LHC COLLIMATION – TOO GOOD OR TOO BAD?

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Abstract

The LHC beam operation at 3.5 TeV has seen a rapid and quite worry-free increase of beam intensity. The energy stored in the proton beams quickly reached more than 10 times the values achieved in other colliders and was not perturbed by quenches of super-conducting magnets from stored beam. Losses were reliably and efficiently intercepted by the phase 1 of the LHC collimation system. The success of the collimation system has triggered the questions whether collimation performance is already sufficient and whether the foreseen completion and upgrade of the system is justified. These questions are addressed in view of the first beam experience.

INTRODUCTION

The LHC collimation system was conceived and approved in 2003 as a phased system [1,2]. The phase 1 system was completed for the LHC start-up in 2009 and is being used for the beam commissioning and operation at 3.5 TeV. Selected parameters of the initial 3.5 TeV run of the LHC are compared in Table 1 to the design parameters.

Stored energies and energy densities are compared in Fig. 1 and Fig. 2 for various accelerators and designs. It is seen that the parameters achieved in the LHC during the 2010 run are already well beyond the achievements in other accelerators (a factor 10 or higher beyond previous records). A stored energy of 28 MJ was reached in the LHC without a single quench of the sensitive super-conducting magnets (limits: 10-30 mJ/cm^3), once stored beam was established. It is noted that the intensity increase in Tevatron and HERA was limited by quenches of super-conducting magnets. The rapid and quite worry-free increase of LHC beam intensity was possible due to the highly efficient first phase of the LHC collimation system [2].

At the same time, predicted system limitations have been measured with beam [2]. Several improvements are under development since 2009 to complete the system and to guarantee that nominal and ultimate beam intensities can be achieved [3]:

- The LHC dispersion suppressors must be equipped with collimators [4] to reduce losses into the super-conducting magnets in this area with the associated risks of quenches and long-term magnet damage.
- Second-generation collimators for faster and more flexible setup must be constructed and installed into the already equipped phase 2 collimator slots. This will also allow achieving the smallest β* values.
- Remote handling, measures to reduce radiation to electronics and measures for lower environmental impact must be constructed and installed.

This paper reviews a few selected topics of LHC collimation in the light of the first LHC beam experience.

Table 1: Collimation and protection relevant parameters compared between 3.5 TeV (up to April 2011) and the nominal LHC at 7 TeV.

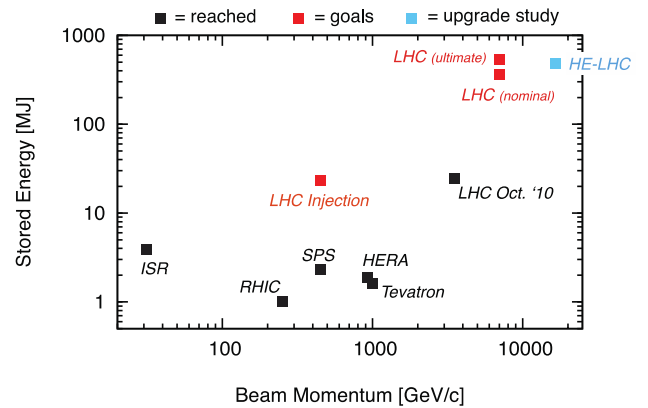| Parameter	2010/2011	Nominal
E	3.5 TeV	7 TeV
γ	3,730	7,461
$\varepsilon_{x,y}$	0.5 nm	0.5 nm
N_p	0.56×10^{14}	3.00×10^{14}
E_{stored} (total)	31 MJ	362 MJ
ρ_e (tot)	248 MJ/mm^2	2.9 GJ/mm^2
E_{stored} (1bunch)	72 kJ	128 kJ
ρ_e (1bunch)	0.6 MJ/mm^2	1.0 MJ/mm^2

Figure 1: Stored energy per beam versus beam momentum for various accelerators. Filled black squares indicate achieved values, red squares show design values and the blue square represents an upgrade study.
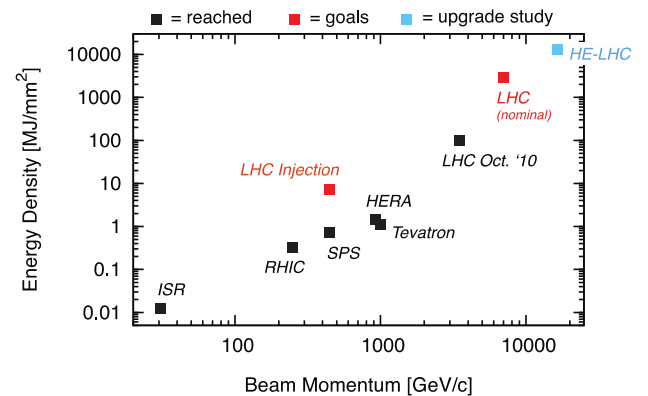

Figure 2: Energy density versus beam momentum.

LIMITS IN DISPERSION SUPPRESSORS OF BETATRON COLLIMATION

The cleaning inefficiency describes the leakage from the collimation systems into critical machine elements, for example all super-conducting magnets. We define a local cleaning inefficiency as the maximum leakage to one meter of critical super-conducting magnets [5]:

$$\tilde{\eta}_{in} = \max_i \left(\frac{\Delta N_i / L_i}{N_{impact}} \right) \qquad (1)$$

Here, ΔN_i is the number of lost protons in the super-conducting magnet number i of length L_i. N_{impact} gives the number of protons that impact on the primary collimators.

Intensity reach from cleaning efficiency

The maximum intensity N_{max} in the LHC is a function of the local cleaning inefficiency, the minimum beam lifetime τ_{min} during the fill and the quench limit R_q [5]:

$$N_{max} \approx \frac{\tau_{min} \cdot R_q}{\tilde{\eta}_{in}} \qquad (2)$$

Ideal performance reach of LHC collimation

Simulations have shown during the design phase that the efficiency of the LHC collimation system will be limited by losses in the dispersion-suppressors of the LHC. The leakage (cleaning inefficiency) gets worse with increased beam energy in the range from 1 TeV to 7 TeV. This is due to smaller multiple Coulomb scattering angles at higher beam energies and an increased probability of single-diffractive scattering.

Single diffractive scattering generates off-energy protons that cannot be intercepted by collimators in the straight sections of the cleaning insertions (lack of dispersive dipole kicks). These off-momentum protons are then lost in the dispersion suppressors downstream of the cleaning insertions. The higher is the beam energy, the higher is the fraction of single-diffractively scattered protons and the higher is the leakage (or inefficiency).

The past performance reach estimates were based on Equation 1. Past assumptions (before beam commissioning) for 7 TeV are listed [6,7]:

- Quench limit R_q (steady state): 7.8×10^6 p/m/s
- Ideal cleaning inefficiency η_{in}: 4.63×10^{-5} m^{-1}
- Minimum beam lifetime τ_{min}:   720   s

With this input we obtain a maximum beam intensity of **1.2×10^{14} protons or 40% of nominal design intensity** (nominal design is 3e14 protons). This is the well-known **ideal performance reach** of phase 1 of LHC collimation. In addition, imperfections were simulated to reduce efficiency by a factor 11 to a realistic performance reach of 3.6% of nominal intensity. This was presented in various committees and published in PhD's and elsewhere.
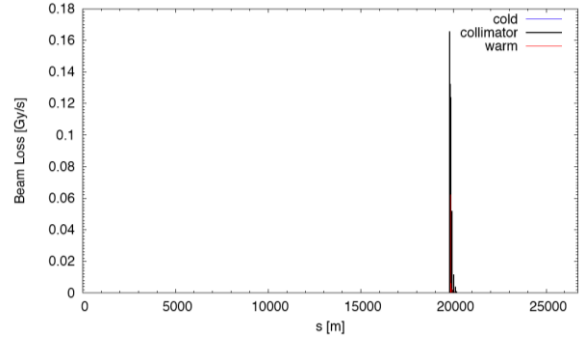

Figure 3: Measurement of proton losses in the betatron cleaning insertion IR7 and around the ring, performed at 3.5 TeV beam energy. Losses are shown in linear scale. The beam runs in direction of s.

2010/11 measurements and raw cleaning inefficiency for protons

Generating beam losses at primary collimators (achieved by moving a selected machine tune onto the 1/3 resonance) assesses the efficiency of the LHC collimation system. Data for 3.5 TeV, as recorded with the LHC beam loss measurement (BLM) system, are shown in Figures 3 and 4 for 2010 conditions ($\beta^* = 3.5$ m). The proton losses are intercepted, as designed, at the primary collimators. The overall efficiency can be assessed roughly by looking into integrated losses appearing in characteristic regions of the ring:

- Losses in cleaning insertions   99.93 %
- Losses in super-conducting magnets   0.07 %

Excellent global collimation efficiency was found. From primary collimators onwards, losses are reduced with additional collimators by about four orders of magnitude. Details can only be assessed on a logarithmic scale, as shown in Fig. 4. There it is seen that single diffractive protons are lost in two characteristic, super-conducting magnets.

The raw cleaning inefficiency is defined as the ratio of two BLM measurements R, namely of (1) the measured peak loss rate $R_{DS,i}$ at any magnet i in the dispersion suppressor and (2) the peak loss rate R_{TCP} at the primary collimator:

$$\eta_{in,raw} = \max_i \left(\frac{R_{DS,i}}{R_{TCP}} \right) \qquad (3)$$

This quantity is used to assess the quench risk of super-conducting magnets, which depends on the local distribution of beam losses and related heating in the magnet. The raw cleaning inefficiency has been monitored over four months in 2010 for the different planes and beams in the LHC [8]. The measured data is shown in Fig. 5. The data is used to define an average performance and a worst case (over the 6 measurements), as summarized in Table 2.
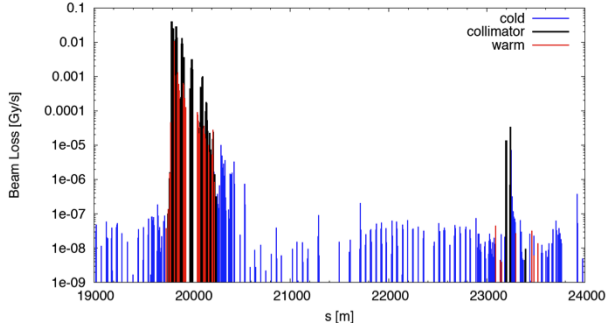
Figure 4: Measurement of proton losses in the betatron cleaning insertion IR7 and through the downstream arc into IR8, performed at 3.5 TeV beam energy. The losses are shown in logarithmic scale. Black bars indicate losses at collimators, red bars at warm machine elements (not critical) and blue bars at superconducting magnets (critical). The beam runs in direction of s.
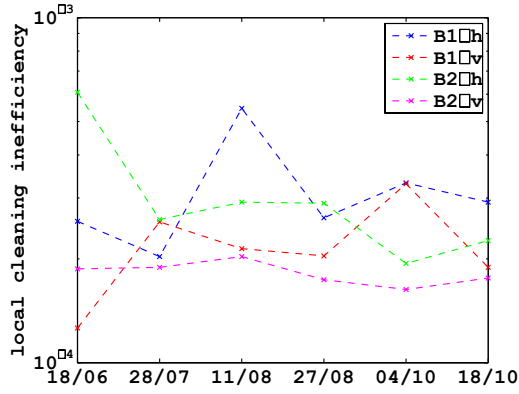

Figure 5: Measured "raw" **cleaning inefficiencies $\eta_{in,raw}$ at 3.5 TeV** during the 2010 run. This data was used to determine an average cleaning inefficiency and the worst case (over 6 measurements). From [8].

Table 2: "Raw" values for cleaning inefficiency at 3.5 TeV. This is the ratio of the peak BLM measurement at a SC magnet (leakage rate) over the BLM measurement at a primary collimator (primary loss rate).

Case	"Raw" cleaning inefficiency (3.5 TeV)
Average 2010	2.6×10^{-4}
Worst measured (out of 6)	6.1×10^{-4}

2010/11 measurements and raw cleaning inefficiency for heavy ions

The collimation performance was assessed for heavy ions and is quickly shown. A measurement of betatron collimation performance is shown in Fig. 6. Again estimating global efficiency in characteristic regions we find:

- Losses in cleaning insertions   98.1 %
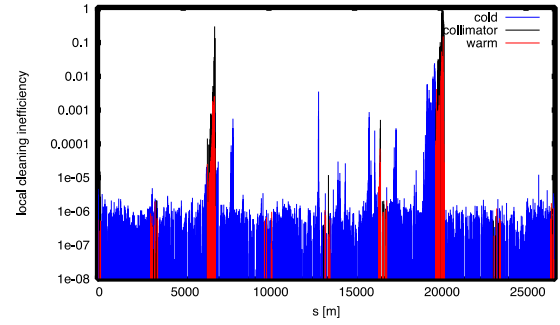- Losses in super-conducting magnets   1.9 %

Figure 6: "Raw" cleaning inefficiency for betatron collimation of heavy ion beams in the LHC. The losses are shown in logarithmic scale. Black bars indicate losses at collimators, red bars at warm machine elements (not critical) and blue bars at superconducting magnets (critical). Here, the beam runs in opposite direction of s ("beam 2").

The integrated leakage into SC magnets is 27 times worse for heavy ions than for protons. Essentially all losses impact again on the two exposed SC magnets in the IR7 dispersion suppressor. In addition, leakage up to a few per mille hits some isolated magnets around the ring, many km's away from the collimation insertion.

It is noted that the increased leakage for heavy ions has been predicted and simulated during the design phase of the collimation system. It is caused by particular physics processes of dissociation and fragmentation of ions. Affected ions behave essentially as off-momentum particles and are lost in the same characteristic locations as single-diffractive protons.

Corrected cleaning inefficiency for protons

The response of BLM's at super-conducting magnets in the IR7 dispersion suppressors and IR7 primary collimators can be very different. The relative response was assessed with a special measurement method [9]:

1. A closed orbit bump is implemented in the Q9 magnet of the IR7 dispersion suppressor, such that the LHC aperture bottleneck is in the Q9 of IR7.
2. The beam is injected and stored at 450 GeV.
3. The primary collimator is set to some number of normalized beam sigmas, initially open and then closed further and further.
4. The stored beam is blown up horizontally by passage through the 1/3 tune resonance, while the BLM responses at the Q9 magnet and the primary collimator are measured simultaneously.
5. The BLM signals to the grazing beam loss are normalized to the amount of intensity loss, yielding values in Gy/s/p.
6. The beam is dumped and the procedure continues from step 2, taking a measurement for a different collimator setting.

As a result one obtains the relative beam loss measurements at the Q9 and the primary collimator as a function

of collimator setting. Two such measurements are shown in Figure 7 for the right and left sides of IR7. It is seen that the beam loss occurs at the primary collimator for small collimation gaps and at the Q9 for large gaps. The two asymptotic values give the difference in BLM response to the same beam loss. This measurement is only possible at 450 GeV and it must be assumed that the response is the same at 3.5 TeV. It is noted that the point of equal losses in the Q9 and the primary collimator is a measure of the magnet aperture (after subtraction of the known bump amplitude). This method is used very successfully for aperture measurements in the LHC.

A consistent difference in BLM response is seen for both beams (Fig. 7). It is probably due to features in material and geometry, but also details in beam loss distribution. A correction factor $C_{BLM,TCP}/C_{BLM,SC}$ is defined in order to take the measured response into account. The data suggest $C_{BLM,TCP}/C_{BLM,SC} = 2$. For the same number of protons lost a BLM at the super-conducting magnet in the IR7 dispersion-suppressor measures about half the signal of the BLM at the primary collimator. The inefficiency is therefore under-estimated and needs to be corrected:

$$\eta_{in,corr} = \frac{c_{BLM,TCP}}{c_{BLM,SC}} \cdot \eta_{in,raw} \qquad (4)$$

The "corrected" values of cleaning inefficiency are summarized in Table 3. It is seen that the peak leakage to a dispersion suppressor magnets can in worst case reach the 1.2 per mille and on average the 0.5 per mille level.

Local cleaning inefficiency

The risk of magnet quenches depends on the longitudinal distribution of losses inside the magnet. The BLM measurements contain no direct information about this. It was seen that proton losses, different by a factor 10, can produce the same BLM signal. A longitudinal dilution length L_{dil} must therefore be assumed from preliminary simulations and FLUKA studies. A value $L_{dil} = 3.5$ m is taken. The local cleaning inefficiency is then given by:

$$\tilde{\eta}_{in} = \frac{c_{BLM,TCP}}{c_{BLM,SC}} \cdot \frac{\eta_{in,raw}}{L_{dil}} \qquad (5)$$

The resulting values for local cleaning inefficiency from 3.5 TeV data are summarized in Table 4. A comparison with the simulation results for the ideal setup is included and shows that imperfections reduce the performance by a factor $4 - 10$, in good consistency with expected effects.

It is noted that this estimate of local cleaning inefficiency can be affected by significant errors. The appropriate value of L_{dil} depends on details of beam loss and imperfections. The quoted value of 3.5 m must be taken as a rough estimate with large uncertainties that can reach a factor 5. It must be assessed by special experiments with LHC beam.
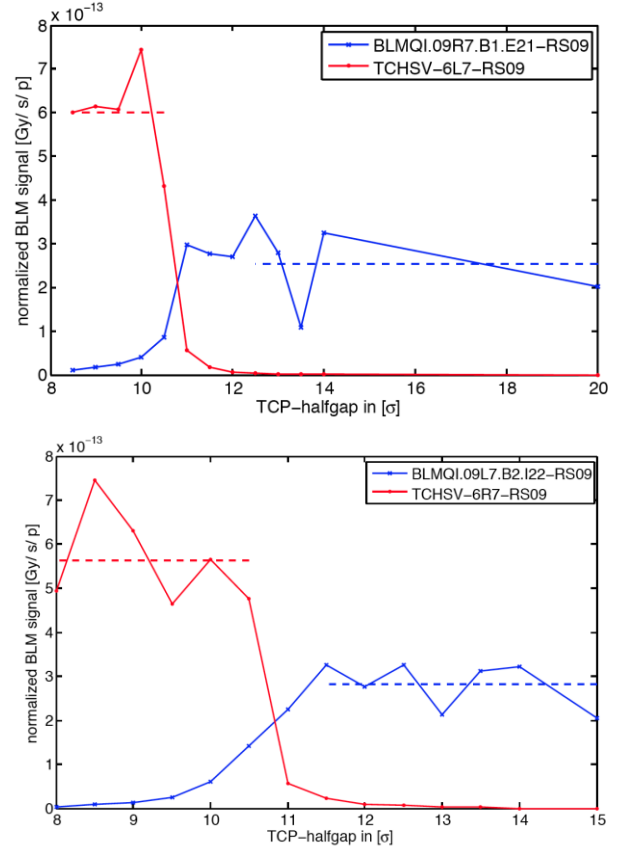

Figure 7: Measurements of relative response of BLM's from primary collimators (here TCHSV) to a cold magnet in the IR7 dispersion suppressor (Q9R7/L7). Shown are beam 1 (top) and beam 2 (bottom). The data have been corrected for intensity fluctuations in the beam. The data suggest $C_{BLM,TCP}/C_{BLM,SC} = 2.4$ (2.0) for beam 1 (beam 2).

Table 3: "Corrected" values for cleaning inefficiency at 3.5 TeV.

Case	"Corrected" cleaning inefficiency (3.5 TeV)
Average 2010	5.2×10^{-4}
Worst measured (out of 6)	12.2×10^{-4}

Table 4: Estimates of **local cleaning inefficiency** at 3.5 TeV.

Case	Estimated local cleaning inefficiency (3.5 TeV)
Average 2010	1.5×10^{-4} m^{-1}
Worst measured (out of 6)	3.5×10^{-4} m^{-1}
Simulation (ideal setup)	0.4×10^{-4} m^{-1}

Extrapolation of cleaning inefficiency to 7 TeV

The energy dependence of the simulated local cleaning inefficiency [5] is shown in Fig. 8 with two possible settings for collimators ("tight" and "intermediate"). It is seen that the LHC cleaning inefficiency gets worse with increased beam energy. The existing simulation data [7] in the range from 1 TeV to 7 TeV can be fitted as a function of beam energy E, here expressed in units of TeV:

$$\frac{\tilde{\eta}_{ineff}}{10^{-4}} = 0.0276 \frac{1}{m} + 0.0231 \frac{1}{m} \cdot E + 0.0051 \frac{1}{m} \cdot E^2 \quad (6)$$

This relationship is valid for so-called "tight" collimator settings, referring to nominal settings with primary collimators at 6 σ, secondary collimators at 7 σ, tertiary collimators at 8.4 σ and absorbing collimators at 10 σ.

The local cleaning inefficiency can be extrapolated to 7 TeV and to nominal collimator settings using the simulated data shown in Fig. 8.

$$\tilde{\eta}_{in}[7 \text{ TeV}] \approx 2.5 \times \tilde{\eta}_{in}[3.5 \text{ TeV}] \quad (7)$$

$$\tilde{\eta}_{in}[\text{tight}] \approx 0.43 \times \tilde{\eta}_{in}[\text{intermediate}] \quad (8)$$

These relationships are used to extrapolate to 7 TeV.

Calculated quench limit

The calculated quench limit R_q of a standard LHC super-conducting magnet is shown in Figure 9 as a function of the beam energy. A concentrated and slow, continuous beam loss is assumed. The following quench limits R_q are used in the context of this study:

$$R_q\,[.45 \text{ TeV}] = 70.0 \times 10^7 \quad p/m/s \quad (9)$$
$$R_q\,[3.5 \text{ TeV}] = 2.40 \times 10^7 \quad p/m/s \quad (10)$$
$$R_q\,[6.5 \text{ TeV}] = 0.88 \times 10^7 \quad p/m/s \quad (11)$$
$$R_q\,[7.0 \text{ TeV}] = 0.78 \times 10^7 \quad p/m/s \quad (12)$$

It is seen that the slow quench limit at 7 TeV is a factor ~3 tighter than at 3.5 TeV and a factor ~90 tighter than at 450 GeV.

The LHC cannot be run just to the quench limit. Instead a margin must be taken into account that is used to set a BLM threshold R_{lim} below the actual quench limit. Once the measured beam loss reaches this limit the beam is dumped before any magnets can quench. The following beam loss limit R_{lim} must therefore be respected:

$$R_{lim} = \frac{R_q}{3} \quad (13)$$

The limiting beam loss rates then become:

$$R_{lim}\,[.45 \text{ TeV}] = 23.3 \times 10^7 \quad p/m/s \quad (14)$$
$$R_{lim}\,[3.5 \text{ TeV}] = 0.80 \times 10^7 \quad p/m/s \quad (15)$$
$$R_{lim}\,[6.5 \text{ TeV}] = 0.29 \times 10^7 \quad p/m/s \quad (16)$$
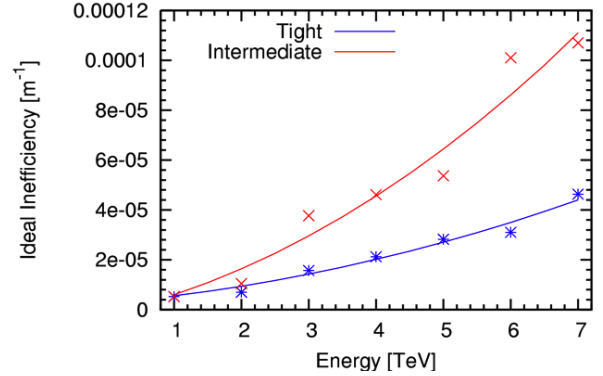$$R_{lim}\,[7.0 \text{ TeV}] = 0.26 \times 10^7 \quad p/m/s \quad (17)$$

Figure 8: Simulated cleaning inefficiency of the LHC multi-stage collimation system. The two curves show two different settings of collimators. The lines show a fit to the data (see text). The data is from [7].
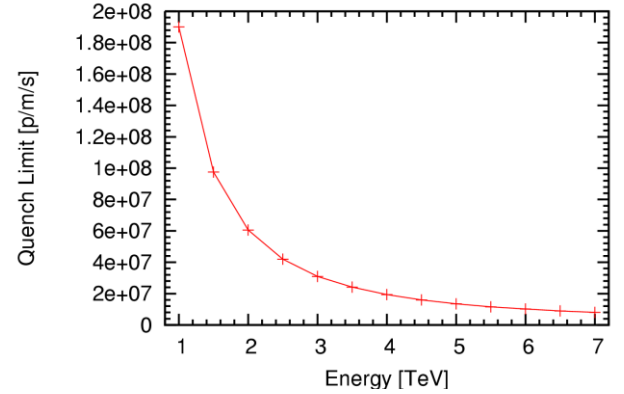

Figure 9: Calculated quench limit R_q of a standard LHC super-conducting magnet versus beam energy for concentrated, continuous beam losses [7]. No relevant experimental data was obtained during 2010/11 operations.

Table 5: Minimum beam lifetimes as found during 5 fills with 368 bunches and high luminosity in 2010. The BLM calibration factor used is 4.8×10^{11} p/Gy.

Integration time	Minimum lifetime [h]
10.24 ms	0.52
1.3 s	0.64

Peak loss rate and minimum beam lifetime

The minimum lifetime of LHC beams was determined by analysing beam loss rates at primary collimators during five LHC fills in 2010 with highest beam intensity [8]. The measured BLM values were converted into proton loss rates with a calibration factor of 4.8×10^{11} p/Gy. The results are summarized in Table 5. It is assumed that high beam intensities have the same beam stability as observed in 2010. An example of beam loss rate versus time is shown in Fig. 10.
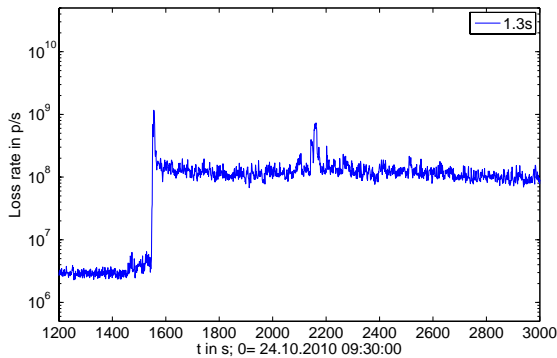
Figure 10: Example of loss rates at primary collimators during a physics fill in 2010. Collisions create beam diffusion and higher loss rates at collimators. The peak loss is encountered when bringing the beams into collision.

PERFORMANCE REACH ESTIMATES

Intensity reach

All parameters for predicting the intensity reach in the LHC have now been introduced and discussed. Using a slightly modified version of Eq. 2

$$N_{max} \approx \frac{\tau_{min} \cdot R_{lim}}{\tilde{\eta}_{in}} \qquad (18)$$

the intensity reach of the LHC can now be calculated. A minimum beam lifetime of 0.64 h and a local cleaning inefficiency of 1.5×10^{-4} m^{-1} are used. Results are summarized in Table 6.

It is noted that nominal beam intensity could be possible with the present betatron collimation system ("phase 1") if the beam lifetime at primary collimators can be kept above 12.8 hours at any time during high energy. A beam lifetime of 5.3 hours would make this possible if tight collimation settings can be used.

The predicted and observed loss limitation of the LHC collimation system ("phase 1") will be overcome by the proposed installation of collimators into the dispersion suppressors of the LHC.

Table 6: Performance reach in LHC intensity, calculated with a minimum beam lifetime of 0.64 hours and average measured cleaning inefficiency in 2010. It is noted that significant uncertainties may affect these predictions.

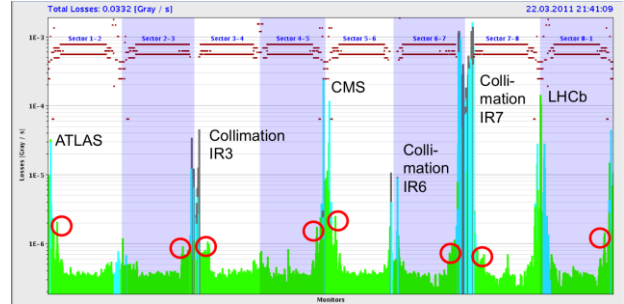| Beam energy	Reach (intermediate coll. settings)	Reach (tight coll. settings)
3.5 TeV	41 %	95 %
6.5 TeV	6 %	15 %
7.0 TeV	5 %	12 %

Figure 11: Beam losses around the LHC ring in a 2011 physics run with peak luminosity of 2.5×10^{32} cm^{-2} s^{-1} (fill #1645, 200 bunches, 2.4×10^{13} p per beam). Leakage into the dispersion suppressors of IR1/3/5/7 are indicated by circles.

Emittance reach

The LHC collimators and protection devices have been designed for nominal and ultimate intensities. We assume that all these elements are robust for ultimate bunch intensity and nominal emittance at 7 TeV beam energy. Then we can establish the following brightness limit [10]:

$$\frac{N_p}{\varepsilon} \leq 3.4 \times 10^{20} \ m^{-1} \qquad (19)$$

Here N_p is the maximum number of protons in a bunch and ε is the geometric emittance. Further experimental studies on damage limits or more robust collimator materials might relax this limit.

It is interesting that the luminosity reach at the robustness limit is:

$$L \leq \frac{10^{40}(cm\ s)^{-1}}{\gamma \cdot \beta^*} \cdot \frac{E_{stored}}{500\ MJ} \qquad (20)$$

It is an easy function of the stored energy, the β^* and γ. The geometric correction factor F from the crossing angle is neglected here.

β* reach

The β^* reach from collimation involves questions of machine protection, collimator hierarchy and operational tolerances. A complete study has been performed and published [11]. The arguments are not repeated here. However, it is noted that the proposed upgrade of LHC collimators with in-situ beam position pickup buttons will significantly improve the β^* reach from collimation. Tight collimation settings could be achieved with much less demanding requirements on operational stability and tolerances.

Luminosity reach

Colliding beams generate off-energy protons during the beam-beam collisions. Some of these protons escape the long straight section and are lost in the same characteristic dispersion suppressor locations as in IR7 and IR3. This is illustrated in Fig. 11 for a high luminosity fill at 3.5 TeV. Simple scaling shows that these losses in super-conducting magnets will reach several kGy per year at 7 TeV and can come close to or reach the BLM limits on these magnets. Risks for long-term operation and quenches must be calculated in detail.

The proposed installation of collimators into the dispersion suppressors will safely intercept these losses and protect the super-conducting magnets.

CONCLUSION

The LHC has seen a quick and worry-free increase of beam intensity at 3.5 TeV. The state-of-the-art in stored energy was quickly surpassed by more than a factor of 10, reaching by now more than 30 MJ. This was achieved without a single quench of a super-conducting magnet due to losses of stored beam. Other colliders were limited with much less stored beam due to beam losses, collimation efficiency and magnet quenches.

The rapid and worry-free increase of LHC beam intensity relies on the "phase 1" of the LHC collimation system that intercepts beam losses reliably and with high efficiency. The collimation performance is helped significantly by the lower beam energy, which results in better efficiency, much larger quench margins, lower collimator-induced impedance and relaxed operational tolerances.

A detailed analysis of performance shows that the "phase 1" of the LHC collimation system performs in fact as designed. The observed cleaning efficiency is fully compatible with detailed design simulations. The predicted residual leakage of protons and ions into the LHC dispersion-suppressors was fully confirmed in location and magnitude. The system behaves as expected.

An attempt was made to extrapolate the performance at 3.5 TeV to higher beam energies. The same model as used for system design and optimization was used. In this model, losses in the LHC dispersion suppressors are predicted to limit the LHC intensity at 7 TeV to something between 5% and 12% of nominal intensity. It is noted that large uncertainties affect these values. They should be taken as indications and cannot serve as firm predictions. Several studies are underway to improve the accuracy of predictions.

The LHC collimation system was the last major LHC sub-system that entered into serious design and construction, as late as 2003. For this reason it was conceived and approved as a phased system. Its "phase 1" was completed in 2009 for initial commissioning and operation. Preparations for the completion of the LHC collimation system started in 2008 and are well advanced by now [12]. The installation of collimators into the dispersion suppressors and second-generation collimators with relaxed operational tolerances will ensure that nominal and ultimate beam intensities and small β^* values can be achieved without facing limitations from collimation.

In summary, the collimation system is neither too good nor too bad. It is the best system that CERN could design, build and install within a very limited time span of 6 years. It performs much better than any such system did before but it has its long-predicted weaknesses. These weaknesses should be addressed and eliminated to ensure that LHC can continue its quick and worry-free increase of beam intensity.

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