OPTICS ISSUES FOR PHASE 1 AND PHASE 2 UPGRADES

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Abstract

A review of the main issues of the upgrade scenarios of the LHC performance is presented. According to recent proposals, the upgrade of the LHC insertions is staged in two parts, which will be considered and discussed in some detail in this report.

INTRODUCTION

A recent result in the studies for the upgrade of the LHC performance is the definition of a staged approach (see Refs. [1-4] and references therein). It is now customary to distinguish between a Phase 1 and a Phase 2 upgrade, where:

- The Phase 1 upgrade aims at a consolidation of the LHC performance with ultimate beam parameters, corresponding to a bunch intensity of 1.7×10^{11} p and luminosity larger than 10^{34} cm^{-2} s^{-1}. The path to this is via a reduction of β^* down to 0.25 m, which requires the design of new large-aperture triplet quadrupoles based on NbTi superconducting cables. The cable is the spare cable used for the production of the LHC main dipole magnets. The overall impact of this upgrade on the long straight section (LSS) should be rather limited, in particular with no modifications to the experimental detectors as well as to the cryogenic system.
- The Phase 2 upgrade aims at an ambitious increase of the LHC luminosity by about a factor of ten, corresponding to 10^{35} cm^{-2} s^{-1}. By no means can such an upgrade be carried out without a deep revision of the insertions, including new triplet quadrupoles based on Nb_3Sn superconducting cables, special protections, and absorber elements. The new magnet technology is needed to improve the resistance of the devices to beam-induced losses: under routine operation the triplets will have to work at 35 MGy/year, which corresponds to less than one year lifetime for the nominal triplet layout. Last but not least, the detectors will have to be upgraded to exploit fully the new potential reach of the LHC ring.

THE PATH TO PHASE 1 INSERTION LAYOUT

The complete layout of the new insertion for the Phase 1 upgrade will require tackling a number of issues in various domains. The main items are discussed in the following.

Magnet technology

The choice of magnet technology imposes a number of constraints on the aperture, length, and operational gradient (see Ref. [5, 6] for a detailed account on these aspects). All these have a direct impact on the optics. As an example, the typical behaviour of the gradient as a function of magnet aperture is shown in Fig. 1 (from Ref. [6]).

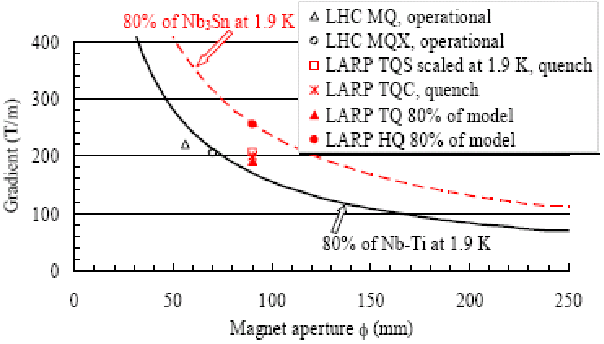

Figure 1: Dependence of the gradient (80% of the maximal critical gradient) as a function of magnet aperture for NbTi and Nb_3Sn quadrupoles at 1.9 K (from Ref. [6]).

Optics design of the low-beta triplet

The first challenge in the design of a low-beta triplet is the huge parameter space to be considered whenever a full optimization is required. In Refs. [7, 8] a full analytical treatment is presented. However, to reduce the complexity of the equations involved a simplification in the model used for the quadrupoles, which are represented as thin lenses, is introduced. Furthermore, a symmetry condition on the triplet layout was also imposed. Recently, two different approaches were proposed to tackle this problem. In the first one [9], a realistic layout is considered, but the parametric dependence of the optical parameters is expressed via fit functions (see Fig. 2 for an example).

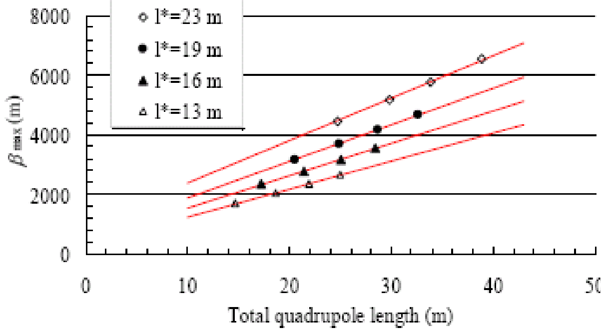

Figure 2: Dependence of β_{max} on the overall triplet length based on the fit approach (from Ref. [9]).

In the second one [10], a constant gradient point-to-parallel final focus is considered constructing a set of functions of one parameter representing the key quantities of the focusing system. These functions are the solutions of a system of equations that can be solved numerically and can be used as a design tool. As an example of this approach the value of β_{max} as a function of the triplet quadrupoles gradient is shown in Fig. 3.

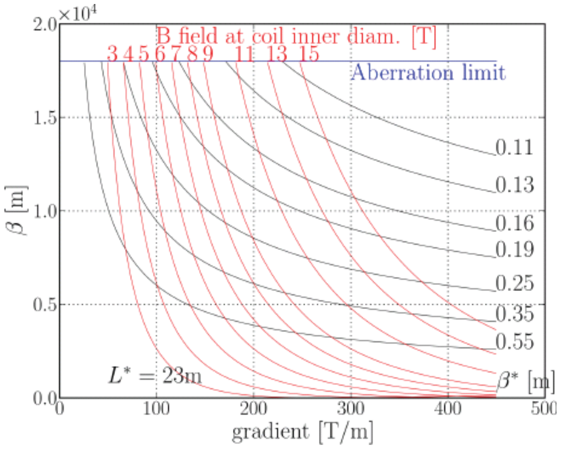

Figure 3: Boundaries of the region in the (β_{max}, gradient) space where a solution for a triplet or a quadruplet insertion for the LHC exists. The regions are limited by the quadrupole pole field and the value of β^* (from Ref. [10]).

The newly proposed approaches can be used to find the best solution to the problem, but still one has to define the correct constraints to be fulfilled by the optimal layout. The most relevant are summarized in the following:

- Aperture: this is the first merit function to be considered. The mechanical aperture should allow accommodating the beam envelop plus additional margin for, e.g., mechanical tolerances, closed orbit tolerances, beta-beating errors (see [11] for a review of the parameter set considered for the design of the nominal LHC ring). In the current design of the Phase 1 insertion upgrade the overall aperture budget is assumed to be 33 σ (for the beams) plus 22 mm (for the other sources) [2]. On top of this rough estimate, one should still consider some extra aperture for mitigation of energy deposition issues [12] and also impedance-related issues with the LHC collimators [13]. Indeed, increasing the triplet aperture would enable increasing the collimators' gap thus alleviating the impedance issue. Nevertheless it is important to emphasize that the impedance reduction due to a larger gap will have to be balanced against a reduced cleaning efficiency. The global solution of the performance limitation of the collimation system will be the matter of the Phase II collimation project.
- Maximum beta-function in the triplet: the driving criterion consists in minimizing it. Not only because of the aperture-related issues, but also because of the direct impact on chromaticity and its correction, off-momentum beta-beating, and single-particle dynamic aperture. A too large chromaticity generated by the low-beta triplets will not be correctable by the arc sextupoles [14]. The off-momentum beta-beating is already rather large for the nominal LHC, between 10 % and 30 % for a momentum offset between 3×10^{-4} and 8×10^{-4}, respectively (the latter takes into account the momentum off-set required for dispersion measurements). This is a potential source of problems for the performance of the collimation system [15] as the correction of the off-momentum beta-beating cannot be performed globally, but only in half of the machine circumference. This might have the effect of a secondary collimator becoming a primary one, thus spoiling completely the hierarchy of the various collimator devices. The choice of the half circumference with corrected off-momentum beta-beating is based exactly on these considerations. The current correction strategy foresees the use of the phase advance between the collision point 1 (ATLAS) and 5 (CMS) together with 32 families of sextupole magnets [14]. Single-particle dynamic aperture is intrinsically related with the field quality of the triplet quadrupoles. A larger value of β_{max} can enhance the harmful effects of magnetic field errors, thus imposing nonlinear corrector magnets to improve the overall field quality of the triplet system (as it is done for the nominal layout of the LHC insertions). An interesting result was obtained by analysing how the magnetic field errors depend on the magnet aperture [16] and by proposing a scaling law for the field quality, whose beneficial impact on the dynamic aperture was tested with numerical simulations [17].

These considerations led to the proposal of four different layouts [2, 3], which are under study to rank them and select the ones with the best performance [18, 19]. In Fig. 4 the four layouts are represented in the (β_{max}, gradient) space. The limitations imposed by the choice of the magnet technology, as well as those imposed by the correctability of the chromaticity are shown.

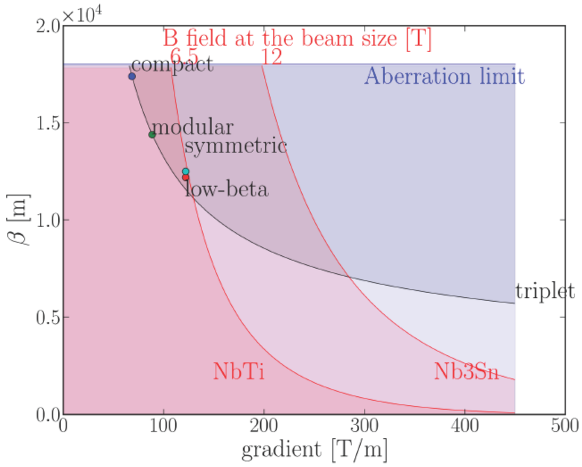

Figure 4: Summary plot in the (β_{max}, gradient) space of the various constraints including also the working points corresponding to the four optical layouts [2, 3] under consideration (from Ref. [19]).

It is worth mentioning that in addition to the study of the various layouts to find the optimum configuration each of them is also considered with flat beam optics [20]: this option is gaining more and more interest for the nice feature of allowing a better use of the available mechanical aperture with an interesting side effect of improving the situation with the beam-beam.

Optics design of the long straight section

Usually, the focus of the studies for the Phase 1 upgrade is on the triplet layout. However, the impact of this change on the performance of the remaining part of the LSS should not be neglected.

In Ref. [21] a complete account of the aperture situation for the current layout of the LSS assuming a Phase 1-like triplet is given. The problematic region is the one between the warm D1 separation dipole and the cold Q5 quadrupole. An attractive solution for overcoming the aperture bottleneck in the warm D1 is presented in [22] even so the option of a cold magnet to replace the nominal configuration is not excluded.

As far as the cold D2 separation magnet and the cold Q4 and Q5 are concerned, their aperture is a bottleneck, but not as severe as the D1. A different orientation of the beam screen might provide enough mechanical aperture. Nevertheless the situation of the LSS requires still some studies before drawing any conclusion about hardware changes.

THE PHASE 2 UPGRADE

As already mentioned, the Phase 2 upgrade aims at a ten-fold increase of the luminosity and hence requires deep revisions of the insertion regions, the detectors, and infrastructure, such as the cryogenic plants for IR1 and 5. Furthermore, while the Phase 1 upgrade was essentially based on the luminosity increase generated by the reduction of β^*, the Phase 2 will require a radical change also at the level of the beam parameters, which has a deep impact on the injectors' chain. Two options emerged [23], namely:

- Early Separation (ES) scheme: such a scheme is based on 25 ns bunch spacing and relies on strong focusing from the low-beta triplet ensuring a β^* value in the range 11 cm – 14 cm combined with ultimate beam parameters. The use of a so-called D0 dipole inside the detector requires deep modifications to the layout of the experimental region.
- Large Piwinski Angle (LPA) scheme: such a scheme is based on 50 ns bunch spacing, larger than ultimate beam parameters, and flat bunch profile in the longitudinal plane. The value of β^* is in the same range as the one foreseen for the Phase 1 upgrade.

A possible optical layout for Phase 2 was presented in Ref. [24]. The smaller value of β^* imposes even deeper modifications of the separation dipoles D1 and D2. In particular the option of a warm D1 might not be feasible anymore due to the too large gap required.

A common feature of the various scenarios for the Phase 2 upgrade is the need of highly-challenging ancillary systems to exploit fully the potential luminosity reach. These devices are essentially needed to mitigate the effect of the crossing angle either in the direction of enabling its reduction or to mitigate the luminosity reduction. In the first group one can list: slim dipoles, wire compensators, electron lenses; in the latter essentially crab cavities.

In all cases, both R&D efforts are required to develop the hardware as well as simulation studies to clarify the beam dynamics issues and machine experiments to probe the actual beam behaviour. This is particularly important in the case of beam-beam effects for which the complexity of the problem makes it necessary an experimental cross-check of the simulation results. This consideration leads to the conclusion that a vigorous R&D programme should be launched even before the implementation of the Phase 1 upgrade. In particular, according to the results shown in Fig. 5, where the average luminosity for the two Phase 2 upgrade scenarios as a function of β^* are shown including some sub-options, it seems clear that the feasibility of a crab cavity for a proton machine is a crucial issue for choosing between ES and LPA schemes. Hence, this piece of hardware could be the first item to be studied in the near future.

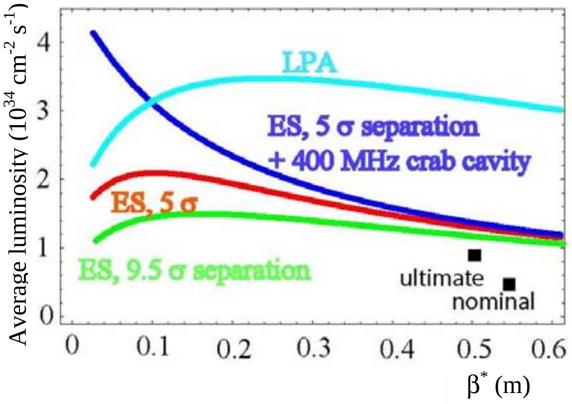

Figure 5: Average luminosity as a function of β^* for the two scenarios for the Phase 2 luminosity upgrade. For the sake of comparison, the luminosity for the nominal and ultimate performance is also shown (from Ref. [23]).

It is also important to mention that the Phase 2 upgrade opens up crucial operational issues. Indeed, the short luminosity lifetime imposes mitigation measures to be put in place as the huge luminosity variation will force the detectors to work in a highly non-optimal mode. Luminosity levelling could be performed by varying either the crossing angle or β^* [25]. None of these approaches was ever tried so far [26, 27]: experimental studies should be envisaged to have a non-controversial statement on the feasibility of luminosity levelling methods.

CONCLUSIONS AND OUTLOOK

The path towards a Phase 1 upgrade of the LHC insertions is essentially based on the development of new triplet quadrupoles with proven technology, i.e. NbTi magnets. In this respect, the strategy is unique and no alternative scenario is under development. The set of parameters for the required triplet quadrupoles is still to be finalized, but the main criteria were reviewed and presented in this report. The four proposed layouts were studied in details and two were selected for further optimization. The next steps will consist in providing a layout compatible with all hardware constraints; study the tenability of the optics, the injection optics and the squeeze sequence; perform detailed beam-beam simulations; evaluate the performance of the collimation system.

The situation of the Phase 2 upgrade is somewhat different. Two scenarios with different beam and optics parameters are being considered. Hence, in this case the efforts will focus not only on the development of new magnets based on new technology, i.e. Nb_3Sn superconductor, but also on a number of ancillary systems required to overcome the many beam dynamic issues related with the extreme beam parameters under consideration. Such systems are, e.g., crab cavities, wires and electron lenses to compensate the long-range beam-beam effects as well as additional magnets located next to or inside the experimental detectors. These devices are already challenging per se, and given their crucial role in achieving the goals of the Phase 2 upgrade their actual performance should be assessed well-before any final choice of the scenario is taken. In this respect, it seems advisable to launch the necessary R&D programmes quickly and, whenever possible, tests of some of these devices in the early stages of the LHC operation might be envisaged.

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