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The Preparatory Phase of the Large Hadron Collider upgrade (SLHC-PP) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement n° 212114. SLHC-PP began in April 2008 and will run for 3 years.

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1. EXECUTIVE SUMMARY

The goal of the Phase-1 Upgrade was to provide more flexibility for focusing of the beams in the ATLAS and CMS insertions, and to enable reliable operation of the LHC at the luminosity of 2 x 10^{34} cm^{-2} s^{-1}. The upgrade concerned mainly the low-β triplets (WP-6 within SLHC-PP) and assuming the same interface boundaries with ATLAS and CMS as at present.

The new low-β quadrupoles feature a 120 mm aperture (as compared to 70 mm of the present ones) and use the technology of Nb-Ti superconductor cables developed for the LHC dipoles. The D1 separation dipoles, the TAS and TAN absorbers, as well as other elements in the insertions would also need to be modified so as to comply with the larger beam aperture of the triplet. However, the present cooling capacity at 1.9 K of the cryogenic system and other main infrastructure will remain unchanged [1,2,3].

In view of the consolidation of the LHC machine, its revised operational schedule, and the optics and therefore the performance limitations imposed by a minimum β* of 30-40 cm (if only changing the triplets and separation dipoles) [6], WP-6 was re-scoped in 2010. The baseline is now to concentrate on one single upgrade at a later stage around 2020, which will allow studying the potential of Nb_3Sn superconductor technology and a mitigation of the above-mentioned constraints.

It is nevertheless important to summarize the work for the Interaction Region design not only because of the EU framework but because it is included in a wider and longer-term program towards one single upgrade. Consequently, this report presents the Interaction Region design of the Phase-1 Upgrade as it was part of the original WP-6.

The preparation work of the Phase-1 Upgrade also included studies of constraints associated with underground space requirements, radioprotection, existing or missing infrastructure and associated equipment to be installed for the new triplets. The limitations, mitigation measures and the expected performance within the boundary conditions of Phase-1 are also presented.

2. INTRODUCTION

The low-β triplets presently installed in the LHC 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 a feed-box, shown in the foreground in Fig. 1. The triplets are positioned at 23 m from the interaction point, and allow a β*, i.e. the minimum value of the beta-function at the interaction point, of 55 cm for the design LHC luminosity of 10^{34} cm^{-2} s^{-1}.

The cryogenic services are brought to the triplets by a compound cryoline (QRL) from the cryogenic feeders 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 allocated for each triplet is 500 W at 1.9 K, which is the maximum power available at 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 the CMS experiment) is smaller than for the other triplets as the radio-frequency cavities in the insertion region (IR) 4 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 radio-frequency system in IR-4.

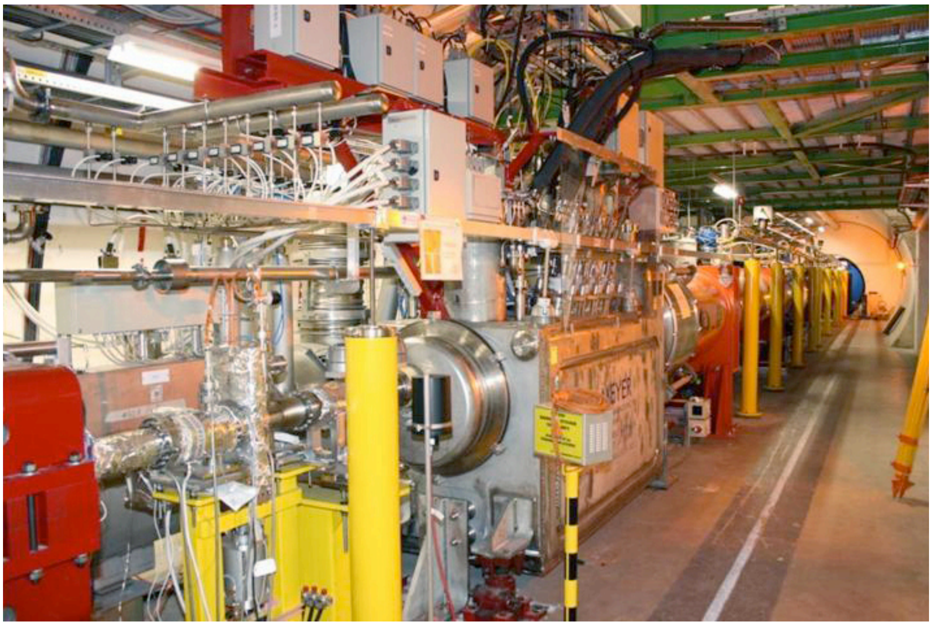

Figure 1: Photograph of the LHC tunnel with electrical feedbox and triplet magnets in the insertion region of the ATLAS experiment.

An increase of cooling requirements, in particular those related to the increase of luminosity above 3×10^{34} cm^{-2} s^{-1} will need dedicated cryogenic plants serving the triplets around ATLAS and CMS and will require additional underground installations.

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 feedboxes, in areas remote from the machine tunnel where the radiation levels are lower [10].

3. LAYOUT AND OPTICS

The present LHC low-β triplet, shown in Fig. 2 (top), is of the symmetric type, where two outer magnets Q1 and Q3 have a magnetic length of 6.37 m, while the two inner magnets, Q2A and Q2B (forming a single cold mass Q2), have a magnetic length of 5.5 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 (bottom), 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 separation dipole (D1) 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.

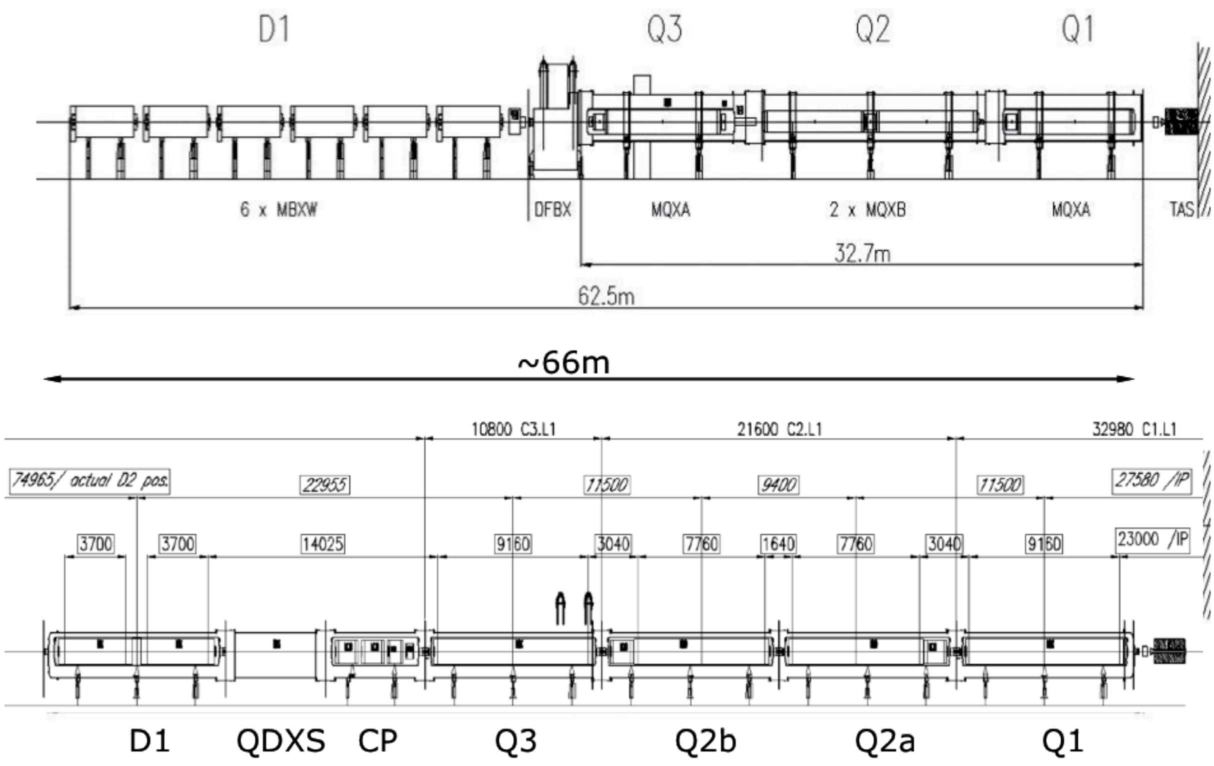

Figure 2: Layout of the present LHC triplet (top) and of the conceptual layout of the Phase-1 triplet (bottom).

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 β^* inevitably leads to a 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 neutral absorber (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 account the implications on the background radiation 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 β^* 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.

The present triplet cooling system, tested in several triplets in the LHC tunnel, provides sufficient cooling power so that luminosity slightly higher than 10^{34} cm^{-2} s^{-1} could in principle be achieved if the LHC could accept beam intensities larger than the nominal 1.15 x 10^{11} particles per bunch. 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-β triplets and that compromises between various parameters have to be made. The main advantage of replacing the present 70 mm aperture low-β 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 β^*. The minimal β^* accepted by the new triplets is 30 cm for 7 TeV proton beams. The new magnet system allows in principle to increase the luminosity up to 3 x 10^{34} cm^{-2} s^{-1}, which is the hard limit given by the available cryogenics power in IR1 and IR5. 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 x 10^{11} particles per bunch. The limitations, mitigation measures and the expected performance within the boundary conditions of Phase-1 are detailed in [6].

4. MAGNETS AND CRYOGENICS

The magnets initially foreseen 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; see reports on Deliverables 6.2.1 and 6.2.2, and Reference [10].

The interfaces between the experiments and the LHC remain unchanged. The new low-β quadrupoles are longer than the actual Q1-Q2-Q3, with a total length of 45.2m instead of 32.7m.

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 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. With this new separation dipole configuration the length of the entire triplet-D1 magnet string is almost unchanged.

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; see report on Deliverable 6.3.1. In addition to improved 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.

The overall transverse dimensions of the new magnets are similar to the previous ones, a constraint imposed by tunnel transport limitations. There is thus no problem to fit the new cryostats in the space occupied by the present triplet-D1 magnet strings at IR1 and IR5. The interface with the cryogenic distribution line would be displaced, and QRL extensions are required: this raised some problems at Point 5 where the tunnel is only 3.8 m in diameter instead of the 4.4 m available in the straight sections around Point 1. The identification of conflicting elements and the optimization of the routings, including modification of the service modules and of the cryo-feed boxes, took almost a year: sound solutions are now available and shown in Figure 3 for IR1.

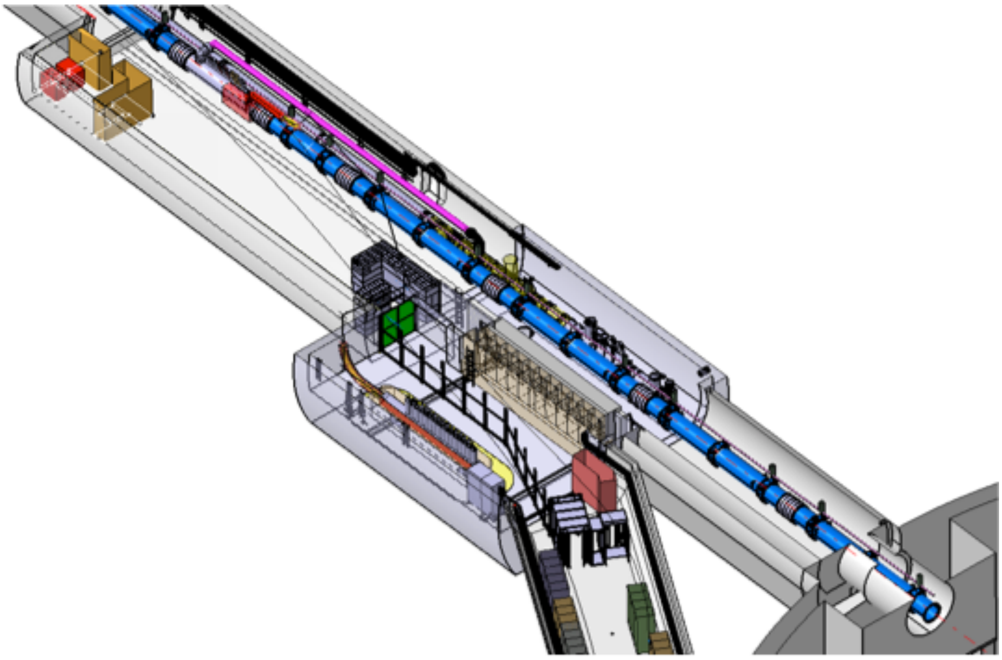

Figure 3: New inner triplet magnets near IR1

5. SHIELDING AND COLIMATION

As soon as the LHC luminosity approaches the design value of 10^{34} cm^{-2} 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 robotized tooling have to be included thereon for any intervention and maintenance work.

Due to larger aperture of the low-β 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-β 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 MGy per 100 fb^{-1}. This corresponds to a lifetime of 1000 fb^{-1} if insulating components similar to those in the LHC dipoles are used for the magnet construction.

The presently installed LHC collimation system provides optimum robustness but its performance is limited to a beam intensity of 40% with respect to nominal [4]. An upgrade program is proposed to reach, and ultimately go beyond, the nominal LHC parameters. It includes the installation of additional collimators at IR1 and IR5, the installation of 30 "advanced phase 2" collimators at IR3 and IR7, the installation of cold collimators in the dispersion suppressors in IR2, IR5 and IR7, and the installation of four additional warm collimators at IR1 and IR5, which requires the preparation of the corresponding infrastructure in the matching section regions.

The installation of the cold collimators requires displacing the twelve cryo-magnets of the dispersion suppressors concerned; this implies disconnecting, transporting, aligning and re-connecting each of these magnets as well as the replacement of the connecting cryostat. This work will occur in activated areas, the proposed collimators are in fact precisely in charge of absorbing the protons losses in these areas. The shift of the dispersion suppressor magnets will require important modifications to the infrastructure and the cryogenic distribution.

6. INFRASTRUCTURE

The installation of the new triplets will require modification of the existing cryogenic distribution. The modification of the TAN was also underlined, the TAS absorber should be replaced as well to match with the aperture of the new quadrupoles. The tasks that must accompany the installation of the new triplets include [11]:

- The dismantling, modification and re-installation of the supports and survey systems;
- The modifications to the beam-pipe and vacuum systems;
- Removal and re-installation of the Beam Loss Monitors;
- A new beam instrumentation with the installation of associated services;
- Re-routing of cable trays and pipes.

Most of these interventions will involve the handling of activated material and thus will require extensive preparations, and development of dedicated methods and tools with potential restrictions concerning co-activities.

The mitigation of Single Event Errors (SEE) in the electronic equipment can be accomplished by the installation of less sensitive equipment, the addition of protective shielding, and/or the relocation of the equipment. These measures will modify the existing environment, thus additional iterations of the integration of the new triplet, and essentially of their associated equipment, will be needed. A proper coordination of the SEE mitigation actions with the preparation for the IR upgrade requires a more precise estimate of the sensitivity of the installed equipment. There is a risk that some shielding or re-routing of services in case of relocation will get modified or dismantled on a yearly basis. The limitations of the LHC underground space around Point 1 and 5 are challenging in this respect [5].

7. POWERING

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 areas remote from the tunnel. 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 in case of failure and for mantainance during shutdown periods.

The available space in the LHC tunnel is almost fully occupied, and integration of the new equipment required lengthy studies. Solutions have been found where the major part of the equipment can be located in a parallel passageway. For both experimental zones the power convertors and feed-boxes are identical, details of equipment location and the routing of the superconducting link are, however, specific for each experimental area.

With the increased level of radiation in the LHC tunnel expected in the Phase-I Upgrade, it is envisaged to place the current leads and their cryostats in a relatively radiation-free area near the power converters at some distance from the beam [5]. The cold power transfer system therefore consists of the current leads, of a cryostat incorporating the leads and providing the cryogen for their operation, and of a superconducting link between the magnets and the leads. The use of a superconducting link brings a number of advantages, the most important of which is easier access to the system that contains electrical devices sensitive to radiation (control valves, level gauges, etc.), and need to be accessed for maintenance and electrical tests during the LHC shutdown periods. The routing of the link should conform to the general tunnel constraints (e.g. stay-clear zone for transport), and should avoid as much as possible the areas exposed to radiation.

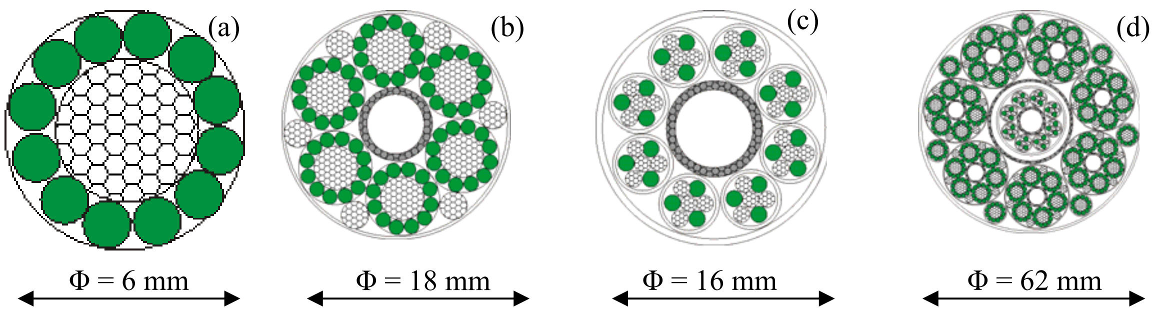

Figure 4: Layout of 3 kA cable (a), 14 kA cable (b), group of 8 x 0.6 kA cables (c), configuration of 7 x 14 kA, 7 x 3 kA and 8 x 0.6 kA cables (d). The MgB2 is shown solid, the copper is shown hatched.

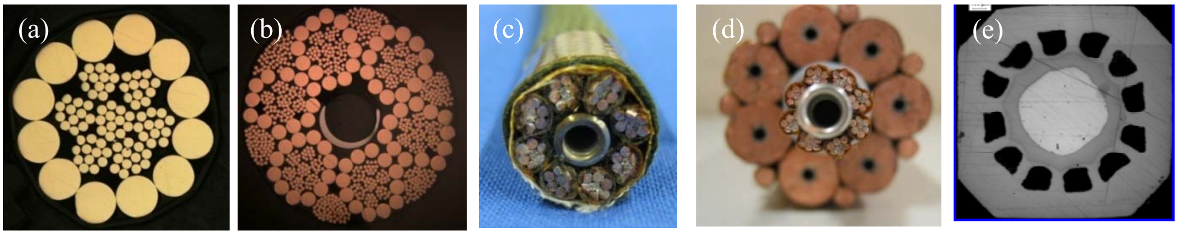

Figure 5: Mock-up made with copper wires of: 3 kA cable (a), 14 kA cable (b), group of 8 x 0.6 kA cables (c), configuration of 7 x 14 kA, 7 x 3 kA and 8 x 0.6 kA cables (d). The external diameter of each assembly is shown in Fig. 4. Cross section of MgB2 wire (e).

As an alternative to a conventional cold power transfer system incorporating a Nb-Ti bus, a proposal based on the use of MgB2 conductors has been studied [5]. The link for the triplet magnets will require four cables rated at 14 kA for the insertion quadrupoles, two cables rated at 8 kA for the beam separation dipole, two cables rated at 3 kA for the trim currents for the quadrupole circuits, and a number of 3 kA and 0.6 kA cables for the corrector magnets. The maximum total current to be transferred, in quasi-dc mode and at temperatures of up to 20 K, is of the order of 115 kA. The cables will be assembled from pre-reacted MgB_2 strands of about 1 mm diameter. The geometry of the cables proposed for this study is shown in Fig. 4, cable mock-ups are shown in Fig. 5.

8. CONCLUSIONS

The goal of the Phase-1 Upgrade of the ATLAS and CMS interaction regions was to remove the known bottlenecks in the low-β triplets and to enable reliable operation of the collider at the luminosity of 2 x 10^{34} cm^{-2} s^{-1}, while maximizing the use of the existing infrastructure and equipment.

We present the layout for this option (changing only the triplet and D1 magnets) and the studies of constraints associated with underground space requirements, radioprotection, existing or missing infrastructure, and associated equipment to be installed for the new triplets.

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