OPTIMIZATION OF THE LHC BEAM CLEANING SYSTEM WITH RESPECT TO BEAM LOSS IN THE HIGH LUMINOSITY INSERTIONS

A.I. Drozhdin and N.V. Mokhov*, Fermilab, P.O. Box 500, Batavia, IL 60510 USA

Abstract

The LHC design performance is achievable only with a dedicated beam cleaning system embedded in the lattice. The effect of the system on the beam loss distribution in the entire machine is studied with emphasis on the two high luminosity insertions. Realistic Monte-Carlo simulations are described, which include a model for beam halo interactions with collimators and other components, multi-turn particle tracking in the lattice, hadronic and electromagnetic shower simulations, and thermal and stress analyses. Methods to mitigate beam-induced effects in the interaction regions at operational and accidental beam loss are proposed, both for injection and collision conditions.

1 INTRODUCTION

The overall accelerator and detector performance at the Large Hadron Collider (LHC) [1] is strongly dependent on the beam loss and background particle rates in machine and detector components [2]. It was shown that the design performance of a high-luminosity collider is achievable only with a dedicated beam cleaning system embedded in the lattice [3, 4, 5, 6, 7]. Selected results on beam loss in the LHC lattice are presented below for various scenarios and beam cleaning system parameters.

2 BEAM LOSS SIMULATIONS

The calculations are based on the assumption of two high-luminosity experiments, ATLAS and CMS, operating simultaneously in the IP1 and IP5 interaction regions, respectively, at the nominal luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ each. An inelastic pp cross section of 80 mb is used, including single diffraction. The calculations are performed for the clockwise 450 GeV proton beam at injection and 7 TeV beam at collisions.

Operational beam loss are simulated taking into account beam-gas scattering using the '97 version of the MARS code [8], pp collisions at IP1 and IP5 using the DPMJET code [9], and interactions of beam halo with primary collimators using the '97 version of the STRUCT code [10]. Consequent multi-turn particle tracking in the full LHC lattice, scoring particles lost at secondary collimators and at all other limiting apertures are performed with the STRUCT code. It is assumed that the beam loss rate in the beam cleaning system is evenly distributed among the two primary collimators (horizontal and vertical) in IP3 and horizontal collimator (momentum cleaning) in IP7, i. e. 10^9 p/s at each of them for each beam. Accidental beam loss are described in detail in the next section.

Starting with the calculated beam loss distributions in the lattice, shower simulations in the components of the beam cleaning system, IRs and arcs are performed with the MARS code taking into account all the lattice details, three-dimensional geometry, material and magnetic field descriptions. At this stage, energy deposition distributions in the machine components and particle fluxes in the CMS and ATLAS detectors are calculated.

3 ACCIDENTAL BEAM LOSS

Prefire of a single module of the abort kicker will result in high-amplitude coherent betatron oscillations of the beam. The disturbed beam can then cause the overheating of an limiting aperture component, a collimator jaw first of all. In the worst case, when abort kicker module prefires just after the longitudinal abort gap, one needs to wait the whole turn to extract the beam. In such a case, collimator overheating can be mitigated via [11]: early abort without synchronization with an abort gap (asynchronous firing of the beam abort kicker) or compensation of the prefired module with a special module with the opposite magnetic field (antikicker). In the second case, the beam abort can be safely delayed until the gap comes, thus eliminating beam loss during the kicker rise time. Beam loss depends on the time between the prefire and the antikicker start.

The collider injection kicker misfire and prefire will result in a coherent betatron oscillation of the injected portion of the beam with pretty large amplitude causing the deleterious effects in lattice components [11].

An asynchronous firing of the beam abort and beam injection kickers will spray the beam across the accelerator aperture. Number of protons sprayed by the abort kicker is equal to $\Delta t/T \times I \approx 10^{13}$, where $\Delta t = 3\mu s$ is a kicker rise time, $T = 89\mu s$ is a revolution time, and $I = 2.8\times10^{14}$ is the beam intensity. About half of this will be sprayed across the abort beam line, and another half will hit a primary collimator. A thin (fraction of radiation length X_0) scattering target, a spoiler of a few X_0 thick, or a thick shadow can be used to protect collimators from overheating. The material of targets, spoilers and shadows must withstand about 5×10^{12} protons at 7 TeV. The instantaneous temperature rise in a $0.42X_0$ thick beryllium, graphite, and even copper and tungsten primary collimator is below the melting point at the nominal size of the circulating beam. Actually, beam size is several times larger because of the beam sweeping across the primary collimator by the kicker. Therefore, the collimators can withstand even higher intensity, i.e., from a thermal standpoint, any of considered materials can be used

* Work supported by the U. S. Department of Energy under contract No. DE-AC02-76CH03000

for targets and primary collimators. From the other hand, no material can withstand the total beam intensity.Further studies of thick spoilers and shadows are needed for specific conditions at injection and beam abort failures.

4 BETATRON CLEANING

A betatron cleaning system is located in IP3. In the collision mode at the nominal luminosity, the rate of protons per beam leaving the stable central core is estimated to be 2.4×10^9 p/s [1]. Slightly more conservative rate of 3×10^9 p/s is assumed in calculations. Proton impact parameter on the primary collimator is of the order of 1μm. Angular distributions of the beam after the primary collimators have angular spread with rms$\sim2\mu$rad, being wider for heavier materials.

Particles pass several times through the primary collimator before being absorbed by it or lost at secondary collimators or other accelerator apertures. At every interaction with a beryllium primary collimator, 25.2% of particles deposit more than 30% of their energy and they are lost in the nearest region downstream of the primary collimator and in the secondary collimators. Corresponding fraction of particles for graphite is 12.6% and for tungsten is 2.3%. Therefore, average number of particle passes through the primary collimator is three times larger for tungsten collimator compared to the beryllium one: 3.25 (Be), 4.55 (C) and 12 (W) passes, respectively.

Although primary and secondary collimators are placed at 6σ and 7σ from the beam axis, correspondingly [1], the tails of halo are extended up to 8σ at injection and up to 7.2σ at the top energy. Large amplitude particles, which escape from the cleaning system, are able to circulate without hitting the aperture in the cold part of the machine, before being captured by the collimators on the later turns. This defines the circulating beam size for the physical aperture calculations.

Calculated beam loss distribution in the LHC IP3 is shown in Fig. 1 for beryllium collimator. Distributions are similar for other collimators, but the rates are higher for heavier materials: maximum beam loss rate in a 14.2 m long superconducting magnet is 4.7×10^5 p/s for beryllium, 7.8×10^5 p/s for graphite and 2.7×10^6 p/s for tungsten. These rates are below the limit for the LHC magnets of $14.2 \times 7\times10^6$ p/s [1].

For the same thickness in units of radiation length ($0.42X_0$), higher rate of inelastic nuclear interactions in beryllium and graphite primary collimators results in increased irradiation of components in the collimation region and at the beginning of the arc downstream of IP3. With tungsten, this irradiation is lower, and significant fraction of outscattered protons is intercepted by the secondary collimators.

5 MOMENTUM CLEANING

A momentum cleaning system is located in IP7. The system consists of one horizontal primary and three secondary

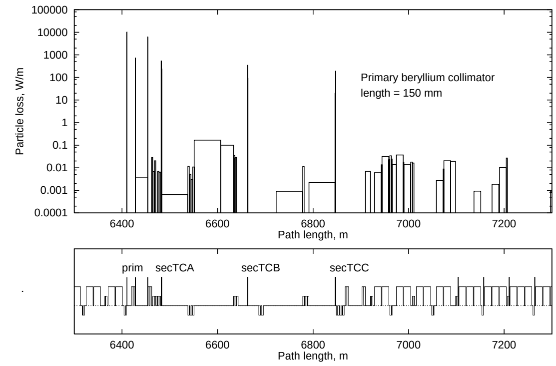

Figure 1: Beam loss distribution in the IP3 beam collimation region at collisions for 150 mm beryllium primary collimator.

collimators positioned similar to the betatron cleaning system. Beam loss distribution at collimation of 10^9 p/s in IP7 with a graphite horizontal primary collimator is shown in Fig. 2 for the entire LHC lattice. The distributions are not very different for other materials of the primary collimators in IP7.

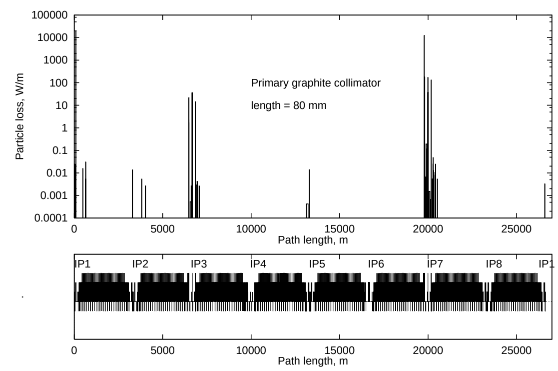

Figure 2: Beam loss distribution in the LHC lattice at momentum cleaning for a 80 mm graphite primary cillimator in IP7.

Figure 3 shows beam loss distributions in IP1 and IP5 for the simultaneous amplitude and momentum cleaning with graphite primary collimators. Total beam loss in IP1 ($26500\leq S\leq26650$ m) is 1.58×10^5 p/s with beryllium, 2.43×10^5 p/s with graphite and 6.17×10^6 p/s with tungsten primary collimators. These are mostly produced by the momentum cleaning system. Total beam loss in IP5 ($13129\leq S\leq13366$ m) is 8.47×10^5 p/s with beryllium, 1.52×10^6 p/s with graphite and 4.21×10^6 p/s with tungsten primary collimators. These are mostly produced by the amplitude cleaning system.

6 BEAM CLEANING AT INJECTION

Even in good operational conditions, about 5% of the beam (1.4×10^{13} particles) can be lost at the beginning of the acceleration ramp during 0.2–1 s. The quench level in the superconducting magnets at injection is estimated to be of the order of 10^{10} p/m [1]. If localized, the above loss can cause additionally a serious problem for cryogenics and for

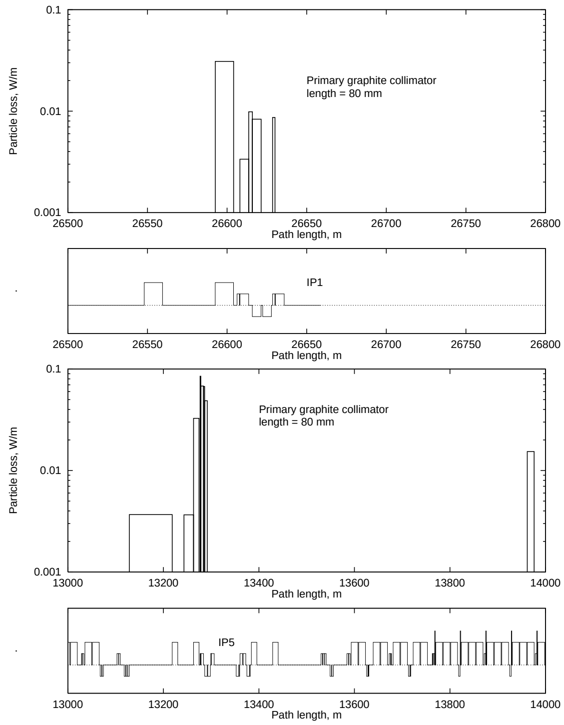

Figure 3: Beam loss distribution in IP1 (top) and IP5 (bottom) at collisions with simultaneous amplitude and momentum cleaning with a 80 mm graphite primary collimators.

the accelerator component lifetime. Experience says that detector components are also experience increased irradiation at injection. Therefore, the interaction regions must be well protected.

Beam loss distribution in the LHC lattice at injection is shown in Figure 4. The interception of 7.0×10^{12} protons during one second by each of the horizontal and vertical primary collimators in IP3 is assumed. The maximum beam loss rate in superconducting magnets is found to be 1.35×10^{9} p/(m·s) with beryllium, 1.86×10^{9} p/(m·s) with graphite and 2.56×10^{9} p/(m·s) with tungsten primary collimators, respectively. These rates are only a few times below the quench level. This can cause a problem if the beam loss rates at injection exceed at some moment the average expected rate. Fortunately, the injection lattice has no high-β region in the vicinity of the interaction regions. Therefore, the beam loss rates at injection are rather low in IP1 and IP5.

7 CONCLUSIONS

Effect of the LHC beam cleaning system operation on the beam induced radiation effects in the entire machine has been studied. Comparison of different materials for primary collimators has shown an advantage of beryllium and graphite compared to tungsten, with almost 10 times lower loss rates in the superconducting magnets. The beam loss with pyrolytic graphite is about 60% larger compared to beryllium, but taking into consideration allignement and

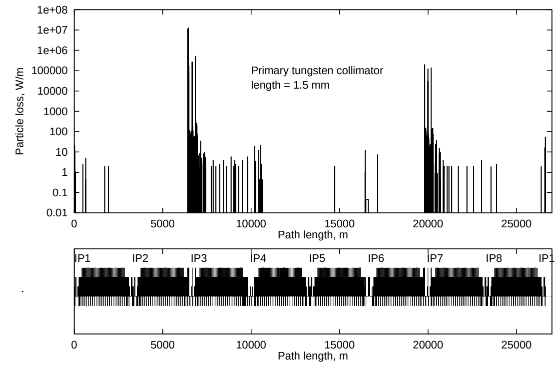

Figure 4: Beam loss distribution in the LHC lattice at injection with a 1.5 mm tungsten primary collimator.

safety issues, pyrolytic graphite seems to be the best material for the LHC primary collimators. The maximum beam loss rate in any single superconducting magnet is below the limit even with tungsten primary collimator. In the IP1 and IP5 high-luminosity insertions, beam loss rates produced by the beam cleaning system contribute about 10% to the total heat load in the inner triplet components, which is dominated by pp collisions. The maximum beam loss at injection, (1.35-2.56)$\times10^{9}$ p/(m·s), is 4 to 7 times below the limit defined in [1].

8 REFERENCES

[1] 'The Large Hadron Collider Conceptual Design', CERN/AC/95-05(LHC), 1995, P. Lefèvre and T. Pettersson, editors.

[2] A.I. Drozhdin, M. Huhtinen and N.V. Mokhov, Nucl. Instr. and Methods, A381, 531, 1996.

[3] L. Burnod and J. B. Jeanneret, 'Beam Losses and Collimation in the LHC: A Quantative Approach', CERN SL/91–39 (EA), LHC Note 167, 1991.

[4] P.J. Bryant, E. Klein, 'The Design of Betatron and Momentum Collimation Systems', CERN SL/92-40 (AP), 1992.

[5] T. Trenkler and J.B. Jeanneret, 'The Principles of Two Stage Betatron and Momentum Collimation in Circular Accelerators', CERN SL/95-03 (AP), LHC Note 312, 1995.

[6] M. Maslov, N. Mokhov and I. Yazynin, 'The SSC Beam Scraper System', SSCL-484, 1991.

[7] A. Drozhdin, N. Mokhov, R. Soundranayagam and J. Tompkins, 'Toward Design of the Collider Beam Collimation System', SSCL-Preprint-555, 1994.

[8] N. V. Mokhov, 'The MARS Code System User Guide, Version 13(95)', Fermilab–FN–628, 1995.

[9] J. Ranft, Phys. Rev., D51, 64, 1995.

[10] I. Baishev, A. Drozhdin and N. Mokhov, 'STRUCT Program User's Reference Manual', SSCL–MAN–0034, 1994.

[11] A. Drozhdin, N. Mokhov and B. Parker, 'Accidental Beam Loss in Superconducting Accelerators: Simulations, Consequences of Accidents and Protective Measures', SSCL-Preprint-556, 1994.