COMPARISON OF LHC BEAM LOSS MAPS USING THE TRANSVERSE DAMPER BLOW UP AND TUNE RESONANCE CROSSING METHODS

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Abstract

The LHC collimator settings are qualified regularly via beam loss maps. In this procedure, the beam is artificially excited to create abnormal loss rates. The transverse damper blow up and tune resonance crossing methods are used to increase the betatron amplitude of particles and verify the efficiency of the collimation cleaning and the collimator hierarchy. This paper presents a quantitative comparison of the methods, based on measurements done at different phases of the LHC machine cycle. The analysis is done using Beam Loss Monitor (BLM) with integration times of 1.3 s and 80 ms. The use of the faster BLM data to study the time evolution of the losses in IR3 and IR7 during off-momentum loss maps is also presented.

INTRODUCTION AND BACKGROUND

The collimator settings at the Large Hadron Collider (LHC) must be regularly validated in order to ensure the cleaning and machine protection functionality of this critical system [1]. Here, the basic concepts are introduced.

Collimation Settings and Cleaning

Beam collimation is required to reduce the transverse spatial distribution of the beam halo, in order to keep losses to sensitive elements around the ring to acceptable levels. The LHC collimation system consists of different types of devices. Primary (TCP) and secondary (TCSG) collimators and long absorbers (TCLAs) in IR7 (betatron cleaning) and IR3 (momentum cleaning) as well as tertiary (TCT) collimators in the insertion regions will be considered in this paper. Table 1 shows the collimator settings in different beam modes during the 2012 operation for these collimator types. The beam modes are discussed in [2].

The local cleaning inefficiency of the collimation system is defined as the ratio of local losses over the losses at the primary collimators. This can be approximated by the ratio between the BLM signal at any element of the ring and the highest peak loss at the primary collimator(s). The cleaning of the collimation system is typically well below 0.001. In order to measure it accurately, significant beam loss rates at the primary collimators are required. This can be achieved in controlled ways with various techniques, by measuring beam losses around the ring.

Beam Loss Monitors

A total of 3557 Beam Loss Monitors (BLMs) detect losses at the LHC ring for 12 different integration times ("Running Sums", RSs, from 40 μs - RS01 - to 84 s - RS12) [4]. Losses are measured with ionization chambers that are situated close to the various lattice elements (cold magnets, collimators, warm magnets, etc.) intercepting the secondary showers created by local primary beam losses. The BLM signal is centrally logged at the rate of 1 Hz. For this analysis we used in addition a dedicated logging of the ~ 82 ms signals at the rate of ~ 12 Hz. The BLMs have a background noise of 10^{-8} to 10^{-6} [Gy/s] that is subtracted from the measured signal. This is to avoid noise in the acquisition chain or offsets from background beam losses that might increase the noise.

Table 1: Collimator Settings expressed in Beam Size Units assuming 3.5 μm rad Normalized Emittance [3]

Settings [σ]	Injection	Squeezed	Colliding
Primary IR7	5.7	4.3	4.3
Secondary IR7	6.7	6.3	6.3
Tertiary IR7	10.0	8.3	8.3
Primary IR3	8.0	12.0	12.0
Secondary IR3	9.3	15.6	15.6
Tertiary IR3	10.0	17.6	17.6
Tertiary IR1 & 5	13.0	26.0	9.0
Tertiary IR2 & 8	13.0	26.0	12.0

Loss Maps

A "loss map" is simply defined as a beam loss profile at a given time as a function of the longitudinal coordinate around the ring, s. For the scope of this paper, the "loss map" label refers to validation tests of the collimation system where the beams are excited artificially in order to create larger loss rates that are sufficient to measure the collimation cleaning. At 4 TeV, this is done in dedicated low intensity fills with up to 3 nominal bunches. In order to validate the settings of IR7 and IR3, betatron and off-momentum are needed respectively. Three types of loss maps have been used at the LHC, as two methods are available for the betatron cases:

- **Tune resonance (QT) loss maps** are generated by moving the tune across a third order resonance. The tune shift is shown in Fig. 1 for loss maps done first in the horizontal (H) plane and then the vertical (V) plane. Tune changes affect all beam bunches, so with this method the results for the second excited plane might be affected by the fact that the beam is already blown up on the other plane. Also note that the total amount of beam lost is not well controlled.

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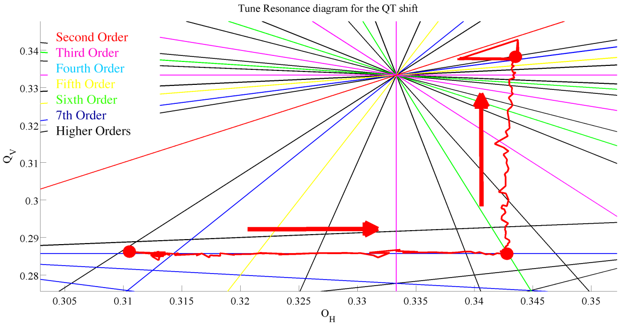

Figure 1: Tune shift during one of the 2012 resonance loss maps. Red trace indicates movement of tune.

- **Transverse damper (ADT) loss maps** are created by adding white noise to the beam. After the development of a bandwidth increase, it became possible to target individual bunches in the train [5, 6], allowing ADT loss maps at top energy with full circulating beam [7]. By using two distinct bunches for the 2 planes, one avoids the cross talk problem of the QT method. The intensity losses can also be controlled precisely.
- **Momentum offset (MO) loss maps** are created by changing the RF frequency, increasing or decreasing to generate both off-momentum sides. When the energy is changed the beam orbit changes and the beam is lost at the primary collimators of IR3.

RESULTS

A subset of the loss maps performed in 2012 is used for the comparison between tune resonance and ADT methods. The inject loss maps were performed in the same dedicated fill whereas the cases at 4 TeV (squeeze and adjust modes) are done in different fills.

Comparison of ADT & Tune Resonance Methods

The cleaning inefficiency of ADT and QT methods was compared at injection and at 4 TeV, using the 1 Hz BLM data at 4 cold magnet BLMs downstream of IP7 (MQx), 4 monitors on collimators and absorbers of IP7 (TCP7, TCSG7, TCHS7[1] and TCLA7), a secondary collimator monitor in IP6 (TCSG6) and a tertiary collimator monitor in IP2 (TCTH). At the end of the ramp, the TCTs sit at 26 σ and are only moved to the settings of Table 1 by the squeeze end. There are essentially no losses at the TCTs at the end of the ramp. Therefore, ADT and QT methods are compared by using loss maps performed in the modes squeeze end adjust, i.e. with squeezed optics before and after establishing collisions. Differences between these two modes at non-colliding IPs must thus be solely dependent on the loss map method.

Figure 2 shows the cleaning at the selected BLMs during a loss map with ADT (green) and QT (yellow). The ratios of BLM signals at the given elements over the TCP losses are shown. For horizontal losses the cleaning is within the measurement uncertainty. However, for the vertical losses, we observed slightly different losses at the collimators in IR7. As losses are higher with the QT method, this feature could be explained by the fact that the beam was already blown up horizontally. Differences are in any case small and do not affect the measured cleaning performance significantly at the cold limiting locations.

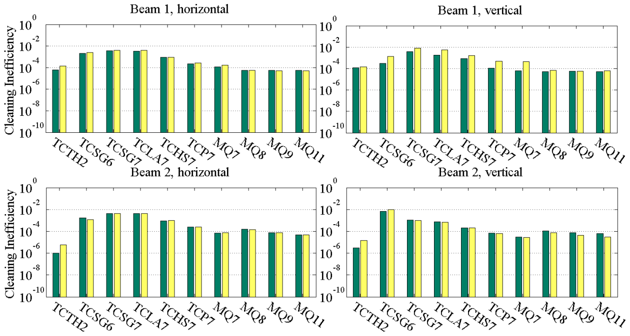

Figure 2: Comparison of selected BLMs at 4 TeV.

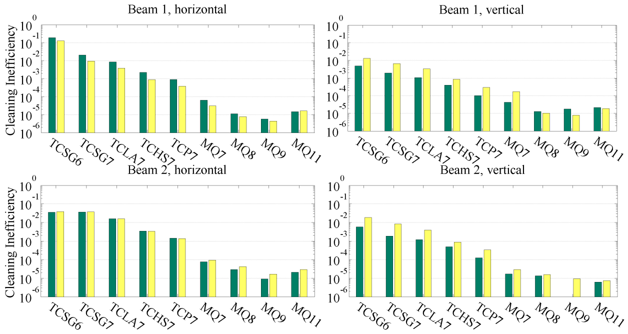

Figure 3: Comparison of selected BLMs at 450 GeV.

As in the previous case, at 450 GeV the measured cleaning inefficiency differs slightly when comparing the vertical losses (see Fig. 3), but the difference is not significant.

IR3 & IR7 Losses for Off-Momentum Loss Maps

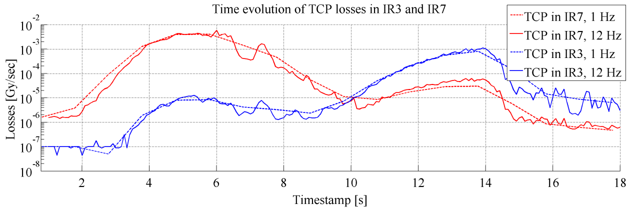

Figure 4: Time evolution of losses for MO loss map at 450 GeV for Beam 2 in vertical direction.

Figure 4 shows the time distribution of losses for an off-momentum loss map obtained with a frequency trim of 500 Hz (momentum offset: $\delta_p = 3.87 \times 10^{-3}$) in the TCPs of IR3 and IR7. Table 1 shows that collimators in IR3 are at $\approx$ 1.4 times the value of IR7 at injection. Losses are thus initially highest at IR7. With increasing momentum offset

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[1] The TCHS are Halo Scrapper collimators currently not installed.

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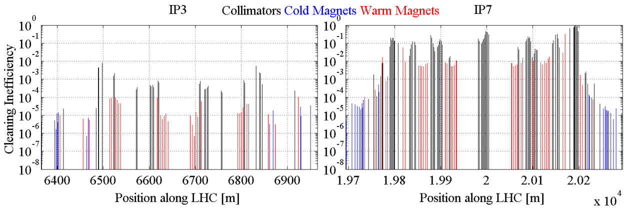
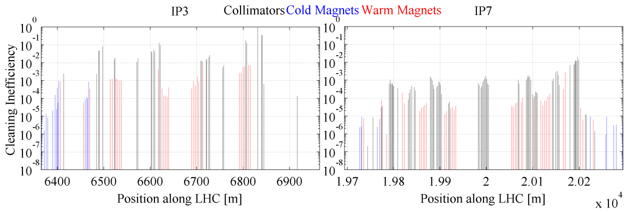


(a) IP3 & IP7 of Off-Momentum (+500 Hz) loss map, injection, 1 Hz



(b) IP3 & IP7 of Off-Momentum (+500 Hz) loss map, injection, 1 Hz

Figure 5: IR3 & IR7 450 GeV off-momentum (+500 Hz) loss maps. Lossmaps refer to maxima in Fig. 4.

and constant magnetic fields, the particles follow new orbits and losses at IR3 increase while they decrease at IR7. Losses reach a maximum of 1.11×10^{-3} [Gy/s] at IR3. Figure 5 shows the lossmaps in IR3 and IR7 at the two maxima at ≈ 6 s and 14 s.

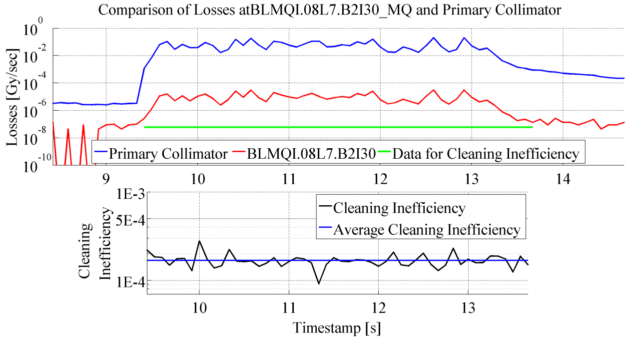
Table 2: Comparison of 1 Hz and 12 Hz Data at 3 BLMs

BLM	**Pos. [m]**	1 **Hz, Injection [10^{-5} Gy/s]**	12 **Hz, Injection [10^{-5} Gy/s]**
TCAPA	6498	3.24	3.44
TCP	20196	399.55	585.37
TCTH	23199	0.27	0.14
Noise:		≈ 0.001	≈ 0.001

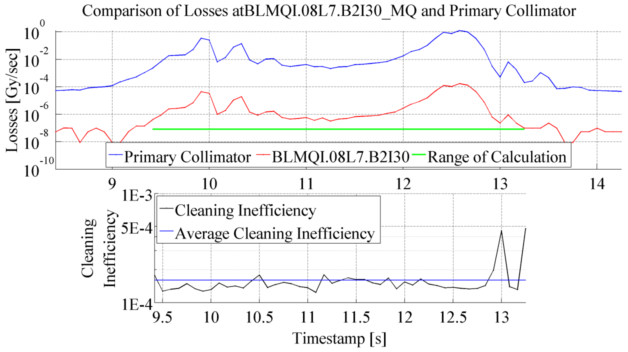
Table 2 compares 1 Hz and 12 Hz data at specific BLMs. Losses found for the TCP are higher by 47% at 12 Hz. The 12 Hz data records the maximum during its interval and is thus able to detect additional peaks, which are visible in Fig. 4.

Time Profile of Losses and Cleaning

Figure 6 shows losses and cleaning calculated for the ADT (top) and QT (bottom) excitation methods. The green lines indicate periods for which the mean cleaning inefficiency was computed. Its vertical position shows the BLM noise level for the cold magnet losses. All values below the green line were neglected for the cleaning calculations because they correspond to background noise. The average cleaning calculated for the ADT method is $1.68 \pm 0.30 \times 10^{-4}$. For the QT method, the average cleaning is $1.61 \pm 0.67 \times 10^{-4}$. Note that the variance around the average is more than 2 times larger. While both methods give similar average cleanings, for the ADT case one can achieve nearly constant loss rates during the time of the excitation. The intensity loss can also be controlled with fine granularity by adjusting the ADT gain settings.



(a) Loss Map at 4 TeV, Squeeze, H, ADT, Beam 2.



(b) Loss Map at 4 TeV, Adjust, H, QT, Beam 2.

Figure 6: Time evolution of cleaning inefficiency.

CONCLUSIONS

ADT and QT methods provide similar loss maps and estimates of the collimation cleaning performance. The ADT method has been adopted in 2012 due to its larger flexibility and to the possibility to perform several loss maps with the same fill. Nearly constant loss rates over several seconds are possible, for more precise estimates of cleaning. The comparison of the 12 Hz and 1 Hz data was also carried out, showing that the 12 Hz data allows us to determine more precisely various aspects of the collimation performance, like the detailed interplay between betatron and momentum cleaning.

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