CMS Upgrades with a focus on detector technologies

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Abstract. In 2026 the Large Hadron Collider after its upgrade will provide an instantaneous luminosity of $5\div7\times10^{34}$ cm$^{-2}$s$^{-1}$, which is three times higher than the nominal luminosity. The so-called High Luminosity LHC will be in operation for about ten years. Such a long operation means that detectors will be exposed to a very high irradiation dose. These two factors - the high instantaneous luminosity and the large irradiation dose - require more robust and higher granularity detectors and significantly faster data transmission and analysis. To face these challenges the CMS detector will be significantly upgraded in the coming years. It is planned to completely rebuild the tracker system, endcap calorimeters and install a new MIP (minimum ionizing particle) timing detector. In this paper a brief review of the CMS detector upgrades will be given, with more details on the tracker, the calorimeters and the timing detector.

1. Introduction

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world. It has been built at CERN in 1998-2008 and has been successfully operating since 2010. The maximum instantaneous luminosity achieved in 2018 is $2.1\times10^{34}$ cm$^{-2}$s$^{-1}$ and the integrated luminosity delivered so far is 185 fb$^{-1}$. By 2024 it is planned that the LHC will reach a total integrated luminosity of over 300 fb$^{-1}$. In 2024-26 the so-called Long Shutdown 3 will take place during which the LHC complex will be upgraded based on a number of innovative technologies that include cutting-edge superconducting magnets, compact and ultraprecise superconducting radio-frequency cavities for beam rotation, new vacuum and cryogenic systems and many other new technologies. The main aim of the HL-LHC project is to provide ten times more proton-proton collisions than before the upgrade. This goal will be achieved by providing a higher instantaneous luminosity of $5\div7\times10^{34}$ cm$^{-2}$s$^{-1}$, which is three times higher than the nominal luminosity and by operating the HL-LHC for ten years. Higher luminosity means more pile-up (PU) events: proton-proton collisions that occurred during the same bunch crossing. Longer operation means larger radiation damage to particle detectors. All four major LHC experiments - ATLAS, CMS, ALICE and LHCb – are now in preparation for their detector upgrades.

In the coming years the CMS detector [1] will be significantly upgraded (called Phase-2 Upgrade within CMS) to face the harsh experimental conditions of the HL-LHC. Based on the detailed measurements taken during the CMS detector operation, radiation tests and detector performance studies it was concluded that the tracker system and the endcap calorimeters must be replaced. Despite these upgrades the very high PU of 140-200 events could still reduce the performance of the CMS

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detector due to challenges in resolving primary interaction vertices in the same event. A new minimum ionizing particle timing detector is proposed that allows for an efficient separation of the primary interaction vertices due to very high timing resolution of about 30 ps. Other sub-detectors and subsystems of the CMS detectors will be also rebuilt or significantly improved. A brief overview these upgrades will be given in the section 2, with more details provided for the tracker system, the endcap calorimeters and the timing detector.

2. CMS detector upgrades

In 2015 the Technical Design Report [2] was submitted where the main goals and the sub-detector upgrades of the CMS Phase-2 detector have been provided. Below the CMS detector sub-systems are listed with a brief description of planned upgrades. The upgrades of the tracker system and endcap calorimeters as well as a new MIP timing detector will be presented in more details.

Tracker. The tracker will be completely re-designed and rebuilt. New technologies will be used for a silicon sensor and readout chip designs. Details are given in subsection 2.1.

Endcap Calorimeter. ECAL and HCAL calorimeters will be substituted with a new high granularity calorimeter. The design of this calorimeter is based on more radiation hard silicon sensors and scintillators. Details are given in subsection 2.2.

Muon Detector. The region 1.5<|η|<2.4 presently occupied by the four Cathode Strip Chambers planes will be complemented by two planes of Gas Electron Multiplier chambers for good position resolution and two low-resistivity Resistive Plate Chambers for good timing resolution. To meet new Level 1 trigger requirements the readout electronics of some Cathode Strip (inner rings) and Drift tube chambers have to be upgraded. The details of this upgrade are described in the Phase-2 Upgrade Technical Design Report of the CMS muon detectors [3].

Beam radiation protection and luminosity measurements (BRIL). To cope with a higher radiation level in the experimental area and higher luminosity sub-systems of BRIL like the beam condition, machine induced background as well as radiation and luminosity monitors will be upgraded or replaced. The Technical Design Report of the Phase 2 Upgrade BRIL system is expected in 2020.

Trigger. The L1 trigger latency will be increased from 3.4 μs up to 12.5 μs to accommodate tracker information and to provide sufficient time for matching tracker, calorimeter and muon systems information. The L1 trigger acceptance rate will be increased from 100 kHz up to 750 kHz. All these changes require upgrades of the readout electronics in the corresponding sub-detectors. The Technical Design Report of the Phase 2 Trigger System Upgrade is expected in 2020.

Data Acquisition and Trigger Control. The Data Acquisition system must handle the increase of bandwidth and provide the computing power needed for accommodation of the larger event size and L1 trigger rate, and the greater complexity of the reconstruction at high PU. The required upgrade of this system will be described in the Technical Design Report of the Phase 2 Data Acquisition and Trigger Control System Upgrade that is expected in 2020.

2.1. Tracker system

The tracker is the detector closest to the proton-proton interaction point. It will suffer from significant radiation damage, will need to resolve individual vertices and tracks in very dense conditions of 140-200 PU events and to provide tracking information to the L1 trigger. All tracker systems have to be radiation tolerant and remain fully efficient up to the expected after ten years of operation integrated luminosity of 3000 fb⁻¹. The granularity of the system will be increased to keep channel occupancy at the percent level in the Outer Tracker (OT) and at the per mille level in the Inner Tracker (IT). The modules in the OT will contribute to the L1 trigger. The material budget will be reduced in the tracker volume and the rapidity coverage will be extended up to |η|=4. These challenges strongly constrain the overall tracker concept, technologies and designs used for individual components: modules, silicon sensors and front-end electronics. A section of the tracker layout in r-z view is shown on Figure 1.
The Phase-2 Tracker upgrade project began in 2015 and in 2019 enters the production and assembly phase. In 2017 the Technical Design Report \[3\] was prepared where major details of the Phase-2 Tracker are provided.

2.1.1. Outer Tracker. The main driver of the OT design and its module concept is the intention to provide tracking information to the L1 trigger. The usage of tracking information will contribute to the mitigation of high PU, will allow the exploitation of track isolation and improve energy/momentum resolution of trigger objects (like jets) at L1. OT will provide tracking information every bunch crossing at a rate of 40 MHz. Such a functionality requires that OT modules should select interesting events by a module front-end ASIC and is achieved by a special module design. An OT module is composed of two single-sided closely spaced silicon sensors that are read out by the same ASIC. Depending on the distance to the interaction point modules are composed of two strip sensors (2-strip or 2S modules) in the radial region above 60 cm and of one macro-pixel and one strip sensor (pixel-strip or PS modules) in the radial region of 20-60 cm. The readout electronics correlates the two signals in the two sensors and selects hit pairs (called “stub”) that are compatible with tracks above the target threshold of 2 GeV (Figure 2 (a)). The design concept and dimensions of 2S and PS modules are shown in Figure 2(b).

The innermost modules of the OT will be exposed to a 1 MeV neutron equivalent fluence of \(1.0 \times 10^{15}\) neq/cm\(^2\). It was decided to use, as a sensor, n-in-p silicon (n-type implants in p-type bulk material) since it is more radiation tolerant and generates less noise after irradiation in comparison with p-in-n material. The sensor thickness will be about 300 \(\mu m\) with an active thickness of about 200-240 \(\mu m\) that makes production of sensors cheaper (for thicker material) but still provides sufficient signal during the full lifetime of the detector. Thinner sensors that require a lower depletion voltage and produce a low leakage current are a preferable choice.

Several front-end ASICs are designed for the OT modules. In a 2S module one readout chip receives hit information from both sensors, correlates them and generates a high \(p_T\) stub data that contributes to the L1 trigger. This chip is developed in 130 nm CMOS technology. In a PS module two different chips are developed, one for strip and one for macro-pixel sensors. These chips are designed in 65 nm technology. The correlation (stub finding) of strip and macro-pixel hits takes place in the macro-pixel ASIC.
2.1.2. Inner Tracker. The IT will be equipped with pixel modules. The modules closest to the interaction point (at about 3 cm) will experience a total ionising dose of 12 MGy, a particle fluence of $2.3 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$, a PU event rate up to 200, and a hit rate up to 3 GHz/cm$^2$. To cope with such harsh conditions several sensor technologies are under evaluation. Planar n-in-p type silicon sensors with thickness of 100-150 $\mu$m segmented in $25 \times 100$ $\mu$m$^2$ or $50 \times 50$ $\mu$m$^2$ pixels provide a good hit resolution and relatively high radiation tolerance. An alternative solution are 3D silicon sensors that have high radiation tolerance due to a shorter charge collection distance and provide the same hit resolution with the same pixel segmentation. The latter technology is more expensive hence it could be used in the regions with the highest radiation doses.

The readout chip has to have the same small segmentation and must maintain high efficiency at the above-mentioned hit rate after being exposed to an extremely high total irradiation dose. Such a chip is under development within the RD53 Collaboration [4], a common project of the ATLAS and CMS collaborations. This readout chip has a size of $22 \times 16.4$ mm$^2$ and is designed in 65 nm technology. Currently the first prototype called RD53A is under evaluation.

2.2. Endcap calorimeter
Forward parts of the CMS electromagnetic and hadron calorimeters will be replaced by a system that is called High Granularity Calorimeter (HGCAL). As in the case of the CMS tracker system the design of HGCAL is constrained by a harsh radiation environment and high PU. Sensors and front-end electronics should be functional and highly efficient after ten years of HL-LHC operation. For the parts closest to the interaction point it corresponds to a maximum particle fluence of $1.0 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ and a total ionization dose of 10 MGy. To mitigate the high PU HGCAL will have a high transverse...
and longitudinal granularity as well as a good timing resolution. Taking into account these conditions and the requirement to build the detector from low cost per unit area material due to a large total surface of HGCAL, the electromagnetic part of the calorimeter is based on silicon sensor technology and covers 585 m$^2$ while the hadronic part is based on silicon sensor and scintillating tile technologies and covers 485 m$^2$. One quota of the HGCAL layout in r-z view is shown on Figure 3(a). A detailed description of HGCAL is given in the Technical Design Report [5].

2.2.1. Calorimeter endcap electromagnetic section: CE-E. Based on the experience collected during R&D on the sensor material for the Phase-2 Upgrade of the CMS tracker system, silicon sensors have been chosen as an active material for CE-E due to high radiation levels comparable with to ones in the tracker volume. The CE-E is composed of 28 sampling layers with a total thickness of 34 cm that corresponds approximately to 26 $X_0$ and 1.7 $\lambda$. The active detector elements will be 190 mm wide hexagonal silicon sensors segmented in 432 hexagonal cells in the inner part of the calorimeter and in 192 cells in the outer part. The module is a sensor on a kapton sheet sandwiched between a 1.4 mm W/Cu (75%, 25%) baseplate and a PCB circuit board with the front-end ASICs HGCROC as shown on Figure 3(b). The HGCROC is designed in radiation hard 130 nm CMOS technology. The main features of this chip are 1) a high dynamic range with low power consumption due to the time-over-threshold (ToT) technique to measure the charge, and 2) precise (25 ps) measurements of the time of arrival (ToA) at 40 MHz frequency.

2.2.2. Calorimeter endcap hadronic section: CE-H. The hadronic part of the HGCAL is composed of a stainless steel absorber with 24 sampling layers of various longitudinal and lateral granularities. The front end of the CE-H consists of 12 layers of 35 mm absorber (3.3 $\lambda$) and the back end consists of 12 layers with 68 mm absorber (5.7 $\lambda$). First eight layers of the CE-H are instrumented with silicon pad modules (with single-sided cassettes). The remaining layers are a combination of silicon pads (at high

![Figure 3](image_url)

**Figure 3.** (a) Sketch of one quarter of the HGCAL layout in r-z view. (b) Stacked layers of the CE-E silicon module. (c) Example of the arrangement of silicon (inner part) and scintillator tile (outer part) modules in the 22nd layer of CE-H.[6]
η) and scintillator tiles read out with Si-PM (at low η). Active detector elements are 190 mm wide hexagonal silicon sensors from 8” wafers and the scintillator tile readout by a silicon photomultiplier. An arrangement of modules of different types is shown on Figure 3(c), where in the center the hexagonal silicon modules are placed while the scintillator tiles are arranged in the outer area of a CE-H layer.

The front-end ASIC of the CE-H modules will be the same one as in the CE-E, HGCROC.

2.3. MIP timing detector

High PU of 140-200 events could lead to a performance degradation of several observables, such as track and vertex reconstruction precision, di-photon vertex location, or b-jet identification. Correct assignment of tracks to primary interaction vertices allows for maintaining a Phase-2 CMS detector performance similar to the present one. It has been demonstrated in the Technical Proposal for a MIP timing detector in the CMS experiment Phase-2 Upgrade [6] that a special detector sensitive to minimum ionizing particles (MIP) with a timing resolution of about 30 ps could provide performance benefits in object and event reconstruction. In [6] the MIP Timing detector is proposed basing on two different technologies. A barrel timing layer (BTL) with a rapidity coverage of |η|<1.48 will be constructed of LYSO:Ce (a Cerium doped Lutetium based scintillation crystal) modules. In the CMS endcap region 1.6<|η|<2.95 in front of HGCAL an endcap timing layer (ETL) composed of silicon detectors with an internal gain will be placed. The main requirements for the MIP timing detector are: 1) timing resolution for charged particles of about 30 ps; 2) radiation tolerance to a particle fluence of 1.0×10^{14} n_{eq}/cm^{2} in the BTL and of 2.0×10^{15} n_{eq}/cm^{2} in the ETL; 3) minimal impact on HGCAL performance; and 4) compatibility of services and mechanics with the tracker and HGCAL systems.

2.3.1. Barrel timing layer.

The BTL detector can be attached to the carbon fiber support tube of the tracker detector. The total area of the BTL detector is about 40 m². The light collection is done by Si-PMs. LYSO:CE crystal tiles are of high density, and have the very fast decay time and high light yield. The front end ASIC (TOFHIR) will be a tailored version of the commercial TOFPET2 chip developed in 110 nm CMOS technology. After prototyping, the TOFHIR chip will be translated to more radiation hard 130 nm CMOS technology. It is already demonstrated that both crystals and chips have good time resolution: 20 ps for LYSO:CE and 37 ps for a chip with a sensor package. The latter resolution is going to be improved to 25 ps, the value already observed in beam tests.

2.3.2. Endcap timing layer.

The ETL detector will be attached to the EC nose in a separate cold volume on the interaction side of the neutron moderator that protects it from back splash from the calorimeter. The total area of the detector is 12 m². The ETL module is similar to the Phase-2 OT PS one except that it is a single layer module. The sensitive volume is a time-optimized Low Gain Avalanche Detector (LGAD) [7] that is a planar silicon detector. This is a quite established manufacturing technology that is radiation tolerant to the particle fluence expected in the innermost part of the ETL detector of about 1.7×10^{15} n_{eq}/cm^{2}. The MIP signal is sufficiently enhanced to guarantee a high enough signal-to-noise ratio for the required timing precision. The time resolution achieved in beam tests is better than 40 ps and further improvements are still possible.

The ETL front end ASIC is still under development. The main specification of the chip is the following: 1) time resolution of a bare chip < 25 ps, and 2) power consumption is about 100 mW/cm². Two complementary design activities, both in 65 nm technology, are under consideration. One of them is the RD53 chip [4] and another is the chip developed within the lpGBT project (joint ATLAS/CMS development). In both cases the goal is to find a way to achieve the required time resolution. In 2019 the Technical Design Report for the Phase-2 MIP timing detector is expected, where definite choices for the detector design will be described.

3. Conclusion
To meet the challenges of the HL-LHC era, the CMS detector will undergo significant upgrades of its subsystems including complete redesign of some of them. The main reason is a very high expected instantaneous luminosity of $5.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ that leads to a very large number (140-200) of pileup collisions in a single event and harsh radiation conditions. A total ionizing dose of 12 MGy and particle fluence of $2.3 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ will be accumulated in the expected ten years of operation by the first barrel layer of the CMS Inner Tracker which is the closest detector to the interaction point.

Most of the CMS detector sub-systems, like the tracker, calorimeters and muon detectors, are already in the engineering and pre-production phases with the production starting as early as 2019 (OT) and not later than 2021 (Barrel ECAL). Other subsystems like BRIL, Trigger and DAQ are still in a prototyping phase and the final production will start in 2021/22. The production should be completed by 2024, and the installation and commissioning are scheduled for 2025/26. The MIP timing detector TDR is expected in 2019 where a concrete outline of the project will be defined.

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