The Phase-2 Upgrade
of the CMS Barrel Calorimeters

Technical Design Report

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Chapter 1

Project Overview

1.1 Introduction

The CMS electromagnetic and hadronic calorimeters [1] are designed to provide hermetic coverage within the pseudorapidity region $|\eta| < 5$. The calorimeters are crucial for the identification and reconstruction of photons and electrons, and for the measurement of jets and missing transverse momentum. For Higgs physics, high resolution and efficient identification for photons is required for the $H \rightarrow \gamma\gamma$ decay process, for measurements of the self-coupling of Higgs bosons and other related parameters. Electrons are important for Higgs physics and for many physics topics beyond the standard model (BSM). Efficient separation of electrons from hadrons requires information from the front portion of the hadron calorimeter as well as information from the tracker and electromagnetic calorimeter (ECAL). Jets and missing transverse energy, $E_T^{\text{miss}}$, in CMS are measured using a particle flow technique [2], which combines information from the tracker and calorimeters.

The CMS electromagnetic calorimeter [1, 3, 4] is a homogeneous calorimeter made of 75,848 lead tungstate (PbWO$_4$) scintillating crystals, located inside the CMS superconducting solenoid magnet. It is made of a barrel part (EB) covering the region of pseudorapidity $|\eta| < 1.48$ and two endcaps (EE), which extend the coverage up to $|\eta| = 3.0$. The photodetectors are Avalanche Photodiodes (APD) in the barrel and Vacuum Phototriodes (VPT) in the endcaps. The barrel region is made of 36 identical supermodules (SM), each containing the crystals, APDs and readout electronics. A preshower detector (ES), based on lead absorbers equipped with silicon strip sensors, is placed in front of the endcap crystals. Electrons and photons are typically reconstructed up to $|\eta| < 2.5$, the region covered by the tracker, while jets are reconstructed up to $|\eta| < 3.0$. The ECAL energy resolution achieved during 2010–2011 is described in Ref. [5] and ranges from 1.1 to 2.6% in the barrel and 2.2 to 5% in the endcaps for photons from the Higgs boson decay.

The CMS hadron calorimeter (HCAL) [1, 6] has four major sections: the HCAL Barrel (HB), HCAL Endcap (HE), HCAL Outer (HO), and HCAL Forward (HF). The HB and HE calorimeters are sampling calorimeters that use a brass absorber and plastic scintillator as the active material. Light from the plastic scintillator is wavelength-shifted (WLS) and captured in fibers. Fibers from the calorimeter tiles are grouped to form projective towers that are currently read out by Hybrid Photodiodes (HPDs) that will be replaced by Silicon Photomultiplier (SiPM) devices as part of the Phase-1 upgrade of CMS [7]. The HCAL Outer calorimeter functions as a tail-catcher for hadronic showers and sits outside the CMS solenoid magnet. The HF is a Cherenkov calorimeter based on a steel absorber and quartz fibers that run longitudinally (parallel to the beam) through the absorber and collect Cherenkov light, primarily from the electromagnetic component of the showers that develop in the calorimeter. Together, these detectors cover $|\eta| < 5.0$ and are important for the measurement of jets and $E_T^{\text{miss}}$. 
The existing CMS calorimeters were designed [3, 6] to meet these challenges up to an integrated luminosity of $500 \text{ fb}^{-1}$ at the LHC over 10 years of data taking at an instantaneous luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. With the Phase-1 upgrades of the hadron calorimeter [7], the detector is capable of operating up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The operating parameters of the High Luminosity upgrade of the LHC accelerator complex, defined below, require a re-examination of the ability of the detector active material and electronics to meet the requirements of up to $4500 \text{ fb}^{-1}$. Based on the studies presented in Ref. [8], upgrades to the calorimeters are necessary.

These involve the replacement of the front-end electronics of the EB and the replacement of the off-detector electronics of both EB and HB. These upgrades will be documented in detail below. The EB photodetectors and lead tungstate crystals will be retained during HL-LHC operation. The absorber, active material and front-end electronics of the HB detector will also be retained. The ECAL and HCAL endcaps will suffer significant radiation damage, necessitating a full replacement prior to HL-LHC [8].

### 1.2 The HL-LHC upgrade

The main objective of the High Luminosity LHC (HL-LHC) upgrade [9] of the LHC accelerator is to deliver a much larger dataset for physics to the LHC experiments, for new physics searches, Higgs boson coupling measurements and precision tests of the standard model. The goals include operating the upgraded accelerator at a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (with luminosity levelling) after 2026. This will allow the delivery of an integrated luminosity of $250 \text{ fb}^{-1}$ per year, with the goal of $3000 \text{ fb}^{-1}$ over about 12 years of operation after the upgrade. This integrated luminosity is about ten times the expected luminosity of the first twelve years of the LHC.

The timeline of LHC and HL-LHC operation is sketched in Fig. 1.1, showing the planned evolution of proton beam intensity through the remaining LHC operating periods (Run 2 and Run 3) and the HL-LHC operating period following the upgrade of the accelerator complex in Long Shutdown 3. The two periods of operation are termed Phase-1 (LHC) and Phase-2 (HL-LHC).
1.3 Technical and physics reasons for the EB upgrade

Table 1.1: Projected HL-LHC operating parameters. The current 2017 operating parameters are included for reference.

<table>
<thead>
<tr>
<th></th>
<th>Peak lumi. ( \times 10^{34} \text{cm}^{-2}\text{s}^{-1} )</th>
<th>Peak pileup</th>
<th>Lumi/year ( \text{fb}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>1.7</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>HL-LHC (baseline)</td>
<td>5.0</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>HL-LHC (ultimate)</td>
<td>7.5</td>
<td>200</td>
<td>320</td>
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140, a delivered luminosity of 250 \( \text{fb}^{-1} \) per year, for a total integrated luminosity of 3000 \( \text{fb}^{-1} \) by 2038. The HL-LHC project has also defined a set of “ultimate” beam parameters, which involve a levelled luminosity of 7.5 \( \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \), a peak pileup of 200, a delivered luminosity of 320 \( \text{fb}^{-1} \) per year, for a total integrated luminosity of 4000 \( \text{fb}^{-1} \).

In this report, the physics performance of the upgraded ECAL and HCAL detectors are evaluated for an integrated luminosity of 1000 \( \text{fb}^{-1} \) and for a pileup of 200 interactions per crossing. This value is considered to be representative of Phase-2 performance. The ageing of detector components is assessed up to an integrated luminosity of 4500 \( \text{fb}^{-1} \). This corresponds to the ultimate LHC scenario, plus a safety margin. Physics object selection and reconstruction algorithms are also assessed up to 4500 \( \text{fb}^{-1} \), using simulated events with detector ageing applied.

1.3 Technical and physics reasons for the EB upgrade

The principal requirement of the EB upgrade is to maintain the Run 1 physics performance for photons and electrons at the higher luminosity and pileup of the HL-LHC. In order to accomplish this, the EB electronics must accommodate the Level-1 trigger requirements on latency and rate, provide more precise timing resolution, and help mitigate the increasing noise from the photodetectors.

The primary technical motivation for the EB calorimeter upgrade is the trigger requirement for an increase of the trigger latency from about 4 \( \mu\text{s} \) in the current (“legacy”) system [4] to a maximum of 12.5 \( \mu\text{s} \), and a Level-1 trigger rate of up to 750 kHz compared to the current 100 kHz. The EB electronics Front End (FE) card and all the off-detector electronics must be replaced to meet these requirements. The legacy system provides trigger primitives of five-by-five crystals and there is no tracking information available. The upgrade will instead provide single crystal information to the Level-1 calorimeter trigger in order to precisely match electromagnetic showers to tracks and to provide better isolation compared to the current system. This significantly reduces backgrounds and enables the calorimeter trigger thresholds to remain at the levels required for precision study of the Higgs boson.

The Very Front End (VFE) card, which provides pulse amplification, shaping, and digitization functions, must be replaced to provide better timing resolution and noise filtering. The pulse shaping will be shortened to more optimally filter the increased APD noise and the sampling rate will be increased to provide better timing resolution. This will allow anomalous signals in the APDs (termed “spikes” [10]) to be almost completely suppressed in the Level-1 trigger. It will be achieved by exploiting their different time development compared to scintillation pulses, in addition to the better isolation provided by the single crystal information. The legacy system provides minimal time discrimination owing to the \( CR - RC^2 \) pulse shaping applied. Without the additional timing and isolation information, the Level-1 trigger would be saturated by spikes at the desired energy thresholds. The upgrade will also reduce the risk of wear-out associated with operating the legacy electronics for 30 years and 4500 \( \text{fb}^{-1} \). The current
electronics were designed [3, 4, 6, 7] for 10 years running and 500 fb$^{-1}$.

The re-optimisation of the APD pulse shaping and sampling rate provided by the new VFE card, together with a reduction in the EB operating temperature, mitigate the increases in APD noise. Studies performed in Ref. [8] show how the Phase-2 upgrade mitigates the radiation-induced noise increase from the APDs and crystal transparency losses. The upgrade will ensure that these sources of noise will no longer dominate the energy resolution for photons from Higgs boson decays. These performance improvements demonstrate that it is essential to implement these upgrades to maintain good EB performance over the HL-LHC running period.

Precision time measurements have not traditionally been a key aspect of calorimeters at hadron colliders. However, such measurements may improve the determination of the location of the production vertex for di-photon events. This will result in improved performance at large pileup (PU) values, $\langle PU \rangle = 200$. CMS is therefore considering the possibility of implementing such capabilities in the upgraded calorimeters. A precision of 30 ps on the arrival time of photons produced by Higgs bosons decays is the target envisaged for the barrel upgrade scenario. With such a precision, a constraint of 1 cm can be placed on the vertex position along the longitudinal axis. To achieve this level of precision, signal oversampling is required, leading to an increase in readout bandwidth from the VFE electronics. The details of the proposed architecture are described in Section 3.2.

1.4 Overview of the EB upgrade

The conceptual design for the electronics system upgrade has been developed using the specifications and constraints provided in Table 1.2. The basic specifications for the new electronics will be similar to the legacy system, since the crystals/APDs will not be replaced. The dynamic range will be between a few tens of MeV to the equivalent of 2 TeV signals from electrons or photons. The lower bound is defined by the intrinsic noise from the APDs, currently around 60 MeV. This will increase further with radiation, as discussed in Section 2. The upgrade will reduce the noise to around 200 MeV through a re-optimization of the preamplifier architecture and characteristics, described in Section 3, and a lowering of the supermodule operating temperature from 18 °C to 9 °C, described in Section 4.

1.4.1 Front-end electronics upgrade

1.4.1.1 Present on-detector electronics

A block diagram of the present ECAL electronics system [3, 4] is shown in Fig. 1.2. The analogue signals from the APDs are processed in a pre-amplifier/shaper and are digitized. The data from a physical region, a so-called “trigger tower”, are combined on detector to form a trigger primitive to be used by the Level-1 trigger processors. The data from every bunch crossing are stored on detector while waiting for the Level-1 trigger decision. The trigger primitive is sent to the Trigger Concentrator Card (TCC) in the back end system that forwards the information to the calorimeter trigger processor. The TCC evaluates the trigger primitive content in order to calculate information that is forwarded to the Selective Readout Processor (SRP). The SRP combines the information from neighboring trigger towers and sends a complete readout map to the Data Concentrator Card (DCC) to decrease the amount of data to be read to the central DAQ. For positive Level-1 trigger decisions, data corresponding to the selected bunch crossing are sent from the front end system to the DCC. The DCC applies the readout map received from the SRP and transfers the corresponding data to the central DAQ. Further details of the legacy architecture can be found in Ref. [1].
Table 1.2: Basic principles and constraints for the upgraded EB electronics.

<table>
<thead>
<tr>
<th>Principle/Constraint</th>
<th>Implications</th>
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| Adapt to on-detector mechanics and modularity                   | • New VFE/FE: Adopt form-factor from legacy VFE/FE  
  • Power dissipation less or equal to legacy electronics system |                                      |
| Provide trigger primitive generation with single crystal granularity | • No on-detector trigger-primitive generation  
  • No on-detector pipeline memory, effectively removing the L1 trigger latency constraint from the front end system  
  • No on-detector event buffers, effectively removing the L1 trigger rate constraint from the front end system |                                      |
| Limit power dissipation in new and compact Low Voltage cabling plant | • Point of Load LV regulation with DC-DC converters located in the front end system, please see [11] for further information about the development of radiation and magnetic field tolerant DC/DC converters |                                      |
| Provide a precision hit timing measurement in addition to hit energy (goal 30 ps resolution for $H \rightarrow \gamma\gamma$ photons) | • Signal oversampling  
  • Application Specific high-speed ADC  
  • Increased front end data transmission rate  
  • Increased readout data volume |                                      |
| Use on-going common developments wherever possible              | • Versatile link plus lpGBT for control and readout. Please see [11] for further information about the versatile link plus development  
  • ATCA (Advanced Telecommunications Architecture [12]) as baseline for off-detector boards |                                      |
A schematic of the present ECAL on-detector electronics is shown in Fig. 1.3. Two APDs are mounted on the rear face of each crystal and connected in parallel in a capsule housing the APDs to form one analogue readout per crystal. The APDs are connected to the passive motherboard (MB) through a Kapton cable that distributes the APD bias voltage and power to the analogue electronics circuits on the VFE as well as connecting the APD signals to the VFE cards. Each VFE card has five readout channels consisting of a multi-gain pre-amplifier (MPGA) with a 43 ns shaping time and a 12-bit analog-to-digital converter (ADC) (least significant bit 40 MeV). In addition, the VFE cards provide monitoring of the APD leakage current as well as temperature through an Inter-Integrated Circuit (I2C) slow control interface. The digitized signals from five VFE cards are passed to a single FE card. The FE card forms the trigger primitive for the $5 \times 5$ crystal array and contains a digital latency buffer and the primary event buffer.

The trigger primitive is the calibrated transverse energy deposited in a trigger tower with two feature bits to qualify the energy deposit. The trigger primitives are transmitted optically to...
1.4. Overview of the EB upgrade

A TCC in the underground service cavern for re-formatting and further transmission to the calorimeter trigger. The per-crystal information is buffered in the FE for transmission to the DCC, with a maximum latency in the event buffer of 6.4 µs and a maximum Level-1 accept rate of about 150 kHz.

The ASICs on the VFE and FE are fabricated with 0.25 µm CMOS technology with appropriate design rules in order to ensure that the system is sufficiently radiation tolerant. The designs were shown to resist the radiation environment of the EB considering the foreseen ten year operation period and an integrated luminosity of 500 fb$^{-1}$. During LHC Run-1 very few failures occurred in the front-end electronics, resulting in less than 1% of non-operational channels. No failure was observed on the MB, LVR or VFE cards. A few faults were observed on the FE cards and can mostly be traced to bad contacts between the FE card and the Gigabit Optical Hybrid (GOH). These failures occurred soon after installation and commissioning. The failure rate is extremely low (one or two failures per year). To date, no failures have been attributed to radiation.

1.4.1.2 Proposed new on-detector electronics

Figures 1.4 and 1.5 show the proposed new architecture. The individual boards will follow the same configuration and form factor as the present electronics, as shown in Fig. 1.3 in order to fit into the same physical space and use the existing services as far as possible.

![Block diagram describing the upgrade EB electronics architecture.](image)

The APDs are connected to the VFE through the legacy passive motherboard. The MB is mounted under the water cooling blocks for the electronics boards. Neither the APDs nor the MBs will be replaced. There is no identified concern with these items (from accelerated ageing or irradiation tests to 3000 fb$^{-1}$) that would justify the risk of disconnecting the cooling block and breaking the cooling system joints [13]. The performance goals of the EB upgrade can be achieved through the replacement of the VFE and FE cards only, together with the associated low-voltage distribution system and optical links.
Chapter 1. Project Overview

Figure 1.5: Schematic of the upgrade EB electronics architecture.

The VFE will be upgraded to yield optimal noise performance and to help discriminate anomalous APD signals using enhanced signal information. The key point of the upgrade of the VFE electronics is a reduction of the shaping time of the signal. The reasoning behind is the following:

- The APD leakage current contribution to the noise term depends on the square root of the shaping time.
- Out-of-time pileup contamination reduces with the shaping time.
- A faster rise time improves the measurement of the arrival time of the signal.
- A reduced shaping time increases the differences between scintillation and spike signals, facilitating their tagging.

The baseline solution is a Trans-Impedance Amplifier (TIA) that outputs a voltage image of the photocurrent generated by the APD, and is only limited by the bandwidth of the system. Two output gains are used to cover the full dynamic range of the signals up to 2 TeV. The best performance for timing resolution and spike rejection is achieved if the signal is sampled at 160 MHz.

The preamplifier ASIC is followed by a data conversion and transmission ASIC, named LiTE-DTU (Lisbon-Torino ECAL Data Transmission Unit). The LiTE-DTU will receive the two analog signals from the preamplifier outputs (corresponding to the two gains) and will convert them to a digital representation of the pulse. For each sampling period, either the high or the low gain samples will be selected and sent to a high-speed serial data link based on the lpGBT [14] e-link protocol. More than 99% of the events can be codified in 6–7 bits. A lossless data compression scheme will be applied in order to reduce the data output bandwidth.

The ADC will be designed by an external company which will provide the core ADC block for the integration in the LiTE-DTU. The ADC block will have differential inputs with 1 V differential dynamic range and will make use of a background calibration procedure to achieve the required performance in terms of differential nonlinearity (DNL), integral nonlinearity (INL), and the effective number of bits (ENOB). The specifications for INL, DNL and ENOB are chosen to ensure that the electronics noise and timing resolution are not degraded by the ADC. The detailed specifications are listed in Section 3.
The analogue ASICs will be implemented using TSMC (Taiwan Semiconductor Manufacturing Company Limited) 130 nm CMOS technology. The digital ASICs and ADCs will be implemented using TSMC 65 nm technology. In both cases, care will be taken in order to ensure robust operation in the now well understood radiation environment in the CMS EB location. The selected technologies are naturally radiation tolerant and provide a power consumption of as low as 25% of that obtained using the equivalent 0.25 µm device along with a 20% reduction in size [15]. The 130 nm technology is used for the analogue circuitry since it yields better performance in terms of dynamic range and noise, especially if thick oxide transistors are used. The 65 nm technology is required for the ADC to implement the higher speed logic needed for the 160 MHz sampling rate. These new ASICs will require a different voltage compared to that provided by the existing low-voltage regulator card (LVR).

A new LVR will exploit the radiation-hard DC-DC converter ASICs developed for use in the LHC experiments [16]. These compact devices are highly efficient and provide very low noise output. All these factors are estimated to reduce the power consumption of the front end from ≈ 100 kW to ≈ 50 kW. In addition, as power will be transferred to the front end at a higher voltage. This will result in a significant reduction in the required volume of copper cables.

Precautions will be applied during the design phase of ASICs and boards in order to ensure that the chosen ASIC architecture is sufficiently radiation tolerant and that the design is resistant with respect to radiation and single event effects (SEE). The maximum ionizing dose experienced by the on-detector readout is expected to be around 1 Mrad after 4500 fb⁻¹ and all on-detector ASICs will be qualified up to 10 Mrad. The chip pin layout and power dissipation will be designed with the goal of long-term operation (more than 10 years), both in terms of performance and in terms of system availability and reliability. All designs will be tested for radiation hardness and subjected to accelerated ageing during the validation phase.

The recent developments in higher speed radiation tolerant optical links provide an order of magnitude higher data transfer rate (lpGBT and Versatile Link plus) than previously possible. It is proposed to design a new Front End card using these technologies to send single crystal data sampled at 160 MHz to the back end electronics system for processing.

The clock distribution as well as the fast and slow control will be carried out through the lpGBT chipset. This allows a significant simplification compared to the legacy system. Each control link will serve a group of 25 crystals.

### 1.4.2 Back-end readout and trigger primitive formation

The off-detector electronics will be upgraded to accommodate the higher transfer rates and the change in architecture. The Level-1 trigger pipeline and the trigger primitive generation will be off-detector. These processors do not need to be radiation tolerant, as they will be located in the CMS service cavern. Commercially available FPGAs will be employed. The processors will be powerful enough to accommodate all processing presently performed by the legacy ECAL FE cards and the off-detector electronics. A processor board will be designed with these FPGAs and high speed optical links. It will be designed to the Advanced Telecommunications Computing Architecture (ATCA) standard [12]. ATCA is an industry standard that specifies the board format, crate backplane and communications fabric for the high speed digital electronics boards.

The specific architecture will be chosen to maximize overlap with developments elsewhere in CMS and will be customised to fit specific ECAL needs. The board will analyze incoming data and transmit a pre-processed set of trigger primitives to the next layer of the Level-1 trigger.
The algorithms include the rejection of spikes and basic clustering of localized energy.

The off-detector requirements, architecture, trigger primitive definitions, and data rates are described in Section 3.8.

The total numbers of on-detector and off-detector readout boards, ASIC, FPGA and optical link counts required for the Phase-2 upgrade, are provided in Table 1.3.

Table 1.3: Numbers of on-detector and off-detector boards, ASICs, FGPAs, links needed for the EB Phase-2 upgrade.

<table>
<thead>
<tr>
<th>ECAL Barrel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Supermodules (SM)</td>
<td>36</td>
</tr>
<tr>
<td>Number of readout channels</td>
<td>61200</td>
</tr>
<tr>
<td>Number of VFE cards</td>
<td></td>
</tr>
<tr>
<td>TIA per VFE card (total)</td>
<td>12240</td>
</tr>
<tr>
<td>LiTE-DTU per VFE card (total)</td>
<td>5 (61200)</td>
</tr>
<tr>
<td>Number of FE cards</td>
<td>2448</td>
</tr>
<tr>
<td>VFE per FE card</td>
<td>5</td>
</tr>
<tr>
<td>SLVR per FE card (total)</td>
<td>1 (2448)</td>
</tr>
<tr>
<td>lpGBT (8.96 Gb/s) per FE card (total)</td>
<td>4 (9796)</td>
</tr>
<tr>
<td>Data links (10 Gb/s) per FE card (total)</td>
<td>4 (9796)</td>
</tr>
<tr>
<td>Control links (2.5 Gb/s) per FE card (total)</td>
<td>1 (2448)</td>
</tr>
<tr>
<td>BCP cards</td>
<td>108 (3 per SM)</td>
</tr>
<tr>
<td>FPGA per BCP (total)</td>
<td>2 (216)</td>
</tr>
<tr>
<td>Input links per FPGA (total)</td>
<td>60 (12240)</td>
</tr>
<tr>
<td>Output links per FPGA (total)</td>
<td>15 (3060)</td>
</tr>
</tbody>
</table>

1.5 EB supermodule cooling and rework of YB0 services

The increases in APD dark current due to the LHC irradiation field, and the associated increases in electronic noise, must be reduced to preserve good electron and photon energy resolution in LHC Phase-2, and to allow the APDs to operate stably up to the end of HL-LHC running [8].

Since the APD dark current scales logarithmically with the APD operating temperature, a necessary step in reducing this contribution is to operate each supermodule at a lower temperature than the current value of 18 °C. Running at the current temperature will directly impact the energy and timing resolution of EB in Phase-2, since both of these depend crucially on the signal to noise level. Simulations presented in Section 9 show clearly the impact of increased energy equivalent noise (represented by different ageing scenarios) on both amplitude and timing reconstruction and physics object performance.

The baseline EB operating temperature for LHC Phase-2 will be 9 °C. This reduces the noise term in the energy resolution formula (see Eq. 1.1) to a level that is comparable or lower than the constant term, for the range of photon energies relevant for the $H \rightarrow \gamma\gamma$ decay (see Fig. 2.14).

This lower operating temperature requires modifications to the cooling plant serving the supermodules, as well as a complete replacement of the coolant distribution pipes. The cooling system within the supermodule must be retained, however.

The Phase-2 cooling system is required to maintain the same cooling stability as the present system and will use the same cooling distribution system inside the supermodule. The new
system must supply a cooling capacity of 3 W per channel, which includes a safety margin. The original design assumed a power dissipation inside the SM of around 2.5 W/channel. The same water flow rate as in the current system will also be retained in the new design. Heat flow insulation from the surrounding subsystems, Tracker and HCAL, must be ensured at the lower EB operating temperature. The system must also be immune to dew point issues in the experimental cavern, which necessitates the presence of an environmental screen.

For operations at 9 °C, chilled water at 6 °C is required. An extra distribution pipe carrying chilled water must be installed from the surface to the underground service cavern, USC55. These modifications (see Section 4) will be undertaken during LS2 (2019–20), to reduce the workload during LS3 (2024–26).

For temperatures below 9 °C, should they be required, more complex and costly interventions will be needed. An extra chiller, with significantly larger capacity, must be installed in USC55. This further upgrade is not in the baseline, and is therefore not foreseen during LS3.

1.6 Longevity of EB lead tungstate crystals and APDs

1.6.1 Lead tungstate crystal longevity

The main concern for the EB crystals is the ageing due to radiation. The lead tungstate crystals are intrinsic scintillators. The main scintillation mechanism is not affected by radiation. Instead, the radiation creates crystal defects which reduce the crystal transparency and the light output is reduced as a consequence.

Studies have been carried out on the effect of radiation on PbWO$_4$ crystals [17]. Electromagnetic radiation induces temporary defects, which anneal spontaneously at room temperature. During LHC operation, the damage and recovery mechanisms reach an equilibrium level that depends on the dose rate. This effect is monitored and corrected using a dedicated light injection monitoring system [18].

At HL-LHC, hadronic damage must be taken into account. High energy hadrons, above a few tens of MeV, create permanent crystal defects, which decrease the overall crystal transparency and shift the transparency band edge towards longer wavelengths [19–22]. The annealing temperature for these defects is too high to be reached in situ, and this damage does not recover. Because the PbWO$_4$ scintillation light spectrum is peaked at 420 nm, and the band edge is typically between 350 and 400 nm, the crystal light output is affected.

The light collection on the photodetector varies as a function of the crystal depth. This is due to the proximity of the photodetector and the focussing effect of the crystal shape. The longitudinal light collection has been carefully made uniform by depolishing one of the crystal faces [23]. However the effect of radiation will reduce the transparency and thus the light emitted closer to the photodetectors will be more effectively collected [24]. Shower-to-shower fluctuations in the shower maximum position are sensitive to differences in the longitudinal light collection non-uniformity, affecting the crystal energy resolution. Energy linearity may also be affected by this mechanism, because the shower maximum position depends logarithimically on the particle energy.

The effects of hadron irradiation on PbWO$_4$ crystals has been studied in test beams [22]. The results have been used to validate Monte Carlo simulations. These simulations are then used to predict the evolution of the EB energy resolution for HL-LHC ageing conditions.

The crystal calorimeter energy resolution can be parametrized as a function of the energy E by
the equation
\[ \frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} \odot \frac{B}{E} \oplus C, \] (1.1)
where \( A \) is the stochastic term, which depends on the photon statistics, \( B \) is the electronic noise term, and \( C \) is the constant term.

The crystal radiation damage affects the energy resolution of the calorimeter in all three terms:
- the stochastic term depends on the square root of the crystal light yield,
- the noise term is amplified by the light output loss,
- the constant term is affected by non-uniformity of the light collection.

Figure 1.6 shows the relative scintillation light output, \( S \), at 9°C, with respect to its initial value, \( S_0 \) at 18°C at the start of CMS running in 2010. This quantity is plotted for a 50 GeV photon shower as a function of \( \eta \) for various integrated luminosities. The loss of light output is between 25% and 40% for an integrated luminosity of 1000 fb\(^{-1}\), and between 50% and 65% for an integrated luminosity of 3000 fb\(^{-1}\).

Figure 1.7 shows the energy resolution expected for photon showers as a function of the incident particle energy for 1000 fb\(^{-1}\) at \( |\eta| = 0 \). The constant term, which amounts to 0.5% in this example, dominates the energy resolution for showers above 70 GeV.

### 1.6.2 APD Longevity

The origins of the radiation damage to the APDs are two-fold: \( \gamma \)-rays create surface defects that may increase the surface current and reduce the quantum efficiency. Hadrons create bulk damage, and cause an increase in the bulk current. The APDs were all screened for \( \gamma \) radiation hardness [25]. The main concern for HL-LHC operation is the increase of the dark current, since the electronic noise depends on the square root of the bulk current.
Figure 1.7: Energy resolution as a function of incident particle energy after detector ageing up to an integrated luminosity of 1000 fb$^{-1}$ at $|\eta| = 0$ and for an operating temperature of 9 °C. The different contributions to the energy resolution are plotted separately (stochastic, noise and constant term).

Based on the evolution of the APD dark current in CMS, an extrapolation is performed to predict the dark current increase as a function of integrated luminosity for running up to the end of HL-LHC, see Fig. 1.8. At $|\eta| = 1.45$, the damage is about 80% larger than in the centre of the barrel. The current will reach about 100 µA, for $|\eta| = 0$ and about 200 µA, for $|\eta| = 1.45$, after an integrated luminosity of 3000 fb$^{-1}$. If no action was taken to mitigate this effect, the electronic noise would increase by a factor of 10, reaching about 1 GeV at 18 °C and for 3000 fb$^{-1}$.

Figure 1.8 shows that a reduction in operating temperature to 9 °C will reduce the dark current to 50% of its value. The noise term in the energy resolution, for 3000 fb$^{-1}$, is 0.6–1.3 GeV for a $3 \times 3$ crystal matrix (the cluster size relevant for the reconstruction of an unconverted photon in CMS), with the range representing the $|\eta|$ dependence of the noise. This takes into account the light output loss from the crystals, as well as the increase in APD dark current, and assumes the lower operating temperature and new front-end electronics with reduced shaping time.

Depending on the performance observed after Run 3, there is also the possibility of a further reduction in temperature to 6 °C, which will reduce even further the noise. This additional step in temperature will require a further intervention to the ECAL cooling plant, and thus it is left as an option for LS4 and beyond (see Section 4 for more details).

### 1.7 Schedule of EB supermodule extraction, rework and test

The schedule for extraction, refurbishment, and reinstallation of the 36 supermodules is presented in a Gantt chart in Fig. 1.9. From the CMS Technical Coordination planning of the Long Shutdown 3 (LS3), the process begins with the installation of the enfourneurs (the tool for SM insertion and extraction) on each side of the barrel. This process will take two weeks (W15–16). The configurations of CMS for SM removal and insertion, showing the presence of the enfourneurs, are shown in Fig. 1.10. A total of four weeks are required for the removal of the 36 supermodules from W17 to 20. The first two weeks (W17–18) are assigned to remove the first
Figure 1.8: The dark current, for APDs operated at 18 °C, is shown by the red curve. The dark current, for APDs operated at 9 °C, is shown by the blue curve. The purple curve shows the dark current for APDs operated at 9 °C until LS4 and then at a lower temperature of 6 °C afterwards. This corresponds to a possible lowering of the APD operating temperature after LS4 (see Section 4). The left plot corresponds to $|\eta| = 0$ and the right plot corresponds to $|\eta| = 1.45$. The vertical shaded lines indicate long shutdowns.

supermodule on each side (the most difficult operation). The following two weeks (W19–20) are required to remove the remaining 17 supermodules on each side. This corresponds to removing two SMs per side per day. The enfourneurs will be dismounted in week 21.

Figure 1.9: Gantt chart of the schedule of EB supermodule refurbishment during Long Shutdown 3.

The reinstallation of the 36 supermodules, including cabling on both sides, is foreseen during weeks W81–83. The installation of the two enfourneurs will take place during weeks 79 and 80 and their removal after insertion will be in week 84. The entire sequence, including the removal of electronics, reinstallation, and recommissioning of the 36 SMs will be 60 weeks, from week 21 to week 81. Electronics integration will be performed in the SX5 surface building at Point 5, where a dedicated zone will be prepared for the ECAL. The full procedure is described in Section 6.
1.7. Schedule of EB supermodule extraction, rework and test

Figure 1.10: CMS configurations for removal (left) and reinsertion (right) of the 36 supermodules.

1.7.1 Overall requirements and time envelope

Electronics integration will be performed in the surface building at LHC Point 5, where a dedicated zone will be prepared for ECAL. This eliminates the need to transport supermodules back and forth to other sites, thus reducing radiation exposure for the people handling the supermodules. The supermodules will be stored at the same location to be readily accessible to perform the entire rework sequence.

An exploded view of a supermodule is presented in Fig. 1.11. The electronics boards (see Section 3), the internal cabling system (see Sections 3 and 4), and the patch panel will be removed and replaced. The cooling system inside the SM (thermal screen, cooling blocks, main manifold) will not be dismounted and the motherboards will not be replaced.

Figure 1.11: An exploded view of an ECAL Barrel supermodule.

The procedures, methods, and tools applied for the modification of the electronics, described
in the following sections, are very similar to those successfully applied during the construction of the EB [1]. The mechanical operations are identical. However, a few small modifications may be necessary in order to adapt to the slightly modified readout electronics.

Thorough testing will be crucial for the electronics integration process. Each electronic component will undergo obligatory burn-in procedures and be received fully tested and functional at the integration center. These components will be registered in the construction database and marked ready for installation. Failure diagnosis and repair of components during installation at the integration center is not feasible. Failing components will be rejected and replaced by new ones. Consequently a sufficiently large amount of working spare components is foreseen.

Thorough testing is of the highest importance during the integration operation. The electronics are installed in layers that cover previously installed components, rendering later iterations very difficult. Careful preparation of the insertion tools and thorough training of the personnel will be required.

It is foreseen to have six test stands to work in parallel on six supermodules. Each of the six main steps takes approximately one week, with the exception of the commissioning, which is planned for two weeks. The total working time for one supermodule is 7 weeks. These operations are carried out in parallel such that, on average, one supermodule per week will be completed. An extra stand will be used in case repairs are needed, to avoid interrupting the production chain.

A minimum of 42 weeks is required to refurbish all 36 supermodules. Some additional weeks for contingency are mandatory. Consequently 60 weeks are planned to complete the rework activity.

1.8 Overview of the HB upgrade

The three main elements of the HB detector are the brass absorber with the active material (plastic scintillator tiles, and wavelength-shifting and clear fibers), the front-end (on-detector) electronics with the photosensors (currently HPDs, to be replaced with SiPMs in LS2), and the back-end (off-detector) electronics.

1. Concerning the active material, the CMS Hadron Endcap (HE) data collected in 2017 has shown that the expected radiation damage of the HB scintillators and fibers will have a negligible impact on the physics performance of CMS for the full HL-LHC period. Therefore, the replacement of HB scintillators and fibers will not be necessary.

2. The Phase-1 front-end electronics with Silicon Photomultipliers (SiPM), to be installed on the HB detector in LS2, will continue to be used for the HL-LHC period.

3. The current HB back-end electronics, based on the μTCA standard, will not be able to sustain the 750 kHz Level-1 trigger rate planned for Phase-2. Therefore, we will produce and install new back-end electronics based on the design developed for the ECAL Barrel.

The degradation of performance of the HCAL detectors due to radiation damage, in particular the HE calorimeter, has been studied since 2010. Using data collected in 2016, it became evident that the overall degradation in response observed over time was not caused exclusively by radiation damage in the scintillator and wavelength-shifting (WLS) fibers. Instead, the data revealed that a significant contribution to the response loss arises from the deterioration in
the performance of the Hybrid Photodiodes (HPDs). Therefore, the scintillator/WLS-fiber radiation damage is less severe than was understood at the time of the CMS Phase-2 Upgrade Technical Proposal.

Disentangling the two contributions has become possible with the analysis of data collected by CMS in 2017, using an HE sector that has been read out with SiPMs since the 2016/17 LHC Year-End Technical Stop. The analysis of the first $22 \text{ fb}^{-1}$ of 2017 data showed that the signal loss in the HE sector read out by SiPMs is significantly lower than the signal loss in the rest of the HE sectors, which are read out by HPDs. It confirmed that a large fraction of the signal loss observed in HE is due to the HPD deterioration. The studies performed up to September 2017, when this TDR was prepared, are described in detail in Section 2.2. Appendix A, added in January 2018, describes the progress in the understanding of radiation damage of HCAL scintillators based on an analysis of the entire 2017 dataset ($48 \text{ fb}^{-1}$).

All HB HPDs will be replaced with SiPMs during Long Shutdown 2 as part of the Phase-1 upgrade. The photodetector replacement will therefore eliminate a major cause for the HB signal deterioration. We expect that the scintillator signal reduction in the region of HB most exposed to radiation, the front layers in the high $\eta$ region, will be approximately a factor of two to three. This will be largely offset by the higher photo-detection efficiency of the SiPMs with respect to the HPDs. Therefore, the impact of scintillator radiation damage on the physics performance of the CMS barrel calorimeter is negligible for the entire HL-LHC operating period, and replacement of HB scintillators is not required.

The Phase-1 $\mu$TCA-based back-end (off-detector) electronics will not be able to sustain the HL-LHC trigger conditions and will be upgraded to the ATCA standard using the same boards being developed for EB. A homogeneous off-detector system optimizes the development and production resources, permits the sharing of spares, and facilitates long-term operations and maintenance. A detailed discussion of the upgrade of the HB off-detector electronics is presented in Section 3.9.1.

1.9 EB performance requirements

1.9.1 Amplitude resolution

The EB amplitude reconstruction algorithm used for HL-LHC should be able to accurately measure the amplitude of in-time signals and efficiently suppress the contributions from out-of-time (OOT) pileup.

The amplitude reconstruction algorithm (termed “MultiFit”) used in LHC Run-2 is also expected to be used for HL-LHC. The algorithm models the signal pulse shape as a sum of one in-time pulse and a series of out-of-time pulses. A pulse template fit is performed to extract the amplitude of the in-time pulse, as well as that of the out-of-time pulses. The MultiFit algorithm requires the knowledge of signal pulse shapes and noise correlation matrices, which are periodically measured in dedicated runs. Figure 1.12 shows that the MultiFit algorithm is effective in suppressing OOT PU from collisions with $\langle \text{PU} \rangle = 200$ to the level of the intrinsic electronic noise, $\sigma_{\text{noise}}$, for values of $\sigma_{\text{noise}} > 10 \text{ MeV}$.

1.9.1.1 Timing resolution

Precise time measurements for high energy photons are a key component of the EB Phase-2 upgrade. The preamplifier, ADC, and precision clock distribution architectures and specifications are designed with the goal of 30 ps time resolution from photons from $H \rightarrow \gamma \gamma$ decays.
Chapter 1. Project Overview

Figure 1.12: Amplitude resolution normalized to noise RMS vs noise RMS for an ECAL channel at $|\eta| = 1.4$ at PU=0 and $\langle PU \rangle = 200$.

The Multifit amplitude reconstruction algorithm estimates pulse amplitudes in each bunch crossing. This permits the removal of OOT pileup from the amplitude samples before applying the time reconstruction algorithm on the in-time pulse. The time reconstruction algorithm currently being studied for HL-LHC is the same as used in Run-2. It involves estimating the time from the amplitude ratios of consecutive samples The performance of this algorithm for HL-LHC conditions with $\langle PU \rangle = 200$ is shown in Fig. 1.13 for $|\eta| = 0$. The time resolution is dominated by noise and in-time pileup. A timing resolution of 30 ps can be achieved for 20 GeV showers at the start of HL-LHC (300 fb$^{-1}$) and for 60 GeV showers at the end of HL-LHC (3000 fb$^{-1}$).

Figure 1.13: Reconstructed time resolution versus the transverse energy of ECAL energy deposits after 300, 1000, 3000, and 4500 fb$^{-1}$ for $|\eta| = 0$. 
1.9. EB performance requirements

1.9.1.2 Anomalous signal rejection

Anomalous signals, consisting of isolated large signals with equivalent energies that can exceed 100 GeV in CMS, have been observed in the ECAL Barrel during LHC proton-proton (pp) collisions [10]. These deposits are observed to occur at a rate that is proportional to the collision rate of the proton beams.

The spikes are understood to be associated with particles (produced in pp collisions) striking the APDs and very occasionally interacting to produce secondaries that cause large anomalous signals through direct ionization of the silicon. This hypothesis has been confirmed by studying the APD response via laboratory, test beam studies, and Monte Carlo simulations.

Since the characteristics of ECAL spikes are localized high energy signals, they will often satisfy the conditions for triggering electrons and photons in CMS. A detailed description of the electron and photon trigger algorithm can be found elsewhere [26]. If untreated, the rate of spikes would be a dominant component of the CMS Level-1 trigger rate bandwidth.

Figure 1.14 shows the rate of ECAL energy deposits (in Hz) above a specific transverse energy threshold, including signals from both spikes and scintillation light. The rates assume \( \langle \text{PU} \rangle = 200 \) and are plotted for integrated luminosities of 300, 1000, 3000, and 4500 fb\(^{-1}\). The spike signals dominate the event rate above a few GeV, as shown in Fig. 9.4. The rate of spikes above 20 GeV is more than 1 MHz, which would saturate the available Phase-2 Level-1 bandwidth if no spike suppression were applied. In order to reduce the rate of spikes to a negligible level (< 1 kHz above 20 GeV) a spike rejection efficiency of better than 99.9% is needed.

Spike-like energy deposits are currently prevented from triggering CMS by exploiting an additional feature of the ECAL front-end electronics. The strip Fine-Grained Veto Bit (sFGVB), which is computed per 5 × 5 crystal array, flags spike-like energy deposits by comparing the energies recorded for each channel to a configurable threshold. The sFGVB is configured to return zero for an isolated energy deposit (a single crystal above threshold) or one for an electromagnetic (EM) energy deposit (multiple crystals above threshold).

The performance of the sFGVB algorithm has been studied for the conditions expected during
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HL-LHC operation. The simulations predict that a satisfactory level of performance can be achieved for LHC Phase-1 conditions, but the required rejection factors for HL-LHC operation cannot be achieved, because of the larger APD noise and pileup [8].

The suppression of spikes in Phase-2 will be undertaken by exploiting the characteristic differences in spike and EM pulse shapes, facilitated by the Phase-2 on-detector and off-detector upgrade of EB. Spike signals have no scintillation component and are thus faster, both in terms of arrival and signal rise time (see Fig. 1.15, left). This provides improved discrimination to complement traditional energy isolation methods for conditions with high pileup and higher electronics noise. Fig. 1.15 (right) shows the resulting event rates after a pulse shape discriminant, which uses ratios of amplitudes in consecutive time samples, is used. If such a method is used, the rate of spikes above 20 GeV drops to a negligible level compared to the 0.5–0.75 MHz bandwidth allocated to Level-1 triggers in Phase-2.

Figure 1.15: Left: Pulse shapes from APD spike and scintillation signals. The amplitude samples from digitization with 160 MHz sampling frequency are shown as dots. Right: event rate of EB energy deposits with spike hits above a specific \( E_T \) threshold for Minimum Bias interactions at \( \langle PU \rangle = 200 \) assuming 2800 colliding bunches per LHC orbit. This plot is produced assuming spike rejection using a pulse shape discriminating variable (described further in Section 9).

1.10 Key Phase-2 physics signatures

The physics studies described in Section 9 are intended to verify the requirement that the performance of the ECAL during HL-LHC running should be as close as possible to the performance of the ECAL at the beginning of LHC operations. The legacy system was designed to study electroweak symmetry breaking through the Higgs mechanism. The benchmark physics modes used were \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ \) where one or both of the Z bosons decays to electrons. These require excellent energy resolution, high efficiency for the detection of electrons and photons, a fast response, and high granularity to mitigate the effects of pileup.

Excellent ECAL performance has also been central to many other physics studies, such as the Standard Model measurements and SUSY searches involving photons and electrons in the final state. However as the Higgs boson channels are the most challenging they remain the appropriate benchmark modes to optimize the design of the Phase-2 detector. The precision study
of these modes is central to the HL-LHC physics. There are new physics channels involving Higgs bosons, such as the search for di-Higgs production which is important to understand the details of the vacuum potential. The highest sensitivity for these searches is found in the channel in which one Higgs boson decays to a di-photon pair and one to a $b\bar{b}$ pair. The sensitivity of the upgraded Phase-2 detector to these signals is calculated for detector ageing corresponding to $1000 \text{ fb}^{-1}$ and $\langle \text{PU} \rangle = 200$.

1.10.1 **Higgs decays to two photons**

The clean signature of the $H \to \gamma\gamma$ decay channel makes it one of the most important channels to characterize the properties of the Higgs boson. Excellent photon identification efficiency and energy resolution are required to maintain the sensitivity of the analysis in Phase-2.

The diphoton invariant mass resolution for $m_H = 125 \text{ GeV}$ is presented for unconverted and converted photons in Section 9.7.1, considering different ageing and pileup scenarios. Figure 9.31 shows invariant mass distributions for unconverted photons and Fig. 9.32 shows the same distributions considering both unconverted and converted photons. Table 9.4 summarizes the diphoton mass resolutions for the different conditions studied.

Further improvements in the diphoton resolution will be obtained by applying multivariate regression techniques that correct for shower containment in the clustered crystals, energy losses of converted photons, and the contamination of the cluster energy from pileup. With this technique, the diphoton mass resolution can reach a level compatible with the one obtained in the Run-2 analysis, for detector ageing corresponding to $1000 \text{ fb}^{-1}$ and $\langle \text{PU} \rangle = 200$.

1.10.1.1 **Benefit of precise timing**

The resolution of the $H \to \gamma\gamma$ invariant mass depends on the resolution of the photon energy measured in the calorimeter and the resolution on the opening angle between the two photons. The latter is derived from the shower positions in the calorimeter and the position of the decay vertex. If the interaction point is known to better than about 10 mm, the contribution from resolution on the opening angle between the photons is negligible, compared to the energy resolution of the calorimeter. The mass resolution at HL-LHC can be preserved by correctly assigning the reconstructed photons to one of the interaction vertices reconstructed from the charged tracks.

According to simulation, the efficiency to identify the correct vertex within 1 cm for $\langle \text{PU} \rangle = 140$ is lower than 40% in processes where the number of charged particles from the primary interactions is small, and degrades to about 30% for $\langle \text{PU} \rangle = 200$ [27].

This efficiency loss can be recovered by means of precise measurements of the time of flight of photons, which enable the vertex position along the beam direction to be determined via triangulation.

The improvement in $H \to \gamma\gamma$ energy resolution and fiducial cross section sensitivity has been evaluated using this method, for several assumptions on the timing measurement capabilities of CMS [27].

The predictions show that precise timing in EB, with an assumed resolution of 30 ps, yields an $\approx 10\%$ improvement on both the fiducial cross section sensitivity and diphoton mass resolution relative to the assumption of no precise timing. These improvements become even larger when precise timing for charged particles via a dedicated timing layer sensitive to minimum ionising particles, now in the CMS Phase-2 upgrade scope, is also assumed.
1.10.2 Higgs decays to tau leptons

Studying the decay of the Higgs boson into pairs of \( \tau \) leptons is necessary to establish the Yukawa coupling between the Higgs boson and fermions. Projections of the Phase-1 \( H \rightarrow \tau \tau \) analyses to the HL-LHC conditions show that a measurement of the coupling modification of the Higgs boson to tau leptons can reach a precision of 2–5%. This measurement will require the excellent performance of the full CMS reconstruction chain. Section 9.7.2 presents the sensitivity of this analysis for the Phase-2 detector, including details of the identification and reconstruction of hadronic \( \tau \) leptons in the \(|\eta| < 1.5\) range, and the mass discrimination between the \( H \rightarrow \tau \tau \) and the \( Z \rightarrow \tau \tau \) peaks.

1.10.3 Di-Higgs production

The study of the Higgs boson trilinear self-coupling using events with a Higgs boson pair has the potential of probing the Higgs field potential. In the standard model, the production cross section for di-Higgs events is very small, and the large statistics offered by the HL-LHC program will be necessary to observe this process. Considering the different Higgs decay modes, the final state that provides the best sensitivity is the one in which a higgs decays to b-quarks, and the other to a di-photon pair. The projected sensitivity of this analysis, which also relies on preserving the diphoton mass resolution in HL-LHC conditions, is described in Section 9.7.3.
Chapter 2

Longevity of existing components

2.1 ECAL Barrel crystals and photodetectors

2.1.1 Introduction

The ECAL Barrel upgrade involves lowering the detector operating temperature and refurbishing the on-detector electronics. The electronics boards that are mounted above the cooling blocks, the VFE, LVR and FE cards, will be replaced. Other components including the crystals, photodetectors, on-detector cooling circuits and motherboards (passive PCBs used for signal connection and bias voltage distribution) will remain, and must be qualified for ageing and radiation hardness to ensure that they will perform well until the end of the HL-LHC program.

In the following sections, the consequences of radiation damage on crystals and electronics components are summarised, and existing measurements from beam tests and in situ operation are used to extrapolate the performance of the ECAL barrel up to the end of HL-LHC running.

2.1.2 Lead tungstate crystals

2.1.2.1 Radiation damage in lead tungstate

The ECAL crystals have been optimised to maintain adequate performance under the ionising radiation doses present in the LHC environment [17]. These are known to cause the formation of color centres that reduce light transmission, while the scintillation mechanism is unchanged. The damage reaches an equilibrium level that depends on the dose rate, and partial spontaneous recovery at room temperature is observed when no radiation is present. However, it has been ascertained by extensive studies that at the HL-LHC, a significant fraction of the transmission loss will be due to energetic hadrons, which produce cumulative damage that does not recover at room temperature [19]. The damage reduces the light transmission through the creation of light scattering centres from local damage created by heavy fragments of Lead and Tungsten [20]. The scintillation mechanism is unchanged [21] and the damage can therefore be monitored through the ECAL laser light injection [18], as is the case for ionising damage.

The changes to the transmission spectrum are qualitatively different between ionising damage, with the appearance of local “dips” due to color centres, and hadrons, where a transmission band edge shift appears and the overall spectrum is depressed according to Rayleigh scattering, visible in Fig. 2.1 (left). The hadron damage tests have been mostly performed in the 24 GeV proton beam of the CERN SPS. It has been shown that the damage can be scaled to the CMS running conditions, where the hadron flux is mostly due to \( \sim 1 \) GeV pions, through FLUKA simulations [28]. This has been confirmed by the measurements shown in Fig. 2.1 (right). A \( 2 \times 2 \) matrix of PbWO\(_4\) crystals was placed inside CMS during 2012 running, and these crystals were exposed to hadron fluences of approximately \( 5 \times 10^{13} \) cm\(^{-2}\) over a period of 8 months [22].
Chapter 2. Longevity of existing components

Exposure in situ to the particle flux originating from LHC collisions results in a transmission loss (red markers) that is consistent with results from dedicated proton irradiation tests.

The damage is quantified through the induced absorption coefficient, $\mu_{\text{IND}}$, which is expressed as a function of light wavelength $\lambda$. It is defined as

$$
\mu_{\text{IND}}(\lambda) = \frac{1}{\ell} \ln \frac{LT_0(\lambda)}{LT(\lambda)},
$$

where $LT_0$ ($LT$) is the Longitudinal Transmission value measured before (after) irradiation over the length $\ell$ of the crystal. Generally, the value $\mu_{\text{IND}}$ at the peak-of-emission wavelength ($\lambda = 420$ nm) is quoted, unless otherwise stated.

**Figure 2.1:** Left: Light transmission curves of lead tungstate crystals after $\gamma$ and proton irradiation. Overlaid (black dotted line) is the lead tungstate scintillation spectrum. Right: Linear fit (red line) to the correlation between hadron fluence and the corresponding induced absorption coefficient, from Ref. [22].

### 2.1.2.2 Extrapolation of crystal light output to HL-LHC

By the end of October 2016, the ECAL was exposed to radiation and particle fluences corresponding to a total integrated luminosity of $74 \, \text{fb}^{-1}$, partly at $\sqrt{s} = 7–8 \, \text{TeV}$ and partly at 13 TeV, as shown in Fig. 2.2 (left). The change of response to the laser monitoring light over time is shown in Fig. 2.2 (right), where a recovery of the component due to ionising radiation can be observed during LHC shutdown periods, as well as the onset of a residual, cumulative signal loss that can be attributed to hadron damage. It is thus possible to extrapolate the longevity of the ECAL barrel crystals at the HL-LHC in two different ways: one makes uses of test beam exposures of irradiated crystals, and depends on simulations and parametrised models to obtain predictions. The other method is data driven: the high-$\eta$ regions of the endcaps have already been exposed to particle fluences similar to those that the EB will experience by the end of HL-LHC running. The expected response loss in EB during HL-LHC can therefore be obtained using existing monitoring data from the appropriate EE $\eta$ region.

Test beam results have been obtained on hadron-irradiated matrices of crystals, and the correlation between light output (LO) and the induced absorption coefficient is shown in Fig. 2.3. The crystal damage has been modeled using FLUKA to estimate hadron fluences and $\gamma$ doses in the CMS detector. The experimental results described above have been used for the attenuation of the light transmission. A full simulation of the electromagnetic shower development in the crystals has been performed with GEANT4. The ray-tracing program SLitrani[29] models
2.1. ECAL Barrel crystals and photodetectors

Figure 2.2: Left: Integrated luminosity versus time delivered to CMS during stable beams, for pp collisions. Right: Relative response to laser light injected in the ECAL crystals, measured by the ECAL laser monitoring system, averaged over all crystals in regions of pseudorapidity, $|\eta|$. The bottom plot shows the instantaneous LHC luminosity delivered during this time period.

The light output as a function of $\mu_{\text{IND}}$. The $\gamma$ damage is simulated as a function of the instantaneous luminosity, assuming that a dynamic equilibrium between damage and recovery is reached. The hadron damage has been simulated by modeling the values of $\mu_{\text{IND}}$ measured in Ref. [19] as a function of the hadron fluence (summarised for the CMS ECAL in Ref. [17]). A comparison of these predictions with test beam measurements shows good agreement (see Fig. 2.3).

Figure 2.3: Test beam measurements of the crystal light output as a function of the induced absorption coefficient $\mu_{\text{IND}}$, from Ref. [22] for hadron-irradiated crystals. The ageing model expectation is superimposed on the data.

Figure 2.4 (left) shows the predicted laser response reduction, $R/R_0$, as a function of $\eta$ for various integrated luminosities. Figure 2.4 (right) shows the ratio $S/S_0$ of the response of the ECAL barrel to a 50 GeV energy shower, plotted with respect to its initial value, as a function of $\eta$ and for various integrated luminosities. The uncertainty in this prediction is about 30%. This
Chapter 2. Longevity of existing components

arises from uncertainty in the hadron fluence and $\gamma$ dose estimates, the spread in the crystal response to $\gamma$ radiation, uncertainties in the effects of hadron radiation on the crystals, and the extrapolation of all of these effects from low to high fluences.

![Graph showing the expected ratio $R/R_0$ of the crystal transparency and ratio $S/S_0$ of the crystal light output for 50 GeV photon showers with respect to their respective initial values for the ECAL barrel crystals, plotted as a function of the pseudorapidity $\eta$ for various integrated luminosities.](image)

Figure 2.4: Expected ratio $R/R_0$ of the crystal transparency (left), and ratio $S/S_0$ of the crystal light output for 50 GeV photon showers (right) with respect to their respective initial values for the ECAL barrel crystals, plotted as a function of the pseudorapidity $\eta$ for various integrated luminosities.

Predictions for 100 fb$^{-1}$ can be compared with the monitoring data in Fig. 2.2 at the end of the October 2016 shutdown, which corresponds to damage accumulated after exposure to 74 fb$^{-1}$. Predictions and data agree well, within the aforementioned uncertainties. It is thus possible to scale the light output loss measured in situ to larger integrated luminosities, using the ageing model. The model predicts that the barrel ($|\eta| < 1.48$) will suffer approximately a 60–80% light output loss for an integrated luminosity of 3000 fb$^{-1}$.

The alternative method to predict the EB crystal transparency at the HL-LHC using the present Endcap performance has also been performed. Figures 2.5 and 2.6 show the dose, charged hadron and neutron fluence calculated by the FLUKA simulation for 100 fb$^{-1}$ with the Phase-1 CMS geometry and for 3000 fb$^{-1}$ with the Phase 2 CMS geometry. The Figures indicate that the damage at $|\eta| = 1.5$ after 3000 fb$^{-1}$ should be the same as the damage observed at $|\eta| = 2.3$ after 100 fb$^{-1}$, and at $|\eta| = 2.9$ after 10 fb$^{-1}$, which corresponds to $\sim 50\%$. This is in agreement with the FLUKA extrapolation, within uncertainties.

This scaling argument, although based on data, is also affected by uncertainties comparable to the other method. In fact the Barrel to Endcap fluence ratio makes use of the Fluka model as well. In addition the barrel and endcap crystals and monitoring light injection are slightly different. This results in an uncertainty of about 30% in the integrated luminosity quoted for a given damage.

2.1.2.3 Temperature dependence of PbWO$_4$ scintillation light output

Light output changes with temperature:

The ECAL light output depends on the ECAL operating temperature. A decrease in the operating temperature from 18 °C to 9 °C is envisaged for HL-LHC running. This provides a substantial reduction in the APD dark current and reduces the contribution of the electronic noise term for energy resolution.
Figure 2.5: Total dose, charged hadron fluence and 1 MeV neutron equivalent hadron fluence accumulated in the ECAL Barrel region for an integrated luminosity of 100 fb$^{-1}$ as predicted by FLUKA for the CMS detector in the Phase-1 configuration.
Figure 2.6: Total dose, charged hadron fluence and 1 MeV neutron equivalent hadron fluence accumulated in the ECAL Barrel region for an integrated luminosity of 3000 fb$^{-1}$ as predicted by FLUKA for the CMS detector in the Phase-2 configuration.
2.1. ECAL Barrel crystals and photodetectors

Figure 2.7: Left: Induced absorption coefficient recovery for Lead Tungstate versus time for a small reference sample and for a 20 cm long crystal measured at 10 °C and at 22 °C. Right: Change of light yield as a function of temperature for unirradiated and irradiated crystals [30].

Studies of the induced absorption coefficient and its spontaneous recovery have been performed at 10 °C and at 22 °C [30]. At 10 °C the recovery rate is observed to be slower than at 22 °C, as shown in Fig. 2.7 left. As a consequence, a relative decrease of 10% in light transmission is observed at 10 °C compared to 22 °C. However, this loss of transmission is compensated by an increase of the crystal light output at 10 °C by 25% [31]. Using the model in Ref. [32], the change of induced absorption from one LHC fill to another can be estimated. The light output variation from fill to fill, when dE/dx saturation is reached, is reduced. Overall, the light yield increases by approximately 10% at 9 °C with respect to 18 °C, as shown in Fig. 2.7 (right).

Pulse shape dependence on temperature:

The upgraded signal preamplifier for Phase-2 is designed to maximise spike rejection and out-of-time pileup by reducing the shaping time of the signal pulse. It has been shown that the envisaged reduction in operating temperature does not affect the Lead Tungstate crystals scintillation pulse shape in a significant way. Signal pulse shapes at different operating temperatures were acquired in the CERN SPS H4 beam line and are summarised in Fig. 2.8. These show the limited extent of changes in scintillation pulse shape due to different operating temperatures.

2.1.3 Longevity of the avalanche photodiodes

The APDs are silicon photodiodes with an internal amplification or gain (G). The gain is obtained by means of a highly doped layer located beneath the photocathode. An intrinsic drift layer reduces the device capacitance. Hamamatsu Photonics S8148 large area APDs were chosen as photodetectors for the CMS ECAL. They were developed by Hamamatsu in close col-
Figure 2.8: Scintillation light pulse shapes from Lead Tungstate crystals exposed to high energy electron beams at various temperatures. These measurements were obtained from a test matrix equipped with the first prototypes of the Phase-2 VFE boards, using transimpedance amplifiers (see Section 3), read out with a high-bandwidth digitiser [33].

Laboration with CMS ECAL [34]. The APDs have an area of $0.5 \times 0.5$ cm$^2$ and two APDs are connected in parallel to form a capsule that was glued onto a crystal with the glue Dow Corning RTV 3145. One in ten capsules also contain a thermal sensor. The characteristics of the APDs are reported in Table 2.1.

Crystals, glued to capsules, are inserted into alveolar supporting structures, which are closed by rivets. Kapton cables of different length (varying between 70 and 165 mm) join the capsules to a connector fixed on the grid which regroups two rows of five crystals. Five rows of five crystals are served by one motherboard, which provides the bias to the APDs and transmits the signals from the APDs to the very front end board, where the preamplifier and ADC are located. Two motherboards (corresponding to fifty crystals) are served by the same high voltage channel. The ECAL APDs are operated at a gain of 50. The dark current, $I_D$, of the APDs is composed of a surface current $I_S$, and a bulk current $I_B$ which is amplified by the gain

$$I_D = I_S + I_B \cdot G.$$  \hspace{1cm} (2.2)

The radiation damage to the APDs is two-fold: $\gamma$-rays create surface defects that may increase the surface current and reduce the quantum efficiency. Hadrons create bulk damage, and consequently cause an increase in the bulk current. The electronic noise depends strongly on $I_D$. This will become the dominating contribution to the ECAL Barrel energy resolution at the end of the HL-LHC program. Surface currents also increase due to irradiation but represent only 10% of the total current. The main concern for HL-LHC operation is therefore the increase of the bulk current.

The APDs were screened for radiation hardness during the quality assurance process [25]. They were irradiated with a $\gamma$ source, tested and annealed. These tests were used to identify and reject all devices with potential surface defects. APDs were also rejected if they were located at specific positions in the production mask, that were particularly sensitive to surface defects.

The bulk current $I_B$ due to hadron damage increases with the hadron fluence $\Phi$ according to
Table 2.1: Characteristics of the ECAL Barrel APD (Hamamatsu Photonics S8148) measured at $G = 50$ and 18 °C.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>$0.5 \times 0.5 \text{ cm}^2$</td>
</tr>
<tr>
<td>Number of APDs per crystal</td>
<td>2</td>
</tr>
<tr>
<td>Capacitance</td>
<td>70 pF</td>
</tr>
<tr>
<td>Serial resistance</td>
<td>3 Ω</td>
</tr>
<tr>
<td>Quantum efficiency (at $\lambda = 420 \text{ nm}$)</td>
<td>70%</td>
</tr>
<tr>
<td>Operating Voltage (at $G = 50$)</td>
<td>350–420 V</td>
</tr>
<tr>
<td>Distance to breakdown (at $G = 50$)</td>
<td>30–40 V</td>
</tr>
<tr>
<td>Temperature variation of the Gain</td>
<td>$-2.3/\text{°C}$</td>
</tr>
<tr>
<td>Bias variation of the Gain (at $G = 50$)</td>
<td>3.3%/V</td>
</tr>
<tr>
<td>Excess Noise Factor (at $G = 50$)</td>
<td>2</td>
</tr>
<tr>
<td>Effective thickness</td>
<td>6–7 μm</td>
</tr>
</tbody>
</table>

the relation:

$$I_B(\Phi) = \alpha \cdot d_{\text{eff}} \cdot A \cdot \Phi,$$

where $A$ is the area of the APD, $d_{\text{eff}}$ is the effective thickness of the APD ($\sim$6–7 μm), and $\alpha$ is a constant ($\alpha \simeq 10 \times 10^{-17} \text{A/cm/neutron}$). Low energy neutrons are the most abundant hadrons in the vicinity of the APDs. High energy charged hadrons are also present. The predicted fluence is a weighted sum of all hadrons taking into account the damage from the different particle types and energies, and scaled to 1 MeV energy equivalent neutron damage. The 1 MeV-neutron equivalent fluence predicted by FLUKA at the APD is $0.67 \times 10^{14} \text{n/cm}^2$ at $|\eta| = 0$ and rises to $1.2 \times 10^{14} \text{n/cm}^2$ at $|\eta| = 1.45$, after 3000 fb$^{-1}$, as shown in Fig. 2.6. Figure 2.9 shows the $\eta$ dependence of the dark current increase, measured in CMS, normalized to the value at $\eta = 0$. At high $\eta$ the damage is about 80% larger than in the centre of the barrel, in agreement with the FLUKA prediction.

![Image](image.png)

Figure 2.9: Relative APD dark current increase versus $|\eta|$ measured at different center of mass energies in CMS during Run-1 and Run-2.

Spontaneous annealing of the bulk current occurs at room temperature. After a few months only a permanent component of the damage remains, which amounts to about 50% of the ini-
tial damage. Figure 2.10 shows the increase of the dark current of the APDs measured in CMS during LHC Runs 1 and 2, and the integrated luminosity. The red curve shows a fit to the data assuming a linear increase of the dark current with integrated luminosity, as predicted in Eq. (2.3). Two exponentials plus a constant term were used to describe the annealing. The fast component was about 30 days and the a long term component was about 600 days. A constant term represented the permanent damage. The values of the various terms are shown in Table 2.2. The permanent dark current increase per capsule, expressed in terms of the delivered luminosity, amounts to about 0.037 $\mu$A/fb$^{-1}$. The dark current is predicted to be $\approx 100\mu$A at $|\eta|=0$, rising to $\approx 200\mu$A at $|\eta|=1.5$, for an integrated luminosity of 3000 fb$^{-1}$.

Table 2.2: Parameters of the fit to the APD dark current measured in CMS between 2011 and 2017. The fast and slow decay times and relative weight of the various components, and the ratio of the damage at 13 TeV with respect to 7 TeV.

<table>
<thead>
<tr>
<th>Component</th>
<th>decay time (days)</th>
<th>relative weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fast</td>
<td>30</td>
<td>50.5</td>
</tr>
<tr>
<td>slow</td>
<td>600</td>
<td>8.6</td>
</tr>
<tr>
<td>permanent</td>
<td>infinite</td>
<td>40.9</td>
</tr>
<tr>
<td>damage at 13 TeV / damage at 7 TeV</td>
<td>1.27</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.10: Dark current increase measured in one HV channel at $\eta = 0$ in CMS from 2011 to 2017 (left side axis) for one HV channel providing a bias voltage to 50 capsules. The blue curve shows the integrated luminosity (right side axis). The red curve is a fit to the data points (see text).

2.1.3.1 Summary of laboratory tests on APD irradiation

About 40 capsules were irradiated [35] in the TAPIRO reactor at ENEA Casaccia and in the ENEA Frascati Neutron Generator plant at fluences of $1-4\times10^{14}$ n/cm$^2$. The permanent bulk current of the capsules measured at 18°C is shown in Fig. 2.11, plotted as a function of the neutron fluence. The measured dark current increase of 0.16 $\mu$A/(10$^{13}$ n/cm$^2$) is compatible with the measured increase in CMS, if a fluence of $5.5\times10^{10}$ n/cm$^2$ per 1 fb$^{-1}$ is assumed. This implies that the FLUKA fluence calculation underestimates the fluence by a factor of two. As a result, all subsequent extrapolations will be based on actual measurements in situ. The 1 MeV-
2.1. ECAL Barrel crystals and photodetectors

Figure 2.11: Bulk current increase as a function of the neutron fluence for several capsules irradiated in the ENEA TAPIRO reactor and at the ENEA Frascati Neutron Generator. The line represents a linear fit to the data.

The APD characteristics were measured in a laboratory setup. The APDs were kept in thermal contact with a PWO crystal, but were not glued. The setup was located in a thermalized chamber and was maintained at a constant temperature during the measurement. The APDs exhibited self-heating for currents above 150–200 $\mu$A. The current caused the APD to heat up such that the working point (temperature and gain) could not be stabilized. For capsules glued to crystals, the onset of the self-heating occurred at higher current (300–400 $\mu$A).

The gain curve moves towards higher voltages for large fluences. A shift of the voltage corresponding to gain 50 of 25–30 V is observed for a fluence of $2.5 \times 10^{14}$ n/cm$^2$.

The quantum efficiency is stable up to a fluence of $2 \times 10^{13}$ n/cm$^2$. A decrease of up to 20–30% is observed after $2.5 \times 10^{14}$ n/cm$^2$.

2.1.3.2 Predicted dark current during HL-LHC operation

The APD bulk current is significantly reduced with decreasing temperature, according to the formula

$$ I_B(T) \sim T^{3/2} e^{-E_g/2K_BT} . $$

A reduction of a factor of 2 in the bulk current is achievable at a temperature of 9 °C with respect to 18 °C. The annealing time constants, $\tau$, also depend on the temperature as reported in Ref. [36]

$$ \tau(T) = \tau(T_0)e^{(E_n/K_BT-E_n/K_BT_0)} , $$

thus slowing down the annealing process.

Figure 2.12 shows the expected evolution of dark current versus delivered luminosity, assuming LHC Phase I delivers an integrated luminosity of 300 fb$^{-1}$ and that HL-LHC delivers 450 fb$^{-1}$ per year for three years, followed by two years of shutdown, and followed by three years at 450 fb$^{-1}$ per year.

The model in this figure uses the parameters reported in Table 2.2, Eqs. (2.4) and (2.5) for the extrapolation at different temperatures. The dark current increase is based on measurements.
from the APDs in CMS. The model also takes into account a 10% additional contribution due to the surface current.

Figure 2.12: The dark current, for APDs operated at $18 \, ^\circ C$, is shown by the red curve. The dark current, for APDs operated at $9 \, ^\circ C$, is shown by the blue curve. The purple curve shows the dark current for APDs operated at $9 \, ^\circ C$ until LS4 and then at a lower temperature of $6 \, ^\circ C$ afterwards. This corresponds to a possible lowering of the APD operating temperature following the upgrade of the barrel supermodule cooling plant in LS4 (see Chapter 4). The left plot corresponds to $|\eta| = 0$ and the right plot corresponds to $|\eta| = 1.45$. The vertical shaded lines indicate long shutdowns.

### 2.1.3.3 Device longevity

All the 40 irradiated capsules (made of two APDs) were fully operational after $2.5 \times 10^{14} \text{ n/cm}^2$. One capsule could not reach a gain higher than 35 after $4 \times 10^{14} \text{ n/cm}^2$. However, this is twice the expected fluence for 3000 fb$^{-1}$ at high $\eta$. More APD irradiations will be performed, there are a few spare capsules left from construction time and a few single APDs which can be used for this purpose.

In the current detector only six HV channels out of 1224 show a dark current of more than 3 mA at a gain of 50. This could be caused by a short circuit in one of the 50 capsules of the HV channel. The number of these problematic HV channels increases by less than one per year. From the DCU dark current measurements on the VFE boards, only one out of these six channels appears to be a short circuit on the APDs themselves or on the capsule kapton cable. The other five problems are due to a short circuit most probably on the HV filter resistors and capacitors on the motherboard. Laboratory tests have shown that when an APD breaks, it can often be operated at low gain. The fault in the single broken channel is most likely a fault in the kapton cable and not in the APD itself.

These tests are considered sufficient to demonstrate the longevity of the APDs through the HL-LHC running period. Additional APDs are available should further tests be needed in the future.

### 2.1.4 Performance evolution

The ageing of crystals and photodetectors, due to their exposure to the HL-LHC environment, will influence all three terms (stochastic term, noise term, constant term) in the energy resolution formula presented in Eq. (1.1). The stochastic term $A$ will increase due to any reduction
of light output. The noise term $B$ will increase due to radiation induced increases in the APD dark current. The loss of light transmission also results in a loss of crystal uniformity. Light produced further from the photodetector will be attenuated more than light produced close to the photodetector. The longitudinal position of the electromagnetic shower maximum fluctuates event-by-event, and so the total light signal measured by the APD will be affected by these fluctuations. As a result, non-uniformity in light collection affects the constant term $C$.

The stochastic term expected after 3000 fb$^{-1}$ is about 3%. The noise term in the energy resolution, for 3000 fb$^{-1}$, is 0.6–1.3 GeV for a 3×3 crystal matrix. This takes into account the light output loss from the crystals, as well as the increase in APD dark current, and assumes the lower operating temperature and new front-end electronics with reduced shaping time.

The expected dependence of the constant term for electrons on the absorption coefficient induced by radiation is shown in Fig. 2.13 (left) [24]. An additional induced constant term of $\sim 1\%$ is expected for $\mu_{\text{IND}}$ between 1.5 and 2.0 m$^{-1}$ after 3000 fb$^{-1}$. The evolution of the total constant term obtained from the ageing model is shown in Fig. 2.13 (right).

The overall energy resolution expected for photons as a function of energy, summing over 3×3 crystals, is shown in Fig. 2.14 for 3000 fb$^{-1}$ for $|\eta| = 0$ and $|\eta| = 1.45$. The noise term for a 3×3 crystal matrix is assumed to be three times the noise of a single crystal. Figure 2.15 shows the energy resolution as a function of the incident particle energy for 300, 1000, 3000, and 4500 fb$^{-1}$. The constant term dominates the energy resolution for showers above 50 GeV. More detailed simulation results will be described in Section 9.

2.2 HB Scintillator tiles and photodetectors

The HCAL Barrel calorimeter (HB) will need to operate at the data rates and sustain radiation doses of HL-LHC. The projected radiation degradation for HB scintillators is best estimated using measurements of signal loss in HE, where doses accumulated so far in Run-1 and Run-2 have exceeded doses expected in HB at the end of HL-LHC.
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Figure 2.14: Energy resolution as a function of incident particle energy for detector ageing for an integrated luminosity of 3000 fb$^{-1}$ for $|\eta|=0$ (left) and $|\eta|=1.45$ (right). The different contributions to the energy resolution are plotted separately (stochastic, noise and constant terms).

Figure 2.15: Energy resolution as a function of incident particle energy for different integrated luminosities for $|\eta|=0$ (left) and $|\eta|=1.45$ (right).

The signal degradation in HE has been studied since 2010. Using data collected in 2016, it has become evident that the decrease in response of HE observed over time is not caused exclusively by radiation damage in the scintillator and wavelength-shifting fibers. Instead, the data reveal that a significant contribution to the response loss comes from the deterioration in the performance of the Hybrid Photodiodes. This implies that the scintillator/WLS-fiber radiation damage is less severe than what was thought at the time of the CMS Phase-2 Upgrade Technical Proposal.

During the 2016–2017 extended year-end technical stop, four of the HPDs in the HE (sector HEP17) were replaced with Silicon Photomultipliers (SiPMs) as part of the first stage of the HE Phase-1 front-end upgrade. Using data collected until September 2017, we have carried out an
initial comparison of the degradation of HE signal in the SiPM sector HEP17 with respect to
current losses in the other HE sectors read out by HPDs, allowing the two contributions (HPD
deterioration and radiation damage of scintillator) to be separated. Analysis of the first 22 fb\(^{-1}\)
delivered to CMS by mid-September 2017 confirms that indeed a large fraction of signal loss
in HE is caused by HPD deterioration and not by the scintillator radiation damage. The HPD
related loss will not be relevant for operation of HB during HL-LHC era, as all HB HPDs will
be replaced with SiPMs during the Long Shutdown 2 as part of the Phase-1 upgrade.

The projection of the radiation damage to HB scintillators and its effect on HB performance
(Section 9.6.3) indicates that replacement of HB scintillators will not be required for HL-LHC
running.

This section on the longevity of the HB detector components is organized in a few subsections.
Section 2.2.1 describes in detail our understanding of the various components of the response
loss measured in HE, and the projections for HB until the end of the HL-LHC. Section 2.2.2 de-
scribes other supporting methods to extract information on the HB response loss. Section 2.2.3
describes how the ageing of the HB scintillator and the increase in SiPM dark current have
been implemented in the MC simulation that is used to study the CMS detector performance
in Chapter 9. The conclusions we make for the HB upgrade using our understanding of the HB
detector ageing are stated in Section 2.2.4.

### 2.2.1 HB longevity studies

In planning upgrades of the CMS barrel calorimeters for the HL-LHC, one of the main ques-
tions is whether or not the scintillator in the Hadronic Barrel calorimeter will survive the radia-
tion expected during the entire HL-LHC running period.

Figures 2.16 and 2.17 show the expected radiation dose and dose rates for HB as a function of \(\eta\)
and scintillator layer for 4500 fb\(^{-1}\), the ultimate integrated luminosity that could be delivered
to CMS by the HL-LHC. The doses for the front HB scintillator layers range from 0.2–0.4 Mrad
in Layer 0 (L0) to 0.06 to 0.2 Mrad in Layer 4 (L4), with corresponding dose rates of 0.7 to
1.3 \times 10^{-2} krad/hr in L0 and 0.2 to 0.6 \times 10^{-2} krad/hr in L4.

![FLUKA Dose Map (HB)](image)

**Figure 2.16:** Expected Dose for HCAL Barrel calorimeter, as a function of \(\eta\) and Layer for
4500 fb\(^{-1}\) of the ultimate scenario of HL-LHC.
HCAL uses a laser calibration system to monitor the response of the detector, and in particular, radiation damage of scintillators. In HE, ultraviolet light is injected into scintillator tiles for two specific sampling layers of, Layer 1 (L1) and Layer 7 (L7). Figure 2.18 shows the signal response loss in L1, the front sampling layer of HE, for various $\eta$ positions of the towers, averaged over all $\phi$ positions, as a function of delivered integrated luminosity. The luminosity delivered in 2012 at a collision energy of 8 TeV is divided by a factor of 1.25 to account for a lower particle flux with respect to the 13 TeV collisions delivered in 2015 and 2016. The detector response is normalized to the signal at the beginning of 2012. The intensity of the laser light used to monitor the detector response varies over time, and the normalization for this variation is obtained using the intensity measured in the the low-$\eta$ ring where radiation damage is assumed to be negligible. Different colored lines correspond to the average response loss in different $\eta$ rings.

At the highest $\eta$ ring of HE L1, corresponding to $\eta = 2.93$, only 40% of the original signal has remained at the end of 2016, with respect to early 2012, after approximately 70 fb$^{-1}$ delivered to CMS in this period. At the middle $\eta$ ring of HE L1, corresponding to $\eta = 2.25$, 70% of signal has remained. We have used an exponential function to describe the signal loss as a function of integrated luminosity, with parameter $D$ (in fb$^{-1}$), the dose constant, corresponding to the value of integrated luminosity in fb$^{-1}$ after which the original signal is reduced by a factor e. A fit to an exponential function was carried out using exclusively 2012 data. Dose constants $D$ range from 275 fb$^{-1}$ (at low $\eta$) to 50 fb$^{-1}$ (at highest $\eta$ of HE). As the figure shows, while the behavior of the 2012 and 2015 data is well described by a single exponential function, the 2016 data is systematically above the fit curve, implying less signal loss than predicted by the 2012 fits.

Figure 2.19 shows the average response loss in HE as a function of the $\eta$ index of the tower, ieta, averaged over all $\phi$ positions, corresponding to the combined delivered integrated luminosity of 41.3 fb$^{-1}$ delivered to CMS in 2016 (Run 2). The response is normalized to the signal at the beginning of 2016, while the normalization for the laser intensity variation is obtained using low-$\eta$ towers. Red (blue) data points correspond to HEM (HEP), solid lines to L1 and broken lines to L7. A large signal loss, especially at high ieta, is seen both in L1 (35% at ieta=28) and L7 (20% at ieta=28).
Figure 2.18: Response loss in HE Layer1 for various \( \eta \) towers, averaged over all \( \phi \) towers, as a function of integrated luminosity. The response was normalized to the signal at the beginning of 2012. The normalization for Laser intensity variation was obtained using the lowest \( \eta \) ring.

Figure 2.19: Response Loss in HE as a function of \( \eta \) tower, averaged over all \( \phi \) towers, corresponding to the delivered integrated luminosity of 41.3 fb \(^{-1}\). The response was normalized to the signal at the beginning of 2016. The normalization for Laser intensity variation was obtained using the lowest \( \eta \) tower. Red (blue) data points correspond to HEM (HEP), solid lines to L1 and broken lines to L7.

Figure 2.20 shows the response loss for HE plus, tower \( \eta = 28 \) (\( \eta = 2.79 \)), as a function of the \( \phi \) index of the tower, \( \phi \), corresponding to a delivered integrated luminosity of 41.3 fb \(^{-1}\). The response is normalized to the signal at the beginning of 2016. Blue data points correspond to measurements using the laser monitoring system, and red data points correspond to the measurements using collision data. As indicated by the figure, there is a significant variation
in the signal loss vs iphi. For example, for iphi = 15, the signal loss is only 5%, while for iphi = 65, the signal loss is almost 40%. For quite some time, the reason for the φ variation of signal loss in HE was not properly identified. In particular, the explanation that the effect is caused by φ variations in the radiation dose reaching HE detector turned out to be false.

Figure 2.20: Response loss for HE Plus, Layer 7 (L7), tower index ieta = 28 (η = 2.79), as a function of tower index iphi, corresponding to a delivered integrated luminosity of 41.3 fb$^{-1}$. The response is normalized to the signal at the beginning of 2016. Blue data points correspond to measurements using the laser calibration system, and red points correspond to measurements using collision data.

Figure 2.21 shows correlations between the fraction of signal remaining after 41.3 fb$^{-1}$ for different pairs of tiles. In the upper two plots, showing pairs of tiles read out by same HPD, there is clear correlation between signal loss in the tiles. On the contrary, in the lower two plots, showing tiles read out by different HPDs, there is no evidence of correlation, even though the tiles are placed next to each other. These measurements are consistent with hypothesis that variations in the response loss seen in different phi sectors of HE are result of the damage of HPD photocathodes, with different level of damage for each HPDs.

During the 2012 and 2016 data taking periods, it was observed that the loss of response, as tracked using the laser calibration of tiles in L1 and L7 of HE Plus and HE Minus, depends not only on the total radiation dose but also upon the dose rate. Scintillator tiles exposed to higher dose rates show lower damage per unit of integrated dose delivered than the tiles exposed to a lower dose rate. The dose constant $D$ (in Mrad) is quantified by observing the light output $L$ as a function of total dose $d$, assuming an exponential loss of signal as is expected from light attenuation resulting from radiation-induced color centers, $L = \exp(-d/D)$.

A dose rate dependence in radiation damage has been reported several years ago (see for example [37]), and a model for this has been developed to explain the large signal losses seen in HE [38]. Figure 2.22 shows the extracted dose constant (in Mrad) plotted as a function of dose rate (in krad/hr) using the signal loss in the HE detector vs. integrated luminosity. Each $\eta/\phi$ tower is represented by an individual point, where red (blue) points correspond to L1 (L7). As shown in the figure, there is a large variation in the damage of individual tiles within the same η ring, with an extracted dose constant that varies from a factor of two to a factor of five. At rel-
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Figure 2.21: Correlations between the relative signal remaining after 41.3 fb$^{-1}$ of delivered integrated luminosity for different pairs of scintillator tiles. The upper two plots show the relative signal of tiles read out by the same HPD: $i$eta = 29 vs. $i$eta = 28 (left) and $i$eta= 26 vs. $i$eta = 28 (right). The lower two plots show the relative signal of tiles read out by different HPDs: $i$eta = 27 vs. $i$eta = 28 (left) and $i$eta = 25 vs. $i$eta = 28 (right).

At relatively high dose rates (above $2 \times 10^{-2}$ krad/hr), the factor of two spread is dominated by HPD damage: scintillator tiles read out by the most damaged HPDs have systematically smaller values of $D$, while scintillator tiles read out by the least damaged HPDs have systematically larger values of $D$. At lower dose rates (below $10^{-2}$ krad/hr), where the response loss in 2016 was small, the spread in the extracted values of $D$ is dominated by the systematic uncertainty of the fits.

These results are consistent with the hypothesis that the response loss in HE observed in 2012–2016 data has two components:

1. damage to HPD caused by the charge drawn from them during pp collisions
2. radiation damage of scintillators and WLS fibers
Figure 2.22: Dose constant $D$ as a function of dose rate using HE data from 2016, with red (blue) points corresponding to L1 (L7) data. Each $\eta$/$\phi$ tower is shown as a separate data point on the plot. Vertical lines of points with same value of dose rate correspond to individual $\phi$ towers within same $\eta$ ring.

The data indicates that the magnitude of damage of the photocathode clearly varies from HPD to HPD. However, at this point, the full mechanism of HPD damage and its dependence on charge drawn from the photocathode is not fully understood.

Up till end of 2016, we did not have sufficient information to directly determine what fraction of the HE response loss can be attributed to HPD damage and what fraction is due to the radiation damage of the scintillator. The installation of Phase-1 front-end electronics in one of the wedges in HE (HEP17) during the 2016–17 extended year-end technical stop also included the replacement of photodetectors. Four HPDs were replaced by arrays of SiPMs. The direct separation of the two contributions to the signal loss in HE, has become possible by analyzing laser and collision data collected in 2017—in particular, data from HE wedge HEP17, which is instrumented with Phase-1 front-end electronics and SiPM arrays (no HPDs).

The 2017 data allowed us to measure the signal loss in HE with two different photodetectors: HPDs (for the majority of the detector) and SiPMs (for the HEP17 sector). Figure 2.23 compares the relative signal loss observed in the highest $\eta$ region of HE detector, ($i_{\eta}=28$), as a function of integrated luminosity, up to 22 fb$^{-1}$ delivered to CMS in 2017 by mid-September. The towers read out by HPDs are shown in thin lines, the two towers read out by SiPM photodetectors ($i_{\phi}=63$ and $i_{\phi}=65$), are shown in bold lines. The plot shows that indeed the two towers read out by SiPMs exhibit much smaller signal loss: 8% signal loss for SiPM towers, compared to signal loss in the range between 8% and 27% for HPD towers.

For the time being, until the full data-set of 2017 in-situ measurements of scintillator signal without using HPDs as photodetectors is available, we estimate the level of radiation damage of scintillators and WLS fibers using the 2016 data as described below. First, we select the $\phi$ regions of the HE detector where the signal loss is smallest, which implies the smallest contributions from HPD damage. We define a set of the “ten best” HPDs (out of 144 installed on HE) considering smallest signal loss in the highest-$\eta$ region ($i_{\eta} = 28$ and $i_{\eta} = 27$). We use measurements of signal loss in 2016 using these ten HPDs to predict the radiation-induced loss.
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Figure 2.23: Early 2017 data: comparison the relative signal loss observed in the highest $\eta$ region of HE detector, ($i\eta = 28$), as a function of integrated luminosity, up to 22 fb$^{-1}$ delivered so far to CMS in 2017. The towers read out by HPDs are shown in thin lines, the two towers read out by SiPM photodetectors ($iphi=63$ and $iphi=65$) are shown in bold lines.

of signal in HB at the end of the HL-LHC running period. This approach may provide a conservative projection of signal left in HB, as even the “ten best” HPDs may have some level of deterioration. The first indications from the 2017 data in Fig. 2.23 suggest that the measurement of the HE response loss using the “ten best” HPDs is consistent with the measurement using SiPMs.

Figure 2.24 shows the dose constant $D$ [Mrad] as a function of dose rate $R$ [krad/hr] using HE data from the last 20 fb$^{-1}$ of integrated luminosity collected during the 2016 run. The points show the average over the ten best HPDs, with red (blue) points corresponding to L1 (L7) data. Error bars are calculated using RMS of the variation in $D$ extracted from the response loss vs. dose of individual scintillator tiles. Solid lines correspond to fits using the parameterization $D = a \times R^b$. Dashed lines indicate the error band associated with the fits. Using the fits, we expect a dose constant $D \sim 0.3$ Mrad at a dose rate of $10^{-2}$ krad/hr for the front layers of HB. This is roughly 3x larger than values of $D$ extracted using data from the average of all HPDs [38], which implicitly includes the HPD deterioration effect. The change in the prediction of the Dose constant $D$ from 0.1 Mrad to 0.3 Mrad is of critical importance, as the expected doses in the most exposed regions of HB will be in the range of 0.2 to 0.4 Mrad at the end of the HL-LHC operations.

In order to predict the radiation damage of the HB scintillator at future times, we need to combine the parameterization of the dose rate dependence of the dose constant with the expected HL-LHC instantaneous and integrated luminosity. The LHC accelerator has presented a schedule for future running conditions and a typical annual running cycle can be assumed for future running of the LHC. The expected peak luminosity is used for estimating future dose rates. The assumed dose rates in future LHC running up to LS3 are approximately a factor of two above those which were obtained in 2016, and a factor of about six for HL-LHC. This information allows us to predict the magnitude of the radiation damage at any future value of delivered luminosity.
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Figure 2.24: Dose constant $D$ as a function of dose rate $R$ using HE data from 2016. The points show the average over the ten best HPDs, with red (blue) points corresponding to L1 (L7) data. Error bars are calculated using RMS of the variation in $D$ extracted from the response loss vs. dose of individual scintillator tiles. Solid lines correspond to fits using the parametrization $D = a \times R^b$. Dashed lines indicate the error band associated with the fits.

The relative signal in HB scintillators predicted for the end of HL-LHC program, compared to signal at the start of Run 1, is shown in Fig. 2.25. We assume a total integrated luminosity of $4500 \text{ fb}^{-1}$, which consists of $300 \text{ fb}^{-1}$ prior to LS3 and $4200 \text{ fb}^{-1}$ in the post-LS3 era. The prediction shown on Fig. 2.25 (left) is based on the parametrization of dose constant $D$, with $D = 3.6 \times R^{0.5}$, extracted from CMS HE 2016 L7 data with an average over the ten “best” HPDs. To provide a sense of the uncertainty of this prediction, Fig. 2.25 (right) shows predictions using a parametrization, $D = 2.4 \times R^{0.5}$, based on the lower dashed blue line in Fig. 2.24. This prediction is $1\sigma$ below the central value of the fit to L7 data. The relative signal of the front layers of HB is expected to be in the range of 40–50% for the central value of the fit and in the range of 30–40% for $1\sigma$ below the central value.

As mentioned earlier, during LS2, the HB front-end electronics will undergo the Phase-1 upgrade, which includes the replacement of the present HPD photodetectors with SiPMs. SiPMs have a significantly higher gain and photo-electron efficiency, resulting in a factor of 2.5 improvement in PE over the HPDs. This will introduce a factor of 2.5 increase in photodetection efficiency. In addition, the signal from the first sampling layer of HB, L0, will be increased by a factor of 2.4, as neutral density filters presently installed on detector will be removed. Figure 2.26 shows the same two scenarios as in Fig. 2.25, accounting for the increased photodetection efficiency of the SiPMs compared to the HPDs and the removal of neutral density filters for L0.

The reason for showing two sets of HB projections, the relative light yield in Fig. 2.25 and the relative light yield times photodetection efficiency in Fig. 2.26, is that the first set provides information on the deterioration of the HB scintillator tiles and WLS fibers with respect to construction time, while the latter set provides information on the relative photo-electron statistics with respect to construction time to reflect the improvement in the photosensors and removal of neutral density filters taking place with the Phase-1 upgrade in LS2. Both sets are useful to
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Figure 2.25: Light yield for HB after 4500 fb$^{-1}$ of delivered integrated luminosity (300 fb$^{-1}$ pre-LS3 + 4200 fb$^{-1}$ post-LS3), relative to the light yield for HB at the time of construction, plotted as a function of layer and tower index ieta. Two different radiation damage models have been used to generate the plots. Left: Radiation damage model using the average of the ten best HPDs observed in HE during 2016. Using a fit to L7 data, the extracted value of $D$ is $3.6 \times R^{0.5}$. Right: Radiation damage model with parametrization $D = 2.4 \times R^{0.5}$, corresponding to a $1\sigma$ shift with respect to the central value of the fit to L7 data.

Figure 2.26: Light yield $\times$ photodetection efficiency (LY $\times$ PDE) for HB after 4500 fb$^{-1}$ of delivered integrated luminosity (300 fb$^{-1}$ pre-LS3 + 4200 fb$^{-1}$ post-LS3), relative to the value of LY $\times$ PDE for HB at the time of construction, plotted as a function of layer and tower index ieta. This includes light loss due to radiation damage to the scintillator tiles, the increase in PDE due to replacement of HPDs with SiPMs ($\times 2.5$), and the additional increase in light yield from the removal of neutral density filters ($\times 2.4$) for L0. Two different radiation damage models have been used to generate the plots. Left: Radiation damage model using the average of the ten best HPDs observed in HE during 2016. Using a fit to L7 data, the extracted value of $D$ is $3.6 \times R^{0.5}$. Right: Radiation damage model with parametrization $D = 2.4 \times R^{0.5}$, corresponding to a $1\sigma$ shift with respect to the central value of the fit to L7 data.

make a judgement on whether megatile replacement is necessary or not.
Figure 2.27 shows the expected signal in photo-electrons in the HB detector for MIP particles after 4500 fb$^{-1}$ of delivered integrated luminosity. The signal is shown as a function of the readout depth segmentation that will be implemented in LS2 as part of the Phase-1 upgrade. For the first readout depth, which is a single-layer double-thickness scintillator, the MIP signal is expected to be of the order of ten photo-electrons.

The ability to discriminate MIP signals in the HB is not expected to affect the jet reconstruction performance. However, retaining such ability provides an additional method for calibrating the detector, which could be particularly useful for the multi-depth segmentation of the HB readout after the Phase-1 upgrade. A reduction of the MIP signal-to-noise ratio with ageing is caused not only by signal reduction (as shown in Fig. 2.26), but also by the increase in SiPM dark current due to neutron exposure, which adds to the electronics noise.

Figure 2.28 shows the dark current noise fluctuation (r.m.s.) as a function of neutron fluence at two different SiPM temperatures. The noise curves are based on measured performance of HE SiPMs. A temperature of $-5^\circ$C is assumed for HB SiPMs during HL-HLC. Note however, that at this point, the final choice of HB SiPM for Phase-1 upgrade have not been made yet. Some of the candidate HB SiPMs exhibit a higher dark noise, compared to the HE SiPMs. By the end of HL-LHC running, we expect $2 \times 10^{12}$ n/cm$^2$ in the location of the HB Front-End. The figure implies that we may expect the dark current from HB SiPM reach the level of 6–12 p.e. by the end of HL-LHC. Combining Figs. 2.27 and 2.28, we expect MIP S/N in the first HB readout depth to be in the 1–2 range and 2–4 range in the second readout depth.

**2.2.2 Additional methods to study the HB response loss**

As we have learned in Section 2.2.1, a large component of the observed detector response loss is due to the degradation of the HPDs, varying considerably from HPD to HPD, and the loss caused by actual radiation damage to the scintillator can be inferred by studying the channels read out by those HPDs that display the least damage.

An alternative method to factorize HPD damage component from radiation damage of scintillator has also been used. When the HE sector HEP17 was upgraded to Phase-1 during EYETS 2016/17, a calibration using the HCAL wire $^{60}$Co radioactive source system was performed prior and after the upgrade. This system uses steel tubes and drivers to guide a wire with $^{60}$Co source inside the detector megatiles. For each HEP17 tile, this has allowed a direct mea-
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Figure 2.28: Dark current noise fluctuation (r.m.s.) as a function on neutron fluence at two different SiPM temperatures. A temperature of $-5^\circ$C is assumed for HB SiPMs during HL-HLC. The measured test beam value for MIPs is 4–5 p.e./(mip*tile).

Measurement of the ratio of the charge collected with HPD and SiPM readouts, $Q_{\text{HPD}}/Q_{\text{SiPM}}$, for the same amount of deposited energy. If the HPD were undamaged, we would expect the $Q_{\text{HPD}}/Q_{\text{SiPM}}$ response ratio to be flat versus the $\eta$ position of the tile. However, we found that this response ratio drops gradually with increasing $\eta$, indicating that there is a component contributing to the loss of response other than coming from the scintillator. These results were used to factorize the observed damage into scintillator and HPD components. The scintillator tile damage estimated using this procedure was found to be in good agreement with the method presented earlier, based on the average of the 10 best HPDs, both for the central fit as well as for the conservative $-1\sigma$ fit shown in Fig. 2.24. We conclude that using these two independent methods of extracting the scintillator+fiber damage from currently available data provides a stable result.

As far as observing directly the (so far small) response loss of the HB detector, direct measurements were obtained from comparing the $^{60}$Co source scans of HB performed in 2005 and 2014 (LS1) as well as from variations of the Most Probable Value (MPV) of the isolated muon signal in HB readout depths vs luminosity in 2016 collision data. Since HB is still fully instrumented with HPD readout, the measured HB response loss includes contributions from both scintillator radiation damage and HPD deterioration. Note that both of these methods implicitly include damage of HB HPDs, not just radiation damage to HB scintillators.

The $^{60}$Co wire source calibration method was described above. In this case, the plot in Fig. 2.29 (left) is produced by: a) normalizing the source signal in each tile to the signal for the same $\eta$ and $\phi$ at layer 13, assuming no significant damage at layer 13; b) repeating the above separately for the 2014 and 2005 source data; c) averaging over all measured $\eta$ and $\phi$ tiles; and d) taking the ratio between the 2014 and 2005 data. This double ratio cancels out various systematic errors, the different source intensity between the two calibration campaigns, and tile-by-tile differences in geometrical acceptance.

Muon calibration is based on energy deposits in HB for isolated muon candidates in the data, having $p_T > 20$ GeV and required to enter and exit the same calorimeter readout depth based
on the associated track measurement. The MPV values were derived from fitting a Landau distribution convoluted with a Gaussian to the energy deposit distributions, corrected for the muon path length in the scintillator tiles. As an example, Fig. 2.29 (right) shows the MPV value for muons traversing the HB tiles in readout depth 1 of ieta=15, which collects the signals from the first 13 layers of HB, as a function of integrated luminosity in 2016.

Figure 2.29: Left: Ratio between the HB response to a $^{60}$Co radioactive source measured in 2014 and in 2005, versus the layer position of the tiles. For each measurement, the response of each given tile has been normalized to the response of the tile in layer 13 at the same $\eta$ and $\phi$ position. The integrated luminosity delivered by the LHC prior to the 2014 measurement was approximately 30 $fb^{-1}$. Right: Most Probable Value (MPV) of the energy deposited by isolated muons in HB readout depth 1 at ieta=15 as a function of integrated luminosity grouped by 2016 run periods, for a total of 36 $fb^{-1}$.

Both the $^{60}$Co source and muon calibration methods indicate a few percent signal losses during the corresponding periods, in agreement with the expectations from the dose rate model calculations for the total signal loss (scintillator/fiber + HPD deterioration) in HB, with the dose rate model parameters determined from HE data on signal loss observed in laser calibration runs in 2012 and 2016. Both methods will continue to be used to monitor the HB response loss as it progresses with integrated luminosity. The muon analysis will be regularly performed while the next HB sourcing campaign is foreseen to take place in LS2.

### 2.2.3 Implementation of the HB ageing in Simulation

#### Scintillator Ageing

As described in Section 2.2.1, analysis of the HE detector response loss in 2016 has brought important advances in the understanding of the radiation damage of the HCAL scintillator and wavelength-shifting (WLS) fibers. A significant portion of the observed response loss is caused by hybrid photodiode (HPD) performance degradation, in addition to the fraction of loss coming from the actual radiation damage to the scintillator and fibers. Since the HPDs will be replaced by silicon photomultipliers (SiPMs), the HPD contribution to the response loss should not be included when projecting the HB scintillator and fiber ageing for HL-LHC. Also, it has been further confirmed that the radiation damage to the scintillator is dependent on the dose rate at which the integrated dose is delivered. For the same integrated dose, a higher dose rate will result in lower damage than a lower dose rate.

A dose-rate dependent model was developed to simulate the effects of scintillator damage. The model uses measurements of the damage in the endcaps and extrapolates them to the barrel region. The uncertainty in this extrapolation is large, and a conservative estimate of the resulting damage was used for the barrel scintillator. The model uses a parameterization shown as
the brown line in Fig. 2.30. This approach provides a more conservative (higher) estimate of the damage than the two parameterizations described in Section 2.2.3, which were developed later. For the very front layers of HB, where the radiation and the damage is higher, the parameterization implemented in the simulation is very similar to the parameterization derived from the $-1\sigma$ error band of the estimate extracted using the ten best HPDs. The simulation uses a dose map from FLUKA to convert integrated and instantaneous luminosity to dose and dose rate values. The expected LHC operating conditions as listed in Table 2.3 are used to account for the dose rate dependence of the scintillator damage. It has been verified that other similar but not identical assumptions of the future luminosity profile give similar results in terms of expected HB scintillator radiation damage.

Table 2.3: The integrated and instantaneous LHC luminosities used for HB light yield modelling up to the end of the HL-LHC.

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017-18</th>
<th>2021-23</th>
<th>HL-LHC</th>
</tr>
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<tr>
<td>Peak instantaneous luminosity ($10^{34} \text{cm}^{-2}\text{s}^{-1}$)</td>
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<td>1.7</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Delivered integrated luminosity (fb$^{-1}$/yr)</td>
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<td>45</td>
<td>45</td>
<td>300</td>
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<td>0.043</td>
<td>0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 2.30: Parameterization of the dose constant versus dose rate (solid brown line, $D = 5 \times R^{0.67}$, where $D$ is the dose constant and $R$ is the dose rate) used for generating the MC samples to study the effects of the HB scintillator ageing on the jet resolution performance. This parameterization interpolates between a fit at high dose rates, where scintillator and HPD damages are well determined and the HPD damage has been corrected for, and no HPD correction at lowest dose rates, which is increasingly conservative where our knowledge of HPD damage was limited. This parameterization is more conservative than the parameterizations described in Section 2.2, which were developed at a later time and are also shown in the plot (solid and dashed black lines). The black horizontal arrow indicates the HL-LHC dose rates for the front layers of HB.

Figure 2.31 shows the projections for the HB scintillator ageing at the end of HL-LHC program as implemented in the simulation using the solid brown line in Fig. 2.30 to parameterize the dose constant versus dose rate. For the front layers of HB, these projection are very similar to those shown in the right plots of Figs. 2.25, 2.26 and 2.27, which are obtained using the parameterization derived from the $-1\sigma$ error band of the estimate extracted using the ten best HPDs shown in Fig. 2.24, also represented as the dashed black line in Fig. 2.30.
Chapter 2. Longevity of existing components

Figure 2.31: Projections for the HB scintillator ageing as implemented in the simulation using the solid brown line in Fig. 2.30, which parameterizes the dose constant $D$ versus dose rate $R$ as $D = 5 \times R^{0.67}$. All plots are shown for 4500 fb$^{-1}$ of delivered integrated luminosity (300 fb$^{-1}$ pre-LS3 + 4200 fb$^{-1}$ post-LS3). Top left: Light yield relative to HB at the time of construction, plotted as a function of layer and tower index $i_{eta}$. Top right: Light yield $\times$ photodetection efficiency ($LY \times$ PDE) relative to HB at the time of construction, plotted as a function of layer and tower index $i_{eta}$. This includes light loss due to radiation damage to the scintillator tiles, the increase in PDE due to replacement of HPDs with SiPMs ($\times$2.5), and the additional increase in light yield from the removal of neutral density filters ($\times$2.4) for L0. Bottom left: The HB readout segmentation to be implemented with the HB Phase-1 upgrade scheduled for LS2, shown versus layer number and tower index $i_{eta}$. Bottom right: MIP signal (in photo-electrons) for HB shown as a function of readout depth and tower index $i_{eta}$.

SiPM radiation damage model

Silicon photomultipliers have a base level of dark current that will increase with neutron exposure. The dark current causes noise by randomly producing photoelectrons in a Poisson-distributed process, and can be decreased by operating the SiPMs at a lower temperature. Based on measurements of HE SiPMs, which are shown in Fig. 2.28, the following model is constructed:

$$I_{DC}(L, T) = [I_{DC}(0, T_{base}) + d_{neutrons} \times c_{neutrons/L}(L - L_{offset})] \exp^{d_{temp}(T - T_{base})}. \quad (2.6)$$

Here, the dark current $I_{DC}$ depends on the luminosity $L$ and the temperature $T$. The parameter $I_{DC}(0, T_{base})$ is the initial dark current at the base temperature $T_{base}$. The parameter $L_{offset}$ accounts for the installation of the SiPMs during LS2 (after the LHC has already accumulated some luminosity). The conversion factor $c_{neutrons/L}$ relates integrated luminosity values to neutron fluence. The dependence on neutron fluence is given by $d_{neutrons}$ and the dependence on temperature is given by $d_{temp}$.
The parameters are given in Table 2.4. SiPMs with diameter 2.8 mm are used to read out depths with up to 4 layers, while SiPMs with diameter 3.3 mm are used to read out depths with more than 4 layers. The HB longitudinal readout segmentation to be implemented during LS2 for the Phase-1 upgrade is shown in Fig. 2.31 (bottom-left). It is expected that the HB SiPMs will be operated at $T = -5^\circ\text{C}$ during Phase 2.

Table 2.4: Parameter values for SiPM radiation damage model (HB). SiPMs of different size have different values for some parameters, as indicated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>[unit]</th>
<th>2.8 mm</th>
<th>3.3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{base}}$</td>
<td>$^\circ\text{C}$</td>
<td>20</td>
<td>0.01</td>
</tr>
<tr>
<td>$I_{\text{DC}} (0, T_{\text{base}})$</td>
<td>$\mu\text{A}$</td>
<td>$5.69 \times 10^{-11}$</td>
<td>$7.90 \times 10^{-11}$</td>
</tr>
<tr>
<td>$d_{\text{neutrons}}$</td>
<td>$\mu\text{A/cm}^2$</td>
<td>$3.67 \times 10^8$</td>
<td>$150$</td>
</tr>
<tr>
<td>$\epsilon_{\text{neutrons/L}}$</td>
<td>$\text{cm}^{-2}/\text{fb}^{-1}$</td>
<td>$0.0631$</td>
<td>$0.17$</td>
</tr>
<tr>
<td>$L_{\text{offset}}$</td>
<td>$1/\circ\text{C}$</td>
<td>$0.17$</td>
<td>$0.196$</td>
</tr>
<tr>
<td>$d_{\text{temp}}$</td>
<td>$1/\circ\text{C}$</td>
<td>$0.17$</td>
<td>$0.196$</td>
</tr>
<tr>
<td>$\lambda_{\text{xtalk}}$</td>
<td>$1/\circ\text{C}$</td>
<td>$0.17$</td>
<td>$0.196$</td>
</tr>
</tbody>
</table>

The effective increase in pedestal width caused by the dark current is considered in the reconstruction. The term $\sigma_{\text{DC}}$, defined below, is added in quadrature to the other resolution terms. As the dark current increases, it begins to induce a non-negligible contribution to the pedestal mean, as well. This term must be included in the pedestal subtraction.

\[
Q_{\text{DC}} = I_{\text{DC}} \cdot (25 \text{ ns})
\]

\[
p_{\text{DC}} = Q_{\text{DC}} / g_{\text{IC/pe}}
\]

\[
\sigma_{\text{DC}} = g_{\text{IC/pe}} \sqrt{p_{\text{DC}} / (1 - \lambda_{\text{xtalk}})^3}
\]

\[
Q_{\text{ped}}^{(\text{eff})} = Q_{\text{ped}} + Q_{\text{DC}} / (1 - \lambda_{\text{xtalk}})
\]

The variable $Q_{\text{DC}}$ is the expected charge from the dark current (in fC), integrating over the 25 ns time slice. The value $g_{\text{IC/pe}}$ is the gain of the SiPM, currently simulated as 44 fC/pe. It is used to convert the charge $Q_{\text{DC}}$ into the number of photoelectrons (pe) $p_{\text{DC}}$. The variable $\lambda_{\text{xtalk}}$ is the parameter of the Borel-Tanner distribution used to model the crosstalk of the SiPM, which increases the observed contribution from the dark current. The combination of the Poisson-distributed dark current and the Borel-Tanner distributed crosstalk results in a Generalized Poisson distribution. The contributions to the pedestal mean and width from the combination of dark current and crosstalk are calculated as the mean and width of this Generalized Poisson distribution.

### 2.2.4 Conclusions of HB longevity studies

The evidence that HPD damage contributes to the observed HE response loss indicates that scintillator/WLS-fiber radiation damage is less than what was thought at the time of the CMS Phase-2 upgrade Technical Proposal. We have used different techniques to disentangle the two contributions in order to estimate the HE response loss that is exclusively due to radiation damage of scintillator and WLS fibers, and have projected it to HB at the HL-LHC radiation conditions using a dose-rate dependent model. Based on this work, our understanding is that a replacement of the HB scintillators for the HL-LHC will not be required.

The justification for retaining the HB scintillators is based on the analysis of the entire 2017
dataset using the HE sector, HEP17, that has already been upgraded to SiPM readout. The full analysis is documented in Appendix A.
Chapter 3

Readout electronics

3.1 Introduction

The main requirement of the EB upgrade is to maintain the Run-1 physics performance for photons and electrons at the higher luminosity and pileup of the HL-LHC. In order to accomplish this, the EB electronics must accommodate the Level-1 trigger requirements on latency and rate, provide more precise timing resolution and help mitigate the increasing noise from the photodetectors.

The EB electronics front end board and all the off detector electronics must replaced to meet these requirements. The very front end board must be replaced to provide better timing resolution and noise filtering. In the legacy system based on a CR-RC charge amplifier followed with a sampling ADC running at 40 MHz, the APD leakage current induced noise is proportional to the square root of the amplifier shaping time (RC). So, the pulse shaping will be shortened to more optimally filter the increased avalanche photodiode noise and the sampling rate will be increased to provide better timing resolution and suppression of anomalous APD signals.

The conceptual design for the electronics system upgrade has been developed using the specifications and constraints provided in Table 1.2. The dynamic range will be between a few tens of MeV to the equivalent of 2 TeV signals from electrons or photons. The lower bound is defined by the intrinsic noise from the APDs, currently around 60 MeV. This will increase further with radiation, as discussed in Chapter 2. The upgrade will reduce the noise to around 200 MeV through a lowering of the supermodule operating temperature from 18 °C to about 9 °C and a re-optimization of the preamplifier architecture and characteristics.

The EB upgrade will use commonly developed components where possible. These include the radiation and magnetic field tolerant FEAST step down direct-current to direct-current (DC-DC) power converters [39] that may be placed on detector to decrease the power consumption compared to the legacy system and consequently reduce the volume of copper cables in the services. The upgrade will also use the low power gigabit transmission (lpGBT) chipset and Versatile Link+ (VL+) optical links. These are high speed optical data transmission links developed to be magnetic field and radiation tolerant. Details of these common LHC development programs can most reliably be found in the proceedings of the annual ACES conference [11].

3.2 Constraints and working hypothesis

In order to optimize the design of the new VFE electronics, it is necessary to define the working hypothesis and models. The main input parameters are the following:

- Nominal collected charge by the APD for non-irradiated crystals (photoelectrons/MeV);
• Nominal shape of the photocurrent generated by the APD;
• Maximum loss of crystal transparency at the end of HL-LHC;
• Variation of light yield, APD gain, APD leakage current and crystal scintillation light output with temperature;
• Model for induced noise due to the APD leakage current.

Some of these parameters have been studied in the previous chapter and will be used as input for the design of the electronics. The others are detailed in the following sections. The following is a list of additional constraints:

• Maximum acceptable signal amplitude: 2 TeV energy deposition in a single crystal;
• Maximum non-linearity allowed: ±2/1000 integral non-linearity over the full dynamic range;
• Maximum quantization induced noise: should be negligible with respect to the electronic noise;
• Maximum intrinsic electronics induced noise: 80 MeV RMS per sample per crystal;
  The intrinsic electronic noise should be lower than the APD leakage current induced noise;
• Timing resolution at the reference energy in the worst case noise and PU scenarios: 30 ps for a 50 GeV energy deposition at the end of HL-LHC with 200 PU events.

A summary table is provided in Table 3.1. The basic architecture of the VFE electronics has been defined according to these specifications.

3.2.1 Amplification scheme

3.2.1.1 Photocurrent shape and amplitude

![Figure 3.1: Scintillation signal from a non-irradiated EB crystal as measured in a test beam with a prototype TIA in 2016 and that expected from simulation.](image)

The light yield of a non-irradiated crystal read out by a twin APD (capsule) at 18 °C was approximately 4.5 p.e./MeV at the beginning of the LHC. Studies performed to estimate the light output of the crystals for HL-LHC are summarized in Fig. 2.4. This includes the effects of crystals ageing under irradiation and the decrease of operating temperature. It is expected that
### Table 3.1: Phase-2 front-end electronics specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Physics</th>
<th>Charge</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$</td>
<td>\eta</td>
<td>= 0$</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>0 fb$^{-1}$</td>
<td>18 °C</td>
<td>9 °C</td>
<td>9 °C (6 °C)</td>
</tr>
<tr>
<td></td>
<td>300 fb$^{-1}$</td>
<td>18 °C</td>
<td>9 °C</td>
<td>9 °C (6 °C)</td>
</tr>
<tr>
<td></td>
<td>4500 fb$^{-1}$</td>
<td>18 °C</td>
<td>9 °C</td>
<td>9 °C (6 °C)</td>
</tr>
<tr>
<td><strong>Crystal light yield</strong></td>
<td>0 fb$^{-1}$</td>
<td>4.5 p.e./MeV</td>
<td>4.5 p.e./MeV</td>
<td>36 fC/GeV</td>
</tr>
<tr>
<td></td>
<td>300 fb$^{-1}$</td>
<td>3.7 p.e./MeV</td>
<td>3.1 p.e./MeV</td>
<td>30 fC/GeV</td>
</tr>
<tr>
<td></td>
<td>4500 fb$^{-1}$</td>
<td>1.8 (1.9) p.e./MeV</td>
<td>1.0 (1.1) p.e./MeV</td>
<td>15 (15) fC/GeV</td>
</tr>
<tr>
<td><strong>Input dynamic range</strong></td>
<td>300 fb$^{-1}$</td>
<td>2 TeV</td>
<td>60 pC</td>
<td>50 pC</td>
</tr>
<tr>
<td></td>
<td>4500 fb$^{-1}$</td>
<td>2 TeV</td>
<td>30 pC</td>
<td>16 pC</td>
</tr>
<tr>
<td><strong>Output dynamic range</strong></td>
<td></td>
<td></td>
<td></td>
<td>1.2 V</td>
</tr>
<tr>
<td><strong>Electronic Gain</strong></td>
<td></td>
<td></td>
<td></td>
<td>3.7 mV/fC</td>
</tr>
<tr>
<td><strong>Shaping/bandwidth</strong></td>
<td></td>
<td></td>
<td></td>
<td>20 ns</td>
</tr>
<tr>
<td><strong>Electronic equivalent input noise</strong></td>
<td>&lt; 80 MeV at HL-LHC start</td>
<td>2.6 fC</td>
<td>170 nA</td>
<td></td>
</tr>
<tr>
<td><strong>APD dark current induced noise</strong></td>
<td>300 fb$^{-1}$</td>
<td>5 $\mu$A</td>
<td>10 $\mu$A</td>
<td>2 fC</td>
</tr>
<tr>
<td></td>
<td>4500 fb$^{-1}$</td>
<td>80 (60) $\mu$A</td>
<td>140 (120) $\mu$A</td>
<td>8 (7) fC</td>
</tr>
<tr>
<td><strong>Average crystal occupancy</strong></td>
<td>200 PU</td>
<td>32 MeV</td>
<td>57 MeV</td>
<td>1.0 fC</td>
</tr>
</tbody>
</table>
there will be 90% of the initial signal amplitude at $|\eta| = 0$ and 75% at $|\eta| = 1.5$ at the beginning of the HL-LHC, and between 50% and 35% respectively of the initial signal at the end of HL-LHC. The working hypothesis for the effective light yield is:

- Between 4.0 ($|\eta| = 0$) and 3.4 ($|\eta| = 1.5$) p.e./MeV at the beginning of HL-LHC;
- Between 2.2 ($|\eta| = 0$) and 1.6 ($|\eta| = 1.5$) p.e./MeV at the end of HL-LHC.

The energy deposition, light emission and transmission in the crystals has been modelled in simulation [29]. This includes both the Cherenkov and scintillation light characteristics [40]. In 2016 an accurate measurement of the photocurrent as a function of time was made at a test beam with prototype trans-impedance amplifiers (TIA) instrumented with discrete components. A trans-impedance amplifier produces, by definition, a voltage signal which is the image of the input current signal. This image is just limited by the bandwidth of the amplifier. This feature makes possible the measurement of the crystal scintillation signal assuming the knowledge of the amplifier bandwidth. The scintillation process parameters of the lead tungstate crystals were tuned by comparing with the testbeam data. Figure 3.1 shows the measured scintillation signal at the output of the TIA superimposed with the expected signal after tuning the simulation parameters. For non-irradiated crystals, the light yield is about 4.5 p.e./MeV. The shape is best reproduced assuming 10% Cherenkov light and a scintillation process with 2 decay times: 100 ns (2% of signal) and 6 ns (98% of signal).

3.2.1.2 APD noise model

Figure 3.2: Measured noise density spectra for two irradiated APDs (red and magenta), superimposed on the expected spectra (blue and cyan) from the SPICE [41] simulation of the electronics used in conjunction with the noise model described in the text. The noise contribution from the electronics alone is displayed in yellow. The results for two different gains are shown. Left, APD gains of 50 (red) and 23 (magenta). Right, APD gains of 49 (red) and 23 (magenta).

When an APD is irradiated, the leakage current increases because of the decrease of the energy gap between junctions. Because of thermal activity, electrons have an increasing probability to jump across the forbidden band to the conduction band. This process mimics the signal generated by a photon absorbed by the photocathode, and generates noise. This process is Poissonian and can be accurately modelled. The expected dark current for APD capsules at the beginning of HL-LHC is expected to be between 5 ($|\eta| = 0$) and 10 ($|\eta| = 1.5$) $\mu$A and between 50 ($|\eta| = 0$) and 100 ($|\eta| = 1.5$) $\mu$A at the end of HL-LHC (3000 fb$^{-1}$). The leakage current of an irradiated APD comprises 90% from the amplification process (bulk current) and 10% from a non amplified process (surface current).
During a time period $\Delta t$, the charge, $Q$, crossing the APD can be written as

$$Q = Q_{\text{surf}} + M \times Q_{\text{bulk}},$$

with $M$ the gain of the APD. The noise generated by the dark current is the fluctuation of charges passing through the APD (shot noise). This fluctuation, $\sigma_Q$, can be expressed as

$$\sigma_Q^2 = Q_{\text{surf}} + M^2 \times F \times Q_{\text{bulk}},$$

where $F$ is the excess noise factor concerning the fluctuations in the amplification process; $F = 2$ for the APDs [42]; $Q$ is the number of electrons. Noting by $\epsilon$ the fraction of the leakage current, $I_{\text{leak}}$, passing across the surface of the APD ($\epsilon \approx 0.1$), the charge noise, $\sigma_Q$, can be written as:

$$\sigma_Q = \sqrt{\Delta t \times I_{\text{leak}} \times q_e \left[ \epsilon + MF(1 - \epsilon) \right]}.$$
Chapter 3. Readout electronics

Figure 3.4: Possible multi-gain scenarios for ECAL front end electronics. Left: Two-gain scenario with gains 1 and 10. Right: Three-gain scenario with gains 1, 6, and 12.

Figure 3.5: Effect of lossy data compression on ECAL overall resolution. Left: Non-linear 12-to-10 bits digital transformation look-up table (LUT), used to compress the ADC data. Right: Overall ECAL resolution after compression.

12-bit sampling ADC. The system with three gains (right) requires a triple 10-bit ADC. In both cases, the quantization noise is negligible with respect to other contributions to the energy resolution. In order to avoid gain switching for photons from precision physics (such as $H \rightarrow \gamma \gamma$ decays), the two gain 12-bit ADC has been chosen as the baseline. For the two gain system, the quantization noise is so small, with respect to the other contributions and especially above 10 GeV, that a compression scheme for the digital data that does not compromise the overall precision of the measurement is possible. Adding a non-linear digital transformation (Fig. 3.5, left) at the output of the ADC can save two bits per sample without any noticeable deterioration of the calorimeter resolution (Fig. 3.5, right). Achieving 30 ps timing resolution for medium energetic electromagnetic objects adds constraints to the digitization process. Figure 3.3 shows the ultimate achievable resolution assuming infinite information about the signal. In this simulation, a 4 Gigasample (GS) per second digitizer has been simulated. Such a sampling rate is not affordable for the 61 200 channels of the EB. However, by using a subset of the raw samples, different sampling rates and sampling phases can be studied. Figure 3.6 shows that 30 ps resolution can be achieved with a sampling rate above 120 MHz. In order to be compatible with the available clock frequencies provided by the GBT chipset, and in order to retain some margin, a sampling frequency of 160 MHz has been chosen for the baseline design.
3.3 Preamplifier design

Two preamplifier designs were considered for the EB upgrade: the Trans-Impedance amplifier (TIA) and the modified version of the legacy charge sensitive preamplifier (MGPA, CSA) [43]. The baseline for EB is the TIA, since it satisfies all of the performance requirements for HL-LHC, and offers better timing resolution. The CSA is also described here as a possible backup solution.

3.3.1 The TIA baseline design

Figure 3.7: Architecture of the front-end electronics with trans-impedance amplifiers.

Figure 3.7 shows a schematic view of the baseline front end electronics architecture. The first amplification stage is a Trans-Impedance Amplifier which is required to correctly handle signals up to 2 TeV. Two gain stages follow the TIA in order to digitize the dynamic range with only two 12-bit ADCs as shown in Fig. 3.4. The ADC architecture, termed LiTE-DTU in subsequent sections, is shown on the right of the figure.

Two studies have been performed to validate the simulations:

- Design and fabrication of a VFE board with a TIA based on discrete components (Operational Amplifiers) to check the basic performance in a test beam before ASIC submission. The board was designed in early 2016 and successfully operated in the CERN H4 test beam in Summer 2016. The main results are summarized in Section 3.3.2.1.
- Design and fabrication of an ASIC fulfilling the specifications described in Section 3.2. The chosen design is based on the “regulated cascode TIA” architecture. A demon-
strator using TSMC 130 nm technology was produced. The design incorporates TIA, Gain 1 and Gain 10 domains on the left of Fig. 3.7. This enabled various design and simulation tools to be validated as well as the architecture choice for the most sensitive parts of the readout line. Multiple options have been implemented in the first silicon die. In particular, two designs were submitted, one using 1.2 V and one using 2.5 V power supply voltages. The latter allows more headroom in the design to optimize the noise and the dynamic range. Results of tests of this first "technology demonstrator” are given in Section 3.3.2.2.

### 3.3.2 Simulation results and technology demonstrators

#### 3.3.2.1 Test beam results with discrete component TIA

![Figure 3.8: Timing resolution function of the noise normalized amplitude obtained at test beam using prototype TIA electronics constructed from discrete components. The performance obtained using 5 GSample/sec and 160 MSample/sec are identical, as expected. A fit with the resolution function $p_0 \oplus \frac{p_1}{\sqrt{N}}$ is represented by the solid blue line.](image)

The timing performance using crystals and APDs has been measured at a test beam with discrete component TIAs. The gain and bandwidth of the discrete TIAs was identical to the ASIC being developed for HL-LHC. The output signals were digitized at 5 GSample/sec using a CAEN V1742 module from which it was possible to simulate any real digitization scenario by taking only one sample out of $n$. Two micro-channel plates (MCP) were put in front of the crystal matrix to provide a reference time stamp for each event. By cross-calibrating both MCPs the resolution of these detectors was measured to be about 20 ps.

Figure 3.8 shows the timing resolution obtained with the test-beam setup, using the full pulse information and using only one sample out of 31 to simulate a 160 MHz sampling rate. Both results are identical as shown in Fig. 3.6. The constant term in the resolution curve is found to be about 20 ps which makes it possible to reach the target of 30 ps resolution for electromagnetic energy depositions of several tens of GeV. This level is reached at a normalized amplitude (amplitude/noise) of 240. This corresponds to an energy deposition of 25 GeV at the beginning of HL-LHC (noise $\approx 100$ MeV) and 50 GeV at the end of HL-LHC (noise $\approx 200$ MeV).

#### 3.3.2.2 Expected and measured ASIC performance

In parallel with the development of the prototype electronics using discrete components, a design of an ASIC has been launched. The goal was to gain confidence with TSMC design and simulation tools as well as to explore the possibility of building a TIA satisfying all the
3.3. Preamplifier design

requirements in terms of noise, dynamic range, linearity and speed requested for HL-LHC running.

A first prototype Calorimeter TIA (CATIA-v0), illustrated by the microphotograph in Fig. 3.9 (left), has been designed and fabricated using the TSMC 130 nm process. This ASIC integrates four TIA channels with different gain architectures and power supply configurations. A TIA channel has a dynamic range from 50 MeV to 2 TeV with two gain outputs, G1 ($\times$1) and G10 ($\times$10), as described in Section 3.2.2. The driver gain stage and filter are external to the chip and defined directly on the test board. The architecture of the TIA is a Regulated Common-Gate (RCG) or Regulated Cascode stage, represented in Fig. 3.9 (right), which offers a reduced input resistance. This is compatible with the high input capacitance (200 pF) providing the high bandwidth required (50 MHz).

The TIA comprises a common-gate stage (transistor M1 polarized by Ip1 current source and load resistance Rc) to which a loop is added containing a voltage amplifier (common-source transistor M2 with active load Ip2). This topology has the effect of dividing the input impedance by this amplifier gain. Thus, it is possible to obtain a low input impedance value of 1 Ω (Fig. 3.10) with the TIA architecture integrated into CATIA ASIC. The TIA trans-impedance gain is obtained with the Rc resistor, whose value must be well defined to achieve the linearity requirement ($\text{INL} < \pm 0.2\%$) at the maximum amplitude of the input current. This linearity is achieved by preventing the M1-M2 stage to work in saturation mode.

A large value for Rc reduces the gain and noise contributions of the two output gain stages that must match to the ADC input dynamic range. The output dynamic range is constrained by the power supply voltage. Two TIA channel designs have been integrated in CATIA using two different power supplies, 1.2 V and 2.5 V. The Rc value is 136 Ω for 1.2 V and 273 Ω for 2.5 V. At 2 TeV, this corresponds to 610 mV and 1220 mV, respectively, as the maximum range for the G1 channel. The same output range is obtained for the G10 channel at 200 GeV. The noise performance has been measured in a laboratory environment and is comparable to the simulation results. Figure 3.11 shows the measured noise density spectrum at the G10 output with the ASIC connected to APDs as in the EB. The simulation result is superimposed.
Chapter 3. Readout electronics

Figure 3.10: Input impedance of CATIA-v0 ASIC.

Figure 3.11: Noise density spectra of CATIA-v0 connected to APDs as in ECAL. In green, without bandwidth limitations, in blue with a low pass filter at 50 MHz and in red the simulation results.

Agreement between both is good and the integral of the spectra, corresponding to the RMS noise, is identical.

A sub-ns laser has been used to measure the single pulse response of the whole acquisition line from the APD through the TIA gain stages. Figure 3.12 shows the response for the gain 1 and gain 10 outputs in the time domain (left) and in the frequency domain (right). The gain 1 and gain 10 outputs provide very similar signals. The $-3\,\text{dB}$ bandwidth limit is 32 MHz for both outputs, as expected. These basic electronic performance characteristics have been used as input for the detector simulation program. The overall performance is detailed in Section 9.

3.3.3 The CSA backup design

The legacy MGPA design is based on a Charge Sensitive Amplifier configuration, with a CR-RC shaper with a time constant of 43 ns. A study has been undertaken to see if the circuit could be adapted to provide good discrimination between scintillation and spike signals, which is not possible with the relatively slow 43 ns shaping. The new circuit also needs to be optimised for higher detector leakage currents. The intention of the investigation is to minimise
3.3. Preamplifier design

Figure 3.12: Signals measured at the output of the G1 and G10 stages with a 50 MHz low pass filter applied (left) when connected to APDs and illuminated with sub-ns laser pulses. The Fourier transform (right) gives the transfer function in the frequency domain from which the −3 dB bandwidth is measured to be 32 MHz.

the changes to the original circuit, and keep the legacy ADC sampling rate of 40 MS/s.

The MGPA design is manufactured using a 250 nm CMOS process which is now on the verge of being obsolete. There are however modern versions of this process that have the option of two gate-oxide thicknesses, a choice of 130 nm or 250 nm design rules. The thicker oxide transistors are very similar in their parameters to the old 250 nm process. The MGPA design has been converted to the new CMOS process, based on the thick-oxide transistors. The new design is known as the MGPA++. It would be possible in theory to convert the circuits to 130 nm design rules, but this would involve significant changes to the circuit architecture because of the lower operating voltage (1.2 V instead of 2.5 V).

The first step in the MGPA++ design is to find the best shaper time constant for noise performance at the higher leakage currents. For 43 ns shaping, noise due to APD leakage current is very high, so it is necessary to reduce the shaper time constant. The optimum for a leakage current of 10 µA was found to be 20 ns shaping, dropping to about 10 ns at 100 µA. The fast 10 ns shaping however would cause difficulty for the ADC sampling, as insufficient points are converted for accurate pulse reconstruction at 40 MS/s. As a result, 20 ns shaping is chosen as a compromise, with enough sample points, but still achieving reasonable noise performance, as the noise varies only slowly as a function of shaper time constant.

The next step involves modeling the difference in the response of the new amplifier to the scintillation and spike signals. The input currents are generated by piecewise linear waveforms derived from mathematical descriptions of the detector signals. The simulation in Fig. 3.13 (left) shows the response to two signals: spike in blue, scintillation in green. The scintillation signal is 5 GeV and the spike is normalised so that the input charge is the same (180 fC). The top trace shows the two currents, with clear differences in the amplitude and timing. However, after the shaper, the difference between the signals is much reduced, so it would be hard to discriminate reliably, particularly for the 40 MS/s conversion speed and in the presence of noise.

The solution is to build a fast analogue channel which takes the output directly from the CSA, before the shaper (Fig. 3.13, right). The CSA has 20 ns CR feedback, which shapes the falling edge of the pulse, but there is no effect on the rising edge. The CSA bandwidth is high enough to capture the fast input current of the spike signal, with a clear difference in the rising edges.
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Figure 3.13: Left: MGPA++ simulation. Spike pulses are in blue, and scintillation pulses are in green. Right: MGPA++ preamplifier, shaper, and differentiator arrangement.

of the two signals. However, if the CSA were to be sampled directly, this difference would be difficult to see in the converted signal, as the voltage difference is significant only for about 15 ns. What is needed is a voltage difference on the timescale of many tens of ns. This can be achieved with a combination of a CR differentiator (5 ns time constant) and a peak-hold circuit. The spike signal now has about twice the magnitude of the scintillation signal, over an extended period (Fig. 3.13 bottom trace). The recovery time is controlled by a baseline restoration circuit within the peak-hold, and can be adjusted over a wide range. Slower recovery is better for multiple sampling, but this increases dead time as the peak-hold will not respond to small signals until it has recovered close to the baseline.

It is important to understand the effect of noise on the spike/scintillation discrimination as this determines the lower limit for the usable range. Figure 3.14 shows the results of transient noise analysis, with ten spike waveforms and ten scintillation waveforms superposed in order to demonstrate the spread. The simulation model includes the detector shot noise for a leakage of 100 $\mu$A. The shaper output shows why it is difficult to distinguish between spike and scintillation pulses of the same charge, as the noise causes overlap of the two sets of waveforms. However, the peak-hold outputs are clearly resolved, so a measurement of the ratio of the peak-hold to shaper outputs can provide accurate spike discrimination.

If the energy is reduced to 2 GeV, the discrimination works reasonably well up to about 10 $\mu$A leakage. Figure 3.15 shows histograms of the peak-hold/shaper ratio for 800 noise simulations, with the ratio for spikes (blue columns) roughly twice the one for scintillation signals (green). At 100 $\mu$A, about 5% of signals are wrongly identified, assuming the decision threshold is set in the middle of the overlapping histogram region.

Another important parameter in the MGPA++ analysis is the timing accuracy for the pulse reconstruction. Transient noise simulations are used to generate large data sets which are then fitted to a noise-free reference waveform by sweeping the timing and scaling of the waveforms, searching for the least-square error. The results in Fig. 3.16 show that the timing accuracy depends somewhat on the position of the sample points over the 25 ns interval. If the shaper output is sampled at its peak (offset = 0) the accuracy varies from 20 to 80 ps over the range of leakage from 0 to 100 $\mu$A. The accuracy is worse for an offset of 15 to 20 ns, as the sample points do not capture the waveform during its fastest transitions.

The same analysis is repeated for the peak-hold output, showing a huge variation in the timing
3.3. Preamplifier design

Figure 3.14: Spike/scintillation pulse comparison at 5 GeV, 100 µA detector leakage current. Left: peak-hold output. Right: shaper output.

Figure 3.15: Peak-hold/shaper ratios for spikes and scintillation pulses at 2 GeV, for 0, 10, 100 µA detector leakage currents.

Accuracy. When sampling captures the fast rising edge (13–23 ns offset), the accuracy is \( \sim 25–45 \) ps over the range of leakage currents. This is considered better than the shaper for the higher leakage currents. It would be possible in theory to combine the statistical timing analyses of the shaper and peak-hold to give a wider range of more accurate timing over the full 25 ns period.

There is one other issue which has been considered in the investigation, relating to the analogue output data volume. The analysis so far has assumed full read-out of the shaper and peak-hold outputs, so the software has multiple data points on both signals. Statistical techniques can then be applied to generate the best estimates for both signal amplitudes. Comparing the two amplitudes gives the most accurate spike/scintillation discrimination. An alternative approach is to make the amplitude comparison directly, within the MGPA++, generating a digital flag to indicate a spike signal. This avoids the need to convert the peak-hold output, thereby halving the ADC data volume. The flag output would need to be transmitted to the data acquisition system, but this is a small overhead.
Chapter 3. Readout electronics

This approach is found to be effective, but only over a narrow range of signal amplitudes. The problem arises within the baseline restoration circuit in its current form, as the pulse shape varies with amplitude. The restoration is a non-linear function, with slower recovery for the larger signals. The peak-hold/shaper amplitude ratio is roughly a factor of two larger for the spikes than for scintillation pulses. This is easy to resolve in software with multiple sample points, as shown in Fig. 3.15. However, the peaks occur at different times, and the ratio of the pulses is not maintained during the recovery period. An analogue comparator can be set up to look for a particular amplitude ratio, but this does not trigger reliably with different amplitudes and timings during the recovery period.

The outcome is that on-chip spike discrimination is not achievable to a sufficient level of accuracy with the existing restoration circuit and a simple analogue comparator. New circuits would need to be developed to improve the consistency of the pulse height comparison. This work is outside the scope of the current investigation, but remains an option for the future. The software approach would be expected to give better results than on-chip spike discrimination because of the availability of multiple sample points and the option of statistical processing for pulse height estimation. The proposal for the MGPA++ is therefore to stay with software discrimination, based on sampling both the shaper and peak-hold.

In summary, the MGPA++ investigation shows that the original MGPA design has the potential to be developed for spike/scintillation discrimination with the ADC sample rate of 40 MS/s. The additional differentiator circuitry provides the fast impulse response required to identify the spikes. The peak-hold/baseline restoration circuit acts as a pulse stretcher which ensures that multiple samples of the peak-hold can be captured at 40 MS/s, along with the shaper output, thereby enabling the accurate pulse reconstruction necessary for spike versus scintillation discrimination over a wide range of energies.

3.4 ADC and LiTE-DTU design

In the proposed electronic readout chain, the preamplifier ASIC is followed by a data conversion and transmission ASIC, named LiTE-DTU. The LiTE-DTU will receive the two analog signals from the preamplifier outputs (corresponding to the two gains) and will convert them
3.4. ADC and LiTE-DTU design

to a digital representation of the pulse, via voltage sampling. For each sampling period, either the high or the low gain samples will be selected and sent to a high-speed serial data link based on the lpGBT [14] e-link protocol. More than 99% of the events can be codified in 6–7 bits. A lossless data compression scheme will be applied in order to reduce the data output bandwidth.

3.4.1 Overview and requirements

The LiTE-DTU comprises three main units: the ADC, the data selection and compression logic, and the serializer. The ADC is the key component of the LiTE-DTU. It is required to provide 12 bit resolution in order to cover the range up to 200 GeV with 50 MeV resolution for the high gain preamplifier output, and up to 2 TeV with 500 MeV resolution for the low gain output. The requested sampling frequency is 160 MS/s in order to separate signals generated in the crystal from spikes. The possibility to reduce the sampling frequency to 120 MS/s is currently under evaluation. This option would relax the requirements on the ADC and the data transmission. On the other hand, it would require a separate clock line or an on-chip phase locked loop (PLL) in order to provide the sampling clock. Table 3.2 summarises the ADC requirements.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Minimum</th>
<th>Typical</th>
<th>Maximum</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling frequency</td>
<td>160</td>
<td></td>
<td></td>
<td>MS/s</td>
</tr>
<tr>
<td>Resolution</td>
<td>12</td>
<td></td>
<td></td>
<td>bit</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>1.08</td>
<td>1.2</td>
<td>1.32</td>
<td>V</td>
</tr>
<tr>
<td>Differential input range</td>
<td>±500</td>
<td></td>
<td></td>
<td>mV</td>
</tr>
<tr>
<td>Analogue input bandwidth</td>
<td>70</td>
<td>80</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Slew rate</td>
<td>100</td>
<td></td>
<td></td>
<td>V/µs</td>
</tr>
<tr>
<td>Sampling clock jitter</td>
<td>2</td>
<td>5</td>
<td></td>
<td>ps</td>
</tr>
<tr>
<td>Power consumption</td>
<td>25</td>
<td>30</td>
<td></td>
<td>mW</td>
</tr>
<tr>
<td>Temperature range</td>
<td>−20</td>
<td>8</td>
<td>85</td>
<td>°C</td>
</tr>
<tr>
<td>INL</td>
<td>1</td>
<td>1.5</td>
<td></td>
<td>LSB</td>
</tr>
<tr>
<td>DNL</td>
<td>0.5</td>
<td>0.9</td>
<td></td>
<td>LSB</td>
</tr>
<tr>
<td>ENOB</td>
<td>10.2</td>
<td></td>
<td></td>
<td>bit</td>
</tr>
<tr>
<td>SNDR</td>
<td>63</td>
<td></td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Latency</td>
<td>10</td>
<td></td>
<td></td>
<td>Clock cycles</td>
</tr>
<tr>
<td>Calibration time</td>
<td>100</td>
<td></td>
<td></td>
<td>µs</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS 65 nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation tolerance (TID)</td>
<td>100</td>
<td></td>
<td></td>
<td>kGy</td>
</tr>
<tr>
<td>SEU cross section</td>
<td>15 (tbc)</td>
<td></td>
<td></td>
<td>MeV cm²/mg</td>
</tr>
</tbody>
</table>

The data selection and compression logic receives two streams of 12-bit data at 160 MHz and controls the output serializers. The unit selects data from the ADC connected to the high gain input, unless the current sample or at least one of the samples in a time window around the current sample is saturated. In this case it selects the data from the low gain input. This feature ensures that all samples belonging to the same particle signal are sent out with the same gain. A separate bit is added in order to specify whether the sample is from high or low gain. A lossless compression algorithm (see Section 3.4.3) can provide a significant data reduction and thus decrease by more than 40% the number of optical fibers required for data output. The serializer is based on the e-link protocol of the lpGBT. The lpGBT can provide 28, 14 or 7 links at 320, 640 or 1280 Mb/s for a total data rate of 8.96 Gb/s out of a line rate of 10.24 Gb/s.
The lpGBT provides three I2C interfaces that can be used to upload/download configuration information.

### 3.4.2 Architecture and layout

The ADC design will be purchased from an external company which will provide the circuit design block for integration into the overall LiTE-DTU circuit design. The design will be based on the successive approximation architecture and will be implemented in CMOS 65 nm technology. The selected technology is not sufficiently fast to achieve a single ADC with the requested performance. Therefore a two core, 80 MS/s, time interleaved architecture will be used. The ADC block will have differential inputs with 1 V differential dynamic range and will make use of a background calibration procedure to achieve the required performance in terms of differential non-linearity (DNL), integral non-linearity (INL) and the effective number of bits (ENOB).

The ENOB value was chosen such that the noise contribution from the ADC is at the level of the LSB (50 MeV). The INL and DNL requirements are typical of modern ADCs. It is foreseen to integrate a charge injection system into the TIA with the purpose of calibrating the linearity of the electronics chain. If this is successful, the requirements on INL and DNL could be reduced. From physics considerations, a non-linearity of about 0.1% over the full dynamic range would be sufficient (i.e. for measuring the invariant mass of potential high-mass resonances).

The ADC will use a single 1.2 V power supply. In addition it requires a precise reference voltage, which can be generated either from a clean 1.2 V external voltage or internally using the radiation tolerant bandgap being developed at CERN. A very low jitter clock (below 5 ps RMS) must be provided to the ADC in order to maintain the ENOB performance. However, since the data analysis is performed on multiple samples, this requirement could be relaxed to around 15 ps.

The ADC core will be designed with special attention to radiation tolerance issues. All p-channel metal oxide semiconductor field-effect transistors (pMOS) will have a channel width of at least three times the minimum value allowed by the process and no thick oxide transistors will be used. The band gap reference circuit, if needed, will be taken from the radiation-proven CERN library. For single event upset (SEU), only the calibration logic and the table holding the internally generated calibration constants will be protected with triple modular redundancy (TMR) and self correction. An SEU in the successive approximation register (SAR) logic or in the ADC nodes would affect only the current sample.

A simplified schematic of the LiTE-DTU ASIC is shown in Fig. 3.17. The two ADC cores continuously send samples to two first in first out buffers (FIFOs), which are used to implement the sample selection algorithm with look-ahead capability. The stream of selected data samples is then encoded in variable length words in order to perform lossless compression. The data are organized in frames divided by a frame delimiter. A synchronization packet is inserted at the start of each run, and whenever no data are available, in order to keep synchronization with the lpGBT ports.

The formatted data are inserted into two FIFOs, that are used to interface with the high speed serializer. The serializer controller continuously reads the FIFOs and transmits the data, thus minimizing the high speed logic. The serial link speed will be chosen as a trade-off between the number of interconnections between VFE and FE and the possible issues to preserve a sufficient signal integrity at high data rates. A data rate of 640 Mb/s could be a reasonable compromise given the short distance between the boards and the relaxed constraints (with respect to the
tracker detectors) in terms of cable mass.

### 3.4.3 Data rates, data compression schemes

The data rates are summarized in Table 3.3. Since no zero suppression is foreseen in the VFE-FE section, the volume of data to be transmitted is large. A minimum number of lpGBT ASICs that are required on the FE board is six, assuming no data compression. However, to have a better match with the VFE modularity, seven lpGBT would probably be required.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channels per VFE board</td>
<td>5</td>
</tr>
<tr>
<td>VFE boards per FE board</td>
<td>5</td>
</tr>
<tr>
<td>ADC sampling rate</td>
<td>160 MS/s</td>
</tr>
<tr>
<td>Bits per sample</td>
<td>12+1</td>
</tr>
<tr>
<td>Data rate/ADC</td>
<td>2.08 Gb/s</td>
</tr>
<tr>
<td>Data rate/VFE</td>
<td>10.4 Gb/s</td>
</tr>
<tr>
<td>Data rate/FE</td>
<td>52 Gb/s</td>
</tr>
</tbody>
</table>

Simulation studies show that the probability of an event with more than 6 bits is below $2.4 \times 10^{-4}$. The data rate can thus be significantly reduced by applying a lossless encoding (e.g. Huffman coding). A possible implementation of Huffman coding is shown in Fig. 3.18. It is based on 32 bit and 16 bit data words in order to keep byte alignment. In this scheme samples with fewer than 7 bits ("baseline samples") are packed in groups of 5 in a 32 bit word, thus reducing the data rate per ADC from 2.08 Gb/s to 1.024 Gb/s. An extra 1.9 Mb/s must be added for samples exceeding the 6 bit limit ("signal samples"), and for baseline samples close to a signal sample such that the 5 samples packet cannot be filled. With an estimated protocol overhead of 50 Mb/s, the overall data rate will be 1.08 Gb/s. A frame delimiter is inserted at
Chapter 3. Readout electronics

periodic intervals in order to keep packet synchronization. A cyclic redundancy check (CRC12) error detection code is included to detect errors in the data. A 16 bit idle packet with a clock-like pattern is introduced in order to keep synchronization. Such a data reduction would be especially suitable for the VFE-FE interface since it would allow a direct connection between the LiTE-DTU output and a single 1.28 Gb/s (or two 640 Mb/s) e-link, as shown in Fig. 3.21. This architecture would reduce the number of lpGBT from six to four, with a simple mapping between input channels and e-link ports. On the other hand, three 1.28 Gb/s links would be left unused.

### 3.5 VFE board design

The VFE card will have five readout channels, each comprising one TIA and one 160 MHz ADC per output gain. The VFE card will connect to the Motherboard via a Samtec® connector (IPT1-125-01-S-D-RA-PL). This connector carries the five APD input signals, the APD temperature sensor signal and two power supplies: one for TIA and one for ADC power. The card also connects to the FE board, for transmission of the digitized and serialized data. The FE board provides the clock for the ADC and a Low Voltage Differential Signalling (LVDS) interface for the configuration and control of the ASICs to the VFE card.

The mechanical dimensions of the VFE card are identical to the legacy VFE. The components on the VFE card will be covered with an anodised aluminum housing, providing a thermal interface between the components and the cooling bars in the supermodules. For this purpose the gap between the components and the housing will be filled with a thermal conducting gap filling material such as Gap Filler 2000 (Bergquist). A soft thermal conducting pad such as DS-GAP-AS45-2.5 (DREYER SYSTEM GmbH) will be glued to the outside of the aluminium housing in order to ensure good thermal contact with the cooling bars. This approach is identical to that presently implemented in the legacy system. A total of 12 240 VFE cards are needed. They will all undergo a full functional test and, if required, a calibration of the TIA gains.

The production will proceed in two steps:

- Fabrication of a pre-production of 500 pieces, and validation of the cards in the spare supermodule SM36;
- Production of the total amount in batches of 500 cards per week.
3.6 Switching low voltage regulator board design

Each batch will undergo a qualification procedure prior to adding the housing, comprising:

- Full functional test (1 week);
- Burn in/ageing procedure (1 week);
- Calibration (1 week).

The production of the 14 000 VFE cards, including spares, will last about seven months. The completed and tested cards will be available one year prior to the start of the re-integration operation. The burn in and ageing procedures will be carefully defined in due course. A small set of pre-production cards will be used to perform power and thermal cycling in order to identify a reasonable testing procedure prior to the start of production. A dedicated test setup for the functional test will be developed and at least three copies built. The setup will provide a precise test pulse signal, to carry out VFE calibration. One setup will be used at the manufacturer to validate production on the spot. The other two test stands will serve for functional tests and calibration.

Figure 3.19: Left: Prototype VFE card for Phase-2 with a discrete implementation of the TIA and a commercial 160 MS/s, 14 bit ADC. Right: Housing for the prototype VFE card, with the gap pad material attached.

3.6 Switching low voltage regulator board design

The switching low voltage regulator board (SLVR) provides power to five VFE cards and to the FE card. The VFE cards will require two voltages, 2.5 V and 1.2 V for powering the TIA and ADC ASICs, respectively. The FE card will require 2.5 V and 1.2 V. If the slow link controller (GBT-SCA) chip (Section 3.7) is used in the FE it requires 1.5 V.

The SLVR will implement a step down conversion from 10 V to the required voltages through the FEAST ASIC [16, 44] using the FEASTMP_CLP module developed by CERN. Six such modules can be hosted on a SLVR card which has the same dimensions as the legacy LVR. A prototype SLVR card capable of powering the presently installed VFE and FE electronics was developed and tested inside SM36. The performance measured with respect to noise (sigma of the pedestal) is identical to that obtained with the legacy LVR cards. It has a redundant power input and enable input. The card features an aluminum housing that couples to the thermal pad of the FEASTMP_CLP modules and to the cooling bars. Because of the thickness of the FEASTMP_CLP modules, the SLVR card has six openings to let the FEASTMP_CLP module...
housing pass to the other side of the PCB. In this way the assembly, including the housing, fits into the available space. Figure 3.20 shows an image of the prototype SLVR card mounted onto its housing.

Figure 3.20: Prototype SLVR card housing six FEASTMP_CLP modules, mounted to its housing.

An SLVR card with the step-down converter ASICs implemented directly in the SLVR board together with a different inductor coil design is under evaluation. A reduction both in the footprint and in the height of each individual step down converter is expected with this layout, potentially allowing for more step down converters on the SLVR card if required. This would probably lead to a more robust design and a total cost reduction.

The power consumption per trigger tower (25 readout channels) is presently around 34 W, with an output voltage of 2.5 V, corresponding to a current of 13.6 A. The new electronics will consume a comparable amount of power. With an efficiency of the step-down converters of 85% the required input power will be about 40 W, corresponding to 4 A at an input voltage of 10 V. This corresponds to an important reduction of the supply current by a factor 3.4. This will allow for a reduction in supply cable cross section for the cables running between the bulk power supplies on the balconies and the supermodules and/or a decrease of losses in the power cable itself. The largest advantage is that it makes the re-cabling work, particularly in the 53 degree crack between barrel and endcap detectors, easier.

A total of 2448 SLVR cards are needed. They will undergo a full functional test. A pre-production of about 100 cards will be produced and tested inside SM36. A small number of cards will undergo power and thermal cycling in order to define reasonable burn in testing procedures for production. The full production will be organized into 5 to 6 batches delivered at a rate of one batch per month. This will allow matching of board production rate with burn-in and testing capacity.

3.7 FE Readout/Clock/Optical links

The on-detector electronics will follow the current ECAL front-end 5 × 5 crystal tower structure. The new FE board will serve five VFE cards as in the legacy system. The major functions of the FE board are:

- Receive and distribute clock and control information to the front end system;
- Receive the 25 channel data streams from the five VFEs;
3.7. FE Readout/Clock/Optical links

- Convert the data to serial data streams and transmit these off-detector via optical links.

The VFE ADC will operate at 160 MHz and deliver 13 bits of information per channel per 160 MHz clock cycle. This will yield a 2.08 Gb/s data flow per channel corresponding to 10.4 Gb/s per VFE card and thus 52 Gb/s per FE card. The maximum data rate for one lpGBT ASIC running at 10.24 GHz is 8.96 Gb/s. The full uncompressed data transmission will thus require a minimum of six lpGBT chips per FE card. With a lossless compression the data rate can be reduced to 1.024 Gb/s per channel, 5.12 Gb/s per VFE card, and 25.6 Gb/s per FE card, respectively. The baseline configuration is a VFE system with lossless compression connected to the FE with four lpGBT ASICs.

The optical data transmission will be performed by Versatile Link (VL+) assemblies which are capable of operating at 10 Gb/s for transmission and 5 Gb/s for reception. A 4Tx & 1Rx assembly (four transmitters and one receiver) is required. The FE card will receive data from the LiTE-DTUs in the VFE cards via serial e-links. The possible e-link data rates are defined by the lpGBT design and are 320 / 640 / 1280 Mb/s. The single ADC data flow for the baseline option, 1.024 Gb/s can be covered by 4 / 2 / 1 e-links, respectively. The e-link is a simple serial link without encoding or error protection. Therefore, a lower data rate is advantageous. The lower data rate option could provide some level of redundancy in the LiTE-DTU to lpGBT connection. Each of four LiTE-DTU outputs is connected to a different lpGBT. In this case each lpGBT chip will have one e-link from each LiTE-DTU from five VFE cards, requiring 25 links in total. In case of an optical link failure, one of every fourth sample from each ADC will be lost, which can be recovered by appropriate approximation from the adjacent samples. The down-link control data will be transmitted via one optical down link of one lpGBT providing four I2C links. The I2C requirements are:

- One I2C master for the slave lpGBT chips on the FE card;
- One I2C master for the VFE card chip;
- One I2C master for the VL+ optical components.

If the three I2C masters foreseen in the lpGBT ASIC is insufficient a fan-out chip or an additional GBT-SCA (Slow Control Adapter) ASIC will be added. The GBT-SCA ASIC is a slow link controller and is part of the currently available GBT chipset and is designed to be compatible with the lpGBT. The GBT-SCA is manufactured in a 130 nm process and requires an additional 1.5 V power supply. A possible layout of the FE card, for the baseline with lossless compression, is shown in Fig. 3.21. The FE card dimension, defined by the legacy tower structure, is 114 mm x 104 mm. This size is sufficient to place all components including the two 50 pin ERNI connectors used in the legacy system. The VFE to FE e-link connections are also included in the figure.

3.7.1 Clock distribution, control, and monitoring

Test beam results performed in 2016 with discrete (TIA) VFE components have shown that a precision of 30 ps can be achieved for an amplitude to noise ratio of 250 corresponding to 25 GeV with 100 MeV noise (HL-LHC start) and 60 GeV with 240 MeV noise (HL-LHC end). The requirement for the clock distribution system is that it should not contribute significantly to the timing measurement uncertainty of the system. The target performance for the EB upgrade is a clock distribution system with a stability better than 10 ps. This implies that both the jitter and phase stability (skew) must be maintained below this level during transmission across the detector and over long LHC running periods.
Chapter 3. Readout electronics

Figure 3.21: Data transfer in the front end system

The existing clock distribution provided by the LHC, called the timing and trigger control (TTC) system, exhibits good performance of RMS jitter according to studies conducted at CERN. The current RF clock delivered by the LHC machine is specified with a 9 ps RMS jitter. Its future evolution using the lpGBT and a possible application of a passive optical network (PON) may provide even better performance.

The legacy trigger control and timing distribution system (TCDS) takes the TTC clock and distributes it to the subdetectors. It has been shown not to degrade the jitter performance of the TTC but the long term phase stability is not well-measured and it was not designed for precision timing applications at the level required. The TCDS will be upgraded for the HL-LHC. The R&D on precision clock distribution for the upgraded TCDS considers two options. The baseline is a tree of encoded clock paths. This should guarantee low jitter at the end leaves of the distribution tree, but with an uncertainty on the phase between the leaves. It is necessary to understand whether the low jitter can actually be achieved, or whether cleaning of the clock with phase locked loops (PLLs) is necessary. It must also be determined whether the phase difference can be controlled or at least monitored to the required precision. The alternate solution is to use a tree of separate clock paths if the encoded clock tree does not achieve the required performance.

If clock cleaning is required, it may be necessary to use radiation hard PLLs in the front end electronics to be deployed after the lpGBT ASIC. The jitter will be determined by the last PLL in
3.8 EB off-detector readout

3.8.1 Overview

The legacy off-detector electronics cannot sustain the expected high Level-1 rate of 750 kHz foreseen for Phase-2, nor provide the required trigger latency of 12.5 $\mu$s, and will be replaced. The upgraded off-detector electronics will accommodate higher data transfer rates, shift the trigger primitive generation off-detector and provide the increased latency needed to comply with L1 trigger upgrade requirements. Commercially-available FPGAs will be employed. A processor board called the Barrel Calorimeter Processor (BCP) will be designed with these FPGAs and high speed optical links. It will be designed to the ATCA [12] standard. The BCP must have a powerful FPGA to analyze the received data and transmit to the Level-1 trigger a pre-processed set of trigger primitives. It must provide the clock and control to the FE board, and also interface with the DAQ. The algorithms required to be implemented in this board include:

- Rejection of anomalous APD signals (spikes);
Chapter 3. Readout electronics

Figure 3.22: Patch box used to organize optical fibers inside supermodules.

- Conversion of digitized pulse data into transverse energy;
- Basic clustering of localised energy;
- Formation of the trigger primitives;
- Generation of clock and control signals to the FE.

A more detailed description of the processing functions performed by the legacy trigger system can be found in Refs. [26, 45].

3.8.2 The BCP requirements

Figure 1.2 shows the data connections from an ECAL tower (5 × 5 crystals) to the off-detector electronics. The off-detector electronics receives and buffers data from the detector front-end cards and implements functions for data integrity checks and alignment of event data to beam crossings. A trigger concentrator function generates the trigger primitives for the Level-1 trigger. A data concentrator block provides the Level-1 trigger latency data buffers and the status of the buffers. Zero suppression and selective readout functions can be implemented if necessary but are not being considered in the baseline design. Data are transmitted to the DAQ following the acceptance of an event by the Level-1 trigger. The off-detector electronics functions will all be consolidated into the BCP board.
The high Level-1 trigger rate (750 kHz), large Level-1 latency (12.5 µs or 500 beam crossings), and increased granularity of trigger information required for LHC Phase-2 require moving the trigger primitive generation from the FE (as it was in the past) to the back-end electronics. The basic functions of the trigger primitives are: the transformation of the input scale from the FE to a transverse energy scale; the digital filtering of the detector signals to extract the transverse energy and the bunch crossing time information.

In order to minimize the contamination from pileup to the trigger primitives, algorithms are being developed that make use of the single crystal information that will now be available to the off-detector processors. Two options are currently being considered: a trigger primitive per crystal and a trigger primitive made out of a cluster of crystals. The single crystal option would guarantee the highest granularity and flexibility for successive clustering in the Level-1 processor, and correlation with other sub-detectors. The cluster option would still ensure high granularity with some pre-processing performed on the BCP. This would significantly reduce the amount of data transferred from the BCP to the Level-1 processor and the number of output links. The architecture described in the next section is flexible enough to accommodate both options.

3.8.3 The BCP architecture and interfaces

Two interfaces must be defined: between the EB front-end and the BCP, and between the BCP and the Level-1 processors. The FE card collects data from each 5 × 5 crystal matrix at a sampling frequency of 160 MHz (Fig. 3.24). Twelve such towers are connected to each of two FPGAs in the BCP via 48 upstream links and 12 downstream control links. The towers are arranged in a 3η × 4φ configuration, comprising 300 crystals, equivalent to a 0.26 × 0.35 (η, φ) region. The interface between the FE and the BCP is shown in Fig. 3.25. The architecture can be made to share boundary data between regions of the detector connected to the same BCP. Sharing will be necessary if the clustering option is chosen. Sharing may also be needed if additional spike removal algorithms are needed after the signal shape analysis. A total of 216 FPGAs will be needed to cover the whole EB, two per ATCA board for a total of 108 BCPs. These will be housed in 9 crates as shown in Fig. 3.26. Each crate will receive data from a 40 degrees φ sector (two supermodules) of the detector and covering both EB+ and EB−.

The interface between the EB back-end cards and the Level-1 processors is shown in Fig. 3.27. The baseline working option is that a 16-bit trigger primitive per single crystal will be sent to the Level-1 trigger. The data transfer between each FPGA and the Level-1 processor will go through fifteen high-speed 16 Gb/s links, a link every 20 crystals, corresponding to a (4φ × 5η) sector. A total of 3060 links will cover the whole EB, i.e. 61200/20. As a result, 36 FPGAs will
Figure 3.24: General overview of the FE-BCP-L1 chain. The trigger concentrator function (TCC) generates the trigger primitives for the Level-1 trigger. A data concentrator block (DCC) provides the Level-1 trigger latency data buffers and the status of the buffers. The clock and control system (CCS) distributes clock and control signals to the front-end electronics.

Figure 3.25: FE to BCP interface. Each of two FPGAs in the BCP receives data from a region made of 20 crystals in $\phi$ and 15 crystals in $\eta$, comprising 12 front-end towers. Each tower requires four upstream and one downstream lpGBT links.
Figure 3.26: Mapping between the whole EB and the back-end crate. The upper part of the picture shows the 18 EB supermodules (horizontal axis) with both EB+ and EB− (vertical axis). Data from four supermodules (40 degrees in φ, positive and negative sides) will be processed by 12 ATCA boards housing two FPGAs each, as shown in the bottom part of the picture. A total of 9 back-end crates will cover the whole EB.
Figure 3.27: BCP to Level-1 interface. Each BCP card will include 2 FPGAs. Each FPGA will process data from 12 towers. A total of fifteen 16 Gb/s links will exist between the FPGA and the Level-1 trigger. A total of 216 FPGAs, two per BCP card, will serve the whole EB for a total of 3060 links.

have only 10 links. Each link will carry a total of 384 bits per bunch-crossing, 320 of which are used for crystal trigger primitives and 32 bits for protocol header, cyclic redundancy check (CRC), and possible additional metadata.

Upon generation, the trigger primitives will be directly forwarded to the Level-1 processor at 40 MHz. The latency estimated today from a preliminary estimate of the trigger primitive processing time is 40 bunch crossings. It will change in the future when detailed studies of the algorithm implementation will be done and the final decompression scheme chosen. The data format for a trigger primitive formed from a cluster of crystals is being studied. At present this amounts to 40 bits per cluster. Studies are ongoing to optimize the balance between bandwidth and granularity.

A third required interface is between the BCP and the DAQ. The number of links is determined by the data event size output from each FPGA. The event size is given by the total amount of data arriving from the front-end plus the size of the trigger primitive data. In addition to being transmitted to the Level-1 processors, the trigger data needs to be saved in the DAQ data stream. Each front-end 5 × 5 tower provides 224 bits per optical link for a total of 896 bits over the four links. Twelve towers are served by one FPGA, which gives a total of 10752 bits per bunch crossing. The readout over five bunch crossing leads to a total size of 53760 bits. If the data is sent to the DAQ with the same oversampling frequency as applied on the FE (at 160 MHz), this number needs to be multiplied by four. The contribution to the event size due to the trigger primitive, in the single crystal option, amounts to 16 bits/crystal × 25 crystals/tower × 12 towers/FPGA for a total of 4800 bits per bunch crossing. The total size is about 8 kb per FPGA, which implies the need of four 16Gb/s (one QUAD) to send the event to the DAQ (DAQ payload needed at ∼ 1 MHz Level-1 trigger rate gives ∼ 59 Gb/s). The total EB event size is about 1.6 MB.
3.8.4 The BCP demonstrator

Figure 3.28 shows the BCP demonstrator card, based on the ATCA format. It is intended to:

- Design and validate the VHDL logic of the algorithms involved, of the infrastructure and control, of the monitoring blocks, and the serializer/deserialiser (SERDES) blocks.
- Evaluate the BCP design for high bandwidth links, sufficient and stable powering, control functions using a Linux operating system integrated in the board, cooling and sensor reading tests.
- Implement the three main functions: trigger concentration, data concentration, and clock and control.
- Provide a flexible system capable to be used also in the HCAL barrel calorimeter.

The demonstrator card will be designed according to the ATCA specification and will support the required technical needs of the EB and HB detectors. The demonstrator shown here will house one FPGA. The processing capability is provided by a Xilinx UltraScale FPGA in a B2104 package. Xilinx provides many pin-compatible parts in this package with varying amounts of logic and serial links: Kintex, Virtex and Virtex+. The package provides at least 64 serial links in each direction, of which 56 would be available for data I/Os and 8 for DAQ and TCDS services.

As shown in Fig. 3.28, the FPGA serial links are supported by optical modules capable to run at 14 Gb/s or 16 Gb/s. The “firefly” modules from SAMTEC provide the flexibility to be easily replaced and upgraded. For DAQ and TCDS, quad and single fiber modules will be placed in the card. A mezzanine board will support additional links hosting eight single fiber connectors for monitoring and debugging. The mezzanine will connect standard pins of the FPGA capable of 1.2 Gb/s transmission to the connections. The clocking infrastructure will be supported by low-jitter clock generators and jitter cleaner devices as well as from an elegant distribution of the clock to the FPGA via Xpoint components. The card would be able to function using a clock recovered by the data stream from the TCDS link (essentially the LHC clock) or generated by the board itself and run in standalone mode. The card will have connectors for testing and additional clock purposes. The powering will be done by switching regulators that will convert the power given by the ATCA backplane to all ATCA hardware needs.

There will be two mezzanines with Xilinx ZYNQ FPGAs. One will perform the board control functions and request power from the crate according to the ATCA specifications; the second, so-called Embedded Linux Mezzanine (ELM), will host the Linux operating system and will control the board. The ELM is based on a legacy µTCA card used in the first layer of the calorimeter trigger after the Phase-1 upgrade [46]. The ELM will act as the master of the board. All other components of the card as well as the FPGA would be directly connected to it as slaves. The ELM provides standard connectivity interfaces and, since it hosts a Linux environment, it is possible to monitor and control the card during operations.

3.8.5 The BCP firmware and rate estimates

In the first option, a trigger primitive is generated for each crystal. The primitive is a sixteen bit word. Ten bits are used for encoding the transverse energy, one bit is for encoding the spike flagging decision and five bits are for encoding the high resolution time information (providing a resolution of 60 ps over a range of 2 ns around the bunch crossing of the triggered
event). At this preliminary stage the LSB for the transverse energy is 125 MeV. This corresponds to 979,200 bits per bunch crossing which corresponds to a rate of 39,168 Gb/s assuming no zero suppression. Figure 3.29 shows the multiplicity per event of crystal trigger primitives for different $E_T$ thresholds as measured in a simulated sample of Zero Bias events with an average pileup of 200 events and EB ageing conditions corresponding to 1000 fb$^{-1}$ integrated luminosity.

In the second option, a trigger primitive is generated from a cluster of crystals. The primitive is a forty bit word, of which ten are used for encoding the transverse energy, one bit is for encoding the spike flagging, five bits for the timing, sixteen bits for the ($\eta, \phi$) position of the cluster, and eight bits for the number of crystals that are included in the cluster. The number of clusters per event with several $E_T$ thresholds was estimated in the same simulated sample as above. The standard CMS software reconstruction was used and the clusters used for the plot are the variable-size basic clusters used as input to the Run-1 ECAL superclustering algorithm. If no lower threshold is applied to the transverse energy of the clusters, the number of objects is $O(500)$, shown in Fig. 3.30. This rate depends on the noise injected in the simulated sample used for this study which is about 120 MeV at $\eta = 0$ and about 170 MeV at $\eta = 1.45$. A higher noise would lead to a larger number of clusters. The total amount of output data for this option would be 40 kb per bunch crossing, equivalent to 1600 Gb/s. Additionally a second set of trigger primitives would contain energy sums from all $5 \times 5$ crystal regions, to account for unclustered energy to use in jet energy sums and in pileup subtraction algorithms. These would be sixteen bit trigger primitives which, with 2448 towers, would amount to additional 39,168 bits per bunch crossing equivalent to 1566 Gb/s.

Tables 3.4, 3.5, and 3.6 summarize the two options for the trigger primitive definition as well as the expected bandwidth required towards Level-1.

The spikes will identified in the BCP based on the signal shape analysis and isolation. It is then possible to not send the corresponding trigger primitive (if single crystal) or not use the crystal in a given clustering algorithm. The algorithm for the trigger primitive generation per channel

---

**Figure 3.28: Block diagram of the Back-End demonstrator setup.**
3.8. EB off-detector readout

**Figure 3.29:** Distribution of the number of single crystal trigger primitives expected per event for several crystal $E_T$ thresholds and a pileup level of 200 events.

**Figure 3.30:** Distribution of the number of cluster trigger primitives expected per event for several cluster $E_T$ thresholds and a pileup level of 200 events.

includes the linearization (multiplication by gain ratios and channel intercalibration constants) and conversion to transverse energy of the digitized signal, followed by the amplitude filtering (weight method) as in Ref. [47]. The final step is the bunch crossing determination, by finding the maximum amplitude value in the digitized frame. The application of the amplitude filtering to a single cluster is sub-optimal as it does not try to reduce the noise (by summing over more crystals), but is considered as a starting point. More sophisticated algorithms will be developed.
Table 3.4: EB crystal word definition.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>N bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$</td>
<td>10</td>
</tr>
<tr>
<td>time</td>
<td>5</td>
</tr>
<tr>
<td>spike flag</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3.5: EB cluster word definition.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>N bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$</td>
<td>10</td>
</tr>
<tr>
<td>time</td>
<td>5</td>
</tr>
<tr>
<td>$\eta$</td>
<td>8</td>
</tr>
<tr>
<td>$\phi$</td>
<td>8</td>
</tr>
<tr>
<td>$N_{\text{crystal}}$</td>
<td>8</td>
</tr>
<tr>
<td>spike flag</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
</tr>
</tbody>
</table>

3.9 HCAL off-detector readout

3.9.1 HB off-detector readout

The off-detector electronics of the HCAL Barrel (HB) calorimeter will be upgraded to operate at the L1 trigger rate of 750 kHz and trigger latency of 12.5 $\mu$s foreseen by CMS for the HL-LHC data taking. The HB Phase-1 $\mu$TCA electronics currently in use will be upgraded to the Phase-2 ATCA standard, and specifically it will use the Barrel Calorimeter Processor (BCP) boards currently being developed for EB and described in the previous section. The choice of a common EB and HB hardware optimizes the usage of development and production resources, enables the sharing of spares, achieves homogeneity in the trigger primitive generation, and facilitates long-term operations and maintenance. Since there will be no further upgrade of the HB on-detector electronics besides the Phase-1 upgrade scheduled to take place during Long Shutdown 2, the number of readout channels, the transverse ($\eta-\phi$) segmentation, and number of longitudinal readout depths of HB will remain as in Phase-1.

The HB on-detector electronics are organized in 36 separate Readout Boxes (RBX), as in the legacy system. Each RBX controls and reads out a 20-degree wedge in $\phi$ in one hemisphere. For each 5-degree slice in $\phi$ there are 15 $\eta$ towers with 4 longitudinal depths and 1 $\eta$ tower with 3 longitudinal depths. This makes 252 detector readout channels per RBX, and a total of 9072 channels for the entire HB. The links from the on-detector to the off-detector electronics will remain unchanged. Each RBX is connected to the off-detector electronics by 32 detector readout links, each carrying 8 (or 7 in four cases) channels and will be operated at 5 Gb/s, as in Phase-1. Including calibration channels and control/status links, the number of links for each 20-degree will not be larger than 40. The preferred architecture of the off-detector electronics for controlling and reading out the 36 RBXs is to have one BCP board per two RBX’s for a total 18 boards.

As in the legacy and Phase-1 HCAL systems, the data from all HCAL sub-detectors will continue to be read out and transmitted at 40 MHz from the on-detector to the off-detector electronics, where the trigger primitives are generated. For HB, the baseline for the Phase-2 trigger primitives is that they will remain similar to the Phase-1 trigger primitives, and will transmit the energy sum of an entire trigger tower (summing 4 readout depths for $\eta$ regions 1 to 15 and
3.9. HCAL off-detector readout

Table 3.6: Bandwidth summary for the two trigger primitive options.

<table>
<thead>
<tr>
<th>Object</th>
<th>Crystal</th>
<th>Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>N bits/object</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>N objects</td>
<td>61200</td>
<td>1000</td>
</tr>
<tr>
<td>N bits/BX</td>
<td>979200</td>
<td>40000</td>
</tr>
<tr>
<td>BW (Gb/s)</td>
<td>39168</td>
<td>1600</td>
</tr>
</tbody>
</table>

3 for \( \eta \) region 16) plus a number of feature bits. There are 2304 trigger towers in HB. A 16-bit trigger primitive will be sent for each HB tower to the L1 system, 10 bits will carry the (transverse) energy information and 6 bits will be used as feature bits. In HB, the pulse shape extends over multiple bunch crossings and is integrated in 25 ns time samples by the QIE11 ASIC, an 8-bit non-linear ADC. For each readout within a trigger tower, the non-linear ADC value from the QIE11 is transformed into a linear \( E_T \) scale by a Look-Up Table (LUT) that also performs pedestal subtraction, and gain and response correction. Then the \( E_T \) values of all depths in a trigger tower are summed, and a peak detection algorithm is applied in order to collect the energy from consecutive bunch crossings and assign it to the correct one even in presence of noise fluctuations and out-of-time pileup. The algorithms to define the 6 feature bits are being studied and will be dedicated to select isolated tracks used for calibration purposes, to trigger on muons/mips, to carry information on the shower shape, and to aid lepton isolation.

For each issued L1 trigger, the HB will send precision data of the corresponding event toward the DAQ for further analysis at the HLT and possible writing to disk. A copy of the corresponding trigger primitives will also be included. For full HB readout (no zero suppression) with eight time samples of precision data per channel, and four bunch crossings of trigger primitives per channel, the payload for the entire HB will be 240 kB/event. This is independent of the amount of pileup.

3.9.2 HF off-detector readout

Although not part of the barrel calorimeter, we briefly mention here the plans for the HCAL Forward (HF) calorimeter. The HF will not undergo a Phase-2 upgrade of the detector or its electronics. Therefore, the detector will continue to be operated with the recently upgraded Phase-1 front-end and the \( \mu \)TCA-based off-detector electronics.

The strategy to cope with the increased trigger rate and latency is to reuse the off-detector \( \mu \)TCA components that will become available with the upgrade of the HB off-detector and the complete replacement of the HCAL Endcap (HE) detector. In this way, the number of \( \mu \)TCA crates and cards devoted to HF can be increased to reduce the number of channels per board, so that the Phase-1 \( \mu \)TCA FPGA resources and the bandwidth will be sufficient to operate at the HL-LHC trigger conditions. The number of \( \mu \)TCA crates to serve the entire HF is foreseen to be 6, each equipped with 12 \( \mu \)HTR cards (HCAL \( \mu \)TCA Trigger and Readout Module). This is twice as many components currently needed to readout HF. The total number of links from the HF \( \mu \)HTR cards to the L1 trigger system can remain unchanged by reducing the current number of trigger links per \( \mu \)HTR card from two to one. In order to interface with the Phase-2 ATCA DAQ system, an adapter will have to be implemented between the legacy \( \mu \)TCA electronics to the standard DTH card (DAQ and TTC Hub).

The HF trigger primitive definition will remain as in Phase-1, where an algorithm determines the best estimate of the tower energy by using all available information: the energy measurement of each of the PMT dual-anode readout channels of both long and short fibers, measured by the QIE10 ASIC (8-bit non-linear ADC), and the time measurement from a TDC embedded
in each QIE10. The energy algorithm includes suppression of the collision-induced anomalous
signals (PMT hits) that arise when charged particles interact directly with the PMT windows. A
LUT is then used to convert the 8-bit ADC value into an 11-bit $E_T$, which is then compressed to
8-bits by another LUT for transmission to the L1 trigger. Two feature bits are available for each
trigger primitive. One is used to indicate that the ratio between energy measured in the long
and short fibers is consistent with the deposit of an electromagnetic shower, while the other is
an ADC-over-threshold with individual thresholds per channel to define minimum-bias trig-
grers.

The HF payload for the DAQ readout will be 60 kB/event for the entire detector. This is con-
sidering full detector readout (no zero suppression) with three time samples of precision data
per channel, and two bunch crossings of trigger primitives per channel. This payload is inde-
pendent of the amount of pileup.

The HF Phase-1 $\mu$TCA system will continue to be able to provide the data for online measure-
ment of the instantaneous luminosity throughout the HL-LHC running period.

### 3.9.3 HO off-detector readout

Regarding HO, the on-detector electronics will neither undergo a Phase-1 nor a Phase-2 up-
grade (the HPDs were replaced by SiPMs in the legacy on-detector electronics during LS1). The
off-detector electronics, which is currently still the original VME-based electronics, is planned
to be upgraded to $\mu$TCA during LS2. The links from the legacy on-detector electronics are op-
erated at the relatively low 1.6 Gbps speed and the $\mu$HTR FPGA resources will be sufficient to
permit operations at the HL-LHC trigger conditions without imposing additional limits on the
number of channels per $\mu$HTR card. A total number of 36 $\mu$HTR cards will serve the entire HO,
and they will be arranged in four $\mu$TCA crates.

Similarly to HF, even HO will need an adapter to interface the legacy $\mu$TCA electronics with the
Phase-2 ATCA DAQ system. In addition, since the HO on-detector electronics will remain the
legacy Phase-0 system, which uses the TTCrx ASIC in the CCM (Clock and Control Module), an
adapter will have to be developed to interface the Phase-2 TCDS with the legacy TTC system.

The HO payload for the DAQ readout will be 30 kB/event for the entire detector. This is consi-
dering full detector readout (no zero suppression) with eight time samples of precision
data per channel, and is independent on the pileup level.
Chapter 4

**EB services and supermodule cooling**

This chapter describes the supermodule cooling requirements and associated systems as well as the services required for the operation of the supermodules following the refurbishment of the on-detector readout.

### 4.1 Overview and requirements

The baseline EB operating temperature for HL-LHC operation is 9 °C. The increased APD dark current due to the LHC radiation environment, and the related increases in electronic noise, must be reduced to preserve good electron and photon energy resolution in the LHC Phase-2 (see Chapter 2). The APD dark current scales logarithmically with the APD operating temperature, and a necessary step in reducing this contribution is to operate each supermodule at a lower temperature than the current value of 18 °C. The reduction in operating temperature from 18 °C to 9 °C will reduce the electronics noise by about 30%.

This lower operating temperature requires a change of the primary coolant water source serving the supermodules, as well as a complete replacement of the coolant distribution pipes serving the supermodules. The cooling system within the supermodule will be retained, however.

### 4.2 Supermodule cooling

#### 4.2.1 Description of the cooling system in the ECAL barrel

The cooling system of the ECAL is described in Refs. [48, 49]. The existing system can be divided in two parts: inside and outside the supermodules. Because of its modularity, the supermodule is designed as a thermally isolated entity. The design complies with the possibility to run at a temperature lower than ambient.

The temperature regulation is based on a two-stage closed loop system. The first stage of regulation is performed in a heat exchanger located in the underground service cavern using the primary water source, currently at 14 ± 1 °C. A more accurate and faster regulation is performed in a second loop by a heater, located in the experimental cavern, which provides input water to the supermodules at 18.1 ± 0.02 °C.

Within a supermodule there are two separate volumes: the volume which encloses the crystals and APDs, between the front thermal shield and the grid, where no power dissipation is expected, and the volume between the grid and the spine backplate (where the on-detector electronics boards are located), where all the thermal power is dissipated.

At present, each supermodule is independently supplied with water at 18 °C. The water passes through a thermal screen placed in front of the crystals. This thermally decouples the EB from
the silicon tracker. The water also passes through pipes embedded in the aluminum grid behind the crystals. Between the grid and the motherboards, a 10 mm thick layer of insulating foam (Armaflex™) is placed to minimize convective heat flow towards the crystals (Fig. 4.1, left). A schematic of the elements of the SM cooling and insulation is shown in Fig. 4.1, right.

Figure 4.1: Left: photograph of the Armaflex insulating foam layer. Right: location of the cooling bars relative to the front-end electronics.

Return pipes distribute the water through a manifold to aluminum cooling bars. These bars are in close contact with the VFE cards and the LVR cards (Fig. 4.2) and have been designed to absorb the heat dissipated by the electronics.

Figure 4.2: A cooling block used to support and cool the electronics mounted on the ECAL supermodules. The cooling bars, which are vertical in this photograph, are in close contact with the VFE and LVR cards.

The layout and components of the supermodule cooling system are shown in Fig. 4.3. It should be noted that the final cooling arrangement is different to that in the ECAL TDR [3]. The current system first cools the crystal volume and then, on its return, cools the electronics boards.
The temperature must be stable to within 0.05 °C, to minimise the effect of the temperature dependence of the crystal light yield (−2.1%/°C), and the APD gain (−2.4%/°C), on the constant term of the ECAL energy resolution [1]. This dictated the flow rate through the supermodule to ensure efficient cooling turbulent flow (Reynolds number).

The system has operated with excellent reliability during LHC operation and has achieved even better temperature stability [50]. The stability is monitored by two independent sets of high precision thermistors. There are 170 thermistors located on the APD capsules (1 every 10 crystals), read out via DCU ASICs located on the VFE boards. Ten Precision Temperature and Humidity Monitor (PTM) thermistors per supermodule measure the temperatures in the volumes on each side of the crystals and on the input and output cooling water. Figure 4.4 shows the excellent temperature stability achieved in 2012 during LHC Run-1, using the DCU thermistors.

Figure 4.4: (Left) ECAL Barrel temperature spread during 2012 data taking, measured at the APD capsules (DCU system). The average temperature is 18.12 ± 0.04 °C, and shows excellent overall temperature stability and homogeneity. In blue, superimposed, are the temperatures of the outer borders of the barrel. The average temperature is 0.07 °C higher than the rest of EB. (Right) RMS Temperature stability of each thermistor over a period of 2 months during 2010 data-taking.
The existing cooling distribution inside the supermodule will not be modified. The cooling circuit inside the supermodules involves the use of dry fittings, whose tightness is limited to a minimal number of mounting/dismounting operations. Dismounting the cooling circuit could generate damage to the fittings and therefore could require an intervention up to the level of the grid, which is a delicate and time-consuming operation.

### 4.2.2 Requirement to change the operating temperature

The Phase-2 cooling system requirements, to operate at 9 °C, using the existing internal distribution system and maintaining temperature stability to within 0.05 °C, are:

1. Ensure a cooling capacity of 3 W per channel that also includes a safety margin. The present front-end electronics design is targeting ≈1 W/channel. The original design assumed an electronics dissipation inside the SM of around 2.5 W/channel.

2. Keep the same water flow rate. The variation of the Reynolds number with temperature is small (goes as 1/viscosity), and changes by only 30% between 9 °C and 18 °C. The turbulent flow mode of operation will be retained.

3. Ensure heat flow insulation from surrounding subsystems: Tracker and HCAL

4. Immunity to dew point issues: necessitates the presence of an environmental screen

5. The services that are located outside the supermodules must be adapted to the new lower operating temperature.

### 4.3 Cooling plant specifications

Two options are studied for the operating temperature: 9 °C and < 9 °C. These options require modifications of the cooling supply to the ECAL cooling plant. The cooling supply is currently water at 14 °C.

For operations at 9 °C, chilled water at 6 °C is required. An extra distribution pipe carrying chilled water must be installed from the surface to USC55. These modifications (see Fig. 4.5) will be undertaken during LS2, to reduce the workload during LS3. The existing heat exchanger and heater will be retained.

For temperatures below 9 °C, should they be required, more complex and costly interventions will be needed. A new heat exchanger, with significantly larger capacity, must be installed in USC55. This further upgrade is not in the baseline, and is therefore not foreseen during LS3.

The flow rate for Phase-2 will be the same as that in the current system (see Table 4.1).

The ECAL cooling system will operate below the ambient dewpoint in UXC55. The cooling pipe insulation will be increased, especially on the YB0 circuit. Extra room will be available in the cable and pipe ducts since the LV cables will be smaller than those currently installed.

### 4.4 Impact, constraints and requirements from other subdetectors

#### 4.4.1 Global environmental screen

The tracker will run colder than the ECAL, and a thermal insulation layer between the outer tracker and the EB will be needed. This must be maintained at the foreseen Phase II EB oper-
4.4. Impact, constraints and requirements from other subdetectors

Table 4.1: Cooling system parameters for the current ECAL and for the Phase-2 upgrade.

<table>
<thead>
<tr>
<th>Value per SM</th>
<th>Legacy cooling system</th>
<th>HL-LHC cooling system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature (°C)</td>
<td>18.1 ± 0.02</td>
<td>9.0 ± 0.02</td>
</tr>
<tr>
<td>Flow (l/s)</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Nominal dissipation (W)</td>
<td>5200</td>
<td>5200</td>
</tr>
<tr>
<td>Cable dissipation in duct</td>
<td>508</td>
<td>508</td>
</tr>
<tr>
<td>HCAL leak (W)</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>Environment leak (5%) (W)</td>
<td>-</td>
<td>260</td>
</tr>
<tr>
<td>Total (W)</td>
<td>5708</td>
<td>6018</td>
</tr>
<tr>
<td>Safety margin, 20% (W)</td>
<td>1142</td>
<td>1200</td>
</tr>
<tr>
<td>Cooling unit design specification (W)</td>
<td>6850</td>
<td>7218</td>
</tr>
<tr>
<td>Number of supermodules</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td><strong>Global values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power (kW)</td>
<td>246.6</td>
<td>259.8</td>
</tr>
<tr>
<td>Flow (l/s)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Cold source temperature (°C)</td>
<td>14 ± 1</td>
<td>6 ± 1</td>
</tr>
<tr>
<td>Heat exchanger output (°C)</td>
<td>17.85 ± 0.25</td>
<td>8.75 ± 0.25</td>
</tr>
<tr>
<td>Heater output (°C)</td>
<td>18.1 ± 0.02</td>
<td>9.0 ± 0.02</td>
</tr>
</tbody>
</table>

Table 4.2: Heat dissipation to HCAL as a function of G10 thickness ($e_{\text{shim}}$) and plate thickness under the shim ($e_{\text{plate}}$). The total thickness is constrained to be 17 mm.

<table>
<thead>
<tr>
<th>G10 thickness (mm)</th>
<th>Heat flow to HCAL (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{\text{shim}} = 2$ mm, $e_{\text{plate}} = 15$ mm</td>
<td>36</td>
</tr>
<tr>
<td>$e_{\text{shim}} = 3$ mm, $e_{\text{plate}} = 14$ mm</td>
<td>24</td>
</tr>
<tr>
<td>$e_{\text{shim}} = 4$ mm, $e_{\text{plate}} = 13$ mm</td>
<td>20</td>
</tr>
</tbody>
</table>

At operating temperature. A global environmental screen including Tracker, ECAL, HCAL with dry air or nitrogen circulation must be installed (CMS-TC responsibility) to avoid humidity in the ECAL. The dry-air or nitrogen injection system will be designed to fulfill the requirement of all CMS detectors located inside the magnet tank.

4.4.2 Insulation from HCAL

The ECAL is attached to the HCAL which will be at the experimental cavern ambient temperature ($\approx 20$ °C). Every supermodule is supported by the HCAL via two sliding pads (see Fig. 4.6).

A thermal study has been carried out [51]. The heat flow between ECAL and HCAL can be minimised by adding a thin layer of G10 insulating material between the backplane and the pad (Figs. 4.6 and 4.7). Table 4.2 gives the heat flow per supermodule to HCAL as a function of material thickness. A conservative number of 50 W is used.
4.5 High voltage, low voltage and slow control

4.5.1 High voltage system for the APDs

Two APDs are glued to each crystal. They are mounted in a unit called a “capsule” and are connected in parallel. The bias voltage for gain 50 ($V_{50}$) is between 350 V and 420 V. The APDs are sorted according to their $V_{50}$ in bins of 2.5 V. Within each bin the APDs are paired starting from the one with the highest and the lowest $V_{50}$ in the bin, such that the average $V_{50}$ of each capsule in the bin is very close to the central value of the bin. The capsules are then glued to the crystals, and the crystals positioned so that groups of 50 crystals have capsules belonging to the same $V_{50}$ bin.

A typical APD gain, $M$, versus voltage, $V$, curve is shown in Fig. 4.8. The voltage dependence of the gain is typically $\alpha_V = 1/G \cdot \delta G/\delta V = 3%/V$ at gain 50. In order to limit variations of
4.5. High voltage, low voltage and slow control

The calorimeter response to below 0.2%, due to high voltage fluctuations, a stable bias must be supplied to the APDs (to better than 70 mV).

The High Voltage power supplies are located in the service cavern. This is practical for accessibility and maintenance, and radiation resistance and magnetic field tolerance (less than 10 mT). The system is located in water-cooled racks, where the temperature is stable at the level of $\pm 2^\circ$C. Cables of about 120 metres are used to carry the bias voltages from the service cavern to the supermodules. The stability of the bias voltages over such long cables has been achieved in the legacy system using sense wires.

Each HV channel provides bias to a group of 50 capsules with very similar $V_{50}$ values. The HV is distributed to the capsules via the motherboards (MB) using a filter circuit on each of the 50 capsule lines, with two bias resistors of 68 k$\Omega$ in series and a capacitor connected to ground in between. The HV cables in the supermodules run underneath the motherboards, and therefore cannot be rearranged.

Each HV channel provides bias to two motherboards, via the HV main cable and the sense cable. There is a local interconnecting cable between each pair of motherboards, in order to close the circuit between the main HV line and its sense line. There are 34 HV channels per each supermodule, resulting in 1224 for the whole calorimeter. The channels are grouped in four connectors located at the supermodule patch panel. Two connectors contain 9 channels and two contain 8 channels. Four cables per supermodule run from the detector to the service cavern where the high voltage system is located.

The legacy High Voltage system [52–54] consists of 18 CAEN SY4527 mainframes. Each mainframe hosts 8 A1520PE boards. The A1520PE boards were developed by CAEN together with INFN Rome. Each board contains nine channels, and is connected to one cable. The channel characteristics are listed in Table 4.3. The maximum bias is 500 V and the maximum current...
Table 4.3: The characteristics of the legacy High Voltage system and of the new High Voltage system for the CMS ECAL Barrel APDs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Legacy HV system</th>
<th>HL-LHC HV system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage range</td>
<td>0–500 V</td>
<td>0–600 V</td>
</tr>
<tr>
<td>Programmable setting step</td>
<td>1 mV</td>
<td>1 mV</td>
</tr>
<tr>
<td>External calibration</td>
<td>±20 mV</td>
<td>±20 mV</td>
</tr>
<tr>
<td>DC regulation at load</td>
<td>±20 mV</td>
<td>±20 mV</td>
</tr>
<tr>
<td>DC stability at load (over 90 days)</td>
<td>±70 mV</td>
<td>±70 mV</td>
</tr>
<tr>
<td>Low freq. noise at load (f &lt; 100 KHz)</td>
<td>±20 mV</td>
<td>±20 mV</td>
</tr>
<tr>
<td>High freq. noise at load (f &gt; 100 KHz)</td>
<td>±20 mV</td>
<td>±20 mV</td>
</tr>
<tr>
<td>Operating temperature at supply</td>
<td>15–40 °C</td>
<td>15–40 °C</td>
</tr>
<tr>
<td>Current limit</td>
<td>15 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>On and off ramp rate</td>
<td>2–50 V/s</td>
<td>2–50 V/s</td>
</tr>
<tr>
<td>Current measurement (from 1µA)</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

per channel is 15 mA. The boards satisfy the EB HV requirements in terms of characteristics, stability and noise.

The legacy High Voltage system was produced in 2003. The maintenance contracts will cease at the end of the LHC program. Some of the components are becoming obsolete and a new system will be prepared for Phase-2.

The specifications for the Phase-2 system in terms of ripple, noise and stability are unchanged. However, the maximum current and voltage must be increased, as shown in the second column in Table 4.3. Because of irradiation, the APD dark current will increase, as described in Section 2.1.3.2, to 200 µA per capsule at 18 °C at |η| = 1.5, after 3000 fb⁻¹. To bias the APDs at 18 °C through to the end of the HL-LHC program, the HV channels must be able to supply up to 10 mA.

If one capsule line goes into short, the HV channel draws an additional current of about 3.5 mA. Currently there are five such channels in the detector. If one capacitor goes into short, the HV channel draws an additional current of about 7 mA and there is currently one such channel in the detector. In both cases, only one of the 50 crystals cannot be read out. For HL-LHC, the specification for the maximum current for each HV channel will be 20 mA, to have a safety margin.

The APD bias voltage required to provide a gain of 50 will increase with radiation by about +30 V at |η| = 1.5 after 3000 fb⁻¹. The bias resistors (136 kΩ in total) will create a voltage drop, which will grow with increasing APD dark current up to a maximum of 27 V at 200 µA. The maximum required voltage, for the channels with the highest $V_{50}$, will approach the legacy system specification of 500 V. A safety margin of at least 50–100 V is therefore required for the new system specification.

The ramp-up and ramp-down voltage rates must be configurable from a minimum of 2 V/s to a maximum of 50 V/s. The voltage must never turn off abruptly. In the legacy system this has been implemented by reprogramming the KILL and INTERLOCK functionality of the channels as a normal turn off command achieved at the ramp-down rate.

The HV system must measure the current drawn by each channel to better than 5%, and it must be possible to check the calibration of the channels periodically to ensure the required stability during LHC operation.
4.5. High voltage, low voltage and slow control

4.5.1.1 The ECAL barrel legacy low voltage system

The legacy ECAL Low Voltage system is described in Ref. [55]. The power cabinets and the rectifier / power factor correction (PFC) units are located in the USC55 S4 area as they are particularly sensitive to magnetic field. From S4, 400 V DC lines transfer power to the YB0 towers and to the X0 location immediately under YB0 where the radiation and magnetic field tolerant low voltage power supplies are located. The power supplies regulate and provide around 5V to the low voltage regulator boards in each $5 \times 5$ crystal region with a granularity of 4 times $5 \times 5$ crystals. The low voltage regulator boards are based on linear low dropout regulators designed to be radiation tolerant. The current for each leg is around 60 A and the cable cross section is $50 \text{ mm}^2$.

![Block diagram describing the baseline upgrade low voltage distribution.](image)

4.5.1.2 The ECAL barrel phase 2 upgrade low voltage system

The baseline architecture for the upgraded EB low voltage distribution system will be identical to the legacy system and follows the outline shown in Fig. 4.9. The power cabinets and the rectifier / PFC units will remain in the S4 area in USC55. The radiation and magnetic field tolerance requirements will stay the same. The voltage will, however, be increased to close to...
12 V in order to exploit the new radiation and magnetic field tolerant switching power modules. As a consequence the current through the power cables will decrease to between a third and half of the legacy system. The cable cross section will be reduced to approximately 20 mm$^2$. The granularity in the distribution will stay the same as the legacy system with one low voltage channel for 100 front end channels. This will free space in the cable ducts on YB0 that will be occupied by the additional insulation of the ECAL barrel cooling pipes.

Studies are ongoing to determine whether it is possible to operate commercial off-the-shelf power supplies in UXC55 X0 where the radiation and magnetic stray field is particularly low. A block diagram of the system under study is shown in Fig. 4.10. If successful, a large power bank combined with a simple fine grain distribution and safety system located in the YB0 towers and in X0 could be envisaged.

![Block diagram](image)

Figure 4.10: Block diagram describing the upgrade low voltage distribution under study.

### 4.5.2 Slow control functions

The legacy detector control system (DCS) [56] and safety systems (ESS and DSS) [57] have been successfully supporting detector operations for more than 10 years and will be used as a reference for the new designs. The CMS ECAL DCS/DSS will be based on the Supervisory Control and Data Acquisition (SCADA) [58] architecture designed for the main CMS DCS. Custom solutions for CMS ECAL specific needs will be developed and integrated to the core
of both systems. Whenever feasible, CERN and CMS framework components will be used to allow homogeneity, long-term support and knowledge transfer among subdetector experts. While a full integration between the control and safety systems is desired, to allow preventive actions at the software level, the role of each system must be carefully defined and preserved.

The basic DCS functions are grouped in five categories:

1. Control and real-time monitoring of:
   - powering systems;
   - racks and crates;

2. Real-time monitoring of:
   - detector safety system;
   - environmental conditions within the detector volume;
   - off-detector (i.e. bias and low voltage crates) and detector cooling systems;
   - external parameters (i.e. CMS ECAL Laser, LHC status, etc).

3. Generation of alarms:
   - based on internal and external conditions;
   - to send instant information via SMS and/or e-mail to experts;
   - to trigger preventive actions.

4. Preventive actions:
   - to move the detector to safe states, before safety limits are reached;
   - to ensure the maximum availability of the control system.

5. Use of online and offline databases:
   - to store relevant parameters, log files, states and monitoring data;
   - to store and load recipes for runtime hardware configuration.

The DCS user interface must provide the operator with a clear indication of the detector conditions, as well as resources to allow quick failure detection.

Temperature and humidity sensors, as well as water leakage detection devices, will be selected and exhaustively tested to ensure their flawless operation under the challenging constraints imposed by the CMS magnetic field and radiation levels. The use of commercial readout electronics is preferable. Custom hardware solutions should only be considered in cases where technical specifications cannot be met.

The data monitoring of VFE and FE electronics, read out by onboard integrated circuits, will also be considered.

The CMS ECAL DSS must be complementary to the main CMS DSS and provide the following resources:

- failsafe hardwired interlocks to powering, cooling and any other relevant systems;
- high reliability, ensured by a fully redundant PLC-based architecture;
- internal health checks (i.e. heartbeat, communication links, etc);
- implement the CMS ECAL safety matrix, to ensure that the detector is always in a safe state;
• transmit CMS ECAL-related problems to the CMS DSS;
• process and react to alarm signals from external systems, such as the CMS DSS and CMS Magnet Safety System (MSS);

The use of custom hardware in the safety system implementations must be avoided.

### 4.6 List of services per supermodule

In order to operate a supermodule a number of services are needed to cool and power the electronics and stabilize the crystal temperature. Below is a list of services to be installed in CMS for each supermodule:

- 2 water pipes to EB cooling plants on the balconies
- 2 gas pipes to UXC periphery (Sniffer and N2 flushing)
- 34 LV power cables to LV power supplies in the YB0 towers [in two sections]¹
- 4 LV control cables to LV power supplies in the YB0 towers
- 1 MEM (Monitoring Electronics read-out Module)) cable to YB0 towers
- 4 HV cables to HV power supplies in USC
- 3 DCS cables to balcony racks
- 3 trunk cables of optical fibres to USC
- 0.5 × 6-way bundle of quartz fibres to laser barric
- 1 grounding cable to corresponding HB wedge.

¹All LV parts will be new as the LV distribution system inside the SM will be changed.
Chapter 5

Calibration and monitoring

There are two principal components to the calibration of the ECAL. One is the calibration of the response using physics events, the other is the monitoring and correction of the response using the light monitoring system (LM). Both components will remain vital for the ECAL operation at HL-LHC. However, several modifications to the calibration and monitoring procedures will have to be employed to cope with the more challenging HL-LHC conditions in terms of radiation dose, pileup, and noise.

5.1 Overview and strategy

The upgraded CMS ECAL Barrel will retain the lead tungstate scintillating crystals and APD photodetectors from LHC Phase-1 operations. The principles of the calibration of the channel-to-channel response, hereafter termed intercalibration, and of the absolute energy scale of the calorimeter will therefore remain similar to the present system.

Differences are expected because of changes in the relative contributions of the noise and constant terms in the energy resolution (see Section 2), which may impact the performance of the calibration methods.

The upgraded detector is designed with a specific focus on precise time measurement capabilities (see Section 3). The time synchronisation of the 61 200 readout channels is therefore an additional task to be accomplished by the calibration methods.

Local intercalibration with physics events will be mostly driven by $E/p$ measurements using electrons from Z and W decays. The momentum $p$, measured by the tracker, will be used as a reference to equalize the energy $E$ measured by the calorimeter. These events will also be used to equalize the response regions of ECAL belonging to the same elementary partition of the light monitoring system (Section 5.6.4.2). Electrons from Z decays will also set the absolute scale of the ECAL, using the invariant mass peak as a reference.

The azimuthal symmetry of the energy flow in minimum bias events will complement the calibration results using electrons and provide a fast feedback of the channel response. This will be especially important during the early Phase-2 running period, where the electronic noise is lower.

Standard candles such as $\pi^0$ and $\eta$ mesons decaying into two photons are also expected to provide a reference invariant mass peak at low energies. These are expected to be more significantly affected both by increased pileup and noise than the W and Z calibration methods. Their importance is therefore anticipated to be more significant at the beginning of Phase-2.

Calibration with MIPs (minimum ionizing particles) is not used in the current ECAL, since the
MIP signal (around 250 MeV) is not clearly visible above noise with the APDs operated at the nominal gain of 50. This will continue to be the case in the upgrade where the APD noise will be larger.

The ECAL light monitoring system will remain essential to regularly measure and provide corrections for the response of each channel, following their variation with the radiation dose-rate.

## 5.2 Channel-to-channel intercalibration

### 5.2.1 Electrons from Z and W decays

Electrons from W and Z decays will constitute the main dataset for channel intercalibration during Phase-2. The intercalibration method will not change with respect to LHC Phase-1 and will use the ratio of the energy $E$ measured in the calorimeter to the reference momentum $p$ measured by the tracker. For a detailed overview of the method, see Ref. [5].

Isolated electrons will be selected at a rate of about 30 Hz with a transverse momentum requirement at the High Level Trigger of $p_T > 30$ GeV. The total amount of data is expected to be around 2M electrons per fb$^{-1}$, allowing for one intercalibration per week, with a precision of about 0.5% at $|\eta| = 0$ and about 1.5% at $|\eta| > 1$.

The width of the $p_T$ distribution of electrons from W decays is dominated by the resolution on the momentum measured by the tracker and expected to be about 10%. Therefore the performance of the method is not expected to significantly change in Phase-2, and it will only be affected by the efficiency in selecting isolated electrons. It is important to keep the Level-1 and HLT thresholds for electrons as low as possible in Phase-2 to acquire sufficient data to allow regular weekly calibrations to be carried out.

Additionally, the experience gained during Phase-1 to select electrons with a dedicated HLT stream, with reduced event content to save bandwidth, may be applied at Phase-2, exploiting even further the full crystal information available at L1.

### 5.2.2 Azimuthal symmetry of the energy flow

Assuming the beam spot is located in the centre of a perfectly $\phi$-symmetric detector, the energy flux originating from minimum bias events impinging on the calorimeter will vary along $\eta$, but, at a given $\eta$, should be constant along $\phi$. An intercalibration in $\phi$ rings can be derived from the ratio of the total transverse energy deposited in one channel to the mean of the total transverse energy collected by all channels at the same pseudorapidity.

These minimum bias events are acquired during Phase-1 operations using a special minimum bias trigger, which optimizes the output data bandwidth by saving only the single crystal energy deposits that are $10\sigma$ above the noise. The amount of data usable for calibration is therefore dependent on the electronic noise. Energy thresholds to select the energy deposits useful for calibration are defined on a channel-by-channel basis. A similar approach is foreseen during Phase-2 operations, with thresholds adjusted for the increased noise levels. The increased pileup expected in Phase-2 is beneficial for the method, since it increases the number of energy deposits per event that are larger than the electronics noise.

A preliminary estimate of the performance of this method in Phase-2 can be obtained by starting from Run 2 data, and considering the most challenging case, corresponding to the end of Phase-2 with about 3000 fb$^{-1}$ acquired. The noise induced by the APD dark current is shown in
Figure 5.1: Expected noise as a function of pseudorapidity after 3000 fb$^{-1}$, showing explicitly the component induced by the APD dark current (left). Expected rate per channel as a function of pseudorapidity (right, solid lines). The (right) dashed lines show the time needed to reach an intercalibration precision limited by systematic uncertainties. Note the inversion of the rate trend versus pseudorapidity due to the large increase in noise.

Fig. 1.8. After including the reduced light output from the crystals of Fig. 2.4, the total effective noise is shown in Fig. 5.1 (left), plotted as a function of pseudorapidity. This figure can be used to obtain the energy thresholds needed to efficiently select energy deposits from minimum bias events.

The results obtained for the total number of expected hits per channel and per hour are shown in Fig. 5.1 (right). These are plotted as a function of the pseudorapidity, assuming a minimum bias trigger rate of 20 kHz and an average pileup of 200. The extrapolation shows that the method should still be usable throughout Phase-2, providing in the most challenging scenario about one intercalibration point per fill.

5.2.3 Photons from \(\pi^0\) and \(\eta\) decays

The invariant mass of \(\pi^0\) and \(\eta\) constitute a reference at low energies, which has been successfully exploited during Phase-1 of the LHC. Such events represent a large dataset for intercalibration, and monitoring of the detector response versus time.

However, with a typical transverse energy of only a few GeV and a cluster size of about 3 \(\times\) 3 crystals, photons from \(\pi^0\) and \(\eta\) will suffer from increases in both pileup and electronic noise. The latter, in particular, is expected to be about 0.5 GeV per photon cluster at the beginning of LHC Phase-2 (see Section 2). Studies are ongoing to clarify whether selections with increased photon \(p_T\) will provide a pair of sufficiently separated and clean photons to be used for calibration.

5.3 Absolute energy scale

The absolute energy scale of ECAL is obtained using a specific reference region in the calorimeter. This is defined as the central 15 crystals in the first module of each supermodule (\(|\eta| < 0.35\)), requiring a minimum distance of 5 crystals from the border of each module in both \(\eta\) and \(\phi\). This definition minimizes both the impact of the upstream material on the elec-
trons and the uncertainties in the energy corrections.

The energy calibration in the MC simulation is computed using 50 GeV unconverted photons and is defined such that the energy reconstructed in a $5 \times 5$ crystal matrix is equal to the true energy of the photons in the reference region.

The absolute energy scale in data relative to the MC simulation can be determined with $Z \rightarrow e^+e^-$ events using the $Z$ invariant mass peak as reference. With a double electron rate for isolated candidates predicted to be around 10-15 Hz (assuming $p_T$ thresholds on the two electrons of 22 and 16 GeV, respectively) one can expect at least $10^4$ selected events per fill, sufficient to provide a measurement of the energy scale with accuracy better than 0.1% and dominated by systematic uncertainties.

5.4 Channel synchronisation

Results from beam tests have shown (see Section 3) that PbWO$_4$ crystals can achieve time resolutions of the order of 20–30 ps. Studies performed using collisions data during LHC Run-1 have attributed the limiting factor to the precision of the clock distribution through the FE electronics.

Although the upgraded ECAL will benefit from specific attention in the propagation of a clock signal through the different FE boards, detailed monitoring and calibration protocols must be foreseen.

Electromagnetic showers from isolated electrons and photons can be exploited to synchronize the information on the arrival time of the particle at the calorimeter, using the same strategy that is adopted for the energy calibration. In particular, while single showers will allow the local synchronization of readout channels, electrons arising from the common vertex of a $Z$ boson decay will permit the synchronization of different regions of the calorimeter. Given that the the average energy of the selected showers from $W$ and $Z$ decays is around 30 GeV, Fig. 3.8 shows that an average spread in the time resolution of about 50 ps can be obtained for a single channel for each event. About 2500 events per channel are therefore sufficient to provide a synchronization at the level of 1 ps. This should be achieved within few hours of data taking.

The light monitoring system can also be exploited to provide a reference synchronization every 40 min. The performance of this method has been studied in LHC Run-2 and a precision of 30 ps has been achieved. This is a promising result that will be further studied to assess its usefulness in HL-LHC conditions.

5.5 Alignment of the ECAL

No changes are expected to the ECAL alignment procedure [5] with respect to Phase-1. The relative alignment of the ECAL with respect to the tracker is achieved using $Z$ boson decays. About 0.5 fb$^{-1}$ of data are sufficient to provide about a thousand electrons per supermodule and reach a position resolution of about 3 mrad in $\phi$ and $10^{-3}$ units in $\eta$, which matches the position resolution of MC simulation with perfectly aligned geometry, and satisfies the track-cluster matching criterion used in electron identification and reconstruction.
5.6 Light monitoring system

5.6.1 Components of the monitoring system

Monitoring the transparency of the lead tungstate crystals of the CMS electromagnetic calorimeter plays a crucial role in maintaining the ECAL energy resolution. To meet the stringent requirements on the light monitoring precision and stability, a diode-pumped blue laser has been commissioned and installed at CERN and has been in operation since 2012. The operating wavelength of 447 nm is close to the emission peak of scintillation light from PbWO$_4$ crystals. The laser unit has a simple structure and is more reliable than the lamp-pumped lasers previously used by the monitoring system. The stability of critical quantities such as the intensity, width, and timing, is better than that of the lamp-pumped lasers.

Two other monitoring wavelengths are used: green (527 nm) and infrared (709 nm). The green laser is used to provide a second measurement of crystal transparency at a different wavelength. In addition, the narrow pulse width permits precise measurements of the individual channel Single Pulse Response (SPR) shape (used in the monitoring signal amplitude reconstruction) as well as the time synchronisation of each channel. The infrared laser is intended to measure channel response and photodetector gain variations, in the absence of crystal transparency losses.

The specifications of the blue and green lasers are listed in Table 5.1.

Table 5.1: Specifications of the existing blue (447 nm) and green (527 nm) lasers for ECAL response monitoring.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>447 nm</th>
<th>527 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per pulse</td>
<td>1 mJ</td>
<td>200 µJ</td>
</tr>
<tr>
<td>Pulse width (FWHM)</td>
<td>15 ns (nominal)</td>
<td>7±3 ns (nominal)</td>
</tr>
<tr>
<td>Pulse stability (100 Hz trigger)</td>
<td>&lt; 5% rms</td>
<td>&lt; 5% rms</td>
</tr>
<tr>
<td>Spatial mode</td>
<td>TEM$_{oo}$</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Polarization</td>
<td>Horizontal</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>&lt; 2 mrad</td>
<td>0.7 ± 0.4 mrad</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>&lt; 50 µrad</td>
<td>&lt; 5% rms</td>
</tr>
<tr>
<td>Pulse to pulse stability</td>
<td>&lt; 3% rms</td>
<td>&lt; 3 ns rms</td>
</tr>
<tr>
<td>Pulse jitter</td>
<td>&lt; 3 ns rms</td>
<td>&lt; 3 ns rms</td>
</tr>
<tr>
<td>Pulse delay from external trigger</td>
<td>≈ 90 µs</td>
<td>300 ± 250 ns</td>
</tr>
<tr>
<td>Single shot repetition rate</td>
<td>up to 200 Hz</td>
<td>up to 30 kHz</td>
</tr>
<tr>
<td>Laser dimensions (mm)</td>
<td>190(W) × 559(L) × 95(H)</td>
<td>311(W) × 120(L) × 90(H)</td>
</tr>
</tbody>
</table>

The ECAL light monitoring system was designed to measure and correct for response changes due to radiation-induced crystal and photodetector response variations. It is extensively described in Refs. [18, 59, 60].

Figure 5.2 shows a schematic view of the present system. Laser pulses from the different light sources are distributed via an optical fiber system organized in three stages. A fiber optical switch sends laser pulses to one of 72 calorimeter regions (2 per SM). A two stage distribution system mounted on each SM delivers monitoring laser pulses to each crystal. The Level 2 (L2) stage distributes the light to groups of 200 crystals within a supermodule and the Level 1 (L1) stage distributes the light within these groups to individual crystals with fiber harnesses. The light is uniformized and de-speckled via a diffusing box that ensures that the ratio of light amplitude between channels remains constant with time. Reference fibers from each harness are
connected to PN diodes which provide the reference amplitudes to normalise the photodetector response. The APD/PN ratios are the monitoring signal, which is a measurement of the crystal transparency loss. The monitoring signal must be measured to a precision of 0.2% to have a negligible impact on the intercalibration precision.

PN diodes are equipped with an amplifier, the FEM (Front-end Module: an ASIC based on 0.8 μm DMILL technology), located near the PN itself at the front of the EB supermodules. The PN signals are digitised and transmitted to the ECAL off-detector electronics by a dedicated electronics readout box (MEM: Monitoring Electronics read-out Module), located at the back of the SMs. The MEMs use Analog Devices AD9042 monolithic 12 bit 40 MHz ADCs and the
legacy ECAL FE cards for data transmission off-detector.

The light source is monitored by a dedicated diagnostic line (based on the MATACQ analog matrix chip), and the APD/PN ratio is corrected for laser pulse width and amplitude variations. The measurements are taken in the LHC abort gap during physics data-taking, with one measurement per crystal approximately every 40 minutes. During LHC Run-1, the corrections for response changes have reached a precision of better than 0.15% \[5\].

5.6.2 Monitoring system requirements for HL-LHC

The laser specifications for Phase-2 remain the same as the legacy system in terms of dynamic range, laser power, pulse width, and the other parameters listed in Table 5.1. At least two wavelengths (close to the current values of 447 and 527 nm) will be needed. Only the blue laser used to derive the monitoring corrections needs to have the full dynamic range.

The monitoring system can be used for detector commissioning, for instance to check the operation of all channels. The green laser will be used for per-channel time synchronisation and single-pulse response measurements. Calibration of timing drifts between channels can be measured, since channels belonging to the same light monitoring region observe the same light pulse. Absolute timing requires an external synchronisation device to measure the time of the laser pulse itself. This could be a MATACQ module or a more precise flash ADC.

The required precision of the light monitoring system may be relaxed at the HL-LHC, as the conditions will be quite different. In particular the noise levels in the photodetectors and the fluctuations of the ECAL electromagnetic deposits due to contamination from pileup, both contributing to the final energy resolution, will be larger. Monte Carlo simulations have shown that an accuracy of 1% will be sufficient for the monitoring system not to dominate the energy resolution for electrons from Z boson decays.

The main concern for the current monitoring system is its radiation tolerance, given the dose rate expected at the HL-LHC (Fig. 2.6). This is most important for the light distribution system and the PN diodes and FEM, placed at the front of the SMs. From previous studies \[60\] the components of the light distribution system, all passive, are radiation tolerant and the ageing is expected to be limited. PN diodes were tested up to \(1.5 \times 10^{13} \text{n/cm}^2\) and to a dose of 2 kGy with minor loss of quantum efficiency. The FEM was tested up to \(1.5 \times 10^{14} \text{n/cm}^2\) and to a dose of 6 kGy with small gain loss and noise level increase. However, due to the obsolescence of the components, the tests cannot be repeated to the full HL-LHC radiation levels. Since the MEM boxes use FE cards for data readout, they will need to be changed as for the rest of the EB.

5.6.3 Proposed architecture for the laser monitoring system at HL-LHC

The proposed upgrade architecture, as shown in Fig. 5.3 involves monitoring the amount of light sent to the detector at the injection point in the laser barrack, located in the service cavern, rather than with the PN diodes at the last distribution step in the supermodules.

This new method of monitoring the laser light implies that the ageing of the light distribution system itself will no longer be included in the measurement. The critical point with this architecture is to take into account the differential ageing of L2 fibers under irradiation due to their different lengths and paths on the ECAL front face. This point is under study using the prototype system installed during LS1 and described in the next paragraphs.

Two monitoring “spy boxes”, with 44 fibers each (sufficient to equip the entire system) have been installed on the light path after the optical switch. A small length of each fiber is lightly
machined and equipped with a suitable photodetector (PiN) in order to extract a small fraction of the light signal. Figure 5.4 shows the system as installed in CMS.

As a result of the small capacitance of the PiN diodes (< 20 pF), and taking into account that only one diode is illuminated at a time, a hardwired signal merging is possible. Eleven diodes have been grouped in parallel and connected to one MGPA preamplifier from the legacy EB front-end electronics for signal amplification and readout. The output signal is digitized by the MATACQ module already present in the legacy system.

These modifications have been commissioned at the beginning of LHC Run-2. The new system is operated in parallel to the legacy system. This permits a thorough long-term characterization of the performance of the new system, and to develop the necessary expertise for post-LS3 running.
If the new monitoring system does not operate with the required precision, a backup solution will be used. This involves reading out the existing PNs with electronics similar to that intended to be used for the readout of the crystals, with new FE cards. This backup solution would require the replacement of the MEM boxes, but would have little impact on the planning of the EB electronics refurbishment during LS3, since the PN diodes and FEM will not be replaced.

5.6.4 Prototype monitoring system test results

The prototype upgraded monitoring system has been running during the second half of 2015 and during the entire 2016 data taking period. It has been used to study the monitoring stability of the proposed system over 11 monitoring regions, corresponding to five and half supermodules. The following measurements were made using the 2016 data:

- Intrinsic stability of the system: measurement of the APD/PiN ratio and the comparison with the legacy APD/PN ratio in LHC beam-off periods, using 10 days of data from May 2016.
- Stability and performance of the system during LHC irradiation: measurement of the APD/PiN ratio and the comparison with the legacy APD/PN ratio during LHC beam on periods.

The same monitoring data are analysed using the two systems. The APD/PN ratio is computed for each channel using the legacy monitoring system and the APD/PiN ratio is computed using the measurements from PiN diodes located in the spy box. The ratio \((\text{APD}/\text{PiN})/(\text{APD}/\text{PN})\) is then calculated and the normalized RMS is computed.

5.6.4.1 Intrinsic stability

Figure 5.5 shows the normalized RMS of the upgraded system versus the legacy system. The stability is around 0.1–0.2%, which is similar to the performance of the legacy system.

![Spybox stability map](image)

Figure 5.5: Intrinsic stability of the measurements performed with the spy box, estimated using the RMS of the \((\text{APD}/\text{PiN})/(\text{APD}/\text{PN})\) ratio. The data were recorded during 10 days in May 2016, in LHC beam-off periods. The results are plotted as a function of the crystal \(\eta\) index (170 crystals in the range \(-1.48 < \eta < 1.48\)) and crystal \(\phi\) index (360 crystals in the range \(-\pi < \phi < +\pi\)).
5.6.4.2 Spy box performance during LHC irradiation

Figure 5.6 (left) shows that the RMS spread of the \((\text{APD}/\text{PiN})/(\text{APD}/\text{PN})\) ratio is larger than in beam-off periods, between 1 and 2%. There is a drift of the ratio versus time, as shown in Fig. 5.6 (right). This drift is correlated with the instantaneous luminosity of the LHC, which indicates that the ratio is sensitive to differential ageing on the L2 fibers. This effect is absent in the legacy system since all photodetectors (APD and PN) are located at the same place in the supermodule.

![Spybox stability map under irradiation](image)

![PN/PiN vs t](image)

Different actions can be performed to account for this drift in the computation of the crystal transparency loss and these actions will be evaluated using Phase-1 monitoring data.

First, the monitoring system can be operated as designed in the ECAL TDR [3]. The system provides monitoring corrections over short periods of 1 to 2 weeks. Any residual drifts over this time period are corrected by updating the intercalibration constants with physics events \((Z,W)\). The effect due to differential aging of distributing fibers can be kept below 0.5% using this method.

Secondly, the differential loss between fibers can be modelled and corrected for. This will use the same radiation damage model as currently used to fit the crystal behavior with a series of characteristic dose rate and time constants. It can be used to reduce the discrepancy between the upgraded and legacy systems over long periods. This study is ongoing. The model parameters will be derived on 2016 data and applied on 2017 data to check the performance.

Third, the crystal transparency can be normalised to a reference crystal in each monitoring region \((\text{APD}/\text{APD}_{\text{ref}})\). The different monitoring regions (72 in EB) will be intercalibrated using physics events. As described in Section 5.2.1, about 30 Hz of isolated electrons are expected above 30 GeV at the nominal HL-LHC luminosity. Assuming a RMS of 10% in the worst case (end of HL-LHC at high \(\eta\)) for the \(E/p\) distribution, about 400 electrons are needed to reach a precision of 0.5% on the intercalibration of each monitoring region. This is achieved within about three hours at nominal HL-LHC luminosity.
Chapter 6

EB electronics replacement

The replacement of the EB electronics will involve the extraction of all the SMs from CMS, replacing the electronics, and reinsertion of all the SMs into CMS.

The planning and execution of the project involve the following:

- Detailed sequences for all steps
- Required infrastructure and tooling
- Required manpower
- Plans for testing and quality monitoring
- Evaluation of risks
- Planning and schedule

All of the operations described in this section (the extraction of SM, electronics refurbishment, reinsertion of SM) have been performed numerous times during the initial ECAL commissioning period. As many tests as possible will be performed prior to LS3 on the spare supermodule to better understand the procedures, the risks, and the manpower needs.

6.1 Introduction and overall schedule

The schedule for extraction, refurbishment, and reinstallation of the 36 supermodules is summarised in Fig. 1.9. The process begins with the installation of the enfourneurs (the tool for insertion and extraction of SM) starting from week 15 of Long Shutdown 3. The supermodules will be extracted and new electronics will be installed. The entire sequence, including removal of electronics, reinstallation, and recommissioning of the 36 SMs will be 60 weeks, from week 21 to week 81. The reinstallation of the SMs will take place during weeks 81 to 83.

6.2 Supermodule extraction

6.2.1 Design of the enfourneur and required modifications

From the planning of LS3, the main constraint is the short time to remove the 36 supermodules (4 weeks) and to reinstall (3 weeks) the 36 refurbished supermodules. The extraction and reinstallation is accelerated by using a second enfourneur complete with its ancillaries. Before producing the second tool set, an operational review of the operation of the current enfourneur was carried out based on the installation experience from 2006. As a result of this review, appropriate modifications were made (see details below). These will be tested during the second half of 2017. The tests are an important step in training new (younger) members of the installation team.
Chapter 6. EB electronics replacement

Figure 6.1: The enfourneur, used for the extraction and reinstallation of ECAL barrel supermodules.

Figure 6.2: Annotated diagram of the enfourneur.

The enfourneur (see Figs. 6.1 and 6.2 ) consists of a rotating cage supported by a cradle upon which supermodules are positioned before insertion inside the HCAL. The cage is shown in red in Figs. 6.1 and 6.2. The supermodules are aligned to the HCAL rails by the manipulation of jacks providing angular and translation movement. The final adjustment is performed using the specific part of the cage that is attached to the support beam of the supermodule. This part, referred to as the cage “sector” is shown in Fig. 6.3. The supermodule can be slid either in or out using the insertion jack and using the tooling rails that join the rail of the supermodule support beam to the rails inside the HCAL.

The enfourneur is described in detail in Ref. [61]. The modifications included:

1. New tooling rails to take into account the surrounding cables (increased length from
440 mm to 765 mm). The relevant mechanical studies were performed by the CMS-Integration-Team (see Ref. [62]). The new rails have been manufactured.

2. The range of the rotating jack was increased to ease handling of the supermodules and to reduce the time needed for supermodule positioning.

3. To ease and to speed up the SM alignment process, new cage sectors with associated adjustment systems (see Fig. 6.3) were studied. The modifications were agreed (see Ref. [62]) and the items have been procured.

![Figure 6.3: Modifications to the enfourneur, new cage sector (left), new adjustment system (right).](image)

The modifications will be certified during a test with dummy supermodules with the same weight and external dimensions. The test setup is being installed in SX5 (see Fig. 6.4). Test insertions will be performed at both the 3 and 6 o’clock positions.

The most crucial point regarding the extraction of SMs, especially the first one to be removed, is to ensure that the HCAL support rails and the enfourneur rails are well aligned. This will ensure that the extraction of the SM will not interfere with neighbouring SMs. Studies are ongoing to validate measurement devices (compact laser sources) that can perform this alignment quickly and easily. These procedures will be qualified with tests using a dummy supermodule prior to LS3.

### 6.2.2 Schedule of SM removal

The SM removal will require two working shifts of 8 hours per day and four teams of 4 skilled persons. The teams will be trained in advance with tests to operate the enfourneur with a dummy SM. The first SM to be removed in CMS will be the SM placed at 12 o’clock, followed by the adjacent SMs, until all 18 on each side are removed.

The detailed operations for the supermodule removing sequence are:

- Measure the clearances between all SM (methods under study);
- Installation of the enfourneur (cradle, cage);
- Installation of the supermodule support beam (including rails);
- Installation of the cage sectors;
- Installation of the tooling rails;
Alignment of the beam rails with the rails inside HCAL, using angular and translation jacks and fine tuning with the sector alignment devices;

- Extraction of the supermodule using the insertion jack;

- Rotation of the cage to position the supermodule at 12 o’clock;

- Extraction of the supermodule with the crane to load it onto the handling frame in order to remove the support beam and install the transport tools;

- SM removal from the underground cavern (UX) to the surface building (SX).

The start of work is scheduled for W17 and is beneficial in view of the ALARA (As Low As Reasonably Achievable) radiation safety principle (see Section 7). Once the SMs are removed from CMS, they will be stored in dedicated storage frames until the electronics integration starts. A total of 36 storage frames are available. The storage frames will be renovated and tested before use.

6.2.3 Risk mitigation

The most delicate operation is the removal of the first supermodule on each side. This requires precise alignment and due care. As a consequence, the extraction time for the first supermodule has been scheduled to be one week.

6.3 Supermodule rework

6.3.1 Introduction

The replacement of the electronics will be undertaken in SX5, where a dedicated zone will be prepared and allocated to ECAL. This eliminates the need to transport supermodules by truck back and forth to other sites, simplifying the ALARA procedure. The supermodules will be stored in the same area and will be readily available.
6.3.2 Design of the integration area

The new ECAL integration zone in SX5 has a total area of 500 m$^2$. There is additional space in an alcove and on a platform for storage and testing. The floor area will be prepared for the use of air-cushions to move supermodules in their integration stands. The use of the crane will be frequent in order to install and remove SMs in various frames and to remove the back plates (200 kg). The SX5 area is served by two cranes. It is agreed that a crane will be available for SM manipulations as and when required. A sketch of the integration area is given in Fig. 6.5.

![Figure 6.5: Layout of the supermodule refurbishment zone at SX5.](image)

The zone will be divided into:

- A staging area for pre and post integration operations;
- A storage area for the supermodules, with additional radioprotection measures if necessary;
- The super module integration stands;
- A cosmic ray stand;
- A storage area for new components;
- A preparation area for the preparation of fibers and cables.

The access to the area at SX5 will fulfill radioprotection regulations, while allowing the use of a pallet truck and forklift for deliveries. The cooling units are installed outside the integration area, in a separate barrack, because of their noise and heat dissipation.

The alcove will host three out of eight integration/test stands. The crane provides access to the
platform for heavier items and in particular for loaded pallets. Extra lights will be installed for all the integration stands in the staging area and on the platform in order to provide appropriate working conditions.

The platform will serve as a storage area and as a preparation area for cables and optical fibers.

**6.3.3 Test stands**

Six fully equipped integration/test stands will be used for the electronics replacement and commissioning. Each stand will comprise low voltage supplies, bias supplies and readout for one supermodule with a computer for DAQ and analysis. Each of the three existing cooling units can remove the heat from two supermodules. Two more identical cooling units will be built. The power supplies will be interlocked against failures of the cooling units via a safety system. The bias supply units presently used in CMS will be used. The low voltage power system will be purpose built.

Six supermodule support frames will be available, one per integration stand. One or two assembly frames will also be available for pre- and post-preparation involving the removal and installation of the SM mounting components.

**6.3.4 Installation items**

The following items need to be installed and tested in each supermodule:

- 68 SLVR cards;
- 340 VFE cards;
- 68 FE cards;
- 5 × 68 optical links;
- Distributed fiber patch panels;
- 17 low voltage distribution blocks.

Mechanical supports will be installed to hold the fibers, cables and other components in place. All services are connected to the patch panels at the end of the supermodules prior to the start of the rework activity. They are stored at the integration center.

**6.3.5 Rework sequence**

The rework of the supermodules is arranged into six steps:

1. Pre- and post-integration operations
2. Removal of installed components
3. Installation of the tower electronics, SLVR, VFE and FE
4. Installation of the optical links
5. Installation of the power distribution, installation of the Temperature Safety Sensors (TSS) and connection of all components to the patch panel
6. Commissioning of the completed supermodule (2 weeks).

A minimum of 42 weeks are required to refurbish all 36 supermodules. Some additional weeks for contingency are mandatory and consequently 60 weeks are planned to complete the rework activity.
6.3.5.1 Pre- and post-integration operations

Supermodules entering the integration area will undergo a pre-integration procedure prior to their final storage consisting of:

- Removal of the mounting support (sliding pad, spine) from the backplane of the supermodule
- Replacement of all stainless steel screws on the support structure by steel screws
- Mounting the SM in a storage frame and moving it into the storage area.

It is likely that the main manifold will need replacing. The water joints on the input and output supermodule pipes (main manifold) will be more than 20 years old. Taking the opportunity to renew these appears like a reasonable action and as these items are not commercially available off the shelf, discussions with the manufacturer have started. The operation will require additional tests that must be included in the pre-integration planning.

The pre-integration will be carried out in a staging area, equipped with two integration frames. The mounting supports (sliding pad, spine, backplate) are stored in the integration area for later re-use. These operations require permanent availability of an overhead crane, in particular for the exchange of the screws, which is carried out with the supermodule suspended on the crane. After completion of this operation, the SMs can be safely installed in their integration stands, with their backplates removed.

Supermodules leaving the integration area for their reinsertion into CMS undergo a post-integration procedure, consisting of:

1. Replacement of all steel screws on the support structure by stainless steel screws
2. Mounting of support rails onto the backplane of the super-module just before installation in CMS.

The location and requirements for post-integration are identical to those of the pre-integration procedure. Both operations are well known from the first installation of SMs in 2006–2007 and will be carried out by adequately skilled and trained technicians.

6.3.5.2 Removal of installed components

The removal of the installed components includes the following steps:

1. Removal of the laser monitoring module on the outside of the SM
2. Opening of the SM, removal and storage of its backplane for later usage
3. Removal of the low voltage cables and low voltage distribution blocks and storage of the parts which will be re-used
4. Removal of the optical fibers
5. Removal of the electronics cards: FE, VFE and LVR.

These operations are well-understood and have been performed on more than 20 supermodules during the original construction. The work is relatively straightforward and no particular skill is required. Care is needed however for the unscrewing of the VFE and LVR card housings from the cooling bars in order to avoid damage to the threads in the aluminum cooling
bars. This step is estimated to take less than one week for two persons per supermodule. The removed material will be stored in an adequate storage area respecting ALARA procedures.

6.3.5.3 Installation of the new electronics

The supermodule will be connected to the cooling system and to the APD HV bias system. The VFE and SLVR cards, pre-tested and prepared with housings, are inserted into the supermodule. Care is needed to avoid damage to the connectors on the motherboards. The housings are screwed to the cooling bars. Finally, FE cards are mounted on top of the cooling bars. During the installation, the bar codes of all installed cards, together with their positions inside the SM, are registered in the construction database.

After completion of the installation, each of the 68 towers is tested in turn using a dedicated test system. The mobile setup provides power, readout, and control for a single $5 \times 5$ data tower. The tests performed include pedestal measurements and test-pulse injection into each readout channel. Faulty components will be promptly replaced. This thorough testing is mandatory. The next step will cover the installed cards, rendering their replacement very difficult. The procedure described is identical to that successfully applied during the construction of the present ECAL barrel in 2005–2007. The operation requires no special skill, but care is required during the insertion of the VFE.

Figure 6.6 shows, as an example, the legacy electronics for one readout tower controlling 25 crystals, mounted in a standalone setup for tests. The single readout tower can be easily tested by connecting the low voltage and the readout fibers.

![Figure 6.6: The legacy electronics for one readout tower controlling 25 crystals mounted on a standalone setup for tests.](image)

6.3.5.4 Installation of the optical links

Optical links are installed onto all FE cards and the fibers are routed to the patch panel. Fiber slack is packed in appropriate protected locations. The bar codes of the optical links are read into the database, together with their locations within the SM. The proper functioning of the data transmission and control interfaces will be tested using the data acquisition and control system at the integration stand. For this purpose, power is provided by a mobile system to
groups of four towers. As in the original construction, pedestal and test-pulse data are used for validation. The test includes the verification of the proper connection scheme. Mistakes are corrected and faulty components are replaced.

Optical fibers are relatively fragile and require proper cleaning before being connected. The operation can be performed by a technician trained in the proper handling of optical fibers.

6.3.5.5 Installation of the power distribution network

The power distribution network, together with the necessary supports, is added last. The network largely covers the previously installed items. Temperature Safety Sensors are installed. All cables are connected to the patch panel and arranged properly.

Upon completion, the full supermodule is powered. Proper functioning is verified by reading pedestal and test pulse data from the whole SM.

6.3.5.6 Commissioning of the completed supermodule (2 weeks)

During a period of two weeks, the supermodule will be permanently kept under power with APD bias, at 18 °C. The temperature may be increased slightly in case there is high relative humidity. Pedestal and test pulse data are recorded for each channel and analyzed at regular intervals. In case of a fault, the reason is investigated and appropriate measures are taken. Faulty components are replaced. At the end of the commissioning period, the supermodule is closed by mounting its backplate. This is followed by another complete checkout. If all 1700 channels are fully operational, the supermodule will be stored. Otherwise the SM will be re-opened and the fault corrected. All supermodules declared ready should be 100% operational.

6.3.5.7 The training of personnel and the use of the spare SM, SM36

The availability of a sufficient number of trained personnel is crucial for the success of the refurbishment operation. Three persons are required for each integration stand. Two mechanical technicians are required for logistical operations, such as opening and closing supermodules. The activities will be supervised and coordinated by an integration facility manager. A total of 27 people is required for the normal operation of the integration area. Extra personnel will also be required for the pre- and post-refurbishment operations.

All personnel will be trained prior to the start of the re-integration campaign. The integration teams will spend a minimum of two months in the integration center, starting a year ahead of LS3. They will completely dismount the existing spare supermodule, SM36, and install prototypes of the new electronics. They will perform all testing steps and commission the completed supermodule. Each person will participate in at least one complete dismounting and mounting exercise using SM36. This training activity will help prepare the new integration for the infrastructure, test-equipment, and test software. Training is mandatory. It is the only possibility to ensure that all crucial elements are operational and that all 36 supermodules will be successfully completed in the very limited available time.

The necessary 27 people will be provided by the various institutes participating in the EB upgrade effort.

6.3.5.8 Risks

There are several issues that could put this project plan at risk:
1. Insufficient manpower: CMS, and in particular the participating institutes, will ensure that the required personnel are available over the requested periods. If necessary, additional personnel will be hired.

2. The integration requires more time than anticipated: The plan includes 10 weeks of contingency. If this is not sufficient, people will be asked to work extra hours. This could include work on Saturday, Sunday, and/or longer hours daily. Two complete shifts per day are feasible.

3. One or more components are not available at the start of the integration effort: The ECAL management, and the participating institutes, are responsible for the availability of all components. All necessary measures will be taken to ensure that this will not happen.

4. Motherboard broken: The motherboard will be replaced, requiring removal of the cooling block followed by its re-installation and leak tightness test, involving the complete supermodule. The required leak-testing equipment will be readily available. A sufficient number of spare motherboards exists from the original production.

5. Threads in the cooling bars damaged: Special clamping will be designed and prepared to fix the VFE card in case the housing cannot be screwed to the cooling blocks.

6. Cooling block damaged: SM36 contains one spare of each type of cooling block.

### 6.4 Supermodule reinstallation

#### 6.4.1 Schedule of SM reinstallation and manpower requirements

The reinstallation of the 36 supermodules including cabling (with local cabling for commissioning tests) is foreseen during weeks W81–83. After installation of each SM, in situ commissioning is mandatory. The dedicated DAQ system, used during the surface electronics installation, will be used. Two systems will be needed, one for each end of CMS. The estimated commissioning time needed is 2.5 hours for one SM, one hour to cable, one hour to test, 0.5 hours to un-cable. All the cables external to CMS ECAL must be installed beforehand.

The supermodule installation sequence is as follows:

- Install the supermodule in the handling frame;
- Remove the transport tooling and install the support beam;
- Move the supermodule with the support beam onto the enfourneur cage at 12 o’clock;
- Installation of the tooling rails;
- Rotation of the cage to the desired position using the rotating and translation jacks;
- Alignment of the rails with the HCAL rails using the alignment devices of the cage sectors;
- Insertion of the supermodule using the insertion jack;
- Alignment and clearance checks during the operation.

#### 6.4.2 Risk mitigation

In case of problems, a supermodule will be removed and another one installed at the same position. This is possible since all supermodules are identical.
5.4.3 SM recommissioning plan

Three sets of tests will be needed on each SM after the new electronics has been installed. A test will be carried out before insertion. A further test will be carried out on each SM, just after insertion. A final test will be carried out on each SM after all 18 SM have been installed at each end.

6.4.3.1 Just before insertion

Electronics integration will have been performed on some supermodules several months before the reinstallation is due. Some simple tests must be made in UXC55 just before inserting the SM into CMS. The following items will be tested:

- FE electronics functional tests;
- LV distribution;
- HV power distribution;
- FE environmental parameters;
- APD connection to VFE (no laser, for safety reasons);
- Functionality of data links;
- I2c device access;
- Monitoring system readout functionality;
- Pedestal run (HV on/off);
- Test pulse run.

These tests must show that the following goals have been achieved:

- Cooling is fully operational;
- Get ESS/DCS connected and fully operational (including testing functionality of cooling interlocks);
- Get LV connected and fully operational;
- Get HV connected and fully operational.

6.4.3.2 After insertion

The same tests that were conducted before insertion in UXC55 will be repeated. A final survey to verify the positions of the installed SMs will be performed.

6.4.3.3 After all services are installed

The following tests must be performed:

- Verify that SM cooling can cope with running all SMs simultaneously;
- Power all SMs simultaneously;
- Verify functionality of DCS commands: single command to turn on all ECAL cooling or LV or HV;
- All SMs simultaneously into Global Run, with nominal CMS trigger and readout data rate;
- Move towards final configuration for data-taking (using beam abort gaps for calibration);
• Perform EB data commissioning and EB synchronisation;
• Develop and validate Data Quality Monitoring software (+ associated alarming system), and validate offline reconstruction software.
Chapter 7

Safety

7.1 Overview of requirements

The safety of the ECAL upgrade will be guided by the CERN Safety Policy [63] that sets out the general principles governing Safety at CERN. These requirements have been incorporated into the ECAL/CMS design from an early stage and are regularly checked and updated to maintain compliance with the CERN and LHC safety policy. The CMS collaboration established a Safety Working Group, with membership mainly drawn from the technical design staff of the major subsystems, to implement the provisions of the codes and instructions which emerge from the policy. The hazard identification process involves a review of the ECAL technical designs by the CMS GLIMOS (Group Leader In Matters Of Safety) and a member from the Health and Safety Executive (HSE) Commission.

The calorimeter design concepts were discussed and evaluated with ECAL engineers, safety working group representatives, and CMS technical management. Hazards can arise from design choices or from specific operational conditions. The process is called an Initial Safety Discussion (ISD). A detailed worksheet has been created, and will be used as a guide to ensure that the scope of the process covers all aspects of hazards at accelerator facilities. Hazards that could cause death, injury, occupational illness, or damage to facilities, systems, equipment or the environment, as well as those not routinely encountered by the public, were the focus of the identification step. The summary the results of the ISD for the ECAL barrel systems is given in this section. It includes supermodule removal, refurbishment and reinstallation during LS3, and ECAL operation during LHC Phase-2. The mitigation strategies used to reduce or eliminate the risks are presented.

7.2 Induced radioactivity, ALARA

7.2.1 Applicable radiation safety policy

The radiation safety policy applied by CMS, follows the radiation dose targets of ALARA and is fully consistent with the CERN radiation safety policy. The policy requires a plan for installation, operation and maintenance of CMS during LHC Phase-2 where the anticipated annual individual doses received by personnel are comparable with the typical annual doses due to cosmic radiation and the local natural environment in the Geneva area. The requirement for the maximum annual individual dose for LS1 activities, CERN wide, was 3 mSv. This is expected to be maintained, or reduced to 2 mSv, for LS2 and LS3. Every effort will be made to keep the dose to each individual involved in a particular work-package/work-stream to less than 100 µSv and the collective dose to the team involved to less than 500 µSv. The dose requirements for specific radiation areas are summarised in the table presented in Fig. 7.1.
Figure 7.1: Summary of the classification of non-designated and radiation areas at CERN, taken from https://edms.cern.ch/document/810149/1.

A detailed radiation study was undertaken by the BRIL-CMS-RS group. The studies were performed with an updated version of the FLUKA simulation package using a detailed simulation of the different materials used in the supermodules. The FLUKA simulations have been validated with data from monitoring sensors inside the CMS detector, although there are no sensors located directly on the supermodules themselves.

Three situations are considered:

1. ECAL Barrel removal process: (in cavern) from week 15 to 20 (this includes two weeks of enfourneur installation, see Sections 6.1 and 6.2).
   - Residual dose rate estimate involving all cavern elements present for a particular opening configuration.
   - The exact CMS configuration at the time of the removal, for the situation with no beam pipe, no tracker, and the endcap in retracted position.

2. Electronics integration: ECAL Barrel supermodule in SX5 (week 21 to 73).
   - Relevant for teams working on the barrel electronics refurbishment once the SMs are removed from the underground cavern
   - Compute residual dose rates with supermodule backplate removed
   - Determine if any shielding is required to work on SM refurbishment

3. ECAL Barrel re-installation in UX5 (week 79 to 83)
   - The CMS configuration inside the cavern will be different. The Endcap calorimeter will have been removed. This will lower the ambient radiation dose. The level of radiation from of other components will also be lower, following one more year of activation cooling (although this has a marginal effect).
7.2. Removal process (and re-installation)

The radiation level has been estimated for the removal of the supermodules. CMS will be in a configuration without the beam pipe and tracker and with the endcap calorimeter either in the garage position or fully removed. More detailed calculations with a more refined description of material inside the supermodules are still ongoing. The final results must be endorsed by the CERN Radiation Protection Group. It is expected that the radiation figures will be similar. The ambient equivalent dose rates are considered after 20 weeks cooling-time. This corresponds to the start of the removal work. The ambient equivalent dose rates are illustrated in Fig. 7.2.

![Figure 7.2: Ambient dose equivalent rates (in \(\mu S\)v/h) after 20 weeks of cooling time, averaged over the full barrel length from zero to 300 cm.](image)

The ambient dose equivalent rates at the edge of the calorimeter, where the enfourneur will be located are shown in Figs. 7.3, 7.4, and 7.5.

The above results show that the dose rates are low. However, the working time is an important parameter (see Section 6) and will be considered and optimized during the training sessions. These studies also show that the ambient dose equivalent rates are all less than 5 \(\mu S\)v/h, well below the limit of 15 \(\mu S\)v/h for a supervised radiation area (see Fig. 7.1 above).

7.2.3 Electronics installation

Estimates for the radiation levels have been carried out for individual SMs in SX5. The results are shown in Fig. 7.6 for week 1, after the start of LS3, and week 20, corresponding to the date of SM removal. The figures illustrate the benefit of radiation cooling before removing the supermodules. The ambient dose rate decreases by nearly a factor of four. The dose rates are below 0.4 \(\mu S\)v/h after 20 weeks outside the supermodule. With respect to Fig. 7.1, the refurbishment work could be carried in a supervised radiation area or in a non-designated area. This will need to be discussed and agreed with CERN RP.
Figure 7.3: Ambient dose equivalent rates (in $\mu$Sv/h) after 20 weeks of cooling time, averaged over 360 degrees in $\phi$.

Figure 7.4: Ambient dose equivalent rates (in $\mu$Sv/h) after 20 weeks of cooling time as a function of radius, $R$, averaged over 360 degrees in $\phi$, and over the $Z$ range $305 < Z < 350$ cm. The estimation region is indicated on the left-hand plot.

### 7.3 Mechanics, supermodule extraction, rework + replacement

It is important to understand the required working time for removal/installation to provide input to the ALARA evaluation. The training foreseen in 2017 with a dummy supermodule (see Section 6) will be an important input to this appraisal. The specialized tooling for the supermodule extraction and storage (enfourneur, assembly, integration, storage frames) used during LHC Phase-1 are certified for further use. They will be inspected prior to being used following the CERN safety rules for handling tooling.

### 7.4 Cooling, humidity

The ECAL Barrel cooling temperature will be lowered from the Phase-1 temperature of 18 $^\circ$C to 9 $^\circ$C. The ECAL Barrel is cooled by water circulation. Inside the supermodules, the cooling circuit will remain the same as in Phase-1. It will not be changed or modified during the recom
Figure 7.5: Ambient dose equivalent rates (in $\mu$Sv/h) after 20 weeks of cooling time as a function of $Z$ position, averaged over 360 degrees in $\phi$, and averaged over a radial range from $0 < R < 129$ cm. The estimation region is indicated on the left-hand plot.

Figure 7.6: Supermodule activation in LS3 after a 1 week (left plot) and a 20 week (right plot) cooldown period. The ambient dose equivalent rate (in $\mu$ Sv/h), averaged over the most activated part of the supermodule, is plotted as a function of radius $R$. The region inside the supermodule is indicated on both plots.

missioning of the SMs. The flow and pressure will remain the same (see Section 4). The cooling safety issues described in the ECAL TDR are still valid and have been proved during the current 10 years of operation. Nevertheless pressure and leak tests, similar to those performed at the construction phase, will need to be repeated before re-installation. The main change is that the ECAL Barrel will be operating below the cavern dew point. This requires a better insulation of all the cooling circuits (see Section 4) and operating inside a dry environmental screen. The control and safety systems will remain the same.

### 7.5 Electrical protection

The high voltage electrical systems will remain the same while the low voltage system will be upgraded. The electrical protection philosophy, will remain the same as the legacy system (see discussion on slow control functions in Section 4).
7.6 Lasers

The ECAL light monitoring system will remain the same as in LHC Phase-1 (see Section 5.6). The light monitoring system [60] uses three light sources from three different lasers: one 447 nm, one 527 nm and one 709 nm. These are Class IV lasers. The light beam is successively switched to 72 barrel optical transfer fibres. The sources and the switching system are installed in a dedicated ECAL laser room in USC55. The system has run since 2010 without safety issues. The ECAL light monitoring was installed at CMS in 2008. However, the system has been modified: the blue lasers have been replaced and a green laser has been added. The two new blue lasers are DPSS (diode pulsed solid state) DP2-447 lasers from Photonics. These lasers use an Nd:YVO4 crystal and a proprietary intra-cavity frequency triple technology. They have a simple structure and compact design, and are more reliable than the alternative lamp-pumped lasers.

A major modification of the laser room occurred in 2012, in order to accommodate the space for the new lasers, keeping the old one in place during the commissioning period. The laser room has access limited to CERN-authorized experts, who have passed all the required safety training courses. The laser room has a flash light visible from outside as well as a shutter, also for the three inner doors. The lasers are well enclosed and there is no direct visible path to the light source. Suitable safety goggles in sufficient quantities are available for all authorised personnel present in the laser area.

The lasers are registered with the CERN safety commission, as are all lasers of Class 3 or 4 at CERN. Each laser has a ISILaser Form (Initial Safety Information on Lasers). The relevant characteristics of the laser, with respect to safe operation, are provided on the form together with the name of the responsible person and other persons authorised to operate the equipment. Authorisation to use the laser is only granted when appropriate information has been given. The related safety inspection for the ECAL lasers are accessible on EDMS.

Chapter 8

Project organisation, schedule and costs

8.1 Project management and WBS structure

The ECAL Barrel upgrade has two co-managers who report to the ECAL system manager. They are appointed by the ECAL system manager for two year terms subject to approval by the ECAL Institution Board. The Institution Board consists of one member per institution working on the ECAL project. The project is organized according to the organizational chart shown in Fig. 8.1, with the ECAL upgrade managers in the highest level (level 1). The HCAL system has a system manager and a deputy. The HCAL Barrel Phase-2 upgrade is managed by the HCAL “Detector Maintenance and Upgrades” manager, who is appointed by the HCAL system manager subject to approval by the HCAL Institution Board for (renewable) terms of two years. The HCAL Barrel Phase-2 organization chart is shown in Fig. 8.2. The shaded areas correspond to the megatile replacement, which is no longer needed as described in Appendix A.

8.2 Institutional responsibilities

The institutional responsibilities as presently understood are shown in Tables 8.1 and 8.2 for the ECAL and HCAL, respectively. The institution is taken here as the international group responsible for a certain deliverable of the upgrade. Installation and common test benches and testbeams are the responsibility of the ECAL and HCAL technical coordination teams, which comprise members from several institutions.

8.3 Overall planning, schedule and milestones

The project has been scheduled using the Merlin project management software which has been adopted as the standard tool by the CMS upgrade project. The schedule includes dependencies between elements of the upgrade, estimated durations and milestones. An example of this is given in Fig. 8.3 for the VFE. A representation of the high level milestones is shown in Fig. 8.4, and the labelled milestones are explained in Table 8.3.

For each of the major electronics boards there is a development cycle starting with a demonstrator board followed by one or two prototypes. The boards are bench-tested and are also then used to instrument a crystal matrix (ECAL) or scintillator tower (HCAL) in a testbeam. The on-detector electronics will be qualified for radiation and magnetic field tolerance. After the prototyping stage there is also time available for an additional pre-production development cycle. The off-detector electronics follows a similar development cycle but 18 months is budgeted for each iteration and the delivery date is one year later than the on-detector electronics because it will take one year to install the on-detector electronics. Early production versions of the BE will be used to instrument the test stands used in the on-detector electronics integration.
Chapter 8. Project organisation, schedule and costs

Figure 8.1: The ECAL upgrade organisation chart with the associated WBS (Work Breakdown Structure) numbers.

The intent is to wait until as late as possible to fabricate the BE electronics in order to exploit the latest FPGA.

The ECAL on-detector electronics requires 12240 VFEs, 2448 LVRs and FEs plus 10% spares to account for yield. The quality assurance procedure for the VFE is described in Section 3.5. Similar procedures will be required for the FE and LVR boards. The off detector electronics requires 108 boards to be produced for the ECAL and 18 identical boards for the HCAL plus 5% spares for yield in both detectors. They will be tested in three different production testing centers, with a burn-in and quality assurance tests to ensure each board meets the performance specifications.

Comprehensive Reviews of project progress are held annually. Engineering Design Reviews (EDRs) will be performed after the final prototyping is complete. After approval, the pre-production versions will be produced with the full engineering run ASICs. The Engineering Systems Review (ESR) will follow and, after approval, full-scale production will begin. Production includes quality control testing and burn-in procedures. The ASICs used in the on detector boards will be tested prior to the board fabrication.

A completely qualified set of components will be delivered to the technical coordination group for integration. The integration schedule is discussed in detail in Section 6. The ECAL on-detector boards will be delivered one year before installation so that final versions are available for the SM integration training that will take place in the year before integration. The HCAL BCP is exactly the same hardware as used for the ECAL so the development and production
Figure 8.2: The HCAL upgrade organisation chart with the associated WBS numbers. The shaded areas correspond to the megatile replacement, which is no longer needed as described in Appendix A.

8.4 Costs

The costs of the deliverable elements for the ECAL are given in Table 8.4. The costing is done with the baseline design described in the previous chapters and follows the CMS costing rules, which exclude most labor and all R&D costs. Costs of standard components are taken from the CMS costing book. Each item includes the cost of spares needed due to production yield and components to instrument the test benches. The VFE ASIC costs include both the cost of the chip submission and the cost of the packaged ASICs. The LVR, FE, BCP and DTH costs include the components and fabrication of the boards. The cooling and cabling costs include the technician labor. The costs are given in Swiss Francs using the standard currency conversion rates in the CMS costbook for components purchased in other currencies. The costs of the deliverable elements for the HCAL are given in Table 8.5.
Table 8.1: ECAL institutional responsibilities.

<table>
<thead>
<tr>
<th>Description</th>
<th>WBS Reference</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFE PreAmp ASIC</td>
<td>1.1.1</td>
<td>France (Saclay)</td>
</tr>
<tr>
<td>VFE ADC ASIC</td>
<td>1.1.2</td>
<td>Portugal (Lisbon) &amp; Italy (Milano,Trieste,Torino,Roma)</td>
</tr>
<tr>
<td>VFE Board</td>
<td>1.1.3</td>
<td>Switzerland (ETH)</td>
</tr>
<tr>
<td>LVR Board</td>
<td>1.2.1</td>
<td>Switzerland (ETH) &amp; CERN</td>
</tr>
<tr>
<td>Low Voltage Power</td>
<td>1.2.2</td>
<td>Switzerland (ETH) &amp; CERN</td>
</tr>
<tr>
<td>High Voltage System</td>
<td>1.2.3</td>
<td>Italy (Milano,Trieste,Torino,Roma)</td>
</tr>
<tr>
<td>Front End Board</td>
<td>1.3.1</td>
<td>USA (Minnesota,Northeastern,Notre Dame, Virginia,Wisconsin)</td>
</tr>
<tr>
<td>Fiber Optics</td>
<td>1.3.2</td>
<td>USA (Minnesota,Northeastern,Notre Dame, Virginia,Wisconsin &amp; UK (RAL,Bristol)</td>
</tr>
<tr>
<td>SuperModule Patch Panels</td>
<td>1.3.3</td>
<td>UK (RAL,Bristol)</td>
</tr>
<tr>
<td>BCP Board</td>
<td>1.4.1</td>
<td>USA (Minnesota,Northeastern,Notre Dame, Virginia,Wisconsin)</td>
</tr>
<tr>
<td>DTH Board</td>
<td>1.4.2</td>
<td>CERN</td>
</tr>
<tr>
<td>Off Detector Patch Panels</td>
<td>1.4.3</td>
<td>UK (RAL,Bristol)</td>
</tr>
<tr>
<td>Cooling Plant &amp; Pipes</td>
<td>1.5.1</td>
<td>CERN</td>
</tr>
<tr>
<td>Enfourneur</td>
<td>1.5.2</td>
<td>CERN &amp; Italy (Milano,Trieste,Torino,Roma)</td>
</tr>
<tr>
<td>Cabling and Connectors</td>
<td>1.5.3</td>
<td>CERN &amp; Switzerland (ETH) (LV) &amp; Italy (Milano,Trieste,Torino,Roma) (HV)</td>
</tr>
</tbody>
</table>

Table 8.2: List of currently declared interests and participation for HCAL institutes and institute groups in the HCAL Phase-2 upgrade.

<table>
<thead>
<tr>
<th>Description</th>
<th>WBS Reference</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCP Board</td>
<td>1.3.1</td>
<td>USA (Minnesota,Northeastern,Notre Dame, Maryland,Notre Dame,Virginia,Wisconsin)</td>
</tr>
<tr>
<td>DTH Board</td>
<td>1.3.2</td>
<td>CERN</td>
</tr>
<tr>
<td>HO and HF Back-end</td>
<td>TBD</td>
<td>USA (Iowa,Minnesota)</td>
</tr>
<tr>
<td>Electronics I&amp;C</td>
<td>TBD</td>
<td>USA (Baylor,Minnesota)</td>
</tr>
<tr>
<td>Controls and Online Software</td>
<td>TBD</td>
<td>USA (Alabama,Baylor,Minnesota)</td>
</tr>
<tr>
<td>Simulation Studies</td>
<td>TBD</td>
<td>USA (Baylor,Fairfield,Iowa,Texas Tech)</td>
</tr>
<tr>
<td>Trigger Algorithms</td>
<td>TBD</td>
<td>USA (Brown,Iowa,Princeton,Texas Tech)</td>
</tr>
</tbody>
</table>
Figure 8.3: The ECAL VFE upgrade schedule with dependencies.
Figure 8.4: The ECAL and HCAL Barrel upgrade schedule with milestones.
Table 8.3: The ECAL and HCAL project milestones.

<table>
<thead>
<tr>
<th>Milestone Code</th>
<th>Description</th>
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<tbody>
<tr>
<td>EB</td>
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<tr>
<td>VFE.1</td>
<td>VFE architecture specification complete</td>
<td>Q4 2017</td>
</tr>
<tr>
<td>VFE.2</td>
<td>VFE first VFE prototype tested</td>
<td>Q4 2018</td>
</tr>
<tr>
<td>VFE.3</td>
<td>VFE second VFE prototype tested</td>
<td>Q4 2019</td>
</tr>
<tr>
<td>VFE.4</td>
<td>VFE radiation/ B field qualification complete</td>
<td>Q2 2020</td>
</tr>
<tr>
<td>VFE.5</td>
<td>VFE production ready</td>
<td>Q2 2021</td>
</tr>
<tr>
<td>VFE.6</td>
<td>VFE CATIA and ADC-DTU ASICs tested and delivered</td>
<td>Q4 2021</td>
</tr>
<tr>
<td>VFE.7</td>
<td>VFE Boards tested, burnt-in and delivered</td>
<td>Q4 2022</td>
</tr>
<tr>
<td>FE.1</td>
<td>FE architecture specification</td>
<td>Q4 2017</td>
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<tr>
<td>FE.2</td>
<td>First FE prototype with GBTx (4.8 Gb/s) tested</td>
<td>Q4 2018</td>
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<td>FE.3</td>
<td>Second FE prototype with lpGBT (9.6 Gb/s) tested</td>
<td>Q4 2019</td>
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<tr>
<td>FE.4</td>
<td>Radiation/ B field qualification of Second FE prototype</td>
<td>Q2 2020</td>
</tr>
<tr>
<td>FE.5</td>
<td>FE production ready</td>
<td>Q2 2021</td>
</tr>
<tr>
<td>FE.6</td>
<td>FE Boards tested, burnt-in and delivered</td>
<td>Q4 2022</td>
</tr>
<tr>
<td>LVR.1</td>
<td>LVR architecture specifications</td>
<td>Q4 2017</td>
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<td>LVR.2</td>
<td>First LVR prototype tested</td>
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<td>LVR.3</td>
<td>Second LVR prototype tested</td>
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<td>LVR.4</td>
<td>Radiation/ B field qualification of Second LVR prototype</td>
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<td>LVR.5</td>
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<td>LVR.6</td>
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<tr>
<td>BE.1</td>
<td>Definition of trigger primitive</td>
<td>Q1 2017</td>
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<tr>
<td>BE.2</td>
<td>Specification of back-end electronics architecture</td>
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<td>BE.3</td>
<td>BCP demonstrator tested</td>
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<tr>
<td>BE.4</td>
<td>BCP prototype tested</td>
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<td>CO.1</td>
<td>Specification of super module power consumption</td>
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<tr>
<td>CO.3</td>
<td>Specification of cooling system complete</td>
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<td>Design of cooling system complete</td>
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<td>ME.1</td>
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<td>Preliminary choice of scintillator/WLS materials</td>
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<td>SC.2</td>
<td>Results of scintillator/WLS material CASTOR tests</td>
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<td>BE.1</td>
<td>Specification of back-end electronics architecture</td>
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</tr>
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<td>BE.2</td>
<td>BCP demonstrator tested</td>
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</tr>
<tr>
<td>BE.3</td>
<td>BCP prototype tested</td>
<td>Q3 2020</td>
</tr>
<tr>
<td>BE.4</td>
<td>BCP production ready</td>
<td>Q1 2022</td>
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<tr>
<td>BE.5</td>
<td>BCP Tested, burnt-in and delivered</td>
<td>Q4 2023</td>
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Table 8.4: Costs of the deliverable elements of the ECAL upgrade.

<table>
<thead>
<tr>
<th>Description</th>
<th>L3 WBS Number</th>
<th>Cost (kChF)</th>
</tr>
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<tbody>
<tr>
<td>VFE CATIA ASIC</td>
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<td>VFE Lite-DTU ASIC</td>
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<td>LVR board</td>
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<td>Low voltage power supplies</td>
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<td>Front end board</td>
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<td>Fiber optics</td>
<td>1.3.2</td>
<td>559</td>
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<td>Supermodule patch panels</td>
<td>1.3.3</td>
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<td>BCP board</td>
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<td>DTH board</td>
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<td>ATCA crates</td>
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<td>Off detector patch panels</td>
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<td>Cooling plant &amp; pipes</td>
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<td>Enfourneur</td>
<td>1.5.2</td>
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<td>Cabling and connectors</td>
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<td>Integration test stands</td>
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<td><strong>Total</strong></td>
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Table 8.5: Costs of the deliverable elements of the HCAL upgrade.

<table>
<thead>
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<th>Description</th>
<th>L3 WBS Number</th>
<th>Cost (kChF)</th>
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</thead>
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<td>DTH</td>
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<tr>
<td>ATCA crates</td>
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<td><strong>Total</strong></td>
<td></td>
<td><strong>580</strong></td>
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</table>
Chapter 9

Detector performance

9.1 Introduction and requirements

This section describes the detector performance studies used to optimize the design of the ECAL barrel upgrade. The studies are driven by the basic physics requirement that the performance of the ECAL during HL-LHC running should be as close as possible to the performance of the ECAL at the beginning of LHC operations. The legacy system was optimised to study electroweak symmetry breaking through the Higgs mechanism. The benchmark physics modes used were $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ where one or both of the $Z$ bosons decays to electrons. These require excellent energy resolution, high efficiency for the detection of electrons and photons, a fast response, and high granularity to mitigate the effects of pileup. The legacy system achieved all of these and CMS was successful in observing these Higgs boson decay modes. The ECAL has also been essential in many other physics studies, such as the standard model measurements and SUSY searches involving photons and electrons in the final state. However as the Higgs boson channels are the most challenging they remain the appropriate benchmark modes to optimize the design. The precision study of these modes is central to the HL-LHC physics. There are also new physics channels involving Higgs bosons that are central to the HL-LHC program. An example is the search for di-Higgs production which is important to understand the details of the vacuum potential. The highest sensitivity for these searches is found in the channel in which one Higgs boson decays to a photon pair and one to a $b \bar{b}$ pair. The same performance criteria for the precision study of the Higgs to di-photon decays will also maximize the sensitivity for the Higgs pair search.

This section is organised in several parts. First, the simulation of the signal obtained from the upgraded EB electronics is described. This includes the effects of APD dark current increases and crystal transparency losses. The performance of ECAL amplitude and timing resolution is estimated for signals with $\langle PU \rangle = 200$ and the efficiency for the rejection of spikes using both signal pulse shapes and shower shapes is calculated. Secondly, the reconstruction and identification efficiencies for electrons, photons, tau leptons and jets, including those from b quarks, are presented. These include the full simulation of ECAL and HCAL light losses expected during Phase-2. The performance of preliminary Level-1 electron/photon algorithms that use the full crystal granularity is also shown. Finally, the performance of the upgraded detector for key physics signals, including $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$ in the Vector Boson Fusion (VBF) channel, and $HH \rightarrow q\bar{q}q\bar{q}\gamma\gamma$, is shown. The improved sensitivity offered by precision ($\sim 30$ ps) timing is calculated for the $H \rightarrow \gamma\gamma$ channel.
9.2 The ECAL barrel HL-LHC pulse simulation model

9.2.1 Simulation of photocurrent

The simulation of the EB signal pulse at the input of the front-end electronics is performed in several steps. The evolution of a shower from an incoming photon in a crystal is simulated with GEANT4 [40]. Emission and propagation of photons from Cerenkov radiation and PbWO₄ scintillation (optical photons) is simulated separately. Figure 9.1 shows the average photocurrent produced in the APDs from an EM shower. The individual contributions from Cerenkov and scintillation processes are shown in addition to the total contribution.

![Graph showing photocurrent over time](image)

Figure 9.1: Simulated average pulse shape from EM shower at the APDs (photocurrent). Contributions from Cherenkov and scintillation emissions are shown separately.

The scintillation photons are emitted isotropically with the respective wavelengths and decay times set according to previous measurements [3]. The SLitrani [29] package is used to simulate the transport of optical photons through the crystal volume until they are detected by the APDs. The simulations use realistic crystal geometry with a pair of APDs attached to the rear using optical glue. The photon propagation takes into account the wavelength dependence of the refractive index and of the absorption length of lead tungstate. The peaks in the distribution arise from the internal reflection of the photons. Photons can traverse the full length of a crystal multiple times until detection in the APDs, resulting in the multiple peaks shown in Fig. 9.1.

Radiation damage effects are introduced by means of additional induced absorption coefficients, with a wavelength dependence characteristic of both ionizing radiation and hadron damage. The optical properties of the coupling between crystals and APDs, and the photon detection efficiency of the APDs as a function of wavelength are also modeled. The overall light output from Cherenkov and scintillation processes has been validated using a variety of experimental measurements [19, 22, 65]. More details on the properties of lead tungstate crystals can be found in [3, 17].

Although Fig. 9.1 shows an average pulse shape, simulations of individual pulse shapes are performed as well. There are two main contributions to fluctuations in the photocurrent from individual hits with the same deposited energy in a ECAL crystal. The first is due to fluctuations in the shape of EM showers that produce variations in the path length of the detected optical photons. This results in a timing jitter of the pulse shape of less than 20 ps. The second
9.3. Suppression of ECAL spikes at the HL-LHC.

The anomalous energy deposits due to hadrons interacting with the APDs, known as spikes, are described in Section 1.9.1.2 and Section 3. The suppression of spikes in the L1 trigger is critical for HL-LHC operation. It is accomplished exploiting the timing evolution and crystal isolation difference between a spike and a scintillation signal pulse.
Figure 9.3 shows the rate of events with ECAL hits with measured energy above a given $E_T$ threshold for HL-LHC conditions with 200 minimum bias interactions per bunch crossing. The measured energy of a simulated ECAL hit is the sum of two contributions. The first contribution arises from particle interactions in the ECAL crystals. It is detected as photoelectrons from both crystal scintillation and Cherenkov radiation. The second contribution comes from energy depositions in the active region of the APDs. For the overwhelming majority of ECAL hits, the second contribution comes from ionizing losses of showering particles in APD and is negligible. For results in this section, the “signal” is defined as hits with 90% or more of its measured energy coming from detected photo-electrons.

Figure 9.3 shows the fraction of events with signal hits represented by the blue line. ECAL hits with anomalous energy deposits in APDs can also have simultaneous energy depositions in a crystal. Figure 9.3 shows the fraction of events with “spike” hits as the red line, where “spikes” are defined as ECAL hits with 50% or more of the measured energy coming from the APD. The expected rate of events with ECAL hits above 10 GeV is dominated by hits with anomalous energy deposits within the APDs.

![Graph](image)

**Figure 9.3:** Fraction of events, for $\langle PU \rangle = 200$, that have ECAL energy deposits above a given $E_T$ threshold. Separate contributions from scintillation hits and APD “spikes” are shown. The amplitude of APD hits corresponds to undamaged crystals with the Phase-1 front-end architecture.

The results shown in Fig. 9.3 are for ECAL energy deposits in undamaged crystals with the legacy front-end electronics (CR-RC shaping time, $\tau = 43$ ns). The amplitude scale for APD hits is a factor 1.48 higher for the HL-LHC TIA architecture, due to the shorter shaping time of TIA. The amplitude scale for scintillation hits will decrease with radiation damage in HL-LHC while the APD energy scale will remain unchanged, further increasing the level of spike contamination in high $E_T$ signals.

Figure 9.4 shows the expected rate of events for ECAL energy deposits including both scintillation and spike signals above a given $E_T$ threshold in HL-LHC. These calculations are based on 2808 collision bunch crossings per LHC orbit (giving a maximum rate of events of 31 MHz). The rate of events for the expected electron and photon Level-1 trigger thresholds in HL-LHC ($E_T > 30$ GeV) is more than the total allocated Level-1 bandwidth of 750 kHz and is dominated by APD spikes. Highly efficient suppression of spikes at both the Level-1 trigger stage, and in
offline reconstruction, is therefore needed to reduce the rates to acceptable levels.

![Figure 9.4: Expected rate of events, for \( \langle PU \rangle = 200 \), that have ECAL energy deposits including both scintillation and spike signals above a given \( E_T \) threshold. HL-LHC conditions with integrated luminosities of 300, 1000, 3000, and 4500 fb\(^{-1} \) are shown.]

**9.3.1 Spike discrimination with pulse time development.**

The APD pulses from spikes have a faster rise time and much shorter duration than scintillation pulses. They arise from direct ionization in the silicon rather than the de-excitation of electrons from excited states which is responsible for scintillation. The legacy preamplifier used CR-RC shaping which made the spike and scintillation pulses very similar and limited the ability to discriminate between the two. In contrast, the Trans-Impedance Amplifier (TIA) proposed for the upgrade has a very fast response and a short shaping time, which preserves the spike discrimination and also significantly enhances the timing resolution. The resulting pulse is digitized with a 160 MHz sampling frequency, as described in Section 3.

Figure 9.5 shows the average analogue pulse shapes and digitization samples for an in-time signal and an APD spike hit. These pulse shapes are based on measurements with TIA ASIC prototype in a test beam, described in Section 3.

A simple and fast algorithm can be executed online to tag spikes. It is based on three consecutive amplitude samples after pedestal subtraction: \( a_{i-1} \), \( a_i \) and \( a_{i+1} \). In the following study, sample triplets centered on a maximum sample are considered (\( a_i \geq a_{i-1} \) and \( a_i \geq a_{i+1} \)) but the algorithm will work on any set of three consecutive samples. A pair of ratios is formed,

\[
R_- = \frac{a_{i-1}}{a_i}, \quad R_+ = \frac{a_{i+1}}{a_i}.
\]  

(9.1)

If all three samples are above pedestal and belong to the signal pulse then the relation between \( R_- \) and \( R_+ \) is well defined by the pulse shape shown in Fig 9.5. A discriminant value is calculated as

\[
LD = R_+ - \sum_{i=0}^{3} p_i \times R^i_-.
\]  

(9.2)
Figure 9.5: Average pulse shapes from APD spike and scintillation signals. The amplitude samples from the digitization at 160 MHz sampling frequency are shown as dots and squares.

with the weights

\[ p_0 = +1.48322 \]  
\[ p_1 = -2.20018 \]  
\[ p_2 = +1.89766 \]  
\[ p_3 = -0.68344 \]  

The parameters \( p_i \) correspond to a polynomial fit of the signal pulse shape \( R_+ \) vs. \( R_- \). The quantity \( R_+ (R_-) \) is constructed from the signal pulse shape \( A(T) \), and can be obtained from dedicated measurements in test beams or in-situ. Theoretically, \( LD = 0 \) for signal samples in the absence of any deviations from the average pulse shape. Noise fluctuations and out-of-time pileup result in smearing of \( LD \) values for signal pulses. APD spikes have a different pulse shape and result in \( LD \) values clustered away from \( LD = 0 \).

Typical distributions of the discriminant value, \( LD \), for APD spikes and scintillation signals in the presence of noise are shown in Fig. 9.6. An APD spike can be tagged if the \( LD \) value is below a user-defined threshold, \( LD_{\text{max}} \). The distributions in Fig. 9.6 suggest that a good value for \( LD_{\text{max}} \) is between \(-1.5 \) and \(-0.5 \).

The spike tagging performance with the discriminant \( LD \) in HL-LHC conditions (\( \langle PU \rangle = 200 \)), expected noise levels and radiation damage effects, described in Section 3 and Section 2, was evaluated by using an analogue waveform of the entire LHC orbit in a specific ECAL channel. The number of minimum bias interactions in each bunch crossing was generated using a Poisson distribution with an average pileup of 200. Energy depositions from each pileup interaction were generated according to probability density functions (pdf) obtained from a large sample of simulated minimum bias events.

The analogue waveform is a sum of the signal pulse shapes from each bunch crossing with amplitudes proportional to the pileup energy in each bunch crossing. An in-time bunch crossing was randomly chosen and a signal or APD spike pulse shape was added to the waveform. A signal pulse shape of the desired amplitude was simulated with arbitrary readout phase with respect to the LHC clock. An APD spike hit was simulated to have an amplitude and tim-
9.3. Suppression of ECAL spikes at the HL-LHC.

Figure 9.6: Distribution of pulse shape discriminant, $LD$, for APD spikes (red) and scintillation signals (blue) with a random readout phase. The distributions are shown for pulses with amplitudes of $10 \times \sigma_{\text{noise}}$ (left) and $50 \times \sigma_{\text{noise}}$ (right).

Figure 9.7 shows the performance of APD spike tagging with $LD_{\text{max}} = -0.1$ for events with $\langle \text{PU} \rangle = 200$ and 2808 colliding LHC bunches. It demonstrates that this method of spike tagging is nearly 100% efficient for signal hits above 10 GeV and reduces the spike rate to a few Hz for the HL-LHC era up to $4500 \text{ fb}^{-1}$.

If the pulse is sampled at 80 MHz instead of 160 MHz, the above algorithm will not work. For this lower sampling frequency, spike pulses will always have only two samples above zero, whereas signal pulses will have either two or three samples above zero, depending on the readout phase. Two samples above pedestal are insufficient to distinguish between pulses of different width.

9.3.2 Spike tagging using event topology

In the legacy system, spike suppression is performed offline by exploiting the fact that spikes result in an apparent energy deposition isolated in a single crystal whereas electromagnetic showers have a Gaussian lateral profile characterized by the Moliere radius for the crystal material. In EB, this is roughly the same as the lateral size of a single crystal. It has been shown in [8] that spike discrimination based on the different lateral profile is inadequate to fully suppress spikes necessitating the need to augment it with timing discrimination.

In the proposed upgrade, single crystal information will be provided to form the Level-1 trigger primitive rather than the present $5 \times 5$ crystal scheme. The legacy offline algorithm for spike suppression will be implemented online and combined with the timing information to provide a very powerful and robust suppression. This offline algorithm is based on the energy sharing
Figure 9.7: Performance of spike tagging with $L_D^{\text{max}} = -0.1$ in minimum bias interactions at $\langle \text{PU} \rangle = 200$. Left: Signal efficiency. Right: Event rate with spike hits above a given $E_T$ threshold.

between neighboring crystals. A topological variable known as the “Swiss-cross” is defined as $1 - E_4 / E_1$, where $E_1$ is the energy of the seed (central) crystal of a $3 \times 3$ array of cells, and $E_4$ is total energy of the four adjacent cells in the $3 \times 3$ array. Figure 9.8 shows a typical distribution of $1 - E_4 / E_1$ for scintillation hits and for APD spikes. Figure 9.9 shows the discrimination between scintillation and spike signals using this algorithm for simulated minimum bias events with an average pileup of 200. The simulation uses ageing conditions for 300, 1000, 3000, and 4500 fb$^{-1}$. The signal efficiency versus spike acceptance is shown for a set of representative $E_T$ thresholds. Figure 9.10 shows the expected rate of events with spike hits above a given $E_T$ threshold, with the efficiency for correctly identifying signal pulses set to 90%.

Figure 9.8: Distribution of the “Swiss-cross” variable for ECAL seeds with $E_T > 3$ GeV. The open histogram shows all hits, including APD spikes. The shaded histogram includes hits that have less than 1% of their energy from APD spikes.
Figure 9.9: The Swiss-cross algorithm performance for different $E_T$ thresholds. The vertical and horizontal axes show the fraction of signal and spike hits passing the algorithm requirements, respectively. Left top: $300 \text{ fb}^{-1}$. Right top: $1000 \text{ fb}^{-1}$. Left bottom: $3000 \text{ fb}^{-1}$. Right bottom: $4500 \text{ fb}^{-1}$.
Figure 9.10: The event rates due to APD spikes after spike tagging with the “Swiss-cross” algorithm, assuming a signal efficiency of 90%.

In summary, the ECAL upgrade allows for two independent methods of tagging spike energy deposits. The most powerful method is based on pulse shape discrimination, and is summarized in Fig. 9.7. This method alone can reduce spike rate to the required levels. The other method is based on topological discrimination and is summarized in Fig. 9.10. Both methods combined will reduce the event rate at the Level-1 trigger to negligibly low levels throughout HL-LHC operation.

9.4 Energy and timing reconstruction

The ECAL performance for measurements of the energy and timing of incoming particles depends on many factors. The impact of the proposed changes in the pulse shape and digitization rate of the upgraded detector, and the new running conditions for noise and pileup levels at HL-LHC, should be evaluated using realistic reconstruction algorithms.

Amplitude and timing reconstruction will be performed on digitized samples using algorithms run in the off-detector electronics as well as in offline reconstruction. The algorithms used in this section are based on those currently in use in the legacy system. They will perform well in HL-LHC conditions and are used to illustrate the expected HL-LHC performance. More advanced and robust algorithms are expected in the future.

The readout of an ECAL channel is a set of amplitude samples. It is formed by pulses from different LHC bunch crossings on top of the pedestal. Pulses are digitized at 160 MHz sampling frequency. It is sufficient to have 4–5 samples to measure the in-time hit plus a maximum 10 preceding samples to estimate the pedestal and the contribution from the out of time pileup. Figure 9.11 shows a possible choice of data frame consisting of 20 amplitude samples. The readout delay is adjusted to have the signal peak at the 15th sample. Pedestal and noise levels are set to zero in this figure for illustrative purposes.

9.4.1 Amplitude reconstruction

The MultiFit algorithm [66] currently used in the legacy system models the data frame as a sum of an in-time signal pulse and a series of out-of-time pulses. The algorithm was configured
9.4. Energy and timing reconstruction

![Graph showing signal pulse shape and possible choice of data frame.](image)

Figure 9.11: Left: signal pulse shape (red line) and possible choice of data frame (black dots). Right: illustration of amplitude reconstruction for a data frame with significant out-of-time pileup.

for the HL-LHC studies to use the sum of five pulses in the bunch crossing interval \([BX0 - 3; BX0 + 1]\). A template fit is performed, minimizing \(\chi^2\) for the best combination of in-time and out-of-time pulses. The algorithm requires knowledge of the signal pulse shape and noise correlation matrix. These are periodically measured in dedicated collision data runs.

Figure 9.11 shows the MultiFit performance for a data frame with significant contributions from out-of-time pileup. The reconstructed in-time amplitude is a sum of signal and in-time pileup. The algorithm cannot separate these contributions based on amplitude samples alone. However, it is possible to estimate the in-time pileup contribution at a higher level of reconstruction, based on the topology of energy deposits in neighboring ECAL crystals.

The amplitude resolution is estimated from the measured fluctuation of the reconstructed in-time amplitude with respect to its true value, including the in-time pileup. Figure 9.12 shows the amplitude resolution, scaled to the electronics noise RMS of a single sample, plotted as a function of the electronics noise RMS, for an average pileup of 200. The amplitude resolution is dominated by noise for all practical values of noise levels and signal amplitudes. The amplitude resolution is less than the noise RMS of a single sample because the reconstruction algorithm combines multiple samples and properly taking correlations into account. The algorithm suppresses the contribution from out-of-time pileup to negligible levels.

The expected contribution from in-time pileup is shown in Fig 9.13. It is a highly asymmetric distribution. In the worst case scenario, for an ECAL channel at \(|\eta| = 1.4\) and \(\langle PU \rangle = 200\), the interval that covers 68% of the distribution \((\pm \sigma_{\text{effective}})\) is \(\pm 0.028\) GeV. It shows that the in-time pileup contribution is much smaller than the electronics noise on average. However, a small fraction of ECAL hits will be significantly affected by in-time pileup.

**9.4.1.1 Energy resolution**

The energy resolution can be estimated as the sum of three independent contributions described by noise, stochastic, and constant terms, as shown in Eq. 1.1. The three contributions are shown in Fig. 9.14 after 1000 fb\(^{-1}\), assuming an electromagnetic shower that is contained in
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Figure 9.12: Amplitude resolution normalized to noise RMS vs noise RMS for an ECAL channel at $\eta = 1.4$ at $\langle PU \rangle = 0$ and $\langle PU \rangle = 200$, respectively.

Figure 9.13: Distribution of energy deposited by in-time pileup interactions per ECAL cell at $|\eta|=1.4$ and $\langle PU \rangle = 200$. The effective width of this distribution is 0.028 GeV.
9.4. Energy and timing reconstruction

a $3 \times 3$ array of ECAL cells. Figure 9.15 shows the energy resolution after 300, 1000, 3000, and 4500 fb$^{-1}$.

![Energy resolution graphs](image)

Figure 9.14: Energy resolution for an EM shower in a $3 \times 3$ array of ECAL cells after 1000 fb$^{-1}$. Contributions from noise (blue), photo-statistics (green), and constant terms (red) after including the effects of radiation damage, are shown separately as well as the total resolution (black). Left: $|\eta|=0$. Right: $|\eta|=1.45$

![Energy resolution graphs](image)

Figure 9.15: Energy resolution for an EM shower in a $3 \times 3$ array of ECAL cells after 300, 1000, 3000, and 4500 fb$^{-1}$. Left: $|\eta|=0$. Right: $|\eta|=1.45$

9.4.2 Time reconstruction

The precision measurement of the time of an ECAL signal pulse timing can be performed with different methods taking into account a number of factors such as pileup, noise and radiation damage effects. This section describes the performance of the algorithm used for ECAL timing reconstruction in the legacy system adapted for new TIA pulse shape and increased sampling.
frequency. It is called the “ratio method” [67]. This algorithm assumes the universal character of the pulse shape that remains unchanged for all hits in the same ECAL channel. Variations of pulse shapes from this average might arise from the non-linear response of the preamplifier or from shower fluctuations. However, a timing resolution of better than 20 ps was obtained at a test beam using prototype TIA electronics, as shown in Fig. 3.8 in Section 3. These results demonstrate the stability of the time reconstruction and validate the assumption of the universal character of the signal pulse shape.

Figure 9.16 (left) shows the time structure of a typical signal pulse the front-end TIA (solid line). The amplitude of the pulse, \( A \), is shown as a function of the time difference \( T - T_{\text{max}} \), where \( T_{\text{max}} \) is defined as the time when the pulse reaches its maximum value, \( A_{\text{max}} \). The pulse is then digitized with 160 MHz sampling frequency, providing a discrete set of amplitude measurements (red dots). The ECAL time reconstruction is defined as the measurement of \( T_{\text{max}} \) using the set of available readout samples.

An alternative representation of the pulse shape is provided by a ratio variable, defined as \( R(T) = A(T)/A(T + 6.25 \text{ ns}) \). Figure 9.16 (right) shows the measured pulse shape using the variable \( T - T_{\text{max}} \), plotted as a function of \( R(T) \). In view of the universal character of the pulse shape, this representation is independent of \( A_{\text{max}} \). It can be described with a simple polynomial parameterization. The corresponding parameters can be determined in electron test beams for a representative set of ECAL crystals or measured in data.

Each pair of consecutive samples gives a measurement of the ratio \( R_i = A_i/A_{i+1} \), from which an estimate of \( T_{\text{max}, i} \) can be extracted, with \( T_{\text{max}, i} = T_i - T(R_i) \). Here \( T_i \) is the time when the sample \( i \) was taken and \( T(R_i) \) is the time corresponding to the amplitude ratio \( R_i \), as given by the parameterization corresponding to Fig. 9.16 (right). The uncertainty on each \( T_{\text{max}, i} \) measurement, \( \sigma_{T_i} \), is the product of the derivative of the \( T(R) \) function and the uncertainty on the
value of $R_i$. The latter has three independent contributions, which are added in quadrature. The first contribution is due to noise fluctuations in each sample. The second contribution is due to the uncertainty on the estimation of the pedestal value subtracted from the measured amplitudes. The last contribution is due to truncation during digitization.

The number of available ratios depends on the absolute timing of the pulse with respect to the triggered event. Ratios corresponding to large derivatives of the $T(R)$ function and to very small amplitudes are not used. There are at least three ratios available that satisfy these requirements. The time of the pulse maximum, $T_{\text{max}}$, and its error are then evaluated from the weighted average of the estimated $T_{\text{max},i}$.

### 9.4.2.1 Time resolution

Time resolution is defined as the width of the quantity $T_{\text{rec}} - T_{\text{true}}$, where $T_{\text{rec}}$ is the reconstructed time of a given pulse and $T_{\text{true}}$ is the time of arrival of a particle in a particular ECAL crystal. The time resolution can be expressed as the sum in quadrature of three terms, and may be parameterized as

$$\sigma_T^2 = \left(\frac{N \cdot \sigma_n}{A}\right)^2 + \left(\frac{S}{\sqrt{A}}\right)^2 + C^2. \quad (9.7)$$

$A$ is the reconstructed amplitude, $\sigma_n$ is related to the noise level for individual samples, and $N$, $S$, and $C$ represent the noise, stochastic, and constant terms, respectively.

The noise term contains the three uncertainties mentioned above in the discussion of the uncertainty on $T_{\text{max},i}$. The stochastic term arises from fluctuations in photon propagation through the crystal, associated with the finite time of scintillation emission. It is negligible and is not considered in this study. The constant term has several contributions. The first contribution is correlated with the starting position of the shower within the crystal. These effects were measured at an electron test beam and found to be less than 20 ps, as described in Section 3. The second contribution is due to systematic effects in the time reconstruction, due to small differences in pulse shapes for different channels, the precision of the time intercalibration of individual channels, and the stability of the clock signal propagated to the front-end electronics.

The dominant contribution to the timing resolution is the timing noise term, $N$. To estimate $N$ for the HL-LHC conditions, signal pulses were simulated with a random readout phase within a wide range of amplitudes ($A/\sigma_n$) with $\langle\text{PU}\rangle = 200$ and assuming 2808 colliding bunches per LHC orbit. The time jitter of hits from individual pileup interactions within a bunch crossing is expected to be a few hundred picoseconds. This jitter was not included in these simulations because it is negligible compared to the simulated random timing of the signal pulses within the 25 ns window. Each ECAL hit is reconstructed with the Ratio Method described in the previous section. The fluctuations of the reconstructed time of the signal pulse, $T_{\text{max}}$, scaled to the amplitude $A/\sigma_n$ is a measurement of $N$.

Figure 9.17 shows the estimated values of $N$ plotted versus $A/\sigma_n$. The noise term is found to be around $N = 7 \text{ ns}$ for the relevant range of signal amplitudes and noise levels. The value of $N$ slightly increases for very low values of $A/\sigma_n$ due to an additional contribution from pileup. The expected value of $N$ for HL-LHC is five times smaller than the measured value of $N = 35 \text{ ns}$ in the legacy system. This is due to the narrower TIA pulses in the HL-LHC. The performance of the ratio method in these conditions is approaching the achievable limit described in Section 3. Radiation damage effects will degrade the timing resolution by changing the $A/\sigma_n$ scale. The larger APD noise expected in HL-LHC will increase $\sigma_n$ and the loss of crystal transparency will decrease $A$ resulting in lower values $A/\sigma_n$ for the same signal.
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9.5 Phase-2 electron/photon Level-1 trigger performance

The electron and photon trigger algorithms for Phase-2 will use information from the electromagnetic calorimeter as well as from the tracking detectors. The algorithms, to be implemented in firmware, should be sufficiently simple and fast such that the latency for trigger processing...
does not exceed $\sim 4 \mu s$ when using stand-alone calorimeter information, or $\sim 6.5 \mu s$ using combined tracking and calorimeter information. The algorithm should preserve the ability to reconstruct electromagnetic clusters with $p_T$ above a few GeV with high efficiency (95% or greater above 10 GeV) as well as achieve high spatial resolution which should be as close as possible to the offline reconstruction.

Following the upgrade of both on-detector and off-detector electronics for the barrel calorimeters in Phase-2, the EB will provide energy measurements with a granularity of $(0.0174, 0.0174)$ in $(\eta, \phi)$, as opposed to the current input to the Phase-1 trigger consisting of trigger towers with a granularity of $(0.087, 0.087)$. The much finer granularity and resulting improvement in position resolution of the electromagnetic trigger algorithms is critical in improving electron/photon trigger efficiency and suppressing background at high pileup.

The algorithm currently assumed for the Phase-2 Level-1 electron/photon (EG) trigger follows closely the one used in Phase-1 offline reconstruction and physics analyses, albeit with a number of simplifications required by trigger latency constraints. A core cluster is defined as a set of $3\eta \times 5\phi$ crystals around a seed crystal with $p_T$ above 1 GeV, with a possible further extension along the $\phi$ direction to take into account bremsstrahlung energy losses. The cluster position is determined as the energy-weighted sum of the individual crystals within the cluster. Level-1 EG candidates are required to be isolated. The relative isolation of each cluster is calculated using the sum of energy in a $27 \times 27$ crystal matrix around the seed crystal divided by the cluster transverse momentum. Shower shape variables, computed from the $3 \times 5$ crystals within the core cluster, help to reduce the background from neutral hadrons in jets. The HB information is not directly used to identify electromagnetic objects, but is used to provide an indication of possible electromagnetic energy leakage. Finally, tracks from the Level-1 track finder are extrapolated to the ECAL surface and matched to the core cluster.

Figure 9.5 shows the comparison between the Level-1 EG trigger algorithm in Phase-1 (black) based on trigger towers and the algorithm foreseen for Phase-2 (grey), based on single crystal information. The left plot shows the position resolution of the EG candidates, expressed in terms of $\Delta R$ with respect to the generated electron. The right plot shows the Level-1 EG trigger efficiency plotted as a function of the transverse momentum of the generated electron. An electron gun sample, with flat $p_T$ spectrum between 8 and 100 GeV and an average pileup of 200, was used for both measurements in Phase-2. To provide a like-for-like comparison, the sample used to shown the performance of the Phase-1 algorithm also has an average pileup of 200.

The finer spatial information provided by the single crystal information in Phase-2 leads to an improvement in efficiency. The improved spatial resolution provides better geometrical matching between the cluster and the tracks produced by the Level 2 track finder and improved measurements of the activity around the EG candidates.

### 9.6 Object performance

As shown in Section 2, the HL-LHC running conditions will affect the performance of the Barrel calorimeter as a result of ageing related to the instantaneous luminosity and dose. The ECAL response to energy depositions from electromagnetic showers will be affected by radiation damage that causes increased noise in the photodetectors and degradation of the signal amplitude due to loss of crystal transparency. The loss of transparency is most pronounced in the front of the crystal leading to a non-linearity of light collection. The leads to a degradation of the energy resolution because the showers fluctuate in crystal depth. The effect on ECAL
performance is described in detail in Section 2.1. These effects together with improvements of amplitude reconstruction from new front-end electronics are included in CMSSW simulations.

In the HCAL Barrel, a dose dependent model, extracted from the legacy endcap HCAL (HE) performance in 2016 and extrapolated to the HCAL Barrel, has been developed to simulate the effect of the ageing of Barrel scintillators due to the integrated luminosity as described in Section 2.2. The scenarios considered in the simulations correspond to different values of integrated luminosity and ageing of the Barrel calorimeter, such as 300 fb$^{-1}$, 1000 fb$^{-1}$, 3000 fb$^{-1}$, and 4500 fb$^{-1}$. In all cases the pileup amounts to 200 interactions per crossing. The results from studies of electron, photon, tau, jet and b tagging performance obtained with the CMSSW full event simulation for different ageing and pileup scenarios are presented in this section.

9.6.1 Electrons and Photons

Electron and Photon reconstruction

In the barrel the electron reconstruction uses a combination of information from the EB, HB, and the tracker. It is discussed in detail in Ref. [68]. In the HL-LHC upgrade, the tracking performance has been shown to be similar or better than the legacy performance [69]. It is expected that the main challenge will be in the seed forming step, which is sensitive to the ageing in the calorimeters. The efficiencies for reconstructing electrons with 200 pileup interactions in four ageing scenarios are shown in Fig. 9.20. Additionally, the reconstruction efficiencies in Run-2 (2016) conditions, as well as the 1000 fb$^{-1}$ ageing scenario with no pileup, is shown. The performance is maintained with age, despite the preliminary tuning of the clustering parameters, to which the electron efficiency at low $p_T$ is quite sensitive.

The photon reconstruction is discussed in detail in Ref. [70]. The decline of the photon reconstruction efficiency is primarily caused by the worsening of the ECAL clustering performance. The efficiency for reconstructing photons with 200 pileup interactions in four ageing scenarios is shown in Fig. 9.21. The impact of pileup and ageing can be further mitigated with the optimization of the clustering algorithm.
### Figure 9.20: Electron reconstruction efficiency for several ECAL barrel ageing conditions.

The efficiency is defined as the number of reconstructed electrons matched within $\Delta R(\eta, \phi) < 0.1$ of a generated electron, divided by the number of generated electrons within the acceptance region $|\eta| < 1.4$. The electrons were generated with a uniform distribution in transverse momentum.

### Figure 9.21: Photon reconstruction efficiency for several ECAL barrel ageing conditions.

The efficiency is defined as the number of reconstructed photons matched within $\Delta R(\eta, \phi) < 0.1$ of a generated prompt photon from $H \rightarrow \gamma\gamma$ events, divided by the number of generated photons within the acceptance region $|\eta| < 1.4$. 


Electron and photon identification

The electron and photon identification strategy is analogous to the one employed for LHC Runs 1 and 2 [68, 70]. The identification algorithms utilise information from the calorimeter shower shapes, the compatibility of the shower and a track, and track-based requirements. Compared to the Phase-1 detector, the amount of material in the tracker is reduced by almost a factor of two over the full pseudorapidity range, which reduces the amount of bremsstrahlung for electrons and photon conversions significantly.

To account for the changes in the detector, the identification variables for electrons and photons also employed in Run 1 are fed to a Boosted Decision Tree (BDT) that is specifically trained for Phase-2 conditions, including pileup sensitive variables. For photons, the BDT that is trained on a mixture of simulated $\gamma +$ jets, $Z \rightarrow ee$, and multijet events. Signal photons are defined as reconstructed photons matched to an isolated prompt photon within $\Delta R = 0.1$. The electron BDT is trained on a $Z \rightarrow ee$ sample as signal and with multijet events as background. Prior to the training, the electron and photon $p_T$ and $\eta$ distributions are reweighted such that they have identical shape for signal and background. The training is performed with 200 pileup. The variables used in the photon and electron BDT training are listed in Tables 9.1 and 9.2, respectively.

Several working points can be defined based on the BDT score. For electrons, we have defined three working points corresponding to background misidentification probabilities of 0.1%, 1% and 10%, respectively. The corresponding signal efficiencies are 30%, 81% and 98% for electrons with $10 < p_T < 20$ GeV, and 60%, 92% and 99% for electrons with $p_T > 20$ GeV.

<table>
<thead>
<tr>
<th>Type</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter variables</td>
<td>$\sigma_{\eta\eta}$</td>
<td>$\eta$-width in $5 \times 5$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\phi\phi}$</td>
<td>$\phi$-width in $5 \times 5$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\eta\phi}$</td>
<td>$\eta - \phi$ correlation in $5 \times 5$</td>
</tr>
<tr>
<td></td>
<td>$\eta$-width</td>
<td>Supercluster $\eta$-width</td>
</tr>
<tr>
<td></td>
<td>$\phi$-width</td>
<td>Supercluster $\phi$-width</td>
</tr>
<tr>
<td></td>
<td>R9</td>
<td>Ratio of $E_{3\times3}/E_{\text{supercluster}}$</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>Ratio of $E_{2\times2}/E_{\text{supercluster}}$</td>
</tr>
<tr>
<td></td>
<td>$H/E$</td>
<td>Ratio of hadronic to electromagnetic energy</td>
</tr>
<tr>
<td>Isolation variables</td>
<td>$E_{h^+}/E_{\text{supercluster}}$</td>
<td>Particle-flow (PF) relative charged hadron isolation ($\Delta R = 0.3$)</td>
</tr>
<tr>
<td></td>
<td>$E_{h^0}/E_{\text{supercluster}}$</td>
<td>PF relative neutral hadron isolation</td>
</tr>
<tr>
<td></td>
<td>$E_\gamma/E_{\text{supercluster}}$</td>
<td>PF relative photon isolation</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{trk}}$</td>
<td>Track energy sum in cone around supercluster ($\Delta R = 0.4$)</td>
</tr>
<tr>
<td>Electron rejection</td>
<td>hasPixelSeed</td>
<td>True if seed cluster in calorimeter can be matched to pixel hit triplet</td>
</tr>
<tr>
<td></td>
<td>conversionSafeElectronVeto</td>
<td>True if cluster can be matched to a track that is not from a (displaced) conversion vertex in the tracker</td>
</tr>
<tr>
<td>Kinematic variables</td>
<td>$E_{\text{supercluster}}$</td>
<td>Supercluster energy</td>
</tr>
<tr>
<td></td>
<td>$\eta_{\text{supercluster}}$</td>
<td>Supercluster pseudorapidity</td>
</tr>
</tbody>
</table>

The achieved identification performance is compared to Run 2 conditions in Fig. 9.22. Even with pileup of 200, physics performance comparable to Run 2 can be maintained.
9.6. Object performance

Table 9.2: Variables used in the training of the electron identification BDT.

<table>
<thead>
<tr>
<th>Type</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking variables</td>
<td>$N^\text{hits}_\text{GSF}$</td>
<td>Number of hits of the GSF track</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{GSF}}$</td>
<td>Fit $\chi^2$ of the GSF track</td>
</tr>
<tr>
<td></td>
<td>$N^\text{hits}_\text{KF}$</td>
<td>Number of hits of the KF track</td>
</tr>
<tr>
<td></td>
<td>$\chi^2_{\text{KF}}$</td>
<td>Fit $\chi^2$ of the KF track</td>
</tr>
<tr>
<td></td>
<td>$f_{\text{brem}} = 1 - p_{\text{in}}/p_{\text{out}}$</td>
<td>Bremsstrahlung fraction</td>
</tr>
<tr>
<td>Calorimeter variables</td>
<td>$\sigma_{\eta\phi}$</td>
<td>$\eta$-width in $5 \times 5$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{\phi\phi}$</td>
<td>$\phi$-width in $5 \times 5$</td>
</tr>
<tr>
<td></td>
<td>$1 - E_{3 \times 5}/E_{5 \times 5}$</td>
<td>Shower circularity</td>
</tr>
<tr>
<td></td>
<td>$R^9$</td>
<td>Ratio of $E_{3 \times 3}/E_{\text{supercluster}}$</td>
</tr>
<tr>
<td></td>
<td>$\eta$-width</td>
<td>Supercluster $\eta$-width</td>
</tr>
<tr>
<td></td>
<td>$\phi$-width</td>
<td>Supercluster $\phi$-width</td>
</tr>
<tr>
<td></td>
<td>$H/E$</td>
<td>Ratio of hadronic to electromagnetic energy</td>
</tr>
<tr>
<td>Calorimeter-track matching</td>
<td>$E_{\text{seed}}/p_{\text{out}}$</td>
<td>Energy ratio at outermost state</td>
</tr>
<tr>
<td></td>
<td>$E/p$</td>
<td>Energy over momentum matching at the vertex</td>
</tr>
<tr>
<td></td>
<td>$\Delta \eta$</td>
<td>Difference in $\eta$ evaluated at the calorimeter</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi$</td>
<td>Difference in $\phi$ evaluated at the calorimeter</td>
</tr>
</tbody>
</table>

Figure 9.22: Photon (left) and electron (right) efficiency and event-normalized fake rate in simulated $\gamma + \text{jets}$ samples for the BDT training described in the text. Signal candidates are matched within $(\eta, \phi) < 0.1$ to generated photons and electrons. Background particles are defined as reconstructed photons found in the same kinematic phase space, but not matched to an isolated generated particle. The performance of a Run 2 cut-based ID is presented, evaluated on a similar sample produced using the Run 2 conditions.
Photon energy resolution

The energy resolution of a reconstructed photon arises from three sources: fluctuations due to photon shower containment, calorimeter resolution, and local pileup energy fluctuations. The degradation in calorimeter resolution is mainly due to pileup rather than detector ageing, even after 4500 fb$^{-1}$ of integrated luminosity. The reconstruction is not optimized for conditions with 200 pileup events. However, a simple method to mitigate the effect of the pileup contribution has been developed in order to evaluate the performance of the detector in the context of physics analysis. The energies of the top $n$ most energetic crystals in the supercluster are summed rather than the entire cluster. The working point $n = 15$ has been chosen as the optimum balance between loss of shower containment at small $n$ and larger pileup contributions at large $n$. This $n = 15$ method is used in the following sections as the photon reconstruction algorithm (max15). The resolution obtained for all photons with this method is shown in Fig. 9.23. The resolution is improved if we consider only the subset of unconverted photons using the same method, as shown in Fig. 9.24. In order to have an idea of the ultimate resolution achievable once all the algorithms are optimized for conditions with 200 pileup events, it is worth looking at the resolution of the unconverted photons using the sum of the energy in a $3 \times 3$ region around the seed crystal of the photon supercluster (E3×3), as shown in Fig. 9.25.

The resolution degrades above 500 GeV due to longitudinal shower leakage. This can be eliminated using Monte Carlo-based energy regression techniques similar to those used in Run 2, but which are not employed here.

The energy resolutions obtained for the various photon categories and the different detector ageing conditions are summarized in Table 9.3.

### 9.6.2 τ leptons

The reconstruction of tau leptons in their hadronic decay modes is performed using the hadron-plus-strip algorithm [71]. In this algorithm, electrons and photons are combined in “strips” to build $\pi^0$ candidates. The $\pi^0$ candidates are then combined with tracks to build the $\tau$ lepton candidates. The reconstruction of photons in the barrel calorimeter therefore has an important role in τ-lepton reconstruction. In this study, the detector geometry and data taking conditions assumed are those proposed for HL-LHC with calorimeter ageing applied corresponding to 1000 fb$^{-1}$ and an average of 200 pileup interactions. The $\tau$ leptons come from the decay of...
9.6. Object performance

Table 9.3: Single photon energy resolutions for simulated photon gun samples with various detector conditions and photon categories.

<table>
<thead>
<tr>
<th>Detector conditions</th>
<th>Photon category</th>
<th>$\sigma_{\text{eff}}(E)/E$ \quad \text{for} \quad p_T = 50 \text{ GeV}</th>
<th>$p_T^\gamma$ = 100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pileup 200, 300 fb$^{-1}$ ageing</td>
<td>E3×3, unconverted photons, max15, all photons</td>
<td>1.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Pileup 200, 1000 fb$^{-1}$ ageing</td>
<td>E3×3, unconverted photons, max15, all photons</td>
<td>2.1%</td>
<td>1.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Pileup 200, 3000 fb$^{-1}$ ageing</td>
<td>E3×3, unconverted photons, max15, all photons</td>
<td>3.0%</td>
<td>2.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.8%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Pileup 200, 4500 fb$^{-1}$ ageing</td>
<td>E3×3, unconverted photons, max15, all photons</td>
<td>3.9%</td>
<td>2.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.0%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>
Higgs bosons produced in the gluon-gluon and vector boson fusion channels. The background events are simulated using the SM Z+jets process, where a jet is misidentified as a hadronically decaying tau lepton.

Figure 9.26 (left) shows the reconstructed mass of the tracks+$\pi^0$ candidates for different ageing and pileup scenarios. The peak on the left side of the plot corresponds to events where only a track was found, without any associated $\pi^0$. The reconstructed $\tau$ mass distribution is similar for zero and 200 pileup events. The right plot shows the transverse momentum resolution for the reconstructed candidates with respect to the generated visible transverse momentum of the $\tau$ leptons.

Figure 9.27 shows the $\tau$ lepton reconstruction efficiency plotted as a function of $\tau$ transverse momentum, and the probability for a jet to be misidentified as a $\tau$ lepton. The misidentification rate increases with $p_T$ since the jets are more likely to be boosted and have a higher probability to mimic $\tau$ lepton decays. For all plots in this section the $\tau$ lepton candidates are only required to pass the decay mode reconstruction without any additional isolation requirements. The performance of the tau decay mode reconstruction is similar to the one obtained in the ongoing Run 2 CMS data taking.

![Figure 9.26: Left: Hadronic $\tau$ mass reconstruction for selected tracks+$\pi^0$ candidates. Right: Transverse momentum resolution for the $\tau$ lepton candidates.](image)

### 9.6.3 Jets and b tagging

#### Jet transverse momentum resolution and HB ageing

In order to assess the impact on the detector performance of the HCAL scintillator ageing, the jet transverse momentum resolution was evaluated by turning on and off the HB scintillator ageing using a simulation sample with no pileup, and with EB ageing applied.

The implementation of the HB ageing in the simulation has been described in Section 2.2.3. The simulation of the depth segmentation of the HCAL barrel calorimeter includes the increase from one to four compartments, which is scheduled for LS2 as part of the Phase-1 upgrade, and a recalibration of each depth according to its received dose, which is applied to compensate for the layer-dependent reduction of the detector response.
Figure 9.27: Left: Hadronic $\tau$ lepton identification efficiency versus the $\tau$ lepton transverse momentum. Right: Probability for jets to be misidentified as hadronic $\tau$ lepton decays.

The comparison of the jet transverse momentum resolution with and without HB scintillator ageing is shown in Fig. 9.28 for an integrated luminosity of 4500 fb$^{-1}$. The results indicate that the projected ageing of the barrel scintillator can be recovered by recalibration and does not have a significant effect on jet $p_T$ resolution. This supports the statement made in Section 2.2.4 that, if our current projections of the HB scintillator ageing will be confirmed by the analysis of the entire 2017 dataset, the replacement of a few front layers of HB megatiles in LS3 will not be necessary.

Regarding the ageing of the HB photo-sensors, the SiPM dark current will increase with neutron exposure. The extent of this effect depends on characteristics of the SiPMs and their operating temperature, and it is simulated as discussed in Section 2.2.3. This increase is relevant for the ability to discriminate MIP signals, but is moderate compared to typical jet energies and does not impact the jet $p_T$ resolution, as shown in Figure 9.28.

**B tagging**

The efficiency to identify b quark jets has been studied as a function of integrated luminosity, restricting the analysis to the barrel calorimeter acceptance and taking into account calorimeter ageing. Simulated multijet events are used, selecting jets with $|\eta| < 1.5$ and $30 < p_T < 200$ GeV. The b-tagging algorithm “cMVAv2”, same as that used in the tracker TDR [69], has been studied here. The operating point of the b tagger is adjusted for each pileup and ageing scenario so that the probability to misidentify jets from light (udsg) flavors is 0.01 (medium working point). The study covers scenarios with 0, 140, and 200 pileup events and ageing conditions corresponding to 0, 300, 1000, 3000 and 4500 fb$^{-1}$ (Fig. 9.29).

The b tagging efficiency is lower at high pileup and decreases slightly as a function of the integrated luminosity. For each pileup scenario, a linear fit to the b tagging efficiency is performed, with a dispersion around the fitted value that is smaller than 1% (hatched areas). The relative decrease of b tagging efficiency is observed to be only 4% at the end of life of the calorimeter (4500 fb$^{-1}$).

The b tagging performance as a function of the overall pileup density, given in pp collisions per
9.7 Physics performance

9.7.1 Higgs → γγ

The clean di-photon signature of the $H \rightarrow \gamma\gamma$ decay channel makes it one of the most important channels to characterize the properties of the Higgs boson. Excellent photon identification efficiency and energy resolution are required to maintain the sensitivity of the analysis, making this channel a benchmark for calorimeter performance.

There are two components to the di-photon mass resolution: the photon energy resolution and the vertex position resolution. The contribution of the photon energy measurement to the di-photon mass resolution is expected to degrade as the detector ages. We expect that the HL-LHC detector will achieve the same photon energy resolution with an average of 200 pileup events after an exposure of 1000 fb$^{-1}$ as the current detector during Run 2. The energy resolution is expected to degrade by about a factor two as the detector ages during HL-LHC operations to collect the ultimate integrated luminosity corresponding to 4500 fb$^{-1}$. Some of the lost resolution can be recovered by correcting for shower containment, photon conversions, and pileup energy. With increasing numbers of pileup events, the determination of the position of the Higgs production and decay vertex will dominate the di-photon mass resolution. Precision timing measurements will mitigate this effect. The time of arrival of the photons in the calorimeter determines the vertex position with sufficient precision for photon pairs with large separation in pseudorapidity. For photon pairs with small separation in pseudorapidity, a measurement of the vertex time using the timing of the associated tracks can reduce the number of...
9.7. Physics performance

Figure 9.29: Efficiency of b tagging (with the cMVAv2 tagger) in simulated multi-jet events as a function of the integrated luminosity. Jets are required to satisfy $|\eta| < 1.5$ and have a $p_T$ value in the 30–200 GeV range.

Figure 9.30: Efficiency of b tagging (with the cMVAv2 algorithm) in the pseudorapidity range $|\eta| < 1.5$, as a function of the density of pileup events along the z beam axis. The b tagging efficiency is computed for a fixed misidentification probability of light jets (udsg) of 0.01. Results are based on multijet Monte Carlo simulation for Phase-2 conditions with an average pileup of 140 (red) or 200 (green). The full symbols are for designed barrel calorimeter conditions. The empty symbols are for calorimeter ageing corresponding to an expected ultimate integrated luminosity (averaged between 3000 and 4500 fb$^{-1}$). Statistical uncertainties are shown with linear fits superimposed.

vertices compatible with the photon pair to a level comparable to Run 2. Thus, if both ECAL and tracker timing are available, the contribution of the vertex position to the di-photon mass resolution will be similar as during Run 2.
This study is based on full simulation samples of Higgs bosons decaying to di-photon pairs, produced in the gluon-gluon fusion channel, for both 0 and 200 pileup events. Different ageing scenarios are considered in simulation, to compare the performance of the current barrel calorimeter with one aged to 300 fb$^{-1}$, 1000 fb$^{-1}$, 3000 fb$^{-1}$, and 4500 fb$^{-1}$.

The performance of photon reconstruction in the high pileup conditions expected at the HL-LHC was demonstrated in Section 9.6.1. The selection requires two photons with $p_T > 25$ GeV (leading photon) and $p_T > 15$ GeV (subleading photon), within the EB acceptance, $|\eta| < 1.45$, and matched to a generator-level photon. Photon identification and isolation effects were found to have a negligible impact on resolution, and they have not been taken into account for the following results.

The determination of the primary vertex from which the two photons originate has a direct impact on the di-photon invariant mass resolution. In order to disentangle resolution effects due to vertexing and those due to calorimeter energy resolution, the generator level vertex is used to reconstruct the Higgs candidate. The relative worsening of the di-photon mass resolution, for the 1000 fb$^{-1}$ ageing scenario, due to vertexing is estimated to be 13%, ignoring any possible future improvements of vertex reconstruction due to precision timing detectors. With improved vertex efficiency, the mass resolution will also improve.

Figure 9.31 shows the Higgs di-photon invariant mass, comparing the different ageing and pileup scenarios, considering only unconverted photons. Figure 9.32 shows the same distributions considering both unconverted and converted photons.

Figures 9.31 and 9.32 show the mass resolution of the Higgs decay into two photons. The most energetic 15 ECAL energy deposits in the standard supercluster were used to determine the energy(max15). Using fewer crystals to determine the energy reduces the relative effect of pileup and noise. This clustering algorithm is simplistic and gives an over-estimate of the final di-photon mass resolution that is measured with the upgraded ECAL. For events in which neither photon converts, a better estimate of the mass resolution can be gained using the energy sum of the $3 \times 3$ crystals centered on the most energetic crystal in the candidate electromagnetic supercluster (E3x3). This further reduces the negative effects due to pileup and ageing, but is only useful for the tight showers of unconverted photons. The unconverted photons can be seen in Fig. 9.33 with this clustering algorithm.

Table 9.4 summarizes the Higgs mass resolution for the different conditions studied. Further improvement to the di-photon resolution will be obtained by applying a multivariate regression technique that corrects for the containment of the electromagnetic showers in the clustered crystals, the energy losses of converted photons, and the contamination of the cluster energy from pileup [72]. The di-photon mass resolution in Run 2 is improved using the multivariate regression technique from 2.0 GeV (E3x3) to 1.0 GeV for a pair of tightly identified photons ($R_9 > 0.93$), or from 3.0 GeV (15 crystal energy sum) to 1.4 GeV for inclusively selected photons (no $R_9$ selection). The $R_9$ variable is defined as the energy sum of the $3 \times 3$ crystals centered on the most energetic crystal in the candidate electromagnetic cluster divided by the energy of the candidate. The showers of photons that convert before reaching the calorimeter have wider transverse profiles and lower values of $R_9$ than those of unconverted photons. This procedure will be adapted and applied to photons at the HL-LHC, further improving the energy resolution for all events and targeting a performance similar to Run 2.
## 9.7. Physics performance

### Figure 9.31: Higgs di-photon invariant mass comparing different ageing scenarios, for unconverted photons. Left: 0 PU. Right: 200 PU. The photon energy is calculated by summing the energy of the 15 highest energy ECAL crystals in the standard photon object (max15).

### Figure 9.32: Higgs di-photon invariant mass comparing different ageing scenarios, for both unconverted and converted photons. Left: 0 PU. Right: 200 PU. The photon energy is calculated by summing the energy of the 15 highest energy ECAL crystals in the standard photon object (max15).

### Table 9.4: Di-photon mass resolutions for different ageing and pileup scenarios. The effect of an optimized multivariate photon regression method is not taken into account.

<table>
<thead>
<tr>
<th></th>
<th>300 fb$^{-1}$</th>
<th>1000 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
<th>4500 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unconverted photons (max 15)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 PU</td>
<td>1.5 GeV</td>
<td>1.8 GeV</td>
<td>3.6 GeV</td>
<td>5.1 GeV</td>
</tr>
<tr>
<td>200 PU</td>
<td>2.2 GeV</td>
<td>2.4 GeV</td>
<td>4.2 GeV</td>
<td>5.3 GeV</td>
</tr>
<tr>
<td><strong>Unconverted photons (E3x3)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 PU</td>
<td>1.7 GeV</td>
<td>1.8 GeV</td>
<td>2.7 GeV</td>
<td>3.4 GeV</td>
</tr>
<tr>
<td>200 PU</td>
<td>1.9 GeV</td>
<td>2.0 GeV</td>
<td>2.8 GeV</td>
<td>3.6 GeV</td>
</tr>
<tr>
<td><strong>All photons (max 15)</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 PU</td>
<td>2.0 GeV</td>
<td>2.3 GeV</td>
<td>3.8 GeV</td>
<td>5.2 GeV</td>
</tr>
<tr>
<td>200 PU</td>
<td>2.8 GeV</td>
<td>2.9 GeV</td>
<td>4.3 GeV</td>
<td>5.6 GeV</td>
</tr>
</tbody>
</table>
Figure 9.33: Higgs di-photon invariant mass comparing different ageing scenarios, for unconverted photons. Left: 0 PU. Right: 200 PU. The photon energy is calculated using the E3x3 algorithm.

### 9.7.1.1 Improvements with precision time information

The resolution of the di-photon invariant mass is determined by the resolution of the photon energies measured in the calorimeter and by the resolution on the opening angle between the two photons, derived from the shower positions in the calorimeter and the position of the decay vertex. If the longitudinal position of the interaction point is known to better than about 10 mm then the resolution on the opening angle between the photons makes a negligible contribution to the mass resolution [73]. Thus the mass resolution can be preserved by correctly assigning the reconstructed photons to one of the interaction vertices reconstructed from the charged tracks.

If the vertex multiplicity is relatively low, the reconstructed primary vertex that most probably corresponds to the Higgs boson interaction can be identified using the kinematic properties of the tracks associated with the vertex and their correlation with the di-photon kinematics [73]. Figure 9.34 shows the dependence of the efficiency for correct vertex assignment as a function of the number of reconstructed vertices in $H \rightarrow \gamma \gamma$ decays at a center-of-mass energy of 13 TeV for vertex multiplicities corresponding to LHC operating conditions in 2015–2016.

At high multiplicities, the identification of the vertex is a major challenge. According to simulation, at 140 collisions per beam crossing the efficiency to identify the correct vertex within 1 cm is lower than 40% in processes where the number of charged particles from the primary interactions is limited, such as $H \rightarrow \gamma \gamma$ events produced via gluon-gluon fusion. It falls to about 30% in the scenarios with 200 pileup events. This efficiency loss can be partially offset by measuring the photon time-of-flight (TOF) to obtain the vertex position along the beam direction ($z$ coordinate) by triangulation. The required time resolution has been estimated in a dedicated study with simulated $H \rightarrow \gamma \gamma$ events ($m_H = 125$ GeV), for photons from Higgs boson decays with $p_T > 30$ GeV and $|\eta| < 2.5$ [73].

A reconstructed time is assigned to each photon as described in Section 9.4.2. This time, represents the TOF of a photon originating from the nominal impact point. In this study, we assume that all photons are measured with 30 ps time resolution. The results of the analysis are summarized in Fig. 9.35, which shows the distribution of the distance between the virtual and the true vertex position. Results for the sample with large pseudorapidity gap between the photons (|$\Delta \eta$| > 0.8) are displayed in the left panel for a time resolution of 30 ps for each photon.
9.7. Physics performance

Figure 9.34: Efficiency for correct vertex assignment as a function of the number of reconstructed vertices in $H \rightarrow \gamma\gamma$ decays at a centre-of-mass energy of 13 TeV and for vertex multiplicities corresponding to LHC operations in 2015 [73].

The uncertainty on the vertex scales linearly with the timing precision, so a 1 cm precision can be achieved for 30 ps timing resolution, and a 2 cm precision can be achieved with 60 ps timing resolution, along with a resultant degradation of the vertex identification efficiency.

Figure 9.35: Distribution of the distance between the virtual vertex and the true vertex position along the beam direction, $z$, in Higgs boson decays to di-photons. Decay into photons with pseudorapidity gap of $|\Delta\eta| > 0.8$ and $|\Delta\eta| < 0.8$ are shown in the left and right panels respectively.

In the complementary, and equally populated, sample of photons produced at small pseudorapidity gaps ($|\Delta\eta| < 0.8$), the RMS becomes comparable to the beam spot size and thus the photon timing alone does not provide any useful information, as shown by the red histogram of the right panel of Fig. 9.35. Great benefit would be obtained from knowing the vertex $t_0$. Both the $|\Delta\eta| > 0.8$ and $|\Delta\eta| < 0.8$ samples are mainly populated by photons falling within the barrel acceptance, which indicates the importance of having precision time measurement for high $p_T$ photons in the ECAL barrel.

9.7.2 Higgs$\rightarrow\tau\tau$

The study of the Higgs boson decaying into pairs of $\tau$ leptons measures the Yukawa coupling between the Higgs boson that is responsible for generating the fermions masses. Projections of the legacy LHC $H \rightarrow \tau\tau$ analyses to the HL-LHC conditions estimate that a measurement of the coupling modification of the Higgs boson to $\tau$ leptons can reach a precision of 2–5% [74].
This complex measurement requires excellent performance of the full detector reconstruction chain including ECAL barrel.

The discrimination of the Higgs signal from the dominant \( Z \to \tau\tau \) background is one of the most challenging aspects of the \( H \to \tau\tau \) analysis and requires excellent mass resolution. The \( \tau \) leptons are reconstructed both in the hadronic and leptonic decays. In hadronic decays the \( \tau \) mass resolution mainly depends on the performance of the reconstruction of the photons produced in the \( \pi^0 \) decays in the \( \tau \) hadronic final states. In case of leptonic decays, the reconstruction of electrons and muons become important.

In this study the ECAL barrel performance is inspected within the frame of the \( H \to \tau\tau \) analysis, but it is not completely factorized from other possible contributions. The detector geometry and data taking conditions assumed in this study are those proposed for HL-LHC Run-4, and a barrel calorimeter aged to 1000 fb\(^{-1}\). Fully simulated signal samples are used with 0 and 200 pileup events. The Higgs bosons are assumed to be produced through the vector boson fusion channel. Fully simulated events were also produced for the SM process \( Z \to \tau^+\tau^- \).

The di-\( \tau \) mass can be reconstructed in several ways. For the purposes of this study it is sufficient to compare visible mass reconstruction for the comparison between the LHC and HL-LHC conditions. The visible mass is defined as invariant mass of the visible di-\( \tau \) decay products. The \( e\tau_h \) final state of the di-\( \tau \) pair is studied, where \( \tau_h \) indicates a hadronically decaying \( \tau \) lepton.

Events are selected by requiring an electron with \( p_T > 25 \) GeV and \( |\eta| < 1.5 \), and a hadronically decaying \( \tau \) lepton with \( p_T > 20 \) GeV and \( |\eta| < 2.3 \). The particles are required to be separated by \( \Delta R > 0.5 \). The electron must be compatible with a \( \tau \to e \) decay at generator-level and hadronically decaying \( \tau \) lepton must be compatible with a \( \tau \to \tau_h \) decay at generator-level. No isolation requirements are applied at the reconstructed level.

Figure 9.36 (left) shows the \( m_{\tau\tau} \) visible mass distribution in the \( e\tau \) final state for the \( H \to \tau\tau \) signal sample. The Run 2 reconstruction is compared with HL-LHC reconstruction results. It is demonstrated that the mass resolutions for Run 2 (23\%) and HL-LHC (24\%) conditions agree within uncertainties of the measurement and do not depend on the number of pileup events. The right plot shows the separation of reconstructed Higgs and \( Z \) masses (\( Z \to \tau\tau \)) for pileup 200. The backgrounds with fake \( \tau \)s are not considered in this plot, the simulated events include the effects of detector ageing. The studies show that in case of the HL-LHC and for the \( H \to \tau\tau \) analysis the same performance as for the Run 2 conditions is expected.

### 9.7.3 \( HH \to bb\gamma\gamma \)

The study of the Higgs boson trilinear self-coupling using events with a Higgs boson pair helps determine the shape of vacuum potential of the universe. It is of great interest because present data indicates that the universe is in a meta-stable vacuum with the possibility to decay into a lower more stable state. This would change the Higgs couplings to the particles of the SM and thereby their masses. The consequent release of energy would then destroy the bound states of matter in the universe.

In the standard model, the production cross section for di-Higgs events is very small, and the large statistics offered by the HL-LHC program will be necessary to observe this process. The final state with one Higgs boson decaying to b quarks and the other Higgs boson decaying to a photon pair provides the best sensitivity. An extrapolation of a search for \( HH \to \gamma\gamma bb \) events with an integrated luminosity of 2.3 fb\(^{-1}\) of LHC collision data was performed to estimate the sensitivity with 3000 fb\(^{-1}\) [27]. In this section we update the earlier projections including the state-of-the-art knowledge on the expected CMS detector behavior with the ageing of ECAL.
after 1000 fb$^{-1}$ of collected data and with 200 pileup events per bunch crossing.

The performance of the upgraded detector for photon isolation efficiency, photon energy resolution and vertex-finding efficiency is taken into account. Contamination, due to pileup interactions in the detector, can worsen the isolation efficiency. To account for this, a reduction of 2.3% in identification efficiency for prompt photons has been applied in the barrel and a 10% reduction has been applied in the endcaps, for both signal and background events.

High pileup can also lead to a drop in vertex-finding efficiency. Nevertheless the presence of additional jets in the final state significantly improves the identification of the primary vertex, even in a complex pile-up environment, compared to the gg $\rightarrow$ H $\rightarrow$ $\gamma\gamma$ search. Therefore we assume no significant degradation in the di-photon invariant mass resolution due to a wrongly identified primary vertex. Finally, a di-photon mass resolution of corresponding to ageing after 1000 fb$^{-1}$ and 200 pileup events has been considered in the extrapolation, following the conclusions of the studies documented in Section 9.6. An improvement in the di-photon mass resolution from energy regression technique similar to that estimated from Run 2 data has been included in the projections.

Uncertainties of 1% have been applied to the jet energy scale and to the identification of jets originating from b quarks. The improved performance of the Phase-2 CMS tracker [69], will provide an increase in signal efficiency for the same background level due to the improved b tagging capabilities of the new detector. The increase in b tagging efficiency from 69% to 74% per jet leads to a global increase of the signal efficiency by 15%, as well as of VH, ttH and bbH backgrounds.

The extrapolations shown in this section assume $\sqrt{s} = 14$ TeV. They have been obtained by scaling the SM HH gg-fusion cross section as well as the single Higgs production from $\sqrt{s} = 13$ TeV to $\sqrt{s} = 14$ TeV using the YR4 predictions [75]. The nonresonant background is scaled by a factor 1.08 $\approx$ 14/13.

The results of the projections are shown in Table 9.5. A significance of 1.9 standard deviations in the $\gamma\gamma$bb channel is expected. Further improvements to this sensitivity are anticipated as the projections do not yet account for the improvements in combinatorial backgrounds from fake photons that can be gained from precision timing information in ECAL and the tracker.

Figure 9.36: Left: The visible mass distribution for $H \rightarrow \tau\tau$ events reconstructed in $e\tau\nu$ final state for Run 2 (PU 25) and HL-LHC (PU 0 and 200) reconstruction. Right: The reconstructed mass for the gluon fusion Higgs boson signal events compared to the $Z \rightarrow \tau\tau$ background events for HL-LHC simulated samples with PU 200.
Table 9.5: Projection of the sensitivity to the SM HH → γγbb production at 3000 fb⁻¹. The projections are based on a 13 TeV analysis performed with data collected in 2015. The median expected limit, expected significance, and uncertainty in the signal modifier, \( \mu_r = \sigma_{HH}/\sigma_{SMHH} \), are provided with and without systematic uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>Median expected limits in ( \mu_r )</th>
<th>Significance</th>
<th>Uncertainty as fraction of ( \mu_r = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH → γγbb</td>
<td>1.1</td>
<td>1.9</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>2.0</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The comparison of projected signal and backgrounds are shown in Fig. 9.37 for \( M(\gamma\gamma) \) and \( M(jj) \). The \( M(\gamma\gamma) \) observable allow to separate the signal from nonresonant background but not form resonant single H boson background. The \( M(jj) \) observable improves the separation between single H and HH signal.

![Figure 9.37: The \( M(\gamma\gamma) \) (left) and \( M(jj) \) (right) distributions for ECAL ageing after 1000 fb⁻¹ for an integrated luminosity of 3000 fb⁻¹. Note that some contributions are magnified by a factor of 10 in order to be visible on the \( m_{\text{jetjet}} \) distribution.](image)

9.7.4 Triggerring on soft leptons

Supersymmetry (SUSY) is considered one of the most compelling theories to address the hierarchy problem. Recently the focus has moved to the so called natural scenarios that are motivated by the observation of a low-mass Higgs boson and that are not excluded by the measured exclusion limits. In natural scenarios, higgsino-like \( \tilde{\chi}^0_1 \), \( \tilde{\chi}^0_2 \), \( \tilde{\chi}^\pm_1 \) are expected at or below the hundred GeV scale.

The cross section for the associated production of these electroweak particles has small cross section (well below one picobarn), and can only be fully explored with the high luminosity provided by the HL-LHC. Among all processes of electroweakino pair-production, the \( \tilde{\chi}^\pm_1 \tilde{\chi}^0_2 \) exhibits the highest cross section, and can lead to final states with multiple leptons (via virtual-W and Z decays of the SUSY particles) for which very low background rates are expected. However, since the higgsinos are almost mass degenerate in this class of SUSY models, the leptons at the end of the decay chain of such processes are expected to have very low \( p_T \). This is demonstrated in Fig. 9.38 (left) where the \( p_T \) distribution for the leading and the subleading leptons, of one \( \tilde{\chi}^\pm_1 \tilde{\chi}^0_2 \) model with a \( \Delta m(\tilde{\chi}^\pm_1, \tilde{\chi}^0_2) \) of 7.5 GeV, is presented. The mass splitting between the higgsino states is typically smaller than 7.5 GeV, resulting in softer \( p_T \) distributions.

In this search, events are selected if they contain exactly two reconstructed tight electrons or
muons with impact parameters smaller than 0.01 cm. This analysis is performed in DELPHES [76] with an average of 200 pileup events.

![Figure 9.38: Left: Transverse momentum of leading (blue) and subleading (red) electron for the \( \tilde{\chi}^\pm \tilde{\chi}^0 \) signal point with \( \Delta m(\tilde{\chi}^\pm, \tilde{\chi}^0) = 7.5 \) GeV. Right: Invariant mass of the two reconstructed electrons for the same process.](image)

The efficiency to reconstruct low \( p_T \) electrons and their energy resolution is expected to highly degrade in the current calorimeter due to the radiation-induced noise and pileup levels expected at the HL-LHC. This would require raising the \( p_T \) thresholds on electrons limiting significantly the acceptance to the SUSY signals under consideration. For example 60\% (40\%) of the events have sub-leading electrons (muons) with \( p_T \) smaller than 5 GeV in the selected signal. The loss of signal acceptance caused by raising the \( p_T \) requirement from 2 to 5 GeV can be seen clearly in Fig. 9.38 (right) presenting the invariant mass of the two reconstructed electrons.

A main driver of the ECAL barrel calorimeter upgrade is the requirement for a trigger latency of 12.5 \( \mu \)s and a Level-1 trigger rate of 750 kHz, allowing the use of granular information provided by the upgraded ECAL electronics in order to construct advanced trigger primitives at L1. At the HL-LHC candidate higgsinos events can be selected by triggers based either on MET (where the MET is mainly produced by the \( \tilde{\chi}^0 \) escaping detection) or on a single jet (only suitable for candidate events containing a very high momentum initial state radiation jet balancing the \( \tilde{\chi}^\pm \tilde{\chi}^0 \) production). The requirement of an high \( p_T \) ISR jet or large values of missing \( H_T \) (MHT) suppresses significantly the event yield. Likewise, a MET trigger with a 100 GeV threshold only allows to probe events where the \( \tilde{\chi}^0 \) is produced with significant \( p_T \).

The upgraded calorimeter provides the highest crystal granularity information at L1 for better precision in the association to the tracker information, and thus improves the identification and isolation of the electromagnetic objects. Sharper turn-on of MET and MHT based triggers are also expected. These improvements will allow to maintain Run 2-like thresholds for the MET and MHT triggers. Furthermore requirements on the presence of low \( p_T \) electrons in the event, additional constraints on their invariant mass, can be implemented in order to reduce the threshold on the MET and MHT and thus to further improve the acceptance of the search [8].
Chapter 10

Glossary of Special Terms and Acronyms

- $\mu$HTR = HCAL $\mu$TCA Trigger and Readout Module.
- $\mu$TCA = Micro Telecommunications Computing Architecture.
- $\mu$IND = Index of Induced Absorption.
- ADC = Analogue to Digital Converter.
- ALARA = As Low As Reasonably Achievable.
- APD = Avalanche Photo Diode.
- ATCA = Advanced Telecommunications Computing Architecture.
- BCP = Barrel Calorimeter Processor.
- CATIA = Calorimeter Trans Impedance Amplifier.
- CMOS = Complementary Metal-Oxide-Semiconductor.
- CMS-TC = CMS Technical Coordination Group.
- COTS = Commercial Off-The-Shelf.
- CSA = Charge Sensitive Amplifier.
- DCC = Data Concentrator Card.
- DCS = Detector Control System.
- DNL = Differential Non-Linearity.
- DSS = CMS Detector Safety System.
- DTU = Data Transmission Unit.
- EB = ECAL Barrel.
- ECAL = Electromagnetic Calorimeter.
- EE = ECAL Endcaps.
- ENOB = Effective Number Of Bits.
- ES = ECAL Preshower.
- ESS = ECAL Safety System.
- Enfourneur = EB supermodule extraction and installation tool.
- FE = Front End Card.
- FEM = Front-End Module.
- FGPA = Field Programmable Gate Array.
• GBT = GigaBit Transceiver.
• GBT-SCA = Slow Control Adapter for the GBT chipset.
• HB = HCAL Barrel.
• HCAL = Hadron Calorimeter.
• HE = HCAL Endcaps.
• HF = HCAL Forward Calorimeter.
• HL-LHC = High Luminosity Large Hadron Collider Project.
• HO = HCAL Outer Calorimeter.
• HPD = Hybrid Photo Diode.
• INL = Integral Non-Linearity.
• LS3 = LHC Long Shutdown 3 (2024-6).
• LUT = Look-Up Table.
• LVR = Low Voltage Regulator Card.
• LY = Light Yield.
• LiTE-DTU = Lisbon-Torino ECAL Data Transmission Unit.
• MB = MotherBoard.
• MEM = Monitoring Electronics Readout Module.
• MET = Missing Transverse Energy.
• MGPA = Multi Gain Pre-Amplifier.
• MHT = Missing Transverse Hadronic Energy.
• MIP = Minimum Ionizing Particle.
• ODU = Optical Decoder Unit.
• OOT PU = Out-Of-Time Pileup.
• PDE = Photo Detection Efficiency.
• PFC = Power Factor Correction.
• PLC = Programmable Logic Controller.
• PLL = Phase Locked Loop.
• PON = Passive Optical Network.
• PU = Pileup (number of concurrent interactions per LHC bunch crossing).
• RBX = HCAL Readout Box.
• SAR = Successive Approximation Register.
• SEE = Single Event Effects.
• SEU = Single Event Upset.
• SLVR = Switching Low Voltage Regulator Card.
• SM = SuperModule.
• SM36 = Supermodule 36 - the spare EB supermodule.
• SUSY = SuperSymmetry.
• SX = CMS Surface Building.
• SiPM = Silicon Photo-Multiplier.
• Spike = Anomalous signal in CMS ECAL APDs.
• TCC = Trigger Concentrator Card.
• TCDS = CMS Timing and Control Distribution System.
• TIA = Trans Impedance Amplifier.
• TMR = Triple Modular Redundancy.
• TSMC = Taiwan Semiconductor Manufacturing Company Limited.
• Trigger Tower = Legacy ECAL readout unit corresponding to a $5 \times 5$ crystal matrix.
• USC = CMS Underground Service Cavern.
• UXC = CMS Underground Experimental Cavern.
• VFE = Very Front End Card.
• VHDL = VHSIC Hardware Description Language.
• VL+ = Versatile Link.
• WLS = Wavelength Shifting fibre.
• lpGBT = Low Power GigaBit Transceiver.
• sFGVB = Strip Fine Grained Veto Bit.
Appendix A

Recent progress in understanding the radiation damage of HCAL scintillators

A.1 Introduction

The main body of this TDR was written in mid-2017, when only a fraction of the 2017 dataset was available to study scintillator radiation damage using HEP17, the wedge of the HCAL Endcap upgraded to SiPM-based readout during EYETS 2016–17 (see, in particular, Section 2.2). This appendix was added in January 2018 after the analysis of the entire 2017 dataset was completed, confirming the conclusions drawn in September 2017 that the HCAL Barrel scintillators and fibers do not need to be replaced for HL-LHC running.

A.2 Overview

The HCAL Barrel (HB) must sustain the radiation dose of the HL-LHC and maintain adequate performance. The projected radiation damage of the HB scintillators is best estimated using measurements of signal loss in the HE, where the doses accumulated so far in Run 1 and Run 2 exceed the dose expected in the HB at the end of the HL-LHC run.

In early 2017, we upgraded the front-end electronics and photosensors of a $\Delta \phi = 20^\circ$ wedge of the HCAL Endcap (HE) calorimeter. In particular, the Hybrid Photodiodes (HPD) [77] in this wedge were replaced with Silicon Photomultipliers (SiPM) [78]. Previous in-situ assessments of the radiation damage of HCAL scintillators\(^1\) were performed using HPDs as photosensors, which are known to suffer from operation-induced deterioration. The upgraded wedge has allowed us to make a direct measurement of radiation damage of HE scintillators read out by SiPMs, which maintain their response to within a few percent after the irradiation expected at the HL-LHC.

At the time of writing the TDR, we made the assumption that the scintillator radiation damage could be represented by the signal loss measured in tiles read out by a selected subset of the least deteriorated HPDs (the ten HPDs that have the smallest signal loss, later referred to as the ten best HPDs). Now, having completed the analysis of the scintillator data from the upgraded HE wedge, corresponding to 48.3 $\text{fb}^{-1}$ of luminosity delivered to CMS in 2017, we can confirm that the radiation damage of scintillator tiles read out by SiPMs is consistent with the signal loss measured in tiles read out by the ten best HPDs.

Using a scintillator radiation model based on 2017 data from the HE channels read out by SiPMs, the radiation damage is consistent with the estimated damage of the HB scintillators.

\(^1\) SCSN-81 from Kuraray Corporation, Otemachi, Chiyoda-ku, Tokyo 100-8115, Japan is used in all layers except layer 0, where PVT (BC-408) from Bicron, Newbury, OH, USA is used (now available from Saint-Gobain Crystals, Courbevoie, France).
SiPMs, we project that the light output from the front layers of the HCAL Barrel (HB) will be reduced to 30–50% of the original light output at the time of construction by the end of HL-LHC running. This assumes that 4500 fb\(^{-1}\) of integrated luminosity is delivered to CMS during ten years of HL-LHC operations at 5–7\( \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\). The simulation of the HB performance with the above scintillator radiation damage shows that there is no impact on detector performance throughout the entire HL-LHC program. Therefore, we have decided to eliminate the HB scintillator megatile replacement from the scope of the Phase-2 upgrade of the CMS Barrel Calorimeter, together with the associated concurrent replacement of the SiPMs and the Optical Detector Units.

A.3 Assessment of Scintillator Radiation damage as of September 2017

The HCAL uses a laser calibration system to monitor the response of the detector and, in particular, the radiation damage of the scintillators. In the HE, which has the geometry shown in Fig. A.1, ultraviolet light is injected into the scintillator tiles of two specific sampling layers, layer 1 (L1) and layer 7 (L7), as shown by a set of dots in Fig. A.1 (right).

Figures A.2 and A.3 (Figs. 2.16 and 2.17 from Section 2.2, reproduced here for convenience) show FLUKA simulation\(^3\) results for the integrated doses and the average dose rates in HB expected for the ultimate scenario of HL-LHC operations (4500 fb\(^{-1}\) and 5–7\( \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\)). In the front layers of HB, we expect doses between 0.1 and 0.4 Mrad and dose rates between 0.2 and 1.2 \(\times 10^{-2}\) krad/hr, depending on \(\eta\) and layer.

At the time of the writing of the TDR, data used to understand the degradation of HCAL scintillator response were from channels read out using HPDs. However, it had already been recognized\(^7\) that HPDs suffered a deterioration of their response and, as a consequence, the observed decrease of the HE response over time was not caused exclusively by radiation damage in the scintillator, and in wavelength-shifting or clear fibers. It was also known that the HPD deterioration varied significantly from HPD to HPD, some being more prone to damage than others, causing a marked \(\phi\)-asymmetry in the overall signal loss that followed exactly the non-trivial granularity of the HPD readout. In order to separate signal loss in HE into the two contributions, HPD deterioration and scintillator radiation damage, we made the assumption that the scintillator loss per se could be described by the signal loss measured in the channels read out by the least damaged HPDs.

We assume that the loss of scintillator light output is described by an exponential function that depends on the received integrated radiation dose, as described by:

\[
L(d) = L_0 \exp^{-d/D},
\]

where \(L(d)\) is the light output after having received a dose \(d\), \(L_0\) is the light output before irradiation, and \(D\) is the dose constant. By fitting the measured signal loss as a function of integrated luminosity, exponential constants are first extracted in units of fb\(^{-1}\) and then converted to exponential constants, \(D\), in units of Mrad. For this step, we use the FLUKA MC simulation to predict the dose received by each scintillator tile per unit of integrated luminosity, as a function

\(^2\) If the megatile replacement had been necessary, the plan would have been to implement a finer granularity of the light collection in the replaced tiles. To accommodate this, an additional replacement of SiPMs (with larger area SiPMs) and new ODUs would have been necessary at the time of the megatile replacement.

\(^3\) An implementation of FLUKA specific to the CMS detector was used (version v3.0.0.0).
Figure A.1: Left: Example of a the transverse ($\eta$-$\phi$) segmentation of two adjacent HE megatiles, covering a $\Delta \phi$ angle of 20°. Right: Longitudinal and angular segmentation of the HE calorimeter. The dashed lines point to the interaction point. Tower pseudorapidity index $i_{\eta}$ is given in red, while $\eta$ ($\theta$) boundaries are given in blue. The two lines of dots in L1 and L7 represent the location where UV light is injected into the scintillator for calibration and monitoring.

Figure A.4 (Fig. 2.24 from Section 2.2) shows the dose constant as a function of dose rate for HE scintillators using 2016 data based on the average of the HE ten-best HPD channels. A dose-rate dependence of the dose constant is evident. This is in agreement with earlier studies of radiation damage of plastic scintillators [80–82]. At the dose rates expected in the high-$\eta$ front scintillator layers of HB, $\sim 1 \times 10^{-2}$ krad/hr, the value of the dose constants are in the range

---

4 Because we use damage measured in HE after a certain delivered integrated luminosity to extrapolate to the damage in HB and project it to the integrated luminosity at the end of the HL-LHC, the absolute FLUKA uncertainty cancels out. Only the uncertainty on the extrapolation from HE to HB matters.
Figure A.2: Expected dose for the HCAL Barrel calorimeter as a function of $\eta$ and layer for 4500 fb$^{-1}$ of delivered integrated luminosity, corresponding to the ultimate scenario of the HL-LHC.

Figure A.3: Expected dose rate for the HCAL Barrel calorimeter as a function of $\eta$ and layer for $\sim 6 \times 10^{34}$ cm$^{-2}$s$^{-1}$ of instantaneous luminosity, corresponding to the ultimate scenario of the HL-LHC.

0.4–0.5 Mrad, for an expected integrated dose of less than 0.5 Mrad after 4500 fb$^{-1}$.

Figure A.5 (Fig. 2.25 from Section 2.2 shows the expected relative light yield in HB after 4500 fb$^{-1}$ based on the radiation damage model, shown in Fig. A.4, extracted from the 2016 data of the ten best HPDs in the HE. In the high-$\eta$ region of the front scintillator layers of HB, the most exposed to radiation damage, 30–50% of light signal remains after 4500 fb$^{-1}$. However, the response of the HB readout will improve after the Phase-1 upgrade in LS2 by a factor of 2.5 due to the higher photo-detection efficiency (PDE) of SiPMs compared to (undamaged) HPDs, and a further factor of 2.4 in layer 0 due to the planned removal of legacy neutral-density filters. The plots that include these factors were presented in Fig. 2.26, and are not repeated here.

Figure A.6 (Fig. 9.28 from Section 9) shows the comparison of the jet transverse momentum
Figure A.4: Dose constant $D$ as a function of dose rate $R$ using HE data from 2016. The points show the average dose constants over the ten best HPDs, with red (blue) points corresponding to L1 (L7) data. Error bars are calculated using the RMS of the variation in $D$ extracted from the response loss vs. dose of individual scintillator tiles. Solid lines correspond to fits using the parametrization $D = a \times R^b$. Dashed lines indicate the error band associated with the fits.

Figure A.5: Light yield for HB after 4500 $fb^{-1}$ of delivered integrated luminosity (300 $fb^{-1}$ pre-LS3 + 4200 $fb^{-1}$ post-LS3), relative to the light yield for HB at the time of construction, plotted as a function of layer and tower index $i_{eta}$. Two different radiation damage models have been used to generate the plots. Left: Radiation damage model using the average of the channels read out by the ten best HPDs in HE during 2016. Using a fit to L7 data, the extracted value of $D$ is $3.6 \times R^{0.5}$. Right: Radiation damage model with parametrization $D = 2.4 \times R^{0.5}$, corresponding to a 1$\sigma$ shift with respect to the central value of the fit to L7 data.

resolution in the low $\eta$ ($|\eta| < 0.5$) and high $\eta$ ($0.5 < |\eta| < 1.3$) regions of HB using a MC simulation of the HB scintillator response without and with light yield degradation (ageing). The radiation damage model for the scintillator used in the simulation samples for this study was consistent with the $-1\sigma$ band of the fit to the channels read out by the ten best HPDs of
the HE. This provides an additional safety margin under the assumption that the central value of the ten-best-HPD fit was representative of the scintillator damage.

The conclusion in Section 9 was that there is no performance degradation when the HB scintillators are aged as projected for the entire HL-LHC program \((4500 \text{ fb}^{-1})\). However, because of the reliance on the assumption that the ten best HPD channels indicate the degradation in scintillator tile performance, it was considered prudent to maintain the tile (and associated SiPM and ODU) replacement within the project scope for Phase-2 until sufficient data with SiPMs could confirm this assumption.

Figure A.6: Jet \(p_T\) resolution of particle-flow jets in \(|\eta| < 0.5\) (left) and \(0.5 < |\eta| < 1.3\) (right), as a function of jet \(p_T\), for simulated samples that do not include pileup interactions. The plots show HB scintillator not aged (blue dots), HB scintillator aged to \(4500 \text{ fb}^{-1}\) (red squares), and both HB scintillator and SiPMs aged to \(4500 \text{ fb}^{-1}\) (green triangles). EB ageing at \(4500 \text{ fb}^{-1}\) is applied to all curves.

**A.4 Analysis of the HE Scintillator/SiPM data collected in 2017**

During the 2016–17 extended year-end technical stop (EYETS), four of the HPDs in the HE (sector HEP17, covering a \(\Delta \phi = 20^\circ\) wedge and the entire HE pseudorapidity range \(\eta = 1.5 – 3.0\) in the positive \(z\) hemisphere) were replaced with Silicon Photomultipliers (SiPMs) as part of a first stage of the HE Phase-1 front-end upgrade. This replacement allowed us to make a direct measurement of the radiation damage of HE scintillators read out by SiPMs. The analysis of the \(48.3 \text{ fb}^{-1}\) delivered to CMS in 2017 confirms that a large fraction of signal loss in HE, up to 60\%, is caused by HPD deterioration instead of being exclusively due to radiation damage of the scintillator. In addition, we were able to confirm the assumption made while writing this TDR, namely, that the signal loss in HE caused by scintillator radiation damage and measured with SiPMs is well represented by the HE signal loss measured using the channels read out by the ten best HPDs.

Figure A.7 shows the signal loss in the front part and high \(\eta\) region\(^5\) of the HE detector, L1 and \(\eta = 2.5–2.65\) (ieta = 27) and \(\eta = 2.65–2.868\) (ieta= 28) as a function of integrated luminosity in

\(^5\) Figure A.1 (right) indicates the HE \(\eta\) coverage and defines the tower pseudorapidity index ieta.
A.4. Analysis of the HE Scintillator/SiPM data collected in 2017

2017. The lines in each of the two plots represent the response loss of all 72 tiles at different \( \phi \) sections, and at the same \( \eta \) and layer position. Thin lines correspond to individual tiles read out by HPDs, and the two bold lines correspond to the tiles read out by SiPM photodetectors. The figures illustrate that the signal loss for two scintillator tiles read out by SiPMs is smaller compared to scintillator tiles read out by HPDs.

Figure A.7: Signal loss in the HE detector: L1, \( \text{ieta}=28 \) (upper plot) and L1, \( \text{ieta}=27 \) (lower plot), as a function of integrated luminosity in 2017. The lines represent the response loss of all 72 tiles at different \( \phi \) sections, and at the same \( \eta \) and layer position. The thin lines correspond to individual tiles read out by HPDs, while the two bold lines correspond to the tiles read out by SiPMs.

Figure A.8 shows the signal loss after 48.3 \( \text{fb}^{-1} \) in the region of the HE detector most exposed to radiation, L1, \( \text{ieta}=28 \). The blue histogram corresponds to tiles read out by HPDs and the
red histogram corresponds to the two tiles read out by SiPMs. The signal loss of the two tiles read out by SiPMs is similar to the signal loss for the tiles read out by the least damaged HPDs.

Direct confirmation of the damage that has occurred to the HE HPDs has recently become available [83, 84]. Following the removal of HPDs from HEP17 during EYETS 2016–17, a post-mortem scan with laser light was performed on the photocathode of a highly damaged HPD. The results of the scan are shown in Fig. A.9 and compared to a scan performed on a new HPD at the time of detector construction.

The extracted exponential dose constants for the scintillator tiles with SiPM readout are shown in Fig. A.10. Each data point corresponds to the average of individual dose constant measurements for scintillator tiles at the same dose rates (same layer and $\eta$, different $\phi$). Red and blue points correspond to layer 1 (L1) and layer 7 (L7) scintillators, respectively. At dose rates relevant for the scintillators in the high-$\eta$ front layers of HB, $\sim 1 \times 10^{-2}$ krad/hr, the measured dose constants are in the range 0.3–0.4 Mrad for an expected integrated dose in that region of less than 0.5 Mrad after 4500 fb$^{-1}$.

The plot in Fig. A.10 confirms a strong dependence of the dose constant on dose rate. In particular, tiles irradiated at lower dose rates have lower exponential constants and thus experience more damage per unit of integrated dose than tiles irradiated at higher dose rates. The black line shows a fit to the dose constants, measured with SiPM 2017 data, using a parameterization $D = a \times R^b$, where $D$ is the dose constant (Mrad) and $R$ is the dose rate (krad/hr). The result of the fit is $D = (3.4 \pm 0.2) \times R^{(0.49 \pm 0.05)}$, where the uncertainties on the fit parameters have been scaled up by the value of $\chi^2/n.d.f.$ of the fit. The systematic uncertainty on $D$ is approximately 10% for the scintillator tiles where the radiation damage is sufficiently large that $D$ is well measured. For the data collected so far by HE, this corresponds to scintillator tiles exposed to dose rates above $10^{-2}$ krad/hr. The agreement of this fit using 2017 SiPM data with the central fit for the ten best HPD channels using 2016 data (see Fig. A.4) is very good.

Figure A.11 shows the projections for HB scintillator ageing by the end of the HL-LHC program as derived using the parameterization of the dose constant versus dose rate extracted from 2017 SiPM data as shown in Fig. A.10. In particular, Fig. A.11 (top) shows the projected light yield after 4500 fb$^{-1}$ of delivered integrated luminosity relative to the original HB light yield at the time of construction. These SiPM-based projections are very similar to those derived using the
Figure A.9: Scan of HPD photocathodes using laser light. The z-axis is proportional to the response of the device. Top left: a new HPD scanned before installation on the HCAL detector; the response is uniform across the entire device. Top right: a highly damaged HPD extracted from the HE wedge (HEP17) upgraded to SiPM readout in EYETS 2016–17; the response is reduced in a highly not uniform way and, in addition, localized damage spots have appeared at the locations of incoming light from single fibers from the scintillators. Bottom left: finer scan (100 µm step size) of the single pixel area from the HPD on top-right, with several localized damage zones corresponding to the fibers carrying light from individual tiles comprising a single readout depth (13 layers). Bottom right: picture of an HPD.

central fit to the ten best HPDs (left plot of Fig. 2.25) and more optimistic than those based on the $-1\sigma$ fit (right plot of Fig. 2.25). Figure A.11 (bottom) shows the projected light yield times photodetection efficiency after 4500 $fb^{-1}$ relative to HB at the time of construction. This plot accounts for the improvement in response of the HB readout by a factor of 2.5 after the Phase-1 upgrade in LS2, due to the higher PDE of SiPMs compared to (undamaged) HPDs, and a further factor of 2.4 in L0 due to the planned removal of legacy neutral density filters.

A.5 Conclusions

Data collected in 2017 have confirmed the predictions described in this TDR. In particular, we expect that the remaining light output in the front layers of the HCAL Barrel after 4500 $fb^{-1}$ will be 30–50% of the original light output at the time of construction. The light loss will largely be recovered by the higher SiPM photodetection efficiency with respect to HPDs after the Phase-
Figure A.10: Dose constant (Mrad) vs. dose rate (krad/hr). The data points show the values of dose constants derived from the scintillator signal loss in the HE sector read out by SiPMs using 48.3 fb$^{-1}$ delivered to CMS in 2017. Red points correspond to layer 1 (L1) scintillators, and blue points correspond to layer 7 (L7) scintillators. The black line represents the best fit of the 2017 data using a parametrization $D = a \times R^b$, where $D$ is the dose constant (Mrad) and $R$ is the dose rate (krad/hr).

1 HB upgrade in LS2. Monte Carlo simulations confirm that there is no impact on detector performance from scintillator degradation through the end of the HL-LHC program. Therefore, we have decided to eliminate the HCAL Barrel scintillator megatile replacement from the Barrel Calorimeter Phase-2 scope, as well as the associated further replacement of SiPMs and Optical Decoder Units.
A.5. Conclusions

Light deterioration for Phase1+2 HB due to radiation damage

Relative photoelectron sensitivity of Phase1+2 HB (SiPM) vs. Run0 HB (HPD)

Figure A.11: Projections for HB scintillator ageing using the 2017 SiPM-based parameterization of the dose constant $D$ versus dose rate $R$, $D = 3.4 \times R^{0.49}$. All plots are shown for 4500 fb$^{-1}$ of delivered integrated luminosity (300 fb$^{-1}$ pre-LS3 + 4200 fb$^{-1}$ post-LS3). Top: Light yield relative to the HB at the time of construction, plotted as a function of layer and tower index ieta. Bottom: Light yield $\times$ photodetection efficiency (LY $\times$ PDE) relative to the HB at the time of construction, plotted as a function of layer and tower index ieta. With respect to the top plot, this includes the increase in PDE due to the replacement of HPDs with SiPMs ($\times2.5$) and the additional increase in light output due the removal of legacy neutral-density filters ($\times2.4$) for L0.
Appendix A. Recent progress in understanding the radiation damage of HCAL scintillators
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