# FIRST CLEANING WITH LHC COLLIMATORS

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*Abstract*

The LHC has two dedicated cleaning insertions: IR3 for momentum cleaning and IR7 for betatron cleaning. The collimation system has been specified and built with tight mechanical tolerances (e.g. jaw flatness $\sim 40\,\mu\mathrm{m}$ ) and is designed to achieve a high accuracy and reproducibility of the jaw positions ($\sim 20\,\mu$m). The practically achievable cleaning efficiency of the present Phase-I system depends on the precision of the jaw centering around the beam, the accuracy of the gap size and the jaw parallelism against the beam. The reproducibility and stability of the collimation system is important to avoid the frequent repetition of beam based alignment which is currently a lengthy procedure.
Within this paper we describe the method used for the beam based alignment of the LHC collimation system, its achieved accuracy and stability and its performance at 450 GeV.

## INTRODUCTION

The LHC collimation system was designed to handle the 362 MJ stored energy per beam at nominal momentum (7 $\mathrm{TeV/c}$) and intensity ($\sim 3 \cdot 10^{14}$ protons). The uncontrolled loss of only a small fraction of a beam in the superconductive magnets of the LHC can cause the loss of their superconducting state (quench limit at 450 GeV/c: $R_q = 7 \cdot 10^8\,\mathrm{ps^{-1}m^{-1}}$; at 7 TeV/c: $R_q = 7.6 \cdot 10^6\,\mathrm{ps^{-1}m^{-1}}$ ) [1, 2]. The collimators are designed to intercept these unavoidable beam losses and are mainly installed in two dedicated cleaning insertions. IR3 collimators are used for the cleaning of off-momentum particles and IR7 to intercept particles with too large betatron amplitudes. In addition the collimators provide a passive machine protection [3, 4, 5]. Figure 1 shows a simplified sketch of the gap opening arrangement of the different classes of collimators normalized by beam size. The primary collimators (TCPs) are the ones closest to the beam and cut the primary beam halo. The secondaries (TCSGs) intercept the secondary halo, i.e. particles scattered by the primaries, and absorbers (TCLAs) catch showers produced by the other

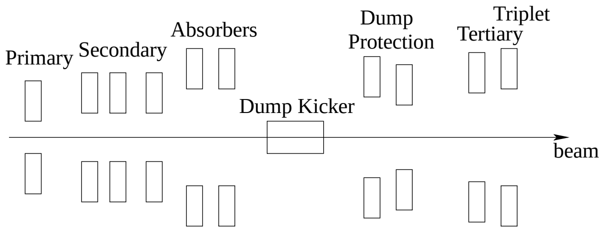



Figure 1: Simplified sketch of the gap opening arrangement of collimator classes normalized by beam size.

| Collimator type | $N_i$ | Collimator type | $N_i$ |
|---|---|---|---|
| TCP IR3 | 8 | TCDQ IR6 | 8 |
| TCSG IR3 | 9.3 | TCSG IR6 | 7 |
| TCLA IR3 | 10 | TCLI IR2/IR8 | 6.8 |
| TCP IR7 | 5.7 | TCT IR2/IR8 | 25 |
| TCSG IR7 | 6.7 | TCT IR1/IR5 | 15 |
| TCLA IR7 | 10 | TCL IR1 | 20 |

Table 1: Half gap openings $N_i$ for different collimator families. The half gap in mm is calculated by $N_i\sigma_i$, with the measured beam size $\sigma_i$ [8].

collimators at the end of each cleaning insertion. The dump protection collimators (TCSG-IR6, TCDQs) protect the superconductive arcs against mis-kicked beams. The tertiary collimators (TCTs) are arranged around the experimental insertions, to catch the debris during collisions and to protect the triplets against mis-kicked beams [6, 7].

Setup procedures and settings for the LHC collimators have been studied intensively and the settings for the different collimator families at injection (450 GeV/c), as shown in table 1, were verified by tracking simulations [8, 9, 10]. The complete phase-I collimation system was successfully tested and commissioned before the restart of the LHC at the end of 2009.

## SETUP AT 450GEV

Two beam based setups of the collimation system at injection momentum (450 GeV/c) were performed during the current 2010 LHC run. The goal of the beam based alignment of the collimators was thereby to determin the local

center ($\Delta x_i$) and size ($\sigma_i$) of the beam at each collimator. This is essentiel to achieve a setup of the collimation system, which respects the desired collimator hierarchy.
During both setups the collimators in B1 and B2 were treated in parallel. About 42 collimators per beam were set up, including the injection and dump protection devices installed in the ring. Beam intensities during the setups were $\sim 5 \cdot 10^9$ and $\sim 1 \cdot 10^{11}$ protons. Collimator jaws were moved with a stepsize of $100\,\mu$m and $40\,\mu$m respectively.

### *Setup procedures*

In the first setup, reference edges in the horizontal and vertical plane of the beam halo were generated by closing the final two tertiary absorbers (TCLAs) in IR7 to a half gap of $N_0 \cdot \sigma_i^n$, with $N_0 = 4.5$. The nominal beam size $\sigma_i^n$ in the collimator plane (hor, ver or skew) was derived from the nominal geometrical emittance, $\epsilon$, the nominal beta functions, $\beta_{x,i}$ and $\beta_{y,i}$, at collimator $i$ and the rotation angle of the collimator jaws $\psi_i$ by

$$\sigma_i^n = \sqrt{\beta_{x,i}\epsilon \cos^2 \psi_i + \beta_{y,i}\epsilon \sin^2 \psi_i}. \quad (1)$$

The remaining collimators were then moved one by one in reverse order - as seen from the beam - to the edge of the beam halo and centered. The two collimator jaws - called left (L) and right (R) - were then set to

$$x_i^{L,set} = N_i \cdot \sigma_i + \Delta x_i \quad (2)$$

and

$$x_i^{R,set} = -N_i \cdot \sigma_i + \Delta x_i, \quad (3)$$

with the measured beam size

$$\sigma_i = \frac{x_i^{L,m} - x_i^{R,m}}{N_0} \quad (4)$$

and beam center

$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2}. \quad (5)$$

$x_i^{L,m}$ and $x_i^{R,m}$ were the measured positions of the centered collimator jaws. $N_i$ was chosen depending on the collimator type as given in table 1.

For setup-II a refined method was used. The reference beam edge was defined by the primary collimators of the corresponding plane in IR7. After each centering of a collimator the reference primary was re-centered around the beam. The measured beam size was therefore achieved as

$$\sigma_i = \frac{x_i^{L,m} - x_i^{R,m}}{(N_0^{k-1} + N_0^{k+1})/2}, \quad (6)$$

with the half gap opening of the reference primary in units of $\sigma_{tcp}^n$ before ($N_0^{k-1}$) and after ($N_0^{k+1}$) the centering of collimator $i$. The jaws were then set following equations (2) and (3).

### *Setup Results*

An overview of the ratios between measured and expected beam sizes for the collimators in IR7 and both setups is shown in figure 2. The beam sizes found during

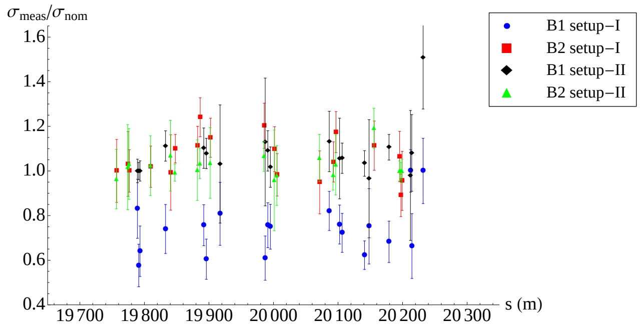


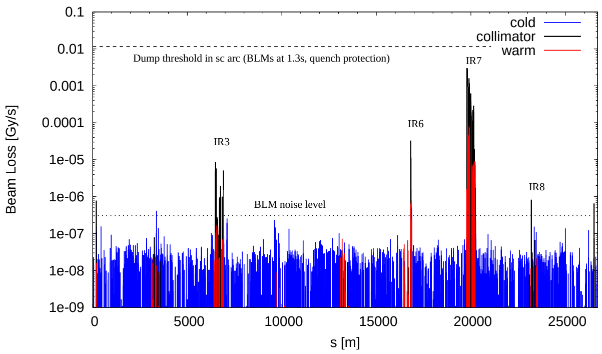

Figure 2: Ratio between nominal beam sizes and beam sizes found during the collimation setups at collimators in IR7.

setup-I for B1 were at most locations smaller than expected. The ratio between measured and expected beam size varied from $\sim$ 0.5 to $\sim$ 1.0. The average beam size found at the collimators in B1 during the setup was $\sim 0.74\sigma_i^n$. In B2 the ratios between found and expected beam sizes vary from $\sim 0.9$ to $\sim 1.4$. The average beam size at the collimators in B2 was $\sim 1.04\sigma_i^n$. This behaviour cannot only be explained by beta beating, which was corrected to $\leq 20\%$ [11] before the setup of the collimation system. The reason was that, due to the low beam intensity, the halo is not repopulated fast enough during the setup. In this case each collimator cuts deeper into the halo. The assumption that the beam edge was defined by the tertiary absorbers set at the beginning of setup-I then does not hold any longer. For B2 a second effect has to be considered: during the setup a periodical excitation of the beam was observed, which was much stronger in B2 than in B1. This excitation may have increased the re-population rate of the beam halo periodically. This lead to overall bigger beam sizes for B2 as compared to B1.

The beam sizes found in both beams during setup-II were in general in good agreement with the expected beam sizes (see figure 2), except for the collimators in IR3. The average beam size was $\sim 1.2\sigma_i^n$ for B1 and $\sim 1.14\sigma_i^n$ for B2. The comparison between setup-I and setup-II shows clearly that the variation of the ratio between measured and expected beam size was lower for the latter, where both beams show a comparable behaviour. Therefore, the refined setup procedure is more independent of beam properties like the re-population speed of the beam halo and therefore gives better results.

## SUMMARY OF SETUP VALIDATION

The settings found during each setup were validated by generating multi-turn losses. The full beam was thereby lost in about 1 to 2 seconds. Figure 3 shows, as examples, horizontal betatron losses generated by crossing a 1/3 integer tune resonance for B1 with the settings of setup-I (top) and II (bottom). The highest losses were found in the cleaning insertions and at primary collimators. The loss pattern show that the hierarchies of collimators are preserved.



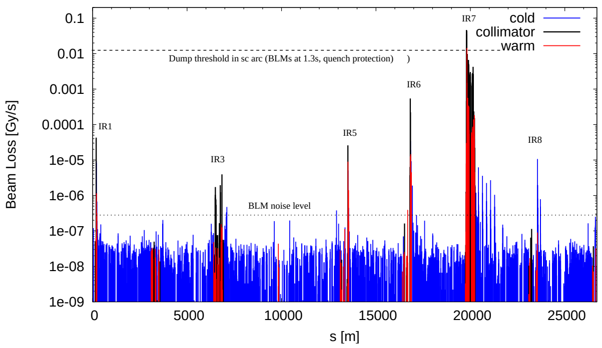




Figure 3: Horizontal betatron losses in B1 generated by crossing a 1/3 integer tune resonance. Blue/red/black bars indicate losses in the cold aperture/ warm aperture / collimators. The noise level of the beam loss monitor signals shown in the plot is $\sim 3 \cdot 10^{-7}\,\mathrm{Gy/s}$ [12]. Top: setup-I; Bottom: setup-II

The highest loss signal in the cold arperture for setup-I was $\sim 4 \cdot 10^{-7}\,\mathrm{Gy/s}$. This is a factor 28000 below the dump threshold defined to protect the superconductive (sc) magnets against quenching ($1.19 \cdot 10^{-2}\,\mathrm{Gy/s}$). As about $5 \cdot 10^{9}$ protons were lost during this experiment, the intensity limit for this setup is $\sim 1.4 \cdot 10^{14}$ protons. For setup-II the highest losses in the sc aperture, generated by a overall loss of about $5 \cdot 10^{10}$ protons, were a factor of 1200 below the BLM dump threshold. This results in an intensity limit of $6 \cdot 10^{13}$ protons.

The settings achieved during setup-I were validated regularly by multi-turn losses and are currently in use for injection momentum and low beam intensities ($< 10^{11} p$).

Table 2 gives an overview of the local cleaning inefficiency

$$\eta_j = \frac{L_j}{L_{tcp}} \qquad (7)$$

for the location with the highest losses in the cold aperture. $L_j$ are the losses in Gy/s at location $j$ and $L_{tcp}$ the highest losses at a primary collimator in Gy/s. This definition of the local cleaning inefficiency clearly assumes, that one proton lost in a collimator or somewhere in the aperture gives a comparable signal in the beam loss monitors (BLMs).

The highest cleaning inefficiency in the cold aperture for

| | sim [1/m] | setup-I | setup-II |
|---|---|---|---|
| B1 hor | 2e-4 | 2e-4 | 1.8e-4 |
| B1 ver | 5e-5 | 2.5e-3 | 3.2e-5 |
| B2 hor | 1e-4 | 2e-4 | 1.8e-4 |
| B2 ver | 2e-5 | 2.5e-3 | 1.4e-5 |

Table 2: Local cleaning inefficiency $\eta_j$ for betatron losses to the cold aperture (simulations [8] and measurements). The primary collimator with the highest losses in IR7 were used as reference. Only beam loss monitor signals above the noise level of $\sim 3 \cdot 10^{-7}\,\mathrm{Gy/s}$ [12] were taken into account.

setup-I was measured during vertical betatron losses in B2 as $\eta = 2.5 \cdot 10^{-3}$, i.e. the cleaning efficiency for this setup was better than 0.9975. For setup-II the highest leakage into the cold aperture was measured during horizontal betatron losses as $\eta = 1.8 \cdot 10^{-4}$, i.e. the cleaning efficiency was better than 0.99982.

The cleaning inefficiencies achieved during the validation of setup-II were very close to the values predicted in tracking simulations. For setup-I this is only true for losses in the horizontal plane. The vertical plane is about two orders of magnitude worse than expected.

Setups for the collimation system at 3.5 TeV are currently ongoing and their results will be presented in a later publication.

## REFERENCES


[1] R.W. Assmann et al. Requirements for the LHC Collimation System. In *Proceedings of EPAC 2002*.

[2] J.B. Jeanneret et al. LHC Project Report 44, CERN, 1996. Technical report.

[3] R.W. Assmann. Collimators and Beam Absorbers for Cleaning and Machine Protection. In *LHC Project Workshop - 'Chamonix XIV'*, pages 261–267, 2005.

[4] The LHC design report, Vol. Chapter 2. Technical report, CERN, 2004-003.

[5] The LHC design report, Vol. Chapter 18. Technical report, CERN, 2004-003.

[6] R.W. Assmann et al. The Final Collimation System for the LHC. In *Proceedings of EPAC 2006*.

[7] A. Bertarelli et al. The Mechanical Design for the LHC Collimators. In *Proceedings of EPAC 2004*.

[8] G. Robert-Demolaize. *Design and Performance Optimization of the LHC Collimation System*. Cern-thesis-2006-069, Universite Joseph Fourier, Grenoble, 2006.

[9] R.W. Assmann. Operational Experience with LHC Collimation. In *Proceedings of PAC 2009*.

[10] C. Bracco. *Commissioning Scenarios and Tests for the LHC Collimation System*. PhD thesis, Ecole Polytechnique Federale de Lausanne, 2009. These No 4271.

[11] R. Tomas. LHC Optics Model Measurements and Corrections. In *this proceedings*. TUXMH02.

[12] privat communication with A. Nordt and B. Dehning.