Review of the LHC Collimation System – Report of the Review Committee

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1. General Impressions

The LHC collimation system is complex in view of the engineering design of the components and individual mechanical units as well as the interaction with other aspects of the accelerator as beam dynamics, machine protection or machine controls. The committee is impressed by the quality and quantity of the work that has been achieved so far. Particularly the analysis of the IR3 momentum collimation system has been performed very thoroughly and in great detail. Also the mechanical and heating tests of the prototype collimator units are promising.

The committee has not seen a single issue that could be considered as show-stopper. However, many issues are still being investigated and major problems may still arise. The committee feels that several aspects are critical and there is not yet enough information available to assess them in depth. The approach of building the system in several phases is considered to be prudent given the tight schedule. However, the committee is concerned by the lack of a detailed plan for the transition between phases.

The LHC collimation project organization is clearly well coordinated, realizes where it needs to go and is moving as rapidly as resources allow to get there.

2. Response to the Charge

Are the baseline assumptions for the collimation design reasonable?

The assumption of a minimally tolerable beam lifetime of 0.2 hours over a short period seems reasonable based on experiences made at the TEVATRON, HERA and RHIC. However, a wide spectrum of combinations between enhanced loss rates and their durations exists and fast loss mechanisms were insufficiently considered. Details on halo production models and the resulting impact parameter distributions were not presented in depth.

While the studies on collimation of momentum induced losses were presented in a complete and clear way, the corresponding work on losses caused by large betatron amplitudes is still in progress.

An explicit assessment of safety factors and tolerances throughout the design and parameters was not presented.

Have the LHC collimation requirements been specified thoroughly and completely?

A simple model for quench protection was used to provide guidance for system design. Detailed studies, such as that used in IR3, are preferable. Full tracking of lost particles and specification of tertiary collimators and absorbers in IR7 is needed.

Concern remains that detector related requirements were not fully considered. A presentation of quantitative estimates for allowed and expected beam losses in the experimental areas would have been desirable.

Another concern remains that source terms to the energy deposition studies were not fully explored.

The requirements for the Machine Protection System (MPS) and their connection to the collimation system need further definition.

Does the phased approach of the LHC collimation system address the requirements?

The committee supports the phased approach as it allows additional time to solve difficult engineering issues. However, radiological issues may complicate the implementation of Phase II. A detailed plan for Phase II installation will be required.

Are the basic hardware choices correct?

The committee fully agrees that C-based materials are appropriate for the secondary collimators. It may be beneficial to revisit high Z materials for the primary collimators.

The committee has concerns about the risk of coating the carbon collimators with Cu and does not see significant gains from the coating. The diagnostics required to operate the system were not presented in detail corresponding to their importance.

What problems (with the basic system) should be expected?

Radiation damage assessments are required for the collimator material considered, especially the C-C, but also concerning the NEG coating and the metallic springs which have an important function for the efficient cooling of the jaws. The motors and possibly other components are critical in this context as well.

The committee recommends to develop a backup plan for the case that unexpected difficulties arise during operation of the collimation system. Other laboratories, e.g. BNL and FNAL, can be consulted to benefit from their experiences concerning material damage.

Is the detailed engineering solution adequate or can any problems be identified?

The mechanical design of the collimator units looks well considered. To achieve the goal of 25μm flatness of the jaws under heat-load may be difficult. On the other hand, it is not clear if this is a real design requirement.

A detailed plan for the control system was not presented, especially in view of the high reliability which is required to fulfil the function of a MPS.

Concerns remain with respect to maintenance and serviceability of the system given their significant impact on up-time due to long cool-down periods.

Are the preliminary thoughts on collimation set-up and operation reasonable?

The basic thoughts presented in this critical area are certainly correct.

The committee is concerned that the plan presented relied on low current setup. It is advisable to develop a plan for high current operation. Furthermore a detailed plan for a collimation setup that considers machine protection is required.

An adequate diagnostics to achieve a correct setup of the jaw positions and to allow for tuning is required. A feasible system for jaw damage detection has to be developed.

3. Performance Limiting Concerns and Required Studies

3.1. Insufficient Halo Cleaning Efficiency

A collimation system shaves the beam halo and localizes beam losses in the dedicated warm regions, thus providing the tolerable radiation levels in superconducting magnets and collider detectors. The main purposes of the collimation system are to reduce beam losses in superconducting magnets below the quench limit and minimize machine-related backgrounds in the detectors at normal operation, and to protect these critical components against damage at accidental beam losses. While the beam loss minimization in the superconducting arcs and machine protection are considered by the LHC collimation team in great details, the effect on the collider detectors is hardly ever addressed. But as the Tevatron and HERA experience says, the backgrounds in the detectors and protection of expensive detector components is the most demanding issue to the collimation system performance and efficiency. This is, of course, with a well tuned machine, probably after two or three years after commissioning. The detailed well documented MARS studies at Fermilab over last 8 years have shown that the main concern is that large instantaneous ionization over the sensitive detector elements could cause irreversible damage by creating breakdown in these components. Background rates at normal operation and integrated dose at beam accidents is of much lesser worry, of course, with all the proposed collimation system components in IR1, IR3, IR5, IR6 and IR6 at their optimized conditions. The Committee recommends to consider these issues and to add detector backgrounds and protection to the collimation system specs, certainly for the Phase II.

The TEVATRON and also HERA suffer from bursts of losses over a short time. These losses may lead to trips of the drift chambers in the experiments and other detector components, but with more stored energy it is also imaginable that quenches are triggered. In principle there exists a whole spectrum of enhanced loss rates and durations of these losses. In the presentations two points within this spectrum were considered – the average equilibrium loss rate corresponding to a beam lifetime of 20 hours, and the enhanced loss rate of 0.2 hours lifetime that can be accepted for a few minutes. This spectrum should be extended towards shorter timescale of the order of milliseconds. For example a short burst of losses with a duration of 50 ms might not damage the collimators but might lead to a quench because of the limited efficiency of the collimation system. Ideally these studies result in a curve that separates safe and unsafe operating conditions

in a plane spanned by loss rates and loss duration. Next one should consider the expected loss mechanisms in more detail to find out whether the machine will remain most of the time within the stable area. If this is not the case it could be possible that frequent beam dumps triggered by the loss monitor system interrupt the desired continuous luminosity operation.
A possible way to decrease the sensitivity of the loss rate on transverse beam motions is the installation of a thin pre-target at the front edge of the primary collimator with a thickness of a fraction of a radiation length. Details are found in an addendum to this report.

Another concern is a decrease of the collimation efficiency due to damage of the jaw surface. The high collimation efficiency seems to rely on the flatness of the collimator surface. On the other hand the deterioration of the collimator surface may be hard to detect. Possibly this danger can be minimized by performing specialized tests of the collimator material in the SPPS.

3.2. Reliability of the System

The LHC has a number of subsystems with complexity, and presumably reliability requirements similar to the collimation system. The review committee did not see specific requirements for collimation system reliability / uptime, but the committee suggests that it should be designed to cause no more than a hundred hours of unscheduled downtime per year. There are several possible downtime effects from collimation system failures.

- Beam abort: Incorrect positioning of the collimator jaws can produce excessive beam loss and trigger a beam abort. This will cause a loss on the order of an hour of beam time per occurrence.
- Downtime until repair: The committee did not see an analysis of which, if any, specific collimators could fail (in the open position) without preventing beam operation. It is likely that (a less probable) failure of any of the collimators in the closed position would prevent beam operation. Any failure resulting in air to vacuum, or water to vacuum leaks, or leading to obstruction of the beam aperture would prevent beam operation. Radiation cool down time is expected to cause approximately 2 weeks or more of downtime before repairs could begin.
- Failure of MPS: The collimation system is expected to protect downstream components including bend magnets from various machine failures, including abort kicker errors (inadvertent single cell firing, or missed abort gap). If the collimator jaws are incorrectly positioned and such a fault occurs, substantial downtime could result.

Category 1 failures: The required position for the collimator jaws is a function of the beam energy and optics. Collimator control hardware (for example a run-away stepper motor controller), or software can drive the collimator jaws into the beam and produce a dump. Incorrect collimator position could also result from a jaw position read-back error (hardware or software). There are 4 control motors and read-backs per collimator, for a total of about 600 devices. Individual device reliability (against incorrect positioning), must be >>10,000 hours. The committee was not provided with estimates of the expected reliability of the system. This MTBF is reasonable for automated mechanical systems.

Note that it may also take considerable beam time to develop the correct collimator position control algorithms, and that these may under some conditions result in improper positioning and beam dumps, even without hardware or software failures. The committee recommends that to the extend possible, the collimator tuning algorithms be studied as soon as practical. In addition any setup or tuning algorithm depends on input from other beam diagnostics equipment such as loss monitors and beam position monitors and possibly profile monitors. The reliability requirements for these components need to be defined and included in reliability estimates for the collimation system. Failure or offsets in the loss monitor or beam position monitor system will contribute to any category of collimation failure.

<u>Category 2 failures</u>: Electronic failures may have short repair times if they occur in equipment outside of the tunnel, but hardware failures most likely require a full two week cool down to allow time for either component, or entire collimator replacement. This long down time (~200 hours), suggests that less than 1 failure / year can be tolerated. The committee does not know which collimators are critical for beam operation, but even 10 such collimators, containing 40 motors, would require motor MTBFs on the order of 200,000 hours. The mechanical systems are operating in a high radiation environment. The dose on the motors has not been calculated yet. The dose at the jaws was reported to be 30X the limit for the present motors.

While many failures of the motors will allow for automatic jaw retraction, there will be a class of failures where the collimator jaws seize in the inserted position. This could for example be due to radiation damage to the lubrication, or to ozone cause corrosion of moving parts.

The cooling of the collimator jaws requires good contact with the water cooled backing plate. Failure of the springs or warping of the carbon jaws can result in a run-away condition where increasing thermal warping decreases the cooling efficiency. This scenario is likely to require replacement of the entire collimator system.

Jaw cooling also requires high water flow rates. The design water speed of 3m/s is near the limit for erosion damage in the copper cooling lines. The erosion locations are in the bends in the cooling lines near the jaws, and would lead to water to vacuum leaks. The committee believes that either the maximum design power should be reduced (with reduced water flow), or more erosion resistant piping materials be considered (eg. Glidcop).

Non-uniform energy deposition in the vacuum flanges could result in warping and vacuum leaks. The radiation hardness of the NEG vacuum coatings used in this system is also unknown. These issues and other unknowns about the performance of the vacuum system under high radiation need to be assessed.

<u>Category 3 failures</u>: The collimation system is required to protect downstream components from failures including partial beam dumps, and in this sense it must be considered part of the Machine Protection System. The committee believes it is important that the effects of mis-positioning (too wide) of the collimator jaws be considered in the event of abort system failure. If the downstream systems including the main bend magnets are at risk if the collimator jaws are mis-positioned, there are strong requirements on the reliability of the mechanical systems, software, and control algorithms.

Another potential source of down time or performance reduction arises from routine operation/positioning. It is not recommended to move collimators 'blindly' to preset positions (i.e. values in databases or files). Since configuration setup is required to happen with low beam currents possible differences between low and high beam current operation such as beam instabilities, beam emittances and store to store differences have to be considered and taken into account. Positions found at low currents or in another store cannot simply be used for high current operation. Save and reliable positioning mechanisms for high current operation need to be investigated and their processing time needs to be optimized. No such possible mechanism was presented.

3.3. Impedance

The status of the impedance and beam stability calculations was presented by Elias Metral. The present estimates of the collimator impedance indicate that the collimators will be a very large contribution to the total machine impedance and will limit the beam current to roughly half of the design value – this implies a significant limitation on the LHC luminosity.

The impedance of the Carbon LHC collimators is difficult to calculate. The normal resistive wall theory does not work in the LHC collimator regime where the skin depth is large compared to the collimator gap. Modifications to the theory have been developed by Vos and by Burov and Lebedev. These modified theories predict significantly lower impedance from the Carbon collimators than does the normal resistive wall theory. The modified theories were not discussed in detail. Published papers can be found in the literature although this is still a topic of active research.

Additional support for the LHC collimator impedance estimates comes from HFSS calculations. The HFSS code should be able to perform the full calculation correctly although it also should be noted that complex computer codes like HFSS can be prone to error due to set up difficulties; the details of the computer calculations were not presented to the committee.

The stability of the LHC ring was calculated based on the estimated impedance. Distributed octupoles have been included to control transverse beam stability in the LHC. However, the design strength of the octupoles is not be enough to accommodate for the impedance of the graphite collimators 2 mm from the beam and it was found that the ring would only be stable with 45% of the nominal bunch charge. It was also stated that the transverse feedback system could easily suppress the resistive wall instability and it would be expected that the beam-beam collision would also suppress the instability. Thus, the primary concern about the resistive wall impedance arises because the present LHC operating procedures called for suppressing the transverse feedback system before establishing collisions to prevent emittance growth during the store.

One possible solution to reduce the collimator impedance was presented where a few micron coating of Copper would be added to the collimator surface. It was suggested that this would allow operation at a higher bunch charge although the full improvement was not clear.

The other element of the collimator impedance comes from trapped modes in the vacuum tank and the tapers at either end of the collimator section. The trapped modes have been calculated using GDFIDL for two different geometries. These calculations were not discussed in detail but seem less developed than the resistive wall calculations. However it is not expected that a fundamental limitation will be encountered due to trapped modes and beam tests that will resolve some of these issues are planned in the SPS this fall.

Recommendations:

1) The committee would urge investigating alternate methods of improving the beam stability including (but not limited to): increased chromaticity, increased detuning due to increased octupole strengths, verifying that the beam-beam collision will stabilize the beams, or different operational procedures such as establishing collisions before turning off the transverse feedback (assuming that the beam-beam forces do suppress the instability).
2) The committee would urge extensive beam and wire impedance measurements of the prototype (uncoated) collimators as planned.
3) The committee would also suggest revisiting the Carbon thickness in the collimator. Since the skin depth of Carbon was stated to be 2cm, reducing the Carbon thickness to 1cm may reduce the impedance however such a choice should be based on impedance measurements and knowledge of the possible failures due to showers in the Copper cooling plates.
4) The committee had concerns about the possible failure modes of a Copper coating on the collimators and thus would recommend to avoid using a coating on the collimators unless it is clear from additional stability calculations and additional impedance measurements that nominal Phase I operation is not possible with the uncoated collimators.

4. Major Concerns

4.1 Disfunction of the Collimation System as Machine Protection System

A general concern is connected with the anticipated role of the collimation system as machine protection system and the necessity to use relatively complicated algorithms for the proper positioning of the jaws. The jaw positions depend for example on the beam energy and the machine optics. The optimum jaw angles generally depend on the jaw positions. If the jaws are not continuously driven to their required positions the safety of the magnets and other components may not be guaranteed. The involved software may fail, but a hard wired solution seems to be excluded because of the complexity of the algorithms. Obviously there is no simple solution to this problem. One should try to design the control system as reliable as possible and to include hard wired interlocks wherever possible. A detailed plan for the jaw adjustments in the individual machine conditions has to be developed. Tolerances for the jaw positions within which machine protection is ensured have to be determined.

The radiation hardness of the collimator material at the required doses raises concerns. It is well known that carbon suffers from radiation damage effects. A summary of radiation damage effects in graphite can be found in chapter 7 of Ref. [i]. Most of the properties of interest to the designer, change as a result of irradiation: induced changes in dimensions, thermal expansion coefficient, thermal conductivity and Young's modulus. In this case the use of the material is essentially a design problem, i.e., to utilize the properties to advantage and to accommodate the volume conserving dimensional changes for as long as possible. Issues would be: (1) damage by atomic displacements, and (2) products from nuclear transmutations (e.g., gas which may induce swelling). A lot is known about radiation damage in graphite (mainly by neutrons) because of its use as a moderator in fission reactors. This is now also true for some type of C/C composites, which are of interest in fusion. More details on possible damage mechanisms and references on this subject are given in an addendum to this report by G.Federici. An ad-hoc evaluation of the damage must be seriously carried out, and compared with theory. Only when this information is available, it will be possible to estimate the longevity of the collimator jaws.

The committee recommends to perform a material properties characterisation program to measure material properties (physical, thermal, mechanical) to check data provided by the manufacturer before procurement. This should be done for samples coming from different material batches. The critical properties to be considered include thermal conductivity properties, thermal expansion, Young's modulus, mechanical strength, coefficient of thermal expansion, etc.

Some attention must be given in further tests of jaw performance in the SPS accelerator to check whether macroscopic effects of sputtering and chemical erosion of the jaws are observed and they lead to the formation of visible debris.

The committee feels that the C-C composite would be a good choice for the jaw material. There exist experimental results at BNL that support this choice. However, given the uncertainty concerning the stability of the material the committee recommends to consider a backup plan for the case that the C-C composite fails. Possibly one could consider an alternative material with lower allowed beam current. At BNL studies are under way to characterize other potential collimator materials. Some comments on this subject are given in another addendum by N.Simos.

4.2. Failure to Detect Jaw Damage

The carbon collimator jaws are designed to not be damaged under both normal operation and expected fault conditions. It is possible however, that damage can occur either from unexpected fault events, or from long term radiation damage. Damage could consist of "grooves" eroded into the jaw surface, or large scale cracking of the jaws. Accelerators at SLAC, HERA, and other locations have unknowingly operated for extended periods of time with damaged collimator jaws.

Damaged collimator jaws could produce tuning difficulties, and result in a decreased efficiency. A more dangerous possibility is that damaged jaws may fail to protect downstream components against damage from abort kicker pre-fires. The Committee believes that it is important that a method for detecting jaw damage be developed.

The collimator group recognizes that direct imaging of the collimator jaws is likely to be impractical due to radiation darkening of windows, or the necessity of using long UHV periscope systems to relay the image to a shielded environment.

One suggested method was to use sensors to detect the acoustic signals produced when the collimator jaws are damaged. This technique is in principal simple and non-invasive, however preliminary testing of a similar system at SLAC (using copper rather than carbon) jaws failed to discriminate between damage and normal beam impacts.

An alternate proposal is to slightly move the collimator jaws transverse to the beam and measure the scattering by a downstream instrumentation. Under stable low current beam conditions, this method is likely to reliably detect damage. The invasiveness of this method to beam running should be considered by the collimation team, especially at high beam currents.

5. Other Concerns and Comments

The committee feels that the production of the collimator units needed to go on-line is very ambitious regarding the schedule. One key concern is the availability of the CC-composite material in the form that is considered in the collimator design and at quantities that can support the fabrication of all the units. The possibility that, in order to meet the tight production schedule, there will be more than one vendor working on the production should be explored. That of course, will complicate matters regarding availability of raw, custom-made material. It is recommended that the vendor for the production of the composite is in the loop early on and is aware of both the quantities and the schedule.

Given that the LHC collimator design has no provisions for integrated shielding, the motors supporting the function of the collimator will experience high levels of activation. In the SNS collimator design, which included heavy, multi-layered shielding around the collimating elements, special care was taken for the motors to be protected from radiation. This was due to the fact that there are questions regarding the claim of radiation-hardened motors or other components as defined by the industry that produces them. In the case of the LHC, the motors are both unprotected and inaccessible for replacement. The committee recommends that the selected motor design be tested (possibly after irradiation exposure) to verify the claim of it being irradiation-hardened prior to committing an all-out purchase. The committee also feels that a layout option be explored that will allow for the back-side motors to be accessible from the isle-side. A design modification, already discussed with the LHC design team during the review proceedings, may easily accomplish that and thus allowing a much quicker turn-around in the event of a motor failure.

Estimated activation levels in the collimator section of a few mSv/h even after cool-down times raise serious concerns about the serviceability of the collimator components. Given the presented activation levels and allowable yearly doses of 2 mSv/y for personnel it seems unrealistic to do maintenance or repair within the limit of 1-2 hours per person per year. In addition there is only a limited number of knowledgeable and trained personnel available for about 90 collimators and absorbers. For the transition to phase II it is necessary to install the yet to-be-designed phase II collimators within or very close to the area of highest activation, exposing the same personnel to high radiation levels. A "plug-in" design for the phase I (and supposedly phase II) collimators was mentioned but not detailed.

The issue of tritium production in the cooling water has not been addressed.

Parasitic bunches in the abort gap are potentially harmful. Limits for the population of such parasitic bunches were not presented. The option of abort gap cleaning was not discussed.

A formula for an allowable intensity – used throughout many presentations at the Review – contains two not well-defined terms: (1) a beam loss rate of 7.5e6 p/m/s that depends on a magnet type, geometry and parameters of beam interaction with the aperture – rather than a well-known quench limit; (2) some dilution length of 50 m – rather than a calculated peak loss rate.

Beam loss distributions which are uniform as a function of the azimuthal angle, as presented, are rather unlikely to occur in practice.

Results on the energy deposition in collimators jaws were shown for a fixed impact parameter with a pencil beam rather than for a calculated transverse beam density distribution.

6. General Recommandations

1. Add minimization of machine-related backgrounds and protection of the collider detector components to the collimation system specifications.
2. The Committee agrees with the choice of carbon based material for the secondary collimators and recommends to go ahead with the production of the Phase I system. One should reconsider the use of a thin high-Z spoiler for the primary collimator without changing the basic mechanical design.
3. It is important to make the choice between C-C and graphite as collimator material relatively quickly and to start the production.
4. The possibility to avoid major damage to critical machine and detector components in a catastrophic beam loss scenario by "sacrificial collimators" should be evaluated.
5. Safety margins and tolerances on engineering and beam physics throughout the system should be carefully collected and tabulated.
6. Consider use of local shielding for the hottest spots in IR3 and IR7 as implemented already in the IP1 and IP5 interaction regions
7. It might be helpful to organize another external review before industrial contracts are finalized.
8. Use experience on high-energy beam radiation damage to graphite at BNL and Fermilab with establishing a possible collaboration in addition to contacts with Kurchatov institute on low-energy data.

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[i] B.T. Kelly, Physics of Graphite, Applied Science Publishers, London and New Jersey, 1981.