DO WE REALLY NEED A COLLIMATOR UPGRADE?

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Abstract

Several improvements are foreseen for the LHC collimation system during the LS1 and beyond. The changes are matched to the required performance reach during the HL-LHC era. The scenarios for system upgrades are determined based on the present operational experience with the operation at 3.5 TeV, well about the beam stored energy regime of 100 MJ. The present upgrade strategy, and the uncertainties on the performance extrapolation to 7 TeV are presented. The collimation activities in LS1 are outlined and the possible works for LS2 and LS3 are presented.

INTRODUCTION

The plans for the LHC collimation system upgrade [1] as discussed at Chamonix 2011 had a major change in June 2011 when it was decided to postpone the implementation of the combined betatron/momentum cleaning in the insertion region (IR) IR3, following the recommendation of an international collimation review [2]. The good cleaning performance of the system together with the outstanding LHC performance in various respects (beam lifetime above expectations throughout the operational cycle, quench limits of super-conducting magnets well understood, good reproducibility and stability of settings, etc.) suggested that the IR3 works are not immediately required for the operation at an energy close to 7 TeV. Indeed, the present overall performance legitimates to pose the question whether collimation upgrade are needed at all in the future.

In its initial proposal [3], the IR3 upgrade required a position change of several magnets at either side of the collimation system to make space for collimators in the dispersion suppressor (DS) regions. Postponing this activity has the advantage that one can wait for the availability of the shorter 11 T dipoles that would allow implementing cryo collimators by "simply" replacing individual dipole magnets without change of quadupole positions [4]. This technology was not ready for an implementation in 2013. In principle, this concept also makes it easier to upgrade several IRs with cryo collimators, as the layout changes are minor compared to the other scheme.

In this paper, the scope of possible collimator upgrades is recalled and the recent studies on the performance limits of the present system are reviewed. The present baseline for the collimation works in LS1 is presented in details and possible further upgrade scenarios of LS2 and LS3, which will depend on the observed system limitations during the operation at top energy, are outline. Then, some conclusions are drawn.

Collimation works and deliverables are matched to the present major shutdowns in preparation for the HL-LHC era [5]: a first long shutdown (LS1) after the 2012 operation will allow operating the LHC at a close-to-nominal energy starting at the end of 2014, mainly by consolidating the defective splices between magnets. A second shutdown (LS2) is presently foreseen in 2018 to address some limitations for the operation at high luminosity and beam intensity. The real LHC era will start after a long LS3 presently scheduled in 2021 for the main HL-LHC installations.

SCOPE OF COLLIMATION UPGRADES

The LHC collimation system has been conceived since 2003 as a staged system [6] where the initial installation based on robustness could be extended and complemented by adding new collimators as required by the LHC challenges. Primary concerns were the cleaning efficiency of the system and the induced impedance, which were expected to severely limit the total LHC intensity reach [7]. The scope of collimation upgrades is however much broader and includes aspects not only related to the beam dynamics. The main goals for collimation upgrades are:

- Improve the collimation cleaning performance by addressing the system limitations, notably the dispersive losses in the DS magnets downstream of the cleaning insertions.
- Improve the collimator impedance without reduction of the cleaning performance.
- Improve the collimator robustness without compromising the impedance.
- Improve operational aspects such as alignment speed, β^* reach, machine protection aspects. Improve the flexibility of the LHC collimation against changes of machine configurations (optics, crossing angles).
- Improve the IR7 infrastructure for a better radiation handling [8].
- Update the collimation layout downstream of the TAN in the high-luminosity regions, for a full compatibility with design luminosity at 7 TeV.
- Replace collimators that have aged, possibly with improved designs/features. Note that the LHC collimator was designed for a lifetime of about 10 years in high radiation environment.

- Achieved a full collimator remote handling in high-radiation environment.
- Improve distribution of radiations in the warm insertions, e.g. to improve the lifetime of warm magnets in IR3/7 (local shielding).
- Minimize the radiation to accelerator systems from collimation or beam losses (e.g.: continuous losses in the cold magnets should be minimized even if they are well below the rates that can induce quenches).
- Improve super-conducting magnet shielding in IP6.
- Continue R&D studies for advanced collimation concepts.

In Chamonix 2010 it was proposed to include collimation upgrade scenarios in the CERN medium-term planning [9]. Note that several studies listed above rely on important work within international collaborations (European program, US-LARP, collaborations with Kurchatov institute, etc.). Technical details are not discussed in this paper.

The possibility to upgrade the LHC collimation with minor impact on schedule and tunnel infrastructure has been built into the present system. This includes vacuum layout for new collimator slots, space reservations, new collimator supports, cabling, design features for fast disconnection and compatibility with remote handling. The presence of new collimator slots makes it possible to add collimators (e.g. new metallic secondary collimators) by complementing rather than replacing the present system. On the other hand, it is clear that more important changes like the addition of collimators in the cold regions to remove the cleaning limitations in the DS are major changes.

REVIEW OF COLLIMATION PERFORMANCE STUDIES

Without giving the full technical detail of the LHC collimation performance, the studies carried out so far are reviewed. For more details, see the recent collimation review [2] of June 2011 (see also [10]). The operational experience accumulated after June 2011 confirmed the results presented at the review [11, 12].

The performance of the LHC collimation in the first operation at 3.5 TeV and β^* down to 1 m is remarkable. Cleaning efficiencies in cold regions below 99.995 % were achieved throughout the 2011 operation [11] with one single collimator alignment campaign performed for the betatron and momentum collimators. The collimation alignment procedures and software were successfully improved to reduce the impact on the machine efficiency. Overall, the collimator hardware and low-level control software worked very reliably with minor impact on the machine [13]. System limitations identified during the 2010 operational remain, such as reduced operation flexibility in particular in the IRs, dependence of collimation performance on the machine reproducibility, limitation of the β^* reach, etc. [1].

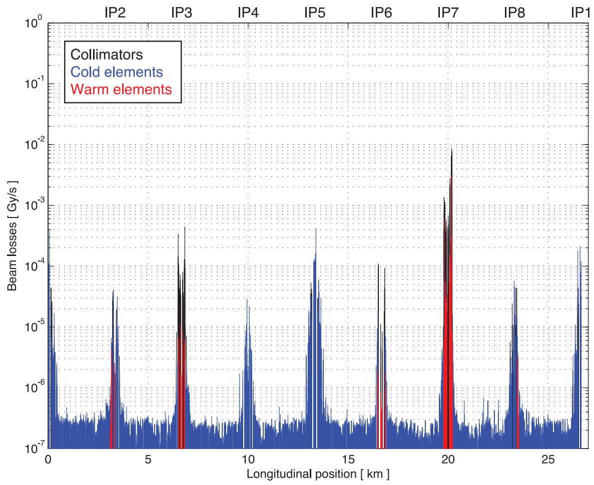

Figure 1: Losses recorded around the LHC rings in the fill 2242 for proton physics. The peak luminosity was about $3.4\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at a beam energy of 3.5 TeV.

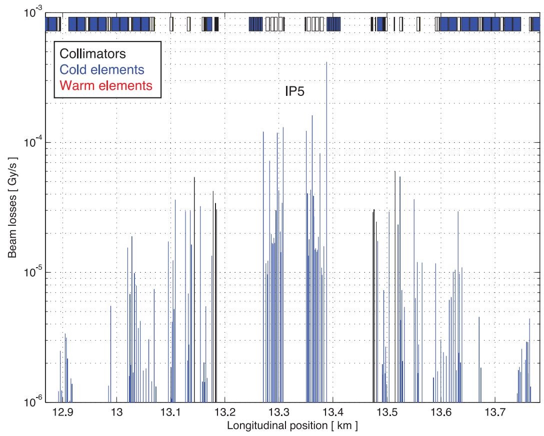

Figure 2: Zoom out of Fig. 1 around IP5.

But clearly one can conclude that so far all the collimation design choices were successfully validated by the operational experience.

As predicted by simulations, the limiting factor from collimation cleaning remains the dispersive losses in the dispersion suppressors of IR7, i.e. the DS magnets are the cold locations with highest losses in case of beam losses. This becomes a concern in case of reduction of beam lifetime which could potentially lead to quenches of super-conducting magnets. In addition to losses in IR7, the operation at high luminosities show continuous losses in the dispersion suppressors of the experimental regions. An example is shown for protons in Fig. 1 and Fig. 2. These losses are not caught efficiently by the physics debris collimators (TCLs) that are located in low-dispersion areas. An example of losses in IR2 during an ion physics fill is given in Fig. 3. See [14] for more details on the ion performance.

The extrapolated performance reach at higher beam energies and smaller β^* values has been done by taking

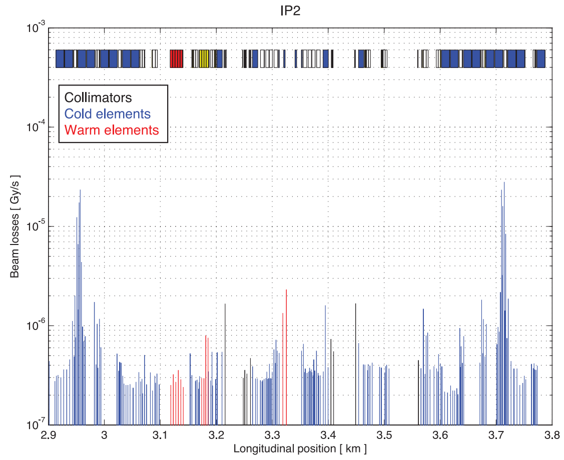

Figure 3: Losses around IP2 during the ion physics fill 2328, with a luminosity of about $450 \times 10^{24}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

into account the latest beam relevant beam measurements. Achieving reliable estimates is a complex problem which relies on assumptions not only related to the collimation cleaning: the quench limit of super-conducting magnets, the minimum beam lifetime, the impedance induced by collimators, overall impact on machine efficiency, etc. must also be taken in proper account. The present understanding [2] indicates that the LHC collimation is compatible with a total intensity about 4 times larger than nominal at 7 TeV [12, 10]. For ions, a total intensity at least 5 times nominal is within reach [15]. These figures are obtained by scaling the achieved loss rates during dedicated collimation quench tests at 3.5 TeV [16] to the 7 TeV case. Cleaning inefficiency for 7 TeV settings, quench limits and loss distributions are also scaled [2].

Note that the performance reach estimates take into account only limitations from betatron cleaning in IR7 and not the losses from luminosity debris in the experimental regions. It is also important to stress that these figures rely on various critical assumptions:

- Quench tests performed with collimation losses in the DS's of IR7 failed to quench the any super-conducting magnet. The performance reach estimate based on the achieved loss rates are therefore conservative.
- The assumed minimum lifetime at 7 TeV is inferred from the measurements at 3.5 TeV and at $\beta^* = 1$ m, with 50 ns spacing. Note that this is a factor 5-20 better than the design assumptions of 0.2 h. The value of 1 h was conservatively assumed [2].
- The duration of losses in collimator quench tests was 1-2 s (design: 10 s), limited by the resonance method used [16]. Beam tests were only performed with injection optics at 3.5 TeV and not with squeeze optics.
- The peak loss rate could be achieved only for one beam (B2 during the proton studies, B1 during the ion studies). There is no reasons to expect differences but this should be checked with beam data.
- There are uncertainties on the scaling of quench limits at 7 TeV. The magnets are typically operating at half the current that they will see at nominal energy.
- There are uncertainties on the scaling of collimation cleaning at 7 TeV, with different collimator settings than the ones used up to 2011.
- The machine reproducibility at top energy is assumed to be the same observed in 2011. This has an important impact on the collimation performance.
- The 2011 operation used collimator gaps larger than at 7 TeV [17]. The bunch spacing was 50 ns instead than the nominal 25 ns (the latter might only be feasibly with larger emittance). The extrapolations of the impedance of the system to the 7 TeV LHC have therefore some uncertainties [18].

These uncertainties must be addressed with beam tests in 2012. The final confirmation can only be achieved after the initial operation at nominal currents in 2015.

IMPROVEMENTS UNTIL 2012

It is important to realize that several improvements of the LHC collimation have already taken place after the initial completion of the present system, i.e. in the short winter shutdowns 2010-11 and 2011-12. This includes:

- A new collimation layout in IR2 to improve ALICE data taking by removing conflicts with the 2-in-1 collimators of type TCTVB's [19, 1]. This required replacing two TCTVB's with 2 TCTVA (single-beam collimator) by moving them further upstream from the IP, in the region with separated beam pipes.
- The development of a semi-automated software for faster and more robust collimator alignment [11].
- The improvement of the protection functionality of the collimator controls thanks to new limits defined as a function of the β^* [1].
- The update of controls hardware to mitigate the LHC down time from radiation effects on the collimator racks in IR1/5.
- The automation of hardware commissioning sequences for the remote validation of the collimator machine protection functionality.

LS1 COLLIMATION ACTIVITIES

The upgrade of IR3 to foreseen in LS1 [1] to achieve a combined betatron/momentum cleaning [3] in conjunction with DS collimation has been postponed as recommended by the June 2011 review [2]. The possibility to modify the cleaning insertion(s) by adding DS collimators for a better cleaning is kept as an option for the future, in case the evidence of the need for an improved cleaning will be observed at 7 TeV. Important improvements are expected from the new design with embedded BPMs [20] (faster alignment and better β^* reach). Other collimation activities are under consideration. Our plans are:

1) Replace all tertiary (TCT) collimators in the experimental regions and of 2 secondary (TCSG) collimators in IP6 with the new BPM-embedded design. TCT's will be built with an industrial productions whereas the TCSG's will be built in house. This change was approved by the management [21].

2) Upgrade the IR7 infrastructure, in particular to add a new air duct to reduce activation effects [8].

3) Change the IR8 layout to replace 2-in-1 TCTVB collimators with the new BPM design (as done for IP2 in the 2011-12 shutdown).

4) Upgraded TCL layout in IR1/5 for the collimation of luminosity debris: if previous estimates are confirmed [22], this might require the removal of one of the TOTEM Roman pot stations in IR5.

5) Possibly add new absorbers in IR3 to improve the lifetime of the warm MQW quadrupoles.

6) Install Tungsten collimators in IR6 to improve the shielding of the super-conducting Q4.

7) Perform beam tests as R&D on advanced collimator concepts: crystal experiment and hollow electron lens as beam scrapers.

8) Commissioning of new collimators and re-commissioning of the existing system.

The items (1), (2), (3) and (8) are approved and will be done. The other ones in the list require still some studies and will be proposed to the management in detail during 2012 (followed up by the collimation WG).

It is interesting to note that items (4) and (6) might be done earlier than foreseen [9] thanks to the availability the collimators that will be removed from the IRs as part of (1). The study of TCL layout upgrade includes for example the possibility to add a new collimator in the cell 6 of IR1 as a part of the study for a new forward physics detector proposed by ATLAS [23].

COLLIMATION UPGRADES IN LS2/LS3

The strategy for the shutdowns beyond LS1 will depend on the operational experience at the LHC with energy close to 7 TeV. The emphasis of present studies is focused on assessing the need for local DS cleaning in the experimental regions, in particular the high-luminosity IR1/5 as well as IR2 in view of the ion operation. For this purpose, a Collimation Upgrade Specification meeting was started in January 2012 [24]. The first milestone of this working group is to determine by the end of the year the need for DS collimation in IR1/2/5. This is important for the HL-LHC era and depends critically on the feasibility of the 11 T dipole.

It is important to realize that, in case of limitations observed at 7 TeV after LS1, studies of IR collimation must be ready in time for a first possible implementation already in LS2, i.e. for the present IR layout and independently on new HL-LHC IR optics schemes [5]. Clearly, the constraints from the HL-LHC IR layouts will be taken into account to find compatible collimator solutions, if possible. Also note that the DS upgrade in IR3/7 also remains as an option if required, and it will also profit from the 11 T dipole technology.

According to the present understanding, the possible upgrade scenarios in LS2 and LS3 are:

- LS2:
  – Possible first upgrade of experimental regions with DS collimators;
  – Improved collimator design and new materials for reduced impedance and improved robustness (complement present system by adding new collimators in IR3 or IR7).
  – Adding more collimators equipped with BPMs.
  – Systematic investigations of collimator HW aging and lifetime issues. Take actions as required.
  – Implementation of partial remote handling in radiation environment;
  – Continue or start R&D for new collimation concepts. Possible implementation of new concepts tested with beam after LS1 (crystals, hollow e-lens), if needed.

- LS3:
  – Implementation of a full re-design of the collimation in IR1/2/5 (DS collimation and additional local protection if required by the new optics layouts);
  – Complete DS collimation in all the required IRs, including IR3/7 if required;
  – New collimator materials and design to replace collimators that have aged, or complement the existing system by adding new collimators in the existing slots for upgrades;
  – Adding more collimators equipped with BPMs.
  – Implementation of the full remote handling of collimators in high radiation environment;
  – Implement, if needed, new concepts for improved cleaning and reduced impedance (crystals, hollow lens, etc.).

Note that the existing slots for new collimators allow an easy improvement of the system by adding new collimators – which will feature the latest design features in terms of material, BPM integrated and mechanics – to complements the installed system. This only applies to secondary collimators whereas in other cases like primary and absorbers the collimators must be changed.

CONCLUSIONS

There is certainly a need to continue the collimation upgrades studies in preparation for the HL-LHC era. The operational experience at 3.5 TeV indicates that the present collimation system might be compatible with the LHC nominal energy and luminosity. The upgrades of collimation insertions to improve the cleaning (DS collimators in IR7 or combined betatron/momentum cleaning in IR3 with DS collimators) are maintained as options until the first operation at energies close to 7 TeV will confirm the extrapolations from the 3.5 TeV measurements. Detailed studies, covering other aspects related to the LHC intensity reach like quench limits, impedance and lifetime studies, must continue with high priority in 2012 at 4 TeV to improve the extrapolations to 7 TeV.

The main approved activity for LS1 foresee the replacement of 18 installed collimators with a new BPM-embedded design, for smaller β^* reach, improved machine protection and enhanced flexibility of IR optics configurations. This important upgrade has also the advantage that it will make available additional spare collimators, which makes it possible to consider the possibility to improve other IR's without the need to restart a collimation productions chain (assuming the these TCTs can be easily handled and do not pose RP constraints). This options include improved cold magnet shielding in IR6 and an upgraded outgoing beam commissioning in IR1/5. Another important work foreseen is the upgrade of the IR7 infrastructure to mitigate the effects of air activation.

The present LHC collimation is not designed for local cleaning in the dispersion suppressors and this predicted limitation is confirmed in operation. Losses in IR3 and IR7 are a concern in case of reduced lifetime that might induce quenches, whereas losses in the experimental regions occur continuously due to the luminosity debris. The present studies are focused on the understanding of the limitations that might be induced by these losses during the operation at 7 TeV. The possibility to add DS collimation in conjunction with the 11 T dipole concept must be addressed with high priority for possible actions in LS2. Other important collimation studies include the remote handling in view of the operation at design parameters and the R&D program for advanced collimation concepts. The studies on new materials for improved jaw robustness and collimator impedance will also continue with high priority.

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