THE PHASED IMPLEMENTATION OF LHC COLLIMATION

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Abstract

The phased implementation of the LHC collimation system and the consequences for the LHC upgrade plan are described.

INTRODUCTION

The LHC nominal beam parameters foresee to store 360 MJ in each proton beam and up to 1 GJ in some upgrade scenarios. This is far beyond the present world record of 2-3 MJ in storage rings. The very intense LHC beam must be handled in a super-conducting environment with quench limits of the super-conducting magnets around 5-30 mJ/cm^3. Particle losses can be minimized but cannot be completed eliminated. A powerful collimation system is therefore required to intercept lost protons and to safely absorb them, such that super-conducting magnets will not quench. Here, we concentrate on the more demanding requirements for proton beams. However, we note that collimation is also demanding and performance limiting for ion beams, even though only 5 MJ is stored in each ion beam for the LHC.

The efficiency of the LHC collimation system must reach around 99.999% for protons with requirements that surpass Tevatron and HERA goals by 2-3 orders of magnitude. Within the boundary conditions that were faced in 2002, it was shown that a system with such exceptional performance could only be realized in a phased approach. Such a phased concept was agreed in 2004. In the context of the LHC upgrade plans, collimation is a special case, as an upgrade (namely phase II of collimation) is already required for reaching nominal and higher LHC beam intensity. All other LHC systems should be compatible with the ultimate design parameters of the LHC [1].

THE LHC COLLIMATION CHALLENGE

The LHC design defines a nominal intensity goal (2808 bunches of each 1.15×10^{11} protons) and an ultimate intensity goal (2808 bunches of each 1.7×10^{11} protons) [1]. The beam energy is specified to be 7 TeV for both cases. These two scenarios are in the following referred to as <u>nominal</u> and <u>ultimate</u> design values. The nominal design luminosity is 10^{34} cm^{-2}s^{-1} [1]. The LHC upgrade studies examine upgrade concepts for reaching a luminosity of 10^{35} cm^{-2}s^{-1} or higher, requiring beam intensities above ultimate design [2]. Collimation is intensity- and aperture-driven. Its performance affects all upgrade scenarios.

The total stored energy E_{stored} of a proton beam is a function of the number of protons N_p stored in each bunch, the number of bunches N_b and the beam energy E_b:

$$E_{stored} = N_p \cdot N_b \cdot \frac{E_b}{(\mathrm{GeV})} \cdot 1.6022 \times 10^{-10}\,\mathrm{J}$$

The total stored energy is an important input parameter for the design of the LHC collimation system.

Table 1: Overview of present state-of-the-art, LHC nominal and upgrade goals at 7 TeV and relevant limits for transverse energy density ρ_E and stored energy E_{stored}.

	Energy density ρ_E at collimators for 7 TeV	Stored energy E_{stored}
State-of-the art (Tevatron, HERA)	1 MJ/mm^2	2 MJ
Nominal LHC	1 GJ/mm^2	360 MJ
LHC upgrade scenarios	2 GJ/mm^2	800 MJ
Limit (avoid copper damage/quench)	50 kJ/mm^2	5-30 mJ/cm^3

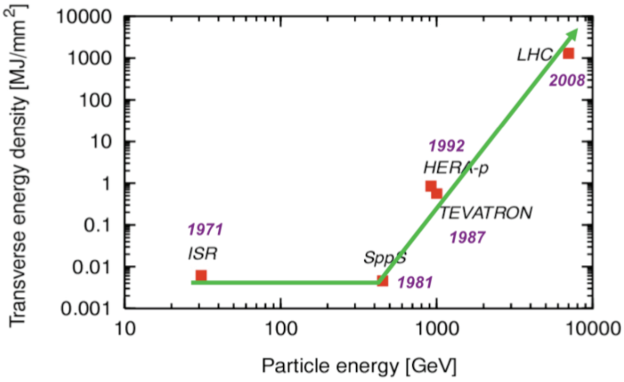

Figure 1: Transverse stored energy density in proton beams at a typical collimator location versus beam (or particle) energy as achieved and planned for various proton storage rings. The year of first beam operation for the various projects is listed.

The nominal stored energy of one LHC beam is 360 MJ, equivalent to about 80 kg of TNT explosive. To assess quench and damage risks one often uses the transverse energy density ρ_E of the beam. It is calculated with the transverse beam sizes σ_x and σ_y at a given location:

$$\rho_E = \frac{E_{stored}}{\pi \cdot \sigma_x \cdot \sigma_y}$$

Taking a typical collimator location in the LHC, the transverse energy density is around 1 GJ/mm^2 for the nominal LHC at 7 TeV. It is much higher in the interaction points.

Table 1 lists nominal, ultimate and upgrade goals for stored energy and transverse energy density, comparing to typical limits from super-conducting magnet quench limits and damage limits for a copper piece. The transverse stored energy density is shown in Figure 1 as a function of beam energy for different past and present collider projects.

It is seen that the LHC will extend the frontier in high intensity beams by 2-3 orders of magnitude. Already at

1% of its nominal design intensity, the LHC will enter into unknown territory in what concerns beam loss and collimation. The high transverse energy density and the destructive potential of the LHC beams did impose a major redesign of the LHC collimation system in 2002. The previously foreseen collimation solution did not have sufficient robustness for withstanding the expected beam losses. As part of this work, a phased approach towards nominal and higher LHC beam intensities was defined.

COLLIMATION REQUIREMENTS AND TRADEOFFS

During the redesign of the LHC collimation system in 2002 the requirements for LHC collimation were reviewed and analyzed in detail [3]. Here, we list the main constraints for the LHC collimation design:

1. Fast failures from injection and dump kickers: The primary and secondary collimators must be the closest elements to the LHC beam, such that they always intercept those protons and ions that are lost over many turns from the beam. These collimators and the surrounding accelerator equipment shall survive fast failures from injection and dump kickers [4,5,6] without damage. This translates into collimator survival with up to 2 MJ beam impact (equivalent to 0.5 kg TNT explosive), or up to 1 MJ/mm^2 in terms of transverse energy density. The energy is deposited in 0.1-3 μs, depending on the failure mode. Strong thermo-mechanical shock waves are excited [7].
2. Slow particle losses: The collimators shall intercept and clean up to 0.1% of the stored beam per second, without quenches in super-conducting magnets, damage to collimators or overheating of neighboring accelerator equipment. This translates into handling impacting losses of up to 0.5 MW and required cleaning efficiencies of up to 99.999% per meter of super-conducting magnets [3]. During the start of acceleration up to 1 MW of un-captured beam shall be intercepted and safely cleaned [3]. The cleaning performance must also be adequate for the background requirements in the particle physics experiments.
3. Impedance: The collimators shall induce acceptable resistive impedance for the LHC. The collimators are the closest material to the LHC beam with many gaps as small as 2-3 mm at 7 TeV. Collimator jaw materials can therefore produce high resistive impedance and impedance is an important design constraint [8].
4. Operational efficiency: The collimators shall be constructed and act as precisions devices with safe and accurate settings that are remotely controlled and reproducible over weeks or even months. The small operational gaps of the LHC collimators, their role for passive protection and the special, time-consuming requirements for beam-based alignment of collimators make this a practical necessity for maximizing integrated luminosity. This translates into requirements for accuracy, surface flatness, and control in the 5-30 μm range.
5. Radiation-resistance: The collimators and the neighboring accelerator equipment shall survive the beam-induced radiation for at least 5 years, ideally for 20 years. It is estimated that several 10^{16} protons are lost at the primary collimators per year [9]. The role of collimators is to intercept proton losses, which will then locally induce elevated levels of radioactivity. The collimation regions are designed to collect and concentrate the radioactivity due to beam losses.
6. Radiation impact: The radiation impact from collimators shall be fully compatible with the environmental requirements and with the required maintenance work in the tunnel. Where needed, fast handling and remote handling shall be prepared.
7. Tunnel constraints: The collimators shall fit into the existing tunnel layout and shall not impose modifications to the civil engineering nor the design of the super-conducting parts of the rings, including their infrastructure. Such, it could be avoided to induce delays and significant over-cost for the completion of the LHC ring. However, certain limitations for collimation performance had to be accepted.
8. Schedule: A collimation system shall be ready for the start of LHC beam operation, originally foreseen for 2007.

The listed constraints imposed various conflicting requirements. For example, the robustness of collimators requires a low Z material and fiber-reinforced carbon was identified as a suitable material choice [10]. However, the low electrical resistivity induces high resistive impedance [8] and the low density results in low absorption. The requirements on tunnel constraints and schedule also prevented the implementation of various possible improvements.

An ideal system specification to satisfy all requirements could therefore not been found. Instead, it was decided to define a phased approach for LHC collimation, addressing the needs in steps. The following phased system was defined and agreed in 2004:

1. Phase I: The phase I collimators define a system that offers maximum robustness against beam damage, has no impact on the super-conducting regions of the rings and was ready for beam startup in 2007. It is noted that the phase I collimation system defines the initial installation and has no connection with the phase I IR upgrade (defined in 2007).

   The 108 installed collimators and absorbers of phase I [11] will always be used in less stable parts of operation (for example ramp and squeeze) and initially for beam commissioning and early physics. This system should advance the state-of-the-art by more than a factor 20. However, in the decision to pursue maximum robustness various compromises on cleaning efficiency and impedance were accepted. It is therefore predicted that the phase I system cannot support nominal and ultimate beam intensities, given the specified maximum beam loss rate of 0.1% per second [12,13,14].

2. Phase II: The phase II collimators will implement advanced and improved collimator features. These collimators will not replace but complement the phase I system. Many of the phase II collimators will have a reduced robustness (for example using well conducting metallic jaws with high density) and can therefore only be used in the stable parts of the LHC cycle. It is noted that phase II of LHC collimation has no connection with the phase II IR upgrade of the LHC (defined in 2007). It is required well beforehand (it must be noted that the phase I IR upgrade foresees ultimate beam intensity). The phase II collimation upgrade was prepared to a maximum extend during the phase I collimation installation from 2006 to 2009: water connections were prepared, cables were pulled, vacuum pumps and beam loss monitors were installed and base supports have been placed for phase II collimators [11].

   An adequate solution for phase II collimation was recently presented, bringing the total number of collimators to 158 [15,16]. The phase II collimation system should allow to reach at least nominal beam intensities and, if possible, also ultimate beam intensities. It was proposed for implementation during the first years of LHC operation. The proposed solution is predicted to improve cleaning efficiency by a factor 15-90, while allowing also reduced impedance compared to the phase I system. Work on collimation phase II is done in collaboration with and supported by the LARP effort in the U.S.A. [17] and the EUCARD-ColMat work package in FP7 [18]. Completion of the various parts is presently envisaged for the years 2012-14.

3. Further upgrades: The LHC upgrade program foresees a further increase of the beam intensity as part of the phase II IR upgrade. At this time it cannot be guaranteed that the phase II of LHC collimation is sufficient for supporting up to 1 GJ stored per beam. A further upgrade of LHC collimation beyond phase II has therefore been envisaged. The total number of collimators and absorbers in an ultimate upgrade can be extended to 168 in the present layout. Novel techniques are pursued for further improved cleaning, for example crystal collimation [19,20], non-linear solutions [21] and hollow e-beam lenses as primary collimators [22]. It is also noted that studies are ongoing to combine the two cleaning insertions into one [23]. Among the various benefits would be a much reduced radiation to electronics for the same beam loss.

The various collimators around the LHC ring and the transfer lines are summarized in Table 2, indicating the location of collimators and the number of components used in phase I, phase II, and a potential ultimate upgrade.

Table 2: Total number of collimators to be used for efficient cleaning and passive protection for both LHC beams. The staging for phases I and II is indicated, as well as a possible ultimate upgrade (last column). The new proposal of cryo-collimation [15,16] is included in the listed number of collimators.

Functional Type	**Phase I**	**Phase II**	**Ultimate Upgrade**
IR3 primary collimator	2	2	2
IR3 scraper	0	2	2
IR3 secondary collimator	8	16	16
IR3 passive absorber	2	2	2
IR3 high-Z collimators	8	8	8
IR3 cryo collimators	0	4	4
IR7 primary collimator	6	6	6
IR7 scraper	0	6	6
IR7 secondary collimator	22	44	44
IR7 passive absorber	6	6	6
IR7 high-Z collimators	10	10	10
IR7 cryo collimators	0	4	4
IR7 collimator reservations	0	0	10
Injection protection collimator (IR2, IR8, transfer lines TI2, TI8)	22	22	22
Dump protection collimator (IR6)	2	2	2
High-Z collimators in experimental regions (IR1, IR2, IR5, IR8)	20	24	24
Total	**108**	**158**	**168**
Total (movable only)	*97*	*147*	*157*

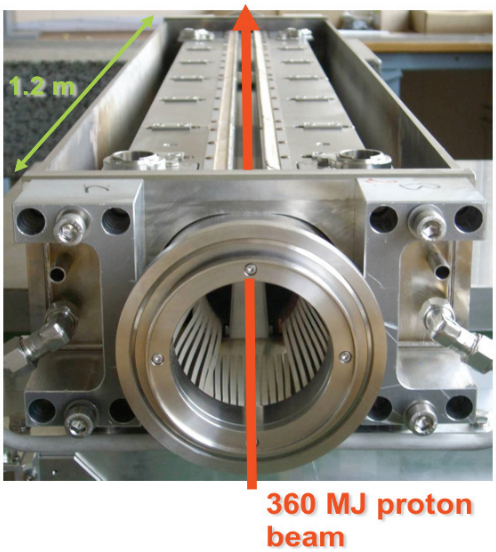

Figure 2: View into an open vacuum tank of an LHC phase I collimator. The two parallel jaws are visible. The total jaw length is 1.2 m with a tapering at the front and the back of the jaws. The jaw "flat-top length" of 1 m defines the collimation gap. The standardized flange to flange length is 1.48 m. The tank dimensions have been selected to allow passage of the second beam pipe in all orientations, while providing sufficient jaw movement to open the gaps and to track the potentially offset beam.

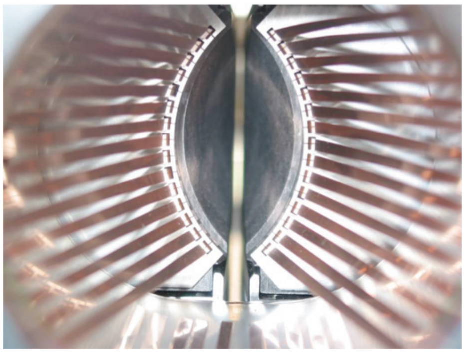

Figure 3: View along the beam line in a horizontal secondary collimator. The black-coloured jaws with fiber-reinforced carbon material are visible. A typical LHC gap size is shown. The RF fingers are used to guide image currents.

THE PHASE I COLLIMATOR CONCEPT

The phase I collimator concept [10] is mainly based on a single beam design: one beam is passed through a collimator. The two movable, parallel blocks of material are called "jaws". They are placed into a vacuum box which must provide the ultra-high vacuum conditions required for LHC beam operation. Photographs of an open collimator box and the view along the beam path are shown in Figures 2 and 3.

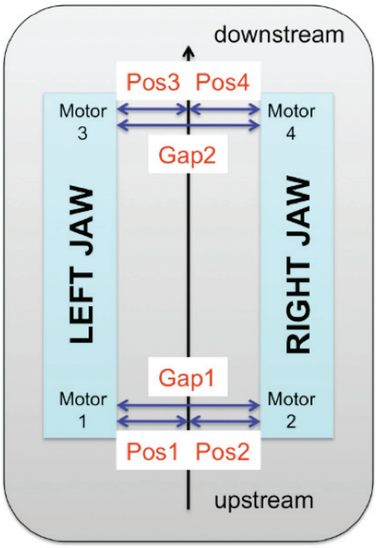

Figure 4: Remote control and survey (4 motors, 4 positions and 2 gaps) on each collimator.

The jaws in the phase I collimators have various materials depending on their function and location: Fiber-reinforced graphite for maximum robustness. Graphite for good robustness and higher density. Tungsten for optimal absorption and benign damage in case of beam hit (tungsten is a brittle material and will not explode). Copper for good absorption and good electrical conductivity.

The length of the vacuum tank is standardized to 1.48 m and the flat top length of the jaws to 1.0 m, except for primary collimators where 0.6 m is used. The other beam is passed besides the vacuum box with a completely separate vacuum sector. Phase I also includes a two-beam design, only used for 6 collimators in IR2 and IR8.

Each of the jaws is remotely movable with stepping motors in position and angle (minimal step size of 5 μm). Six high precision sensors ("LVDT's") monitor the jaw positions and the collimation gaps (see Figure 4), providing important redundancy [24,25]. Another four resolvers on the stepping motors provide another layer of control safety. The phase I collimators are then used in various orientations and materials to implement a multi-stage cleaning system.

From Table 2 it is seen that most collimators are installed in IR7, which is one of the two cleaning insertions of the LHC. Here, multi-stage cleaning of betatron halo is implemented with horizontal, vertical and skew collimators. This implements a 3 stage cleaning to the downstream super-conducting arc and a 4 stage cleaning to the triplets in the experimental insertions with the particle physics detectors. The principle of multi-stage betatron cleaning is illustrated in Figure 5.

A high number of collimators is also installed in IR3, the second cleaning insertion of the LHC. Here, off-momentum particles are intercepted and cleaned in a 3-4 stage cleaning approach, equivalent to the one used in IR7. As off-momentum losses are all in the horizontal plane, the IR3 collimators are mostly horizontal.

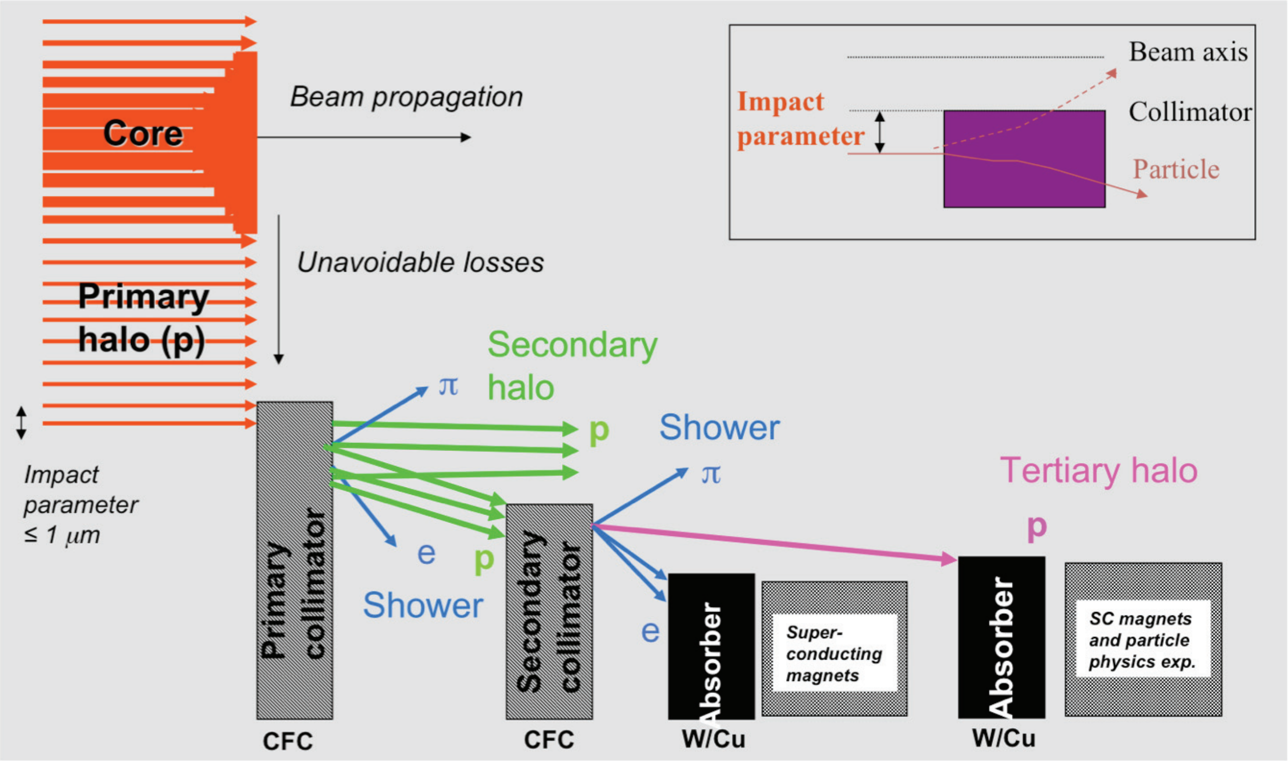

Figure 5: Illustration of the multi-stage cleaning concept of the LHC. Robust collimators (fiber-reinforced graphite CFC) close to the circulating beam intercept the primary and secondary halo particles and dilute them over the length of the cleaning insertion without super-conducting magnets (~250 m). At the end of the cleaning insertion and in the experimental insertions, high Z collimators (copper/tungsten) intercept and absorb the residual halo flux before the super-conducting magnets and particle physics detectors.

PHASE I PERFORMANCE LIMITS

The performance of the multi-stage LHC collimation has been the subject of intense studies [12] and various PhD theses [13,14]. Over the last years the predicted ideal performance was improved with the phase I system from below 1% of nominal intensity to about 40%. It would go beyond the scope of this report to explain and review all the studies done. The key results are shortly summarized:

1. Proton cleaning inefficiency (see [26] for definition): The target for cleaning inefficiency depends on the magnet quench limits, the BLM thresholds, the shower development, the beam energy, the beam intensity and the loss rate.
   For nominal beam intensity, nominal loss rates and 7 TeV the target is 1.8×10^{-5} m^{-1}. The simulated ideal performance of the phase I collimation system is, however, $\sim5\times10^{-5}$ m^{-1}. This means that the ideal intensity reach for the phase I collimation system is limited to about 40% of the nominal LHC intensity.
   The basic limitation is related to a physics process (single-diffractive scattering) in the collimator jaws and well understood: a small fraction of protons loose energy but receive a small transverse kick. They are then lost after the first strong bending dipoles in the downstream super-conducting arc (the SC dipoles act as spectrometer and off-momentum halo dump).
   Unavoidable imperfections increase the inefficiency significantly. This has been shown already early on in the LHC collimation design [27] and matches the experience in other colliders. The latest studies predict a factor 11 increase in inefficiency with realistic imperfections [14]. A likely consequence is that the LHC intensity must be limited to significantly below 40% of nominal design. In the worst case, if the LHC loss rates cannot be reduced to below 0.1% per second, the LHC performance can be limited around 5% of nominal beam intensity for phase I collimation. A complete intensity model for the LHC has been presented [28].
2. Ion cleaning inefficiency: The ion intensities in the LHC are well below the proton intensities and cleaning requirements are relaxed. However, ions experience dissociation and fragmentation in the primary collimators. Ion fragments have a different magnetic rigidity and can be considered as effectively off-

momentum ions. They bypass secondary collimators and high-Z collimators and are lost at similar locations in the SC dispersion-suppressor as the single-diffractive protons (SC dipoles act again as spectrometer and off-momentum halo dump). Ion intensity is predicted to be limited at around 50% of their nominal design value [29] for the specified beam loss rates in the LHC.

3. Resistive impedance: The effect of collimator-induced resistive impedance depends on beam intensity and the tune spread. Detailed studies have shown that the LHC beam intensity might be limited to 40% of nominal intensity after the energy ramp and before collisions due to impedance [8]. This limit assumes that the octupoles are operated at maximum current. Recent studies, however, indicate that the transverse damper of the LHC might be able to damp impedance-induced instabilities.
4. Other beam-loss related issues: The simulation studies indicate that the super-conducting link cable in IR3 can quench if more than 3.5% of the beam is uncaptured and lost at the start of the energy ramp [30]. For example, if 10% of the beam would be uncaptured, the LHC beam intensity may be limited to 30% of its nominal design value.

   Recently, it has been realized that some LHC electronics is not adequately designed for radiation levels in the underground alcoves where they are installed, especially close to the cleaning insertions [31]. Intensity limitations can arise [31]. A modified collimation scheme may help to overcome this limit [23].

   Vacuum equipment close to collimators receives heating of up to 500 W/m for nominal beam loss rates [32]. As the equipment is not cooled, problems may arise. The vacuum group has installed additional temperature sensors to monitor beam-induced heating [33].

   Radiation damage to the room temperature magnets has been greatly improved from below 1 year to around 5 years by designing, building and installing special passive absorbers [34]. Still, long-term radiation damage is a concern and must be addressed with the phase II collimation system upgrade.

   The environmental radiation impact was verified for up to ultimate beam intensities [35]. Intensity upgrades beyond ultimate require a full reevaluation.

It is concluded that the very high intensity beams of the LHC push the frontier in collimation technology. The phase I of LHC collimation is the best compromise for the start of the LHC but cannot reach all goals. The predicted collimation-related limitations for the LHC are important. It is noted that other colliders, though operating with much lower stored beam energy, have required significant improvement programs for their collimation systems. The Tevatron required a full second-generation collimation system for their Run-II [36,37]. This second generation system allowed Tevatron to reach satisfactory levels of beam-loss induced quenches and backgrounds in the particle physics experiments.

THE PHASE II SOLUTION AND BEYOND

The first beam experience with phase I collimation during 2008 is reported in [11], verifying the precise functioning of the LHC collimators. Due to the short beam time available, beam cleaning and collimation efficiency could not be assessed. The 2009/2010 run of the LHC will provide important further insights into the real problems and limitations related to LHC beam intensity, beam loss and collimation.

However, in view of the predicted limitations the time until beam experience is being used to already develop the phase II upgrade system, to design advanced phase II collimators and to be fully prepared for a construction decision on the phase II collimation upgrade. This early work on collimation upgrade is crucial for achieving the challenging LHC goals in the fastest possible time. For the phase I system, it took 5 years from start of design work to installation in the tunnel. Collimation phase II work has therefore been included in the new initiatives at CERN. In view of the new territory that LHC collimation will explore, a final decision on the phase II implementation details will only be taken after sufficient LHC beam experience, ideally in the second year of LHC beam operation.

A detailed technical concept for phase II collimation has recently been presented, reviewed and published [15,16]. The detailed description of the phase II solution is not repeated here. The proposed solution is an evolution of the phase I system, extending the chosen classical collimation concept with advanced features, adding the possibility for beam scraping and fixing an important hole in the 6D phase space coverage. It relies on adding 30 advanced secondary collimators, 8 collimators into the cryogenic regions of the dispersion suppressors around IR3 and IR7, and four hollow e-beam lenses for beam scraping. The concept is complemented by a beam test facility HiRadMat [38,39] for qualifying collimators and absorbers before installation into the LHC.

The phase II collimation work is performed in collaboration between CERN, several US labs (LARP program) [17] and several European partners in research institutes and universities (ColMat work package in the EuCARD program funded by the EU through FP7) [18].

Work beyond phase II collimation is pursued in parallel, studying new concepts, like for example collimation with bent crystals. This technology still remains to be proven for efficient collimation of halo particles. Beam tests at Tevatron and SPS are underway [40,41]. If the results are positive, these new technologies might offer another improvement of collimation efficiency beyond the phase II program. However, major changes in the cleaning insertions might be required to integrate such a system [42].

IMPACT ON LHC UPGRADE PLANS

The HHH program allowed discussing and presenting the expected collimation limitations for LHC. LHC enters into a new regime of beam intensity and the related new problems for beam loss control and collimation were not fully appreciated for some years. The discussions in the HHH program showed that any LHC upgrade must take into account the collimation related issues. In particular, the following issues should be respected in order to ensure a fully successful LHC upgrade:

1. The intensity, beam-loss and collimation related limitations should be taken into account for estimating LHC performance before and after an upgrade. This is especially important if the upgrade foresees increased beam intensities.
2. Any LHC upgrade should not decrease beam stability and should not increase beam loss rates.
3. Any LHC upgrade should not deteriorate the chromatic behavior of the LHC (for example, do not increase the off-momentum beta and dispersion beat at collimators).
4. Any LHC upgrade should not decrease the available aperture, as this would require even smaller collimation gaps and increased impedance.
5. Full simulations of beam loss, power loads and energy deposition around the ring should qualify any significant change in the LHC machine, preferably with imperfections or a large safety margin.
6. Side effects from higher beam intensity must be considered from the start: beam dump, radiation, SC link cable, environment, …

Consideration of these points will maximize the benefits of the foreseen LHC upgrades.

CONCLUSION

The HHH program offered an efficient framework to present and discuss the LHC issues related to intensity, beam loss and collimation. The awareness of all major players about the unique collimation challenges that the LHC faces is crucial for a consistent and successful upgrade program. The collimation system is special in the sense that it requires an upgrade already for achieving nominal beam intensity. The major constraints for LHC collimation, the conflicting requirements and the logic of the phased approach are described in this report.

The predicted phase I limitations are well understood and a phase II concept for an improvement by more than a factor 10 was recently proposed. Work for phase II collimation is ongoing in international collaboration (CERN, US, EU-FP7), while a final decision on detailed design choices will only be taken after sufficient beam experience. Various innovative collimation concepts are being pursued for evaluating the most promising path to further collimation upgrades beyond phase II of LHC collimation.

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