BEAM BASED VALIDATION OF LHC COLLIMATOR SETTINGS

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Abstract

The collimator system provides efficient beam halo cleaning and plays an important role in passive machine protection. About 100 movable collimators are precisely aligned to the beam orbit with gaps as small as $\sim 2\ \mathrm{mm}$. In order to ensure the required collimation functionality, the collimator positions need to be validated. This is done by acquiring regularly controlled loss maps in each machine configuration.

During 2012, the use of the transverse damper (ADT) to excite transversally the beams in a controlled way has reduced the time to produce betatron loss maps. However, the validation of the off-momentum losses and asynchronous dumps still determines the minimum number of required fills. The experience with the loss maps in the 2010-2013 running period is reviewed and possible improvements are discussed. Aspects related to the minimum time between re-validation by loss maps, possible further improvements such as loss maps at the end of every physics fill and better online monitoring are also discussed.

INTRODUCTION

The LHC collimation system provides a multi-stage cleaning in two main cleaning insertions, IR3 for momentum cleaning and IR7 for betatron cleaning. The primary collimators (TCPs) are the closest elements to the beam in normalized transverse space, cutting into the primary halo. The secondary collimators (TCSGs) cut the particles scattered by the primaries (secondary halo) and the absorbers (TCLAs) stop the showers from upstream collimators [1, 2, 3]. The tertiary collimators (TCT) protect directly the triplets at the experimental IRs. Including the passive absorbers, the physics debris absorbers, transfer line collimators, injection and dump protection makes a total of 108 collimators. Hundred of them are movable and need to be aligned within $10-50$ µm precision to achieve the required cleaning.

During 2010-2011 betatron loss maps were made by exciting the beam by crossing the 3rd order resonance. This methods was proven to be adequate to generate loss maps of the full LHC ring, however losses were difficult to control and the full injected beam was excited with this method. In most of the cases, the fill was dumped after the first betatron loss map. In 2012, a new procedure was set in place. Loss maps were regularly acquired by exciting selected bunches with white noise using the transverse damper (ADT) [4]. This reduced the time spent in the betatron loss map validation enormously, however, due to beam-beam cross-talk, loss maps during physics had still to be generated with the tune resonance. This is now avoided by establishing the physics loss maps using non-colliding bunches with the ADT. Nowadays, all the LHC machine phases can be validated with betatron loss maps in a single fill.

We review in this paper the requirements to validate the collimation system. We discuss several improvements for better online monitoring and for loss maps procedures with a special focus on the off-momentum loss maps. The extrapolation of the loss map procedure to $7\ \mathrm{TeV}$ is also discussed.

MINIMUM REQUIRED VALIDATION

All collimators are set up symmetrically around the beam orbit for each phase of the LHC operational cycle (*i.e.* injection, flat top, squeeze and collisions). The alignment procedure consists of moving the collimator jaws towards the beam until a beam loss monitor (BLM) spike is observed when the individual jaws touch the beam halo. The beam centre is calculated as the average of the two aligned jaw positions. This is done only in dedicated low intensity fills with up to 3 nominal bunches, which is the safe limit to mask a subset of beam interlocks like collimator positions and BLMs.

The operational strategy during 2011 and 2012 run periods was to perform one full alignment per year of the main cleaning insertions (IR3 and IR7) and monitor regularly the losses along the ring to validate if a new alignment was needed by looking at the cleaning in the cold region and at the collimator hierarchy. For most of the new physics configurations, only the 16 TCTs collimators at the colliding IRs require to be re-aligned. This strategy proved to be successful thanks to the excellent reproducibility of the machine (orbit, optics, etc.) and collimator settings stability.

Beam loss maps are an effective way of validating the collimation system performance and of calculating the collimator BLM dump thresholds. During LHC commissioning, at the beginning of the year, all collimators are re-aligned at each individual phase of the operational cycle (*i.e.* injection, flat top, squeeze and collisions). A set of cross-checks are made during the generation of the settings, both manual and automatic [5], but the final check consists of analyzing the loss maps made in dedicated low intensity fills to quantify the leakage to the cold magnets and confirm the collimation hierarchy for both betatron-like losses and off-momentum-like losses.

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Table 1: Minimum required loss maps for commissioning.

Period	Fills	Description
Alignment	1	Parasitic betatron loss maps done during alignment
Inj. energy	3	Betatron (parasitic), positive off-momentum (1), negative off-momentum (1) and asynchronous dump (1)
Top energy	3	Betatron at flat top, squeeze and colliding (parasitic), positive off-momentum (1), negative off-momentum (1) and asynchronous dump (1) at colliding.

The two verification methods are completely complementary since loss maps will only spot losses of collimators that are close to the beam, for instance they might not spot a case when one jaw is at the correct position and the other is further out.

Table 1 shows a summary of the minimum required regular loss map validation that should be done either every 8 weeks, or after a technical stop, or after a change of the collimator settings or the machine configuration. For the first commissioning of the year, off-momentum loss maps are also required at every phase of the LHC cycle. For changes on the TCT configuration (in the colliding IRs) the minimum validation is required only for squeeze and colliding beams.

Betatron loss maps are done parasitically in all the cases. Nowadays the limiting factor are the off-momentum loss maps and the asynchronous dump, which require dedicated fills. We will review here the maximum RF frequency change required for the off-momentum loss maps.

BETATRON LOSS MAPS

Betatron loss maps are essential to check the leakage to the cold sector. This is the basic test that ensures that the machine is protected from standard collimator beam losses during the fill. Some of the quantities checked with betatron loss maps are:

- **Maximum leakage to cold sector:** for betatron losses this occurs in the dispersion suppressor (DS) of IR7. The local cleaning inefficiency is approximated to the maximum leakage to the cold magnets normalized by the losses at the primary collimator measured by the BLM:

$$\eta_c = \frac{\mathrm{BLM}^{\mathrm{Q8-9}}}{\mathrm{BLM}^{\mathrm{max}}}$$

  where $\mathrm{BLM}^{\mathrm{Q8-9}}$ is the measurement of the losses in Q8 or Q9 cell in IR7, which correspond to the magnets that will quench first in case of high losses. $\mathrm{BLM}^{\mathrm{max}}$ is the loss at the primary collimator. This quantity, the cleaning inefficiency η_c, was shown to be stable during the year but depends on the collimator settings. Any displacement from the expected value would indicate a problem on the alignment or a degradation of the cleaning system. Cold losses at the rest of the ring are also checked to be well below the maximum leakage, otherwise a detailed investigation of the loss peak is done.
- **Leakage to other collimators:** we compare the normalized losses in all IPs (at the collimators) with previous loss maps. The ratio with respect to the primary needs to be preserved, see Fig. 1.
- **Collimation cleaning hierarchy:** the cleaning hierarchy is consistently checked by looking at the distribution of the losses at the collimators in the cleaning insertion (in this case IR7). The losses at the collimators should decrease with the beam direction. This is seen in Fig. 2 for Beam 1 betatron cleaning.

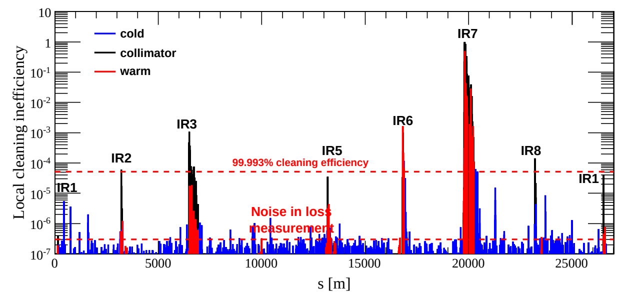

Figure 1: Distribution of the losses in the LHC ring while exciting Beam 1 in the horizontal plane.

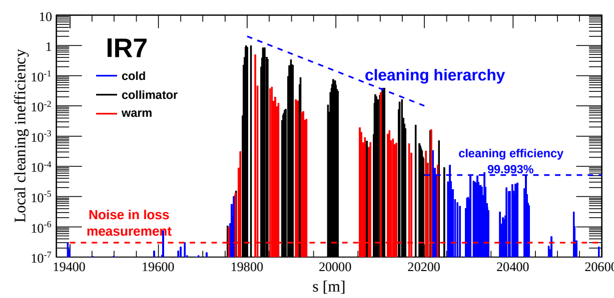

Figure 2: Distribution of the losses in the betatron cleaning insertion (IR7) while exciting Beam 1 in the horizontal plane.

OFF-MOMENTUM LOSS MAPS

Off-momentum cleaning in IR3 is also validated in dedicated low intensity fills by looking at losses artificially generated by changing the LHC radio frequency (RF) by ± 500 Hz in order to generate an off-momentum shift big enough to dump the beam on the TCP of IR3. Fig. 3 and 4 show the cleaning inefficiency for this type of losses. The quantities checked in these loss maps are:

- **Maximum leakage to cold sector:** typically the off-momentum cleaning inefficiency is about 10^{-4}.
- **Leakage to other collimators:** in off-momentum loss maps, for the IR3 settings used in 2010-2012, the highest loss occur at IR3 as opposed to the betatron

losses were the peak appears in IR7. The leakage to all IPs is checked with particular emphasis of TCTs. These are metal collimators with high-Z (Tungsten) to protect the triplet quadrupoles, they have enhanced efficiency but are more sensitive to damage. These TCTs catch the off-momentum leakage from IR3 and therefore the leakage to these collimators should be controlled, see Fig. 3.

- **Collimation cleaning hierarchy:** the losses peak at both TCPs (Beam 1 and 2) because the RF is coupled to the two beams, see Fig. 4. The losses should still decrease with the beam direction (as for the betatron loss maps).

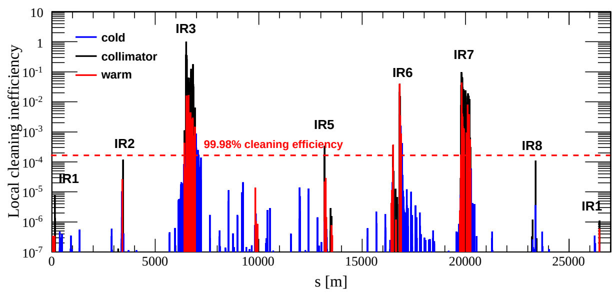

Figure 3: Distribution of the losses in the LHC ring for a negative off-momentum loss map.

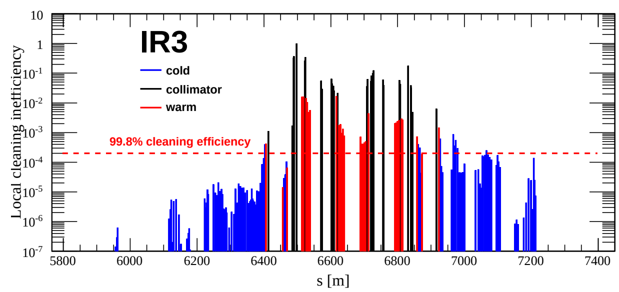

Figure 4: Distribution of the losses in the momentum cleaning insertion (IR3) for a negative off-momentum loss map.

THE NEED OF LOSS MAPS REFERENCES

During the previous running periods, the loss maps were extremely useful to spot problems during the collimator alignment. An example of this is shown in Fig. 5. This shows a broken cleaning hierarchy for Beam 2 during the proton-lead commissioning since the losses are not decreasing with the beam direction. The error was at the TCLA.A6L7.B2 collimator that was displaced by $700\ \mu\mathrm{m}$. The problem was caught before the end of the alignment and corrected within few minutes (see Fig. 6). The correct settings were released for operation.

However, misalignment problems cannot always be spotted. Loss maps cannot catch cases where the misalignment is very small, neither can they distinguish between impacts at the left or the right collimator jaw. It is very important to have reference loss maps to compare the expected losses with the measured ones. For example, in

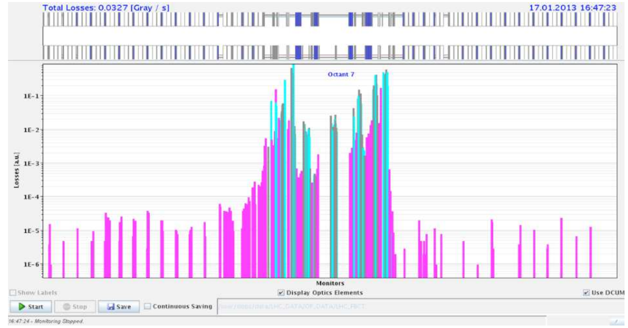

Figure 5: Distribution of the losses in IR7 during an alignment problem.

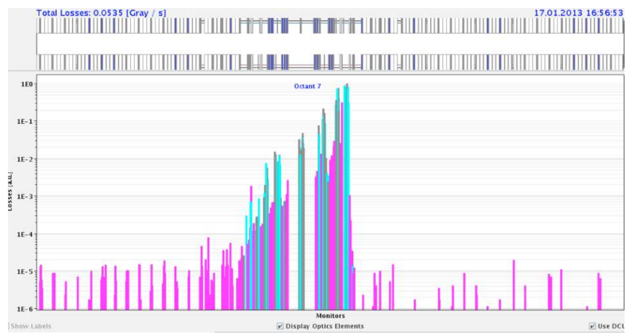

Figure 6: Distribution of the losses in IR7 after the correction of the alignment problem at the TCLA.A6L7.B2.

2012 we had a misalignment of the TCT in IR2 that could not be spotted in the first loss maps because it was the first time that they were measured with tight collimator settings at $4\ \mathrm{TeV}$. In this case it was observed that the cleaning at the triplet was satisfactory but we could not spot that the losses at the TCT were higher than required due to the lack of references. Instead, the misalignment was spotted by the manual check of the generated settings. Since dedicated simulations did not reach the needed accuracy level to predict the exact leakage to other IRs, it is very difficult to predict the exact leakage to the other IRs for major changes to the collimator settings and optics. The simulations are being improved to increase the accuracy of the predictions, see [6].

PROSPECTS FOR IMPROVEMENTS

Betatron loss maps

At higher beam energies it will be more delicate to measure loss maps. At $7\ \mathrm{TeV}$ the beam is more dangerous and it is more difficult to mask interlocks, therefore we will be acquiring loss maps very close to the dump limit. The latest estimation of the damage limits for a tertiary (tungsten) collimator shows that about $5 \cdot 10^9$ protons impacting a tertiary collimator could permanently damage it [7, 8, 9]. Therefore, we evaluate here the minimum intensity loss to measure the betatron loss maps and how to control the loss rate:

- **Minimum excited beam intensity:** the minimum intensity loss, $\mathrm{R}_{\mathrm{min}}$, needed to measure a cleaning inefficiency at Q8 of $\eta_c \approx 5 \cdot 10^{-5}$, is defined by the following formula

$$\mathrm{R}_{\mathrm{min}} = \frac{\mathrm{BLM}_{\mathrm{bkg}}}{\eta_c} \times f_{\mathrm{Gy}\to\mathrm{p}}$$

where $\mathrm{BLM}_{\mathrm{bkg}} \approx 3 \cdot 10^{-7}$ Gy/s is the BLM background or noise level and $f_{\mathrm{Gy}\to\mathrm{p}} \approx 1.2 \cdot 10^{12}$ p/Gy the calibration factor to convert the BLM measured signal into number of protons lost per unit time. Thus the minimum intensity loss is of the order of $\sim 8 \cdot 10^{9}$ p/s [10]. This was tested during the proton-lead run, where loss maps were routinely made by exciting single pilot bunches of $\sim 10^{10}$ p/bunch with enough resolution to measure the cleaning.

- **Control of intensity loss rate:** the transverse damper has demonstrated its ability to control the intensity loss rate very effectively. As an example of small losses controlled by the ADT, several aperture measurements were done in 2012. In those cases the ADT was used to slowly blow up 1 pilot bunch ($\sim 10^{10}$ protons).
- **Excitation of individual bunches:** during the 25 ns run in December 2012, it was also proved that excitation of single bunches separated by 25 ns in a 12 bunch train was possible with the ADT, while leaving the adjacent bunches unaffected. This opens the possibility to make loss maps during standard fills *i.e.* fills with beam intensity above the setup beam flag (SBF) limit.

Off-momentum loss maps

Nowadays, off-momentum loss maps and asynchronous dump tests are the limiting tests after changes in the machine, since they require a dedicated fill at top energy each. This will remain the case for asynchronous dump. However, in the case of off-momentum loss maps, the fill is usually dumped by the unmaskable BLMs when the losses become too high. We investigate here the possibility of reducing the RF frequency change required to have dominating off-momentum losses.

Minimum frequency change For this analysis we use a 12 Hz logging of the BLM data, the 81.92 ms running sum (RS07), to identify precisely when the off-momentum losses dominate over the betatron losses. Fig. 7 and 8 show the evolution of the losses in the primary collimator of IR3 and primary horizontal collimator in IR7 for a negative off-momentum loss map at flat top using the 1 Hz logged data (~ 1.3 s running sum, RS09) and 12 Hz logged data (RS07) respectively. Beam losses start to appear after the RF frequency change (Δf) started, this is shown in Fig. 9. The losses in IR3 (off-momentum cleaning) start dominating over the losses in IR7 (betatron cleaning) when the RF frequency change is ~ 150 Hz and the maximum peak loss in IR3 happens at $\Delta f \approx 200$ Hz which is also when the beam is dumped. However, this strongly depends on the collimator settings, in particular on the sharing between IR3 and IR7. Nevertheless, this shows that in principle it is possible to stop the frequency change earlier (before triggering a beam dump) to observe the off-momentum cleaning hierarchy in IR3.

A detailed MD study is needed to get the optimal frequency change for the off-momentum loss maps, but tentatively a value around 150 Hz seems indicative from the present data.

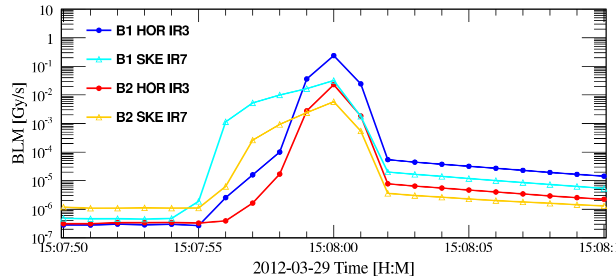

Figure 7: Loss distribution as a function of time for primary collimator in IR3 and primary skew collimator in IR7 using the slow logging of the BLM data (1 Hz).

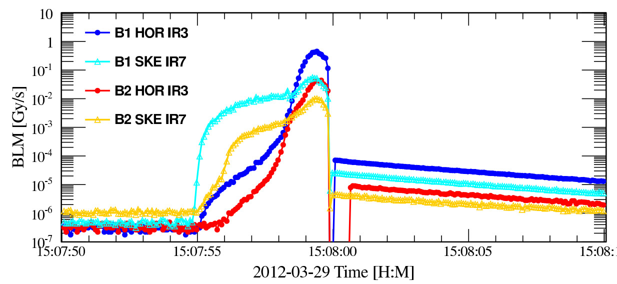

Figure 8: Loss distribution as a function of time for primary collimator in IR3 and primary skew collimator in IR7 using the fast logging of the BLM data (12 Hz).

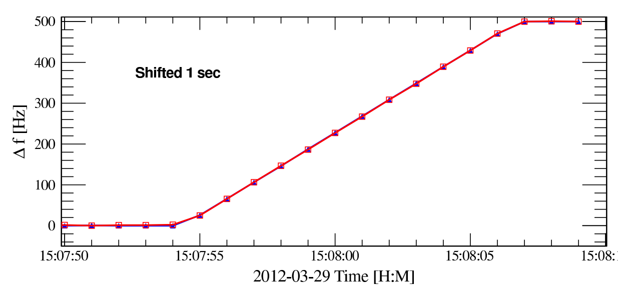

Figure 9: RF frequency change as a function of time.

OTHER IDEAS

Continuous loss maps during the cycle

During 2010-2013, loss maps were only taken at the start and end of each LHC cycle. However, if a combined ramp-squeeze at 6.5 TeV is envisaged it would be important to validate the cleaning during the ramp. Similarly, a continuous loss maps validation during the squeeze should be required if more complex squeeze configuration will be used *i.e.* moving secondary collimators closer to the beam after reaching a certain value of $\beta^\star$. On this subject, two

MDs were made in 2012 in order to check the possibility of making continuous betatron loss maps in Beam 1 and 2 (horizontal and vertical) during the energy ramp [11]. The cleaning at Q8 was measured as a function of beam energy while the collimators were moving from injection settings to tight settings. It is observed that the cleaning was stable during the cycle, see Fig. 10.

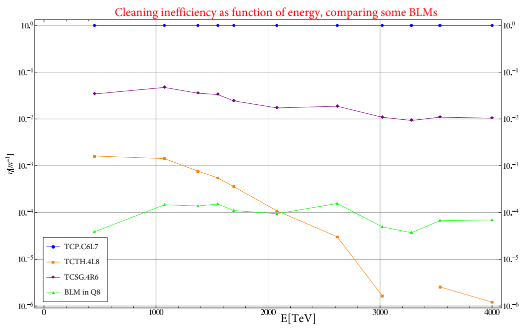

Figure 10: Leakage to Q8 and tertiary collimators during the energy ramp [11].

Online monitoring and post mortem analysis

During regular fills there are losses at the collimators due to beam instabilities, orbit shifts, etc. If the level of the losses is high enough ($> 10^{10}$ p/s) it is possible to observe the cleaning hierarchy in IR7 and to measure the cleaning inefficiency. An example of this is shown in Fig. 11, however:

- it is difficult to distinguish losses from the 2 beams
- it is difficult to disentangle the plane of the losses.

On the other side, a more realistic approach for semi-online monitoring would imply to perform end of fill loss map acquisitions and post mortem analysis, provided that we can control the loss rate, interlock the ADT, etc. However, the option to measure loss maps before dumping regular physics fills needs further studies (*i.e.* can we excite the beam with full intensity in the machine?).

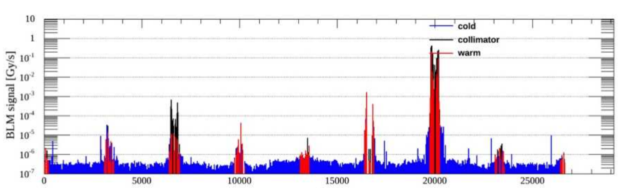

Figure 11: Losses during a regular fill on 2012-12-04 18:09:29 along the LHC ring.

CONCLUSIONS

The minimum requirements to validate the collimation system performance were shown. The adopted strategy (every 8 weeks or after a technical stop or after major machine configuration changes) was found to be adequate. The 8 weeks re-validation was hardly needed, almost all validation loss maps were driven by major machine configuration changes or technical stops.

Regarding improvements of the the betatron loss maps, the ADT was shown to be extremely useful. The beam losses can be controlled to keep the losses below the dump thresholds and moreover, individual bunches with 25 ns spacing can be excited independently. The ADT is also capable of generating continuous losses in dynamic situations *i.e.* during the energy ramp and squeeze. The minimum intensity loss needed for the loss maps was found to be about a pilot bunch of 10^{10} protons for an excitation of 1 second. This should be the similar at 7 TeV.

At this point, the off-momentum loss maps still need dedicated fills but there is the possibility of controlling more precisely the RF frequency change needed, to the point of not dumping the beam. In this case, we could envisage to measure both off-momentum sides in the same fill, reducing the operational time requirements for the loss maps validation, including the asynchronous dump test, to one fill instead of 3 fills. A more detailed evaluation on the minimum intensity and the masks required for the loss maps is under discussion, but it is important to remind that we need at least 3 bunches to find collisions everywhere. Moreover, the bunches should be in the dynamic range of the BPMs, so that the orbit before the test is reliable.

Online monitoring cannot easily substitute the standard validation with clean loss maps, since this would require having beam instabilities that generate high beam losses in the 2 planes in all the different phases of the operational cycle. However, online monitoring can give extra information between validation loss maps. Regular loss maps at the end of the fill, provided that there are non-colliding bunches and that they can be done safely with high intensity in the machine, might be a better option for a more regular validation of the cleaning. Overall, not much time was needed for the betatron loss maps validation, due to the dramatic improvement provided by the ADT. Moreover, this time was in the shadow of the machine commissioning. The majority of the beam-time needed for collimation setup and validation is nowadays coming from the fills for off-momentum loss maps and asynchronous dump test.

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REFERENCES

[1] LHC design report v.1. : The LHC main ring. CERN-2004-003-V1, edited by O. S. Brning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock.

[2] B.Salvachua *et al.*, Cleaning and collimator operation - outlook, Proceedings of the LHC Beam Operation Workshop, Evian, 2013.

[3] B.Salvachua *et al.*, Cleaning performance of the LHC collimation system up to 4 TeV, Proceedings of IPAC 2013, Shanghai, China, p.1002.

[4] W.Hofle *et al.*, Controlled transverse blow-up of high-energy proton beams for aperture measurements and loss maps, Proceedings of IPAC 2012, New Orleans, Louisiana, USA, p.4059.

[5] G.Valentino *et al.*, Settings generation, management and verification, these proceedings.

[6] R.Bruce *et al.*, Simulations and measurements of cleaning with 100 MJ beams in the LHC, Proceedings of IPAC 2013, Shanghai, China, p.52.

[7] M.Cauchi *et al.*, High energy beam impact tests on a LHC tertiary collimator at CERN HiRadMat facility, Proceedings of IPAC 2013, Shanghai, China, p.954.

[8] M.Cauchi *et al.*, Preliminary comparison of the response of LHC tertiary collimators to proton and ion beam impacts, Proceedings of IPAC 2013, Shanghai, China, p.3412.

[9] L.Lari *et al.*, Simulations and measurements of beam losses on LHC collimators during beam abort failures, Proceedings of IPAC 2013, Shanghai, China, p.996.

[10] D.Wollmann *et al.*, Upgrade studies for the LHC collimators, Proceedings of IPAC 2011, San Sebastian, Spain, p.3750.

[11] E.Quaranta *et al.*, Cleaning inefficiency of the LHC collimation system during the energy ramp: simulations and measurements, Proceedings of IPAC 2013, Shanghai, China, p.975.