Performance of the LHC Collimation System during 2015

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PERFORMANCE OF THE LHC COLLIMATION SYSTEM DURING 2015

G. Valentino, R. Bruce, M. Fiascaris, H. Garcia, P. Hermes, R. Kwee, A. Mereghetti, D. Mirarchi,
E. Quaranta, S. Redaelli, A. Rossi, R. Rossi, B. Salvachua, P. Theodoropoulos, A. Valloni, J. Wagner
CERN, Geneva, Switzerland

Abstract

During the long shutdown, a total of 32 collimators were replaced or installed to improve the Run 1 system, including 18 new collimators with embedded beam position monitors, additional physics debris collimators, additional passive absorbers and the re-installation or displacement of existing collimators. The commissioning experience as well as the performance of the collimation system in 2015 is reviewed following these upgrades. In particular, the operational experience with the embedded BPM collimators is discussed, emphasizing the improvements on alignment efficiency and the strategy for better orbit monitoring. Improvements of collimation setting validation through an optimized loss map strategy are also presented. Further improvements planned for 2016 are discussed.

INTRODUCTION

The LHC collimation system has demonstrated excellent performance at intermediate design energy during Run 1 [1]. During Long Shutdown 1 (LS1), several hardware and software changes were made to improve the performance with beam parameters closer to the design values. Almost a third of the system was changed following various upgrades which affected all IRs. Eighteen new collimators with embedded BPMs replaced the previous TCTs in the experimental IRs and the TCSGs in IR6. This installation also improved the IR8 layout, where the existing two-beam collimators were replaced by single-beam collimators. The TCL layouts in IR1 and IR5 were improved, adding a total of 8 TCLs in cells 4 and 6. New passive absorbers were installed in IR3. Finally, 3 primary collimators in IR7 were removed and re-installed due to ventilation work, and another IR7 primary collimator was replaced due to heating problems.

The collimator controls rack configuration was upgraded, and the monitoring of the PXI systems was improved. In addition, the middleware controls were updated to FESA3 [2]. During Run 1, electromagnetic interference from nearby quadrupole magnets was found to affect the readings of some IR3 collimator LVDTs. Ten sensors on 5 collimators were replaced with a new design (I2PS) [3]. The BLM-based and BPM-based alignment feedback loops were moved from the Java collimator alignment application to a new FESA3 class [4].

HARDWARE COMMISSIONING

The configuration databases, logging variables and LSA parameters were updated with the new collimator devices. LVDT calibration tests were performed for all collimators, as well as temperature interlock tests, RBAC tests and the interlock response to power cuts and PRS reboot. Over 1500 machine protection tests were executed to ensure that the 18 position limits for each collimator could trigger an interlock in the expected conditions. This was the first major test campaign since 2011. The collimators have been imported into the AccTesting framework [5], and the tests are implemented as sign-only for now.

BEAM COMMISSIONING

The operational collimator settings are determined from the beam centers and beam sizes at each collimator, which are measured during beam-based collimator alignment campaigns [6]. During beam commissioning, the alignment was done using the BLM-based technique for all collimators due to the unavailability of the DOROS BPM electronics. The alignment time for all ring collimators is now 4 hours, down from the ~20 hours in 2010. The number of aligned collimators and total beam time required over the years, both for standard commissioning at the start of the year and machine reconfiguration throughout the year are shown in Fig. 1.

A list of the collimator settings used throughout the standard $\beta^* = 80$ cm machine cycle in 2015 is shown in Table 1. It was decided to keep the same settings in mm as in 2012 of the TCPs and TCSGs in in IR7, in order not to increase the impedance too much. The TCTs, as well as the IR7 TCLAs, were kept more open than in 2012, in order to increase the machine-protection margins [7]. During physics, when the TOTEM Roman pots were inserted, the TCLs in cells 4, 5 and 6 of IP5 were set to 15, 35 and 20 σ respectively.

SYSTEM PERFORMANCE

The performance of the collimation system in terms of cleaning inefficiency is measured using beam loss maps. The loss map procedure to qualify the betatron collimation is done by means of a transverse blow-up of the beam in the horizontal and vertical planes using the ADT transverse damper, while the momentum collimation is qualified by trimming the RF frequency by up to ±500 Hz from the operational value. At the start of 2015, three fills were used to qualify each point in the machine cycle after each tech-

Table 1: Collimator settings in units of σ at each stage of the machine cycle for the standard $\beta^* = 80$ cm physics runs.

Collimator Family	Injection	Flat Top	Squeezed	Collisions
TCP IR3	8.0	15.0	15.0	15.0
TCSG IR3	9.3	18.0	18.0	18.0
TCLA IR3	12.0	20.0	20.0	20.0
TCP IR7	5.7	5.5	5.5	5.5
TCSG IR7	6.7	8.0	8.0	8.0
TCLA IR7	10.0	14.0	14.0	14.0
TCSP IR6	7.5	9.1	9.1	9.1
TCDQ IR6	8.0	9.1	9.1	9.1
TCT IR1/2/5/8	13/13/13/13	37/37/37/37	13.7/37/13.7/15	13.7/37/13.7/15
TCL 4/5/6 IR1 and 5	parking	parking	parking	15/15/parking

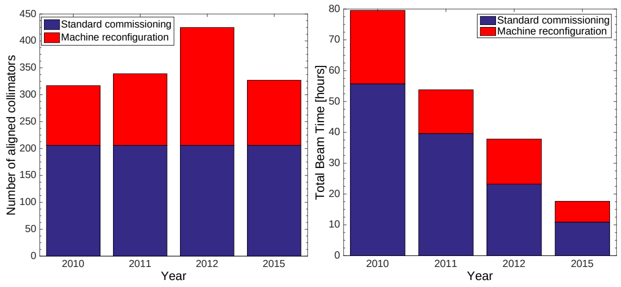

Figure 1: Number of collimators aligned (left) and total beam time used for alignment (right) for the standard commissioning and machine reconfigurations.

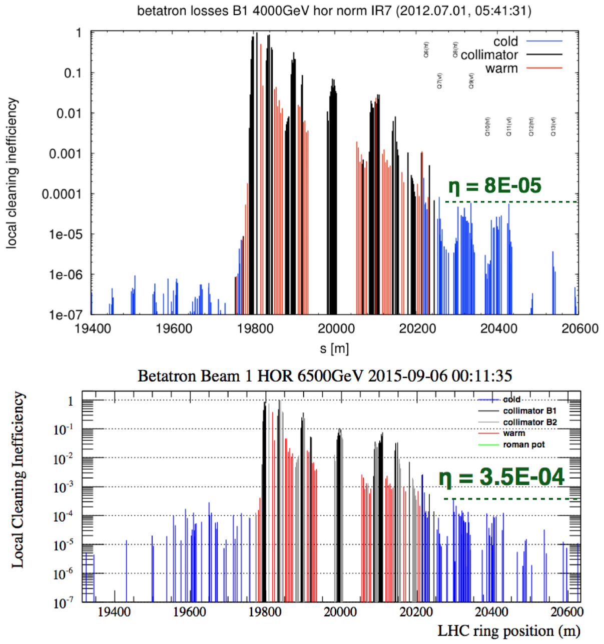

Figure 3: B1 horizontal loss maps with zoom in IR7 for proton beams, showing the comparison between the cleaning at 4 TeV in 2012 (top) and at 6.5 TeV in 2015 (bottom).

nical stop, however the loss map validation strategy was changed to that in Table 2 (as long as the collimator settings do not change) once the stability with 6.5 TeV operation was demonstrated [8].

The trend of the cleaning inefficiency in 2015, defined as the highest local leakage of beam particles out-scattered by collimator jaws to the IR7 dispersion suppressor, normalized to the losses at the primary collimator, is shown in Fig. 2, with a comparison to Run 1. The cleaning in 2015 is worse than in Run 1 as expected due to the higher energy and more open TCLA settings in IR7, and the collimation system continues to have stable performance despite only one full alignment per year. This is due to the very good machine stability and reproducibility. Zooms of the hierarchy in IR7 for loss maps done in collisions at 4 TeV in 2012 and 6.5 TeV in 2015 are shown in Fig. 3.

The availability of the collimation system during 2015 was high, providing the second least contribution of the systems which resulted in LHC downtime [9]. General issues observed throughout the year included LVDT glitches, temperature interlocks and problems with β^* limits. A tank misalignment was found for two collimators. A large offset of 3 mm with respect to the other IR7 collimators was noted for the TCLA.D6R7.B2 during beam commissioning. Survey measurements were performed, but it was not possible to make corrections during technical stops. The collimator is stable, and will be left as it is for 2016 and possibly fixed in the following end-of-year technical stop (it is possible to correct the offset via the settings determined from beam-based alignment). A tilt of over 2 mrad was observed in the TCL.6L5.B2 during beam commissioning, after a 400% measured-to-nominal beam size ratio was determined from beam-based alignment assuming both jaws to be parallel to the beam. The tilt was corrected during TS2, which was confirmed by a subsequent beam-based alignment and validation.

In 2012, the validation efficiency bottleneck for betatron loss maps was removed thanks to the deployment of the ADT blow-up technique [10]. In 2015, it was possible to greatly mitigate the remaining bottleneck for off-momentum loss maps with a new Java application that could send real-time RF trims up to 150 Hz (instead of the standard 500 Hz via LSA parameters) with a 12.5 Hz feedback from the BLMs. Several tests were performed in the shade of regular validation fills, including loss maps with a controlled emittance blow-up from RF [11]. Thanks to the

Table 2: Post-TS2 strategy for validation of collimator settings. The settings for the TCLs in collisions are for the case when the TOTEM Roman pots were not inserted.

Machine Mode	Betatron Loss maps	Positive Off-momentum	Negative Off-momentum	Asynchronous Dump	Fills
Injection	Yes	Yes	Yes	Yes	3
Flat Top	Yes	Alternate side	Alternate side	No	1
Squeezed	Yes	Alternate side	Alternate side	Yes	2-3
Collisions	Yes	Yes	Yes	Yes	3

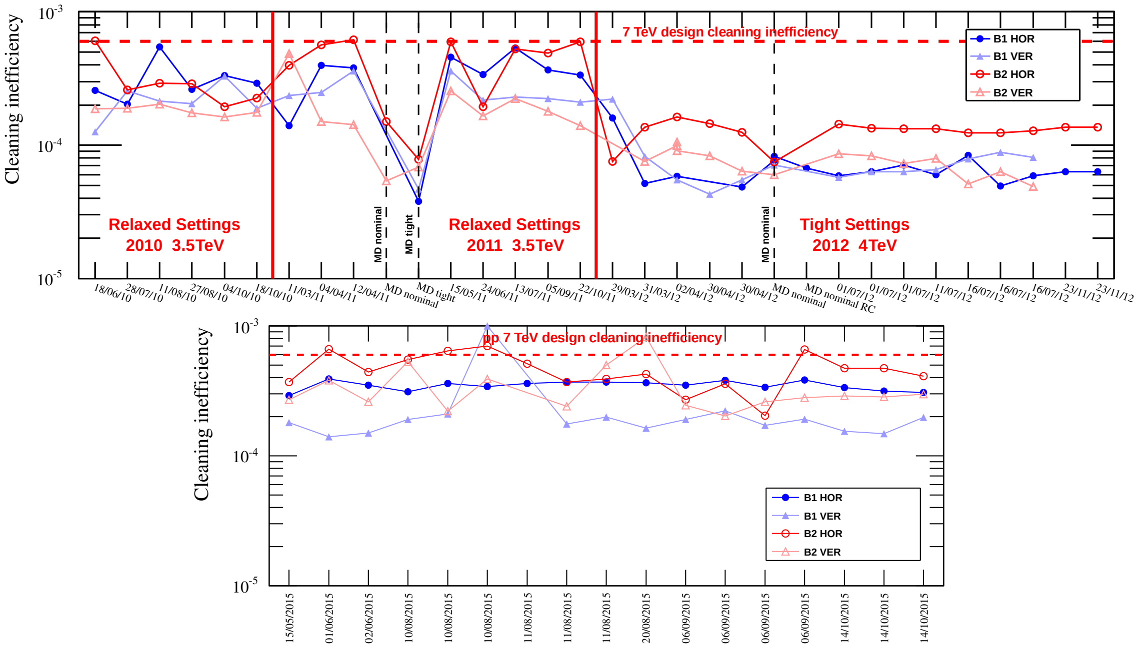

Figure 2: Cleaning inefficiency at top energy of the LHC collimation system in Run 1 at 3.5-4 TeV (top) and in 2015 at 6.5 TeV (bottom).

Java application, it was possible to reduce the number of fills required in several validations towards the end of the year. An example is shown for the post-TS2 validation in Fig. 4, where it was possible to perform the betatron loss maps in both beams and planes, as well as both signs of the off-momentum loss maps (positive and negative), and finally an asynchronous dump test, all in the same fill. This validation would normally have required 3 fills. Due to lack of opportunity, it was not possible to systematically reproduce these excellent results, and more commissioning time is needed in 2016 to make the method more robust and fully usable by the operational shift crew.

The cleaning performance of the collimation system with heavy ions is worse than for protons as expected (see Fig. 5). Higher losses in the B1 horizontal TCT in IR2 could be connected to observations of higher background in ALICE. Tracking simulations established that asymmetric IR7 TCP settings could help to mitigate the higher losses in IR2. The results were confirmed by means of an end-of-fill study done in the shade of the IP2 polarity switch validation, however the settings were not implemented due to time constraints as requested by ALICE.

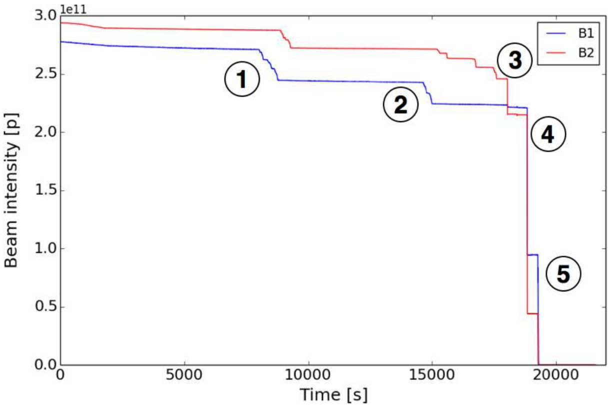

Figure 4: Beam intensities as a function for time during a post-TS2 fill for collimator settings validation: 1) Betatron H and V squeezed; 2) Betatron H and V collisions; 3) Positive off-momentum; 4) Negative off-momentum; 5) Asynchronous dump test.

EMBEDDED BPM COLLIMATORS

Two main reasons motivated the replacement of the 16 tertiary collimators at the experimental IPs and the IR6

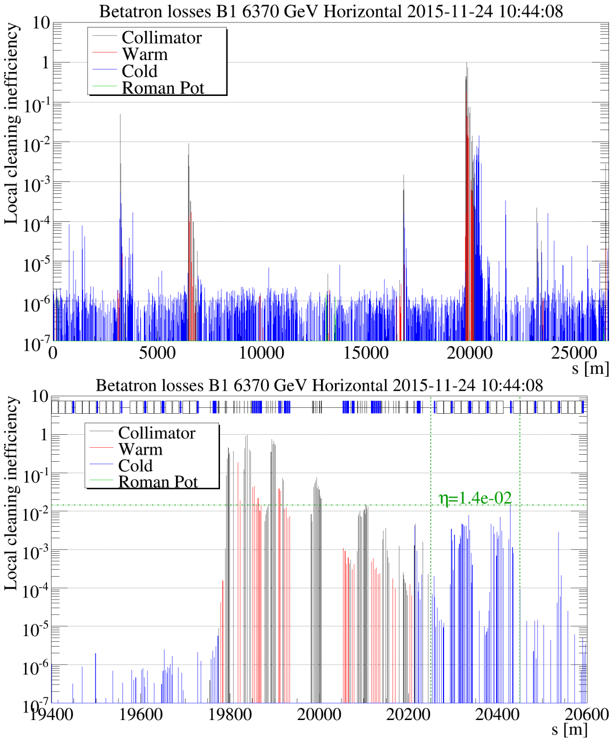

Figure 5: B1 horizontal betatron loss maps for ion beams, showing the high losses in IR2 in the full ring (top) and the reduced cleaning efficiency in IR7 (bottom).

TCSGs by new collimators with embedded BPM pick-ups. Embedded BPMs allow the possibility to perform the beam-based alignment faster, as demonstrated with beam in the SPS [12], and therefore respond more quickly to IR configuration changes such as crossing angle or β^*. Secondly, a direct monitoring of the orbit at the collimator locations allows to reduce the existing orbit margins in the TCSP-TCTP collimation hierarchy, which could lead to more room to push the β^* [13].

During beam commissioning, the IP1 TCTPs were equipped with the BPM acquisition electronics and software. The remaining TCTPs as well as TCSPs were eventually equipped for an MD in July [14]. The final version of the acquisition software with automatic calibration of gains and offsets in the electronics was deployed during TS2. The differences between the BLM-based and BPM-based alignment techniques are shown in Fig. 6. Apart from the drastic gain in time ($\sim$1 hour with the BLM feedback to $\sim$2 minutes with the BPM feedback), the BPM-based technique does not perturb the beam, and can be performed while maintaining the same initial gap in mm.

A fill-to-fill analysis was performed for the collimator BPM data acquired during several parts of the machine cycle, as shown in Fig. 7, specifically ramp, squeeze and stable beams. The fill-to-fill reproducibility is good, and perhaps this could be exploited in the dynamic parts of the cycle (ramp and squeeze) by means of a feed-forward into the collimator functions in 2016. On the other hand, in stable beams the intra-fill stability is much better than the inter-fill reproducibility, where a spread of up to 400 μm was found.

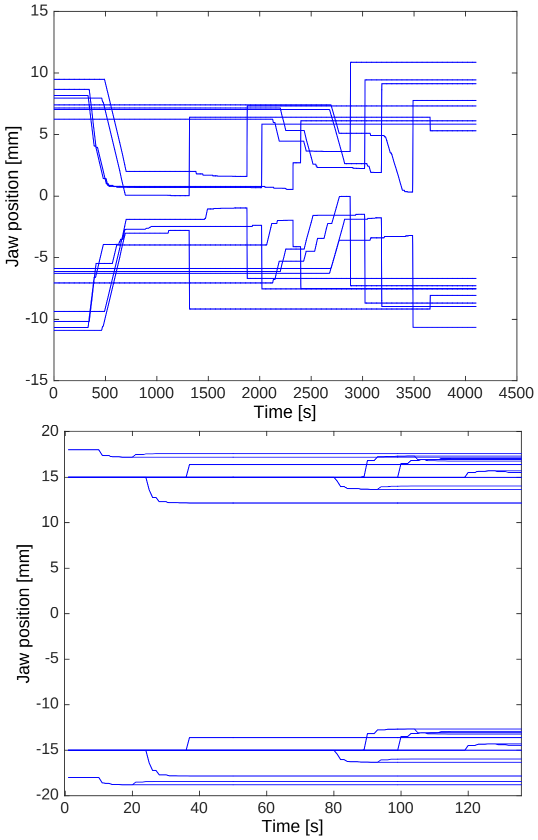

Figure 6: Time required to align the 8 TCTs in IP1 and IP5 in 2012 with the BLM-based alignment (top) and in 2015 with the BPM-based alignment (bottom).

The same analysis was also performed for the BPM data acquired during the combined ramp and squeeze during the p-p reference run at 2.51 TeV (see Fig. 8). These are the first measurements of the orbit during combined ramp and squeeze at the collimators, and will serve as a useful input for a possible implementation in 2016. The measured orbit will be compared in detail to MADX simulations to see if there is a good understanding of the dynamic behaviour.

The direct monitoring of the orbit at the TCSPs and TCTPs would have to be interlocked if the orbit margins in the collimator settings are going to be reduced to push the β^*. An interlock threshold scan was performed to determine the number of dumps that would have occurred during operation. A dataset of $\sim$50 fills after TS2 (when the DOROS acquisition software was final) with respect to a reference fill (first fill after TS2) was used. The analysis was done considering both individual interlocks and combined TCTP-TCSP interlocks, as shown in Fig. 9. Setting a conservative margin of $\sim$1 σ, which would not have caused any dumps in the post-TS2 fills, would already be a big improvement compared to previously assumed margins based on Run 1 data.

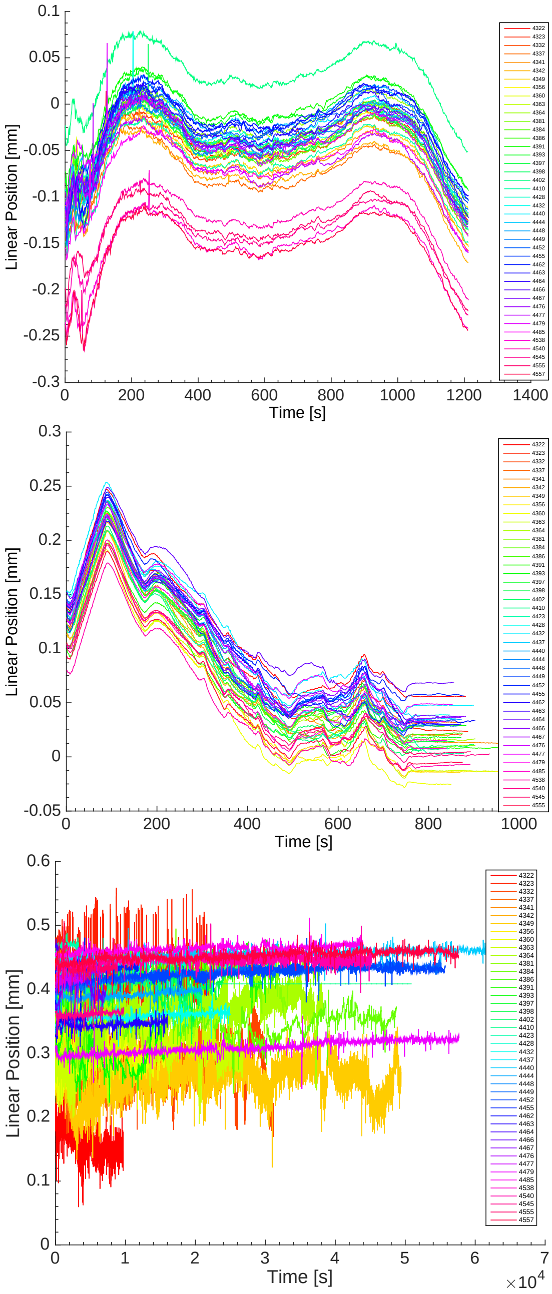

Figure 7: Fill-to-fill orbit measured at the TCTPH.4R1.B2 during the ramp (top), the TCTPV.4L8.B1 during the squeeze (center) and the TCTPH.4R5.B2 during stable beams (bottom).

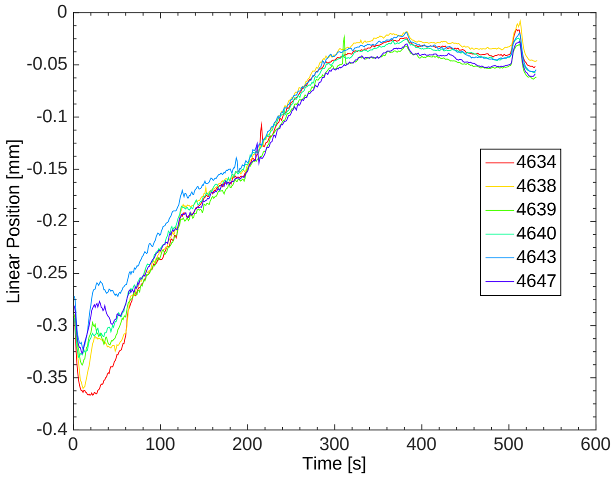

Figure 8: Fill-to-fill orbit measured during combined ramp and squeeze at the TCTPH.4L1.B1 in the 2.51 TeV p-p reference runs.

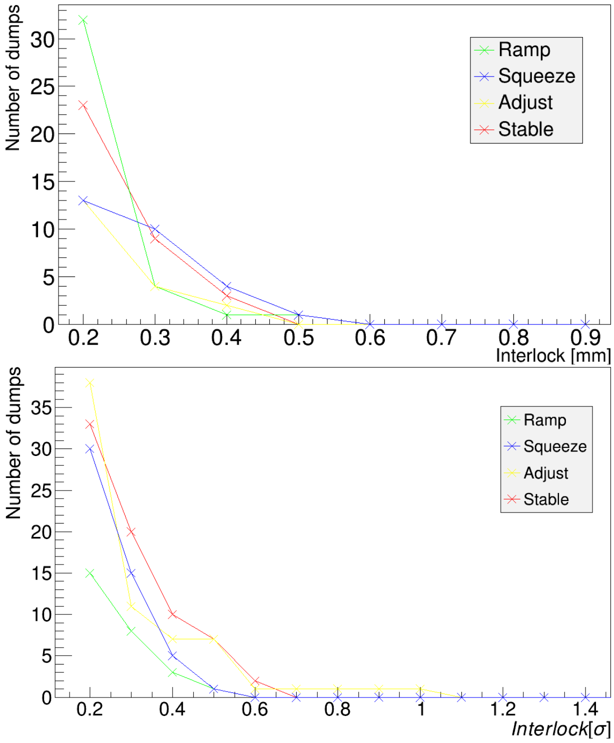

Figure 9: Number of predicted dumps for different BPM interlock thresholds for individual collimators (top) and a TCTP-TCSP combination (bottom).

COMMISSIONING PLANS FOR 2016

As no major changes will be made to the collimator control software, only a subset of the machine protection tests will be performed without beam, to ensure that the BIC in each IP is tested. With beam, several of the tests for the embedded BPM collimators performed throughout 2015 will be repeated. These include detailed BLM vs BPM alignment cross-checks and collimator scans to measure BPM non-linearities. In addition, tests of the new BPM interlock implementation would need to be performed. All the tests would ideally be done as soon as the nominal bunch is available (even if optics and orbit and not fully corrected yet) to be able to fully profit for the standard alignments shortly afterwards. After the embedded BPM tests, the usual alignments and validation at the 4 points in the machine cycle (injection, flat top, squeeze, collisions) will need to be performed. Feasibility tests are ongoing to see whether the alignment could be performed at a new BLM data rate of 100 Hz (up from 12.5 Hz in 2015).

CONCLUSIONS

After several hardware and software changes during LS1, the LHC collimation system continues to build on the performance achieved during Run I in terms of cleaning efficiency, stability and availability. Few issues were encountered in 2015, in particular related to tunnel misalignment, which were partially resolved during technical stops. The embedded BPM functionality is already being used for the collimator alignment, and the experience gained during 2015 will come in handy for the commissioning and operation during 2016. In addition, it is hoped that the direct orbit monitoring will be used to reduce the TCSP-TCTP collimator margin as one of the ingredients to push the β^*.

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