Status report of the CMS ECAL Upgrade plans

The ECAL Group

June 11, 2013

1 Introduction and motivation for upgrades

The purpose of this document is to summarize and assess the feasibility of the possible upgrade options for the CMS ECAL, based on our current level of understanding. These take into account the longevity of the existing detectors and the physics and triggering requirements that are envisaged for the Phase 2 detector operating in HL-LHC beam conditions. HL-LHC is expected to have an instantaneous luminosity of around 5×10^{34} cm^{-2}s^{-1} and integrate a total luminosity of around 3000 fb^{-1} by about 2035 (ten years of running).

We define a 'working hypothesis' for Phase 2, in order to provide a focal point for RRB scope and cost-scale discussions, and outline the work needed in the next several months to further clarify this scenario. We also list a limited number of technically-feasible, but limited scope, backup solutions that could provide an intermediate upgrade option at a lower total cost.

1.1 Longevity and physics performance

The effects of radiation damage on the $PbWO_4$ crystals have been studied in depth. Two main processes affect the light transmission of the crystals. Ionising damage causes a dose-rate dependent transmission loss due to the formation of colour centres. These spontaneously anneal at room temperature such that the transmission tends to a rate dependent equilibrium during long periods of LHC operation [1]. The variations in crystal response are tracked and corrected for using a dedicated light monitoring system.

The dominant concern for HL-LHC running is the cumulative damage due to hadrons, predominantly charged pions with an energy of the order of 1 GeV. The cause of transmission loss in this case is understood to be due to interactions with the lead or tungsten nuclei resulting in either spallation or fission products that are highly ionizing and cause damage to the crystal lattice. These defects do not anneal at room temperature, although recovery via high temperature (350 °C) and partial recovery with modest elevated temperatures and/or optical stimulation has been achieved in laboratory tests.

A model simulating the effects of the reduction in light transmission of the crystals due to ionizing and hadronic damage mechanisms has been developed and implemented in CMSSW. This simulation has been validated against test beam data using matrices of proton-irradiated crystals [2, 6]. The simulation predicts a strong eta-dependent reduction in the crystal transmission for integrated luminosities corresponding to HL-LHC (e.g. relative response <1% for

L>500 fb^{-1}, $|\eta| > 2.6$). The increase in electronic noise due to bulk damage of the APDs from neutron irradiation is also simulated.

The effect of these processes on object reconstruction and physics sensitivity is currently being evaluated. An eta-dependent degradation of energy resolution with increasing luminosity, culminating in a gradual loss of acceptance for electrons, photons and jets at high eta in EE, is expected for L>500 fb^{-1} [3]. It is expected that the more moderate losses in transparency of the EB crystals will not significantly impact the physics performance, even after 3000 fb^{-1}.

Regarding the longevity of the on-detector electronics, the ECAL mostly uses ASICs with 0.25 micron feature size. The degradation with neutron damage (and accumulated dose) is negligible and susceptibility to SEEs (single event effects) is limited. The current rate of failure of the on-detector electronics leading to loss of readout channels is small. However the electronics are already more than 5 years old and will be greater than 15 years old by the start of Phase 2. We are currently pursuing thermal-cycling and accelerated ageing tests on the existing spares, as well as conducting a full examination of the installed electronics, to determine if there are any obvious weak points that may limit the overall longevity.

1.2 Trigger rate and L1 latency constraints of the existing system

The EB/EE front-end (FE) electronics have a pipeline memory with 256 cells, corresponding to a maximum latency of 6.4 μsec. The ES front-end has a 192-cell pipeline memory, corresponding to a maximum latency of 4.8 μsec. The electronics, both on-detector and off-detector (OD), were designed to have a maximum L1A rate of 110 kHz.

The maximum L1A rate that can be achieved with the existing electronics is about 150 kHz, following firmware modifications. Reducing the number of samples being read out (e.g. from 10 to 4) could result in a higher rate being possible, estimated to be up to 200 kHz if the OD electronics are replaced [4]. However, the impact of reducing the number of samples on the rejection of out-of-time pileup needs to be assessed.

The proposed Phase 2 triggering requirements (ballpark numbers: 0.5-1 MHz readout, 10-20 μs latency) cannot be accommodated by the existing electronics. A complete replacement of the on-detector and off-detector electronics would therefore be necessary.

2 Summary of upgrade options

Several upgrade options have been considered, and are summarized in Table 1. These can be broken down into options to a) compensate for the loss of response in the EE by a full or partial replacement of the active detector medium; b) options to increase the trigger latency and L1A rate by replacing the ECAL front-end and associated off-detector electronics; c) options to partially compensate for the noise increase in EB and the loss of transparency in EE that do not require the replacement of the FE electronics or the active detector material.

The upgrade options are judged in terms of the level of radiation exposure, estimated overall cost, the time taken to perform the intervention, and an estimate of the level of physical risk to the detector. The effect on performance is qualitatively evaluated in terms of energy resolution, triggering capability, pileup (PU) mitigation and the rejection of EB anomalous signals (spikes). Each upgrade option is rated with respect to the case where no upgrade is performed. Note that these expectations, particularly resolution and PU mitigation, must be verified using Monte Carlo simulations. Finally a qualitative assessment of the feasibility of each upgrade option is provided.

2.1 "Full" upgrade options

The first upgrade option involves a full replacement of the barrel FE electronics. This would be required if CMS requires a L1 trigger latency of greater than 6.4 μs or an L1 accept rate of greater than 200 kHz. It would require a full dismount of the barrel supermodules and design of new FE and OD electronics. The replacement of the front-end cards would be performed after moving the supermodules to a specially-prepared integration area on the surface at the CMS site. A detailed survey of the time required to dismount, replace FE cards and remount the supermodules, yielded a total duration of 26 months [5], including opening/closing of CMS and replacement of the inner Tracker, assumed to take place in the same long shutdown. Replacement of the FE electronics can provide other benefits, such as mitigating longevity concerns on the existing components, and further improve noise and spike rejection. The rejection of spikes at L1 can also be improved by adapting the FE to read out more granular trigger information. Replacement of the EE FE electronics without changing the active detector medium is considered impractical due to radiation concerns, as will be discussed later.

The second option is to replace the EB FE electronics and, at the same time, replace the EE+ES with a new radiation-hard detector that improves the detector lifetime in the forward region and has adequate energy resolution, acceptance and PU rejection for the HL-LHC conditions. In this option, the FE electronics for the new EE+ES will also be designed to accommodate any increased latency and L1A rate requirements. Options for improved PU mitigation include finer transverse segmentation and more precise timing capabilities using a separate dedicated detector layer. Several strawman options for replacement EE+ES detectors have been proposed, although the viability, scope and cost estimates for these need to be refined. In addition, the feasibility of replacing both the EB electronics and replacing the EE+ES in a single long shutdown needs to be assessed, and a detailed time estimate for this option is in progress.

2.2 Options to mitigate degraded detector response

Several options have been considered to mitigate the response loss in EE without full detector replacement, and to reduce the increased electronic noise in EB due to APD bulk damage.

The first option is to run EB at a lower temperature (8-10 °C rather than the current 18 °C; the lower temperature is limited by humidity concerns) to reduce the EB electronic noise by reducing the APD dark current by almost a factor of two. This will mitigate the impact of noise on the energy resolution for electrons and photons, and will also improve the L1 spike rejection at higher integrated luminosity (since the single channel threshold used in the online spike rejection algorithm must be set according to the level of electronic noise). The feasibility of this option is being investigated - at the moment it appears to be technically possible, but would require significant, but feasible, changes to CMS infrastructure.

The second option is to attempt to partially recover the hadronic damage in the EE crystals by a combination of in-situ thermal annealing and optical bleaching. Heating of the crystals up to approximately 60 °C could be provided by one of the existing EE cooling loops, and the optical bleaching could be provided by a light distribution system attached to the front face of the EE, using space liberated by the removal of ES. This option could be used to partially recover the response in the inner region of EE during technical stops, potentially extending the useable region of the detector for HL-LHC luminosities. But this is a very challenging option and laboratory tests are ongoing to assess its feasibility.

The third option considered is to mitigate the effects of radiation damage at the highest eta by installing a new compact radiation-hard calorimeter in front of the existing EE, using space liberated by removing ES and probably some space from the existing Tracker envelope. The new calorimeter would only cover a limited range in the highest eta region, with the existing EE completing the coverage. This could provide a cost-effective solution to recover the majority of the performance in the inner region of EE, if insufficient funds are available for a full replacement. One disadvantage of this approach is that the enhanced triggering capability (1 MHz readout, 20μs latency) would not be possible over the full eta range, since the existing EE FE electronics would not be replaced. Another disadvantage is the limited space available (ES thickness is approx 20 cm). Given the requirement of an approx 8 cm polyethylene moderator to protect the Tracker from neutrons generated in the calorimeter volumes, it is likely that some of the moderator material would need to be built into the Tracker volume. It is also likely that any new services would need to run over the front of the existing EE.

2.3 Rejected options

Several options have been considered and subsequently rejected as impractical due to cost, time, technical difficulty or radiation dose issues.

Replacement of the barrel APDs would enable the issue of ECAL spikes to be cured at source. However, the difficulty of liberating the APDs from the supermodule structure - which essentially demands a complete dis-assembly of the supermodule and crystal superstructure renders this approach impractical. The time taken to perform such an exercise is considerable (estimated to be 5 years) and involves significant technical risk for a small gain.

The possible removal of just the innermost EE supercrystals, and replacement with a radiation-hard alternative detector, was considered. This was deemed not to be technically feasible - removal of the inner supercrystals is impractical without resorting to destructive methods. The super-crystals can only be dismounted with a full disassembly of the electronics and mechanical structure, which is not feasible due to time and radiation concerns. The destructive solution to cut away the inner eta rings has the obvious risk of compromising the remaining structure and services of EE. Even if this were possible, there is no obvious way of using any space liberated without impacting on the performance of the rest of EE.

The third option involves replacing the EE FE electronics while retaining the existing lead tungstate crystals. This approach was deemed impractical for two related reasons. The difficulty of accessing the electronics, given the arrangement of existing services and readout/trigger cables that cover the FE boards, means that any electronics replacement will take a long time. And the radiation dose rate at the location of the EE FE electronics during LS3 precludes the type of close-contact work that would be required (the estimated activity after 500 fb^{-1} and 6 months of "cooldown" is 100 μSv/hour).

Action	Radiation	Cost	Time	Risk	Resolution	Trigger	PU	Spikes	Feasibility
None	LOW	LOW	LOW	LOW	SAME	LIMITED	SAME	SAME	YES
Full replacement options									
New EB elec.	LOW	MODERATE	26Mo	HIGH	SAME	BETTER (EB)	SAME	BETTER	YES
New EB elec.+ new EE	MODERATE	HIGH	30-50Mo	HIGH	BETTER	BETTER	BETTER	BETTER	YES
Mitigating options									
Cool EB by 8-10 C	LOW	LOW	?	MODERATE	BETTER	SAME	SAME	BETTER	YES
Bleaching/annealing	MODERATE	LOW	LOW	MODERATE	BETTER?	SAME	SAME	SAME	R&D
EE cone at high η	MODERATE	MODERATE	?	HIGH	BETTER	SAME	BETTER?	SAME	POSSIBLE?
Rejected options									
APD replacement	LOW	HIGH	60Mo	HIGH	SAME	SAME	SAME	BETTER++	Impractical
Partial EE repl.	HIGH	HIGH	??	V.HIGH	BETTER?	SAME	BETTER?	SAME	Impractical
Replace all elec.	V.HIGH	MODERATE	n/a	V.HIGH	SAME	BETTER	SAME	BETTER	Impractical

Table 1: Summary of upgrade options.

2.4 Working hypothesis

Since the potential funds for Phase 2 upgrades are uncertain, we consider that it is important to maintain the set of feasible fall-back solutions listed in this document. However, in order to provide a definite focus for cost scale and project scope estimates for the October RRB, we consider that the option to refurbish the EB electronics and replace the existing EE+ES with a new radiation-hard detector should be the default 'working hypothesis' for the CMS ECAL. In addition to this, we consider that the option to reduce the operating temperature of EB to 8 °C in order to mitigate the noise contribution from APD dark current should be pursued. The working hypothesis would provide the possibility of achieving and maintaining the required performance of the forward calorimeter in the high PU and radiation conditions of HL-LHC. It would also yield the maximum flexibility for increased CMS triggering capabilities.

The most efficient scenario for these upgrades is to perform them all in a single long shutdown. As the replacement of the EB electronics should be done at the same time as the Tracker replacement, the clear preference is to do these things in LS3. The question arises as to the feasibility of replacing the EE+ES in a later shutdown (e.g. LS4, after an integrated luminosity of about 1000 fb^{-1}). The physics performance of the existing detector as a function of integrated luminosity is currently being simulated, but results are not expected for a couple of months. A preliminary judgement, based on extrapolations of the light collection efficiency, triggering thresholds and $H \longrightarrow \gamma\gamma$ mass resolution (at generator level) indicate that the performance of EE will be significantly degraded after 500 fb^{-1} so this sort of staging scenario is extremely unattractive.

It is clear that a considerable amount of work needs to be done in the next several months. First of all, a set of strawman options for the EE+ES replacement detector need to be defined, with associated cost scales. Options that include the possibility of coupling EE+ES replacement with changes to HE, should also be assessed. In addition, the technical feasibility of performing all of these operations in one long shutdown must be demonstrated. Staged approaches should also be developed where possible but, as mentioned above, these may impact the performance significantly. Regarding physics, simulations that show the effect of the degradation in performance of the current EE+ES will need to be completed in order to support the case for a potential replacement of the detectors. This work is being carried-out by ECAL in collaboration with several upgrade working groups and task forces, as well as CMS Technical Coordination.

Regarding the replacement of the FE and OD electronics, a putative design and cost scale will need to be provided as input to the RRB cost scale submission. In parallel, in the event that the envisaged trigger for HL-LHC can exist within the current envelope of L1 latency and L1A rate, the longevity of the existing electronics must be demonstrated. Work is underway to assess the lifetime of the on-detector electronics components, and further accelerated ageing tests are foreseen.

References

[1] See, for example, P. Adzic et al. *"Radiation hardness qualification of $PbWO_4$ scintillation crystals for the CMS Electromagnetic Calorimeter"*, J. Instrum., **5**, P03010, (2010) `doi::10.1088/1748-0221/5/03/P03010`

[2] F. Nessi-Tedaldi, *"Response evolution of the CMS ECAL and R&D studies for electromagnetic calorimetry at the HL-LHC"*, CMS-CR-2012/296, http://cms.cern.ch/iCMS/jsp/openfile.jsp?type=CR&year=2012&files=CR2012_296.pdf

[3] R. Rusack and M. Mannelli, *"Forward Detector Upgrade Interim Report"*, February 2013, https://indico.cern.ch/getFile.py/access?subContId=2&contribId=4&resId=0&materialId=0&confId=234593

[4] O. Buchmueller and W. Smith, *"Trigger Performance and Strategy Group Interim Report"*, February 2013, https://indico.cern.ch/getFile.py/access?subContId=1&contribId=4&resId=0&materialId=0&confId=234593

[5] W. Zeuner et. al., *"On the possibility to exchange the digital electronics of all ECAL supermodules in the third long shutdown of LHC (LS3)"*, November 2012, https://cms-docdb.cern.ch/cgi-bin/DocDB/ShowDocument?docid=11875

[6] M. Lucchini et. al., *"Test beam evaluation of CMS ECAL EE Super Crystal made of gamma- and hadron-damaged crystals"*, CMS DN-2013/007 (in preparation)