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REQUIREMENTS FOR THE LHC COLLIMATION SYSTEM

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Abstract

The LHC requires efficient collimation during all phases of the beam cycle. Collimation plays important roles in prevention of magnet quenches from regular beam diffusion, detection of abnormal beam loss and subsequent beam abort, radiation protection, and passive protection of the superconducting magnets in case of failures. The different roles of collimation and the high beam power in the LHC impose many challenges for the design of the collimation system. In particular, the collimators must be able to withstand the expected particle losses. The requirements for the LHC collimation system are presented.

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Abstract

The LHC requires efficient collimation during all phases of the beam cycle. Collimation plays important roles in prevention of magnet quenches from regular beam diffusion, detection of abnormal beam loss and subsequent beam abort, radiation protection, and passive protection of the super-conducting magnets in case of failures. The different roles of collimation and the high beam power in the LHC impose many challenges for the design of the collimation system. In particular, the collimators must be able to withstand the expected particle losses. The requirements for the LHC collimation system are presented.

1 INTRODUCTION

The Large Hadron Collider LHC [1] at CERN will accelerate proton beams to a beam energy of 7 TeV. The nominal luminosity will be achieved by storing 2808 proton bunches per beam, each populated with $N_p = 1.1 \times 10^{11}$ protons and a normalized emittance of 3.75 μm in both planes. The bunches are separated by 25 ns and leave about 3 μs for a beam abort gap. The rms bunch length is 18.6 cm (0.62 ns) at injection and 8.4 cm (0.28 ns) at top energy.

We introduce the transverse density $\rho_e = E_t/(2\pi\sigma_x\sigma_y)$ of stored energy E_t, the beam energy E_b, and the demagnifications $d_x = \beta_x/\beta_x^*$, $d_y = \beta_y/\beta_y^*$ of the beta functions from the observation point to the IP. In this notation the luminosity L can be written as:

$$L = \rho_e \frac{f_{rev} N_p}{2E_b} \sqrt{d_x d_y} \qquad (1)$$

For a given revolution frequency f_{rev}, luminosity is optimized by increasing the number N_p of protons per bunch, the demagnification at the IP, and the transverse density of stored beam. The latter increases the robustness requirements on collimator materials, as transverse energy density is the most important parameter for material damage.

The transverse density of stored beam energy is shown in Fig 1 for different accelerators or accelerator designs. We note that a transverse energy density of 1 MJ/mm^2 is safely handled at HERA and the Tevatron. The transverse energy density in the LHC at 7 TeV is about 1 GJ/mm^2, three orders of magnitude above the presently achieved levels. This energy must be handled in a mostly super-conducting environment. About 10^{-8} of the total beam power is sufficient to quench a magnet. Strict requirements are imposed on the materials that are closest to the stored beam, namely the collimator jaws in the warm sections. They locally reduce

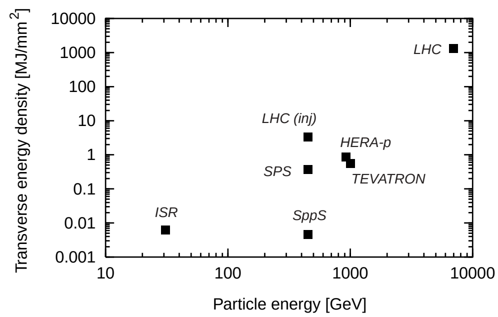

Figure 1: Transverse energy density at the collimators versus beam energy for different proton storage rings.

the full aperture to about 2-4 mm with nominal collimation depth of 6 σ (primary) and 7 σ (secondary). We report on the work of the LHC Beam Cleaning Study Group [2] on specifying the beam-based requirements for the LHC collimation system.

2 REGULAR PROTON LOSSES

Regular proton losses can occur due to beam dynamics (particle diffusion [3], scattering processes, instabilities) or operational variations (orbit, tune, chromaticity changes during ramp [4], squeeze, collision). These losses will be minimized but cannot be avoided completely.

2.1 Beam lifetime and expected power impact

Based on the experience with other accelerators we expect that the beam lifetime during a fill of the LHC can temporarily drop substantially below the normal value. The collimation system should handle increased particle losses, in order to avoid beam aborts and allow for correction of parameters to increase the lifetime. In particular, the range of acceptable lifetime must allow commissioning of the machine and performance tuning in nominal running. For periods of up to 10 s we require that beam lifetimes of 0.1 h (injection) and 0.2 h (top energy) can be accepted. For continuous losses we specify a minimum possible lifetime of 1 h at injection and top energy. For details see [5]. Table 1 summarizes the specified lifetimes and the corresponding maximum power deposition in the cleaning insertion. The collimators should be able to withstand the quoted impact of protons.

Low beam lifetimes can occur due to orbit and optics changes, e.g. during injection, start of ramp, or squeeze. It is therefore reasonable to assume that proton losses can oc-

Mode	T [s]	τ [h]	R_{loss} [p/s]	P_{loss} [kW]
Injection	cont	1.0	0.8×10^{11}	6
	10	0.1	8.6×10^{11}	63
Top energy	cont	1.0	0.8×10^{11}	97
	10	0.2	4.3×10^{11}	487

Table 1: Specified minimum beam lifetimes τ, their duration T, the proton loss rate R_{loss}, and maximum power deposition P_{loss} in the cleaning insertion.

cur locally at one collimator jaw, where they develop into nuclear showers. Power is only to a small extent dissipated in the jaw itself; the downstream elements and the surrounding materials absorb most of the power.

2.2 Running at the quench limit

The LHC foresees two separate two-stage collimation systems which are installed in two warm cleaning insertions for betatron (IP7) and momentum (IP3) collimation [6]. The impacting protons are scattered at the primary collimators (mostly elastic). As part of the secondary beam halo they can then make several hundreds of turns with additional scattering in the primary collimators, until they are finally intercepted at a secondary collimator (inelastic scattering). The protons that escape the secondary collimators populate the tertiary halo. The tertiary halo and a small fraction the secondary halo can be lost in the cold aperture and possibly induce a magnet quench [7]. We assume:

- The nominal cleaning inefficiency η_c is 10^{-3} (ratio between the number of protons that can reach the normalized mechanical aperture at 10 σ and the number of absorbed protons).

- Losses are diluted over $L_{dil} = 50$ m. An accurate determination of L_{dil} remains to be done.

- The quench level R_q at 450 GeV (injection) and for slow, continuous losses is 7×10^8 protons/m/s. For 7 TeV (top) and for slow, continuous losses it is 7.6×10^6 protons/m/s. At top energy additional limits can arise for the heat load in a LHC sector.

The local cleaning inefficiency $\tilde{\eta}_c$ is defined as η_c / L_{dil} and is about 2×10^{-5} m^{-1} for an ideal system. Assuming the minimum required beam lifetimes of 0.2 h at top energy and 0.1 h at injection, the maximum allowed beam intensity can be calculated as a function of local cleaning inefficiency. The result is shown in Figure 2. The design inefficiency allows to go to nominal intensity with a lifetime of 0.2 h. If the LHC operation can always maintain a beam lifetime of at least 1 h then we have a factor of 5 margin in inefficiency. We note that unavoidable imperfections will deteriorate the collimation inefficiency in the LHC, so that a considerable safety margin is required. In [7] we analyze tolerances required for maintaining a good inefficiency, showing that transient beta beating should be below

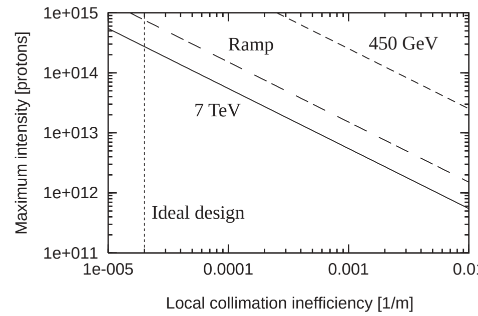

Figure 2: The maximum total intensity is shown as a function of the local collimation inefficiency for injection, top energy, and the start of the ramp. A beam lifetime of 0.2 h at top energy and 0.1 h at injection is assumed. The ideal design inefficiency is indicated.

8%, orbit drifts below 0.6 σ ($\approx$100 μm), collinearity jaw-beam below 50 μrad, and surface flatness about 10-25 μm. The operational procedure for adjusting the settings of the 10 primary and 36 secondary collimators is under study.

2.3 Radiation protection issues

In addition to its other functions, the cleaning insertions collect the radiation deposited from proton losses. For radiation studies it is estimated that about 30% of all stored LHC protons will end in the cleaning insertions. The associated issues in radiation protection have been studied in detail. In particular it has been shown that the warm magnets and other accelerator equipment in the cleaning insertions can withstand the expected radiation [8]. Additional studies are ongoing to estimate the effect of radiation on Beam Position and Beam Loss Monitors in the cleaning regions. The accumulated dose in the collimator tanks and the surrounding shielding is expected to be 1-100 MGy/year. The exchange of collimator jaws will therefore likely require remote or at least fast handling.

3 IRREGULAR PROTON LOSSES

Equipment failures or errors can affect the beam such that part of it can impact on the collimators. In this case it is important that 1) the beam loss is detected and a beam abort is triggered as early as possible and 2) that the collimators can withstand the beam impact without being destroyed or damaged. Effects from different failure modes are described in [5, 9, 10].

3.1 Beam abort trigger for machine protection

Primary proton losses will occur at the collimators if they are at nominal positions. The beam loss at the jaws is continuously monitored. In case an abnormal increase of beam loss signal is detected, a beam abort is initiated and will be completed within 2-3 turns (178-267 μs). In order to ensure the efficiency of this procedure the Beam Loss Monitors in the cleaning insertions must be fully operational at all times, ensuring high sensitivity to proton losses. The expected beam loss signals are being studied, involving details of proton losses, showering, and instrumentation [11].

3.2 Collimator survival

The beam-based requirements for collimator robustness have been analyzed in detail [5, 9]. Due to the high transverse energy density no material can withstand a large fraction of the LHC beam. The collimators should, however, not require frequent replacement. The material choices are presently under investigation with a strong preference for low Z materials.

The most severe requirements are at top energy for abnormal beam dump actions. Two failures have been analyzed: 1) The dump fires not synchronized with the beam abort gap, such that the LHC beam experiences the dump kicker rise time (”asynchronous dump”). 2) A spontaneous trigger of one of the 15 MKD dump kicker modules, followed 1.3 μs later by a re-trigger for the 14 other modules, almost certainly out of phase with the beam abort gap (”single module pre-fire”). The frequency of such failures is difficult to predict. It is assumed that they will happen at least once per year. The maximum beam impact on a primary collimator for the presently assumed MKD performance is shown in Fig. 3. We note that the case of a one module pre-trigger is much more severe than an asynchronous beam dump. The horizontal beam distribution on the collimator jaw is not flat but can be quite varied. The peak impact occurs for a pre-fire of MKD 15 and is about 6 nominal LHC bunches within one σ_x (200 μm), just close to the edge of the collimators. Studies are under way to alleviate the failure scenario of a single module pre-trigger, with the object of reducing the severity to that of an asynchronous dump.

4 CONCLUSION AND OUTLOOK

The LHC will store proton beams with transverse energy densities that are up to three orders of magnitude above the presently achieved values. The handling of this stored energy in a super-conducting environment imposes demanding requirements on the LHC collimation system:

- A beam power impact of up to 500 kW must be accepted for low beam lifetimes, while avoiding collimator deformations on the 10-25 μm level.

- A global cleaning inefficiency of 10^{-3} must be ensured. From preliminary studies we require transient beta beating to be below 8%, orbit drifts to be below 0.6 σ ($\approx$100 μm), collinearity jaw-beam to be below 50 μrad, and surface flatness to be about 10-25 μm.

- The high radiation levels in the cleaning insertions might require remote handling of collimators.

- The Beam Loss Monitors must monitor beam loss with good sensitivity in the high radiation environment of the collimators and reliably initiate beam aborts for irregular proton losses.

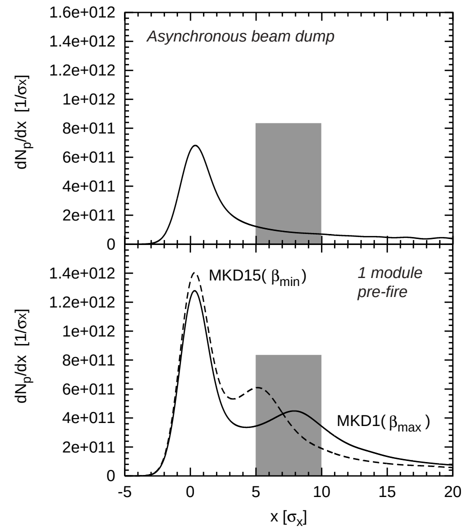

Figure 3: Time integrated horizontal distribution of LHC proton beam downstream of the MKD dump kickers, after an asynchronous beam dump (top) and a single module pre-fire. It is assumed that protons between 5 σ_x and 10 σ_x can impact on a primary collimator (shaded area). The TCDQ element is assumed to intercept beam above 10 σ_x.

- For abnormal beam dump actions, the present design means that a beam impact of up to 20 nominal LHC bunches would have to be accepted in a small rectangular area of about 1 mm (full width) $\times$ 200 μm (rms width). Studies are under way to reduce this figure to about 5 or 6 bunches, i.e. to a level similar to an asynchronous dump.

An activity has been started at CERN to complete the technical and mechanical design of a collimation system, corresponding to these requirements. In parallel further aspects of operation, physics, instrumentation, radiation, control, and integration are being studied.

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