CERN-ACC-NOTE-2014-0061

22 August 2014
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Study on off-momentum tail scraping in the LHC

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Keywords: LHC beam scraping, off-momentum tail, collimation, abort gap cleaning

Summary

A study on off-momentum tail population in the LHC was performed through collimator scraping at high dispersion region. High intensity measurements at the end of a physics fill with 25ns bunch spacing were carried out on 16th December 2012, using primary collimators (TCPs) in the momentum cleaning insertion (IR3) as scrapers. The off-momentum cuts were applied up to the level where the IR3 primary collimator is the aperture bottleneck for all particles outside the bucket, and the TCPs in the betatron cleaning insertion (IR7) are still the primary restriction of aperture of the machine in the transverse plane for particles inside the bucket. This because whether a particle is lost in IR3 or IR7 is not given only by the momentum offset but also by the betatron amplitude, as explained in the text. A significant decay of the abort gap (AG) population was observed, while moving in the collimator jaw on the side where particles with negative off-momentum are expected. The level of the AG popupation achieved was at a similar level as when the active AG cleaner was on, opening the possibility to establish a passive AG cleaning with TCPs. At the end of the measurement the closed collimator jaw was opened in one step, allowing to see the repopulation time of the abort gap.

Table 1: Optics parameters and operational settings of TCPs used, including the momentum cut performed for zero betatron amplitude. The σ values are given for a normalised emittance of $\epsilon = 3.5\ \mu$m rad.

Coll. Name	**IR**	**beam**	β_x**[m]**	D_x**[m]**	σ_x**[**μ**m]**	Nσ	δp/p cut
TCP.6L3	3	1	131.52	2.11	344	12	2.0e-3
TCP.C6L7	7	1	150.53	0.48	368	4.3	3.3e-3
TCP.6R3	3	2	131.52	2.48	344	12	1.7e-3
TCP.C6R7	7	2	150.53	0.39	368	4.3	4.1e-3

1 Introduction

There were several aims of this MD, with the main ones being:

- Study settings for the TCP in IR3 which leads to a beam loss sharing between the two collimation insertions IR3 and IR7.
- To study the AG population, and the level of AG cleaning which can be achieved using passive absorbers placed at the edge of the RF bucket

With beam loss sharing it is meant to spread the beam loss between the two collimation insertions, in order to have about the same amount of losses in the two IRs (usually in operations IR7 has much higher losses than IR3 [1]). This is related to studies on machine hardware damages, induced by the high level of radiations in the collimation insertions [2].

In order to achieve the items above, scraping with TCP in IR3 was performed. One of the key points of the experimental procedure was to determine the final position of the TCP jaw with respect to beam orbit, which gives the δp/p cut. The difficulty comes from the fact that the two collimation cleaning insertions IR3 and IR7 are not completely decoupled. As it is well known, betatron cleaning is performed in IR7, while IR3 is dedicated to momentum cleaning. In order to have the two insertions completely decoupled, one would ideally need to have $D_x \simeq 0$ in IR7. As can be seen in Table 1, LHC does not fulfil such condition, making the two insertions partially coupled. To find a solution to this problem of coupling, one needs to look at the equation which describes the relative components playing a role in the displacement of each particle. The equation which describes the particle trajectory in the real space (taking into account that the trajectory in the phase space is dense due to the multiturn effect) is reported in Eq. (1), where s is the coordinate along the ring, N is the number of betatron sigma, ϵ is the geometric emittance which is calculated assuming a normalized emittance of 3.5 μm rad and $\frac{\delta p}{p}$ the momentum deviation, while $\beta_x(s)$ and $D_x(s)$ are the twiss parameters:

$$x(s) = N\sqrt{\beta_x(s)\epsilon} + D_x(s)\frac{\delta p}{p} \qquad (1)$$

Assuming now that the collimator jaw is placed at N_c betatron sigma, and taking into account particles with a $\frac{\delta p}{p}$ equal to the RF bucket height (i.e. 3.6×10^{-4}), using the settings in Table 1, the real cut (N) in units of betatron sigmas performed in IR7 on such particles is:

$$N = (N_c^{IR7}\sqrt{\beta_x^{IR7}(s)\epsilon} - D_x^{IR7}(s)\frac{\delta p}{p})\frac{1}{\sqrt{\beta_x^{IR7}(s)\epsilon}} \simeq 3.8\sigma_x \quad (2)$$

Replacing this real cut in the eq. (1), it is possible to find:

$$N_c^{IR3} = (N\sqrt{\beta_x^{IR3}(s)\epsilon} + D_x^{IR3}(s)\frac{\delta p}{p})\frac{1}{\sqrt{\beta_x^{IR3}(s)\epsilon}} \simeq 6.0\sigma_x \quad (3)$$

This is the position of the collimator jaw in IR3 which leads to have the tightest cut on off-momentum particles, while ensuring at the same time that the TCPs in the IR7 are still the primary restriction of aperture of the machine for particles inside the RF bucket, without breaking the collimation hierarchy.

2 Beam Conditions and MD Experimental Procedure

Measurements were performed on the 16th December 2012, after more than 6 hours of collisions at 4 TeV. The fill number was 3453, and a summary plot of beams intensity during the whole fill is shown in Fig. 1. The injection scheme was: 396 bunches at 25 ns spacing, intensity of $\sim 4.0 \times 10^{13}$ p, with peak luminosity of 6×10^{32} cm^{-2}s^{-1}. The MD started at 21:50.

For each beam, the IR3-TCP jaws on the negative off-momentum side were closed in steps from 12 to about 6 σ while monitoring beam losses in IR3/7, beam intensity and population of the abort gap. As monitors for beam losses the standard LHC-BLM system was used [3], BCT and FBCT (Beam Current Transformers and Fast BCT) were used to measure beam intensity [4,5], and Synchrotron-Light Telescope (BSRA) to estimate the particle population in the AG [6]. The measuremets consisted in the movement toward the beam core direction of the collimator jaw in IR3, useful to catch particles outside the RF bucket that lose energy due to synchrotron radiation. Particles with negative momentum deviation were expected to be on the right or left side, for beam 1 or beam 2, respectively (i.e. where the displacement due to $D_x \times \delta p/p < 0$). Jaw movements were made with initial steps of 10 μm, decreased to 5 μm while approaching the circulating beam. As the length of the steps, their repetition rate was changend accordingly. It ranged from 3 s, while moving toward the off-momentum halo with 10 μm steps, to 10 s once it was reached, decreasing the steps to 5 μm. The movement of the selected jaw of the TCP in the IR3 was stopped once it reached settings corresponding to the condition of being the aperture bottleneck for all particles outside the bucket, while particles inside the bucket still see the IP7 primary at 4.3 σ as the bottleneck. This position can be calculated as explained in Section 1.

Once the final position of each jaw was reached, and after waiting for achieving steady conditions, the jaws were opened in one step. This allowed to see the repopulation time of the abort gap.

A summary plot of the movements performed by the TCP jaws used, and of the AG population, as function of time for the whole fill are shown in Fig. 2 and 4, respectively. A zoom of the TCP jaws movements during the MD is shown in Fig. 3.

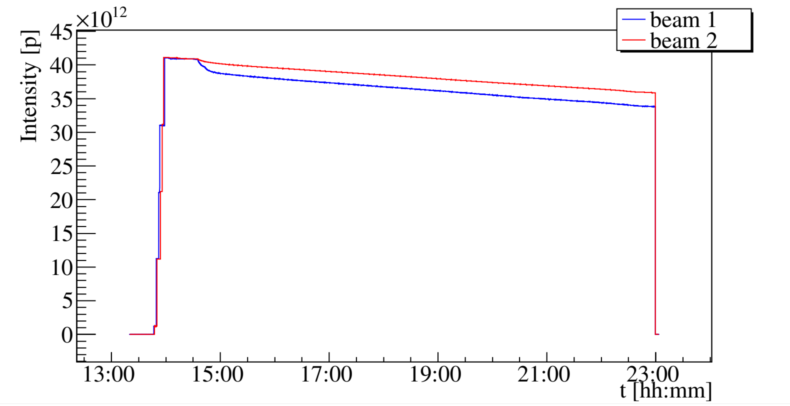

Figure 1: Circulating intensity in the LHC during fill 3453, for beam 1 (blue) and beam 2 (red)

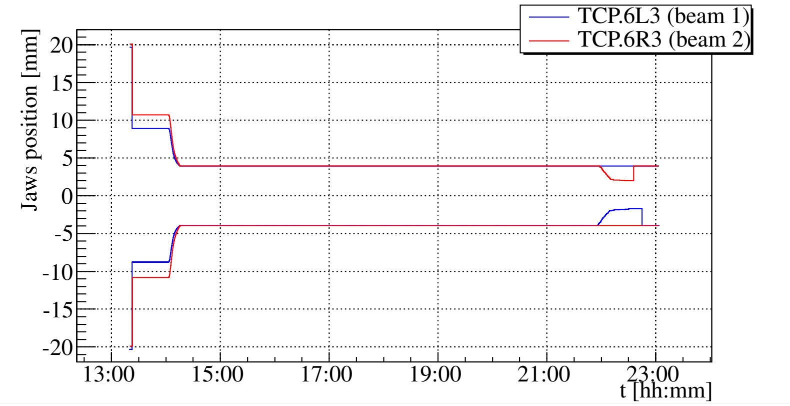

Figure 2: Movements performed by TCP's jaws in IR3 during fill 3453, for beam 1 (blue) and beam 2 (red), in mm.

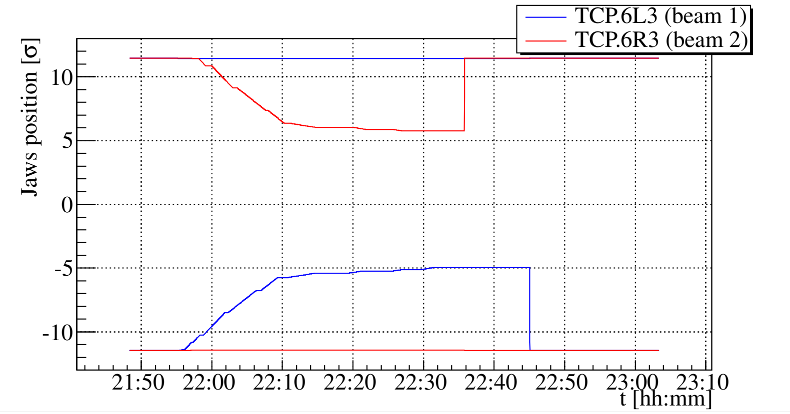

Figure 3: Movements performed by TCP's jaws in IR3 during the MD, for beam 1 (blue) and beam 2 (red), in unit of beam sigma.

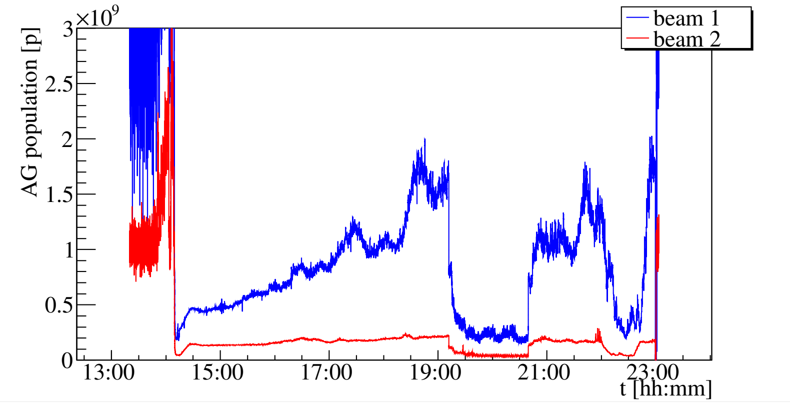

Figure 4: AG population during fill 3453, for beam 1 (blue) and beam 2 (red)

In order to compare the AG cleaning performance achieved using the TCPs in the IR3 as scrapers, with respect to the active AG cleaning method through transverse damper excitations gated on the AG [7], the AG cleaner was turned off about 1 hour before starting the MD.

In the closed position, the IR3 primary was at 6 betatron sigma, while the secondaries remained at 15 σ, meaning that there in principle was a 1-stage cleaning in IR3. The cleaning inefficiency in the IR3 dispersion suppressor was about 10^{-3}. On the other hand, the leakage to the TCTs in IR2 (beam 2) and IR5 (beam 1) was on the order of 10%. Occasionally we reached 30% of the dump limit on these collimators during the scraping.

3 Data Analysis

In the first part of this section a general analysis of the MD procedure is presented, while in the second one a more detailed analysis regarding the AG population is reported. We mainly show: checks that the procudures were well made (first part), and comparisons between the performance of active and passive AG cleaning methods (i.e. through transverse damper exitations or using TCPs jaw). In the second part a first estimation of the AG re-population rate is given too.

3.1 MD general analysis

As introduced in Section 2, the main observables used during the TCP jaw movements were beam losses in IR3/7, beam intensity and population of the abort gap. A summary plot for the scan on beam 1 and beam 2 is given in Fig. 5 and 6, respectively. From these plots can be seen that the beam loss sharing between IR3 and IR7 can be achieved without too many difficulties. This last sentence needs more explanations regarding the assumptions implicitely made in it. In the Fig. 5 and 6 are shown the signals of the BLMs placed just after the TCP which is moving in IR3 and the one placed at the end of the collimation insertion in IR7 (blue and red, respectively). Regarding the BLM in IR3 this is justified by the assumption that the signal of a BLM placed just after a TCP is proportional to the number of particles

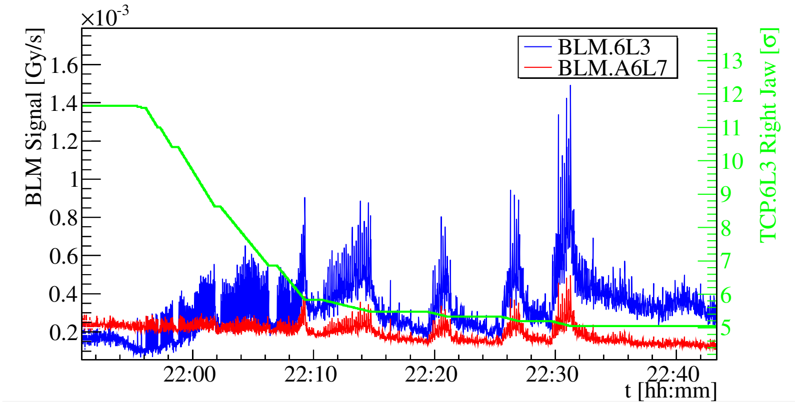

Figure 5: Beam 1 losses recorded in IR3 (red) and IR7 (blue) and half gap of primary collimators in IR3 (green) versus time during the whole scan

impinging on it. In the IR7 the "natural" choose would be to look at the signal of the BLM just after the TCP acting in the same collimation plane of the one moving in IR3 (for example the TCP.C6R7 for beam 1). However the presence of nonlinerities makes different planes coupled, and to compare BLMs which are so distant between each other and with so different overall position in the insertion geometry would needs to take into account the development of the various particle showers seen by the BLM. For this reason it is taken the BLM at the end of the IR7 insertion which sees the whole losses developed in the collimation system, which are shared between the various collimators. Hence the sentence from where we started it is valid only in first approximation. On the other hand, the final collimator settings for which this condition is achieved, agree well with the theoretical expectations reported in Section 1, which supports the assumptions just made. In particular for beam 2 in Fig. 6, the TCP scan and beam loss sharing are very good, while for beam 1 in Fig. 5, the TCP scan was a bit too deep into the beam direction. In any case from this last figure it is possible to see that when the TCP jaw was within 6 and 7 σ a good level a beam loss sharing was achieved, while once the jaw crossed over the theoretical value of 6 σ the losses in IR3 were higher than in IR7, meaning that tighter cuts on the circulating particles were performed in IR3 than in IR7.

Beam intensity and AG population versus the TCP momentum cut for zero betatron amplitude is given in Fig. 7, for both beams during the whole scans. Since the beam intesity data are taken from BCT which integrates over bunched and un-bunched particles, from this plot it is possible to see that only a fraction of a percent of beam was measured in the range between 0.8 and $1.0\times10^{-3}\delta$p/p.

Unfortunately due to a failure in the logging system, FBCT (which integrates only on bunched particles) data were not available for further offline analysis.

3.2 Abort Gap Population

As introduced above, a study on the AG population was performed during the MD. To have a reference of how the AG population decreases using the active AG cleaner, it was switched on with different gains about two hours before the MD, and then swithed off after about one

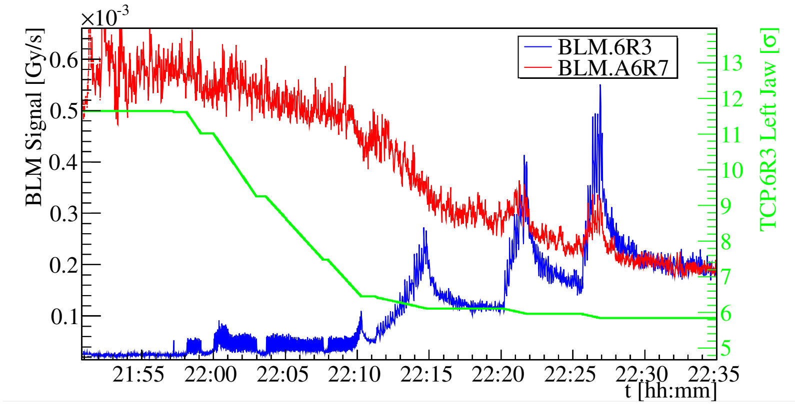

Figure 6: Beam 2 losses recorded in IR3 (red) and IR7 (blue) and half gap of primary collimators in IR3 (green) versus time during the whole scan

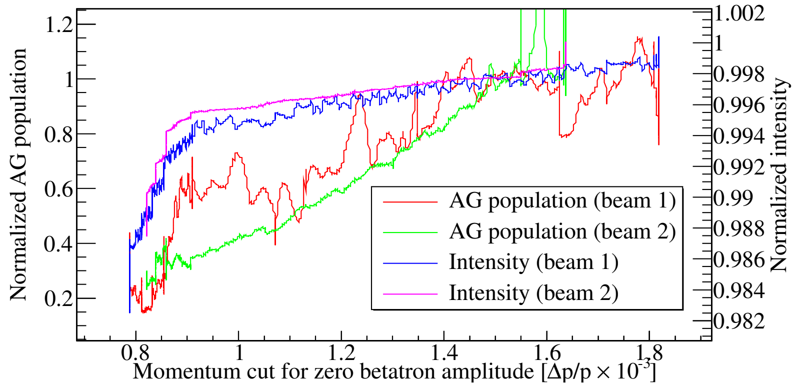

Figure 7: Beam current and abort gap population versus the momentum cut during the scan of Fig. 5 and 6, normalized to their initial value at the beginning of the scan.

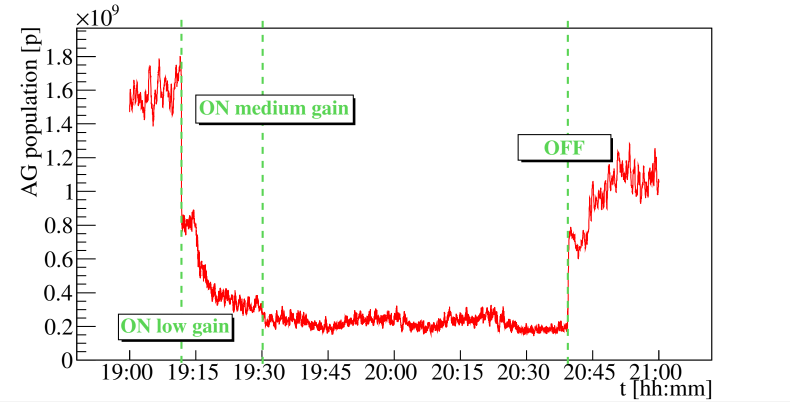

Figure 8: Effect of the active AG cleaner on beam 1. Reported the AG population as function of time.

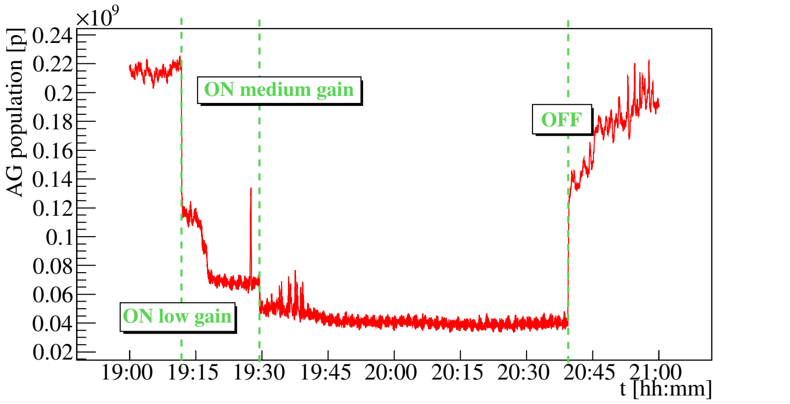

Figure 9: Effect of the active AG cleaner on beam 2. Reported the AG population as function of time.

hour, in order to recover a steady population for the beginning of the MD. In Fig. 8 and 9 the effect of the active AG cleaner is shown, for beam 1 and beam 2 respectively. Here it is clearly visible when it was switched on with low gain initially, which then was increased to medium gain, and finally switched off at about 20:40. As can be seen from these plots, the data for beam 1 are much more noisy than for beam 2, which was the case during the whole MD and for different observables.

The AG cleaning achieved by the IR3 TCP scraping is shown in Fig. 10 and 11, for beam 1 and beam 2 respectively. Here the AG population as function of the jaw position is reported. What is interesting to note in the last four figures mentioned (i.e. Figs. 8–11), is that at the beginning of the MD the AG population for beam 1 is almost one order of magnetude higher than for beam 2, which will play a role in the following.

A direct comparison of the reduction of the AG population achieved with the two methods are shown in Fig. 12 and 13, for beam 1 and beam 2 respectlively. The behavior of the abort gap population, with the two cleaning methods, are shown as function of time and normalized to their initial value. As can be seen from these figures, the final reduction of the AG population achieved with the two methods is comparable. This could open the

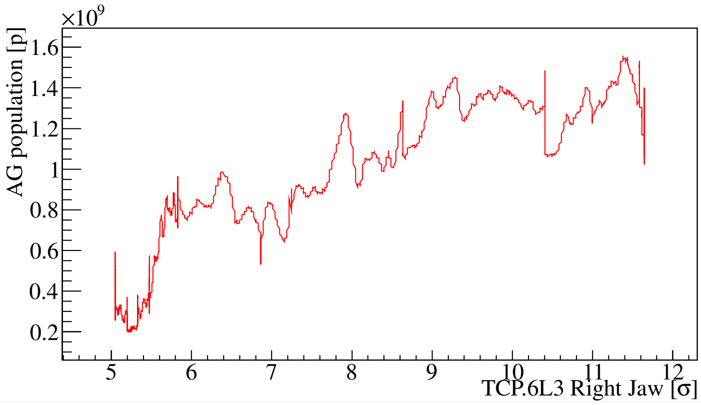

Figure 10: AG population as function of collimator jaw position during the IR3 TCP scan, for beam 1.

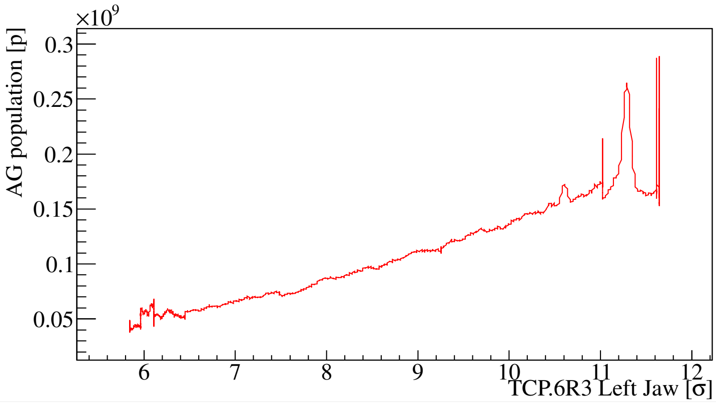

Figure 11: AG population as function of collimator jaw position during the IR3 TCP scan, for beam 2.

possibility to establish a passive AG cleaning with the TCPs. It is important to note that this would not be done through a scan. Instead the IR3 TCP would be left at the desired final setting (at the level of the RF bucket height) at the end of the ramp. On the other hand this would imply to go closer to the beam core also with the rest of the collimation chain in IR3 in order to keep down the inefficiency of the system, inducing an increase on beam impedance which needs to be studied in detail. The spikes visible in Fig. 13 and not in Fig. 12 are due to the stepping movement of the TCP jaw in IR3. These spikes are hidden in background losses for the case of beam 1 due to much bigger absolute AG population with respect to beam 2, as mentioned above.

As introduced in Section 2, after waiting some minutes with the jaw closed in order to stabilize all the observables taken into accout, the jaw was moved out in one step. Assuming a constant re-population rate of the AG, it can be extrapolated by a linear fit on the AG population. This fit ranges from the point in which the jaw was retracted until when the steady state of the AG population is restored. This measurement is reported in Fig. 14 and 15, for beam 1 and beam 2, respectively. The slope of the linear fit gives the re-population rate of the AG, which is $\sim 2.1 \times 10^6$ p/s and $\sim 2.9 \times 10^5$ p/s for beam 1 and beam 2

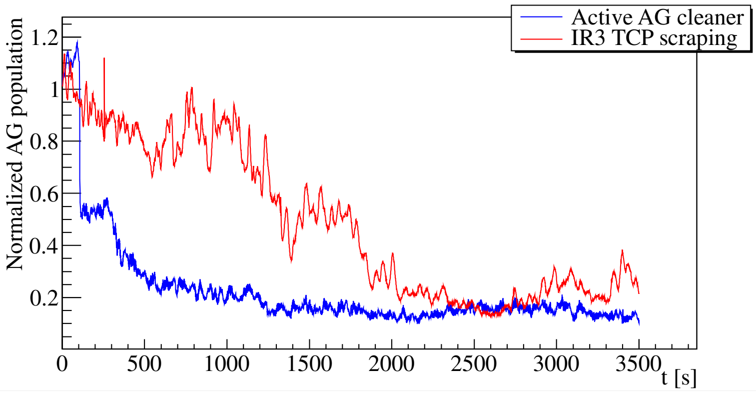

Figure 12: Comparison between active AG cleaner (blue) and IR3 TCP scraping (red) effects on AG population as function of time, for beam 1.

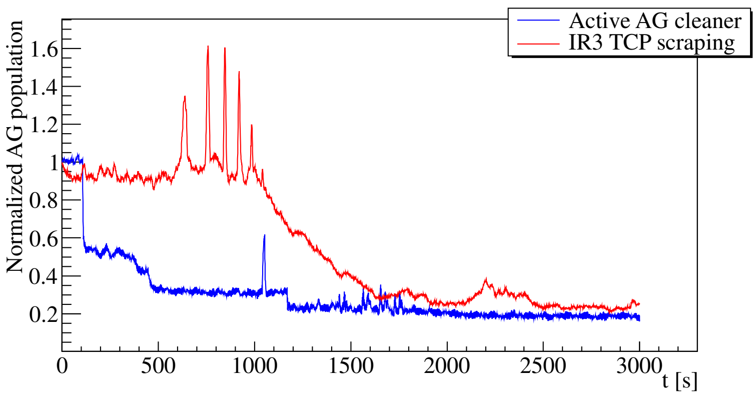

Figure 13: Comparison between active AG cleaner (blue) and IR3 TCP scraping (red) effects on AG population as function of time, for beam 2.

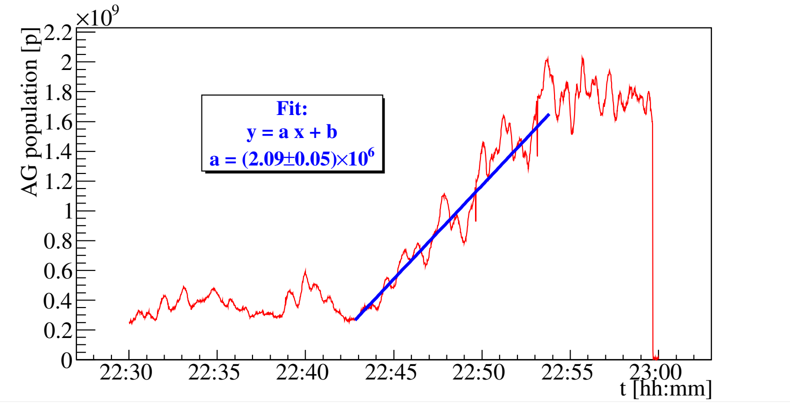

Figure 14: Measurements of AG repopulation rate for beam 1. Reported AG population as function of time, with relative linear fit and its parameters.

respectively. This can be translated, assuming the same debunching rate for each bunch, as $\sim 5.3 \times 10^3$ p/s/bunch and $\sim 7.3 \times 10^2$ p/s/bunch for beam 1 and beam 2 respectively. The order of magnitude of difference between the two re-population times is strictly related to the order of magnitude of difference in the absolute value of AG population, which could be given by a different calibration of the detectors for the two beams. Since the steady state of the AG population is reached in about the same time range, the difference of about one order of magnitude in the AG populations is directly translated in one order of magnitude difference in the AG re-population time.

Interesting to note is the difference in the AG re-population when either active or passive cleaning is performed. In case of active AG cleaner, when it is switched off, the re-population of the AG is almost instantaneous (Figs. 8 and 9); while when the TCP jaw used for the scraping is retracted, a constant re-population of the AG is seen, which last $\sim$10 minutes (Figs. 14 and 15). This demonstrates that the active AG cleaner acts only on the off-momentum particles which are within the AG, hence particles which are on its edge migrates immediately in it when the cleaner is switched off. On the other hand scraping with IR3-TCP acts on all particles outside the bucket, giving a complete cleaning of off-momentum particles all around the ring.

4 Conclusion

A report of the MD performed on the 16th December 2012, regarding the study on off-momentum tail scraping in the LHC, has been presented. A few topics were investigated, the main of which was to study the possibility of beam losses sharing between IR3 and IR7, and the level of AG population cleaning that can be achieved through a passive method intercepting particles outside the RF bucket with TCPs in IR3.

Regarding the beam losses sharing, it has been demonstrated that it can be achieved without too many difficuties, and with collimator settings which well agree with the theoretical expectations.

For the passive AG population cleaning using TCPs in IR3, it has been demonstrated

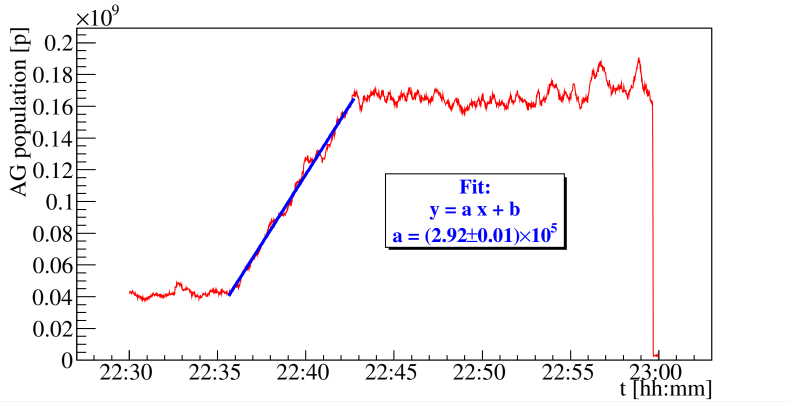

Figure 15: Measurements of AG repopulation rate for beam 2. Reported AG population as function of time, with relative linear fit and its parameters.

that it can reach a similar level achieved using transverse damper excitations gated on the AG. This opens the possibility to establish a passive AG cleaning with TCPs, leaving them at the level of the RF bucket height at end of ramp (without breaking the collimation hierarchy with respect to IR7).

While probing the off-momentum cuts up to the level where the IR3 primary collimator is the aperture bottleneck for all particles outside the bucket, while TCPs in IR7 are still the bottleneck for particles inside, it has been possible to observe that only a fraction of a percent of beam was measured in the range of δp/p between 0.8 and 1.0$\times 10^{-3}$.

The AG re-population rate has been measured too. Assuming a constant re-population rate, and the same debunching rate for each bunch, it has been estimated to be $\sim 5.3 \times 10^3$ p/s/bunch and $\sim 7.3 \times 10^2$ p/s/bunch for beam 1 and beam 2 respectively, where the order of magnitude of difference could be related to a different calibration of the detectors for the two beams.

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