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The upgrade programme of the major experiments at the Large Hadron Collider

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Abstract. After a successful data taking period at the CERN LHC by the major physics experiments (ALICE, ATLAS, CMS and LHCb) since 2009, a long-term plan is already envisaged to fully exploit the vast physics potential of the Large Hadron Collider (LHC) within the next two decades. The CERN accelerator complex will undergo a series of upgrades leading ultimately to increase both the collision energy and the luminosity, thus maximizing the amount of data delivered to all experiments. As a consequence, the experiments have also to cope with very high detector occupancies and operate in the hard radiation environment caused by a huge multiplicity of particles produced in each beam crossing. In parallel to the accelerator upgrades, the LHC experiments are planning various upgrades to their detector, trigger, and data acquisition systems. The main motivation for the upgrades is to extend and to improve their physics programme also in the increasingly challenging LHC environment. In this paper a general overview of the upgrade programme of the major experiments at LHC will be given, with some additional details concerning specifications and physics programme of new detector subsystems.

1. Introduction

The Large Hadron Collider (LHC) is the most powerful particle accelerator built to date. Since 2009 it has successfully provided collisions to the four large experiments installed along its circumference: ALICE, ATLAS, CMS and LHCb. The ATLAS and CMS experiments are general-purpose detectors, designed to see a wide range of particles produced in LHC collisions and to search for new phenomena, including the Higgs boson, supersymmetry and extra dimensions. The ALICE experiment is mainly devoted to research in heavy-ion physics and Quark Gluon Plasma (QGP) formation, whereas LHCb is primarily designed to investigate the decays of B-particles and so provide an insight into the phenomenon of CP-violation.

During its first 4 years of operation, the LHC ramped up its energy from the start-up energy of 900 GeV up to 8 TeV, which is just over half of the design energy of the machine for proton-proton collisions. In November 2012 the LHC reached a peak instantaneous luminosity of 7.7×10^{33} cm^{-2}s^{-1}, close to the design luminosity of 10^{34} cm^{-2}s^{-1} (even though at half the design energy and twice the beam crossing time). The first LHC heavy-ion PbPb collisions took place in 2010 at a center-of-mass energy of 2.76 TeV. The LHC continued providing more PbPb data at the same energy during the consecutive years. Finally, in 2012 the LHC successfully demonstrated its capability to deliver asymmetric collisions by providing a short, 4-hour long "pilot" run of pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, which was replicated and extended during 2013.

These data-taking periods comprise the so-called LHC Run 1, which has successfully ended in February 2013, bringing the LHC to the first long shutdown necessary for its energy upgrade to the design specifications. This is the first step of a more ambitious upgrade programme that the LHC will undergo in the next long-term future. The exciting discoveries achieved during the first years of LHC operation have lead the high energy physics community to foresee a challenging upgrade of the accelerator, called High Luminosity LHC (HL-LHC). In order to further increase its discovery potential beyond 2022, LHC needs an upgrade to increase its luminosity by a factor of 10 beyond its design value. As a highly complex and optimized machine, such an upgrade of the LHC must be carefully studied and requires about 10 years to be implemented. A more powerful LHC would provide more accurate measurements of new particles and enable observation of rare processes that occur below the current sensitivity level.
To meet with the foreseen higher luminosity at the High Luminosity LHC, also the four big LHC experiments will take the opportunity to perform upgrades and routine repairs.

A detailed description of the LHC upgrade programme is discussed in Section 2, whereas the future plan of the main LHC experiments is described in Section 3.

2. The High Luminosity LHC Project

According to its envisaged schedule, the LHC is expected to continue providing collisions over the next 7 years. In this period, the LHC will achieve its design energy and luminosity, with a 25 ns beam crossing time (instead of the current 50 ns). Two major shutdowns (the so-called LS1 and LS2) of longer than a year each will be needed to accomplish these objectives. At that point many elements of the machine, as well as many sub-systems of the LHC experiments, will be damaged by radiation and will need to be replaced. This situation has lead to a foregone question about the future of LHC beyond 2022.

Thanks to the spectacular performance of the accelerator and to the interesting discoveries obtained by the experiments, the upgrade of the machine has become one the highest priority in the European Strategy for Particle Physics [1] - recently adopted by the CERN Council at Brussels - to extend and improve the physics program of the LHC experiments. The novel machine configuration will provide a considerably higher annual integrated luminosity, perhaps by a factor of 5, over that achieved in the past. That would allow the LHC to deliver $\sim$3000 fb^{-1} to the experiments by 2036, allowing them to complete their exploration and study of physics at the Terascale. At the same time as the accelerator is upgraded, the experiments will also undergo major transformations to handle the higher luminosity: indeed, most of the detectors, including the main tracking systems, must be rebuilt to deal with the extreme radiation levels and large numbers of interactions per beam crossing.

This twenty year period of LHC operation, from its start-up to 2030, will be characterized by three long shutdown periods, that correspond to three evolution phases of the machine performance:

Phase-0 In this stage, which started with the first long shutdown in February 2013, the LHC will increase the center of mass energy of pp collisions to $\sqrt{s}$ = 13 - 14 TeV with a peak luminosity of $L_{peak} = 10^{34}$ cm^{-2}s^{-1} delivering about 100 fb^{-1} of data. During the 18 months of LS1, the magnet interconnections will be consolidated and a long list of other improvements will be carried out to bring all the equipments to the level needed for 7 TeV beam energy. Most of the LHC experiments will also undergo several consolidation works in order to cope with the new running conditions.

Phase-1 In this period, which will start with the second long shutdown in 2018 and will extend until 2020, the LHC will achieve its design energy and luminosity through a series of improvements, including the installation of a new injector. Towards the end of this period,

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the LHC will reach a peak luminosity of 2 - 3 $\times$ 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, beyond the original design value, and deliver about 300 fb^{-1} of pp collision data. Improvements and upgrades to the LHC experiments will be necessary to fully exploit the luminosity, especially towards the end of this phase.

Phase-2 In its ultimate running conditions (beyond 2022, after the third long shutdown) the LHC is expected to reach a peak luminosity of 5 - 7 $\times$ 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (depending on the leveling option). By exchanging aged parts with improved components (performance-improving consolidation) the upgrade will be done gradually. An example for this is the replacement of the new focusing magnets. The expected delivered luminosity at $\sqrt{s}$ = 14 TeV of about 3000 fb^{-1} will further increase the physics reach of the LHC experiments.

A schematic timeline of the LHC roadmap is shown in Figure 1.

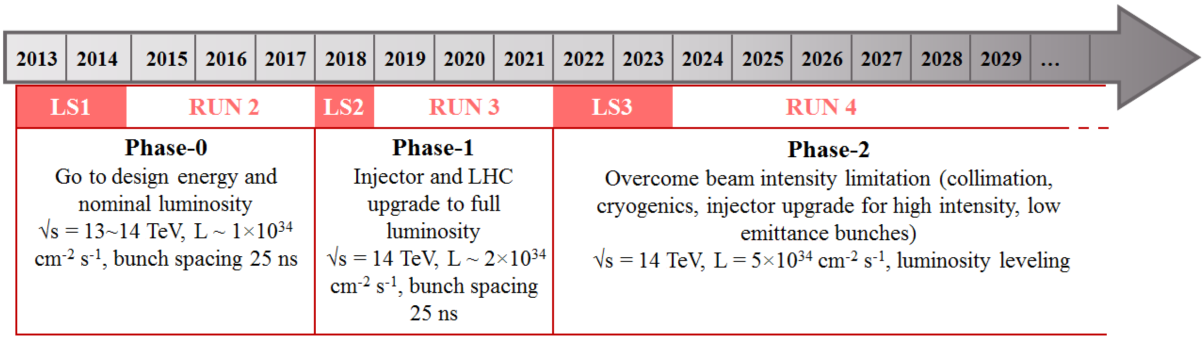

Figure 1. LHC roadmap to achieve its full potential.

At the same time, the experiments will have to upgrade their detectors significantly to cope with the higher luminosity and the foreseen long running time. Some of the upgrades and replacements of detectors become necessary at around 2022, independent of the future increase in luminosity. Especially to be mentioned here is the replacement of the large inner tracking systems of ATLAS and CMS, which will reach the end of their lifetime by that time. The detailed upgrade programme of the major LHC experiments is described in the next Section.

3. The upgrade of the major LHC experiments

The four major LHC experiments, ALICE, ATLAS, CMS and LHCb, have been taking excellent data with high efficiencies. Today, after the initial phase of LHC operations at roughly half of its design energy, some new milestones have already been achieved. Hundreds of scientific papers have been published by the four LHC experiments in only three years of activity. Some of the results are listed below:

- First, the highlight of physics achievements is clearly the discovery of a new particle, compatible with the Standard Model Higgs boson within the present experimental errors and with a mass near 125 GeV. After the discovery, both ATLAS and CMS worked hardly to measure various properties of the new particle: today the Higgs boson mass has been measured to a remarkable precision (0.43% in ATLAS and 0.34% in CMS), as well as its production cross section relative to the SM prediction (σ/σ_{SM}).
- In flavour physics, the LHCb experiment has now overtaken the remarkable achievements of the B factories and Tevatron experiments. In particular, the first evidence of the rare $\mathrm{B}^0_s(\mu\mu)$ decay seems to finally hint a deviation from the SM predictions, but still awaits

for a confirmation from ATLAS or CMS. Moreover, there are important new results on CP-violation in the heavy-flavor sector, as observed in B_s^0 decays.

- Physics studies of ultra relativistic heavy ion collisions by ALICE, ATLAS and CMS made a new step, opening a new horizon. Unprecedented and very exciting new results were obtained for example on jet quenching, dijet production, jet-photon correlations, elliptic flow, multiparticle correlations and charm suppression.

A complete list of results and technical information can be found on the web-sites of the LHC experiments [2, 3, 4, 5].

Investigation of new physics has just started and further studies are needed to conclude the exploration of the TeV scale. Concrete upgrade plans have already been proposed, requiring time and resources for at least the next 10 years. The installation of the upgraded detector components presents a serious challenge, due to many factors, such as difficulties to access some detectors, risk of physical damage to the detectors, radiation exposure and accident risk in the pits, limited time windows to perform upgrade operations. All the experiments have produced detailed documents about their upgrade strategy, whose activity will be distributed over the three long shutdowns foreseen by the machine.

In the following we briefly describe the major LHC experiments and their upgrade plans in view of the realization of the HL-LHC.

3.1. ALICE

ALICE [6] is a general-purpose detector, especially suited for the investigation of heavy-ion collisions at the LHC energetic regime. The ALICE detector has a central part, which is made of several subdetector systems placed inside a solenoidal magnet providing a field up to 0.5 T, and a forward muon spectrometer, together with additional small detectors located at small angles and at large distances from the interaction point. The central barrel includes a set of detectors with full azimuthal coverage: the Inner Tracking System (ITS), a large Time-Projection-Chamber (TPC), a Time-of-Flight Detector (TOF), and a Transition Radiation Detector (TRD). Electromagnetic calorimetry is provided by two e.m. calorimeters with different segmentations, covering a large range in ϕ and located such as to be able to detect back-to-back jet correlations. A high momentum particle identificator, based on a Ring Imaging Cherenkov Detector, is also embedded in the central region.

The overall organization of the ALICE detector allows a detailed study of several observables, both in pp and heavy ion collisions, which arise from the detection of hadrons, electrons, muons and photons. The physics results achieved by ALICE during the first phase of LHC data taking, with pp, pPb and PbPb collisions, have demonstrated the feasibility of most of the physics program planned since the beginning. The observation of a hot hadronic matter at extreme values of temperature, density and volume, together with precision measurements of all QGP probes, has confirmed the initial picture of a QGP as an almost perfect liquid. High precision measurements of rare probes will benefit of the LHC upgrade, thus extending the potential for a detailed characterization of the nuclear matter under extreme conditions. The detailed characterization of the QGP requires the investigation of various properties, with measurements of different probes. In-medium parton energy loss mechanisms, jet-jet and photon-jet correlations, quarkonium dissociation, study of charm and beauty are only a few of the planned studies in this respect.

To address such topics, the ALICE detector would require high statistics measurements. The experimental setup is then being modified to allow the readout of all interactions, and become able to accumulate 10 nb^{-1} of Pb-Pb collisions. The upgrade strategy of the ALICE experiment [7] follows the LHC plans to increase progressively, after the long shutdown LS2, the luminosity of heavy ion beams in order to reach an interaction rate of about 50 kHz, i.e.

instantaneous luminosities of L = 6×10^{27} cm^{2}s^{-1}.

The planned ALICE upgrades include at the moment several items: a new beampipe with smaller diameter; a new, high-resolution and low-material budget Inner Tracking System possibly entirely based on small size pixel detectors; the upgrade of the TPC with GEM detectors and new readout electronics; the upgrade of the readout electronics of TRD, TOF, PHOS and Muon Spectrometer for high rate operation; the upgrade of the forward trigger detectors, online systems and reconstruction. The inclusion of additional detectors or modification of the existing ones is also being discussed in view of long term decisions by the involved funding agencies. Concerning in particular the role of the Inner Tracking System (ITS), its upgrade is fundamental to improve its resolution and readout rate capabilities. The recent progress in Si detector technology, an improved integration to reduce the distance between the interaction region and the first layer of the ITS and a minimized material budget will make it possible for ALICE to address such goals.

3.2. ATLAS

ATLAS [8] is the largest detector at the Large Hadron Collider, with overall dimensions of 44 m length and 25 m diameter. ATLAS is a general-purpose experiment, especially designed to measure pp collisions at the presently envisaged frontiers of LHC, i.e. center-of-mass energies up to $\sqrt{s} = 14$ TeV and peak luminosity of 10^{34} cm^{-2}s^{-1}.

The main components of the ATLAS setup include the Inner Detector, operating inside a solenoidal field of up to 2 T, a Calorimeter and the Muon Spectrometer with a toroidal magnet and a field up to 0.5 T.

The physics topics of interest for the ATLAS Collaboration include most of the physics potential discovery at LHC: measuring the Higgs properties, searching for new physics beyond the Standard Model, especially supersymmetry studies and new gauge bosons.

In response to the new challenges offered by the LHC upgrade, in particular by the High Luminosity improvement of the machine, major changes are required to improve the detector performance in an environment providing higher detection occupancy and radiation level. While the barrel calorimeters and muon chambers are able to cope with the new scenario, significant improvements are needed for the Inner Detector, forward calorimeters and muon spectrometer.

Following the planned program of the LHC machine towards the HL-LHC, with its three long shutdown periods, the ATLAS Collaboration has split its upgrade program in three phases [9, 10]. Apart from a series of small modifications and improvements, Phase-0 (taking place during the 2013-2014 shutdown), will focus on the installation of a new barrel layer in the present Pixel Detector, with a new Beryllium beam pipe in the central region. This will improve the vertex capabilities of the tracker, extending the potential for physics analyses.

For the Phase-1 in 2018, after which the LHC luminosity will be increased by a factor 2, thus reaching 2×10^{34}cm^{-2}s^{-1}, a partial replacement of the Muon Spectrometer is envisaged, in order to ensure efficient tracking at high particle rate and large pseudorapidity. Due to the increased collision rates, also better trigger strategies will be implemented, to allow on-line selection algorithms for b-tagging and lepton identification.

Finally, a further Phase-2 upgrade is scheduled for 2022-2023, to fully exploit the high luminosity feature of HL-LHC. In this final upgrade strategy a new Inner Detector is planned, together with trigger and calorimeter upgrades. This is partly due to the need to replace the previous silicon detector and associated electronics due to cumulated radiation damage, and at the same time to provide a new system able to handle a detector occupancy between 5 and 10 times higher than before. Even though most of these new facilities are still in the R&D status, the new silicon Inner Tracker should consist of several pixel and Si-strip layers in the barrel part and in the endcap regions, with an overall higher granularity, smaller material budget and increased radiation tolerance for the readout electronics.

3.3. CMS

The CMS detector [11] is built making use of a large (13 m long, 6 m diameter) superconducting solenoid providing a magnetic field up to 4 T. This is large enough to accommodate with a modular strategy the tracking detector, based on Silicon microstrip and pixel devices, the electromagnetic calorimeter (ECAL) which uses $PbWO_4$ crystals and the lead/scintillator sampling hadron calorimeter (HCAL). Additional calorimeters extend the coverage of the CMS detector at larger rapidities. The iron yoke is equipped with four stations for muon tracking, covering most of the 4π solid angle.

The physics interests of the CMS Collaboration include all the potential which can be addressed by the study of pp and heavy-ion collisions at LHC, due to the setup capability to detect electrons, muons, τ, W and Z-bosons, top quarks, and other probes. During the first period of LHC data taking, CMS has already studied a wide amount of physics topics, from the Standard Model precision measurements to Higgs physics, Supersymmetry, top and B physics, quarkonia, as well as heavy ion physics.

Going towards the increase of the LHC luminosity within the year 2022, the machine peak luminosity will exceed the value for which CMS was originally designed, and a series of modifications/improvements are needed to successfully operate in the new conditions, from the point of view of instantaneous and cumulated luminosity and non collisional background. Other issues of concern for an upgrade deal with the optimization of data taking (minimization of the periods when the detector is not ready to take data), as well as with the replacement of obsolete equipments after long operational periods, as it is usual for experiments running for a long time.

The main changes that are proposed by the CMS Collaboration to handle the new LHC conditions after the LS2 period will be concentrated on the upgrade of the Muon System, the Hadron Calorimeters, the Pixel System, the Trigger and Data Acquisition [12].

For the Muon System it is mainly planned to add a new layer of Cathode Strip Chambers, improving also the associated readout electronics and trigger, and an additional layer of Multigap Resistive Plate Chambers to extend pseudorapidity coverage. In the hadron calorimeters, the upgrade activity will address the problem to handle an increased instantaneous and integrated luminosity, as well as to increase the robustness and efficiency. This will require to replace the HPD photosensors in the central calorimeters with the new Silicon photomultiplier devices, and the existing photomultipliers in the Forward Hadron Calorimeter with new devices having thinner glass windows and larger radiation tolerance. Since the present Pixel System cannot sustain the future high luminosity conditions still maintaining a high tracking efficiency, significant changes are planned to replace several of the existing layers in the barrel and in the end-cap. The upgraded detector will have a reduced innermost radius and material budget, thus improving tracking capabilities, vertexing and b-jet identification. The trigger will be improved switching to a new, more flexible, technology no more based on the existing VME standard, while the Data Acquisition System will have an increased band width, by a factor 2 to 5, in order to follow the expected increase in data collection.

3.4. LHCb

The LHCb experiment [13] is a single-arm spectrometer that covers the angular region from approximately 10 mrad to 300 (250) mrad in bending (non-bending) plane, corresponding to the pseudo-rapidity interval $1.9 < \eta < 4.9$. The spectrometer consists of: the vertex locator (VELO) system (including the pile-up veto stations), for a precise measurements of track coordinates close to the interaction region; the tracking system made of a Trigger Tracker (a silicon microstrip detector TT) in front of the spectrometer magnet, and three tracking stations behind the magnet, made of silicon microstrips in the inner parts (IT) and of Kapton/Al straws for the outer parts (OT); two Ring Imaging Cherenkov counters, the first positioned directly behind the VELO (RICH1), the second located behind the magnet and the tracking system (RICH2), both aimed at identifying charged particles over the momentum range 1-150 GeV/c; the calorimeter system composed of an electromagnetic (shashlik type) calorimeter (ECAL) and a hadron (Fe and scintillator tiles) calorimeter (HCAL), designed to stop particles as they pass through the detector, measuring the amount of energy lost as each one grinds to a halt; the muon detection system, that comprises five rectangular stations composed of MWPCs and GEM detectors, designed for the detection of muons of B meson decays; the spectrometer magnet, a warm dipole magnet providing an integrated field of 4 Tm.

The main purpose of the LHCb experiment is to study indirect evidence of new physics (beyond the Standard Model) in the beauty and charm sector. This is performed through the precise measurement of CP violation and rare decays of beauty and charm hadrons. LHCb runs at a lower luminosity than ATLAS and CMS, to avoid excessive pile-up of pp interactions, since it is designed to study the vertex structure of events. Nevertheless the experiment has now accumulated $\sim$3 fb^{-1}, about a factor of ten less than ATLAS and CMS, but corresponding to an enormous sample of the order of 10^{12} produced B decays.

The operation and the results obtained from the data collected in LHC Run1 demonstrate that the detector is robust and functioning very well. However, following the improved performance of the LHC, the expected luminosity could in theory double the amount of beauty and charm decays generated, while reducing the complexity of events by a factor two. For this reason the prospect to increase the physics yield in the LHCb dataset seems very attractive, but it can not be pursued without improving the detector. The strategy for the upgrade of the LHCb experiment consists of ultimately removing the first-level hardware trigger entirely [14]. The direct consequences of this approach are that all LHCb sub-detectors with silicon sensors will need to be redesigned to cope with an average luminosity of up to 2×10^{33} cm^{-2}s^{-1} and to be equipped with new trigger-less Front-End electronics, and the entire read-out architecture must be redesigned in order to cope with a multi-Tb/s readout network and the full 40 MHz dataflow.

The installation and commissioning of the upgraded detector and readout system is planned for the LHC LS2. After that, the LHCb will perform measurements beyond Flavor Physics: many of the current exploration studies will become precision studies, enabling LHCb to reach a sensitivity comparable to the theory's one.

4. Concluding remarks

The LHC began operation in late 2009 and the first three years of excellent performance of the machine and detectors brought in the first major discovery and a whole new program of precision measurements and searches. However, a series of improvements and upgrades to the machine are foreseen in order to extend the detectors research program. This will represent a great challenge for the LHC experiments, which will have to cope with unprecedent track densities, from the high instantaneous luminosity, and with extremely high radiation levels. In order to keep the performance roughly at present levels in the harsher HL-LHC conditions, the major LHC experiments are planning a series of detector upgrades synchronized to the LHC upgrade schedule, with a large number of detector installations foreseen during the three long shutdowns.

Such upgrade plans require detailed schedules and a long phase of R&D activity, that is already started. The upgrade of an operating detector presents a serious challenge, and many practical issues have to be taken into proper account. Indeed, even if most of the detectors can be quickly opened at the beginning of a shutdown, some components are not readily accessible and upgrading them within the planned shutdowns requires an elaborate planning. At the same time, the risk of physical damage to the detector due to upgrade activity must be minimized, as well as the exposure to ionizing radiation and contamination of the workers maintaining the detector.

For this reason the upgrade of the accelerator and detectors is a long process, that will cover a period of at least 10 years. The official approval of the upgrade projects of the LHC experiments is almost completed and part of the activity have already started during the ongoing long shutdown.

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