LHC Collimation Review 2011, report of the review committee

Review committee:

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1. Introduction and charge to the committee

LHC is presently operating very successfully at 3.5 TeV beam energy with steadily increasing intensity. The first two long shutdowns of LHC are currently planned for 2013-14 (LS1) and 2018 (LS2). In addition to the technical improvements required to allow the LHC to reach its design energy, it was suggested that the beam collimation system also be upgraded during the LS1 shutdown. This upgrade would consist of installing betatron collimators in IR3 in already prepared slots and installing new additional collimators in the cold dispersion suppressor region of IR3 that would intercept slightly off energy single diffractively scattered protons. Although these additional "Dispersion Suppressor (DS)" collimators would capture a comparatively small flux of particles in terms of power deposition, they would decrease the collimation inefficiency by an order of magnitude. Simulation studies, coupled with estimates of magnet quench limits and dilution lengths, suggested that this upgrade would be needed to reach the nominal LHC intensity. On the other hand actual experiments with beam, performed in the spring of 2011, provoking high losses in IR7 at 3.5 TeV, indicate a much higher intensity reach than expected. Thus the key question arises, whether the work-intensive collimation system upgrade in LS1 is really necessary to reach the nominal LHC intensities. The issues of reducing radiation to electronics in IR7 by shifting the betatron system to IR3 and of increasing operational efficiency and margin by installing new BPM equipped secondary and tertiary collimators were also presented and discussed.

Charge to the committee:

1. Are collimation performance and limitations properly analyzed and adequately addressed by the upgrade plans?

2. Can the collimation upgrade in the IR3 dispersion suppressors, presently foreseen for the 2013/14 shutdown, be delayed by three years without limiting LHC performance at 7 TeV?

3. Have any issues or risks been overlooked that should be addressed in the collimation upgrade plan?

2. General observations

In a series of presentations, the committee was comprehensively educated in all the important aspects of the LHC beam collimation system and the proposed upgrade plans. The general progress of LHC, and particularly the performance of the collimation system, is outstanding. Agreement between the simulations and the experimental observations of collimation efficiency and loss distribution is in general very good. The committee is impressed by the quality of the design and preparatory engineering work on the special collimator units foreseen for installation in the cold magnet string of IR3.

3. Experimental observations and extrapolation to high energy

In 2011 an experiment with artificially provoked high losses at 3.5 TeV was performed to estimate the quench threshold and to determine the collimation efficiency. These results were used to extrapolate the maximum beam intensity that could be safely operated at the full proton energy of 7 TeV. In a first machine development (MD) a loss rate of 9E11 protons per second (~ 500 kW) at the primary collimator was generated for a time of 0.5 seconds by operating the beam on the third order resonance. No quench occurred during this experiment. In a second separate MD with tighter jaw settings, improved collimation inefficiency was demonstrated (albeit for lower power loss on the primary collimator).

The experimental result at 3.5 TeV can be scaled to the full energy of 7 TeV with factors assumed for collimation inefficiency and quench limit. Since these factors describe relative changes they can be considered as relatively reliable, even though they are based on simulations (for the collimation inefficiency) and theoretical estimations (for the quench limit). The minimum lifetime at 7 TeV was also assumed to be no worse than that observed in 2011 at 3.5 TeV. For protons one then obtains an intensity limit for LHC of 1.3E15 protons per beam, roughly four times the nominal intensity.

This predicted intensity limit is thus much higher than the previous predictions that were based on theoretical estimates without significant operational experience. In one of the presentations a factor 80 improvement compared to 2010 estimates was presented. Potentially weak points of the extrapolation of the 2011 results to 7 TeV are that the new estimates are based on very few experimental results (essentially one measurement point), and that the applied mechanism to generate high losses may not reproduce well the operational conditions that result in low lifetime in practice. In addition, operation at 7 TeV with smaller collimator gaps, higher impedance and 25 ns bunch spacing may introduce additional effects which adversely affect the minimum lifetime attainable.

However, the committee acknowledges the fact of large uncertainties in the former theoretical predictions, especially concerning the important factor of quench threshold × loss length. Thus the recent experimental results should be weighted high for future plans. The safety factor four in the intensity prediction results in a relatively high confidence that the nominal intensity can be reached with the present configuration of the collimation system.

For heavy ions the situation is less certain. The results of the proton beam experiments have been used to improve the predictions for ions as well, however the scattering mechanisms for ions are fundamentally different, which makes the predictions less reliable. In contrast to protons, for ions the dominant losses are expected in the main dipoles (MD), where the quench limits are lower than in the main quadrupoles. Fragmentation and neutron removal will lead to very localized energy deposits in the MDs. The presented extrapolation predicts a reach of 50% of the nominal intensity. The reliability of this prediction should be improved with dedicated measurements using ions.

4. Comments on operational aspects and studies with beam

Operational experience

Operational experience of running at 3.5 TeV has been encouraging. By July 2010 the LHC was running with around half design intensity with a total beam intensity of 1.6e14 protons in 1380 bunches of around nominal intensity (1.15e11 protons per bunch). The following general features may be noted.

- The machine is magnetically and optically well understood with excellent agreement between the magnetic and optics models and measured beam parameters.
- The LHC is magnetically reproducible. This has proved important because machine set-up remains valid from fill to fill, and indeed from month to month. Collimator set-up is stable as well and its validity is regular tested with loss maps.
- The aperture has been measured carefully and is as expected.
- The operational sequence allows the beams to be taken through the ramp, squeeze and into collision essentially without loss.
- Better than nominal beam intensity and beam emittance (although with larger than nominal bunch spacing) is delivered by the injectors resulting in excellent luminosity performance for a given beam current.
- It was possible to collide nominal bunch currents with smaller that nominal emittances with no serious problems from head-on beam-beam. This important result is another key reason behind the impressive luminosity performance.
- There was excellent cleaning by the collimator system and good control of beam losses at all stages of operation. There were no accidental beam induced quenches above injection energy. There are only a few dumps triggered by the beam loss monitors, indicating that most fault scenarios are caught at source and not by their effect on the beam.

It is worth noting that the collimation system performs two critical roles: in its cleaning role it prevents protons from impacting the LHC’s cold mass; its secondary role is as passive protection in certain beam loss scenarios. In both roles it has performed impeccably.

Beam lifetime

The stated required cleaning efficiency of the collimator systems is based on estimated minimum beam lifetimes and beam lifetime dips. Experience up to now has shown excellent single beam lifetimes through the operational cycle with the LHC able to essentially ramp and squeeze without loss.

- The single beam lifetime in steady state is well above the design report’s stated 100 hours.
- The emittances delivered by the injectors have been typically around 70% of the nominal at injection.
- The known non-linearities of the machine are well compensated and the inherent non-linearities look to be very acceptable. There is good tune, chromaticity and orbit control through the cycle, and good control of the injection process. These factors taken together have meant that transverse emittance growth is well under control with minimal transverse blow-up observed through the cycle.

- The predicted required cleaning efficiency was based on predictions of beam lifetimes at various timescales. Operational experience has shown that these predictions were somewhat pessimistic.
- Low emittance growth and better than predicted beam lifetimes have reduced the demands on the cleaning efficiency of the collimation system. Settings have been relaxed and so-called intermediate collimator settings used.

In evaluating the future needs for cleaning efficiency, key assumptions about beam lifetimes and closely associated emittance growth must be made. At present the minimum lifetime routinely experienced during the operational cycle is when the beams are brought into collisions. At this point the lifetime dips to around 1 hour and this is clearly reflected in increased losses on the primary collimators in the betatron cleaning section at IP7. The effect is thought to be beam-beam driving particles into the tails that are then lost on the aperture limiting collimators. The lifetime dip is short-lived and the single beam lifetime recovers steadily and continues to gently increase over the length of a fill. A variation in minimum lifetimes from fill to fill is noted.

It is important to note that it is assumed here that the minimum beam lifetime will be approximately the same at 3.5 and 7 TeV. Also implicit here is the increase of beam intensity from around 50% of nominal at 3.5 TeV (present situation) to around nominal at 7 TeV (stated acceptable limit for operation without DS collimators) will not impact the routine minimum lifetime considerably.

It might be useful to anticipate and tests possible procedural changes aimed at improving the lifetime dips. These might include: colliding at IPs 1 and 5 and then tackling IPs 2 & 8; colliding longitudinal via RF re-phasing. Colliding before squeezing is not thought to provide any benefit.

Radiation to Electronics (R2E)

A variety of critical equipment is situated in IR7 and the vicinity. Samples of some of this equipment have been tested and shown sensitivity to high levels of radiation. A far reaching and global solution would appear to be necessary. Mitigation measures will include shielding, relocation and development of radiation hard solutions. The power converters, in particular, pose a risk.

An additional option is the relocation of the betatron cleaning function to IR3. The scheme would involve adding additional collimators in IR3, primarily in the vertical plane. There is no particular risk for R2E effects in IR3 and the scheme would provide additional flexibility.

If the proposed mitigation measures go ahead as planned, they should be sufficient to reduce R2E effects at IR7 to an acceptable area. In this case, the shift of betatron cleaning to IR3 will not be required. It is felt, however, that preparation for the move should be undertaken. This would cover problems or delays in implementing the mitigation measures or worse than expected radiation levels at higher energy.

Quench limit studies

A number of studies aimed at studying the quench limits of superconducting magnets on various timescales were presented. It is perhaps worth recalling the simple formula relating allowed intensity and beam lifetime, quench threshold, BLM threshold, loss length and cleaning inefficiency.

$$N_p^{\max} = \tau \cdot R_q \cdot F_{BLM} \cdot L_{dil} / \eta_c$$

The quench threshold and the closely related BLM threshold factor are clearly of importance. The BLM system is set to protect against quenches, and the BLM threshold factor is normally taken to be 30% of the predicted quench level.

Machine development was carried out in 2011, which provoked high losses on a primary collimator (short beam lifetime). The BLM thresholds were raised. 505 kW was incident on the primary collimators in IR7 without quenching the downstream magnets. Although not establishing the quench limit this experiment does establish a very useful limit.

The committee recognizes the importance of these studies and encourages further machine development along these lines with the aim of firmly establishing quench limits at various timescales. These will be vital in anticipating the potential beam intensity that can be safely handled at high energy.

Experimental data should be collected with heavy ions to similarly establish the equivalent limits.

5. Comments on theoretical studies and simulations

The Committee was impressed by the amount, thoroughness and quality of simulation studies done on the collimation system performance, beam losses and associated effects to the LHC superconducting magnets, collimation system components, electronics and environment. Agreement between simulations and data is very good – within a factor of two in most cases - while comparisons are consistent. An excellent agreement was found on Single-Event Upset in the IP7 electronics in benchmarking FLUKA against measurements. On the contrary, measurements of the cleaning efficiency in the real machine with imperfections differ by a factor of 7 from simulations without imperfections. A consistent description of single diffractive production is certainly the issue in IP7 for both protons and heavy ions, there are additional peaks not seen in simulations. Uncertainties in FLUKA predictions for heavy ions – which are higher than those for protons – can be reduced by tuning the code by recent ALICE measurements.

A comprehensive FLUKA benchmarking was performed for the controlled beam losses induced by a beam wire scanner and stable pp-collisions in IP1. A very good agreement was found for integrated dose in BLMs, although in the IP1 inner triplet, FLUKA results are systematically 50-100% higher than data. The measurements with the wire scanner are integrated over 40 ms, i.e. transient. It would be very helpful for understanding the quench stability of the LHC superconducting magnets to repeat these studies for shorter (~1 ms) and longer (~hundreds of ms) times.

A beam loss dilution factor used throughout the collimation project – found to be helpful in quick estimates of tolerable beam losses – can be quite misleading in specific regions of the machine: quench limit times dilution factor was measured to be at least a factor 14.5 higher than expected.

Impressive theoretical studies were performed on limitations of the current collimation system and ways to upgrade it. The issues include cleaning efficiency (need for collimation in DS IR3 with IR7 at a later stage, high-Z materials, thermo-mechanical stability), operational efficiency (need for BPM buttons, in particular TCT with W-jaws – in 2012 shutdown), radiation damage & RF impedance (need for advanced materials – metal diamond and SiC with better thermal conductivity, rad hardness and robustness, advanced simulations and beam tests), and collimator design (need for a modular design, GlidCop jaws).

Radiation damage to magnet materials needs further thorough analysis. If the peak power deposition in the SC coils is kept at 1/3 of the quench limit of ~15 mW/cm^3, the insulation will fail after about 7 years at the nominal luminosity and after ~1.5 years at the upgraded luminosity. The reduction of electrical conductivity of SC cable stabilizing material due to radiation damage should certainly be addressed for the upgrade scenario.

The committee strongly recommends continuing the quench limit studies to benchmark simulation predictions and create a link to a 1-D beam loss model used throughout the collimation project in IR3 in particular.

According to the presented studies the impedance limit is just reached at 7 TeV for tight collimator settings, high intensity and the small emittances observed at 3.5 TeV. Further experimental studies should be undertaken to make the 7 TeV prediction more reliable, and ways to mitigate the limitation (improved feedback, stronger octupoles) should be explored.

6. Comments on upgrade strategy

In the LHC a limited collimation system was installed initially (phase 1), thought to allow for 40% of the design proton intensity. A possible upgrade is now under consideration. Despite the very impressive progress that has been made in predicting localized beam losses with simulations, considerations for an upgrade can now also be based on measurements with beam. This strategy allows taking advantage of the experience gained in operation before further increasing the size and complexity of the collimation system. The committee fully endorses such a strategy.

The results of the recent MDs, on collimation efficiency and collimator positioning accuracy, when extrapolated to 7 TeV and nominal squeeze, indicate a comfortable margin with respect to the nominal beam intensity (1.15E11 protons/bunch, all bunches filled 25 ns spacing).

This extrapolations assumes a level of accuracy of the positioning of the collimator jaws similar to what has been achieved to date in the dedicated MDs: given the time needed to validate the collimator settings with today's (lengthy) iterative procedures, the committee feels that the proposed installation of BPMs embedded collimators should take high priority: equipped with such local BPM the collimators setting up will be much faster, more reliable and possibly allow tighter settings.

Fundamental for relying on the extrapolation are also the FLUKA simulations of expected energy deposits: these have been validated by comparing the measured energy deposits in Q11 during the collimator MD (the detailed simulation was not available for the beam used in the MD and symmetry arguments allowed comparison only for the Q11 region and not the Q8 which collected most energy)

In this respect the committee notices the larger uncertainties linked to a similar extrapolation for the Heavy Ion (HI) program: here several uncertain scaling factors need to be adopted to estimate worst case scenarios. If taken at face value the extrapolation implies that the present collimation system will allow at most 50% of the nominal HI intensity. The committee notes that in any case the HI issue is more complex, as the collimation upgrade in the DS of IRs may not be sufficient to allow the full luminosity in the experimental IRs, which will need additional local collimation in these IRs. This needs to be carefully considered since postponing the IR3 DS installation may adversely affect the overall installation schedule for these collimators.

The committee thinks that the DS collimator upgrade implies non-negligible risk: the number of elements of the machine that would need repositioning is comparable to the number of elements that needed re-installation during after the 2008 incident. Such activity concurrent with the splice consolidation program during LS1 will inevitably cause competition for some specialized resources.

The committee feels nevertheless that the upgrade of collimation in the IR3 and IR7 DS should be carried out in the long term (LS2) as it will allow for increased machine performance. The additional time should be used to complete a proper prototyping of the special cryogenic bypass module. The committee feels that the increased activation of the machine elements in the IR3 and IR7 DS region between LS1 and LS2 should not increase significantly the exposure risks.

During the review the possibility of installing a system for combined betatron and momentum cleaning in IR3 by the installation of additional vertical collimators: the committee notes this as a possible action to be taken in case the mitigating action planned for LS1 to reduce the R2E problems in IR7 would not be sufficient and operation hindered severely by radiation issues in IR7.

Alternative scenarios could profit from development of stronger dipoles or higher gradient quadrupoles. The integration of fixed masks into magnets with high local energy deposition, or the integration of a collimator between two short high-field dipoles, might provide adequate performance reach while avoiding the wide-ranging layout changes required to make the longitudinal space available for the present upgrade proposal. Another option under discussion in the past involves the concept of a hollow electron beam collimator (Fermilab). Since no material must be placed close to the beam, there exists no damage risk with this scheme. Beyond a certain betatron amplitude the hollow e-beam would generate high diffusion rates for the protons. It can be expected that this mechanism also smoothens out spiky loss rates in time. With high intensity and primary collimators placed close to the beam, such non-uniformly distributed loss rates can be an operational problem.

Delaying the upgrade until LS2 will give time to investigate these alternatives, which might reduce the impact to the LHC.

7. Summary and response to charge

1.) Yes, collimation performance and limitations are properly analyzed and adequately addressed by the upgrade plans.

2.) On the basis of the evidence presented, the committee concludes that the nominal proton beam intensity of LHC at 7 TeV can be achieved without the installation of additional collimators in the IR3 dispersion suppression region during the LS1 shutdown. For heavy ion beams less experimental evidence exists and thus the extrapolation to full energy entails more uncertainty.

3.) The committee has not identified serious “show stoppers” for the planned operation at nominal parameters. A number of comments and recommendations are given in this document.