase II program.

Barrel Timing Layer

Findings/observations

The BTL schedule has not changed since the TDR submission, retaining 8 months of float. In response to our request several milestones have been added to earmark transitions from R&D to production. The schedule is now linked to CMS common system schedules, and to the tracker schedule: 3 tracker milestones define the BTL integration/installation schedule to prevent overlap or interference with tracker activity. The schedule for each ASIC includes 1 yr for prototyping, 1 yr for production

The detector cost estimate (50% for sensors) is also unchanged, as is the TST cost (shared with the tracker). The project is in contact with 6-8 qualified vendors for the LYSO crystals, with the choice to be made in January '20. Even though the large orders are not on the critical path the project is working closely with vendors to confirm schedules, and an additional vendor could be engaged to meet schedule if needed. For the SiPMs, two prospective vendors are considered. Spare capacity for tray assembly is also available.

Comments

The project is well organized with a credible schedule and cost. The BOE's and QF's are conservative.

However the current schedule is tight. Nine months are reserved for ASIC design fixes, but this is in parallel with testing and might not be sufficient if results from radiation and cold tests come in late.

To verify the timing resolution, we suggest that CMS prepare a "timing budget," laying out and propagating the upper limits to the uncertainty induced by each link in the chain: clock distribution, ASIC, downstream electronics etc.

Interface specifications from connected systems (e.g. SiPM) do not seem well defined and should be developed in detail to avoid any surprises.

It is important to validate the assembly sites and establish common Q/A Q/C specifications early. Also, testing in cold boxes at assembly sites is necessary but not sufficient, as the boxes do not represent the actual temperature gradient and thermo-mechanical behaviour. Accordingly CMS will also test the prototype with the correct CO2 cooling to check thermomechanical issues.

Recommendations

1. Define and document well in advance the criteria for "success" of the full-tray testing.
2. To mitigate risk of increased radiation levels, place priority on possible implementation of lower operation temperature and enhanced annealing of the SiPMs.
3. Plan for the effort necessary to train the number of unskilled labor/students that will be needed for the Assembly efforts (6.2 FTE -> order of 20 to 25 people, and perhaps more).

End Cap Timing Layer

Findings/Observations:
The ETL schedule allows 2 years for prototyping, 1 year production and 1 year for integration. Though highly undesirable, if necessary the detector could be installed in technical stop. ASIC progress is well under way: ETROC1 has been submitted, with a decision next year whether the next version ETROC 2 can be production model; if an ETROC3 version is needed it is not on critical path. The final round of LGAD prototyping is focused on optimizing the final pad design and sensor boards. LGAD preproduction on critical path, production is not. Module prototyping, including radiation tests, assembly procedures, etc. will all be done at production sites in preparation for assembly. Module preproduction is on the critical path. The bump bonding process is being developed, and is a year off the critical path. Integration at P5 will be done in batches to keep off the critical path until last batch. Milestones have been doubled for thermal screening, feedthrus, etc.

Cost changes are minimal, with improved QFs in many major areas. Cost drivers are LGADS and ASICs. ASIC cost is largely defined by size so uncertainties are small. Changes under consideration to optimise LGAD design are minimal and don't affect cost.

The inner detectors may need to be replaced at some point. The project will deal with this risk if and when it is realised. If during testing they will buy more at that time; they will also retain adequate expertise and an assembly site at FNAL to make sure they can respond if the risk is realised after long-term operation.

Comments
As for BTL we suggest that CMS prepare a "timing budget" laying out the upper limits to the uncertainty induced by each link in the chain: clock distribution, H-tree distribution, waveform sampling, ASIC, downstream electronics etc.

The bump bonding process with a low number of bumps is not yet proven, so R&D is required. The team should try to profit from experience of other groups.

The plans presented for system tests did not have enough detail for us to review. They should be developed in detail to cover schedule, tasks, manpower, etc.

The 6-9 months planned for each iteration of ASIC improvements might not be long enough should serious problems are found during the irradiation tests done in parallel.

A system test should be performed as early as possible to study any degradation of performance due to sensor to sensor crosstalk.

Recommendations
1. Write down and hold to a firm schedule for transition from R&D to production: perfection is the enemy of good enough. Be conservative!
2. Make sure to understand the long-term availability of LGADs, electronics, and expertise in case more modules are needed.
3. Make sure to carry out system tests at a sufficiently large scale to reveal coherent effects.

Clock Distribution

Observations
The performance of the clock distribution system is mission critical, requiring < 15 ps (better 10 ps) jitter. Two approaches are being developed and explored in parallel. The baseline

consists of an encoded clock in standard VL+ data link, centrally developed by CERN. This brings advantages of no extra hardware and no extra cost. Full system performance, including the lpGBT v2 chip is scheduled for BTL in Q1/2021 and ETL in Q3/2021. The back-end validation lies in the shadow of the front end. To mitigate baseline schedule risk, CMS is developing a backup system. Consisting of a pure clock link, this requires development of a rad hard (200 Mrad) fanout ASIC and PCDM board, and deployment of ~2000 additional fibres and possibly also feedback fibres. Two iterations for the fanout ASIC and the PCDM board are required. Full system demonstration is scheduled for Q1-Q2/2021. The additional cost (900k) is documented in cost book.

Comments
Given the current status of the clock distribution (deterministic jitter in lpGBT v1, little-populated ATCA crates, more tests ahead), it is wise to continue work on a risk mitigation approach via the pure-clock system. It is positive that the central HPTD team (CERN) and detector teams are working jointly on characterization of both systems.

Recommendations
1. Unless performance is compromised, the common (baseline) system should always be favored, in view of maintenance, upgrade, sharing of experience (ATLAS HGTD), cost, …
2. In view of tight resources, a decision should be made as soon as performance of the options is clearly demonstrated and understood.
3. Tests should be realistic, i.e. involve sufficient number of links to see collective / interference effects

CO2 cooling system

Comments
The CO2 system design is well advanced and there is close cooperation between CERN, CMS (and ATLAS). Costs for MTD project are understood and based on fraction of the cooling power MTD needs.

MTD responsibility for CO2 system is concentrated on design, validation and commissioning of on-detector part. There are well defined contacts between the CO2 system design team and MTD systems and both BTL and ETL. The schedule includes providing required cooling performance for testing, integration, commissioning and finally operation of the MTD system. This includes specification for testing of cooling lines, DSS system elements, etc.

The schedule does not seem to have included tests of cooling with manifolds. If these are part of other tests, perhaps they should be called out explicitly.

Recommendation
1. The CO2 system spans MTD and central CMS equipment, so the complete system, including interfaces, should be reviewed to make sure it meets specifications.

Power systems

Comments
The system cost assumes that radiation hard and magnetic field tolerable options will cost the same as currently available commercial versions. This carries substantial risk.

The time scale for vendors producing new versions of power supplies is long: a year or more for design/construction plus extra time for irradiation/testing by CMS. Although all

components are available, development of radiation hard devices is hard and could cause delays both in testing with or without irradiation.

Recommendations
1. Finalize locations of the power supplies in the CMS cavern
2. Finalize all specifications for the power supplies, including radiation doses and magnetic field levels
3. In cooperation with other CMS (and ATLAS?) groups, pursue development of radiation and magnetic field tolerant power supplies. Confirm how much testing time is needed, with and without irradiation.
4. Develop time schedule and cost estimate for these efforts by the next LHCC meeting

DSS

Comment
Finer granularity may be added to the schedule to visualise that the DSS will be installed at the earliest suitable time for each detector independently so that no sub-detector is left in an "unsafe" state.

Recommendation
1. Formal approval of the Alarm-Action-Matrix is not in the schedule with milestones and could be added.

DAQ

Comments
The MTD/DAQ group have addressed the questions received from the UCG. There was an in-depth discussion of firmware. The MTD team have explained why the development team is small but stable (the core 1 FTE developer has a permanent position and the students have a stable supervisory structure in place). Some contingency plans are in place. So far the cost estimate is stable. The main risk is late arrival of the ASICS, which may propagate into delays.

Recommendations
1. Firmware developments should be monitored closely. It might be useful to track the delivery of individual firmware blocks. Any changes to the development team should be immediately flagged.
2. The DAQ team should indicate the optimal time for making a decision on the size of the FPGA, based on cost & technical considerations.
3. A backup plan could be added for the slice tests in the case of ASIC delays.

Conclusions and Recommendations
- The cost estimates and the current and planned resources are reasonable for this stage.
- The schedule, risks and manpower are at normal levels, provided they continue to be proactively managed.

We recommend Step 2 approval by the RB and RRB to allow resources to become available and MOU's to be signed.