Upgrade Cost Group Review of the ATLAS High-Granularity Timing Detector [1]

N. Bacchetta, C. Biscarat, R. Calabrese, F. Di Lodovico, A. Frey, G. Hall, K. Kruger,
I. Laktineh, H. Sandaker, C. Schwanda, F. Simon, AJS Smith, I. Vila Alvarez, W. Wisniewski

Process

The review began with a kickoff meeting in May, at which ATLAS guided us through the cost package and other appendices to the TDR. We then sent ATLAS a large number of questions, which were discussed in an interim Zoom meeting on July 9, and followed up with a few additional questions. The review, held remotely September 3 and 4, consisted of overview presentations from HGTD management and 6 parallel sessions.

Overview

The HGTD consists of endcap detectors based on ~8000 Low Gain Avalanche Diodes (LGADs) deployed in two layers, and several common items include cooling, power, clock system, DSS, DCS, and DAQ. The ATLAS HGTD team produced a detailed responsive cost/schedule/resources package for the review, and addressed the 88 UCG questions completely and accurately, both in writing and at a Zoom meeting on July 9. The presentations at the September 3-4 review were carefully prepared. The project is well organized, with strong leadership, management, technical personnel, and a credible succession plan to sustain the effort long term. The cost and manpower estimates and the schedule are at an appropriate level of detail for this stage of the project, and it appears that adequate financial and human resources are available. We note with concern that the HGTD, as a project with much R&D still in progress, has been and will continue to be seriously impacted by COVID-19: travel restrictions, vendor delays, unavailability of radiation-testing facilities, delays in completion of R&D and prototypes, etc.; but is coping as well as can be expected. The risks have been carefully studied and quantified, with reasonable mitigation plans. However, as we were a year ago with the CMS MTD, we are concerned that the current schedule appears marginal to carry out sufficient radiation testing before orders are placed, and warn against taking shortcuts.

Management

The leadership and organization are strong, with a strong set of L2 and L3 coordinators and reasonable succession plans. The schedule has been modestly updated since July to obtain 6.5 months of float on the project, responding to concerns expressed in the LHCC review of the TDR. The HGTD team is to be commended for working to generate this 6.5 months of float in the overall schedule. (Experience with production, of course, will determine the actual float.) The right choice was made to trade off a small M&S increase to reduce schedule risk. HGTD should continue to seek out opportunities to increase float further through process improvements. Though the current float is substantial, the duration of the project is quite long compared to the float. The HGTD team has prepared, and regularly updates the risk register which uses ATLAS-wide conventions. This is a commendable practice. Good understanding of the interconnectedness of the different project elements and detailed schedules was demonstrated in the presentation of the Demonstrator plans.

Cost Situation

The total estimated cost of the HGTD is 11.3 MCHF, a modest well-justified 1.6% increase over an earlier version presented in July, caused by the decision to establish an additional assembly site to reduce schedule risk. The largest cost items are 2.4M for LGAD sensors; 3.1M for electronics (ASICs, PEBs, HV/LV, DCS, Interlocks); 1.55M for modules and detector units; 2.5M for mechanics, fixtures and infrastructure; and 1M for DAQ. . The quality factors, averaging 2.2 weighted for cost, are reasonable for this phase of the project. However, this depends on a successful sensor procurement based on prices quoted by vendors who have not yet produced a full-sized sensor, whereas HPK, the only vendor

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who has produced full size parts, appears to be approximately twice as expensive at this time. The worst-case cost risk – having to buy from HPK at the current price – could be as large as 1M. Other cost risks are minor.

The confidential preliminary "money matrix" was reviewed by the UCG, SG and LHCC chairs, the lead ATLAS LHCC referee and the chair of the LHCC HGTD review panel. Already about 98% 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.

Schedule

The schedule is now credible, containing a reasonable level of detail: 1300 lines and including ramp-up times in the schedules for production. The next few years of ASIC development are crucial, as the availability of the ALTIROC V2 and V3 ASICs could be a main choke point. To deal with this the schedule allows for several version of chips, and delivery is broken down into small batches to keep all the sites busy and establish QA/QC. The first batch is on critical path. Another possible choke point is the rate achieved for module production. The modules are relatively simple and increasing the number of production sites to six helps a lot. Using cooling plate as support structures for assembling detector units can allow progress while waiting for components. The HGTD group is evaluating whether replacing wire bonding with bump bonding could advance the schedule further. However, this change is simply not worth it unless it quickly becomes clear there are significant gains and that the risks are negligible.

Risks

The risk register is at appropriate detail, covers all the risks we could think of, and is in the process of being incorporated into the ATLAS-wide risk-management structure. The project meets every month and ATLAS will incorporate any significant changes, retirements, etc. every 3 months. The cost risk is low, except for an increase in sensor cost if the project has to go with HPK and cannot negotiate a bid reduction. They claim there are no > 6 month schedule risks, but when asked they allowed that finding bad clock distribution during preproduction and/or production could rise to that level. This problem can be spotted and mitigated by measuring jitter along the line to make sure specs are being met.

<u>Recommendation.</u>

1. The possibility of significant increases in the sensor cost (worst-case ~1 MCHF) should be added to the risk register.

Sensors

<u>Findings/observations</u>. Though the sensor R&D is well underway with lots of successes, many sensor variants of sensors remain to be studied. Some of the parameters are defined by the manufacturers and not under the control of the project. Surprisingly, spurious pulse rates and stable operational conditions are not (yet?) specified as requirements. The R&D on large sensors is scheduled to be completed by Q4 2021 in parallel with the Market Survey, which will assess and characterize large sensors obtained from all vendors: yield, radiation tolerance, operational parameters, and finally the performance before and after irradiation of large-sensor modules (LGAD+ALTIROC2). HPK has recently produced samples of P2 LGADs, now under study to inform the specification review scheduled for the end of September. FBK is developing carbonated sensors, which present reduced acceptor removal constant (factor 2-3).
As mentioned above the price estimate based on the two lowest quotations is a problem because they haven't produced a full-size sensor, and HPK, which has produced, is significantly higher. We are very concerned to see that the process from Market Survey, to tendering and then to contracts is not yet firmly established.

<u>Comments</u>. A better cost estimate is needed, taking into account that the companies with lowest cost may not fulfill the requirements. A negotiation with the company to have the same price for 5% as for the 95% should be discussed. The final electronics used for sensor evaluation does not include the final ASIC. There is a lack of clarity about the procurement of the UBM, which some vendors will provide

and others not. This probably has an impact on price, and even more on wafer handling and transportation during assembly.

Recommendations.

1. A standard for the sensor specifications must be established, as it seems quite vague. We understand this issue will be addressed at the upcoming SPR.
2. It is critical to have a complete assessment of radiation tolerance of single diodes (and large) sensors for mixed fields (neutrons and protons), with special focus on the carbonated sensors.
3. Define and, if needed, implement a fallback strategy to include the results of beam testing in the Market Survey process. If travel and facility access constraints remain in place for all the year 2021, consider creating local team(s) at test beam facilities not affected by the Covid-19 quarantine and travel restrictions.
4. Only vendors accepted in the CERN MS should be allowed to bid, even if the deliverable is "in kind." We strongly advise against taking shortcuts with the aim of reducing costs; instead, it would be better to negotiate with the best vendors.
5. If multiple vendors are chosen,
    a. make sure their schedules are realistic and allow sufficient time for thorough testing.
    b. consider placing their products in different rings, as they may have different qualities while fulfilling the requirements.
6. ATLAS should work with CMS to negotiate the cost with the LGAD production companies and purchase through CERN.

ASICS

Findings/Observations. The ASICs are on the critical path, so we are pleased to report that this part of the HGTD project is well-organised and managed. They have adopted professional standards and incorporated expert advice from CERN experts and other projects, review their developments internally and with outside help, and are fully aware of the uncertainties, most of which are not easy to control fully (e.g. prediction of time needed to complete design work, impact of COVID, evaluation of prototypes, etc). Progress of the design is promising: the analogue part of the ASIC now seems to be well proven with successful small corrections in ALTIROC1_v3, and a pixel cell, ALTIPIX, is now available and ready for testing including the digital circuitry. The design of the full size ALTIROC2 is well advanced with a good understanding of what remains to be done. Naturally there remains uncertainty about the time needed for completing the final blocks, including the impact of COVID. The process is 130nm TSMC and we see no serious risk of the ASICs not being available in 2024 and beyond.

The effort available appears sufficient, with more engineers becoming available during 2020. The modest support from CERN CHIPS adds a lot, e.g. quick resolution of design tool issues and expert input on similar designs. Effort on evaluation is also increasing, but this is still probably the weakest area. Wafer scale probe testing comes quite late and can't be easily started until the full size ASIC is available. This means that the earliest hybrid assemblies must use untested ASICs, which will probably add time to distinguish faulty ASIC effects from assembly issues.

The number of needed ASICs assumes 80% yield, based on experience with similar size ASICs, but which cannot be confirmed until a couple of lots have been measured. ASIC production testing is shared between 2 institutes and the time estimates per ASIC look realistic. TSMC has good yield models but probably not usable until full size design is complete (10% lower yield would add ~€50k to project cost). The most likely scenario is that ALITROC2 works well enough to verify assembly processes and establish QA, but requires fine tuning of small details to finalise ALTIROC3. The TSMC delivery schedule can be tuned to match assembly at no extra cost, avoiding the need to deliver the complete order in a single batch and have long term storage

Comments. As is common to all ASIC projects monitoring of Total Ionising Dose (TID) along batches not fully clarified, but stability during production is an unlikely problem if TID performance is proven early. Costs should be reliable, since ASIC contracts are well established. The ALTIROC schedule is success oriented: the time planned for each iteration of the chip may not be long enough if problems are found, considering that design, verification, beam and irradiation tests will be done in parallel. We commend the great effort this summer in spite of COVID, with people "coming and going and doing tests in garages." COVID is making it difficult to exploit efficiently the French and SLAC expertise required for the final design of full-size ASICs, and delaying radiation testing because France and Spain are high-risk zones. ATLAS is trying to get access to DESY, but will only be able to send a limited number of people.

Recommendations

1. The project should strengthen the evaluation effort, especially to advance wafer probe testing. This includes software and firmware development, which may be a. lengthy process.
2. Digital-on-Top methodology is an unfamiliar technique, adopted and highly recommended by CERN. Accordingly it would be desirable to add further effort to the design team if possible.
3. Increased support from the CHIPS initiative for this technology and also for verification procedures for the whole ASIC design would greatly benefit the project.

Module hybridization, loading and assembly

Findings/ Observations. The overall schedule is now ambitious but not unreasonable, now that the project has increased the number of production centers from 5 to 6. The management structure seems adequate, well prepared and motivated. This part of the project has been well thought out, risks and mitigations seem reasonably understood and complete (see comments and recommendations). Strict and thorough testing of parts before assembling them together is of the utmost importance in order to keep production yield as high as possible (hence creating spare parts and giving the opportunity to choose best parts). In this regard the Demonstrator (see below) is a very important first step to validate the process of putting together modules, detector units, cables etc., and carefully assessing technical choices and resulting performance. Wide participation of institutes and experts in the Demonstrator should be encouraged.

Recommendations.

1. The yield achieved at each step is of the uttermost importance in order to conclude the project successfully. Therefore the project management should watch progress and milestones carefully to be able to intervene promptly as soon as either the schedule falls behind or parts start to be consumed.
2. A quality-assurance system to properly qualify all production centers should be organized and implemented.
    a. Experience gaining and training of production centers should be centrally organized and strictly followed up by the management.
    b. As soon as possible, strict protocols and monitoring for QA/QC and criteria for acceptance should be formally established at all production centers.
3. To ensure the *average* output rate can be sustained in the face of unforeseen issues during production, the project should work to increase the *peak* output rate per center. Mitigations such as double shifts, if needed, should also be planned.
4. During production, the database which is used to track parts among many sites during assembly will be vital to ensure success of the work and avoid delays. This will be needed from the outset so should be prepared and well tested in advance.
5. A careful assessment of advantages vs disadvantages and risks of alternative bare module hybridization processes, e.g. bump bonding, should be made before too much time and effort is invested. Alternatives to the baseline should only be pursued if they do not pose risks and will significantly reduce the cost and schedule.

Demonstrator

Findings/Observations. The Demonstrator is a new subproject to address several critical issues: 1) a heater demonstrator to test the cooling capacity; 2) a DAQ and PEB demonstrator to test the luminosity system, DAQ software/FELIX, etc.; and 3) a Full Demonstrator, with full LGADs, ALTIROC2, modules, flexes, etc. to test the full readout chain and verify the time resolution. Vessel components and support structures have been ordered for installation in November at CERN and tests with modules in 2021. Silicon heaters will be used to replace modules in the heater tests.

Comments. This is a well-defined project addressing several critical issues, including cooling, readout path, PEB, clock distribution and jitter, FELIX boards, time resolution of the entire readout chain, and luminosity capabilities. Work seems to be going well, and information should come in time to validate the important parts of the system and spot problems. The Demonstrator is also an excellent resource to continue system development in case of unexpected delays.

Recommendation.
ATLAS should make sure the demonstrator project receives sufficient priority and support to come on line on schedule, and operate efficiently as a test bed.

Luminosity system

Findings/Observations. FELIX-I functionality probably fulfils Luminosity needs, and there is a very low risk FELIX-II is insufficient. The boundary with TDAQ is clearly defined (data-handler software is HGTD, machines TDAQ). The system might serve as an example for 40 MHz functionality of future luminosity detectors. The person-power will mainly be for work on firmware and software.

Comments. It is important to keep an eye on the emulator to make sure that it provides lumi functionality. Firmware development relies on new engineering so it is important to make sure this person is available on time.

HV/LV

Findings/Observations. Both HV and LV systems will be based on existing commercial products. No changes since first UCG package in 6/2020, except that the spending profile has been adjusted to the new schedule. The schedule is consistent with that of the overall HGTD. Evaluation/tests of components can be carried up to mid-2022 (end 2021 for LV).
While all items are costed some uncertainty exists until final tendering (in both directions). This is of concern as it is a very costly item, and full funding is not assured at this point. The manpower estimate appears realistic but similarly is not assured yet. The risk catalogue appears to capture the main items. Mainly cost risks, schedule risk minor.

Comments. The project should work with multiple vendors to mitigate technical/cost risks. HGTD and ATLAS managements need to work on securing funding and manpower for the HV/LV systems.

Peripheral Electronics Boards (PEBs)

Findings/Observations. PEBs are complex rigid-flex PCBs with many components so it is important to monitor progress in detail. The DCDC converters will probably need changes from standard bPOL design, and new MUX chips are required. The plan is to do PCB production and loading in industry, if possible in the same company both for pre-production and production. The cost estimate assumes that non-recurring costs for PCBs can be contained within pre-production.

Comment. Many key technological choices/evaluations need to be made before reaching a baseline technical plan.

Recommendations

1. Need to be very thorough in the evaluation of the technology to be used for the production parts and have appropriate QA/QC in place.
2. Participating institutes are expected to test these boards and they should be prepared and qualified starting as soon as possible by actively participating to the current technical evaluations if possible.

CO2 cooling system

Findings/Observations. The CO2 HGTD project is part of a larger project, and not currently on the critical path: all aspects of the ATLAS and CMS CO2 systems projects are being coordinated by one single body (CO2 Systems Oversight Board). The cooling system is designed to ensure proper cooling is maintained during power failures and other abnormal conditions. A collaboration agreement is taking shape (HGTD CO2 COOLING SYSTEM).

Comments. The cost estimate dates back to 1/ 2020 (1.2 MCHF). New inputs are available (the most relevant being the built cost of the DEMO accumulator from Grenoble), so the HGTD team should take the opportunity to refine it. (This will improve the QF). The cooling team is short on manpower (O.5 FTE). They have a preference for people hired on long term contract at CERN, but if needed they should consider inviting experts from other labs to work on dedicated tasks. ATLAS and CMS share elements with the result that and their schedules are interdependent. They need to sit together to make a realistic schedule. Availability of DEMO, a facility shared by several projects, is of great importance for tests of the HGTD cooling system.

Recommendation.

1. ATLAS should carefully evaluate the time needed for installation and its integration is the global planning. This is crucial because recent experience with the LHCb MAUVE and DEMO system @153 showed that the time needed for installation was seriously underestimated.

Assembly/Integration/ Installation/Commissioning

Findings/Observations. Installation of the HGTD presents minimal conflict with other systems, and the radiation levels have been estimated to be low enough not to impact work. As much as possible of the assembly and Q/A will be done on surface. The major costs are for DCS and Interlocks, tasks for which funding and adequate labour are not yet in hand. Several slots in the leadership team need to be filled, and a plan to augment the group is under consideration. Interlocks are critical to safety of detector –overheating, cooling system failure, ATLAS emergency stop, etc. Fortunately they can lean on the ITk solution, but need to make sure it will be ready when needed, and that it is applicable. The interlock team needs to be significantly expanded to keep the schedule.

The DAQ software has to be carefully validated to make sure it is accurate in carrying out monitoring and calibrations. Embedded in the ATLAS common software, it includes a data base to store module configurations and other HGTD parameters. There are no CORE costs associated with this element.

ATLAS is forming an expert operations team for global commissioning, which will continue during operations. For this to succeed they need to recruit and retain a set of workers with the required skills and with long-term commitments.

Comments. Labour available for assembly and installation is at present not sufficient. In addition, experienced people need to train new persons in order to have a sufficient pool of experts for this important part of the project. Management is already working on this and must continue to give this issue high priority. DCS and interlocks are underfunded and understaffed. ATLAS will put pressure on institutes to provide resources as part of the MOU process, and feels they can marshal the resources required to keep on schedule.

Recommendations.

1. The HGTD group needs to work closely with Pixel group and technical coordination to prepare a detailed plan for installation.
2. The interlock group is significantly understaffed. The situation needs to be resolved as soon as possible.
3. The installation plan takes into consideration ALARA principles in order to minimize the radiation exposure for people who will install detector. This plan has to be verified by radiation experts. This is even more important if installation has to be done in a YETS.

Conclusion and Overall Recommendation

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