MULTI-TURN LOSSES AND CLEANING IN 2011 AND 2012

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Abstract

LHC beam collimation is based on a hierarchical multi-stage cleaning system. Maintaining the correct hierarchy ensures maximal cleaning efficiency and machine protection. The operational collimator positions are established from the beam centres and sizes at each collimator measured in beam-based alignments. These are verified periodically during the year. The improvements made to the collimator alignment algorithm in 2011 are described. The time spent on setup and qualification by loss maps is summarized in detail. The stability of the collimator setup and cleaning efficiency is presented. An outlook to 2012 is given, including detailed considerations on improved setup speed, required frequency of setup and qualification and other possible improvements overall reducing beam time consumption for collimation.

INTRODUCTION

The LHC collimation system is designed to scatter and absorb beam halo particles before they are lost at the superconducting magnets [1]. It protects the machine against regular and irregular proton losses, which may cause magnet quenches and damage to beam pipe equipment. The cleaning system has a four-stage hierarchical design for intercepting multi-turn losses at the collimators. The collimators in insertion regions (IRs) 3 and 7 comprise the large majority, providing off-momentum and large betatron amplitude collimation respectively. Collimators are also placed in front of the triplets to protect the experimental insertion points (IPs) as well as in the dump (IR6) and transfer line regions in IR2 and IR8.

In the four-stage hierarchy, the primary collimator (TCP) jaws are positioned closest to the beam in terms of beam σ. The jaws of the secondary collimators (TCSG) are retracted further, followed by the jaws of the tertiary collimators (TCT) and the absorbers (TCLA), which are positioned furthest from the beam. An illustration of the multi-stage cleaning process is shown in Fig. 1. A list of the half gap openings in beam σ for nominal emittance for the different types of collimators as used in the 2011 run is provided in Table 1. In 2011, the tertiary collimator jaws were positioned more tightly around the beam than in 2010 due to the decrease in $\beta*$ to 1.5 m. The collimation system requires an operational accuracy of 5 μm, and the settings obtained from collimator beam-based alignment are maintained for months with regular qualifications to ensure their validity.

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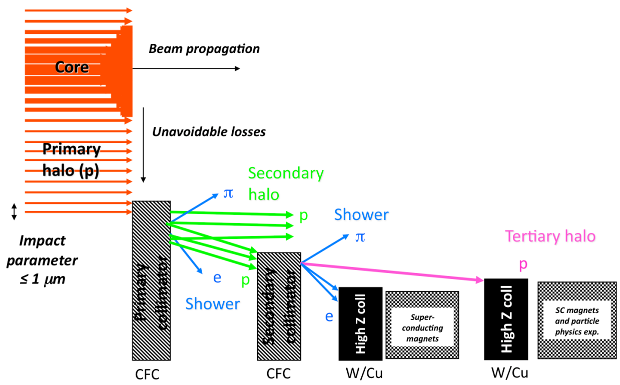


Figure 1: Scattering and absorption of the beam halo by the multi-stage LHC collimation system [2].

Table 1: Half-gap openings in units of beam σ for different energies and collimator types as used in the 2011 run.

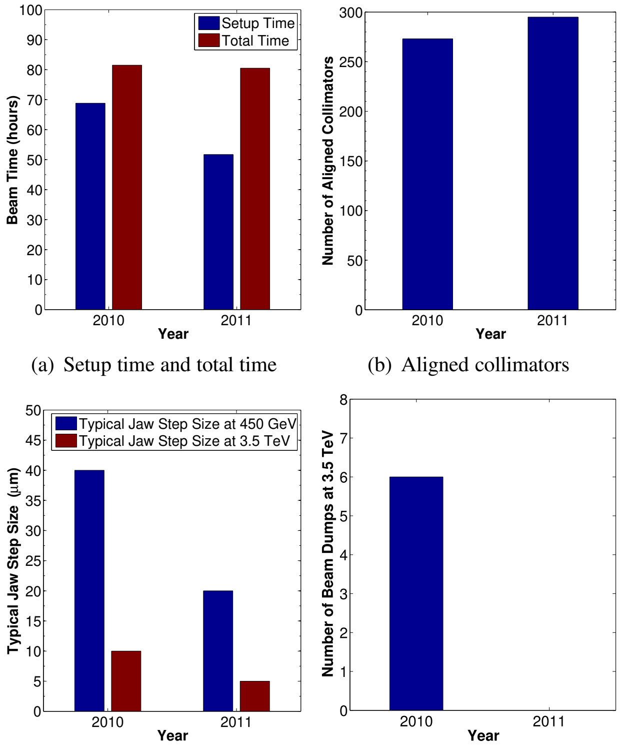
Collimator Type	450 GeV	3.5 TeV (collisions)
TCP IR3	8	10-12
TCSG IR3	9.3	15.6
TCLA IR3	10	17.6
TCP IR7	5.7	5.7
TCSG IR7	6.7	8.5
TCLA IR7	10	17.7
TCT	15-25	11.8
TCDQ / TCSG IR6	7-8	9.3-10.6

COLLIMATOR SETUP

Semi-Automatic Beam-Based Alignment

In order to correctly position the collimator jaws in a multi-stage cleaning hierarchy, the beam centres and beam sizes at the collimator locations must be known. These values are determined from beam-based alignment, in which each collimator jaw is moved towards the beam until a spike is observed in the signal of a beam loss monitor (BLM) located downstream from the collimator. For a detailed description of the setup procedure, see [3, 4].

A semi-automatic alignment algorithm [4] was developed for the 2011 LHC run. It automatically stops the jaw



(a) Setup time and total time (b) Aligned collimators

(c) Typical jaw step size (d) Beam dumps at 3.5 TeV

Figure 2: Summary of the setup parameters used during collimator alignment. Setups were performed with manual alignment in 2010 and semi-automatic alignment in 2011.

movement when the losses exceed a pre-defined BLM signal threshold. The tool allows alignment of jaws in parallel, which also reduces the beam time consumed for setup. The semi-automatic procedure no longer requires operator intervention for every jaw step, thus reducing the possibility of human error during the alignment. The motivation of this work is to develop an automatic alignment tool which can save beam time so that it may be used for physics data-taking and other beam studies.

Setup Highlights

Highlights of the improvements achieved with semi-automatic setup are shown in Fig. 2. A comparison with the results from 2010 shows that the beam time consumed by setup decreased by $\sim$17 hours (see Fig. 2(a)). The total time (which includes the time required for several machine sequences e.g. ramp and squeeze) remained the same although three more setups were carried out at 3.5 TeV in 2011. The reduction in time is also due to an elimination of beam dumps caused by human error during setup (see Fig. 2(d)).

Collimation Hierarchy and Tolerances

An overview of the different collimator settings and the corresponding TCP-TCSG margins is provided in Table 2. In 2010 and 2011, the "relaxed" settings for 3.5 TeV were used. During Machine Development (MD) slots in 2011, the tight and nominal collimator settings at 3.5 TeV were qualified [9, 10].

Setup Stability

The primary collimators are aligned most frequently as they are used to create a reference cut into the beam halo and determine the beam size when aligning another collimator. The variations in the beam centres found from beam-based alignment of these collimators throughout 2011 are shown in Fig. 3. The centre variation for the horizontal primary collimators reaches a maximum of 250 μm, while the largest variation for the vertical primary collimators is of 150 μm.

Due to the dual jaw nature of the collimators, variations in the beam centre at the collimator positions do not affect the cleaning efficiency of the collimation system. However, the loss rates would increase for significant shifts as one jaw would be closer to the beam core than the other. Large variations in the beam centre are only critical if they cause a hierarchy breakdown, for example in the event that a secondary collimator becomes the primary bottleneck.

At the start of the heavy ion run in November 2011, the polarities of the ALICE dipole and solenoid were switched from negative to positive. This meant that the vertical tertiary collimators had to be re-aligned in IR2. Table 3 shows a good comparison (within $\sim$100 μm) between the beam centre change as predicted by the orbit model and the change measured from beam-based alignment. The change in the BPM-interpolated orbit at the collimator positions is also similar.

Another case study involves the IR3 collimators, which were aligned in July 2011 for a MD slot on combined cleaning. The changes in the beam centres at these collimators over a four month period (from the full setups in March 2011) are presented in the form of a histogram in Fig. 4. The average change is of $\sim$90 μm, with the maximum change being $\sim$250 μm.

Collimator Jaw Misalignments

Collimator jaw misalignments introduce imperfections as they reduce the length of jaw material available for collimation. During the full setups in March 2011, large beam sizes at three collimators (TCTH.4L2.B1, TCLA.A7L7.B1, TCSG.A5L3.B2) with respect to the nominal beam sizes was observed. The affected jaws were corrected in the tunnel by the survey team [11], and a misalignment angle of $\sim$1.6 mrad was measured. A model of the jaw misalignment is illustrated in Fig. 5. The predicted misalignment angle α_i for a collimator i is given by the following relation:

$$\alpha_i = \frac{2n_1\Delta\sigma_i - \Delta_i}{L_i} \tag{1}$$

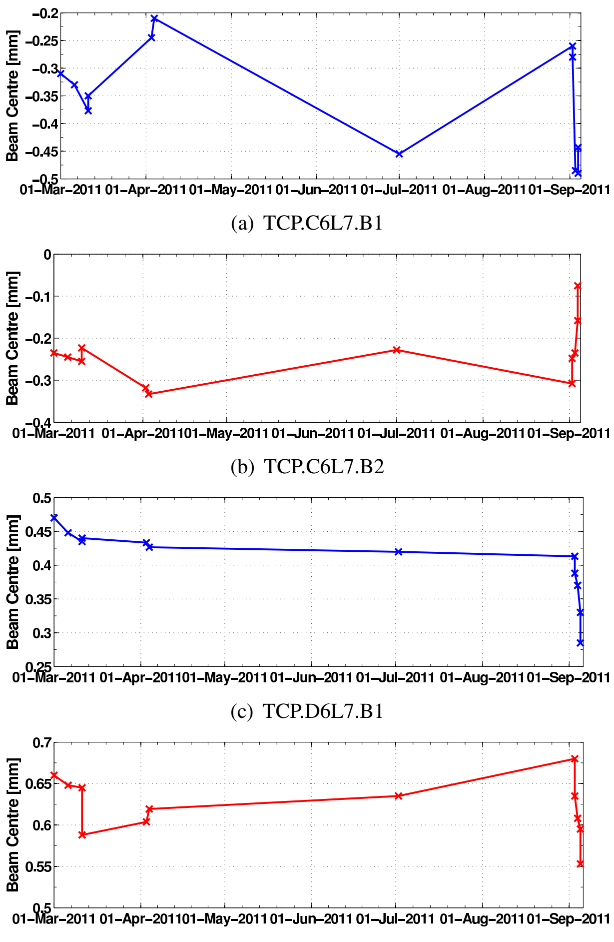
where $\Delta\sigma_i$ is the beam size error and Δ_i is the scale error between the Motor Drive Control (MDC) setting and the

Table 2: Overview of the different collimator settings and the corresponding TCP-TCSG margins.

Collimator	Relaxed 3.5 TeV	Tight 3.5 TeV	Tight 4 TeV	Nominal 7 TeV
TCP IR7 [σ]	5.7	4	4	6
TCSG IR7 [σ]	8.5	6	6	7
Margin [σ]	2.8	2	2	1
Margin [μm]	1050	750	728	274

Table 3: Comparison of predicted to measured beam centre shift following ALICE polarity inversion.

Collimator	Change in Centre (mm)			Difference between
	Orbit Model	Beam-Based Alignment	BPM Interpolation	Alignment & Model
TCTVB.4L2	- 4.698	- 4.805	- 4.550	- 0.107
TCTVB.4R2	- 4.824	- 4.840	- 4.750	- 0.016



(a) TCP.C6L7.B1

(b) TCP.C6L7.B2

(c) TCP.D6L7.B1

(d) TCP.D6R7.B2

Figure 3: The stability of the centres found from beam-based alignment of the primary collimators throughout the 2011 run.

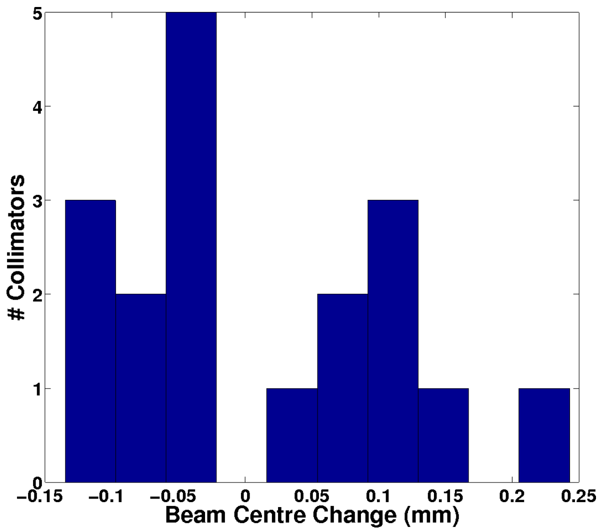
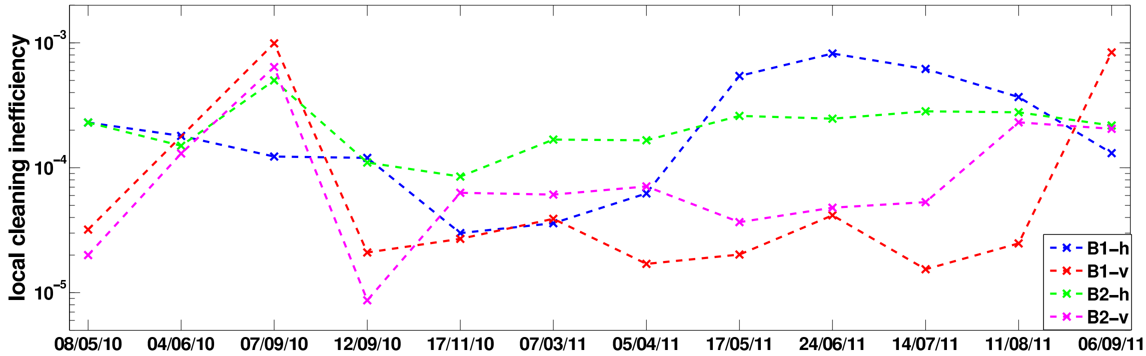


Figure 4: Changes in the IR3 collimator beam centres as measured from beam-based alignment over a four month period.

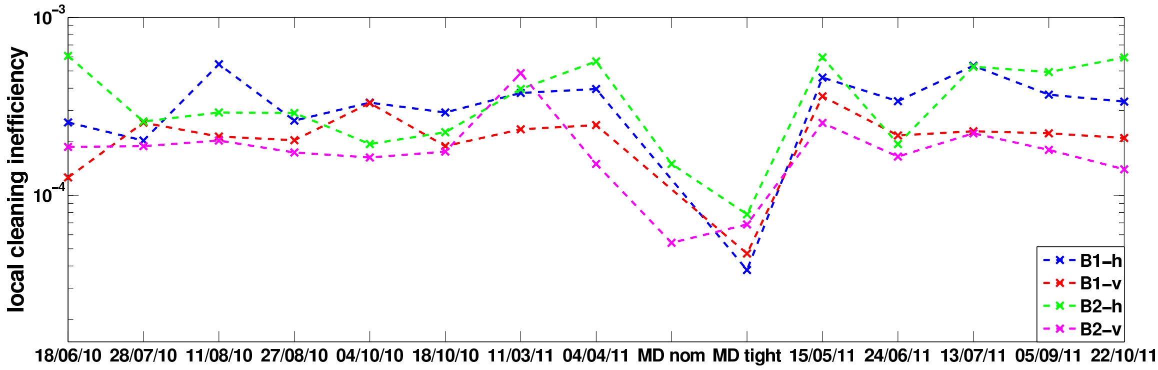
Linear Variable Differential Transformer (LVDT) read-out, which is assumed to be 50 μm. The n_1 parameter is the cut of the primary collimator into the beam in units of σ. A comparison of the predicted and measured misalignment angles is provided in Table 4. The predicted misalignment angles before tunnel alignment are a factor 2 above the measured angles, but are within the expected uncertainties due to the β-beat and Δ_i. After tunnel alignment, the predicted values are found to decrease.

COLLIMATION QUALIFICATION

The collimation system hierarchy is regularly qualified by creating intentional multi-turn losses. To generate betatron losses, the third integer tune resonance is crossed, allowing the creation of horizontal or vertical losses. For momentum losses, the RF frequency is varied by ± 1000 Hz for positive and negative momentum offsets. The quali-



(a) 450 GeV Cleaning Inefficiency



(b) 3.5 TeV Cleaning Inefficiency

Figure 6: Proton cleaning inefficiency throughout 2010 and 2011. The inefficiency remains constant except for when nominal and tight collimator settings were used during MDs.

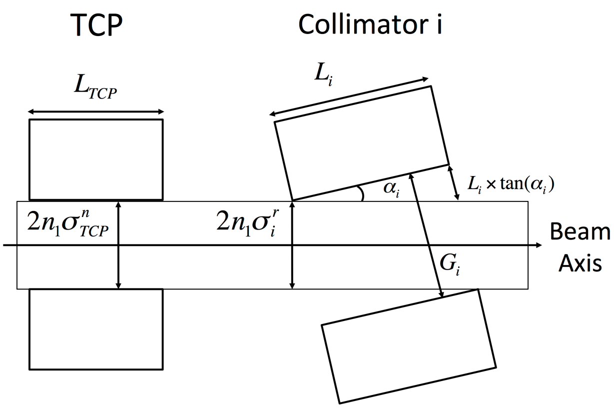


Figure 5: A model of a misaligned collimator and the effect on the measured beam size, assuming a perfectly aligned TCP. Adapted from R. W. Assmann and B. Goddard [8].

fication process is performed with one nominal bunch at 450 GeV or 3.5 TeV, and a major disadvantage is that it requires dedicated fills, given that 30% - 50% of the beam is lost for each loss map. From the beam loss map, the local cleaning inefficiency at any point in the ring can be determined from the ratio to the highest loss. For example, the leakage to the cold aperture is calculated by:

Table 4: Comparison of predicted to measured jaw misalignment angle following tunnel re-alignment.

(a) Predicted misalignment angles before tunnel re-alignment

Collimator	$\Delta\sigma_i$ (mm)	n_1	α_i (mrad)
TCTH.4L2.B1	0.424	3.63	3.0
TCLA.A7L7.B1	0.400	4.40	3.4
TCSG.A5L3.B2	0.442	3.68	3.2

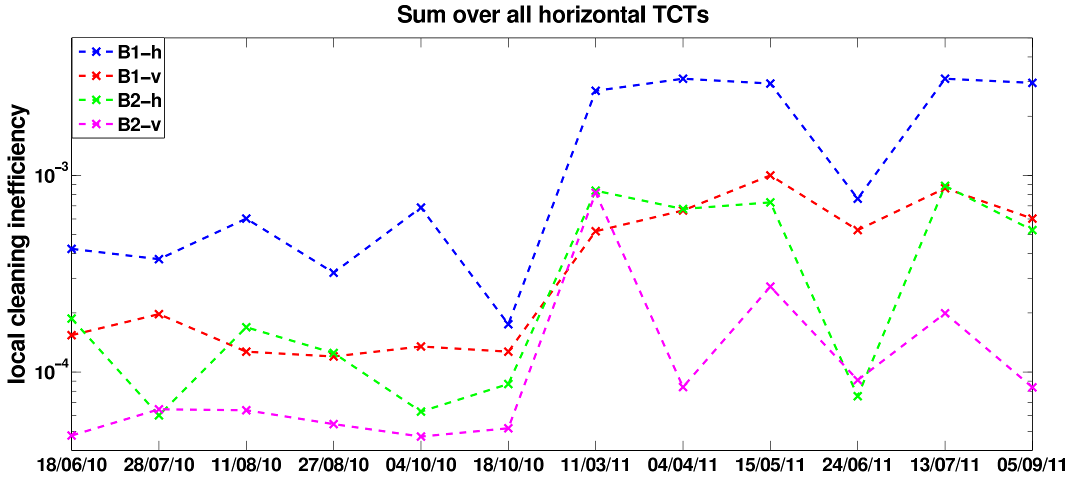
(b) Predicted misalignment angles after tunnel re-alignment

Collimator	$\Delta\sigma_i$ (mm)	n_1	α_i (mrad)
TCTH.4L2.B1	0.144	4.38	1.2
TCLA.A7L7.B1	0.064	4.64	0.54
TCSG.A5L3.B2	0.080	4.56	0.6

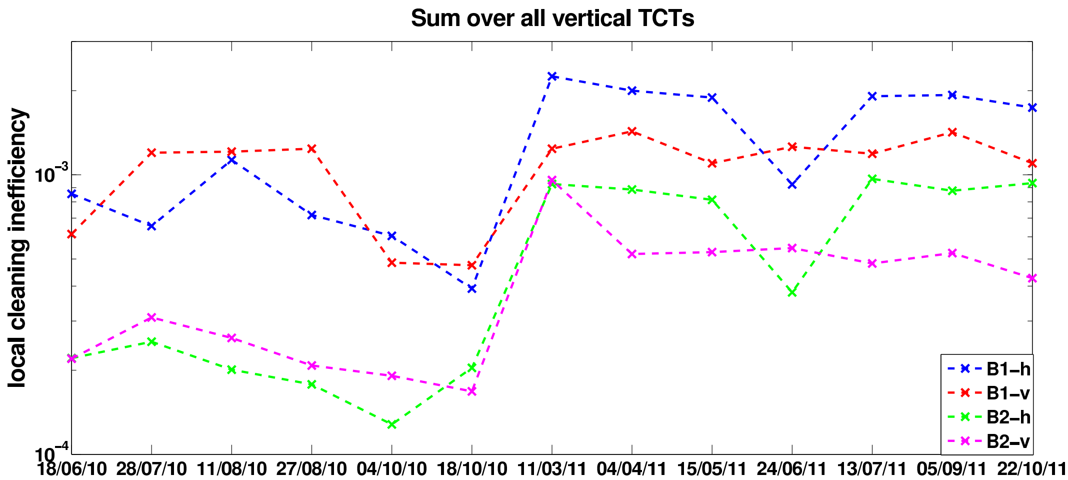
$$\eta_c = \frac{\text{Highest Leakage in Cold Aperture}}{\text{Highest Losses at TCP}} \tag{2}$$

Beam Time consumed for qualification

A total of 59 qualifications were performed in 2011, of which 26 were done at 450 GeV (injection) and 33 were carried out at 3.5 TeV (flat top, squeezed and colliding beams). Around one-third of all loss maps could be



(a) TCTH Leakage



(b) TCTV Leakage

Figure 8: Sum of the leakage to the horizontal and vertical TCTs throughout 2010 and 2011.

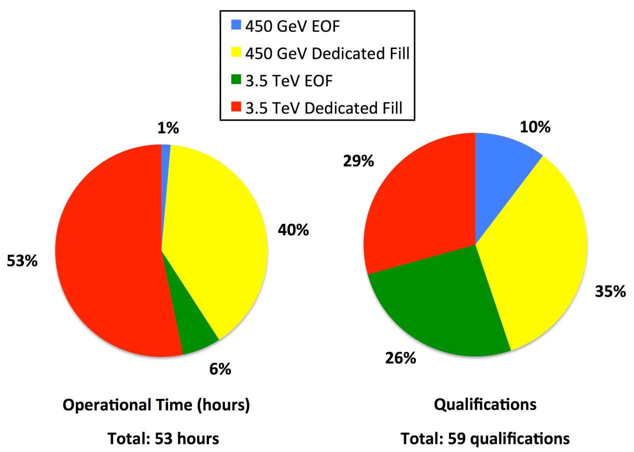


Figure 7: Distribution of the operational time consumed for loss maps in 2010 and 2011.

performed at the end-of-fill (EOF) following a collimator alignment or other beam-based studies. The total time used for qualification was 53 hours, and the time distribution is shown in Fig. 7.

Cleaning Inefficiency

The variation in the cleaning inefficiency for the proton runs in 2010 and 2011 is provided in Fig. 6(a) for 450 GeV and Fig. 6(b) for 3.5 TeV as an extension of the analysis presented in 2010 [5]. The plots show the ratio of the highest cold loss (Q8 in IR7) to the loss in the IR7 TCP with a 1.3 s integration time. The average inefficiency is 3.39×10^{-4} in 2011. An overview of the sum of the leakage to the horizontal and vertical TCTs at 3.5 TeV is given in Fig. 8. The leakage increases by an order of magnitude in 2011 when compared to 2010, as the TCT jaw settings are tighter due to the reduction in $\beta*$.

OUTLOOK FOR 2012

Fully Automatic Collimator Setup

For the 2012 run, a number of improvements are foreseen to reduce the beam time required for setup and qualification. The semi-automatic collimator alignment tool is set to be upgraded to a faster and fully automatic setup procedure. The data rate for the BLMs at the collimator positions will be increased from 1 Hz to 12 Hz, while the maximum collimator movement rate allowed will be increased from 3 Hz to 8 Hz.

Pattern recognition of BLM loss spikes during the alignment using support vector machines has achieved a prediction accuracy of 90% [13]. Work is ongoing to achieve 100% accuracy for the fully automatic setup tool. In addition, a simulator is being developed to train a learning algorithm in taking decisions usually made by the setup expert during the alignment. These decisions involve the setting of parameters including the loss threshold, the jaw step size and the step repetition rate.

New Qualification Procedures

In 2011, tests with the LHC transverse damper (ADT) demonstrated the creation of fully controlled steady losses using wideband noise [6, 7]. This raises the valid possibility of selectively blowing up bunches for beam loss maps and aperture measurements. An advantage of the selective blow-up is that the beam lost for the loss map is significantly less than the standard method of crossing the third-order tune resonance. Therefore, this would prevent the overhead needed for refilling if the beam is dumped prematurely. A MD slot has been requested in 2012 for final commissioning of this technique.

An application of pattern recognition of beam losses in the spatial domain [12] is that of allowing for “online” loss maps. The objective of this ongoing work is to be able to decompose the losses observed during stable beams into the separate B1 and B2, horizontal and vertical components. A fixed display in the CCC could then show continuous loss maps and allow for any hierarchy breakdowns to be noticed immediately.

Alignment and Qualification Requirements for 2012

As in the 2011 run, all collimators will be aligned at the start of the year during re-commissioning with beam. Further setups will be required in case of changes to the optics. After successful validation of the tight settings at 3.5 TeV, these settings will also be used at 4 TeV in 2012. The frequency of qualification will be reduced from one set of loss maps per month to one set every three months. This is motivated by the stability of the cleaning inefficiency as observed from the loss maps. However, the standard loss map qualification method will be complemented by online loss maps and the ADT blow-up method in 2012.

CONCLUSION

The LHC collimation system has performed well so far, with no beam-induced quenches recorded. In 2011, a semi-automatic setup tool provided an improvement in alignment operational efficiency. Based on nominal and tight settings MD results, and the general stability of the orbit, the collimation system is ready for 4 TeV and tight settings in the 2012 run. Work is ongoing to fully automate the collimator alignment procedure, as well as reduce the beam time required for alignment and qualification in 2012.

ACKNOWLEDGEMENTS

The authors would like to thank O. Aberle, P. Bestmann, B. Dehning, E. Del Busto, A. Marsili, A. Masi, N. Sammut, J. Wenninger and C. Zamantzas for valuable discussions, as well as the LHC operator crews during collimator operation.

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