Report from the Upgrade Cost Group: CMS and ATLAS Phase II Upgrades

RRB Meeting
October 26, 2015

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RRBSG **LHCC** **UCG**

General Comments

- For Phase I, UCG worked with complete, LHCC approved TDR's, detailed WBS charts, schedules, and spreadsheets for manpower and funding.
- Phase II is completely new ground!
  - Focus on conceptual designs, cost methodology, past experience, etc.
  - The first stage today addresses the "big picture," leaving details for the TDR's.
  - Step 1 for UCG: evaluate the "Reference Detectors" as well as possible.
  - For Step 1, LHCC and UCG evaluations had to proceed in parallel
- ATLAS and CMS have worked extremely hard and effectively to understand scoping tradeoffs, the capabilities of their collaborations, and the funding situation.
- Cost estimates are very well developed for this stage (WBS level 4):
  - Based on experience with successful detectors
  - Evolution, *vs* going where no-one had gone before.
  - Large effort on risk analysis and mitigation strategies
- Information provided gives a firm basis for UCG report to RB, RRB
  - I can only provide a glimpse today.

Joint LHCC/UCG interactions over the summer with ATLAS, CMS and CERN

- Continuous back and forth with the experiments on SD:
  - As we received them, we reviewed outlines and preliminary versions of scoping document, cost/schedule spread sheets.
  - Lots of reading!!
- Vidyo meetings interspersed with Email exchanges
  - With CMS July 6 and Aug 7
  - With ATLAS July 6 and August 14
- Agreed to have full-day UCG meeting for Monday Sept 21
  - Marvelous cooperation from ATLAS and CMS!!
- **Approval process finally decided (yeah!)**
  - Based on slides presented by UCG to LHCC in November 2014.
  - Semi-infinite number of frank & sincere discussions with all concerned.
  - Following the September LHCC/UCG meetings (!) CERN DRC issued Memorandum for Phase II Upgrades, beginning with the Scoping Documents that had just been endorsed by LHCC/UCG.

UCG Agenda
Monday Sept 21, 2015

09:00 - 09:20 Overview: scoping scenarios, summary of performance
Speaker: Kevin Einsweiler (Lawrence Berkeley National Lab. (US))
UCG_Review_Introd...

09:30 - 09:50 TDAQ *20'*
Speaker: David Francis (CERN)
TDAQ - UCG - SW.p...

10:00 - 10:15 ITk *15'*
Speaker: Stephen Mcmahon (STFC - Rutherford Appleton Lab. (GB)
ITk - UCG - SD.pdf

10:25 - 10:40 LAr *15'*
Speaker: Arno Straessner (Technische Universitaet Dresden (DE))
LAr - UCG - SD.pdf

11:10 - 11:25 Tile *15'*
Speaker: Eirini Vichou (Univ. Illinois at Urbana-Champaign (US))
Tile - UCG - SD.pdf

11:35 - 11:50 Muons *15'*
Speaker: Christoph Amelung (Brandeis University (US))
Muons - UCG - SD...

12:00 - 12:15 Infrastructure *15'*
Speaker: Ludovico Pontecorvo (CERN)
Infrastructure - UC...

Monday, 21 September 2015

14:00 - 14:25 Overview *25'*
Speaker: Didier Claude Contardo (Universite Claude B
UCG_Answers_220... UCG_Answers_220...

14:35 - 15:00 Trackers *25'*
Speaker: Duccio Abbaneo (CERN)
210915_Tracking.p...

15:10 - 15:25 Calorimeters *15'*
Speaker: Roger Rusack (University of Minnesota (US)
HGC-UCG-2015-09... HGC-UCG-2015-09...

15:35 - 15:50 Muons *15'*
Speaker: Anna Colaleo (Universita e INFN, Bari (IT))
MuonUCG_219201... MuonUCG_219201...

16:00 - 16:20 Coffee break

16:25 - 16:35 Trigger & Daq *10'*
Speaker: Frans Meijers (CERN)
FM-20150921-pha...

16:45 - 17:00 Common items and infrastructure *15'*
Speaker: Austin Ball (CERN)
UGC_21Sep2015_A...

17:00 - 18:00 Discussion *1h0'*

Follow-up questions from UCG meeting

1. What major R&D remains on the path to the TDR's? Can you propose a milestone or two to help us judge progress?
2. Please describe your major decision points, with approximate dates and criteria on which to make a decision.
3. Please describe a timeline for updating your simulations of technical and physics performance so they reflect the TDR configurations.
4. What are the most serious risks and worse case scenarios for your system, and your plans to mitigate them?
5. A few very large procurements will have major impact (+ or -) should their actual costs deviate from your estimates, e.g. silicon, FPGA's, power supplies, etc. How are you combining procurement among the your systems and/or among the other LHC experiments?
6. We would like to have a conversation with you to understand the global funding picture and uncertainties (without naming individual FA's).

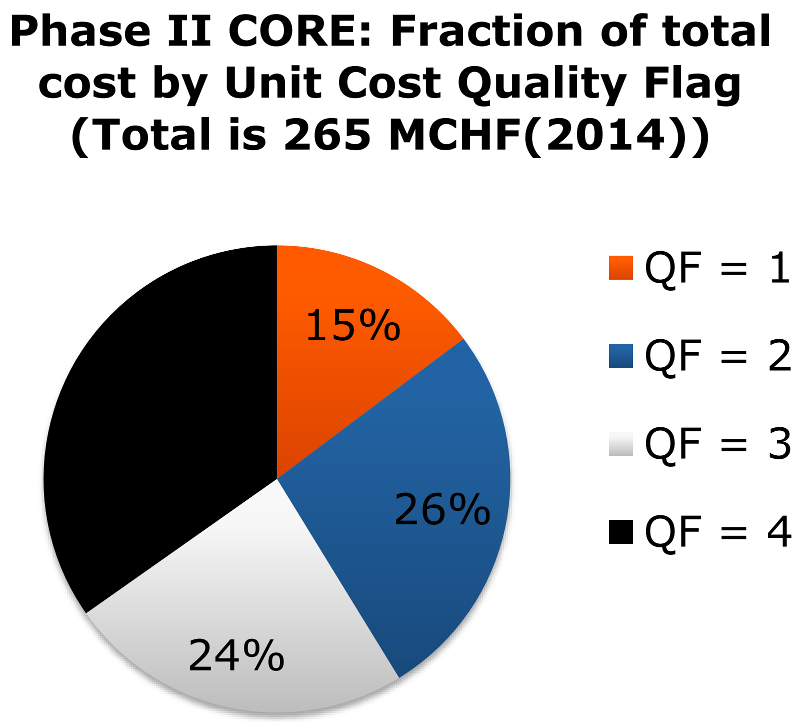
Excellent response from both experiments.
Presentations and discussion at extra UCG session Tuesday Sept 22

CMS Overview

- Reference Detector cost estimate is **CHF 265M**
- Cost estimates are remarkably mature, applying an appropriate level of conservatism.
- Industrial-like assignment of quality flags (QF 0 - 5) for unit costs and for number of required units.
- The level of R&D and prototyping to be completed before the HCG and OT TDR's is relatively large. (Not part of the core costs, but critical.)
- Experiment is actively exploring opportunities to combine procurements with other experiments (si, power supplies, etc.)
- Funding outlook (similar to that of ATLAS):
  - Substantive, relatively encouraging interactions with FA's, much greater detail than at this stage of original construction
  - Large uncertainties, will take a lot of time to secure commitments
  - Strong, almost complete alignment of interests with needs

CMS: Unit-Cost Quality Flag Summary

Breakdown of 265 MCHF by value of unit cost



QF = 1: initial vendor quotes

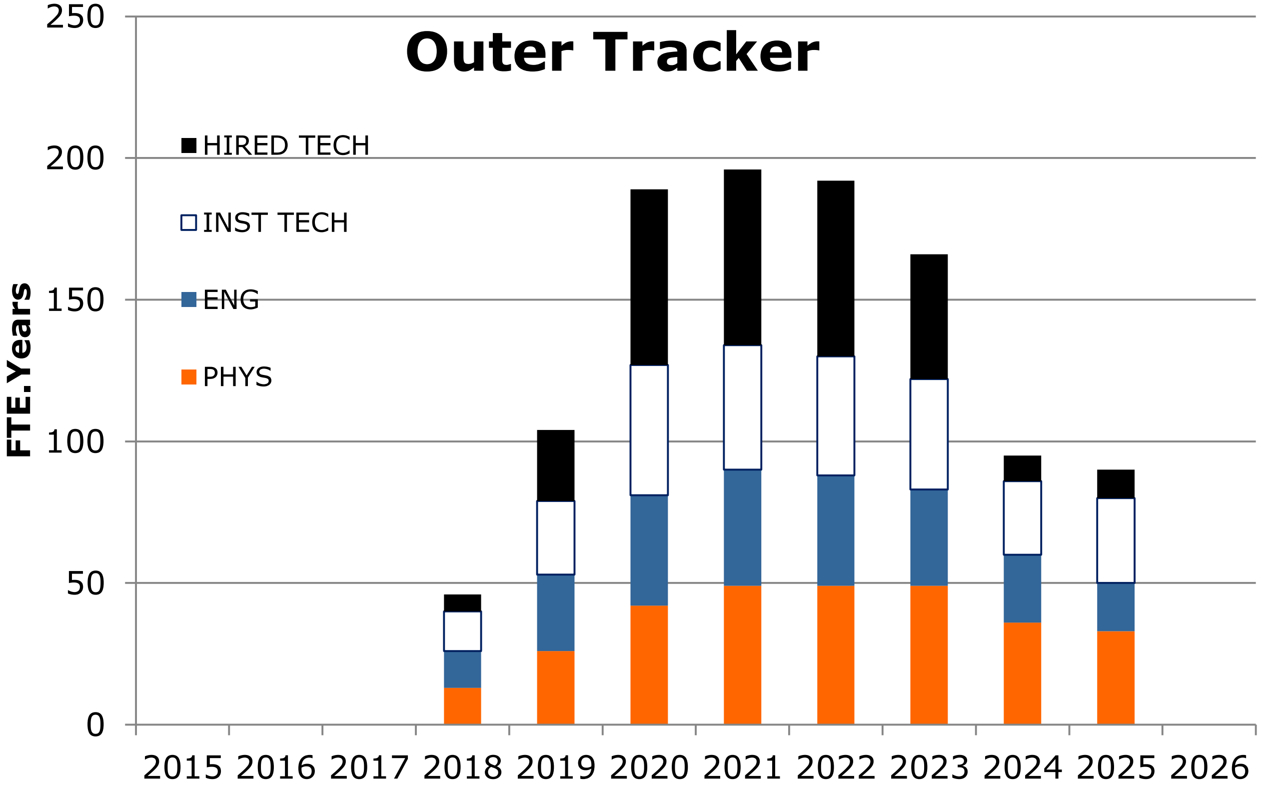
Use QF = 2, 3: for vendor cost information for engineering or conceptual designs

QF = 2: projects that replicate previous work (CSC)

QF = 3, 4: scaling based on earlier projects and estimates for conceptual designs

The distribution of QFs is already quite advanced for the present TP stage of conceptual design.

Example of Project Labour Profile



Initial Assembly Planning

Will be further developed with sites identified by TDRs

- Sensors
- QC – test structures (all batches): 2-3 centers
- Rad testing – test structures: 2 centers
- QC –sensor sample testing: 5 centers
- Hybrids
- QC – test all hybrids: 2 centers

- Modules
- Production lines: 5-6 lines (can involve >1 institution), 2000-3000 modules each
- Integration
- Subsystem integration: 4 centers (PS, 2S, TEDDs)
- Final integration: CERN

CMS Trigger/DAQ – CHF 24 M

- High Level Trigger constitutes 11 MCHF
- Descoping “easily” recoverable, opportunities to defer part.
- Costs based on extrapolation from 2013 to 2025; large uncertainty, but also possibility for gains in processing power from new architectures.
- Part of cost could be covered by M&O-A money for the normal replacement of the farm after 4-5 years.
- Potential savings could result from common procurement with ATLAS.

Recommendations, TDAQ :

1. **A common policy for funding “normal” replacements should be decided for both experiments.**

CMS Tracking - 112 MCHF

- Dominates cost of Phase-II upgrade
  - Pixels CHF 23M; Outer Tracker CHF 89M .
- The project builds on extensive prior expertise.
- Sensor modules ~ 50% of overall project cost
  - Estimates based on preliminary vendor quotes.
- 54% and 41% quality flag 1 or 2 for Pixels and Outer Tracker.
- Well-defined de-scoping options.

Pixels

- Well-known technology; collaboration is very experienced.
- An adequate amount of spare sensors (50%) is allocated and costed.
- Layout still carries significant uncertainty.
- Common readout ASIC and GBT reduce some of the risks.

Tracking risks and mitigation

Outer Tracker

- Based on a well-known technology with which the collaboration is very experienced. Sensor costs based on initial vendor quotes.
- High density flex circuit technology critical for p_T module and track trigger design – historically a risky enterprise
- Fraction of quality 3 and 4 flags is relatively high (59% of total project cost).
  - Very conservative cost estimates have been taken for these items.
  - In line with other experiments and hence not overly conservative.

Recommendations, Tracking:

1. Qualify a second vendor for all tracking components (sensors, bump-bonding, hybrids, flex circuits, …)

CMS Calorimeters – CHF 75M

- HGC (FE and FH): state-of-the-art Si readout technology based on ILC R&D over 15 years.
- BH uses conventional scintillator readout.
- Largest cost driver is silicon sensors ~ 50% of HGC cost.
  - Cost estimate based on close-to-final design and vendor quote (QF =1).
- Brass, esp. machining and assembly, dominates BH cost.
  - Estimate based on past experience.
- **Main cost risks:**

  Sensors
  - **Risk**: Single source, which has an excellent track record of delivering quality sensors at cost. Resulting risk if exchange rate changes.
  - **Mitigation**: CMS is working with two potential additional vendors, one European, the other US. Encouraging results so far.

  Brass
  - **Risk: I**ncrease in cost of machining and assembly, raw material.
  - **Mitigation:** Work with several companies, in case one company cannot perform work for expected cost.

CMS HGC: Main Pre-TDR milestones
(CMS Response to UCG question)

- TP.CA.EC.9 Q4 2017 Submit Technical Design Report
  - TP.CA.EC.3 Q2 2016 Define baseline module design & specifications
  - TP.CA.EC.5 Q4 2016 Define baseline BH megatile & absorber design
  - TP.CA.EC.6 Q1 2017 Submit V1 of front-end ASIC
  - TP.CA.EC.7 Q3 2017 1st tests with V1 front-end electronics
  - TP.CA.EC.8 Q3 2017 Define baseline design, cassettes & mechanics

- Vendor qualification and selection will proceed as for Tracker with MarketSurveys process - choice of technology n-in-p (preferred) p-in-n (descope) will be made for the TDR

- Decision on the wafer size, 6" versus 8," can be decided after the call for tender if earlier information is insufficient (soon after TDR)

CMS HGC – Comments and recommendations

- Even though the silicon readout calorimeter is well developed, this is the first time such technology is to be used at such a large scale and in such a hostile environment.
- Wafer size of 6” is assumed for the costing. A preliminary quote was obtained for 8” wafers, which was only 10% cheaper. However, using 8” wafers could substantially reducethe **total** HGC project cost.
- The collaboration and cooperation with CALICE has been beneficial, and will likely continue to be so, at least for the initial R&D phase

Recommendations, HGC:

1. **Further develop other vendors for silicon to reduce vul-nerability to company policy and exchange-rate fluctuations.**
2. **The collaboration is encouraged to give priority to validating the 8" option, in view of significant potential savings.**

CMS Muons – CHF 25M

Core costs (MCHF):

- DT electronics: **6.1**; CSC electronics: **3.7**; GEM GE11 and GE21: **7.9**; RPC RE31, RE41 extensions: **2.3**; ME0 extension to η 3.0 - **4.5**

Baseline cost looks reasonable (mostly QF 1-2)

- GE11 and other GEM-based detectors: approved TDR -- well understood.
- RPC: based on recent production experience
- CSC electronics upgrade: Phase I actual cost
- DT electronics upgrade: this is the least certain, because prototypes are still to be designed/built. (QF 3-4., vs QF 1-2 for rest of muon upgrade)

Recommendations, Muons: None

CMS Infrastructure – CHF 25M

- Current estimates are of limited precision, based mainly on experience during CMS construction and LS1, and to a lesser extent on initial engineering input (63% QF4, 34% QF3)
- Largest items: tech support (**8.9M**), infrastructure (**6.1M**) and engineering integration (**3.2M**)
- Estimates need continuous refinement as more information becomes available.

Recommendations, Infrastructure

1. We encourage CMS to summarize all infrastructure activities in a coherent reference document
2. Given the recent problems with the cryogenic system for the CMS solenoid, an in-depth assessment of ageing equipment in all critical components should be pursued with high priority
3. **The boundaries of responsibility between the CMS collaboration and the host laboratory should be clearly defined and agreed**

CMS: Summary of Major Risks

- Trigger/DAQ: No serious risk. issues involve scaling and extrapolating performance to the 2020’s.
- Tracker: Radiation tolerance of 1st layer pixel, ASIC delay, management of such a huge project.
- Calorimeters: ASIC delay, major R&D still needed for HGC.
- Muons: No serious risk
- Ageing components and systems.
- Solenoid issues.

ATLAS Overview

- Reference Detector cost estimate is **CHF 271 M**
- Cost estimates are well developed, applying an appropriate levels of conservatism and uncertainty.
- Forward LAr and the Muon system have major technical choices ahead, with possible significant implications on cost and schedule. UCG and LHCC will track this carefully.
- Experiment is actively exploring opportunities to combine procurements with other expts (Si, power supplies, etc.)
- Funding outlook (similar to that of CMS):
  - Substantive, relatively encouraging interactions with FA's, much greater detail than at this stage of original construction
  - Large uncertainties, will take a lot of time to secure commitments
  - Almost complete alignment of interests with needs

ATLAS TDAQ – CHF 43M

- Tracking triggers are 40% of total cost, driven by ITk *η*-coverage, trigger rate and cost of FPGAs and chips.
- **Cost estimate** is based on:
  - cost of IT/DAQ equipment as used in ATLAS since 2007
  - cost of PCBs, AM, FPGA's in current Phase-I FTK project.
  - for FPGAs assume current cost but factor in better performance.
- FTK++ is a large component (~13M)
- No obvious places of concern
- IDR Q1 2016 and TDR Q4 2017, augmented by studies of prototypes to optimise performance and reduce risk.

Recommendations, TDAQ:

1. ATLAS should retain close coupling between FTK++/L1. Project management and design choices should be carefully tracked.

ATLAS ITk – CHF 125 M

- Layout task force have optimised layout w.r.t. performance/cost for $|\eta| \leq 2.5$ but still working on extending further to $|\eta|=4$ (will report in Q1 2016)
- Pixel performance is estimated from the LoI, whereas the costing is based on the Layout Task Force design with reduced material
- Cost of replacing the inner 2 pixel layers is not included in the totals but would cost an estimated 6.8 MCHF
- Strip planning more advanced than Pixels (pixel resources were busy with the IBL): Strips TDR planned for Q4-2016); Pixel TDR will follow in 2017.
- Core costs estimated only up to commissioning (note ITk will be run for 1 year on the surface before installation)
- Optimism that future costings will not show large increases:
  - ATLAS has considerable expertise from building the existing IT
  - They have been conservative in scaling of costs.

ATLAS ITk –Main Cost Risks and Recommendations

- Pixel sensor: front-end chip bump-bonding (30% of pixel total cost): possible low yield because of thin chips.
  - Mitigation: ATLAS are exploring use of new vendors.
- Strip sensors (40% of total strip cost): current costing based only on private communication via ATLAS people working with HPK. Costing assumes 100% yield (from experience with HPK).
  - Mitigation: Market survey (with CMS) underway.
- Infrastructure:
  - IT components re-used where possible – not clear if HV/LV cables can be used and no cost estimate yet for replacements.

Recommendations, ITk:

1. Produce a document listing remaining R&D items and associated milestones, to define clear future review points for the project .
2. Conduct performance simulation studies with the final layout.

ATLAS LAr – CHF 47 M

- **The Reference LAr upgrade detector includes**
  - 40 MHz readout system streaming off-detector **(~31.4 MCHF**)
  - Replacing current **FCal** by a finely segmented **sFCal** (**~11.8 MCHF)**
  - H**igh-precision timing detector** for η range 2.4 - 4.3 (**~ 4.6 MCHF).**
- **Full LAr electronics upgrade required in all cost scenarios:**
  - Replace aged components; Provide adequate radiation tolerance in HL-LHC; support phase-II ATLAS trigger scheme and TDAQ
- **Middle and Low cost scenarios**: Keep current **FCal;** no high-precision timing detector. Results in **~16.4 MCHF** savings
- **sFCal**
  - Encouraging G4 studies; more work needed to develop physics case.
  - Prototypes essential to validate performance in high backgrounds.
  - *Removal of **FCal** and **sFCal** installation entail substantial technical risks*.

LAr (cont'd)

- **Precision timing detector (PTD)**:
  - Present studies depend on the use of crab-kissing collision scheme . Significant future R&D required.
  - Cost is highly uncertain, even with ATLAS's conservative estimate.
- **MiniFCal** as Fallback Option to aid degraded **FCal**
  - Needed if **sFCal** isn't possible and **FCal** will not survive at HL-LHC.
  - Rough cost estimates are +**1.3 MCHF** (cold) or **+3.6 MCHF** (warm).
  - Concept needs more study, and substantial R&D.
- sFCAL and PTD projects are very much works in progress!
- Radiation environment could make interventions in forward region challenging and/or costly, especially if robotics prove necessary.

Technical Unknowns and Risks in the Forward Region upgrade are more worrisome than Cost Risks at present.

LAr Milestones, Decision Points, Recommendations

- R&D Milestones (ATLAS response to UCG questions from Monday Sept 21)
  - Complete Initial Design Review: Sept 2016
  - Signal processing algorithms, pile-up mitigation,
  - readout frequency 40/80 MHz: May 2017
  - Fiber-optic plant technology: May 2017
- Major Decision Points:
  - sFCal decision to proceed to TDR or not: June 2016
  - HGTD decision to proceed to TDR or not: May 2017

Recommendations, LAr:

1. Work to optimize the full LAr electronics upgrade should proceed
2. Broad based efforts (simulation, design, prototyping, installation engineering review) are crucial to understanding the Forward CAL Region and should be vigorously pursued during the next 6 months.
3. The LHCC and the UGC should be kept updated as this work proceeds.

Tile Calorimeter – 8.6 MCHF

- **Cost drivers**: FPGAs, complex PCBs: 14-16 layers, ATCA crate system, optical fiber system)
- Good level of confidence, with demonstrator tests in beam, and changes based on run 1 experience.
- **Cost risks** look moderate: affect only 20% of cost.
  - Recent fabrication of a demonstrator increases cost confidence.
  - Most scintillators and PMTs assumed to be re-used unchanged

Recommendations, Tile:

1. Explore opportunities to reduce FPGA cost.

ATLAS Muons – 34 MCHF

- RPC's.
  - Doubts about longevity at high operating efficiency and it is not possible to replace all of them, so ATLAS has lowered the HV to ensure they will survive, resulting in efficiencies as low as 65 %. To mitigate this problem ATLAS will install new ones in BI, in loose coincidence with existing BM and BO. This restores efficiency-acceptance to 95%.
  - Decision on scope of BI, FE electronics, trigger: March 2016.
- MDT's. Need to replace by sMDT to save space to install new RPC layer.
- Front-end electronics: preferred scenario is to replace everywhere, including a 3-station trigger).
- Want to have muon tagging at high η
- May have to replace entire power system to simplify maintenance.
- Cost
  - Power system is biggest cost, distributed among systems
  - Big difference in scoping costs in replacing RPC's

Muons – Risks

- Resources are limited and need to be well managed
  - Heavy demand during RPC-BI and power system replacement
  - Currently the Muon project is longer than the duration of LS3
- BI is very challenging – fragile, huge cable services
  - Current RPC performance cannot be sustained.
  - Power supply cost estimate is uncertain
- Cost risks
  - Electronics based only on conceptual designs
  - High η configuration is uncertain
  - Power system is biggest cost
    - Coordination with other LHC expts might save costs

Recommendations, Muons:

1. Make it high priority to resolve the issues on a schedule consistent with the pre-TDR milestones / decision points givento the UCG..

ATLAS Infrastructure/Installation – CHF 17 M

- Cost estimates for safety infrastructure (3.5MCHF) assume no robotics will be needed for LS3 installation.
  - A verification of this assumption is expected for summer 2016.
  - *If robotics are needed additional costs could be substantial but have not been estimated.*
  - *Nor has there been a feasibility study of using robotics .*

- Installation schedule very tight and presently does not fit within LS3 time window (3m overrun).
- sFCal installation (1.8MCHF) is a challenging operation (modification of activated cryostat) with substantial uncertainty in cost.
- Precise evaluation of power, cooling and ventilation needs will be done at later stage (requires TDR’s).

Infrastructure and Installation cont'd)

Comments

- Common infrastructure, detector integration, installation requested to be funded through common fund (17.4MCHF) under TC & RC responsibility
- Cost for technical manpower budgeted; lack of core engineering resources needs to be dealt with
- Disposal of decommissioned components not budgeted

Recommendations, Infrastructure

1. Perform review of cost and overall schedule for TC, common infrastructure and installations in 2018 (all TDRs will be available, needs & cost on safety, power, cooling will be close to finalized)
2. An in-depth assessment of ageing equipment in all critical components should be pursued with high priority
3. The boundaries of responsibility between the collaboration and the host laboratory should be clearly defined and agreed

Conclusions

Both experiments have attained levels of preparation and understanding that meet, and in some areas exceed, requirements for Step 1 approval.

- Estimates are detailed, and based on experience and vendor quotes
- The reference scenario is well matched to the science, without overkill.
  - cost savings via further optimisation are possible.
- The lesser scenarios will diminish capability and reduce efficiency.
- For ATLAS, the forward region presents the most serious challenges and largest risks to cost and schedule, involving LAr, Muons and infrastructure.
- For CMS, though the cost and schedule estimates for the HGC are reasonable for this stage, much R&D is needed to produce a detailed design and TDR.
- Though the UCG deals only with core costs, clearly these projects depend on adequate and sustained support for manpower and other resources at the participating institutes.

- **We recommend that you strongly support this unique, exciting program, and approve resources to allow the experiments to develop detailed designs and TDR's in preparation for Step 2.**

BACKUP

Phase-1 Upgrades

- **CMS**
  - *HCAL*
  - *Trigger*
  - *Pixel*
- **ATLAS**
  - *IBL*
  - *LAr*
  - *NSW*
  - *FTK*
  - *TDAQ*
- **LHCb**
  - *VELO*
  - *Tracker (UT and SciFi)*
  - *PID (RICH –CALO)*
  - *Online*
- **ALICE**
  - *ITS*
  - *TDAQ*
  - *TPC*
  - *Offline-Online (O2)*
  - *MFT (< UCG threshold)*

(Approved) **(Approved by LHC and UCG in Sept)**