MULTI-TURN LOSSES AND CLEANING

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Abstract

In the LHC all multi-turn losses should occur at the collimators in the cleaning insertions. The cleaning inefficiency (leakage rate) is the figure of merit to describe the performance. In combination with the quench limit of the superconducting magnets and the instantaneous life time of the beam this defines the cleaning dependent beam intensity limit of the LHC. In addition, limits can arise from radiation-induced effects, like radiation damage and radiation to electronics. In this paper the used collimator settings, the required setup time, the reliability of collimation (all multi-turn losses at collimators), and the achieved proton/ion cleaning inefficiency are discussed. Observed and expected losses are compared. The performance evolution during the months of operation is reviewed. In addition, the peak losses during high intensity runs, losses caused by instabilities, and the resulting beam life times are discussed. Taking the observations into account the intensity reach with collimation at 3.5 and 4 TeV is reviewed.

INTRODUCTION

At nominal particle momentum ($7\,\mathrm{TeV/c}$) and intensity ($\sim\ 3 \times 10^{14}$ protons) the LHC has a stored energy of 362 MJ per beam. Uncontrolled losses of just a small fraction of beam at the superconducting magnets of the LHC can cause a loss of their superconducting state (quench limit at 7 TeV/c: $R_q = 7.6 \times 10^6\,\mathrm{ps^{-1}m^{-1}}$) [1, 2]. Therefore collimators are needed to intercept these unavoidable beam losses.

For installing the full LHC collimation system a phased approach has been taken. The collimators of the current phase-I system are mainly installed in two dedicated cleaning insertions. IR3 collimators are used for the cleaning of off-momentum particles and IR7 to intercept particles with too large betatron amplitudes. In addition the collimators provide a passive machine protection [3, 4, 5]. A sketch of the layout of the phase-I collimation system with 44 collimators per beam is shown in figure 1.

Figure 2 shows a simplified sketch of the gap opening arrangement of the different classes of collimators normalized to the beam size. The primary collimators (TCPs) are the ones closest to the beam and cut the primary beam halo. The secondaries (TCSGs) intercept the secondary halo, i.e. particles scattered by the primaries, and absorbers (TCLAs) catch showers produced by the other collimators at the end of each cleaning insertion. The dump protection collimators (TCSG-IR6, TCDQs) protect the superconducting arcs against mis-kicked beams. The tertiary collimators (TCTs) are arranged around the experimental insertions, to protect the triplets locally [7, 8].

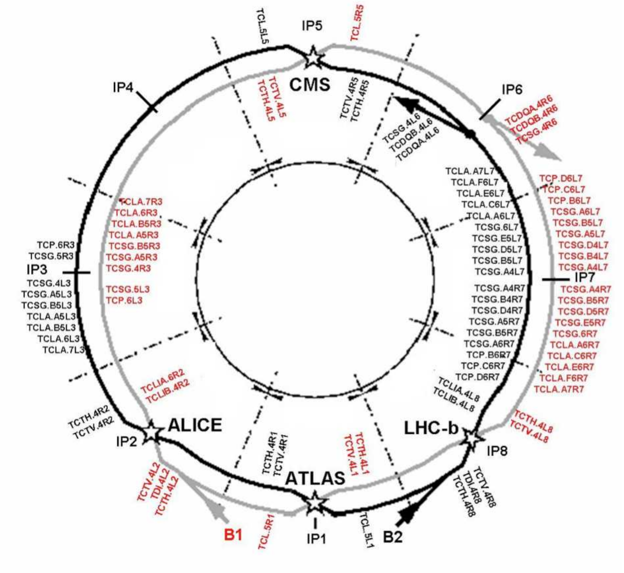

Figure 1: Sketch of the layout of the present phase-I collimation system. Beam 1 (beam 2) collimators are shown in red (black). [6].

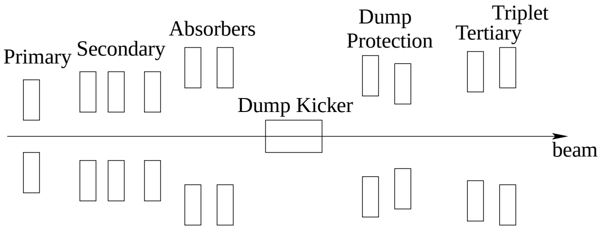

Figure 2: Simplified sketch of the gap opening arrangement of collimator classes normalized by beam size [9].

A measure for the performance of a collimation system is the local cleaning inefficiency

$$\eta_c = \frac{N_{local}}{N_{total}\Delta s}, \tag{1}$$

with N_{local} the number of protons lost within an longitudinal aperture bin Δs and N_{total} the total number of lost particles. The calculated local cleaning inefficiency of the phase-I system with imperfections ($\eta_c = 5 \times 10^{-4}\,\mathrm{m}^{-1}$) was expected to limit the maximal possible beam intensity stored in the LHC at 7 TeV/c to 4% of the nominal [7, 6].

During the physics running period in 2010 the LHC was operated at 3.5 TeV/c with a maximum of 368 proton bunches per beam (i.e. $\sim 4.2 \times 10^{13}\,\mathrm{p}$) and a bunch spacing

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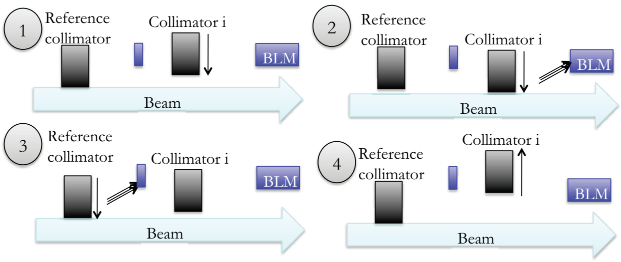

Figure 3: Simplified sketch of the beam-based setup procedure for one collimator [9]. Note: the sketch only shows one jaw per collimator whereas in reality the collimators in the LHC are in most cases double sided.

of 150 ns providing collisions to the particle physics experiments. During the last month of the 2010 operation the LHC was running with a maximum of 137 lead ion bunches per beam (i.e. $\sim 1.7 \times 10^{10}$ ions) at $3.5 \times Z$ TeV/c, with the atomic number $Z = 82$. The half gap openings used in 2010 for different families of collimators in units of beam sigma are given in table 1.

BEAM-BASED SETUP AND QUALIFICATION

To centre the collimator jaws around the beam and achieve the correct hierarchy of the collimation system a beam-based alignment procedure has been established during the LHC run in 2010 [9]. Figure 3 shows a simplified sketch of this procedure. A sharp edge is created in the beam halo by a reference collimator, which is usually a primary collimator (1). The jaws of collimator i are then moved to the edge of the beam halo and centered (2). After each centering of a collimator the reference collimator is re-centered around the beam (3). The measured beam size is therefore achieved as

$$\sigma_i = \frac{x_i^{L,m} - x_i^{R,m}}{(N_0^{k-1} + N_0^{k+1})/2}, \tag{2}$$

with the measured positions of the centered collimator jaws $x_i^{L,m}$ and $x_i^{R,m}$ (L: left, R: right) and the half gap opening of the reference collimator in units of the local beam size before (N_0^{k-1}) and after (N_0^{k+1}) the centering of collimator i. Collimator i was then opened to its nominal settings using table 1 (4). At 450 GeV/c (injection) the full gap openings are relatively large (~ 12 mm) and therefore the influence of measurement errors on the achieved beam sizes value can be tolerated. At 3.5 TeV/c (smaller beam sizes) it turned out to be more precise to use the nominal beam sizes for the collimator settings [10].

The net setup time in 2010 was about 15-20 mins per collimator. In total two full setups (44 collimators per beam, B1 and B2 in parallel) were performed at 450 GeV/c and 3.5 TeV/c. One was performed for low ($\sim 1 \times 10^{9}$ p) and one for nominal bunch intensity ($\sim 1.15 \times 10^{11}$ p). The net beam time per setup was between 10 and 13 h. In addition several setups of all 16 tertiary collimators (TCTs) or a subset were performed due to changes in the beam crossing angles in the interaction points (IPs). To ensure the correct settings of the collimation system the centers of the collimators were partly re-checked when switching the LHC from proton to lead ion operation. With the reproducibility of the LHC orbit and collimator positioning achieved in 2010 the validity of a full setup was about 5 - 6 months.

The hierarchy and cleaning efficiency have to be qualified for each set of collimator settings and after each change in the collimation system or the LHC orbit. In addition the validity of the settings has to be regularly re-checked and the performance change of the system has to be monitored over time. For this purpose intentionally multi-turn losses are created. Over a time of 1-2 s 30-50 % of the beam (one nominal bunch) is lost. For betatron cleaning (IR7) the third integer tune resonance is crossed. This is performed for both planes and beams, i.e. B1-h, B1-v, B2-h and B2-v. For momentum cleaning (IR3) the RF frequency is increased (decreased) to qualify the system for negative (positive) off-momentum particles. The off-momentum qualification was done for both beams in parallel to reduce the number of measurements. One full set of measurements needs typically two dedicated LHC fills at top energy. The results of these measurements are plotted as so called loss maps.

CLEANING AND PASSIVE PROTECTION: PERFORMANCE AND PROBLEMS

Inefficiency measurements

Figure 4 shows, as example, vertical betatron losses in beam 1. To estimate the measured local cleaning inefficiency η^j_{meas} at element j signals S_j of the beam loss monitors (BLMs) were normalized to the highest loss signal S_{prim} at a primary collimator:

$$\eta^j_{meas} = \frac{S_j}{S_{prim}}. \tag{3}$$

Note that this definition differs from the one mentioned in equation (1). The highest losses were found in the cleaning insertion and at primary collimators. The highest leakage to the cold aperture was found in the dispersion suppressor right of IR7 in a horizontal focusing (hf) quadrupole called Q8. Losses here are a factor ~ 5000 lower than at the primary collimator. This corresponds to a local cleaning inefficiency in the cold aperture of $\sim 2 \times 10^{-4}$, which is a typical value for betatron losses during the 2010 running period. The lower plot of figure 4 shows a zoom into the betatron cleaning insertion. The highest losses appear at the primary collimators and decline along the cleaning insertion exponentionally to its end. Thus, the collimators in IR7 show the correct hierarchy for this case.

The measured global cleaning inefficiency to the cold

Table 1: Half gap openings in units of the beam sigma for different families of collimators and machine states.

	Injection optics	Injection optics	Squeezed optics
Energy [GeV/c]	450	3500	3500
Primary cut IR7 (H, V, S) [σ]	5.7	5.7	5.7
Secondary cut IR7 (H, V, S) [σ]	6.7	8.5	8.5
Quarternary cut IR7 (H, V, S) [σ]	10.0	17.7	17.7
Primary cut IR3 (H) [σ]	8.0	12	12(B1) / 10 (B2)
Secondary cut IR3 (H) [σ]	9.3	15.6	15.6
Quarternary cut IR3 (H, V) [σ]	10.0	17.6	17.6
Tertiary cut exp. (H, V) [σ]	15-25	40-70	15
TCSG/TCDQ IR6 (H) [σ]	7-8	9.3-10.6	9.3-10.6

aperture is defined as

$$\eta_g = \frac{\sum S_{cold}}{\sum S_{all}}, \tag{4}$$

where $\sum S_{cold}$ is the sum over all BLM signals at cold devices and $\sum S_{all}$ the sum over all BLM signals along the LHC ring. For the example in figure 4 the global cleaning inefficiency was $\eta_g = 2.3 \times 10^{-4}$, which translates to 99.98% of the losses appeared at collimators or warm magnets.

An example of the loss distribution of particles with a positive momentum offset is shown in figure 5. The measurement was performed at 3.5 TeV/c and after putting the beams into collision. The highest losses were found at the primary collimators of IR3. The highest leakage to the cold aperture was found in the dispersion suppressor left of IR3 in the horizontal focusing (hf) quadrupole called Q7. Losses here are a factor $\sim$ 330 lower than in the primary collimator. This corresponds to a local cleaning inefficiency in the cold aperture of $\sim 3 \times 10^{-3}$. The lower plot of figure 4 shows the zoom into the momentum cleaning insertion. The highest losses are found at primary collimators. In this measurement the two beams were not lost at the same time, which explains that the loss pattern is not symmetric between the two primary collimators but dominated by beam 1. The hierarchy seams to be correct for both beams. The global cleaning inefficiency to the cold aperture was $\eta_g = 1.1 \times 10^{-2}$.

Comparison of Simulations with Measurements

Figure 6 shows a comparison of the measured betatron losses discussed above and results of a SixTrack [11] simulation with squeezed optics, at 3.5 TeV/c and the collimator gap openings of table 1. Note that the simulation was performed without imperfections. The measurements are in good agreement with the predictions: position and ratio of loss peaks are in general well reproduced. The measured leakage into the dump region in IR6 is one order of magnitude higher than expected. The reason for this behaviour is not understood yet. The plot at the bottom of figure 6 shows a zoom into the betatron cleaning insertion IR7. There are clear differences in the warm losses. This can be

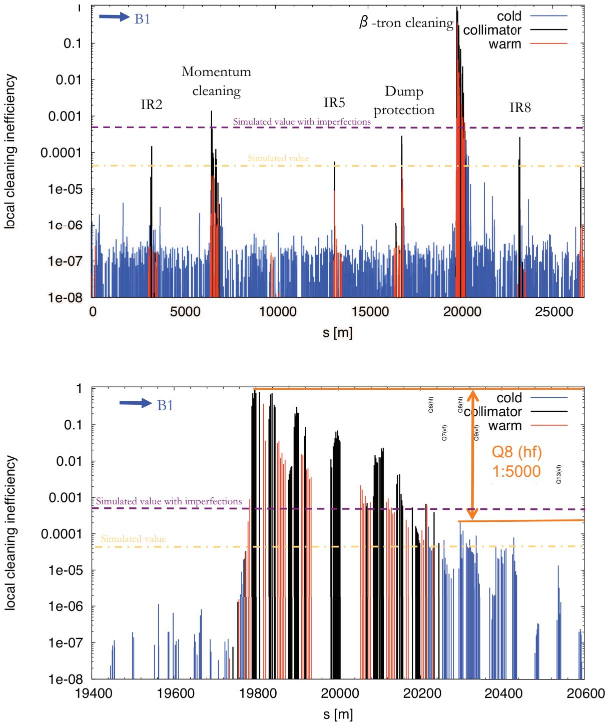

Figure 4: Cleaning with protons: Vertical betatron losses in B1 generated by crossing a 1/3 integer tune resonance. The measurement was performed at 3.5 TeV/c and collision optics. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. The dashed purple (orange) line indicates the simulated maximum cleaning inefficiency into the cold aperture with (without) imperfections for the phase-I collimation system (for 7 TeV/c, nominal collimator settings). Top: Cleaning inefficiency along the whole LHC; Bottom: Zoom into the betatron cleaning insertion (IR7).

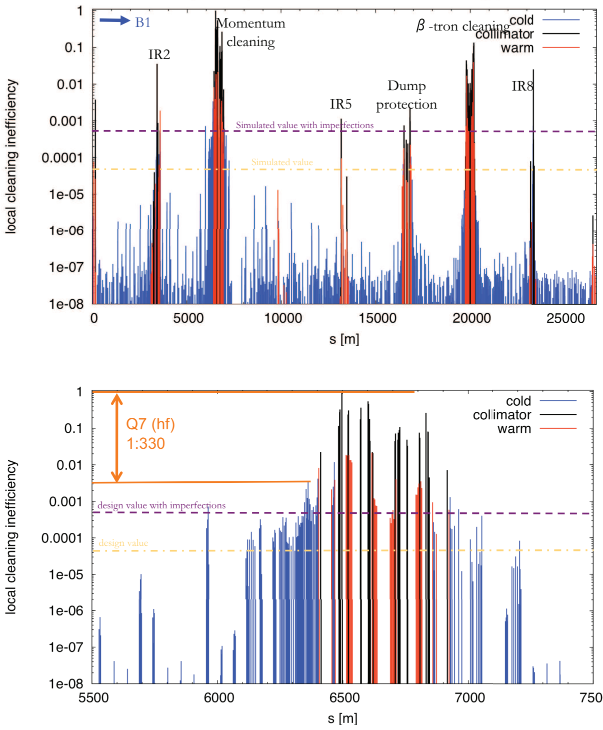

Figure 5: Losses of protons with a positive momentum offset. The measurement was performed at 3.5 TeV/c and collision optics with both beams. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. The dashed purple (orange) line indicates the simulated maximum cleaning inefficiency into the cold aperture with (without) imperfections for the phase-I collimation system (for 7 TeV/c, nominal collimator settings). Top: Cleaning inefficiency along the whole LHC; Bottom: Zoom into the momentum cleaning insertion (IR3).

explained by particle showers which are measured by the BLMs but not taken into account in the simulations (only proton losses). As predicted in the simulations the highest leakage to the cold aperture is found in the Q8 of the dispersion suppressor. The different loss amplitude (1:7) can be explained by the influence of imperfections. Taking also other measurements into account this factor varies between 6 and 10, which is in good agreement with expectations presented in [6].

Problems

Figure 7 shows a breakdown of the collimation hierarchy in IR3 for positive off-momentum particles. The secondary collimator left of IR3 (TCSG.B5L3) experienced the highest losses, i.e. acted as primary collimator. This caused a non-conform radiation profile in the cleaning insertion and higher leakage into the cold aperture downstream of IR3. It was discovered about two months after a full collimation setup. The case of positive off-momentum particles had not been qualified for this setup. The hierarchy problem has been cured by a re-setup of the IR3 collimators and by further closing the primary collimator in beam 2 from 12 to 10 σ (see table 1). This shows that a full set of qualification measurements and a continuous monitoring has to be performed, to guarantee the performance and the provided passive protection of the collimation system.

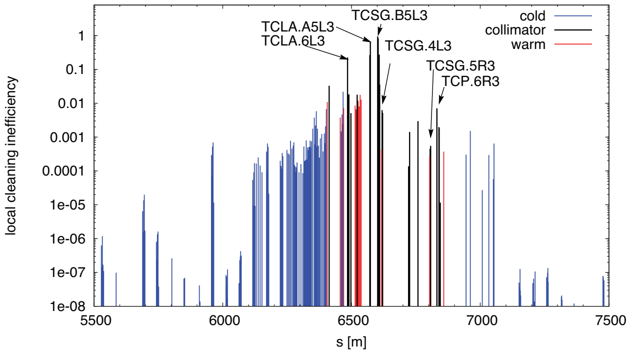

Figure 7: Breakdown of the collimation hierarchy for positive off-momentum protons in the momentum cleaning insertion (IR3) of beam 2. The measurement was performed at 3.5 TeV/c and collision optics by reducing the RF frequency. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators.

Analyses of losses during high luminosity LHC runs showed a non-conform radiation profile in the betatron cleaning insertion of beam 2. The losses at secondary collimators were as high as at primary collimators. Hints of this behaviour have also been seen in beam 2 loss maps for horizontal betatron losses earlier. This did not cause a decrease in cleaning efficiency at this time. These types of non-conformities need to be addressed as the warm magnets in the cleaning insertions could otherwise be damaged by radiation in the long term.

Inefficiency for ions

Collimation for ions is known to be less efficient than for protons [12]. When ions hit a collimator, nuclear interactions and electromagnetic dissociation break up the nuclei in smaller fragments, which have different charge-to-mass ratios from the main beam. Because of the large cross sections of these processes, it is very likely that an ion will fragment before obtaining the required scattering angle from multiple Coulomb scattering to hit the secondary collimators. Instead the main fragments then pass through the whole cleaning insertion but may be lost locally further downstream where the dispersion is higher. The collimation system therefore works with one stage only. Each created isotope has a different effective momentum deviation and may be lost in localized spots around the ring [13].

Figure 8 shows horizontal betatron losses in beam 2 around the LHC ring. As for protons the main losses ap-

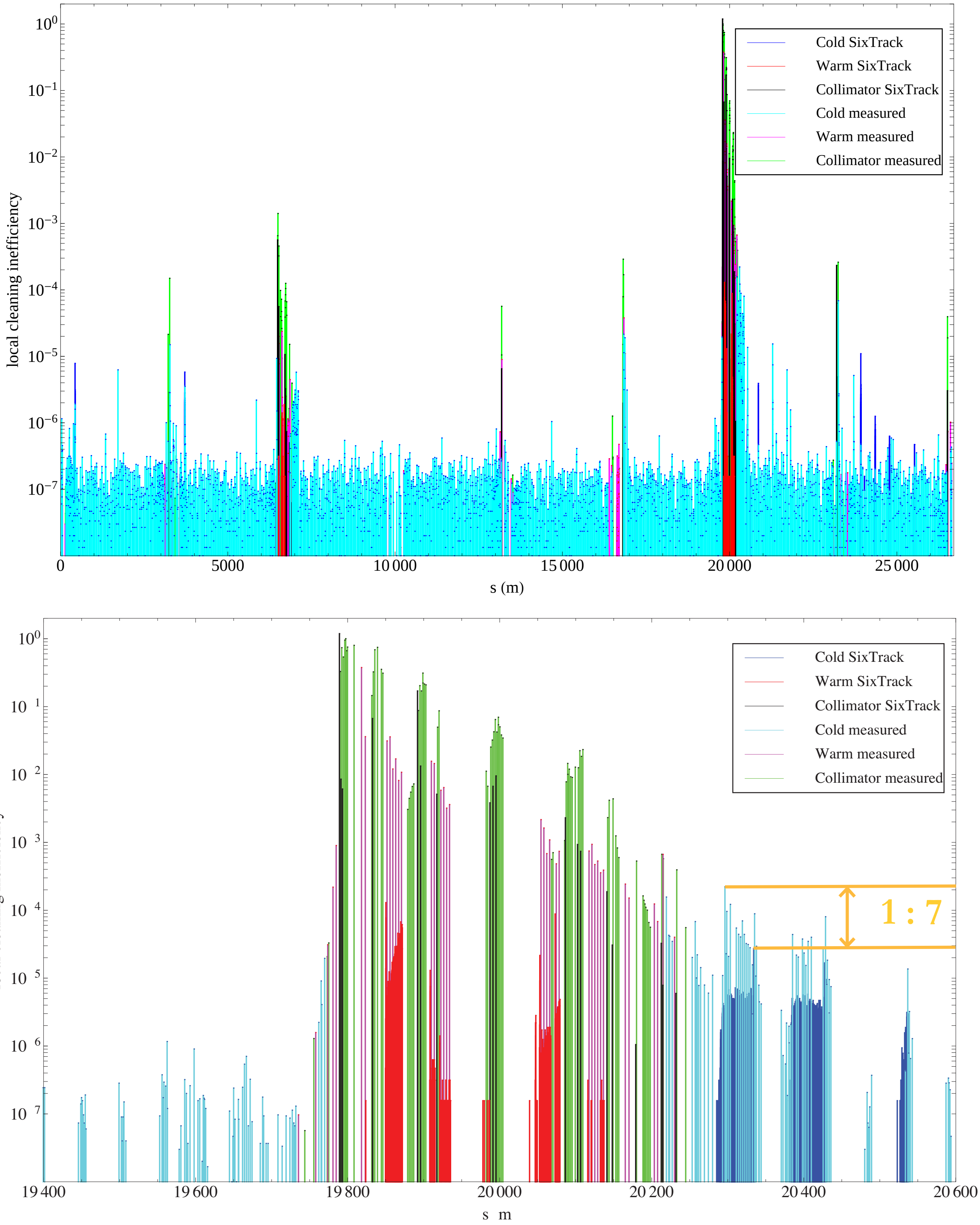

Figure 6: Comparison of simulated and measured proton losses. The measurements show vertical betatron losses in B1 generated by crossing a 1/3 integer tune resonance. The measurement was performed at 3.5 TeV/c and collision optics. The simulation was performed with SixTrack [11] for a vertical halo with squeezed optics, at 3.5 TeV/c and the collimator gap openings of table 1. Blue/red/black bars indicate the simulated local cleaning inefficiency η_c in units of 1/m in the cold aperture / warm aperture / collimators. Cyan/magenta/green bars indicate the measured local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. Top: Cleaning inefficiency along the whole LHC; Bottom: Zoom into the betatron cleaning insertion (IR7).

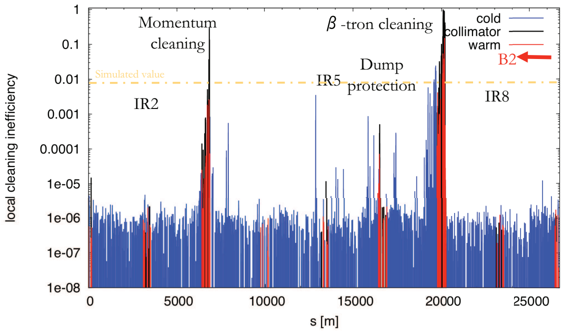

Figure 8: Cleaning with ions: Horizontal betatron losses in beam 2 generated by crossing a 1/3 integer tune resonance. The measurement was performed with lead ions at $3.5 \times Z\,\mathrm{TeV/c}$ and collision optics, with the atomic number $Z = 82$. Blue/red/black bars indicate the local cleaning inefficiency η_{meas} in the cold aperture / warm aperture / collimators. The dashed orange line indicates the highest simulated local cleaning inefficiency in the cold aperture without imperfections for the phase-I collimation system with lead ions.

Table 2: Highest leakage, in local cleaning inefficiency η_{meas}, of ions into specific regions (DS = dispersion suppressor, COLD= cold aperture excluding DS, TCT = tertiary collimators).

loss cases	DS	COLD	TCT
B1h	0.02	0.006	1.0e-4
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8.0e-5
B2v	0.025	0.006	1.4e-4
B1+B2 pos. off momentum	0.045	8.0e-4	0.06
B1+B2 neg. off momentum	0.007	2.0e-4	0.005

pear in the two cleaning insertions. The highest leakage into the cold magnets of the IR7 dispersion suppressor is 3×10^{-2}, which is a factor 100 more than for protons. In addition there are localized loss spots in different parts of the machine with local cleaning inefficiencies in the order of 10^{-3} and 10^{-4}. Table 2 gives an overview of the highest leakage into specific regions of the LHC for the different betatron and momentum cleaning cases. The global cleaning inefficiency to the cold aperture for betatron cleaning with ions was below $\eta_g = 1.86 \times 10^{-2}$.

In figure 9 simulated (bars) and measured leakage (crosses) into the IR7 dispersion suppressor for horizontal betatron losses are compared. The simulations were performed with the code ICOSIM [12] without imperfections. ICOSIM combines optical tracking with a Monte-Carlo simulation of the particle-matter interaction in the collimators for heavy ions. Positions of the loss peaks in the dispersion suppressor were reproduced in the measurements. The absolute level of the leakage differs. The measured leakage is significantly higher than predicted in simulations. The quantitative differences between measured and simulated losses with lead ions need to be further understood. Therefore, simulations with higher statistics are in preparation. Although using a state of the art simulation code there are uncertainties in the cross sections for hadronic fragmentation and electromagnetic dissociation with lead nuclei on carbon / tungsten.

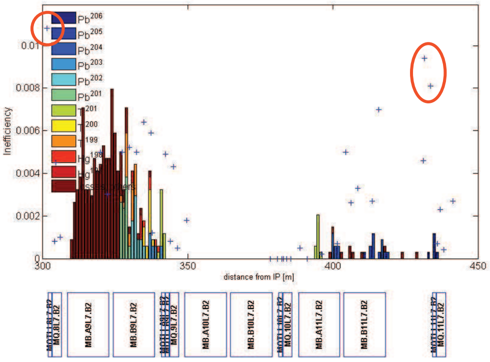

Figure 9: Comparison of simulated (bars) with the measured leakage (crosses) of ions into the IR7 dispersion suppressor expressed as local cleaning inefficiency. Measurement and simulation are shown for horizontal betatron losses in beam 2 at $3.5 \times Z\,\mathrm{TeV/c}$ and collision optics, with the atomic number $Z = 82$. These preliminary simulations were performed with the code ICOSIM [12].

Performance stability

After the full setup of the system for high bunch intensities in June 2010 the performance of the collimation system was continuosly monitored over the following 4 months until the end of the proton run. Figure 10 shows the evolution of leakage into the cold dispersion suppressor magnet called Q8 for betatron losses. As shown in figure 4 the highest local cleaning inefficiency in the cold aperture was found here. It had a value between between 1.3×10^{-4} and 6.1×10^{-4}. In one plane and beam the leakage varied up to a factor 3. The evolution of the leakage from the cleaning insertions into the tertiary collimators is shown in figure 11. The leakage is summed over all horizontal (vertical) collimators for each beam and plane. The maximum cleaning inefficiency for the horizontal (vertical) TCTs was 7×10^{-4} (1.25×10^{-3}). The leakage was varying in one plane and beam by less than a factor 4 (2.6). Together with the leakage into the Q8 these results show good stability of the collimation performance in this period of time.

The evolution of the leakage into the secondary collimators of the dump region (IR6) is shown in figure 12. The maximum cleaning inefficiency was found for horizontal

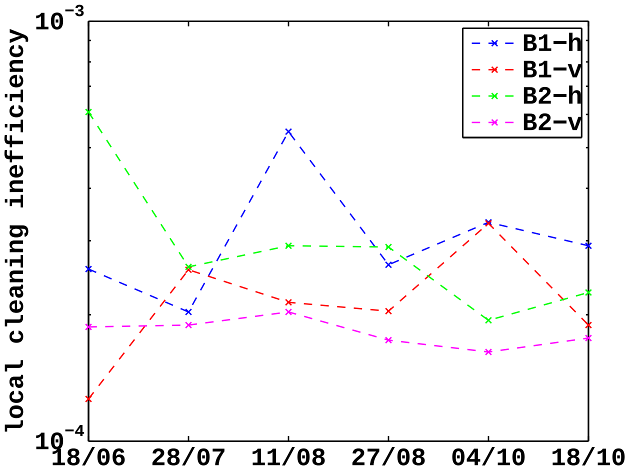

Figure 10: Evolution of the leakage from the cleaning insertions into the dispersion suppressor magnet Q8 over 4 months of LHC operation for betatron losses. Note: The loss response of beam loss monitors at collimators and cold magnets differs by about a factor of 2. This has not been taken into account here.

betatron losses in beam 2 with 5×10^{-3}. The maximum variation in one plane and beam was up to a factor 23. As shown in table 1 the margin between the secondary collimators in IR7 and the TCSGs in IR6 was $0.8\,\sigma$. The coupled orbit variations between these locations were found to be above this margin in certain fills[14]. This can explain the variation of the leakage to the IR6 collimators.

COLLIMATION BEAM LOSS EXPERIENCE 2010 AND OUTLOOK 2011

The collimation related total intensity limit is given by

$$N^q_{tot} = \frac{\tau_{min} R_q}{\eta_c}, \tag{5}$$

with the minimum instantaneous beam lifetime τ_{min}, the quench limit R_q and the local cleaning inefficiency η_c. The instantaneous beam lifetime is defined as

$$\tau(t) \approx \frac{N^q(t)}{R_{loss}(t)} \tag{6}$$

and depends therefore on the loss rate R_{loss} and the beam intensity N^q at the time t [15].

In beam halo scraping experiments the BLM signals at primary collimators in IR7 have been calibrated to the number of lost protons given by the beam current transformer (BCT) signals. Therefore the BLM signals can be directly converted into an instantanous proton loss rate [16]. The estimated error in the convertion of beam loss signals to loss rates was smaller than 20%. This calibration was used in all measurements presented below.

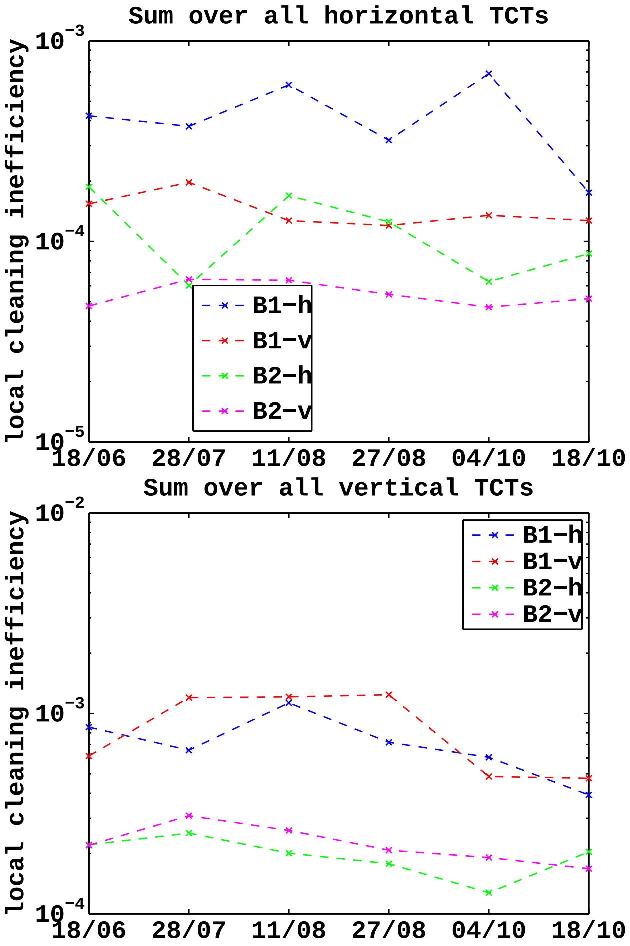

Figure 11: Evolution of the leakage from the cleaning insertions into the tertiary collimators (TCTs) over 4 months of LHC operation for betatron losses. Top: Sum over all horizontal TCTs; Bottom: Sum over all vertical TCTs. Note: The loss response of beam loss monitors at collimators and cold magnets differs by about a factor of 2. This has not been taken into account here.

Losses during high luminosity runs

Eight high luminosity fills have been analyzed: 3 runs with 312 bunches ($\sim 3.6 \times 10^{13}$ p) and 5 runs with 368 bunches ($\sim 4.2 \times 10^{13}$ p). The loss rates have been analyzed for four different integration times of the BLM signals: $80\,\mu$s, $640\,\mu$s, 10.24 ms and 1.3 s. Losses that appear only in the first two integration times can be assumed as transient losses, as these correspond to 1 - 7 LHC turns. Losses that appear also in the latter can be considered as steady state losses (115 - 14600 turns).

Figure 13 shows the calculated loss rates for BLM signals with different integration times at the horizontal primary collimator in the betatron cleaning insertion of beam 1 during a high luminosity run. In all integration times the loss rates showed a spike and the loss rate levels were significantly increased when the two beams were put into collision ($t > 1500$ s). They stayed at this levels until the

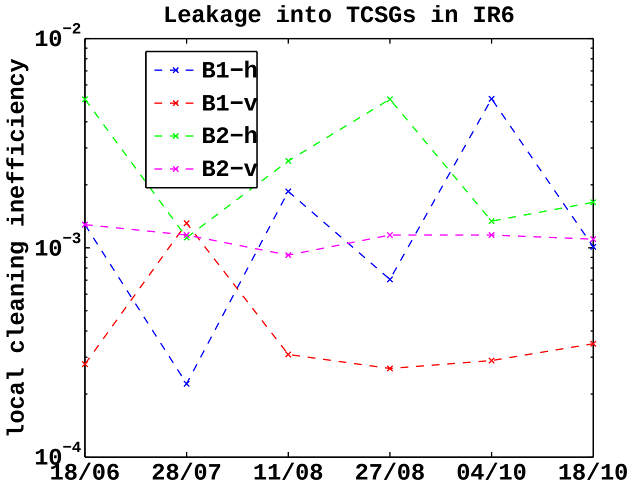

Figure 12: Evolution of the leakage from the cleaning insertions into the dump region (TCSG in IR6) over 4 months of LHC operation for betatron losses. Note: The loss response of beam loss monitors at collimators and cold magnets differs by about a factor of 2. This has not been taken into account here.

beams were dumped. This shows that the losses are mainly induced by beam-beam interactions. Additional loss spikes appeared for the different signals in most cases at the same time. Especially for the 80 μs integration time there were additional transient losses, which were nearly as high as the losses caused by bringing both beams into collision.

In figure 14 the highest measured loss rates are compared to the specified loss rate of 4.5×10^{11} p/s (nominal intensity, 7 TeV/c and $\tau = 0.2$ h). It can be clearly seen that the loss rate for all integration times is below the specification. This still holds when the loss rate is linearly scaled to nominal intensity (dashed lines). Figure 15 shows that the lowest measured instantaneous life times of the high intensity runs are above the specified life time of $\tau = 0.2$ h for all integration intervals. In addition figure 16 shows that the peak proton losses for the lowest two integration times are below the transient quench limit of the superconducting magnets (3.4×10^7 p at 7 TeV/c [2]).

Table 3 compares the 2009 predicted performance of the collimation system as presented in [17] and the resulting collimation related intensity limit with the measured performance 2010. Here it was assumed that the measured cleaning inefficiency is diluted over the length of one metre, i.e. $\eta_c = \frac{\eta_{meas}}{1\,\mathrm{m}}$. As the BLM responses on the same losses are different for a collimator and a superconducting magnet the measured cleaning inefficiency had to be corrected by a factor of 0.36. This factor was inferred from an aperture measurement experiment earlier. The assumed quench limits R_q were taken from [6]. The total intensity limit with the measured minimum life time for steady state losses was then calculated by changing equation (5) to

$$N_{tot}^{q} = \frac{\tau_{min} R_q}{\eta_{corr}} \cdot c_{blm} \cdot c_{fluka}. \quad (7)$$

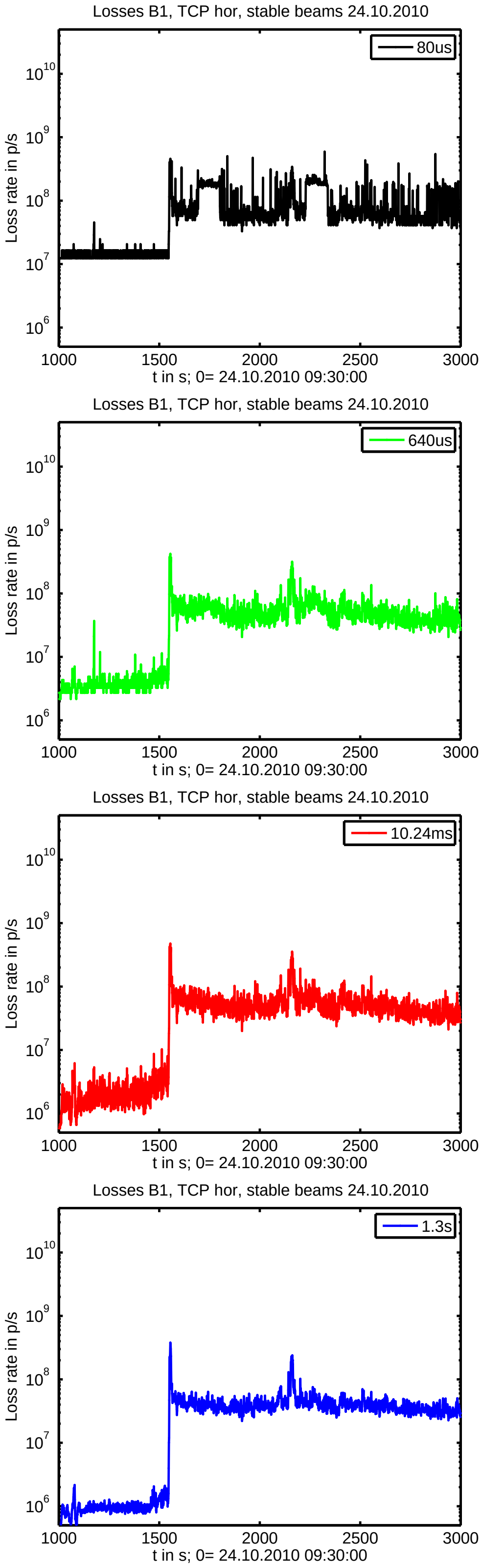

Figure 13: Loss rate at the horizontal primary collimator in the betatron cleaning insertion of beam 1 during 33 mins of a high luminosity LHC run. The different plots show the loss rates calculated from BLM signals with the different integration times: 80 μs, 640 μs, 10.24 ms and 1.3 s.

Table 3: Comparison of predicted and measured parameters for and the results of calculating the total intensity limit. For this analyses the high luminosity fill with the highest loss rate was used. This fill took place at the 26.10.2010 and had 368 bunches per beam with 150 ns bunch spacing.

	2009 prediction	2010 analysis	ratio
η_c [1/m]	2.16×10^{-4}	4×10^{-4}	1.9
BLM response	n.a.	0.36	-
η_{corr} [1/m]	2.16×10^{-4}	1.44×10^{-4}	0.66
τ_{min} [s]	500	4680	9.4
R_q [p/m/s] @3.5 TeV/c	2.4×10^{7}	-	-
R_q [p/m/s] @4 TeV/c	1.9×10^{7}	-	-
BLM factor	0.33	-	-
FLUKA factor	3.5	-	-
N^q_{tot} [p] @3.5 TeV/c	6.4×10^{13}	9.1×10^{14}	14.2
N^q_{tot} [p] @4 TeV/c	5.1×10^{13}	7.28×10^{14}	14.2

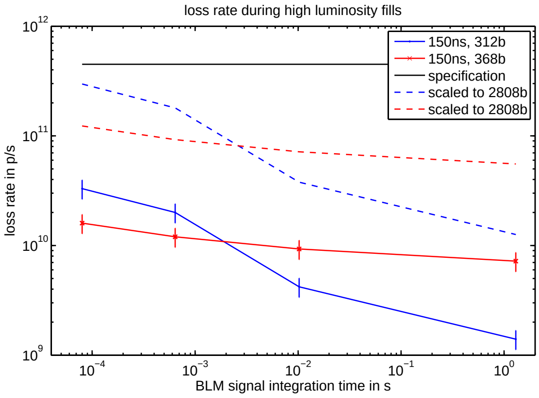

Figure 14: Highest instantaneous loss rates found in the high luminosity LHC runs with 312 and 368 bunches for different integration times of the BLM signals compared to the specified loss rate (4.5×10^{11} p/s at nominal intensity, 7 TeV/c and $\tau = 0.2$ h). The dashed lines show the linear scaling of the measured loss rates to the nominal number of bunches (2808).

The BLM factor c_{blm} reflects the fact that the dump limit of the BLMs is set to 1/3 of the quench limit of the superconducting magnets they should protect. The FLUKA factor c_{fluka} was introduced as a dilution factor for the assumed quench limit [17]. The calculation shows that in 2010 the total intensity limit exceeded the expectations from 2009 by a factor 14. This is mainly due to a life time which was significantly better than expected. Also the corrected cleaning inefficiency was slightly better, which could be explained by a lower influence of imperfections due to a good orbit stability. For 3.5 TeV/c this means that the intensity could be increased by a factor 22 from $\sim 4.2 \times 10^{13}$ p to $\sim 9.1 \times 10^{14}$ p, which would be above nominal intensity. At 4 TeV/c the total intensity would be limited to $\sim 7.28 \times 10^{14}$ p.

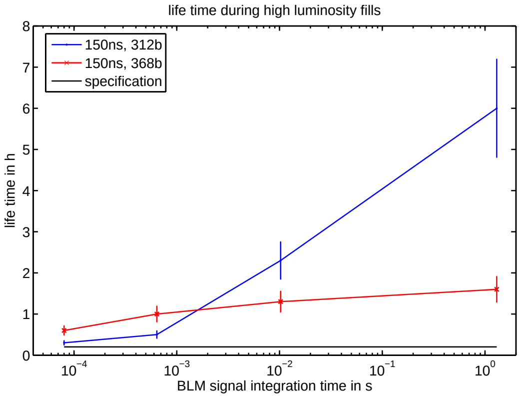

Figure 15: Lowest instantaneous life times found in the high luminosity LHC runs with 312 and 368 bunches for different integration times of the BLM signals compared to the specified life time (0.2 h at nominal intensity and 7 TeV/c).

Losses due to instabilities

Two runs with high losses due to instabilities, which finally caused a beam dump, have been analyzed. Both runs had 108 bunches per beam with a bunch spacing of 50 ns. In the first the beam became unstable at the end of the so-called squeeze, when the beta functions in the interaction points (IPs) are reduced to collision values. The second fill showed high losses before the squeeze, when the transverse damper was turned off.

Figure 17 compares the highest instantaneous loss rates found during these two runs with the specified loss rate. In both cases the loss rates for all integration times were below the specifications. This does not hold any longer, if the loss rates are linearly scaled to nominal intensity. Figure 18 shows that the life time in both cases was significantly below the specifications, whereas the transient losses (see figure 19) were below the transient quench limit. If these were scaled linearly to nominal intensity the transient losses could get close to the quench limit.

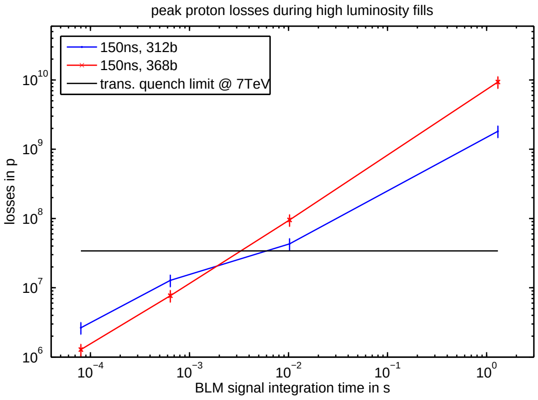

Figure 16: Peak losses found in the high luminosity LHC runs with 312 and 368 bunches for different integration times of the BLM signals compared to the transient quench limit of the superconducting magnets at 7 TeV/c: 3.4e7 p [2]. Note: losses that appear only in the two lowest integration times of the BLM signal, i.e. $80\,\mu$s and $640\,\mu$s, can be consideres as transient losses.

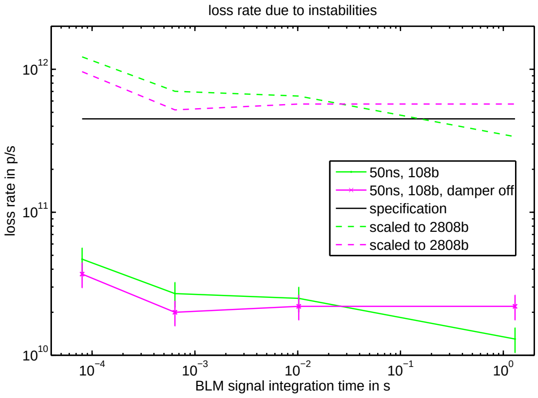

Figure 17: Highest instantaneous loss rates found in LHC runs with instabilities. The first fill with 108 bunches and 50 ns bunch spacing became instable at the end of he squeeze, the second due to turning of the tranverse damper. Different integration times of the BLM signals are compared to the specified loss rate ($4.5 \times 10^{11}\,\mathrm{p/s}$ at nominal intensity, 7 TeV/c and $\tau = 0.2\,\mathrm{h}$). The dashed lines show the linear scaling of the measured loss rates to the nominal number of bunches (2808).

Applying equation (5) with the minimum instantaneous life time for steady state losses found in these two cases of $\tau_{min} = 468\,\mathrm{s}$ gives a limit of the total intensity per beam at 3.5 TeV (4 TeV) of $N^{q}_{tot} = 9.1 \times 10^{13}\,\mathrm{p}$ ($N^{q}_{tot} = 7.2 \times 10^{13}\,\mathrm{p}$), which is a factor ~ 3.3 (~ 4.2) below nominal intensity. This analysis shows that instabilities can cause a collimation indicated limitation of the achievable intensity in the LHC.

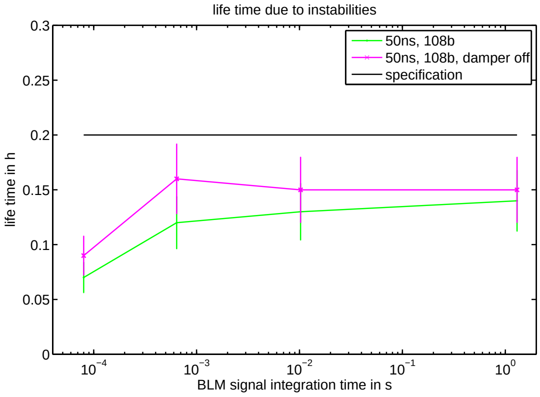

Figure 18: Lowest instantaneous life times found in LHC runs with instabilities. The first fill with 108 bunches and 50 ns bunch spacing became instable at the end of he squeeze, the second due to turning of the tranverse damper. Different integration times of the BLM signals are compared to the specified life time (0.2 h at nominal intensity and 7 TeV/c).

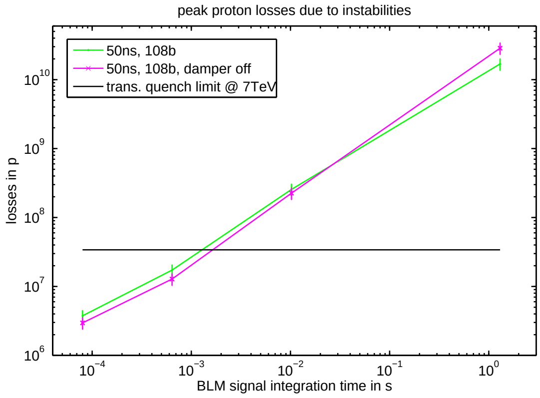

Figure 19: Peak losses found in LHC runs with instabilities. The first fill with 108 bunches and 50 ns bunch spacing became instable at the end of he squeeze, the second due to turning of the tranverse damper. Different integration times of the BLM signals are compared to the transient quench limit of the superconducting magnets at 7 TeV/c: 3.4e7 p [2]. Note: losses that appear only in the two lowest integration times of the BLM signal, i.e. $80\,\mu$s and $640\,\mu$s, can be consideres as transient losses.

Losses due to un-captured beam

Particles which are not captured correctly in the RF bucket, or moved out of it due to an RF failure, will get lost in the momentum cleaning insertion (IR3) as soon as the particle energy is ramped up from 450 GeV/c. In a run with 368 bunches 1.3×10^{12} un-captured protons were lost in beam 1 within 6 s at the beginning of the ramp. This was equivalent to about 2.8 % of the total beam intensity. Figure 20 shows the instantaneous loss rate compared to the specified loss rate. For all integration times this was

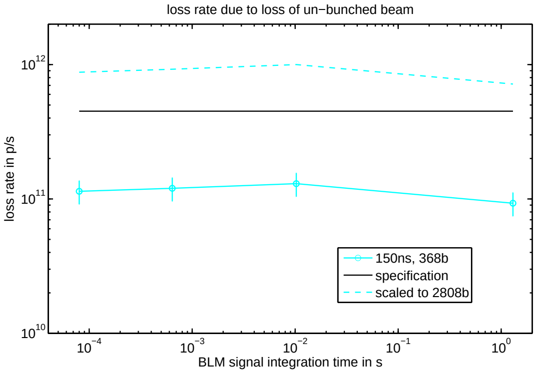

Figure 20: Highest instantaneous loss rates found during the loss of un-bunched beam at the beginning of the ramp on 27th of October 2010. Within about 6s 2.8% ($\sim 1.3 \times 10^{13}\,\mathrm{p}$) of beam 1 were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches with 150 ns bunch spacing. Different integration times of the BLM signals are compared to the specified loss rate ($4.5 \times 10^{11}\,\mathrm{p/s}$ at nominal intensity, 7 TeV/c and $\tau = 0.2\,\mathrm{h}$). The dashed lines show the linear scaling of the measured loss rates to the nominal number of bunches (2808).

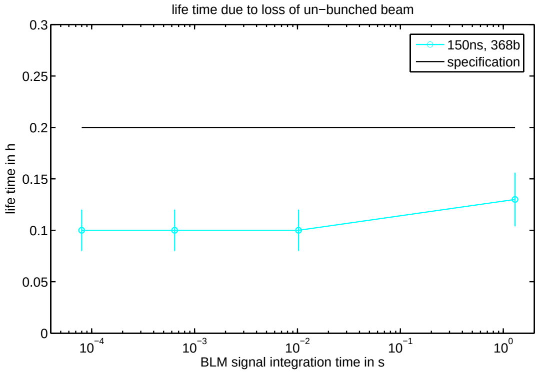

Figure 21: Lowest instantaneous life times found during the loss of un-bunched beam at the beginning of the ramp on 27th of October 2010. Within about 6s 2.8% ($\sim 1.3 \times 10^{13}\,\mathrm{p}$) of beam 1 were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches with 150 ns bunch spacing. Different integration times of the BLM signals are compared to the specified life time (0.2 h at nominal intensity and 7 TeV/c).

below the specifications. Scaling the measured loss rate linearly to nominal intensity shows that this would exceed the specifications. Figure 21 depicts that the instantaneous life time stayed clearly below the specifications for all integration times. These two results indicate that losses due to un-captured beam could limit the total intensity in the LHC. As shown in figure 22 transient losses were far below the transient quench limit at 450 GeV/c. Scaling to nominal intensity this result still holds. The minimum instantaneous life time for steady state losses in this example was $\tau_{min} = 360\,\mathrm{s}$. Using this in equation (5) together with the quench limit at 450 GeV/c, $R_q = 7.0 \times 10^8\,\frac{\mathrm{p}}{\mathrm{sm}}$, this results in a total intensity limit of $N^q_{tot} = 2.7 \times 10^{14}\,\mathrm{p}$, which is slightly below nominal intensity.

Note that for the above discussed intensity limits other possible limitations due to collimation like radiation to electronics (R2E) were not taken into account. It was also assumed that the stability of the beam would stay constant for higher beam intensities, which may not be true. It was not considered that the performance reach of the collimation system will be worse for higher particle momentum (cleaning inefficiency, lower margins at superconducting magnets, lower quench limits). On the other hand cleaning efficiency can be improved by using nominal collimation settings. With the orbit stability achieved in 2010 this is not possible. Finally it needs to be considered that the analysis is based on a limited number of fills.

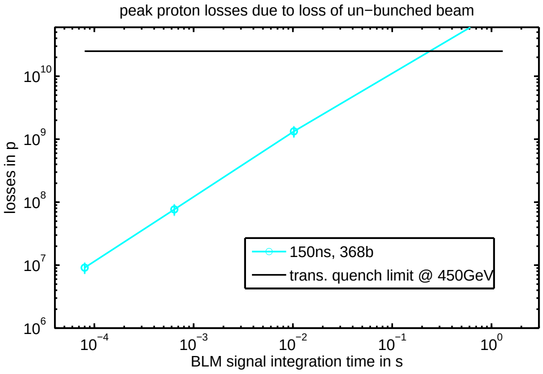

Figure 22: Peak losses found for the loss of un-bunched beam at the beginning of the ramp on 27th of October 2010. Within about 6s 2.8% ($\sim 1.3 \times 10^{13}\,\mathrm{p}$) of beam 1 were lost in the momentum cleaning insertion (IR3). The fill had 368 bunches with 150 ns bunch spacing. Different integration times of the BLM signals are compared to the transient quench limit of the superconducting magnets at 450 GeV/c: $2.5 \times 10^{10}\,\mathrm{p}$ [2]. Note: losses that appear only in the two lowest integration times of the BLM signal, i.e. $80\,\mu\mathrm{s}$ and $640\,\mu\mathrm{s}$, can be consideres as transient losses.

CONCLUSION

The phase-I LHC collimation system delivered the expected collimation efficiency during the 2010 LHC operation. The impact of imperfections on cleaning was about a factor 2 smaller than predicted. This was mainly due to a better control of the orbit in the dispersion suppressor regions. The measured global cleaning inefficiency to the cold aperture was $\eta_g \sim 2.3 \times 10^{-4}$.

The setup procedures of the collimation system have been refined and optimized. During each setup 15 to 20 minutes net beam time per collimator was needed. The validity of collimation setups has been around 5-6 months. After this time the radiation profile started to be non-conform. Assuming a 10 months running period in 2011 two full setups of the collimation system should be expected.

The instantaneous life time during high luminosity LHC runs in 2010 was found to be a factor 9 higher than specified. The intensity limits calculated from the measured life time was $9.1{\times}10^{14}\,\mathrm{p}$ ($7.28{\times}10^{14}\,\mathrm{p}$) at 3.5 TeV/c (4 TeV/c). This means that in terms of cleaning collimation should be ready for nominal intensity at 3.5 and 4 TeV/c. Note that other issues such as radiation to electronics (R2E) have not been considered here.

As seen in several runs 2010 instabilities can decrease the life time significantly. The collimation induced intensity limit with instabilities was found to be $9.1 \times 10^{13}\,\mathrm{p}$ ($7.28 \times 10^{13}\,\mathrm{p}$) at 3.5 TeV/c (4 TeV/c). As instabilities are possible for higher intensities and particle momenta these limitations need to be taken into account. Losses due to uncaptured beam, as experienced in the 2010, could limit the intensity to $2.7 \times 10^{14}\,\mathrm{p}$, which is slightly below nominal. Note that these intensity limits are no hard limits, as they will cause at first beam dumps. The frequency of instability induced beam dumps could then decrease the performance of the LHC.

As expected cleaning with lead ions was much less efficient than for protons. The leakage into the superconducting dispersion suppressor magnets and the tertiary collimators was in the order of percents. The global cleaning inefficiency to the cold aperture was below $\eta_g = 1.86 \times 10^{-2}$.

ACKNOWLEDGMENTS

The authors would like to thank the colleagues from the CERN OP, BI, BTP and BLM teams for their collaboration, support - especially in performing measurements - and helpful discussions.

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