LHC Collimation Review 2013, report of the review committee

Review committee:

Giorgio Apollinari (FNAL), Wolfram Fischer (BNL), Marzio Nessi (ATLAS), Carsten Omet (GSI), Rüdiger Schmidt (CERN/ESS), Mike Seidel (PSI, Chair).

1. Introduction and charge to the committee

The committee should look into the various aspects of the presented upgrade baseline and advise in particular on the need to pursue R&D on 11T dipoles for a possible installation in the LHC for LS2. Are the assumptions for performance reach estimates appropriate and adequately addressed?

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- Is the present upgrade strategy appropriate in view of being able to take a decision in 2015?
- Is there any aspect that has been overlooked?

2. General observations and comments

Since the last review in 2011 the collimation system has demonstrated an excellent performance for beam cleaning but also in view of the operational reliability. The committee is impressed by the quality and amount of work performed in different areas, to name some:

- Further quench tests via provoked proton losses were encouraged also during the last 2011 review. Such tests were performed and give valuable information for extrapolation to the anticipated operating parameters. The presented results show some margin even when extrapolated to design energy and intensities.

- Collimator jaws with Integrated BPM's were successfully developed further and new collimators with BPM's are ready for installation during the present shutdown. This concept will significantly reduce the setup time, thus saving valuable operation time of LHC and it is a major advancement of the overall collimation concept. Already during the last run the automated setup procedure for the jaws was significantly improved which also led to a reduction of the setup time.

- The committee acknowledges the amount of work already invested by CERN and FNAL in the development of the new Nb_3Sn superconducting magnet with 11T bending field.

- The modelling of the energy deposit in the magnets from beam losses shows generally very good agreement with measurements. This is an excellent achievement, in particular since the simulations require the coupling of different simulation methods, i.e. tracking (SixTrack) and radiation transport computations (FLUKA).

- Another area, where significant progress was made is the testing of materials with beam in the HiRadMat facility. Alternative collimator materials can now be tested efficiently and within reasonable turnaround time under realistic conditions.

3. Comments on operational experience

From the operational point of view, despite the large number of movable parts, the collimator system fulfilled its purpose in the long run until the current LS1 very well, both in terms of cleaning efficiency and system reliability. On the other hand, some observations showed that with tight collimator settings, collimator impedance becomes a serious issue.

During the operation from 2008 until today, several minor electrical and position sensor issues came up. As a major concern, failure of the linear bearing cages has been detected and corrected during an exchange campaign, during which the linear bearing cages have been exchanged on 28 collimators. Consequently this issue is most probably resolved.

Unfortunately, one of the most significant problems seems to be not solved at present: roller screws. The collimator jaws generally follow the changing beam size and hence are moved throughout the LHC cycle. Therefore, the roller screws operate mostly at some intermediate distance interval which produces wear on distinct sections of the roller screws. Inspection during technical stops showed that tunnel dust sticks to the parts and corrosion takes place on collimators that were not moved for a long time. This could result in total failure after a number of moves forth and back. Even for the regularly moved jaws, some roller screws run dry with insufficient lubricant left.

Although the lubricant was tested under varying conditions, it may be possible that it loses partially its quality at the elevated bake out temperatures. Another reason for problems could be that insufficient quantities of lubricant were applied at some collimator units.

Despite the observed mechanical problems, no unplanned machine downtime occurred for these reasons during the long run. The LHC staff tried to mitigate the mechanical problems with visual and acoustic inspection and torque measurement. As a result of these inspections some roller screws have been replaced in April 2012.

Several committee members feel uneasy about mechanical problems, since an unplanned shutdown could result from a blocked jaw. Even switching off the stepping motors will not necessarily move the jaw to a safe position far away from the beam (the spring used for compensating backlash will most probably not overcome the blockade).

RECOMMENDATION: Implement a suitable regular maintenance plan (inspection, cleaning, re-greasing, regular movement in long shutdowns) to reduce this risk. For the future operation, a long-term strategy is needed. Thus it should be considered to change the mechanical design in a proper way (e.g. encapsulating and automatic brush away of dust). A re-qualification of the grease for the increased temperatures during bake out must be done.

Currently, the material of the jaws is CFC. Radiation damage can lead to swelling of the jaw material which results in an uneven surface and ultimately in efficiency degradation, the observation of which is difficult to assign to certain collimator units.

RECOMMENDATION: The committee also recommends inspecting a primary collimator that has seen high beam losses, as this would give important information on potential degradation, e.g. quality of surface.

The committee strongly supports the R&D work, which was started to qualify alternative jaw materials, especially in view of reducing impedance drastically.

4. Comments on performance reach with protons and ions

The operating experience and a number of dedicated tests provide a good basis for estimating the performance reach at 7 TeV beam energy. The most important test was the collimator quench test at 4 TeV in February 2013. With relaxed collimator settings a power loss in excess of 1 MW was created on the primary collimator, and a total of 5.8 MJ were lost in about 15 s. No magnet quenched. The so established experimental quench limit gives a maximum proton number 9.9×10^{14} at 7 TeV, a factor of three above the nominal LHC intensity and 60% above the HL LHC design value. These estimates are for tight collimator settings and beam lifetime of 0.2 h, the minimum observed in 2012. The committee understood that based on the calculated quench limit at 6.5 TeV, the intensity reach may be even higher by another factor of two. The results were obtained just before the review, and the committee suggests that the team re-iterates these findings to agree upon the expected margins.

Simulations of quench tests with SixTrack (for beam dynamics) and FLUKA (for the interaction of the beam with materials) reproduced the BLM loss pattern well, and the simulated peak power in the cold magnets is below the quench limit, which is in agreement with the observation.

Extrapolation of the collimation performance from 4 TeV to 7 TeV based on the collimator quench test and accompanying simulations has a number of uncertainties: The quench limit (expected to be reduced by a factor of 4.5), the cleaning inefficiency (expected to increase by more than a factor of 3), and the beam lifetime. While there is reasonable confidence in the prediction of the quench limit and cleaning inefficiency at 7 TeV, there is less confidence in predicting the beam lifetime. With the increase in the energy and luminosity a reduction in the minimum beam lifetime had been observed from 2011 to 2012. A reduction of the minimum beam lifetime cannot be excluded for a number of reasons, e.g.:

- With 25 ns bunch spacing electron clouds may lead to instabilities and fast emittance growth, and increase the UFO rate by an order of magnitude, at least initially.
- The 60% higher collimator impedance may lead to instabilities, in particular at the end of the beta-squeeze period when instabilities have occurred in 2012 and octupoles ran already with the maximum current.
- Yet unknown effects that have an impact on the beam lifetime.

The collimators are the dominant transverse impedance source. Measurements of the tune shift as a function of the opening gap were larger by a factor of 2 compared to calculations. To reduce the impedance a 50 μm Mo coating applied to new versions of TCS collimators is under investigation, that reduces the impedance by factor 10. There is only a small, i.e. negligible, contribution from DS collimators to resistive wall impedance.

The ATS optics, a possible upgrade, requires deliberate orbit and optics distortions. Simulations with SixTrack to date showed that in addition to the losses in the standard optics, there are loss locations in the 8-1 arc at the same level as the DS losses. These additional losses are also dispersive, i.e. from particles with large momentum deviations. With 2 DS collimator units in cells 8 and 10 (a unit consists of two 11 T magnets, a cryogenic bypass and a collimator), the collimation would be improved for both the standard and the ATS lattice.

Four cases of transient losses were studied experimentally. These include ultra-fast (<<1 ms) losses at injection, losses in a location with magnet currents equivalent to a beam energy of 6 TeV, and millisecond losses provoked with a wire scanner and an orbit bump. The injection and wire scanner tests are in agreement with expectations based on Geant4 and FLUKA, the other cases are still being analyzed but are likely to result in a larger than expected quench limit for UFO-timescale losses.

RECOMMENDATION: Complete the analysis of all tests with the objective of a coherent understanding of the quench limits as a function of the loss duration.

Heavy ions

In heavy ion operation the luminosity is limited by secondary beams generated in the collisions, which are lost in the dispersion suppressor. The most important process generating such secondary beams is Bound Free Pair Production (BFPP), which creates a beam of ions with an additional electron. It is estimated that a Pb+Pb peak luminosity of $3x10^{27}cm^{-2}s^{-1}$ can be reached without an upgrade of the collimation in the dispersion suppressor. After a collimation upgrade in the dispersion suppressor the heat load in the dispersion suppressor is reduced by more than an order of magnitude, and a peak luminosity of $6x10^{27}cm^{-2}s^{-1}$ is possible, then constrained by the injector performance. The estimates for performance reach are based on operating data to date, simulations and calculations, and have an uncertainty of about a factor of 2. They strongly suggest to be prepared for a DS collimator upgrade for heavy ions in order to reach the new luminosity goal of $6x10^{27}cm^{-2}s^{-1}$. The minimum upgrade consists of 2 collimator units, one for each of the outgoing beams of IR2 (ALICE). The same upgrade is needed in the experimental insertion regions of ATLAS and CMS, if these experiments were to run at the highest possible heavy ion luminosity.

RECOMMENDATION: Perform quench tests at high energy, e.g. 6.5 TeV, as soon as possible after the restart of LHC in 2015, including tests with ions.

5. Comments on planned DS collimator inserts

The committee was presented with a description of the plans to develop high field (11 T) magnets to be used in a cryogenic bypass collimators unit, to be placed within the string of cold arc magnets. A unit would include two 11 T magnets with a length of 5.5 m each and a slot of approximately 3 m for the collimator. The total length of a unit would be approximately 15.7 m, thus allowing a “switch” between a standard LHC dipole and one of these units with the same bending angle. The reviewers had a chance to observe a prototype of such a cryogenic bypass in the last phases of construction and one reviewer visited the magnet facility where 11 T coils are being prototyped.

The 11 T effort is presently a joined CERN-FNAL collaboration. At FNAL, approximately 9 coils have been produced and 2 magnets tested. From these tests it appears that magnet quality for accelerator operation from injection to flattop is within reach. However some remaining issues include:

- a decision on the final mechanical design
- resolution of the «holding quenches» problems
- observation of a long training curve

In the CERN program, the first prototype model will be assembled and tested by November 2013.

The 11 T effort and recent experience with the HQ program within LARP are clearly indicating that roughly 10-20 coils are needed before performing magnets can be produced. It also looks like that the learning curve is of the order of 2 or 3 years long. Therefore a ramp-up of the effort to produce coils at CERN may be advisable, if an installation of the cryogenic bypass collimator units is foreseen for LS2.

The plans for a 5.5 m long prototype are defined. Field quality measurements in a 5.5 m long magnet are important for the final project. A good coordination between CERN and FNAL on the long prototype may be needed to achieve success.

During the review, the possibility to involve EU companies in the training of Nb_3Sn magnet assembly and construction has been presented by a couple of speakers.

RECOMMENDATION:

- The committee strongly encourages the development and prototyping of one 11 T (5.5 m) dipole magnet, and the cryogenic bypass collimator unit. An early cold test of the almost complete cryogenic bypass may be elucidating alignment issues that could be important for the final application.
- Build at least 4 units (1 unit consists of 2 magnets + bypass + collimator) since this would cover 2 possible cases, as described in section 6 of this report.
- For an LS2 deployment it is clear that serial «learning curves» for making Nb_3Sn coils at CERN and later in EU industries cannot be accommodated. The committee agrees with the early involvement of industrial partners in the assembly of CERN Nb_3Sn prototypes.
- In the US, the continued development of 11 T Nb_3Sn dipoles is being challenged by the needs of IR quadrupole development within the LARP program. However the knowledge acquired in the Nb_3Sn dipole and quadrupole programs are synergetic and can support each other. Develop alternative plans for the first 5.5 m long prototype taking into consideration potential prioritizations in the US Nb_3Sn program.

The collimator (TCLD) will be installed in between two high field magnets and it is supported on the ground. The integration with the cryogenic bypass is challenging since space is tight. A prototype of the cryogenics bypass is available to be cold tested in autumn 2013. With a 1 m long jaw it is difficult to fit the collimator between the magnets in the given space. The collimator mechanics itself is somewhat simpler than collimators in warm sections, since the jaws require only one degree of freedom without angular adjustment.

Several options were mentioned to gain longitudinal space for the magnets. One of them is a reduction of the length of the jaw. The committee believes that all information is available to decide on length and material of the collimators.

RECOMMENDATION: The teams involved in the studies should discuss the different aspects (efficiency of the cleaning for protons/ions, implications on integration and on-going design work), and decide on a solution soon. Later changes of the sectioning within the DS collimator insert will lead to significant additional work for redesigning magnets and collimator. We suggest considering the option of installing a prototype of such collimator in a LHC warm section as a test to gain operational experience.

6. Comments on general upgrade strategy and further studies

As the committee believes, the proposed additional DS collimator inserts represent a strategy that ensures safe operation for protons and ions at design energy and intensity with the best likelihood. In addition this concept provides the best flexibility to react on new findings that might come up in the next run period. The committee believes that only after initial operation at top energy it will become clear where the main bottlenecks are and the decision for the location of the installation can be taken.

RECOMMENDATION: The committee encourages the team to continue the development of DS collimation units (11T magnets plus collimator) with the aim of installation in LS2. The production of more than a few units in time for installation during LS2 appears to be difficult. The committee suggests building at least four units since this would cover two possible cases:

- Installation of two units in IR2 for ion operation if the luminosity is limited due to beam losses from IR2 collisions (then, two spares would be available)
- Installation of four units in IR7 for proton operation if the assumptions for quench level / beam lifetime are too optimistic and the luminosity is limited due to losses in the IR7 cleaning insertion

In order to improve the performance of collimators, new materials were explored. For example Mo-Graphite is of considerable interest and impressive results were obtained. In particular, the HiRadMat facility is an excellent test bed for materials. The committee understood that it is possible to improve the impedance of collimators by coating the surface with a thin Molybdenum layer by about a factor of 10. Coating part of the collimators, e.g. all TCS collimators, would reduce the total impedance in LHC significantly and improve beam stability. This is very promising and should be investigated.

RECOMMENDATION: The team should proceed with further studies on the proposed thin Mo coating, to verify its mechanical stability during grazing beam impact as well as during full impact of a few bunches. A possible impact on adjacent equipment in case of accidental beam impact on a jaw needs also to be taken into account. Another option for reducing the impedance that also could be explored is operation with asymmetric collimator jaw settings. In this scenario the impact on machine protection needs to be discussed.

The longer-term plans with respect to collimation were outlined. Ideas of scraping off halo particles with other methods and an improved understanding of halo formation are being discussed. One option is to use hollow electron beams as it has been demonstrated at FNAL. Other alternatives should be explored, such as tune modulation, crystal collimation etc. The committee considers studies on halo cleaning with different methods for controlling beam losses and for machine protection as very interesting.

In HERA the operation suffered from spiky loss patterns. While the average loss rate was acceptable, the losses during spikes were not and this caused detector trips and sometimes quenches. If such a scenario becomes an issue at LHC, direct control of halo diffusion and the temporal distribution of losses could become important. The hollow electron beam option can be a solution for these issues.

The committee agrees with the initial approach that uses robust collimators. After some operational experience and a better understanding of failure scenarios, parameters might be relaxed (as it has been done during the first LHC run).

Changes of the material with high radiation dose (swelling, changes of the resistance, other parameters) are being studied and the committee welcomes a continuation of these studies.

7. Summary and response to charge

1. **Are the assumptions for performance reach estimates appropriate and adequately addressed?**
   In principle yes. While extrapolation of the intensity is rather straightforward, extrapolation of beam energy is more involved, see section 4. The committee underlines the importance of further quench tests at full energy. Only such tests can provide reliable information on the performance reach at full energy.

2. **Is the present upgrade strategy appropriate in view of being able to take a decision in 2015?**
   Yes, as described in the text the strategy of additional DS collimators should be followed and the remaining time should be used to work out a reliable technical solution. Additional information on the system performance should be gained from routine operation and dedicated experiments at 6.5/7 TeV.

3. **Is there any aspect that has been overlooked?**
   The committee sees several risks as described, however no showstoppers were identified.