ACCELERATOR PHYSICS CONCEPT FOR UPGRADED LHC COLLIMATION PERFORMANCE

R. Assmann, G. Bellodi, J.M. Jowett, E. Metral, CERN, Geneva, Switzerland
T. Weiler, CERN and University Karlsruhe, Germany
T. Markiewicz, L. Keller, SLAC, U.S.A.

Abstract

The LHC collimation system is implemented in phases, in view of the required extrapolation by 2-3 orders of magnitude beyond Tevatron and HERA experience in stored energy. All available simulations predict that the LHC proton beam intensity with the "Phase I" collimation system may be limited by the impedance of the collimators or cleaning efficiency. Maximum efficiency requires collimator materials very close to the beam, generating the dominant resistive wall impedance in the LHC. Above a certain intensity the beam is unstable. On the other hand, even if collimators are set very close to the beam, the achievable cleaning efficiency is predicted to be inadequate, requiring either beam stability beyond specifications or reduced intensity. The accelerator physics concept for upgrading cleaning efficiency, for both proton and heavy ion beams, and reducing collimator-related impedance is described. Besides the "Phase II" secondary collimators, new collimators are required in a few super-conducting regions.

INTRODUCTION

The nominal design luminosity of the LHC requires storing beams of up to 360 MJ in the superconducting ring. A fractional loss rate of 10^{-3}/s should be allowed for, sustainable at high energy for up to 10 s [1]. The resulting beam loss on the collimators can reach almost 500 kW, which can be compared to typical quench limits of around 5 mW/cm^3 in the superconducting magnets. Requirements for ultimate and upgrade parameters are even more severe. A highly efficient collimation system is required for intercepting and safely absorbing intensity losses in the LHC. Such a system has been under design and in construction since 2003 [2].

In view of the challenges, a staged approach has been implemented: a highly robust Phase I system is installed for the beam startup, compatible with requirements for beam commissioning and the more unstable moments of operation. Performance of the phase I collimation system is expected to be inadequate for the nominal intensity and luminosity. The ideal performance reach for protons is predicted to be up to 40% of nominal intensity, while unavoidable imperfections reduce the performance by a further factor of up to 11 [3]. Ion intensity is predicted to be limited by cleaning inefficiency to about 30-50% of its nominal design value [4]. The LHC collimation concept therefore foresees to complete the initial system with a Phase II installation. The Phase II system is supposed to remove the intensity limitations related to beam loss and collimation.

THE PHASE II SOLUTION

The Phase II of LHC collimation is presently suggested to implement several improvements in addition to the existing phase I system [5]:

1. The installation of 30 advanced secondary collimators into pre-equipped slots in the LHC tunnel will achieve/lead to improved operational handling, faster and more accurate collimation setup, better vacuum properties, lower impedance and, last but not least, improved radiation lifetime of the collimators and neighboring equipment.
2. A modification in the super-conducting dispersion suppressors around the cleaning insertions IR3 and IR7 will allow the installation of 8 additional collimators at high dispersion points (4 per IR), improving cleaning efficiency by more than one order of magnitude. This is referred to as "cryo-collimation".
3. The installation of hollow electron-beam lenses will allow safe removal of beam tails and halo below collimator settings, reducing peak losses at the collimators ("removal of spikes") [6].
4. Several minor improvements in the regions of the particle physics detectors will optimize halo losses and experimental signals.

It is beyond the scope of this report to provide an in-depth discussion of the full Phase II proposal for LHC collimation. More details can be found in [5]. In this report we focus on describing the new concept of modified dispersion suppressors and additional collimators around the cleaning insertions (item 2). In the simulations it is also assumed that metallic copper collimators have been installed into the foreseen Phase II locations (item 1).

CRYO-COLLIMATION

The basic limitations of LHC collimation were understood early on in the system design and were related to fundamental nuclear physics processes (single-diffractive scattering of protons in collimator materials, ion fragmentation and dissociation in collimator materials). A fraction of protons and ions that pass through a primary collimator receive a very small transverse deflection but a large effective energy offset (changed magnetic rigidity for ions).

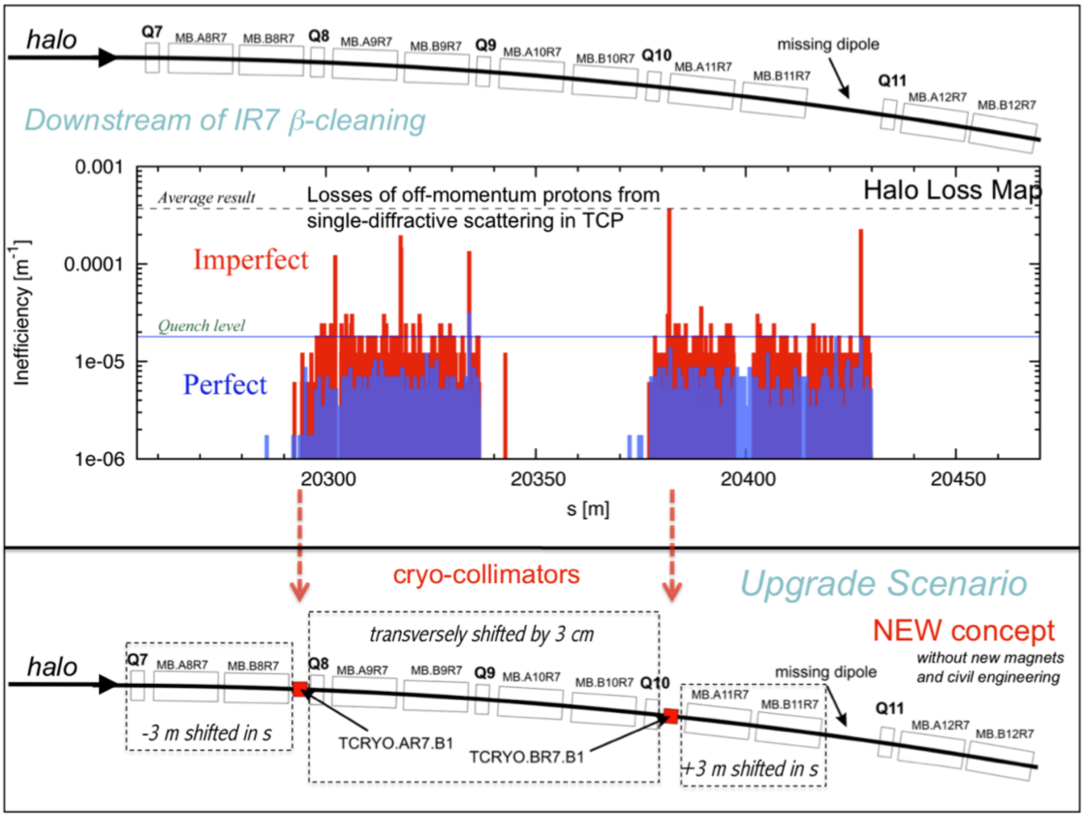

Figure 1: Illustration of present layout and proton losses (top) and proposed modified layout (bottom) in the dispersion suppressors around IR7 (betatron cleaning). Losses are given as local inefficiency and should be below the indicated quench limit for nominal intensity and nominal loss rate. Both the ideal loss map (blue bars, 40% intensity limit) and one typical imperfect loss map (red bars) are shown. Loss maps for ions are qualitatively different [4].

The now off-momentum protons and ions then pass all collimation stages after the primary collimator, are deflected by the first strong dipoles at the end of the cleaning insertion and dumped into downstream magnets. The super-conducting dipoles in the dispersion suppressors around the cleaning insertions then act as both spectrometer magnets and off-momentum halo dump; see the loss maps in Figure 1. It is seen that collimators cannot be placed before the beam losses as there is no space inside the dispersion suppressor.

The concept of cryo-collimation relies on the new idea that the magnets and existing missing dipole space in the dispersion suppressor can be symmetrically rearranged to provide two free slots of 3 m. These slots can be used to place collimators in suitable longitudinal positions. The proposed new layout is illustrated in Figure 1. It turns out that 10 magnets must be shifted longitudinally by ± 3 m and 14 magnets transversely by 3 cm in each IR upgraded with this solution. While a detailed technical design remains to be worked out, anew optics has already demonstrated the feasibility of this solution.

NEW OPTICS

The modified magnet positions for IR7 were implemented into the LHC layout description. The new optics leaves the overall transfer matrix unchanged so matches all LHC configurations in a modular way. A detailed study was performed to evaluate the shifts and some important optics properties:

- Longitudinal shifts for 5 magnets: ± 3 m
- Radial shift between dipole shifts: - 3 cm
- Radial shift in IR7: 19 μm
- Aperture n_1 (beam 1/2): 6.83 / 7.19
- LHC circumference change: -1.872 mm

We note that the radial displacement of IR7 due to the non-commutativity of rotations and translations is small enough (0.019 mm) to neglect. The normalized aperture is not reduced with the new proposal. The reduction of LHC circumference is per IR and will be larger if several IR's are equipped. Similar solutions can be implemented around any IR with collisions. The new optics of IR7 has been used to simulate the performance of the upgraded collimation system, both for ions and protons.

PERFORMANCE SIMULATIONS

The losses downstream of the upgraded cleaning insertions were simulated. Collimators in the cryogenic region are assumed to have two parallel copper jaws with a flat top length of 1 m, defining a gap of $15\sigma_\beta$. Whether they are warm or cold elements is immaterial for their collimation function. The simulations also included metallic Phase II secondary collimators (see item 1 above) at standard settings [7].

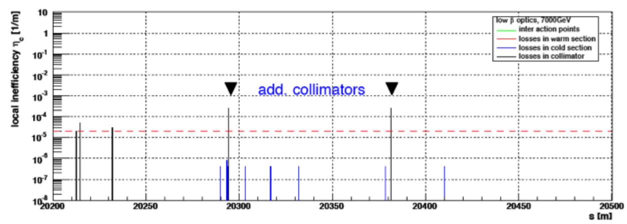

Figure 2: Proton losses (ideal local cleaning inefficiency) downstream of the IR7 betatron cleaning with the phase II system, nominal intensity and nominal peak loss rate on the primary collimator. Blue bars show losses in super-conducting magnets, black bars losses at collimators.

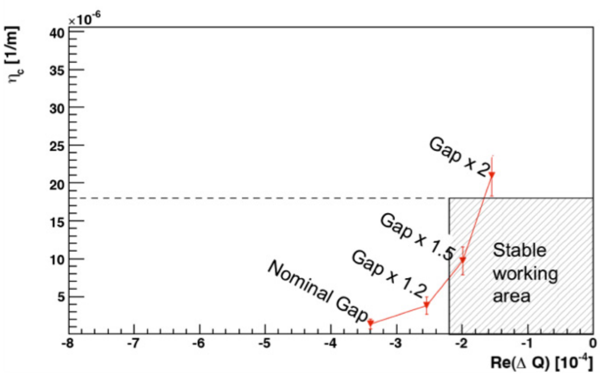

Figure 3: Inefficiency versus tune shift (impedance) for various collimation settings with gaps open. The stable working area for nominal intensity is shown.

Several conclusions were drawn from the simulations:

1. Within the available statistics, losses for ions are completely eliminated by the cryo-collimators. The ion intensity limit from collimation is removed.
2. The proton losses are reduced by a factor 15. A loss map for the phase II system is shown in Figure 2, to be compared with losses in Figure 1 (blue bars).
3. Losses in the various experimental insertions are reduced by a factor of up to 100 (not shown in the loss maps included in this report).
4. The new collimators in the cryogenic region have peak power loads of less than 200 W, reducing power load in downstream super-conducting magnets. This depends on the collimator settings.

Further studies have been started to estimate energy deposition from showers. The first results are very encouraging [8]. Simulations of phase II performance with imperfections remain to be done. It is expected that the impact of imperfections will be much reduced but this remains to be shown in simulations.

IMPEDANCE-EFFICIENCY TRADEOFF

The LHC collimation system places material close to the circulating beams, typically at 2-3 mm distance. As a result, strong resistive wall impedance is induced. It turns out that the overall resistive wall impedance of the LHC is dominated by the collimator contribution [9].

It is predicted that the LHC beam will be unstable even with maximum Landau damping (fully powered octupoles) above 50% of nominal design intensity. It is foreseen that the transverse feedback will be used to actively stabilize the beam at higher intensities. However, the impedance will also benefit from the Phase II collimation. First, the metallic jaws of Phase II secondary collimators will reduce impedance. Second, the gain in cleaning inefficiency can be used to open the collimator gaps. As a result the impedance is reduced while some cleaning efficiency is sacrificed. This operational tradeoff is shown in Figure 3. It is seen that an operating point in the stable working area can be defined with the phase II system.

CONCLUSIONS

An accelerator physics concept for upgraded LHC collimation performance has been worked out. It can be implemented as Phase II of the collimation project, completing the LHC collimation system. The proposal combines several parallel paths of improvement. The new concept of cryo-collimation has been described in some detail. The simulated performance is improved by more than an order of magnitude, allowing for nominal and higher LHC beam intensities. Further studies will work out a detailed conceptual and technical design.

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