III.4.2 LHC and HL-LHC

Oliver Brüning
CERN, Geneva, Switzerland

This paper describes the main concepts and performance goals for the LHC [1] and HL-LHC projects. It summarizes the main technical challenges and highlights the key technologies that have been developed for both projects.

III.4.2.1 Introduction

The performance of a hadron collider can be measured by three key performance parameters:

- **The Center-of-Mass [CM] collision energy**: the Standard Model without the Higgs particle provides inconsistent predictions for CM collision energies above 1 TeV [also referred to as the unitarity problem of the standard model without Higgs particle]. A collider providing CM energies in excess of 1 TeV should therefore either be able to discover the Higgs particle that is necessary to solve the unitarity problem or to study in detail how the measurements deviate from the SM predictions. Choosing protons as the colliding particles for the LHC and HL-LHC projects, this implies beam energies in excess of 1 TeV CM collision energy of interest. Protons are not fundamental particles and consist themselves of quarks and gluons. The collisions in the LHC are therefore actually collisions of quarks and gluons, each of which carrying only a fraction of the total proton momentum. As a proton consists of three quarks and gluons, a minimum proton beam energy of 5 TeV is assumed as a required reasonable goal. The LHC was in the end designed for operation at 7 TeV in order to have sufficient additional headroom. However, the initial operation periods of the LHC were limited to beam energies of 3.5 TeV for the first year of operation and 4 TeV for the remainder of the first running period. The second running period increased the beam energy to 6.5 TeV and the third running period to 6.8 TeV.
- **Instantaneous luminosity**: The instantaneous luminosity gives the rate at which a collider produces events in a detector. The measured rate in the detector is given by the product of the instantaneous luminosity and the cross section of the event of interest. Looking for rare events for the Higgs discovery, a minimum luminosity of 10^{33} cm^{-2} s^{-1} was assumed to be necessary for the Higgs discovery. The instantaneous luminosity is entirely determined by the accelerator and beam parameters and proton particles were chosen as the best candidate for achieving such high luminosity levels and covering a broader energy range in the collisions for the discovery of particles with yet to determine characteristics.
- **Integrated luminosity**: in the end, the success of the experiments relies on a statistical analysis of data and the performance / discovery reach of the detectors relies to a large extend on the total sample of measured events. Therefore, what matters for the experiments in the end is less the instantaneous luminosity but the integral of the produced luminosity over time. This quantity

This section should be cited as: LHC and HL-LHC, O. Brüning, DOI: 10.23730/CYRSP-2024-003.1939, in: Proceedings of the Joint Universities Accelerator School (JUAS): Courses and exercises, E. Métral (ed.),
CERN Yellow Reports: School Proceedings, CERN-2024-003, DOI: 10.23730/CYRSP-2024-003, p. 1939.

describes then the total data volume accessible to the experiments and depends in addition to the machine and beam parameters on the overall machine efficiency and availability and the total time scheduled to produce data—i.e. the physics run period. The integrated luminosity is often measured in inverse barns, where 1 barn is 10^{-28} m^2. The goal for the LHC machine was the production of the order of 300 fb^{-1}. The worldwide data produced in hadronic collisions prior to the LHC amounted to approximately 11 fb^{-1}, mainly coming from the operation period of the Tevatron collider at Fermilab, underlining the ambitious goal of the LHC collider project.

III.4.2.2 LHC in the LEP tunnel

First studies of the LHC project started already in 1983, shortly after the approval of the Large Electron Positron [LEP] collider at CERN and preceding the publication of the LEP design report in 1984. The LEP project featured a 27 km long underground tunnel in the Geneva basin, with approximately 22 km of arcs and 5 km of straight sections distributed over 8 insertions. The LEP tunnel is located approximately 100 meters underground, maximizing its extent through the molasse by featuring a 1.4% slope and minimizing its extent under the Jura limestone while maximizing the overall circumference. The LHC was from the beginning conceived as a follow-up project to the LEP collider using the same tunnel infrastructure. Aiming for a proton beam energy of 7 TeV in a tunnel with 22 km of arcs, requires a magnetic bending field in excess of 8 T, clearly exceeding the performance of superconducting magnets used for previous hadron colliders and the existing Nb-Ti superconducting magnet technology. The Tevatron collider at Fermilab featured magnets with a peak field of 4.5 T, HERA at DESY magnets with 5.3 T and the RHIC collider at BNL magnets with 3.5 T. Pushing the magnetic field beyond 8 T therefore clearly pushed the existing Nb-Ti superconductor technology to its limits, requiring an unprecedented operating temperature of 1.9 K to provide the required operational margins. Using superfluid He at 1.9 K did not only provide additional margins for the peak field generation with Nb-Ti cables, but also allowed an efficient cooling of the cables as superfluid He can easily penetrate all insulation layers and very efficiently remove any heat that is deposited near the coils away from the superconductor. Featuring two counter-circulating beams of the same charge, requires opposite magnetic fields in the apertures of the two beams. The LHC magnets therefore feature a novel 2-in-1 design concept, where the required separate magnetic coils share the same cryogenic and magnetic infrastructure. Figure III.4.14 shows the historical evolution of Nb-Ti superconducting magnet designs for particle colliders.

The LHC features 1232 main dipole magnets and in total over 9000 magnetic elements, operating at 1.9 K, cooled by 150 tonnes of He [out of which 90 tonnes at 1.9 K] and powered by over 1700 power converters and protected by over 7000 quench detection systems. The beams in the LHC are divided into approximately 2800 packages, called bunches, requiring approximately 10^{11} particles per bunch for reaching the LHC performance goals and translating to a net stored beam power of approximately 350 MJ per beam. The stored electromagnetic energy inside the LHC magnet system exceeds 10 GJ. Energies of this order of magnitude require a segmentation of the LHC magnet system into 8 independent sectors and special care and monitoring for the protection of accelerator equipment during operation, including a sophisticated three-stage collimation system that removes any stray particles from the circulating beams before they can end up in the superconducting magnets or other sensitive accelerator component. The

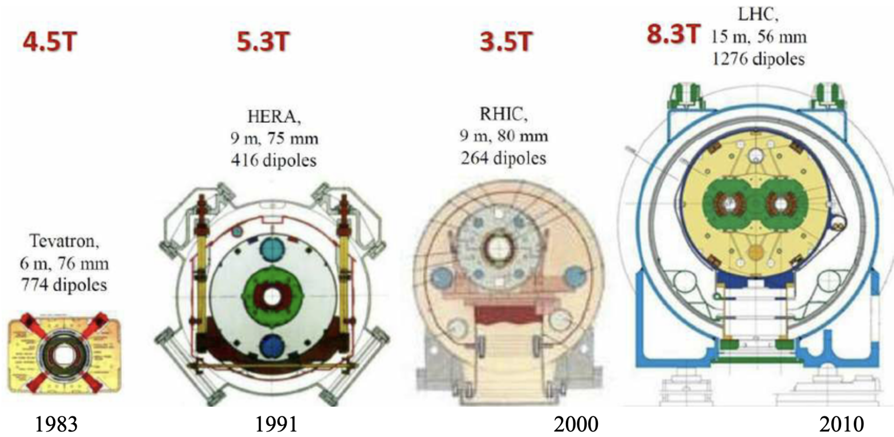

Fig. III.4.14: Magnets from the Tevatron, HERA, RHIC and LHC projects (to scale).

quench tolerance for energy deposition in the superconducting magnets is less than 20 mW/cm^3, corresponding to less than 10^{-6} particles of the nominal beam intensity impacting inside the cold-mass. In addition to operation with proton beams, the LHC operates also with 82^+ Pb fully stripped ions and features four separate experiments (see Fig. III.4.15): ATLAS and CMS as multi-purpose detectors to look for the Higgs particle, the LHCb experiment for high-precision measurements of rare events to probe the accuracy of the Standard Model and to look for physics Beyond the Standard Model, and the ALICE detector for studying the collisions of Pb ions.

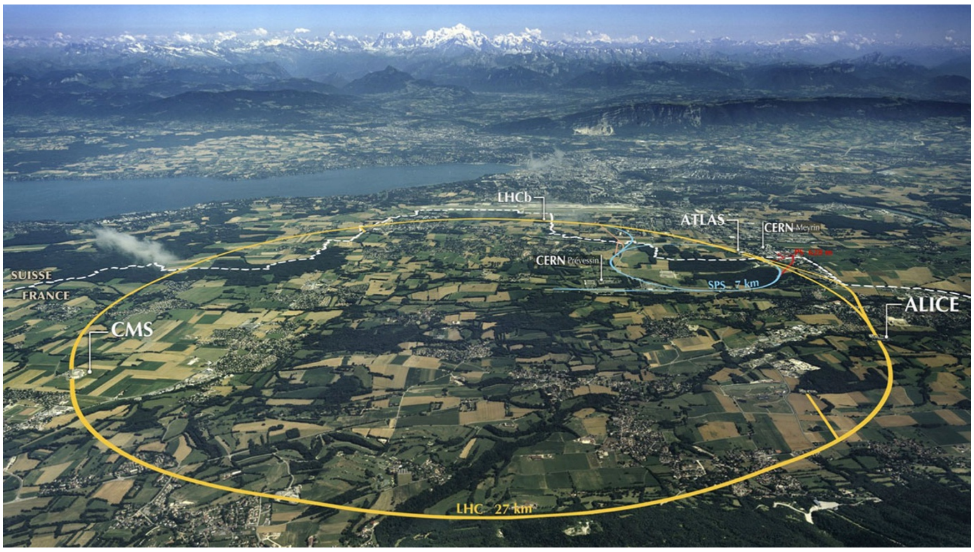

Fig. III.4.15: Overview of the LHC machine layout in the Geneva basin.

III.4.2.2.1 LHC operation and performance

LEP operation was stopped in 2000, followed by the dismantling of the LEP machine and the installation work for the LHC machine. LHC beam operation started in 2008, however, machine operation was interrupted shortly after due to a fault of one of the magnet interconnections during the final steps of hardware commissioning of the superconducting magnet circuits. The fault resulted in an electrical arc that opened the cryogenic lines as well as the beam and insulation vacuum systems and affected most of the magnets in Sector 34 of the LHC machine. The incident illustrates the large damage potential originating from the electromagnetic energy stored in the magnet system. Repair of the affected area and accelerator elements took a little over one year and hardware commissioning resumed by the end of 2009, with beam physics operation restarting in 2010. The cause of the inter-magnet connection fault was an imperfect joint soldering between two adjacent magnets. As similar imperfections could not be excluded in other interconnections, the beam energy of LHC operation was initially limited to 3.5 TeV per beam for the first two years of operation and then raised to 4 TeV after more measurements and analysis became available during the first years of operation [the stored electromagnetic energy inside the magnet system increases quadratically with the magnet current, and thus with the beam energy]. Operation at these lower beam energies were judged safe, as similar events as in 2008 could not occur at these energies and the initial operation phase was used to systematically validate all inter-magnet connections in the machine. This exercise identified several other magnet connections that had similar weaknesses, underlining that a systematic repair work was required before further increasing the beam energy towards its nominal value of 7 TeV. After the first three years of operation at lower beam energies, the LHC entered a Long Shutdown, LS1, from 2013 to the beginning of 2015 where all identified weak splices got repaired and consolidated with additional copper bypasses. Operation started again in 2015 with a new hardware commissioning exercise where the magnets system got trained towards higher beam energies.

Fig. III.4.16: The LHC schedule for the initial three running periods.

During this exercise, the LHC showed another problem: the system of magnets, 154 dipole magnets are powered in series per sector, showed in the tunnel a significant number of retraining quenches [a quench is the spontaneous loss of the superconducting state of the magnet – this can be triggered by energy deposition inside the magnet either from beam losses or by mechanical movements of the coil windings] resulting in much longer training times than anticipated. Each magnet had been individually tested and trained to nominal operating fields before installation in the tunnel. It was assumed that the magnets should keep this "memory" and that only a few magnets would need to be retrained once operated as a string in the tunnel. The magnet training after the first Long Shutdown identified as well another problem, this time with the design of the protection diode of the LHC dipole magnets, where a short between the diode and its metallic enclosure could appear due to the accumulation of metallic debris due to helium circulation after e.g. a magnet quench. This problem limited the number of quenches that the magnets should be exposed to and thus, the beam energy during the second operation period. The Run2 period therefore operated at a beam energy of 6.5 TeV. After another 4 years of operation, the LHC machine entered another Long Shutdown, LS2, from 2019 until the beginning of 2022 where all diode boxes of the LHC magnets got refurbished, allowing in principle the operation at the nominal beam energy of 7 TeV. As the recovery time from a magnet quench in the tunnel can be quite time consuming (typically taking between 8-12 hours), the number of permissible training quenches is ultimately limited by the time that can be allocated to the magnet training. In order to keep the training time at an acceptable level, it was decided to limit the beam energy as well below nominal at the start of the third operation period – and thus reduce the required number of training quenches. The Run3 operation period that started in 2022 features a beam energy 6.8 TeV, still slightly short of the nominal design value. Run3 is scheduled to end by the end of 2025 (see as well Fig. III.4.16). In spite of the limitation of the beam energy, the LHC operation showed otherwise a remarkable performance! The luminosity increased continuously with every operation year and quickly surpassed the nominal design value. Also, the machine availability and efficiency were remarkable already in the early years of operation, allowing also the integrated luminosity to surpass the yearly targets and to allow the Higgs discovery already during the first running period in 2012. Figure III.4.17 shows the achieved integrated luminosity over the first operation periods of the LHC, up to the end of Run2. The performance reached about 160 fb^{-1} during the first two operation periods, with an annual integrated luminosity of about 70 fb^{-1} towards the end of the Run2, paving the way for a total integrated luminosity of about 400 fb^{-1}, well above the original design goal of 300 fb^{-1}, by the end of the LHC operation period in 2025.

For integrated luminosities above 300 fb^{-1}, it is expected that the radiation damage in the focusing quadrupole magnets next to the high luminosity experiments of ATLAS and CMS, the so-called triplet quadrupoles as they have three separate units, will start to compromise the performance of the magnet system. Figure III.4.18 shows the schematic layout of the triplet magnets, with the experiment being on the left side of the figure. Overlaid to the layout is the expected radiation dose, assuming a constant operation configuration throughout the LHC operation. The simulations show that the radiation dose inside the magnets largely exceeds at some places the value of 10 MGy, a radiation level where most epoxy and insulation materials become brittle and lose their mechanical integrity. Figure III.4.18 therefore highlights, that the triplet magnets must be replaced by the end of the LHC Run3 period if the operation is to continue beyond 2025.

III.4.2.3 The HL-LHC project

III.4.2.3.1 Project goals

The HL-LHC upgrade project aims at extending the LHC machine lifetime well beyond the nominal running period, so that the LHC can be operated until the early 2040s, and devise beam parameters and a ma-

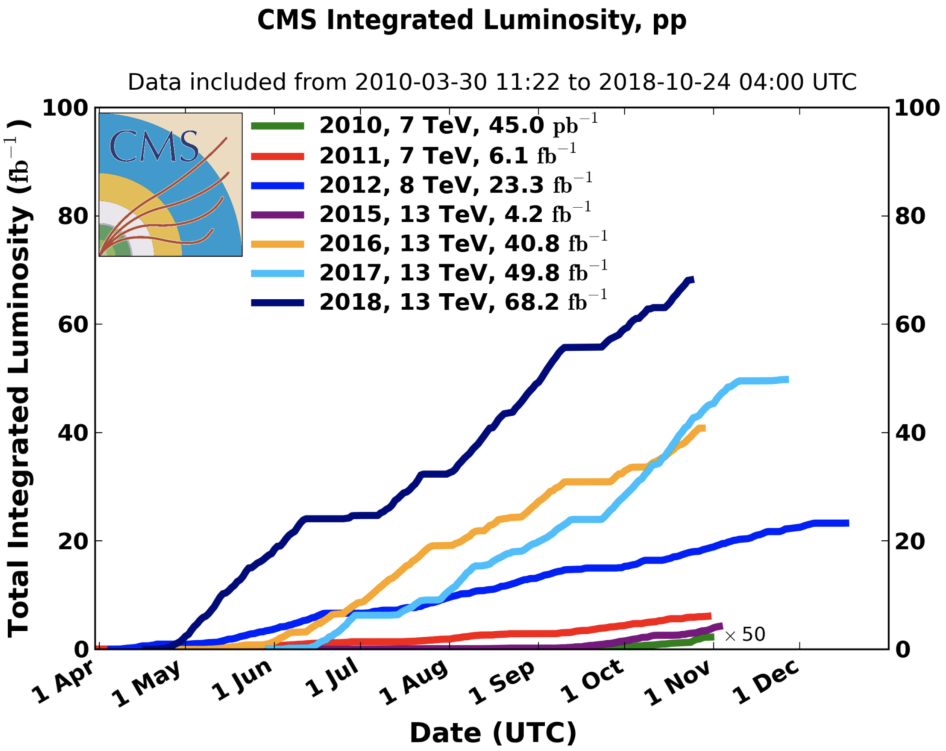

Fig. III.4.17: The Integrated Luminosity recorded by the CMS detector for the different operation years of the Run1 and Run2 periods.

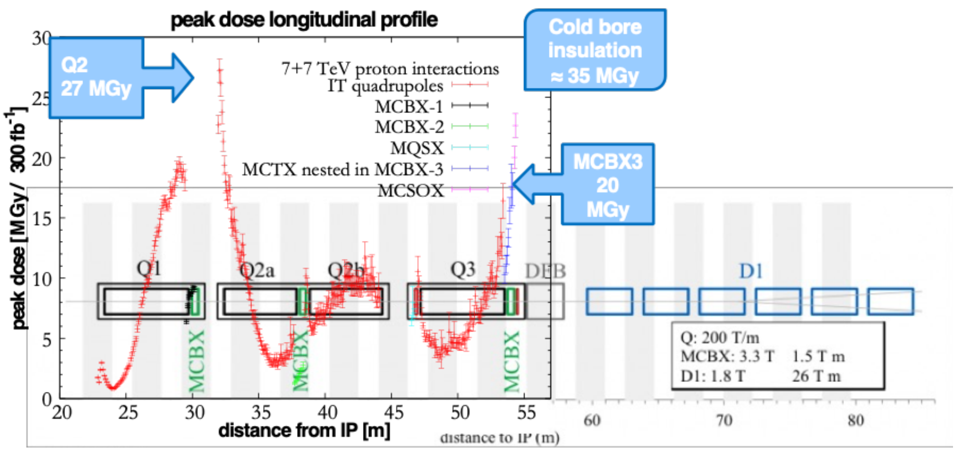

Fig. III.4.18: Triplet layout and expected radiation dose in the ATLAS and CMS insertion regions for an integrated luminosity of 300 fb^{-1}.

chine configuration that allows collecting 3000 fb^{-1} of data over the HL-LHC operation period, a tenfold increase over the nominal LHC design goal. Achieving this goal implies the production of $\sim$ 250 fb^{-1} per year, or in other words, the production of almost the total nominal LHC design luminosity within a given year of HL-LHC operation. A conventional approach would be to increase the instantaneous luminosity proportionally to this goal. However, the LHC experiments presented another design criterion for the HL-LHC that specified that not too much data should be produced at a given moment in order to assure an efficient detector operation and data analysis by the experiments. The experiments therefore requested that the instantaneous luminosity should not be larger than 5 times the nominal LHC design goal: 5×10^{34} cm^{-2} s^{-1} compared to the nominal LHC value of 1×10^{34} cm^{-2} s^{-1}. In this context one should underline that the LHC operation already surpassed this design goal and achieved instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}. Achieving the ambitious HL-LHC design goal of 3000 fb^{-1} therefore requires for the HL-LHC in addition to the increase in the instantaneous luminosity, an increase in the overall machine efficiency and availability and the implementation of a novel levelling operation mode, where the machine is designed for a higher instantaneous luminosity than is digestible by the experiments, and where operation maintains this value in a controlled manner at a level that is compatible with the detector operation during physics production. This concept requires new operational tools as well as a high machine reliability as any premature termination of a fill will imply an even more substantial loss of integrated luminosity compared to LHC operation.

III.4.2.3.2 Luminosity levelling

Different options for the luminosity levelling have been explored since the start of the LHC operation. One of the first tools tested and implemented in the LHC operation was the levelling via transverse beam offsets. Initially, this scheme was requested by the ALICE experiment for data taking during the proton beam operation. Following the initial tests, this method has been fully validated and implemented as a tool for all four LHC experiments. Another levelling option is the levelling through the beam crossing angle at the Interaction Points (IPs). As we will discuss later in the context of the Crab Cavity (CC) RF system, this would have been a very elegant tool for the luminosity levelling. However, this method does not reduce the density of events inside the LHC detectors but effectively only changes the length over which collisions will be produced within the experiments. As the event density is ultimately the key limitation for the detector performance, this method was judged in the end as not very appealing for the experiments. The third option for luminosity levelling is the variation of the beam size at the collision point through changes in the magnetic focusing of the beams left and right from the detector. While this method is clearly the most elegant levelling technique, it is also the most complex technique for the operation of the machine, as changes in the focusing strength will affect also the crossing angle and beam orbit at the IP with potential implications on the machine protection systems. However, all three techniques have by now been successfully demonstrated in LHC operation and have been established as standard operational tools for the LHC operation.

III.4.2.3.3 HL-LHC technology developments

We mentioned already in the second section the limitation of the initial triplet magnets and the need to exchange these magnets as part of the HL-LHC upgrade. In addition to this central upgrade requirement, the HL-LHC upgrade drives additional vital and cutting-edge developments in other technological areas. In the following, we list a brief summary of the new key technologies that are developed for the HL-LHC upgrade.

III.4.2.3.3.1 New triplet quadrupole magnets

Extending the triplet lifetime by a factor 10 from 300 to 3000 fb^{-1} is only possible via the implementation of active shielding that protects the radiation sensitive materials in the coils from the particle fragments that escape from the IPs. For the HL-LHC triplet magnets this is implemented by a novel octagonal beam-screen design that features ca. 2 cm thick tungsten blocks between the beam screen and the magnet cold-bore. The heat deposited inside the tungsten blocks from the beam fragments escaping the IPs is removed by an active beam screen cooling system at temperatures around 60 K before the heat could escape into the magnet cold-mass that is operating at 1.9 K. Figure III.4.19 shows the schematic cross section of the new HL-LHC triplet magnets with the octagonal beam screen, tungsten blocks (highlighted in red) and the active cooling capillaries (highlighted in blue).

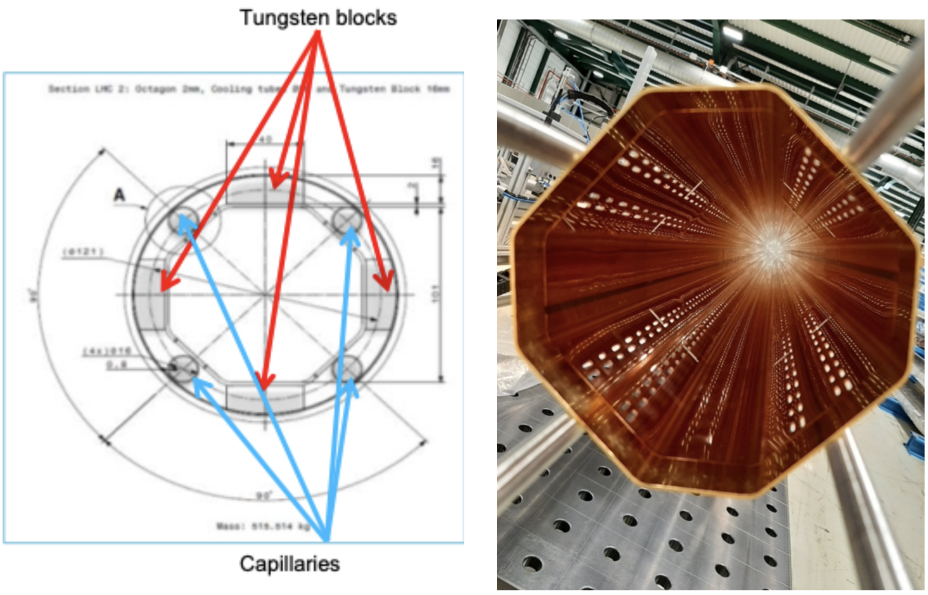

Fig. III.4.19: Left: the schematic cross section of the new HL-LHC beam screen for the inner triplet magnets. Right: a first beam screen prototype (without tungsten blocks and cooling capillaries).

Installing the additional tungsten absorbers requires a larger magnet aperture. In addition, the HL-LHC beam operation targets smaller beam sizes at the collision points, implying larger beam sizes and crossing angles inside the triplet magnets, which implies a further increase in the magnet aperture. The HL-LHC upgrade therefore aims at a coil aperture of 150 mm, compared to the 70 mm coil aperture in the initial LHC triplet magnets. As the triplet functionality is defined by the magnet gradient, a larger aperture ultimately implies a higher peak field inside the coils for a given magnet gradient. The nominal LHC configuration featured triplet gradients of 210 T/m, implying a peak field of about 8 T in the triplet magnet coils. Doubling the magnet aperture and keeping the gradient constant would imply peak fields of ca. 16 T at the magnet coils, a field level that is incompatible with available magnet technologies. As a compromise, the HL-LHC upgrade reduced the triplet magnet gradient to 132.6 T/m, implying a longer length of the triplet magnet string to achieve the required focusing strength. This is the first application of Nb_3Sn magnet technology in an accelerator, providing a peak field of 11.3 T in 7 m long magnets, paving the road for any future collider requiring bending fields above 14 T [2].

III.4.2.3.3.2 New underground civil engineering

The higher luminosities in the HL-LHC era imply additional heat loads in the triplet magnets and require additional cooling capacities for the insertion magnets. Furthermore, the goal of high efficiency and highly reliable operation implies that sensitive electronic components are removed from the tunnel areas where they would be exposed to ionizing radiation from proton losses and instead moved to areas where access during operation is facilitated to ease preventive maintenance and shorten the intervention times. To this end, the HL-LHC project planned for new underground structures and caverns to house the new cryogenic cold boxes and distribution equipment, the new infrastructure and powering equipment along with most of the electronic racks that had previously been installed in the LHC tunnel areas. The new underground constructions feature at each of the two high-luminosity interaction regions a new cavern and an approximately 300-meter-long gallery and two 50-meter-long service tunnels on both sides of the experiments that connect the new gallery to the existing LHC tunnel. In addition to the new underground structures, the HL-LHC upgrade features five additional surface buildings on the existing ATLAS and CMS sites. The new underground areas are constructed in what has been labelled the "Double Decker" configuration, where the new underground areas are located approximately 10 meters above the existing LHC tunnel structure and where the connection of the new and old structures is established via 12 vertical cores of 1 m in diameter for each of the two sites. This configuration provides optimum shielding of the new areas against radiation effects from the existing LHC tunnel and facilitates the connection of the two structures. The bulk of the civil engineering work has been conducted during LS2, when the LHC machine was not operating, in order to minimize the perturbative effect of the heavy civil engineering work on the LHC operation. All underground civil engineering work has been successfully terminated by the end of 2022 and all new surface buildings have been handed over to CERN by January 2023. CERN is now conducting the installation of the technical infrastructures, like cooling and ventilation, electrical distribution, and emergency communications. The installation of the new HL-LHC equipment is scheduled to start by the end of 2023. Figure III.4.20 shows the new underground installations for the ATLAS site.

Fig. III.4.20: The new underground installation. Left: view onto the metallic structure of the cavern. Right: schematic view of the new underground structures.

III.4.2.3.3.3 Crab cavities

The longer triplet magnet length and the reduced beam size at the IPs requires a larger crossing angle at the IPs, 500 µrad compared to the 285 µrad LHC design value and the 320 µrad currently used for the LHC operation. The crossing angle mitigates the detrimental perturbations from the non-linear beam-beam interactions and unwanted [parasitic] bunch crossings along the common beam pipe between the two D1 magnets left and right from the IPs.

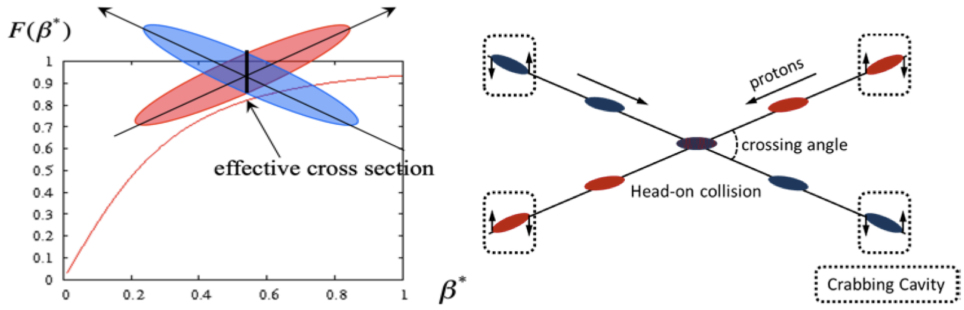

Fig. III.4.21: Functioning of Crab Cavities. Left side: the luminosity reduction factor as a function of β^* for a minimum normalized beam separation of 10 σ. Right side: schematic illustration of the transverse bunch deflection that reconstitutes a perfect beam overlap at the IPs.

Combined with a reduction of the optical β-function from 55 cm in the nominal LHC design and 25 cm in the current LHC operation period to 15 cm at the IPs for the HL-LHC configuration, the overlap of the two colliding bunches at the IP is considerably reduced and thus the attainable luminosity is reduced by about 70%. Figure III.4.21 illustrates this effect and shows the geometric luminosity reduction factor as a function of the optical β-function at the IP for a minimum normalized beam separation of 10 σ at the parasitic collision points. To recover the luminosity, two different CC designs that allow for a transverse bunch rotation were developed in collaboration with the LARP (LHC Accelerator Research Program) collaboration: a Double Quarter Wave [DQW] design optimized for a crossing angle in the vertical plane and an RF Dipole design [RFD] optimized for a crossing angle in the horizontal plane. A DQW prototype cryomodule including two individual cavities has been installed in the SPS machine where the first experimental demonstration of crabbing of a hadron beam was realized. Several key beam experiments have been conducted as part of a test campaign with high energy proton beams in the presence of CC since 2018. Figure III.4.22 [3] shows the measured bunch rotations in the SPS.

III.4.2.3.3.4 New absorbers and collimators

The higher beam intensities in the HL-LHC operation era imply the use of more robust collimator and absorber materials that feature at the same time a lower beam coupling impedance than those adopted for the start of LHC operation. The increase in total beam energy in HL-LHC era, close to 700 MJ as compared to the approximately 350 MJ of the nominal LHC configuration, implies an upgrade of all the beam dump windows and the core of the beam dump absorber. Observations during Run 2 operation period of the LHC, have given indications that the current beam dump core is already degrading from the nominal LHC operation, indicating that an upgrade of the beam dump and its core material is required for reliable

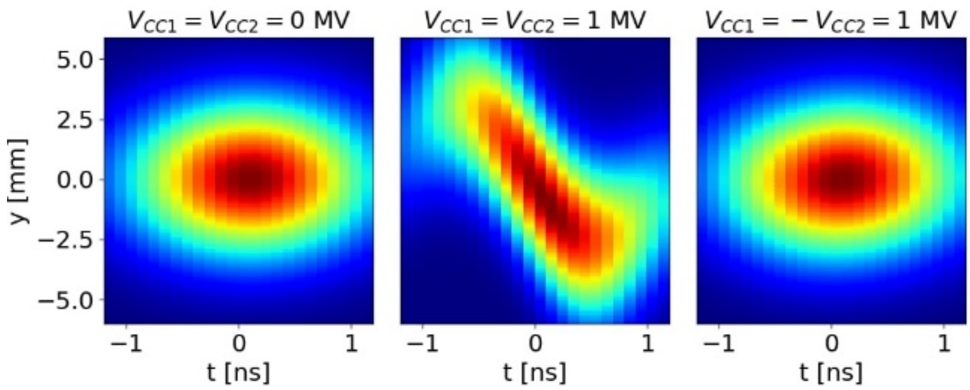

Fig. III.4.22: Intrabunch motion from three different cases [3]. Left: cavities switched off ($V_\mathrm{T} = 0$). Centre: synchronous crabbing with both cavities in phase ($V_\mathrm{T} = 2$ MV). Right: cavities in counter-phase, corresponding to an effective zero kick voltage ($V_\mathrm{T} < 60$ kV).

operation in the HL-LHC era. The new challenges [4] related to operation at lower β^* and at higher peak luminosity also required an upgrade of the absorber blocks at the Machine – Detector interface, the TAS and TAN absorbers and a complete re-design of the collimation systems around the high-luminosity experiments. The HL-LHC upgrade therefore features new, low-impedance secondary collimators and new, additional tertiary collimators in the IRs, which protect the matching section, new inner triplet magnets and the experiments from beam losses, and a more performing physics-debris collimation system. The low-impedance collimators feature new designs using molybdenum coated molybdenum-graphite and copper-coated graphite jaws that feature integrated button pickups for a more efficient alignment with the beams. About half of the LHC secondary collimators have already been replaced during Long Shutdown 2 [LS2] prior to the LHC Run3 period that started in 2022. Figure III.4.24 shows the ongoing production of the prototype jaws for the next set of physics-debris collimators at CERN. Given the criticality of maximising the physics time at the HL-LHC, all new collimators mount in-jaw beam position monitors (based on button pick-ups) for faster alignment and easier handling of the complex levelling gymnastics. For operation with ion beams, the cleaning efficiency in the Dispersion Suppressors [DS] of the ALICE experiment will be augmented by new DS collimators and by careful steering the beam trajectories in the DS so that the beam losses with Pb^{82+} ion beam collisions end up on these new collimators rather than on the downstream magnets. In IR1/5, losses are steered towards the connection cryostat of the DS that does not contain active magnetic elements, so no DS collimator is needed here. The installation of the new DS collimators relies on the development of new connection cryostats that allow the insertion of collimation equipment at room temperature. Two of these devices have been installed during LS2 next to the ALICE experiment. Figure III.4.23 shows a picture of this new collimator assembly during installation. For the cleaning insertion in IR7, the losses in the dispersion suppressor will be mitigated for Pb^{82+} operation via new crystal collimators that enhance the cleaning efficiency in IR7 for ion beam operation. Figure III.4.24 shows the new goniometers and the crystal collimators prior to their installation in the LHC. In addition, the injection protection absorber TDIS had to be upgraded for the increased beam intensities. Recent beam studies in the LHC indicate that additional DS collimators in IR7 are not required for magnet protection during nominal proton beam operation. The current setup with crystal collimators in IR7 therefore seems to be an adequate upgrade path for the moment, confirming the decision to remove the replacement of a nominal LHC Nb-Ti dipole by a more compact Nb_3Sn 11 T dipole magnets and dedicated DS collimators in IR7 from the HL-LHC baseline. The HL-LHC is therefore not only a performance upgrade for the LHC, but also a seedbed for various essential accelerator technologies that will find applications well beyond that of the HL-LHC project.

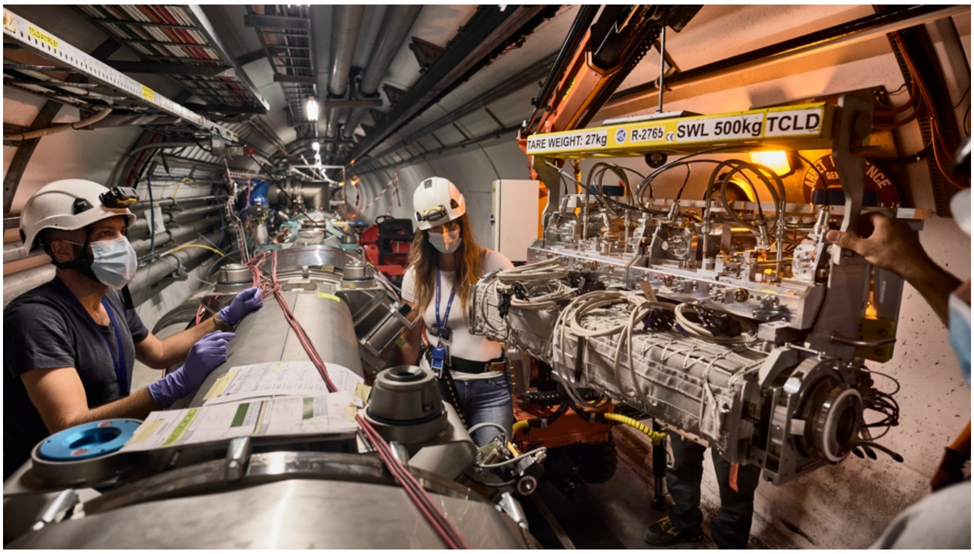

Fig. III.4.23: New DS collimator assembly during installation next to ALICE experiment.

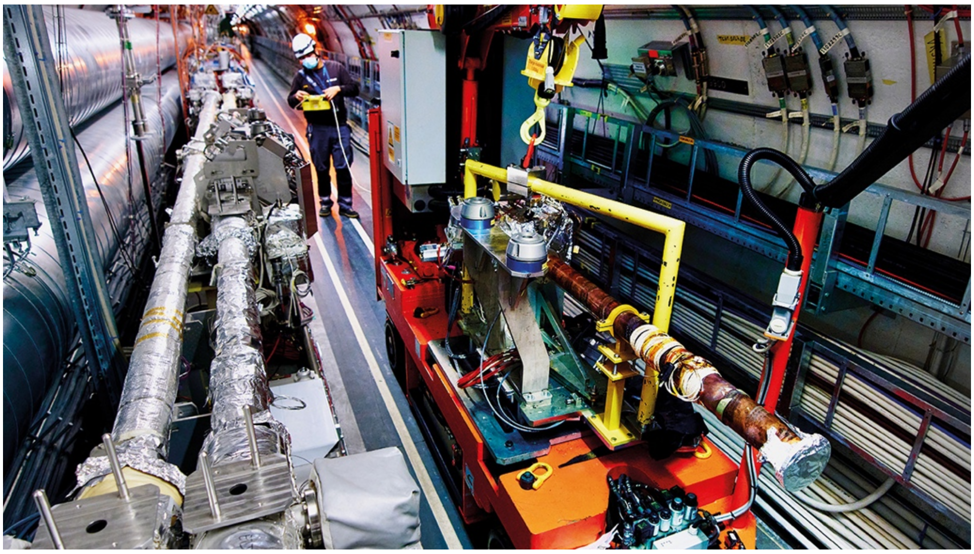

Fig. III.4.24: Goniometers and the contained crystal collimators prior to their installation in the LHC.

III.4.2.3.3.5 New superconducting link

The power converters and electronic racks for the magnet powering and protection of all new HL-LHC magnets will be installed in the new underground galleries, approximately 70 to 100 m away from the actual magnets in the tunnel. The connection between the new power converters and the new magnets in the LHC tunnel will be established with novel superconducting links that utilize high-temperature superconductors based on MgB_2 technology. The MgB_2 superconductor is cooled by gaseous He that is vaporized inside the cryo lines of the new insertion magnets, providing temperatures between 25 and 50 K inside the flexible cryostat of the superconducting link. The connections between the superconducting link to the power converters in the new galleries and the magnet cryostats in the tunnel are provided by new feed boxes that utilize as well novel high-temperature superconductors for these transitions. Prototypes of these links have been tested at the end of 2020 [Demo-2] and beginning of 2023 [Demo-3], demonstrating the ability to transport over 100 kA of continuous currents without ohmic losses at a temperature between 25 and 50 K over a distance of more than 70 meters. Figure III.4.25 shows the prototype system being prepared along with the DFHX protoype for testing on the F2 Testbench in SM18 at CERN. Prototypes of the new distribution feed boxes are currently being assembled and tested at CERN, completing the prototype phase of the first fully integrated cold powering system. The project is now in the phase of series production for all components of the superconducting link, and the cryostating of the first link of the prototype took place in March 2023.

Fig. III.4.25: Superconducting link at CERN in SM18.

III.4.2.4 Summary

The LHC machine has achieved remarkable performance levels, exceeding the nominal performance estimates in many areas by significant factors and delivering close to 1 fb^{-1} per day during its best performance periods. The accumulated radiation damage in the focusing elements next to the high-luminosity experiments implies a replacement of the existing quadrupole magnets at the end of the nominal LHC running period, that is currently projected for the end of 2025. The HL-LHC project developed suitable new quadrupole magnets with a larger radiation tolerance compatible with a tenfold increase in the total integrated luminosity of the LHC, from approximately 400 fb^{-1} from the LHC operation to up to 4000 fb^{-1} [the nominal performance target for the HL-LHC machine is the production of 3000 fb^{-1}, but the machine hardware has been designed to be compatible with the production of 4000 fb^{-1}] and a suite of new technologies to boost the LHC performance to the required levels for achieving this integrated luminosity by the beginning of the 2040s. Table III.4.2 compares some key machine parameters of the LHC with the upgraded HL-LHC machine.

Table III.4.2: Summary of the LHC and HL-LHC Parameters [5]. LHC achieved refers to status of 2023. LHC Achieved and Ultimate HL-LHC parameters are not necessarily assumed to be reached simultaneously [e.g. ultimate beam energy and ultimate luminosity cannot be achieved simultaneously due to limitations of the cryo capacities].

	Nominal LHC	**LHC Achieved**	**HL-LHC**	**Ultimate HL-LHC**
Beam energy in collision [TeV]	7	6.8	7	7.5
Number of particles per bunch [10^{11}]	1.15	1.8	2.2	2.2
Number of bunches	2808	2556	2748	2748
Beam current [A]	0.58	0.71	1.1	1.1
Revolution frequency [kHz]	11.245	11.245	11.245	11.245
β^* [cm]	55	30	15	10
Full crossing angle [µrad]	285	320	500	500
Transverse norm. emittance [µm]	3.75	2.5	2.5	2.5
Stored beam energy [MJ]	362	425	677	725
Events per bunch crossing	27	60	140	200
Luminosity [10^{34} cm^{-2} s^{-1}]	1	2.2	5	7.5

References

[1] O.S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole and P. Proudlock (Eds.), LHC Design Report, v.1: The LHC Main Ring, 2012, https://doi.org/10.23731/CYRM-2020-0010.

[2] E. Todesco et al., “The High Luminosity LHC interaction region magnets towards series production", IOP Publishing, Superconductor Science and Technology, Vol. 34, Number 5, March 2021.

[3] R. Calaga et al., “First demonstration of the use of crab cavities on hadron beams", Phys. Rev. Accel. Beams 24, 062001, (2021).

[4] G. Arduini et al., “High Luminosity LHC: Challenges and Plans", Journal of Instrumentation, Volume 11, (2016).

[5] R. Tomas et al., “Operational scenario of the first High Luminosity LHC run", J. Phys.: Conf. Ser. 2420012003, (2023).