STATUS OF ROBUSTNESS STUDIES FOR THE LHC COLLIMATION

R. Assmann, J.B. Jeanneret, CERN, Geneva, Switzerland
D. Kaltchev, TRIUMF, Vancouver, B.C., Canada

Abstract

The LHC cleaning insertions are required to have an efficiency of better than 10^{-3} in order to avoid spurious quenches of super-conducting magnets. The cleaning efficiency is in general a function of the Twiss functions, the strength of non-linear fields, collimator alignment errors, and beam orbit errors. All of those will be perturbed to some extent during the operational cycle of the LHC with the potential consequence of a reduced cleaning efficiency. Linear and non-linear tracking tools have been developed in the framework of existing LHC tools to estimate the deteriorating effects of the relevant errors and to establish tolerances. The status of this ongoing work is described.

1 INTRODUCTION

The Large Hadron Collider (LHC) requires a total number of 3×10^{14} protons in 2835 bunches for its target luminosity of 10^{34} cm^{-2}s^{-1} [1]. It is an important LHC design issue to ensure safe and reliable handling of the high beam power. A small fraction of the stored beam is sufficient to quench a super-conducting magnet and to interrupt the beam operation [2]. For example, a fast transient beam loss in a super-conducting magnet of 6×10^5 protons per meter within $\approx$10 turns is estimated to cause a quench at 7 TeV. Steady proton losses should be below 6×10^6 p/m/s in order to avoid quenches. Comparing to the total beam intensity, we see that fractional beam losses in the LHC must be controlled on the level of 2×10^{-9} over about 10 turns or on the level of 2×10^{-8} per second. This is far beyond the requirements in previous colliders.

Beam losses in storage rings can be induced from many different sources [3]. The steady rate of beam loss in the LHC was estimated to be about 3×10^9 protons per beam and per second for collisions with nominal parameters [2]. This corresponds to a beam lifetime of about 35 hours, mainly limited due to beam-beam effects. This ”nominal” loss rate is a factor of about 500-1000 above the quench threshold. Two-stage collimator ”cleaning” sections have been designed in IR3 and IR7 for capturing the lost beam [4]. The locations of primary and secondary jaws and their orientations were optimized for best cleaning efficiency [5, 6]. The cleaning efficiency is in general a function of the Twiss functions, the strength of non-linear fields, the collimator alignment errors, and the beam orbit errors [7]. All of those will be perturbed during the operational cycle of the LHC. For example, beta beating might appear during the squeeze of the beta functions in the interaction points.

Beam losses do also occur due to equipment failure. For example, a failure of a magnetic element can perturb the beam orbit and the beam focusing such that a large number of particles is lost in a local aperture restriction. Fast dump systems will be used to protect the machine against different failure scenarios. As the beam in almost all cases first impacts a primary collimator, collimation studies are required to predict the beam loss and its signature in the beam loss monitors downstream of the cleaning section.

2 COLLIMATION SYSTEM

The design of the LHC collimation system has been described in detail elsewhere [5, 6]. In this paper we show tracking examples for the betatron cleaning insertion in IR7. It consists of four primary collimators at normalized angles $0°$, $90°$, $\pm45°$ and 16 secondary collimators. The ”rotation” angle is defined as the angle between the vertical axis and the surface of the planar collimator jaws. Each collimator has two parallel jaws, symmetrically positioned around the beam. The jaws of the primary collimators are made out of Aluminium and have a length of 0.2 m. They are located at $\pm6\ \sigma$ (r.m.s. transverse beam size) in the normalized phase space. The secondary Copper jaws are 0.5 m long and are located at $\pm7\ \sigma$. The cleaning insertions are now included in the LHC sequence and optics version 6.2 [8].

3 SIMULATION TOOLS

The study of the collimation efficiency in presence of errors requires the inclusion of proton scattering in the collimator material into tracking programs.

3.1 Scattering and absorption

Proton scattering is implemented as a callable routine, based on code adapted and modified from the K2 program [9]:

```
COLLIMATE(C_MATERIAL, C_LENGTH, C_ROTATION,
          C_APERTURE, C_OFFSET, C_TILT,
          X, XP, Y, YP, P, S, NP, ENOM, ...)
```

As collimator input we require the material, the length of a jaw, the angle between the jaw and the vertical direction, the distance between the two jaws, an offset with respect to the beam axis, an angle of the jaw surface with the longitudinal direction, and the nominal beam energy. A number

NP of particle coordinates (X, XP, Y, YP, P, S) is passed to the program. The particles are transported through a drift if the jaws are not impacted. In case a particle hits the collimator it is randomly scattered through the material. We include Coulomb and multiple Coulomb scattering, nuclear elastic scattering, proton-nucleon elastic scattering, and proton-nucleus scattering. Depending on the collimator and beam parameters a particle can be randomly absorbed during scattering or it can escape with modified coordinates (in general with large scattering angles). As collimator materials Beryllium, Aluminium, Copper, Tungsten, and Lead are foreseen.

3.2 Beam distribution

The Courant-Snyder invariant describes the beam ellipse in the x,x' phase space (x being the offset and x' the angle). With a beam emittance ϵ_x, and Twiss parameters β_x, α_x, and $\gamma_x = (1+\alpha_x^2)/\beta_x$ the beam ellipse is given as:

$$\gamma_x x^2 + 2\alpha_x x x' + \beta_x {x'}^2 = \epsilon_x \qquad (1)$$

For individual particles we introduce normalized excursions $N_{\sigma x} = |x|/\sigma_x$ and $N_{\sigma y} = |y|/\sigma_y$, with $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y}}$ being the transverse beam sizes. The LHC cleaning insertions cut the phase space above the so called collimation depth C_σ

$$N_{\sigma x}^2 + N_{\sigma y}^2 \geq C_\sigma^2 \qquad (2)$$

with $C_\sigma = 6$ for the primary and $C_\sigma = 7$ for the secondary collimators. A vertical primary collimator cuts all particles with $N_{\sigma y} > 6$. A primary collimator at 45° cuts particles with $N_{\sigma r} > 6$ where $N_{\sigma r}^2 = N_{\sigma x}^2 + N_{\sigma y}^2$. For tracking studies we do generate random particle distributions that cover the phase space from $(C_\sigma - \Delta N)^2\epsilon_x$ to $(C_\sigma + \Delta N)^2\epsilon_x$. The tracking effort can thus be concentrated on the amplitudes of interest. The distribution is uniform in transverse offsets x and y. An example is shown in Figure 1.

3.3 Particle tracking tools

Two different approaches were pursued for tracking. In both cases MAD [10] is used to generate the LHC lattice, the optics, and eventual orbit and focusing errors. MAD output is then used as input for the tracking programs.

As a fast but less complete approach we wrote a program **COLLTRACK** that starts from a file, generated in MAD with the OPTICS command. The Twiss parameters are used to calculate the linear transfer matrices between selected elements (e.g. quadrupoles, markers, collimators). In case the COLLTRACK program finds a collimator, the collimation routine is called. Particles hitting the collimator randomly experience a local scattering or are absorbed. This approach is sufficient for most studies (orbit and focusing errors, failure studies, lumped non-linearities) and is quite fast. As the tracking directly uses the MAD Twiss functions, there is full consistency with MAD. In particular, this allows accurate a priori determination of the collimator settings. Focusing and deflection errors can be added to MAD or superimposed in the tracking. The fast execution speed also enables detailed simulations of beam loss due to magnet failures over thousands of turns.

The COLLTRACK program is limited due to the lack of synchrotron motion, chromatic effects, and distributed coupling and non-linearities. It is therefore complemented by a non-linear tracking tool. The standard LHC tool for estimating the effects from non-linear fields is the **SIXTRACK** program [11] and it was desirable to also use this program for non-linear tracking studies of the LHC collimation efficiency. The program includes non-linear fields, coupling, orbit and focusing errors, synchrotron motion, and chromatic effects to all orders. However, the code had to be adjusted to the needs of our study. Note, that SIXTRACK is mainly targeted at studies of the dynamic aperture, involving 10^5 turns and only a few dozen particles. In contrast, the collimation studies require many particles ($\approx 10^5$) and a few hundred turns. The required changes in the code were implemented and the collimator scattering routine was included. For the time being the collimators must be manually inserted into each new optics description. For the near future we foresee to include collimators into the MAD to SIXTRACK conversion.

4 FIRST STUDIES

The first performance studies were done for the collision optics at 7 TeV, a round geometrical emittance of 0.5 nm, and tunes $Q_x = 64.31$, $Q_y = 59.32$. Figure 1 shows the vertical phase space as tracked for 101 turns and without collimation. The phase space ellipse is preserved during linear tracking, except a rotation from the vertical phase advance.

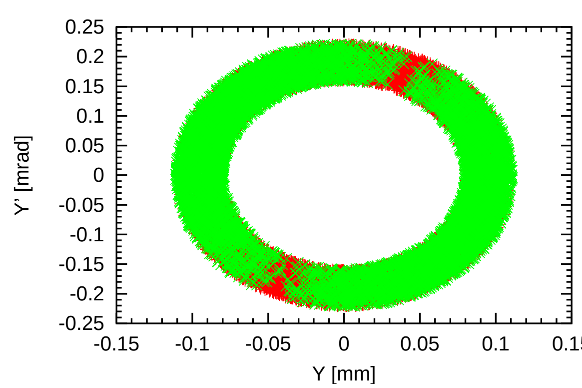

Figure 1: Vertical phase space distribution as generated (bottom layer) and after tracking through 101 turns (top layer).

4.1 Phase space reduction due to collimation

Generating a particle distribution from $N_{\sigma y} = 4$ to $N_{\sigma y} = 8$ in phase space, the effect of the collimation can be illustrated. The vertical phase space is shown in Figure 2 for the initial distribution and after 1, 5, and 50 turns, including the effects of the betatron cleaning in IR7. After 1 turn the cuts in phase space from the secondary collimators at $N_{\sigma r} = 7$ are clearly visible. The secondary collimators absorb about 97% of the particles, while the primary collimators absorb only 30%. Note, that some particles escape the secondary collimators with large scattering amplitudes. After 5 turns particles above $N_{\sigma r} = 7$ are mostly suppressed. The phase space is reduced to $N_{\sigma r} \approx 6$ during the next 45 turns with scattering at primary collimators and subsequent absorption at the secondary collimators. This is seen after 50 turns.

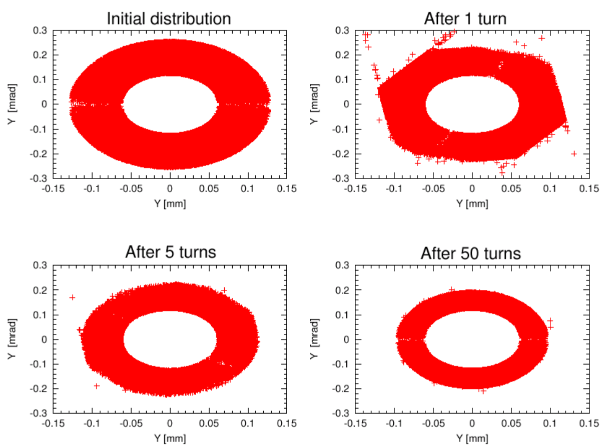

Figure 2: Vertical phase space distribution as generated and after tracking through 1, 5, and 50 LHC turns. Betatron collimation is included.

4.2 *Realistic impact parameters*

The beam halo in the LHC will slowly drift towards the collimators. About 120,000 protons impact the primary betatron collimators every turn with impact parameters of about 1 μm. A phase space distribution with a proper impact parameter was generated. The phase space distribution is shown in Figure 3 before collimation and after 1 and 2 turns. In this simulation 27806 particles impacted on the primary collimator TCP.D6L7.B1 with 18845 particles escaping the jaws. The impact parameter (distance to the collimator edge) is shown in Figure 4 for scattered and absorbed particles. Particles that intercept the jaw on its inner face (due to the particle angle) have been assigned a zero impact parameter. We find impact parameters between zero and 1.2 μm.

4.3 *Particle survival and collimation efficiency*

The particles that impacted and escaped TCP.D6L7.B1 were tracked on for 200 turns. The fraction of surviving particles is shown in Figure 5 versus turn number. More than half the number of particles are absorbed after 12 turns. On the other side 0.5% of the particles survive for 200 turns. Those are mostly particles with amplitudes $6 < N_{\sigma y} < 7$. The secondary halo is mainly at $6 < N_{\sigma r} < 7$, the tertiary halo at $N_{\sigma r} > 7$. Figure 6 shows the fraction of surviving particles for the secondary and tertiary halos.

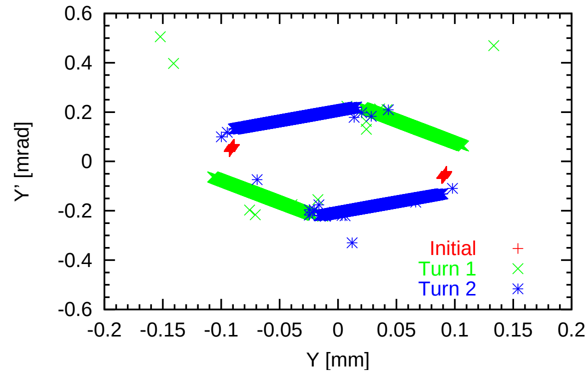

Figure 3: Phase space distribution of the impacting particles, before collimation (initial) and after 1 and 2 turns. Note the large amplitude particles that belong to the tertiary halo.

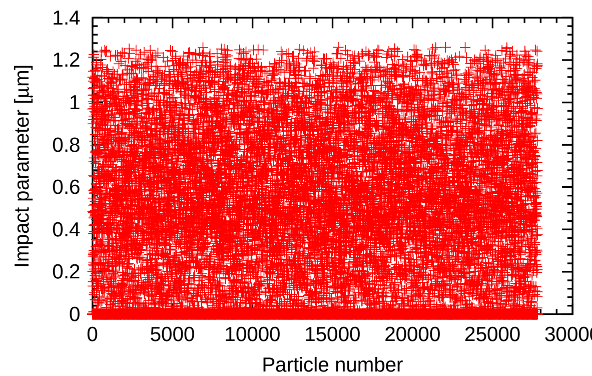

Figure 4: Impact parameter for Figure 3.

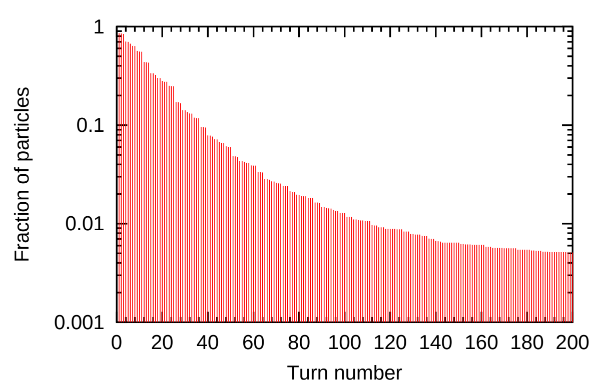

Figure 5: Fraction of escaping particles versus the number of turns.

We define the cleaning inefficiency as the integrated number of particles with $N_{\sigma y} > 8$ divided by the total

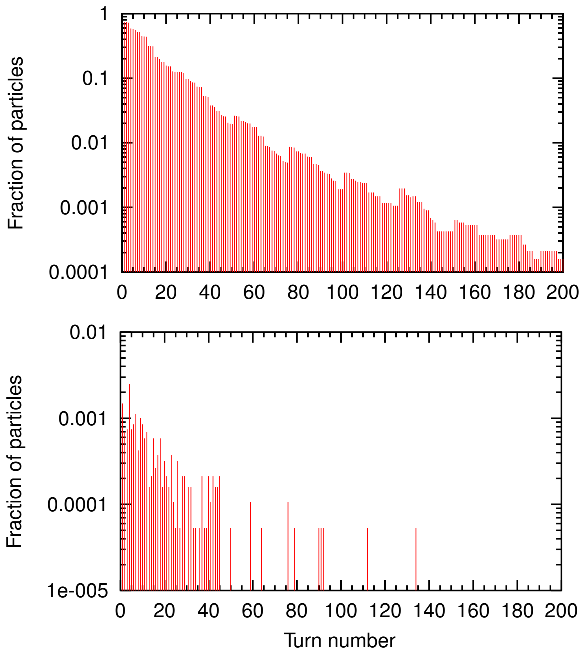

Figure 6: Fractional population versus surviving turn number for $6 < N_{\sigma y} < 7$ (top) and $N_{\sigma y} > 7$ (bottom).

number of scattered particles (27806 in the above case). The so defined cleaning inefficiency is 0.6×10^{-3} for our example. This refers only to amplitudes in vertical phase space, as they were used in Figure 6. In the general case the amplitude in the radial direction must be considered. Note that the scattered particles receive large deflections in the collimator jaws, both in horizontal and vertical directions. Calculating the cleaning inefficiency with the full radial amplitudes, we find a value of 4.4×10^{-3} for $N_{\sigma r} > 8$. The cleaning inefficiency is shown in Figure 7 for different amplitudes in the phase space.

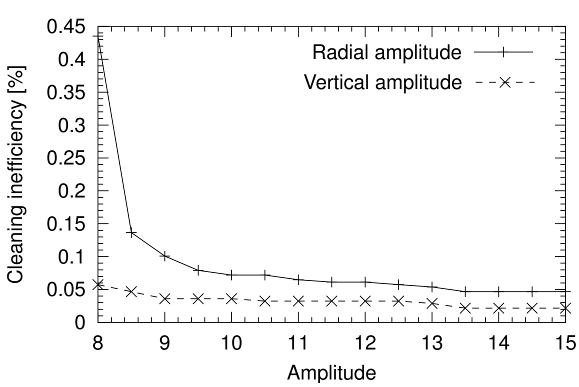

Figure 7: Cleaning inefficiency as a function of amplitude for 200 turns. The cleaning inefficiency was calculated with for both vertical and radial amplitudes.

4.4 *Effect from beta beating*

As an example case for a robustness check we studied the effect of beta beating on the cleaning inefficiency. A beta beating with twice the betatron frequency was induced in the IR7 cleaning insertion. An example of a 10% vertical beta beating is shown in Figure 8. We consider an artificially created beta beating that is implemented as a variation of the collimation depth instead of a variation in beam beta function. This is justified, as the major effect of the beta beating on the collimation system is indeed the modulation of the collimation depth around its nominal value. We could also use realistic beta beating scenarios, as generated with MAD. For this early stage, however, it proves beneficial to introduce a phase-controllable beta beating in the described way.

The simulated case addresses the change of cleaning inefficiency due to a change in beta beating. We assume that the beta beating appears on a time scale that prevents re-optimization of the collimation system (for example during the squeeze). The predicted change in cleaning inefficiency is shown in Figure 9 for different values of beta beating. The cleaning inefficiency is only slightly worse for a beta beating of 10%. For 15% beta beating, however, we observe that the cleaning inefficiency almost triples for $N_{\sigma_r} > 10$. This suggests a tolerance for beta beating close to 10%, in good agreement with earlier estimates [7].

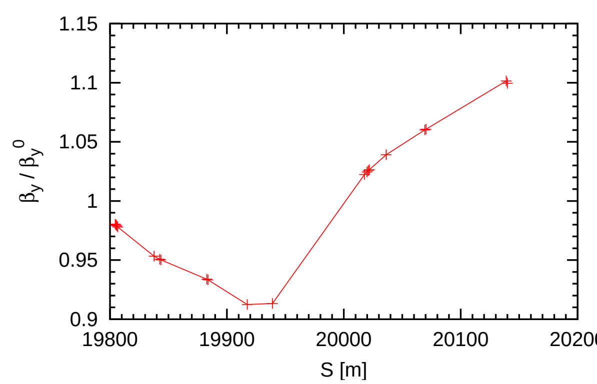

Figure 8: Example of a 10% vertical beta beating in the IR7 betatron cleaning insertion.

4.5 *Non-linear tracking with collimation*

The LHC collimation system was implemented into Sixtrack and particle distributions were tracked with collimation for the injection optics and for one seed of non-linear fields. At the present time it is too early to present results from this study.

5 CONCLUSION

The scattering of protons in the LHC collimation system has been implemented in a new tracking program COLLTRACK and the non-linear SIXTRACK code. The new

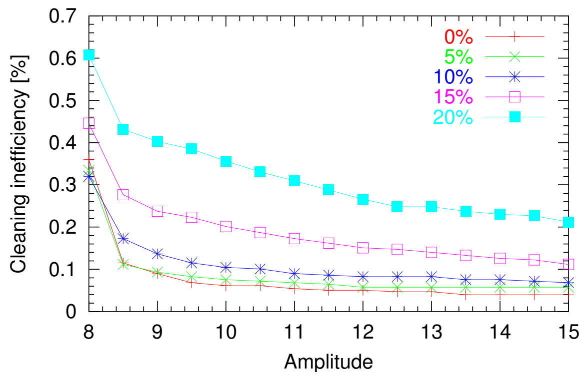

Figure 9: Cleaning inefficiency as a function of radial amplitude, based on a simulations of 20 turns. The curves correspond to different levels of vertical betatron beating with 0% as the nominal collision optics.

tools allow the study of collimation efficiency for the perfect and imperfect LHC. The implemented routines were verified with some simple example cases, reproducing the general results and the predicted cleaning efficiencies from earlier semi-analytical studies. In particular, a clear estimate for cleaning efficiency is provided as output of the computer programs. As a first example for the impact of errors, the deterioration of cleaning efficiency was studied for different levels of beta beating.

A multitude of errors can now be studied in the context of LHC cleaning and beam loss problems: Optical and orbit errors, collimator misalignments, non-linear fields, and magnet failures. Future studies will aim at establishing detailed tolerances for the different sources of imperfections. The new tools will also be used for studying the beam loss signature of transient effects, like fast equipment failures.

6 ACKNOWLEDGEMENTS

The authors express their gratitude to F. Schmidt for his help in modifying the sixtrack program. H. Grote, M. Hayes, J. Jowett, and E. Wildner helped in the MAD part of the simulations. We thank H. Burkhardt, O. Brüning, B. Dehning, W. Herr, H. Schmickler, and R. Schmidt for useful discussions.

7 REFERENCES

[1] The Large Hadron Collider, CERN/AC/95-05(LHC),1995.

[2] J.B. Jeanneret, ”Handling the proton beams above the quench threshold”. Proc. Chamonix X, CERN SL 2000-007 DI, R. Le Roux et al. Eds, February 2000, p. 162.

[3] H. Burkhardt, ”Beam Lifetime and Beam Tails in LEP”. Proc. Int. Workshop on Performance in Improvement of Electron-Positron Collider Particle Factories, Tsukuba, Japan, 21-24 Sep 1999. CERN-SL-99-061-AP.

[4] J.B. Jeanneret, ”Optics of a Two-Stage Collimation System”. Phys. Rev. ST-AB, **1**,081001, 1998, and CERN LHC Project Report 243, 1997.

[5] D.I. Kaltchev et al., ”Optimization of Collimator Jaw Locations for the LHC”. LHC Project Report 37.

[6] D.I. Kaltchev et al., ”Numerical Optimization of Collimator Jaw Orientations and Locations in the LHC”. LHC Project Report 134.

[7] D.I. Kaltchev et al., ”Initial Error Analysis for the Collimation Insertion of LHC”. LHC Project Report 304.

[8] LHC optics version 6.2.

[9] N. Catalan Lasheras, G. Ferioli, J. B. Jeanneret, R. Jung, D. I. Kaltchev and T. Trenkler, Proc. of the Symp. ’Near Beam Physics’, Fermilab, 1997, edited by D. Carrigan and N. Mokhov, p. 117 and CERN LHC Project Report 156, 1998.

[10] H. Grote and F.C. Iselin, ”The MAD program”, CERN/SL/90-13(AP),1995.

[11] F. Schmidt, ”SIXTRACK version 1.2: Users Reference Manual”. CERN-SL-94-56-AP.