VALIDATION OF OFF-MOMENTUM CLEANING PERFORMANCE OF THE LHC COLLIMATION SYSTEM

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Abstract

The LHC collimation system is designed to provide effective cleaning against losses coming from off-momentum particles, either due to un-captured beam or to an unexpected RF frequency change. For this reason the LHC is equipped with a hierarchy of collimators in IR3: primary, secondary and absorber collimators. After every collimator alignment or change of machine configuration, the off-momentum cleaning efficiency is validated with loss maps at low intensity. We describe here the improved technique used in 2015 to generate such loss maps without completely dumping the beam into the collimators. The achieved performance of the collimation system for momentum cleaning is reviewed.

INTRODUCTION

The LHC collimation system [1] provides multi-stage cleaning in two main cleaning insertions. Out of the eight insertion regions (IRs) one of them is dedicated to betatron cleaning (IR7) and another one is dedicated to off-momentum cleaning (IR3). A hierarchy of primary, secondary and absorber collimators ensures the required cleaning in order to avoid quenches of super-conducting magnets during regular operation [2] . The primary collimators are the closest elements to the beam intercepting particles from the primary halo. Secondary collimators and absorbers will intercept secondary halo and absorb showers from upstream collimators. The final collimator settings are validated [3] by analyzing the loss distribution along the ring in pre-define planes (horizontal, vertical and off-momentum), which are called loss maps.

The validation of LHC configuration through loss maps used to be a tedious exercise requiring several fills. Note that the validation is done after every system setup, a few times during the year (typically, after scheduled technical stops) and every time the machine configuration is changed. In particular, off-momentum validation of a single configuration required two dedicated fills where the beams were completely lost on the IR3 collimators through frequency trims (a complete validation required probing both signs of energy errors). This reduced significantly the machine availability for physics so effort was put in speeding up this procedure without jeopardizing the quality of the validation. In this paper, a new method for off-momentum loss maps, which allowed to test losses for both signs of energy errors and leave enough beam to perform other validation tests, is described. The overall performance of the LHC off-momentum system, monitored at 6.5TeV through this new validation method, is also presented.

Table 1 shows the collimator settings used during the 2015 proton-proton run, in IR3 and in IR7 for 450 GeV and 6.5 TeV beam energy. The collimator gaps are expressed in units of beam sigma for the nominal normalized normalized emittance of 3.5 mrad mm without taking into account the off-momentum contribution.

$$\sigma_{\beta_{x,y}}(z) = \sqrt{\epsilon \beta_{x,y}(z)} \tag{1}$$

where ϵ is the emittance and $\beta_{x,y}(z)$ is the beta function for horizontal (x) and vertical plane (y) at the collimator position around the ring (z-axis). For skew collimators tilted azimuthally by an angle θ, the effective beam size at the collimator plane is

$$\sigma_{\beta_\theta} = \sqrt{\sigma^2_{\beta_x} \cos\theta^2 + \sigma^2_{\beta_y} \sin\theta^2} \tag{2}$$

Table 1: Collimator Settings in IR3 and IR7 (Primary / Secondary / Absorber) Used in 2015 for the Proton-Proton Run and Beam Energy of 450 GeV and 6.5 TeV

LHC region	**Beam energy 450 GeV**	**Beam energy 6.5 TeV**
IR7	$5.7\,\sigma/6.7\,\sigma/10.0\,\sigma$	$5.5\,\sigma/8.0\,\sigma/14.0\,\sigma$
IR3	$8.0\,\sigma/9.3\,\sigma/12.0\,\sigma$	$15.0\,\sigma/18.0\,\sigma/20.0\,\sigma$

However, the contribution from the dispersion to the beam size is not negligible in IR3. The dispersion contribution to the beam enveloped is defined as

$$\sigma_D(z) = \sqrt{D(z)^2 \left\langle \left(\frac{\Delta p}{p}\right)^2 \right\rangle} \tag{3}$$

where $D(z)$ is the dispersion along the ring and p is the particle momentum. The total beam size is the contribution from both betatron and off-momentum as follows:

$$\sigma(z) = \sqrt{\sigma_{\beta_{x,y}}(z)^2 + \sigma_D(z)^2}. \tag{4}$$

With the equations presented earlier one can express the collimator gaps taking into account the betatronic and dispersive contributions. The Twiss parameters (beta and dispersion) used are shown in Table 2 for the optics used in 2015. The average bucket half height assumed for the calculation comes

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Table 2: Beta and Dispersion at the Location of the Horizontal Primary Collimator in IR3 and IR7

LHC	Beta (m)	Dispersion (m)
IR7	150	0.375
IR3	132	2.173

from [1] scaled to the RF capture voltage used at the LHC [4]; 6 MV at injection and 10 MV at flat top.

Table 3 shows the equivalent beam sizes for the primary collimators in the horizontal plane in IR3 and IR7 taking into account also the dispersion contribution.

Table 3: Equivalent Settings for the Primary Collimators Assuming Both Betatron and Off-Momentum Contributions

LHC region	Beam energy 450 GeV	Beam energy 6.5 TeV
IP7	5.6 σ	5.4 σ
IP3	6.0 σ	9.7 σ

VALIDATION REQUIREMENTS

In order to validate the collimator alignment and final collimator settings used in the machine, the leakage due to off-momentum losses needs to be quantified [5]. The leakage from off-momentum halo cleaning needs to be below a certain margin in order to avoid the quench of the superconducting magnets in the dispersion suppressor in IR3 due to off-momentum losses.

The technique used in Run 1 (2010 - 2013) to measure this cleaning was to change the RF frequency by an amount large enough to move the beam to the collimators in IR3. This was done with low intensities in the machine, below 3×10^{11} protons per beam. The RF frequency shift used was very large, ±500 Hz. The cleaning leakage was well measured but the beam was lost at the collimators, making the validation lengthy in particular at top energy.

The LHC collimator configuration is validated at several stages during the LHC cycle: injection, flat top, squeezed beams and collisions. This is done after every technical stop or change of configuration. The betatron validation was optimized in 2012, achieving the full validation of the LHC cycle in one energy ramp. However the off-momentum loss map was not optimized and each validation required a ramp. In 2015 there were more than 80 off-momentum loss maps taken to validate the machine.

LOSS MAP PROCEDURE IN 2016

Because the dispersion is very different in IR3 than in IR7, the beam moves faster towards IR3 collimators than towards IR7 following a change of RF frequency. Figure 1 shows the equivalent collimator settings (in total sigma size) as function of the RF frequency shift for injection energy (top) and top energy (bottom). IR3 is shown in red, while IR7 is shown in blue. The minimum frequency when IR3 collimators start catching primary off-momentum losses is when IR3 equivalent settings are below those in IR7. This frequency is about 30 Hz for injection and 130 Hz for top energy. The final shift of frequency should come when the losses in IR3 are measurable by beam loss monitors in the dispersion suppressor of IR3 but an optimum point below the 500 Hz could be found avoiding the beam dump.

Figure 2 shows the ratio between the measured beam losses in IR3 divided by the losses in IR7 as a function time during an RF frequency swap. The point were the losses in IR3 become higher than IR7 is about 200 Hz but the beam is dumped the second after. A feedback loop at 25 Hz was implemented in a Java application, which acquires the beam losses at the primary collimators of IR3 and IR7, as well as the dispersion suppressor in IR3. As soon as the ratio of losses in the IR3 DS to the background signal increases above a pre-defined threshold, and as long as the losses are higher in IR3 than in IR7, the frequency shift is reverted. In addition the swap of frequencies is done faster achieving higher losses with smaller frequency shift and the revert of the frequency is possible in these conditions without dumping the beam.

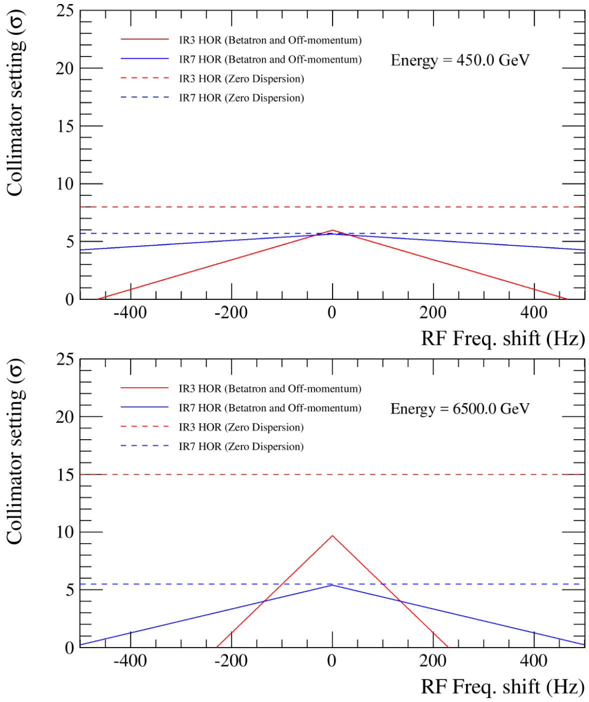

Figure 1: Equivalent collimator settings in IR3 and IR7 as function of RF frequency shift for 450GeV beam energy (a) and 6500GeV (b).

OFF-MOMENTUM CLEANING PERFORMANCE

Out of the 80 off-momentum loss maps done in 2015, 50 were done during proton-proton nominal run. In each of these loss maps the leakage from off-momentum cleaning to the dispersion suppressor is measured and monitored along

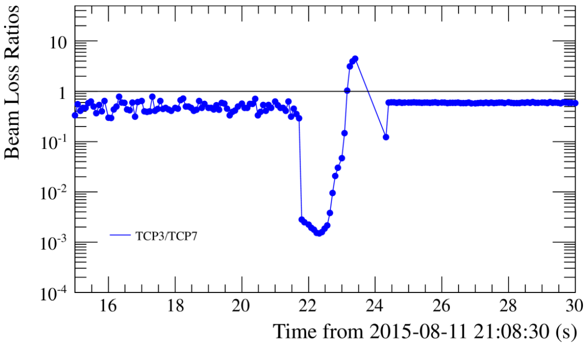

Figure 2: Ratio of measured beam losses at the primary collimator in IR3 divided by measured losses in IR7 as a function of time during an RF frequency swap.

the year. Figure 3 shows the generated beam losses along the ring. The main losses occurs in IR3, as shown in the figure, but the contribution from IR7 is comparable. A zoom around IR3 is shown in Figure 4, where the red lines indicate the leakage into the dispersion suppressor. The losses in the dispersion suppressor are measured and normalized to the highest loss at the corresponding collimator (Beam 1 or Beam 2). This quantity is shown in Figure 5 for all the loss maps analyzed. The cleaning in the dispersion suppressor remains below $4 \cdot 10^{-3}$ all the year and is very stable for Beam 1 and Beam 2 and both off-momentum sides. This was achieved with only one collimator alignment per year therefore it reflects an excellent machine reproducibility during the run.

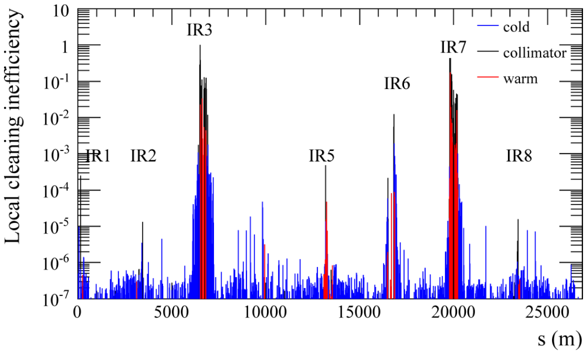

Figure 3: Cleaning inefficiency of the LHC off-momentum collimation along the proton-proton run in 2015.

CONCLUSION

During 2015 the technique used in the LHC to generate off-momentum losses for the validation of the collimator settings was studied and a new optimal point for the RF frequency change needed was proposed and used during the year. This avoided unnecessary beam dumps during the machine protection validation of the LHC gaining time for physics production.

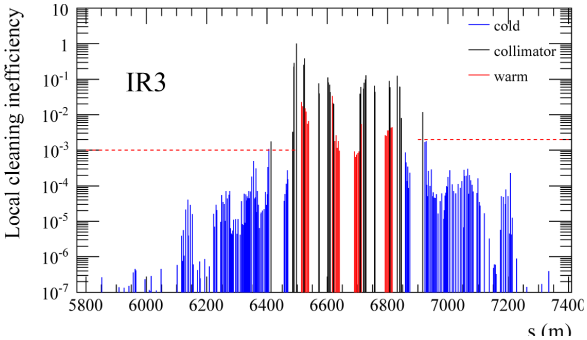

Figure 4: Cleaning inefficiency of the LHC off-momentum collimation along the proton-proton run in 2015.

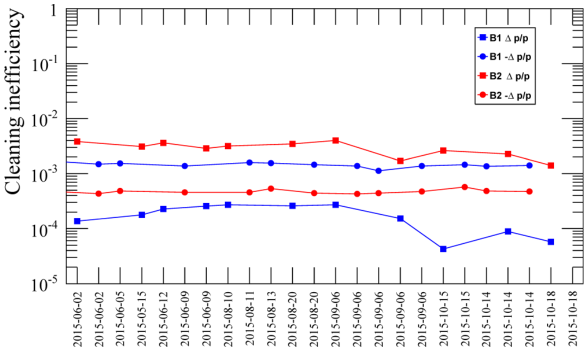

Figure 5: Cleaning inefficiency of the LHC off-momentum collimation along the proton-proton run in 2015.

The cleaning inefficiency in the dispersion suppressor area of IR3 was measured and monitored during the year. The inefficiency remains below $4 \cdot 10^{-3}$ during all the proton proton run at 6.5 TeV beam energy. This was achieved with only one collimator alignment campaign at the beginning of the year during the commissioning phase of the LHC. The good stability of the cleaning inefficiency reflect the excellent machine reproducibility of the LHC during 2015.

ACKNOWLEDGEMENT

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