

# OVERVIEW OF LHC INTERACTION REGION UPGRADE – PHASE-1

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## Abstract

The LHC and its experiments are ready for the first long physics run. The primary goal of CERN is to ensure that the collider is operated efficiently and that it achieves design performance in the shortest term. Since several years the HEP community has been discussing the directions for maximizing the physics reach of the LHC by upgrading the ATLAS and CMS experiments, the LHC machine and the CERN proton injector complex. The first phase of the LHC interaction region upgrade was approved by Council in December 2007. This phase relies on the mature Nb-Ti superconducting magnet technology with the goal of achieving reliable operation of the LHC at the luminosity of  $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  while maximising the use of the existing infrastructure. This report gives an overview of the Phase-1 Upgrade of the LHC interaction regions.

## GOALS OF THE PHASE-1 UPGRADE

The LHC and its experiments are ready for the first long physics run. The LHC construction effort has been considerable and has involved important international participation. The primary goal of the HEP community is to ensure that the collider is operated efficiently and that the scientific reach of this unique scientific facility is maximised [1]. In the first years of LHC running, any consolidation activities in the LHC must therefore comply with the operations schedule and use of the existing infrastructure. On the other hand, the LHC relies on the injectors and their reliability, and these accelerators must have similar priority in maintenance and upgrade. These considerations have lead to a staged approach to the upgrade of the LHC accelerator complex, which includes as the first phase the construction of a 160 MeV H<sup>+</sup> proton linac (Linac4) and the Phase-1 Upgrade of the LHC interaction regions.

The goal of the Phase-1 Upgrade is to provide more flexibility for focusing of the beams in the ATLAS and CMS insertions, and enable reliable operation of the LHC at the luminosity of  $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . The upgrade concerns in the first place the low- $\beta$  triplets and assumes the same interface boundaries with ATLAS and CMS as at present. The new low- $\beta$  quadrupoles feature a 120 mm aperture (as compared to 70 mm of the present ones) and use the technology of Nb-Ti superconductor cables cooled at 1.9 K developed for the LHC dipoles. The D1 separation dipoles, TAS and TAN as well as other elements in the insertions will also be modified so as to comply with the larger beam aperture of the triplet. However, the present cooling capacity of the cryogenic system and other main infrastructure will remain unchanged.

The Phase-1 Upgrade is organized as a CERN project since January 2008. The upgrade relies on information and technical alternatives discussed in dedicated workshops held in the past several years. The conceptual design of the Phase-1 Upgrade has been presented in a review in July 2008, and the completion of the technical design is foreseen for the end of 2010. A planning exercise has indicated that under realistic conditions all major equipment can be available by the end of 2014. The readiness for installation will be confirmed by the completion of the tests on a complete triplet string that should resolve any outstanding issue and minimize the commissioning time of the new magnet systems.

## UPGRADE CONSTRAINTS

The low- $\beta$  triplets presently installed in the LHC, shown in Fig. 1, were built by a collaboration of CERN, Fermilab, KEK and LBNL. The quadrupoles have a coil aperture of 70 mm and use Nb-Ti superconductor cables that allow an operating gradient of 205 T/m. The 1.9 K cooling, electrical powering and all protection and control signals are fed to the triplet by an in-line feed-box, shown in the foreground in Fig. 1. The triplets are positioned at L\* of 23 m from the interaction point, and allow a  $\beta^*$  of 55 cm for the design LHC luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [2].

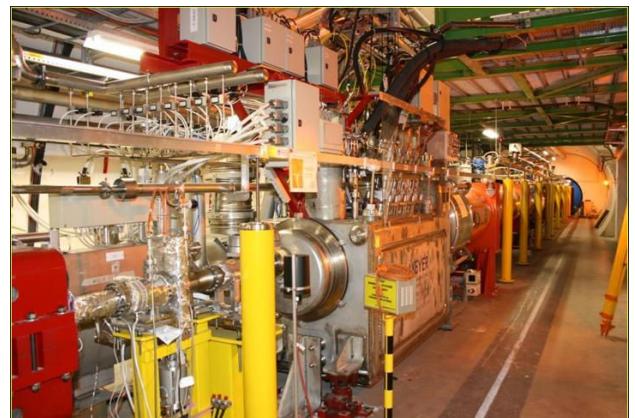


Figure 1: The low- $\beta$  triplet in the ATLAS insertion.

The cryogenic services are brought to the triplets in ATLAS and CMS insertions by the QRL compound cryo-line from the cryogenic islands located in the LHC even points. Since the triplets are at the extremities of the QRL, the total cooling power available for their cooling will depend on the as-built heat loads in the adjacent arcs. In any case, the total power available for each triplet is limited to 500 W at 1.9 K, which is the maximum power provided by the sub-cooler unit installed at the entry of

the triplet. It should be noted that at present the cooling capacity available for the triplet in Sector 4-5 (left of CMS) is smaller than for the other triplets as the RF cavities in IR4 use about 4 kW of the total capacity of the cryo-plant servicing this sector (23 kW at 4.5-20 K). This lack of symmetry between ATLAS and CMS triplets could be effectively resolved by providing a separate cryo-plant for the RF system in IR4.

It is clear that any increase of cooling requirements, in particular those related to the increase of luminosity above  $3 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1}$  will need dedicated cryogenic plants serving the triplets around ATLAS and CMS. Their installation will most likely require additional underground areas. These changes are best done as part of the overall consolidation of these areas of the LHC.

As shown in Fig. 1, all major equipment of the triplets is located in the LHC tunnel, with the exception of the power converters which are housed in the alcoves adjacent to the tunnel. Access for maintenance of the equipment in the tunnel, in particular of the feed-boxes, is difficult and may have consequences on scheduling of the LHC operation. In view of the even higher radiation levels after the Phase-1 Upgrade, it is considered necessary to install all new equipment, including the feed-boxes, in low radiation areas. Such areas are very scarce around the ATLAS and CMS triplets.

## LAYOUT AND OPTICS

The present LHC low- $\beta$  triplet, shown in Fig. 2, is of the symmetric type where two outer magnets Q1 and Q3 have a magnetic length of 6.6 m, while the two inner magnets, Q2A and Q2B (forming a single cold mass Q2),

have a length of 5.7 m. The quadrupoles for the Phase-1 Upgrade will necessarily be longer, as the operating gradient that the Nb-Ti conductor can provide is smaller for a larger aperture coil. Nevertheless, the intention is to follow the symmetric layout as much as possible, as it offers a number of important advantages. A layout of the new triplet is shown in Fig. 2, and features four magnets, having magnetic lengths of 9.1 m and 7.7 m. The multipole correctors are grouped in a separate cryo-unit placed on the upstream side of the triplet. Finally, a superconducting D1 dipole replaces the present normal conducting magnets, such that the full length of the new magnet string is almost identical to the present one.

The present matching sections comprise stand-alone superconducting magnets (D2-Q6) separated by warm sections, which contain the collimators, beam instrumentation and vacuum equipment. The area is also used for forward physics experiments that need direct access to the beam. Most of this equipment will remain in service after the Phase-1 Upgrade. Due to the complexity of the magnet cooling and powering, and the lengthy intervention needed to reposition the magnets, it has been decided that the magnets in the matching sections will remain unchanged in the Phase-1 Upgrade.

Reduction of  $\beta^*$  inevitably leads to tighter aperture in the matching sections. Protection against beam halo, which is at present assured by tertiary collimators designed to protect the triplets, will need to be extended to other magnets as well. In addition, the TAN will require extensive modifications to handle the higher debris power and provide appropriate aperture for the beams. The design of the new equipment must take into

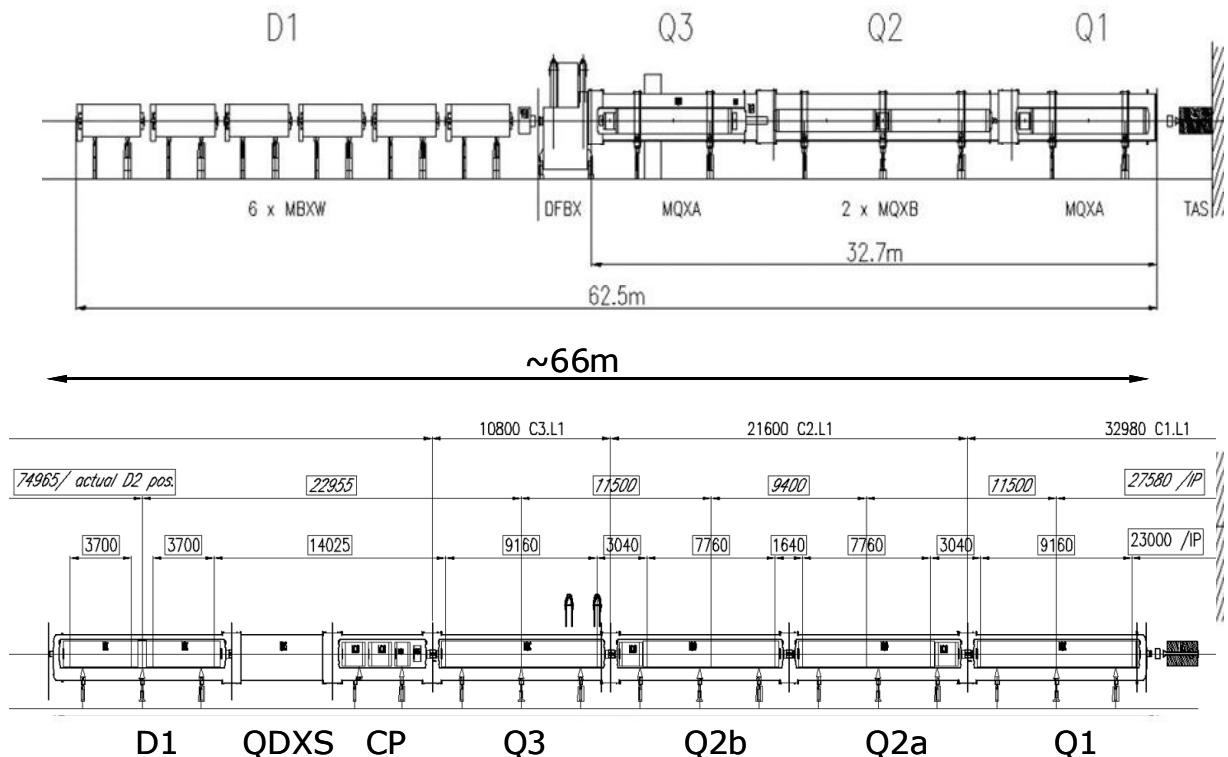


Figure 2: Layout of the present LHC triplet (top) and of the conceptual layout of the Phase-1 triplet (bottom).

account the implications on the background in the experiments, which is expected to be an important issue for high-luminosity runs of the LHC.

It is well known from the beam studies made during the LHC design phase that a reduction of  $\beta^*$  has a number of consequences on the performance of the machine. The chromatic aberrations are particularly serious and must be carefully compensated. As chromatic aberrations concern the LHC as a whole, new optics solutions for all the arcs and insertions need to be devised.

## MAGNETS AND CRYOGENICS

### *Low- $\beta$ quadrupoles*

The magnets for the Phase-1 Upgrade will extensively use the technological developments made for the LHC. Nevertheless, the design of the new magnets is not without concerns due to higher stored energy, forces and stresses, and increased heat loads and radiation dose.

The new low- $\beta$  quadrupoles uses the existing LHC dipole cables arranged in a 120 mm aperture coil. The magnet design will also include as much as possible other materials available from the LHC production, in particular the high-strength steel for the collars and magnetic iron for the laminations. The outer diameter of the magnet is 570 mm, equal to the outer diameter of the LHC dipole.

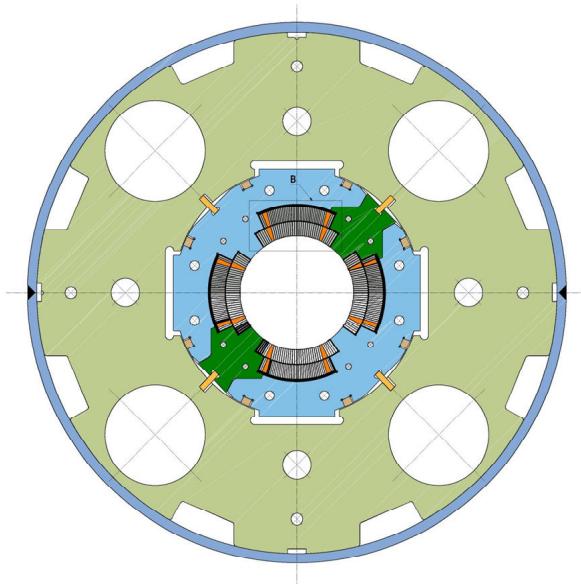


Figure 3: Cross-section of the 120 mm low- $\beta$  quadrupole.

The quadrupoles are cooled in static pressurized helium bath at 1.9 K with a single heat exchanger of the bayonet-type. The heat exchanger has an internal diameter of 95 mm, dimensioned for the maximal cooling capacity of 500 W. The cable and coil insulation, the stand-alone collars and yoke laminations are designed to maximize

the heat transfer from the coil. The cross-section of the magnet is shown in Fig. 3.

The design of the magnet yoke and its helium vessel follows the design of the LHC insertion quadrupoles. A single piece yoke is used to provide the return path for the magnetic flux and magnetic shielding. The mechanical function of the yoke is to align the collared coils, and it does not participate in reacting the internal forces. The final alignment of the magnet is provided by the full length shells, welded at the median plane. This technique has proven to be very reliable, giving excellent results in aligning the magnets. The helium vessel is completed with end-domes, much in the style of the LHC dipoles.

### *D1 dipoles*

The present D1 separation dipole in the ATLAS and CMS insertions comprises six normal conducting magnets with a pole gap of 63 mm, which has to be increased to match the aperture of the triplet. Cost estimates have shown that the most effective solution for the D1 dipole is a superconducting magnet with a field in the 4 T range.

As part of the US contribution to the Phase-1 Upgrade, BNL has proposed to build D1 dipoles based on the optimised design of the RHIC DX dipole. This magnet has a coil aperture of 180 mm, magnetic length of 3.7 m and operating field of 4.4 T. Two such magnets are combined in a single cold mass to produce the necessary field strength.

### *Correctors*

In the proposed layout the corrector magnets are grouped in a separate cryo-unit, located between Q3 and D1. The assembly is cooled in line with the triplet at 1.9 K, and contains horizontal and vertical orbit correctors, skew quadrupole and sextupole correctors, as well as multipole correctors up to dodecapole. The correctors have an aperture of 140 mm, which is needed for their protection from particle debris. Additional dipole correctors will be installed at the upstream and downstream extremities of the Q2A and Q2B quadrupoles for better orbit control in the common beam region between the two triplets. The orbit correctors are also used for generating the crossing angle for the beams and their separation at the interaction point.

The nested dipole correctors based on epoxy-impregnated coils of the type used in the present triplets are not considered appropriate for the performance goals of the Phase-1 Upgrade and an alternative solution using Rutherford-type cables has been developed. Besides helium transparency, this type of coil profits from the larger temperature margin offered by 1.9 K cooling. However, the design requires careful optimization of the complete powering circuit, including the power convertors, since bipolar powering in the 2 to 3 kA range is necessary.

### *Cryogenic scheme*

The low- $\beta$  triplets and correctors operate in pressurized static superfluid helium at 1.3 bar, cooled by two-phase flow of saturated helium in a bayonet heat exchanger. As the triplets in ATLAS and CMS are at the furthest extremity of the QRL (3.3 km from the cold refrigerators), the pressure increase in the 15 mbar header is such that the temperature of the superfluid bath of the triplets rises above 1.9 K as the extracted power increases, reducing sharply the effective thermal conductivity of the superfluid helium. This fundamental feature of the LHC cryogenic system limits the extracted power (and luminosity) in the triplet, irrespective of the magnet technology. Dedicated cryo-plants in both insertions would be needed to circumvent this limitation.

The main 1.9 K cooling loop for the new triplets includes all the features developed for the LHC. In addition, a significant fraction of the dynamic heat load is taken by the beam screen, cooled at 4.5–20 K. The D1 dipole is also cooled at 1.9 K. However, it is not cooled actively, but by heat conduction to the corrector package. A very effective solution was developed for the cooling of the cryogenic feed-box and its superconducting link which needs only a single supply of supercritical helium at 4.5 K. All the control and safety valves are housed in the service module. This architecture allows warm-up and interventions on the triplets independently of the arcs, which is not possible at present. Full sectorization is also provided for the cryogenic feed-box.

### *Protection from particle debris*

As soon as the LHC luminosity approaches the design value of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , particle debris generated in the collisions and beam losses in the machine become the single most important issue for the LHC operation, equipment protection and personnel safety. Careful preparations and robotised tooling have to be included thereon for any intervention and maintenance work.

Due to larger aperture of the low- $\beta$  quadrupoles in the Phase-1 Upgrade, the overall protection efficiency of the magnets is increased by a factor of 2.5 with respect to the present LHC triplets. The improved protection therefore allows increasing the luminosity by the same factor, while the power density inside the coils, which determines the risk of quench in the magnets, remains as in the present triplets. Improvements in the heat transport properties of the cable insulation for the new low- $\beta$  quadrupoles are foreseen, which will further increase the protection margin.

The debris power in the magnets is also a generator of considerable radiation dose. The peak dose in the quadrupole is estimated at  $1.5 \text{ MGy}/100 \text{ fb}^{-1}$ , which corresponds to a lifetime of  $1000 \text{ fb}^{-1}$  in case insulating components similar to those in the LHC dipoles are used in magnet construction. This level of integrated

luminosity is greater than the estimated lifetime of the ATLAS and CMS inner detectors.

### *Powering and equipment integration*

In view of the higher radiation levels in the LHC tunnel expected after the Phase-1 Upgrade, it is considered necessary to place the power converters, the cryogenic feed-boxes with their current leads, and all control electronics in low radiation areas. The feed-boxes are connected to the magnets via a superconducting link, carrying 14 kA for the main quadrupole circuits, as well as lower currents for the D1 and the correctors. Such a system allows easier access to the power converters and the leads, which need to be accessed frequently during the LHC operation and shutdown periods.

The available space in the LHC tunnel is almost fully occupied, and integration of the new equipment required lengthy studies. Solutions for ATLAS have been found, where the major part of the equipment can be located in the UL passageway. The situation in CMS is more difficult, and at present the most promising solution is to place all the equipment in the UL by-pass. As a result, although the power convertors and feed-boxes are identical, details of equipment location and the routing of the superconducting link are specific for each experimental area.

## **PROJECT STRUCTURE AND COLLABORATIONS**

The Phase-1 Upgrade was approved by Council in December 2007 and is organized as a CERN project since January 2008. Twenty work-packages have been identified, following the breakdown structure of the hardware systems. The coordination of the design activities in 2008/09 was done by the Technical Design Group, which included all project engineers. As basis of the technical design report, several functional specifications were prepared and approved following the established mechanisms in the EDMS. Elements of the quality control system and earned value management were also put in place in 2009.

The available resources at CERN for the construction of the magnets and other equipment for the Phase-1 Upgrade are limited and the project relies on a strong international effort. The collaborations with European and US laboratories, which bring in their expertise and resources, have been secured for a considerable part of the new equipment. Nevertheless, the effort at CERN is considerable and the availability of resources in the next few years is a serious concern in view of other priorities for LHC consolidation.

## **PERFORMANCE REACH**

The triplets installed in the LHC were optimized for 7 TeV proton beams and luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . The minimal  $\beta^*$  is 55 cm due to a late decision to include the

beam screens, when the production of the magnets was already well advanced. The triplet cooling system, tested in several triplets in the LHC tunnel, provides sufficient cooling power so that luminosity slightly higher than  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  could in principle be achieved if the LHC could accept beam intensities larger than the nominal  $1.15 \cdot 10^{11}$  ppb. However, such operation would most likely be unstable in long term, as all of the design margins would be exhausted.

The studies for the Phase-1 Upgrade confirmed that it is difficult to improve certain features of the present low- $\beta$  triplets and that compromises between various parameters have to be made. The main advantage of replacing the present 70 mm aperture low- $\beta$  quadrupoles with 120 mm ones is a twofold increase in the clear beam aperture and the improvement of the triplet protection by a factor of 2.5. This leads to a considerably larger flexibility in the choice of the crossing scheme and  $\beta^*$ . The minimal  $\beta^*$  accepted by the new triplets is 30 cm for 7 TeV proton beams. The reliability in operation and the lifetime of the triplet at  $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  are considerably improved. The new magnet system allows in principle to increase the luminosity up to  $3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , which is the hard limit given by the available cryogenics power in ATLAS and CMS. The highest luminosity achievable depends, however, on the ability of the injectors to provide and of the LHC to accept beam intensities in the range from 1 to  $1.7 \cdot 10^{11}$  ppb. In case the beam intensity in the LHC is limited to considerably less than nominal, the new triplets would allow to double the integrated luminosity accumulated in a typical annual run.

## CONCLUSIONS

In order to allow continuous improvement of the LHC performance, two upgrade projects have been approved by Council in 2008, for the construction of Linac4 and for the LHC IR Upgrade Phase-1. The goal of the Phase-1 Upgrade of the ATLAS and CMS interaction regions is to remove the known bottlenecks in the low- $\beta$  triplets and to enable reliable operation of the collider at the luminosity of  $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  while maximising the use of the existing infrastructure. The installation of the upgrade is foreseen during a coordinated CERN-wide shutdown, which will also allow to connect Linac4 into the injector chain and to prepare ATLAS and CMS for higher event rates.

## ACKNOWLEDGMENTS

The work and effort of the members of the Technical Design Group in advancing the design of the Phase-1 Upgrade is gratefully acknowledged.

## REFERENCES

- [1] The European strategy for particle physics, CERN/2685.
- [2] LHC Design Report, CERN-2004-003.