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End-of-fill study on collimator tight settings

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Summary

In 2010 and 2011 the collimation system has been operated with relaxed settings, i.e. with retractions between different collimator families larger than the nominal settings that provide optimum cleaning. This configuration ensured a sufficient cleaning performance at 3.5 TeV while allowing larger tolerances on orbit control. Tighter collimator settings were proposed to push the cleaning performance and to allow larger orbit margins between TCDQ dump protection and tertiary collimators. With the same margins as with the relaxed settings, the β^* could be reduced. After having verified with beam that the cleaning is improved as expected, the feasibility of tighter collimator settings must be addressed with high stored intensity. For this purpose, an end-of-fill study was proposed after a standard physics fill with 1380 bunches nominal bunches at 3.5 TeV, for a total stored energy of 95 MJ. During this test, primary and secondary collimators were moved to tight settings after about 8 hours of stable physics conditions in all experiments. This note summarises the operational procedure followed and the results of beam measurements during this study.

Contents

1 Introduction

An end-of-fill (EOF) study was performed to address operational aspects of collimator "tight" settings. The "tight" settings at beam energies below 7 TeV are defined as the settings in millimetres that correspond to nominal settings at 7 TeV. At 3.5 TeV, one obtains for example 4 $\sigma_{3.5\mathrm{TeV}}$ for the primary collimator of the betatron cleaning insertion (IR7), corresponding to the nominal 5.7 $\sigma_{7.0\mathrm{TeV}}$ settings at the design energy (σ_{E_0} is the betatron beam size at the energy E_0). Tight settings can be defined correspondingly for all the other collimator types. During the first MD block in 2011, the 3.5 TeV collimation based on "quasi-tight" settings was established and the cleaning performance potential of such a system was explored [1]. A summary of the normalised collimator settings used in standard operation and in MD studies is given in Tab. 1.

Previous MD tests for cleaning and orbit stability studies were performed with individual bunches. The feasibility of tight settings also needs beam validations with larger stored intensities. For this purpose, an EOF study was preferred to dedicated MD in order to achieve conditions as close as possible to the ones of the standard high-intensity operation. Beam tests were carried out following a detail proposal [2] compatible with safety constraints, approved by the LHC machine protection panel (MPP). For the first test, only carbon-based, robust collimators were moved closer to the beam: primary and secondary collimators in IP7, secondary and TCDQ collimators in IP6. Since these are the collimators closest to the beam and they drive the collimator contribution to the LHC impedance, this initial beam tests, though preliminary, were considered sufficient to address aspects related to beam instabilities, beam lifetime and tail population issues.

Beam tests were performed on August 21st, 2011, in the fill 2037. In this note, the beam conditions and operational procedures are presented and the observations performed while the collimators were moved close to the beam are discussed. The tests could only be performed for B1 because the beams were dumped while moving the IP6 collimators, due to a software interlock on the TCSG-TCDQ retraction. It was nevertheless possible to achieve tight settings in IP7 and to measure various relevant parameters in these conditions.

Table 1: Collimator settings in unit sigma for various configurations at 3.5 TeV.

Collimator family	OP 2011 [σ]	Nominal [σ]	Tight [σ]	Tight MD1 [σ]	**EOF study** [σ]
TCP-IR7	5.7	6.0	4.3	4.0	**4.0**
TCSG-IR7	8.5	7.0	5.0	6.0	**6.0**
TCLA-IR7	17.7	10.0	7.1	8.0	**17.7**
TCTs IP1/5/8	11.8	8.3	5.9	26.0	**11.8**
TCSG-IR6	9.3	7.5	5.3	7.0	**7.0**
TCDQ-IR6	9.8	8.0	5.7	7.5	**7.5**

2 Beam conditions and operational procedure

2.1 Beam conditions

The beam conditions for the EOF tight collimation study are summarised in Tab. 2. The standard template for the MD request is given, with additional information relevant for machine protection. Beam intensity and lifetime during the fill are given in Figs. 1 and 2. Zoomed-out graph in the times when collimators were moved are also given (right graphs). Beam tests were done at intensities well

Table 2: Beam parameters and machine configuration for the measurements.

Beams required	Both beams
Beam energy [GeV]	3500
Optics	Squeezed, colliding
$\beta*$ IP1/2/5/8 [m]	1.5 / 10.0 / 1.5 / 3.0
Bunch intensity [p]	1.23×10^{11} p (at beginning of collision)
Number of bunches	1380 per beam
Stored beam energy [MJ]	95 per beam
Transv. emittance [μm]	$\approx$ 2 (before collision)
Orbit change	None. Collision conditions with optimised luminosity
Collimator configuration	Tight settings in IP7 and IP7 Nominal physics settings in IP3 and experiments (Tab. 1)
Feedback configuration	Tune and orbit feedback OFF
Transverse damper	Nominal configuration for physics: normalised gain - 0.02
Special conditions	Updated collimator position limit to allow tighter gaps

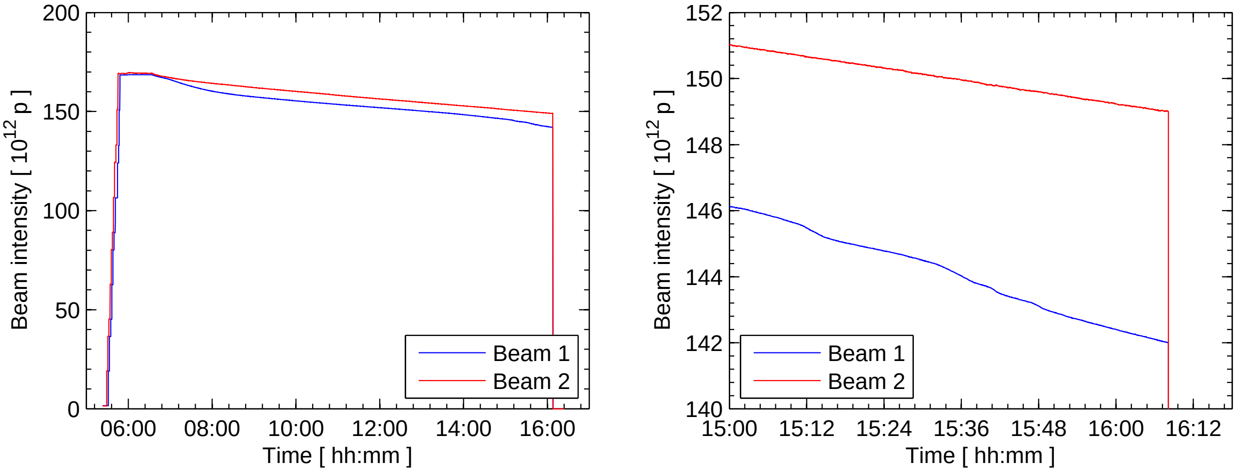

Figure 1: Beam intensity evolution during the fill 2037 of August 21st, 2011. In the right plot, a zoom out during the period when collimators were moved is given. B1 collimators only were moved, leaving B2 unperturbed.

above the safe limit that allow wire scans, so the information on the emittance relies on injection measurements.

2.2 Operational procedure

A detailed step-by-step operational procedure to change collimator limit functions and to moved them with a stored beam energy 95 MJ was prepared prior to beam tests and approved by the machine protection panel [2]. Beam tests were performed in ADJUST mode with experiments set to safe conditions. This was done with the standard handshake protocol for the experiments to leave the stable beam mode. Then, the procedure to move the collimators to tight settings was:

(1) Move primary collimators of IP7 from $5.7\ \sigma$ to $4.0\ \sigma$;

(2) Move secondary collimators of IP7 from $8.5\ \sigma$ to $6.0\ \sigma$;

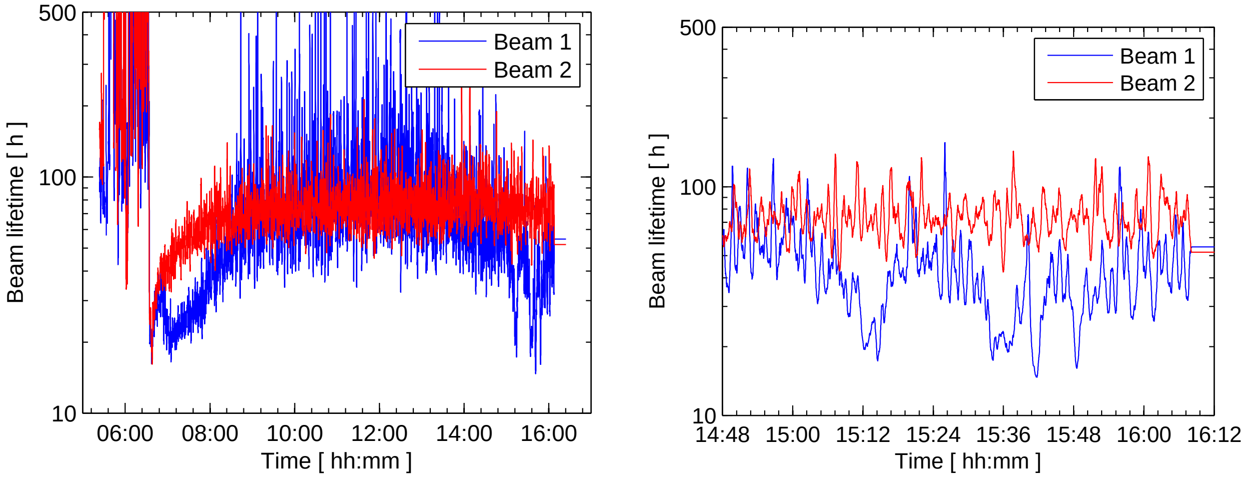

Figure 2: Beam lifetime evolution during the fill 2037 of August 21st, 2011. In the right plot, a zoom out during the period when collimators were moved is given. B1 collimators only were moved, leaving B2 unperturbed.

(3) Move secondary collimator of IP6 from $9.3\ \sigma$ to $6.5\ \sigma$;

(4) Move TCDQ collimator of IP6 from $9.8\ \sigma$ to $7.0\ \sigma$;

The settings in millimetre for each collimator concerned are given in [2]. The full setup of one beam (beam 1) was supposed to be done first in order to achieve the complete set of settings for at least one beam.

A loophole was found in the procedure above: items (3) and (4) cannot be done separately due to a software interlock that prevents increasing the retraction between TCSG and TCDQ in IP6. This aspect was overlooked when the procedure was established for MPP approval with the results that beams were safely dumped when the TCSG in IP6 was moved. Future tests must be done with a function-driven control of these two collimators to ensure that safe retraction is maintained during the test.

Moving the primary collimators (TCPs) into the beam after several hours of stable beam conditions posed some operational concerns due to the uncertainty of the beam halo population. Movements had to be performed in small steps in order to avoid large beam loss spikes that could dump the beams. This turned out not to be a problematic procedure because the tail population between $5.7\ \sigma$ and $4.0\ \sigma$ could be scraped while remaining safely under the BLM dump thresholds. Movements of the other collimators could be done rapidly in single steps because the tail had already been efficiently cleaned by the TCPs.

2.3 Machine protection aspects and recovery of nominal conditions

Since the beam tests were performed with beam intensities well above the setup beam intensity that allows masking interlocks, the nominal configuration of hardware interlock settings was kept (no input could be masked). Likewise, it was decided not to mask any software interlock either. No change of BLM thresholds were put in place. It is also noted that changes of collimator positions were driven by using the so-called *actual* beam process re-generated at each fill from the collision functions. The applied changes were therefore transparent for the following fill (no settings to be reverted).

As mentioned already, only robust collimators built with Carbon-based material were moved into the beam in this first test at high intensity. The Tungsten collimators (TCLA absorbers in IP7 and TCT tertiary collimators next to the experiments) were left to their operational settings.

In order to move safely the primary collimators close to the beam, it was decided to open the collimator position thresholds asymmetrically, leaving in place the outer limits. This ensured that the collimators could not be moved by mistake further apart from the circulating beam, e.g. in the unlikely case of typing errors when setting the collimator settings. Normalised settings for positions and interlocks are summarised in Tab. 3. For redundancy, the energy-based limits for the maximum allowed gap remained unchanged from the standard operational values (see example in the next section, Fig. 3).

Table 3: Settings and dump limits for the collimators moved in the EOF study. The outer limits were unchanged form the standard operation values. Here, average settings are given for the outer limits (400 μm margin are used, to be scaled by the local beam sizes).

Collimator family	Inner limit [σ]	Settings [σ]	Outer limit [σ]
TCP-IR7	2.5	4.0	6.9
TCSG-IR7	4.5	6.0	6.0
TCSG-IR6	5.5	7.0	9.9
TCDQ-IR6	6.0	7.5	12.7

2.4 Preparation and tests without beam

The collimator settings and the position interlock configuration was tested without beam in order to ensure that the settings prepared were safely within the agreed limits defined in [2] and would not cause beam interlocks. The dry-run was carried out at top energy to have the energy-dependent limit set to the physics values. All the collimators to be used during the end-of-fill study were moved to the tight setting positions. An example for the vertical primary collimator of B1 is given in Fig. 3. Note the asymmetry dump interlock values that only allow moving the collimators to smaller gaps.

3 Results of beam measurements

3.1 Collimator movements and beam scraping

The machine was moved to ADJUST mode at 14:41, after 8 hours of stable beams. Collimator position interlocks were updated to enable movements to the tight settings and then the collimator movements started at about 15:00. The primary collimators were moved first to perform the scraping of the beam tails from the initial settings of 5.7 σ to the tight 4.0 σ settings. Collimator gaps and jaw positions versus time are given in Fig. 4. For each collimator, one jaw at a time was move so that the initial scraping was actually done with one jaw only (one-side scraping).

During tail scraping, at every collimator movement a beam loss spike is induced when the jaw intercepts primary beam protons. In addition, the DC level of losses also increases when the jaws are closer to the beam, as shown in Fig. 5. In this phase, small steps of 5 μm or 10 μm were used to maintain the loss spikes well below dump limits. Once horizontal and vertical collimator were set to 4.0 σ, the movements of the skew collimator could proceed faster (Fig. 4). After the beam tails were cleaned by the TCPs, the secondary collimators (TCSGs) could be moved from 8.5 σ to 6.0 σ in one

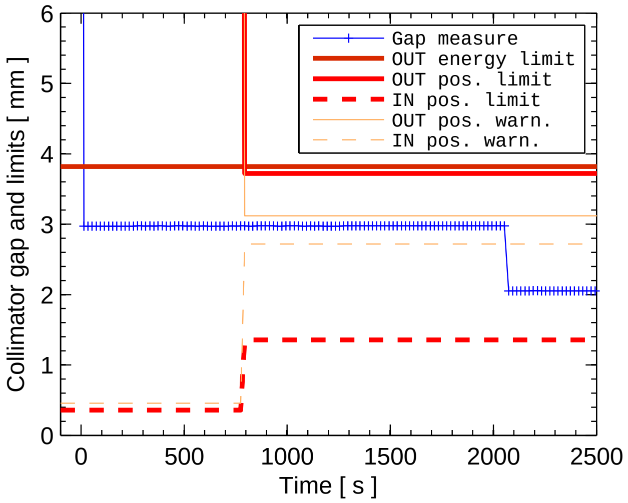

Figure 3: Vertical TCP collimator gap and interlock limits versus time during a dry run performed without beam the 15th of August, 2011. Collimators were moved starting from a parking positions, which explains why the initial limit values are relaxed. The settings of inner dump limits for the EOF tests were changed to allow positions closed to the beam whilst the outer limits remain to the operational values to prevent larger gaps.

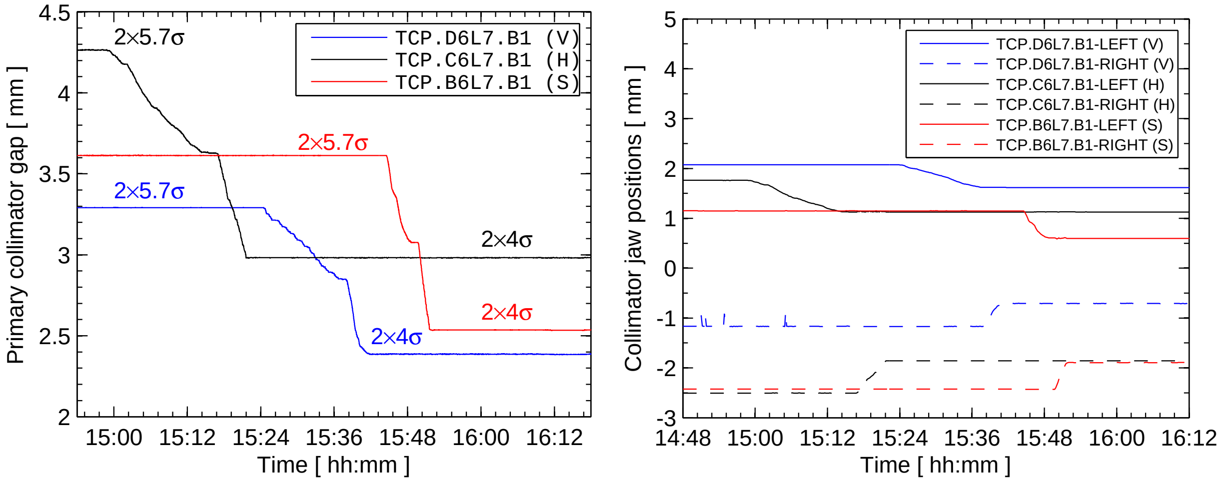

Figure 4: Primary collimator gaps (left) and jaw positions (right) as a function of time during the initial scraping of the beam tail. The collimators were moved in steps of 5 μm or 10 μm from the initial half-gap settings of 5.7 σ to the tight 4.0 σ settings. One jaw at at time was moved.

single step (see Fig. 6) without observing significant losses. The measured beam losses as a function of the TCP collimator gaps are shown in Fig. 7. Note that the largest loss spikes occur when the first collimator jaw is moved into the beam (see also Fig. 4).

3.2 Beam current and lifetime measurements

Total beam current and lifetime calculated from fast current transformers (BCTs) are given in Figs. 1 and 2. The total number of protons lost during the study was approximately 2.8×10^{10} for B1. Taking into account the natural lifetime time observed with collisions in all experiment, 2.0×10^{10} protons were lost from B2. Assuming the same average lifetime for the two beams during the test, one can

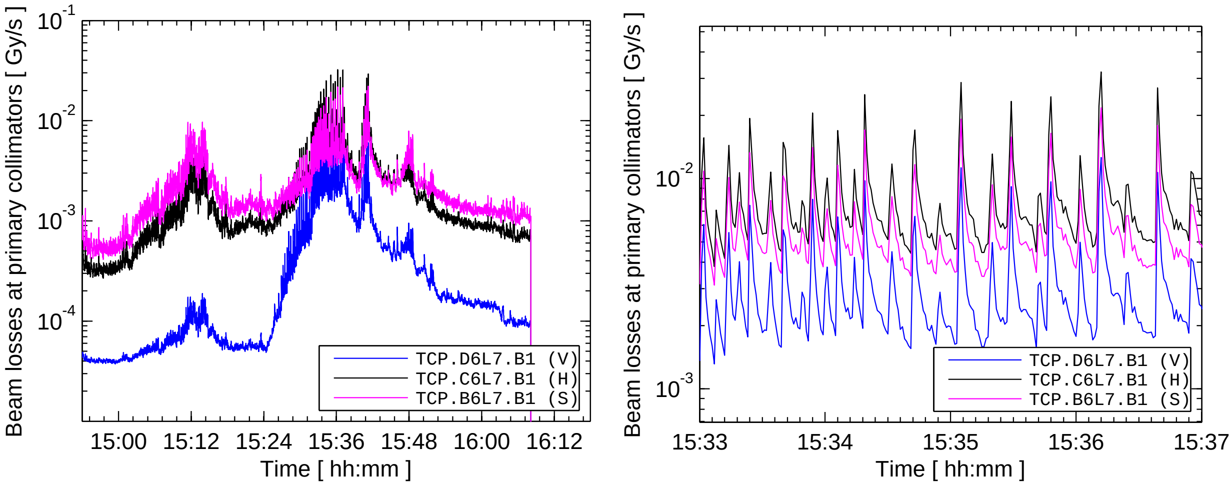

Figure 5: Losses at the IR7 primary collimators versus time. Three beam loss monitors immediately downstream of the vertical, horizontal and skew TCPs are considered. The TCP-V is the most upstream in B1 direction, then followed by the TCP-H and finally by the TCP-S. This explains the higher losses seen at the TCP-S. A zoomed graph is also given (right) to illustrated some details of the loss spike shape during scraping.

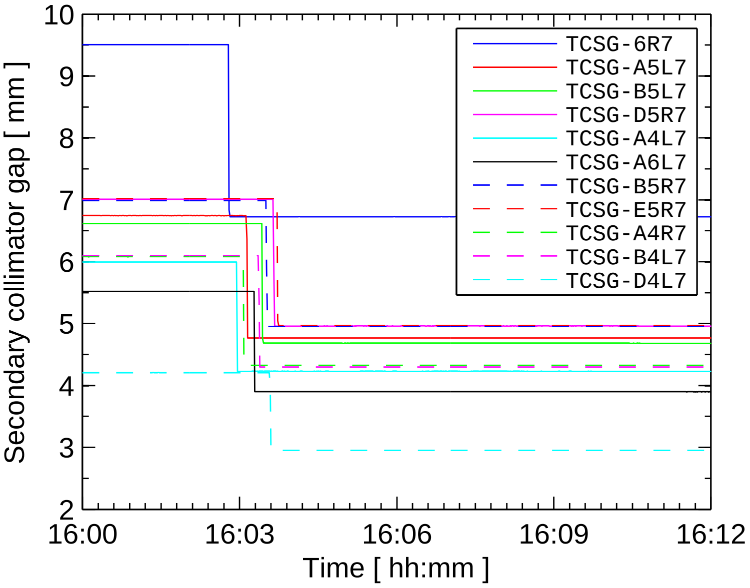

Figure 6: IR7 secondary collimator gaps as a function of time. The TCSGs were moved in one single step from the initial half-gap settings of 8.5 σ to the tight 6.0 σ settings. One collimator at a time was moved, in rapid succession.

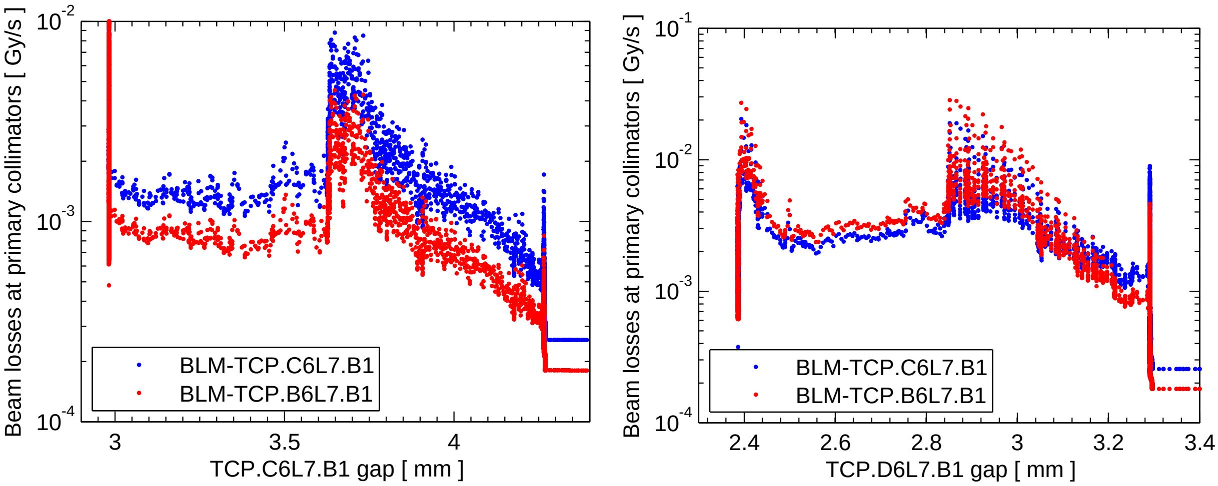

Figure 7: Beam losses at the IP7 primary collimator locations versus collimator gap during the horizontal (left) and vertical (right) tail scraping. Larger spikes are seen during the scraping with the "left" jaws (see Fig. 4) whereas the movements of the "right" jaw intercept fewer halo particles.

conclude that the total tail population between $4.0\ \sigma$ and $5.7\ \sigma$ was 8×10^9 protons for B1. This is a conservative assumption because before the start of our tests B2 had shown a larger lifetime than B1.

After the completion of the movements of the secondary collimators in IP7, the collimator TCSG.4R6.B1 was moved. This triggered a beam dump due to a software interlock that checks the retraction between TCSG and TCDQ in IP6. During the time with TCSGs in IP7 at tight settings, no abnormal reduction of beam lifetime were observed. Indeed, the graphs of Fig. 2 indicate that lifetime has recovered the values observed before starting the beam tail scraping. The trend was not affected the movement of all secondary collimators.

It is noted that the high intensity conditions for this test were not optimised for precise tune shift measurements. Reliable measurements are therefore not available.

3.3 Collimation cleaning aspects

The beam losses measured at the hottest spot downstream of the primary collimators and in the dispersion suppressor on the right side of IP7 are given in Fig. 8. Two BLM at the Q8-R7 quadrupole magnet, which is the limiting location for cleaning with the present collimation system, are chosen. The *local cleaning inefficiency* at a specific location around the ring is defined at the ratio of local beam loss to the losses at the highest loss location, i.e. at the TCPs. The validation of the system settings and the precise measurements of local cleaning inefficiency around the LHC ring is done with dedicated loss maps studies when the loss rates at the TCP collimators are artificially to improve the BLM signal to noise ration at the different loss locations around the ring. The cleaning performance of the system with tight settings was addresses in detail in [1]. A systematic study of the cleaning performance was not easily possible during the EOF study because:

- The steady losses at the TCPs in IR7 were lower by about a factor 10 compared to typical loss rates that provide precise loss maps.
- There is an intrinsic uncertainty on the plane in which losses take plane.
- The total losses showed an important component from off momentum coming from particles that leave the RF buckets and are eventually lost in IP3. The closure of collimators in IP7

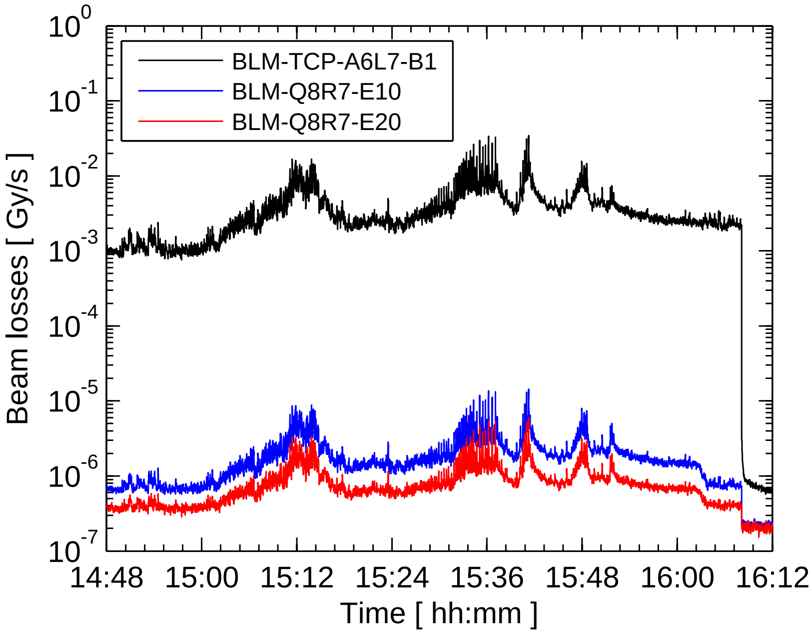

Figure 8: Beam losses measured as a function of time at one BLM downstream of the three primary collimator (black line) and at two locations in the Q8 quadrupole in the dispersion suppressor downstream of IP7 (red and blue lines).

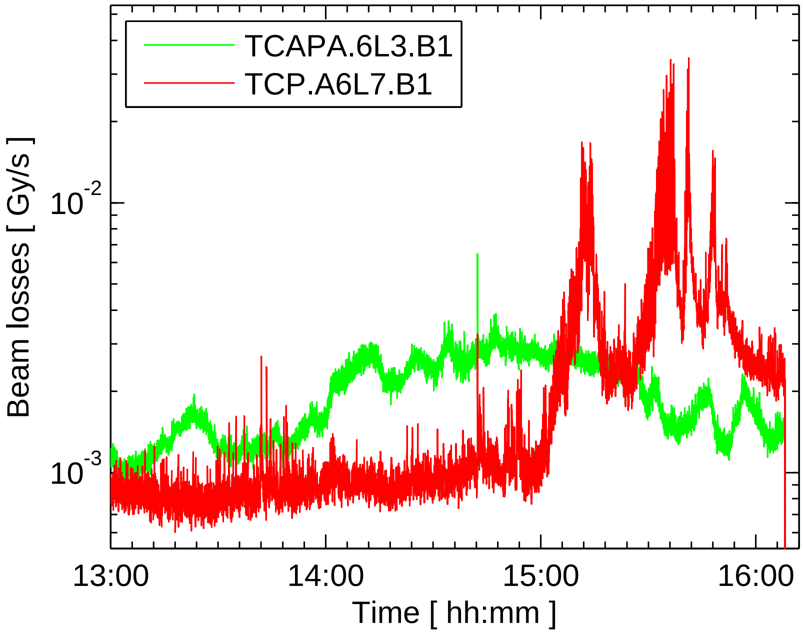

Figure 9: Beam losses as a function of time measured before and during the collimator test at the peak loss locations in IP3 and IP7. Beam scraping to achieve tight TCP settings started at 15:00. In the last hours of physics data taking before the MD started, primary beam losses were higher in IP3 than in IP7.

changed the IP3 to IP7 balance of losses for B1, as shown in Fig. 9. This contribution cannot easily be compensated and remains as a source of uncertainty in the following discussion.

An attempt is nevertheless made to collect observations related to cleaning performance.

The loss maps around the 27 km LHC ring with the relaxed collimation settings (top) and after (bottom) having moved IR7 primary and secondary collimators to tight settings, are given in Fig. 10. One can see high losses in the experimental regions, coming from the collision debris in the IPs. Important steady losses occur also in the cleaning insertions. Momentum losses showed higher levels than betatron losses at the start of the EOF studies (see also Fig. 9).

In order to see details of the differences of the two systems, the IR7 region has to be looked at in more detail. The normalised losses in that region are shown in Fig. 11. The BLM signals for both beams are normalised to the peak loss rate for B1 in the vicinity of the B1 TCPs. The improvement in cleaning of the tight settings is measured by the smaller losses in the dispersion suppressor R7. This is also shown in Fig. 12, where the local cleaning calculated at the first quadrupole magnets in the dispersion suppressor are given. Improvements up to a factor 2–3 are measured on individual BLMs. Note that only TCSGs and not TCLAs collimators were moved to tight settings.

In Fig. 13, the relative losses at the different collimators of B1 are shown. The interpretation of measurements is harder because, unlike losses in the dispersion suppressor R7, losses at the collimators in the warm straight section are affected also by losses from B2. Hence, only a selection of a few collimators located in different IRs is presented: Primary collimators (TCP) and scrapers (TCHS) in IR3 and IR7 and TCT collimators in all IRs are given. For similar primary loss rates in IR7, with tight settings the losses in other IRs are reduced by up to a factor 4. The reduction of IP3 losses is explained by the graph of Fig. 9.

4 Conclusions

The only test performed in 2011 with tight collimator settings and total stored been energies of 95 MJ was done as an end-of-fill MD after about 8 hours of collisions in all interaction points. The results of various beam measurements performed in these conditions were summarised. Even if these tests are not complete, because only a sub-set of collimators could be moved to the desired settings, important feedback could nevertheless be gained. For one beam, it was possible to achieve tight settings with all the primary and secondary collimators in IP7. These collimators are the ones with the smallest normalised gaps and are driving the collimator impedance. This achievement confirmed the good stability of beam orbit and of collimator settings over periods of months. The fact that tight settings were achieved without repeating the collimator alignment, confirmed the proposed settings can be used without additional beam-based alignment campaigns.

With tight settings for primary and secondary collimators in IP7, no apparent degradation of beam lifetime was observed. These conditions were only maintained during about 5 minutes, before the beams were prematurely dumped. Additional information like tune shifts from reduced collimator gaps, could not be addressed in this test since the conditions were not optimised for precise tune measurements. Based on the results achieved in collision conditions, we preliminary conclude that there are no obvious problems to operate the LHC with the proposed tight settings for 3.5 TeV. Other aspects like beam losses and orbit transient during the ramp and squeeze must be addresses in separated studies.

Parasitically, while the primary collimators were moved from $5.7\ \sigma$ to $4.0\ \sigma$, it was possible to probe the tail population after a long period spent in collisions in all experiments. A total tail population of only about 8×10^9 protons was measured in the specified range.

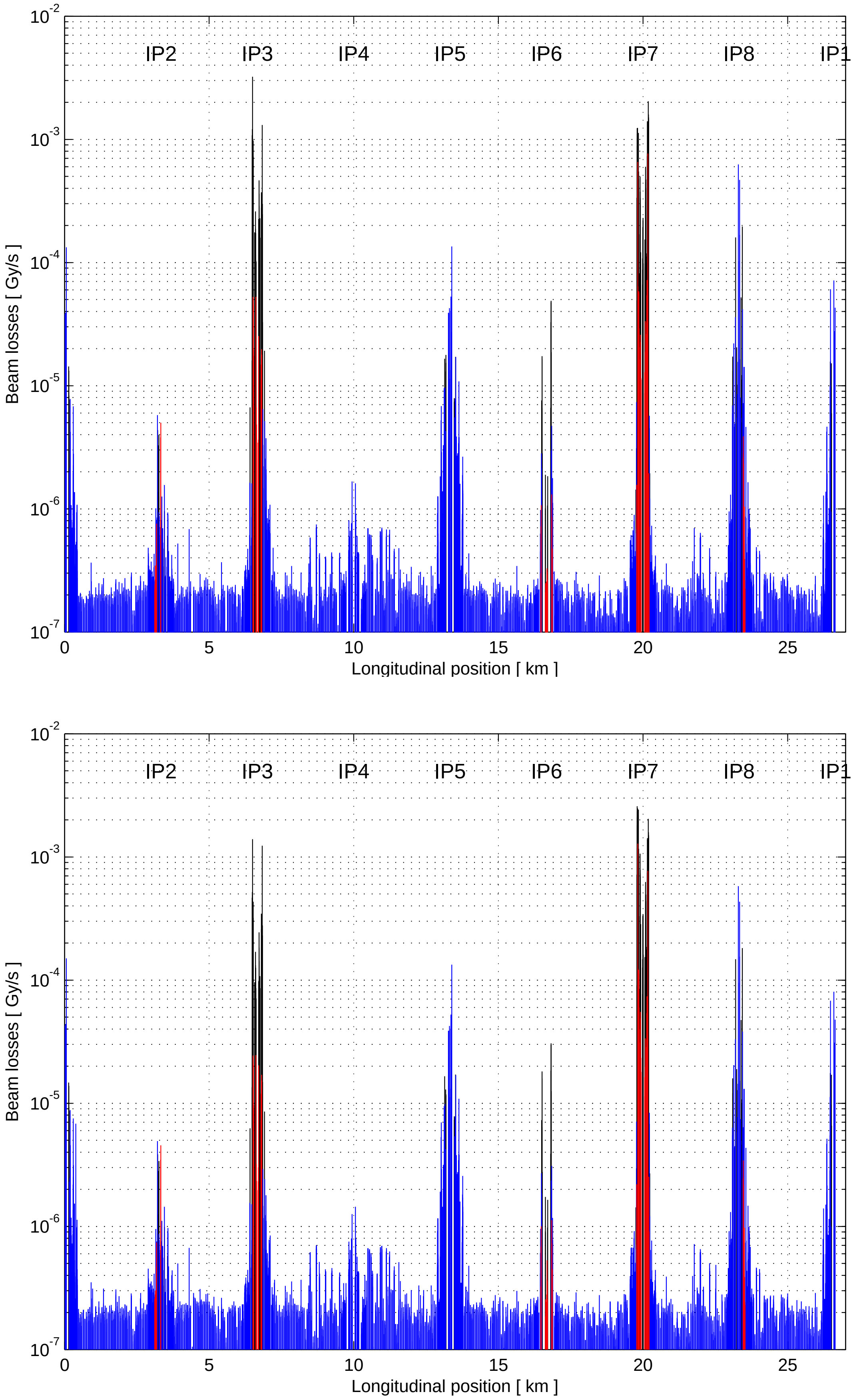

Figure 10: Steady loss maps with relaxed (top) and tight (bottom) collimator settings for B1. B2 remained with relaxed settings. The beam losses are driven by the collision process.

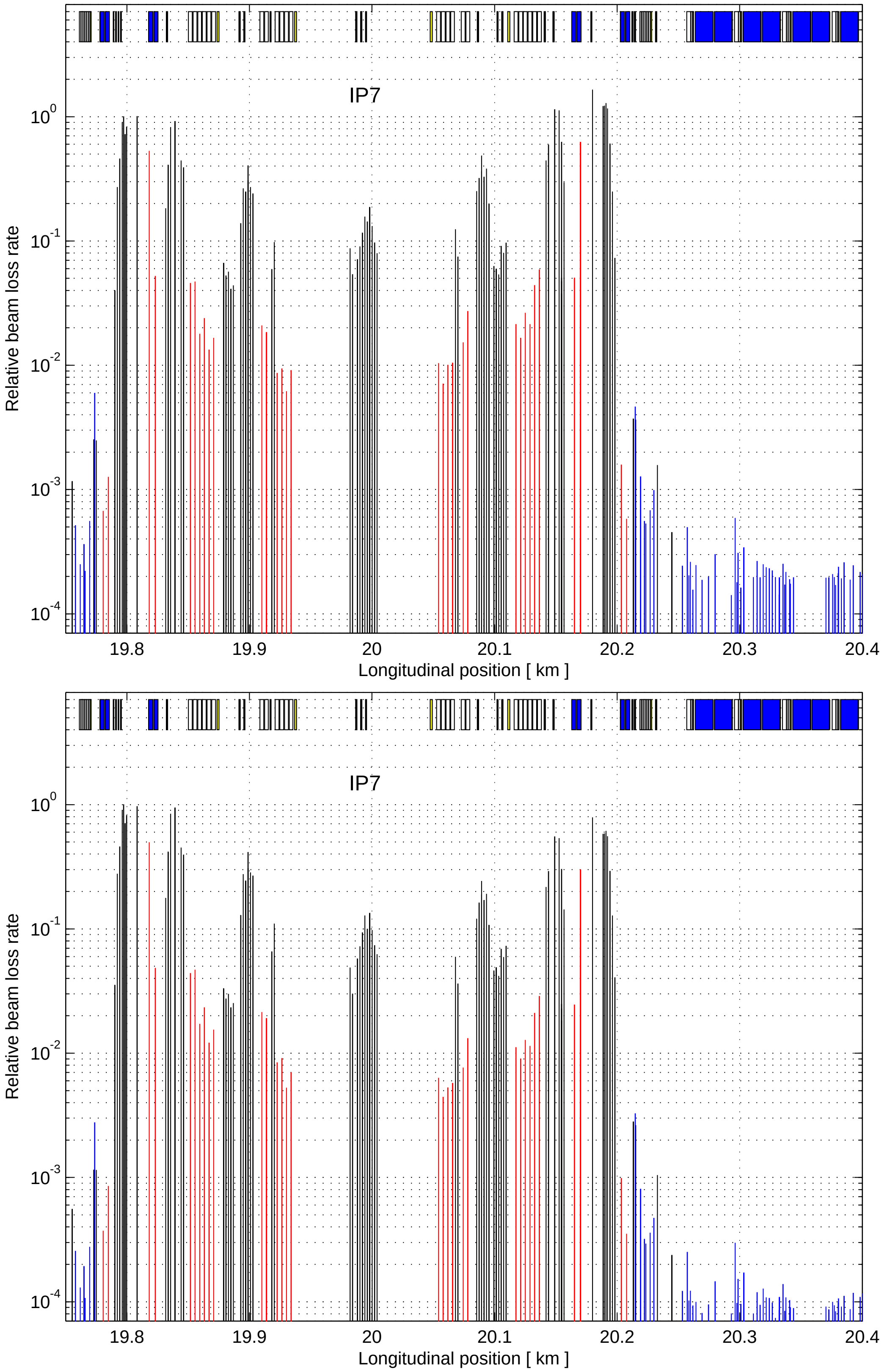

Figure 11: Normalised beam losses around IP7 with relaxed (top) and tight (bottom) collimator settings for B1, used to calculate collimator cleaning efficiency. B2 remained with relaxed settings. The signal of all BLMs is normalised to the highest B1 peak losses close to the B1 TCPs.

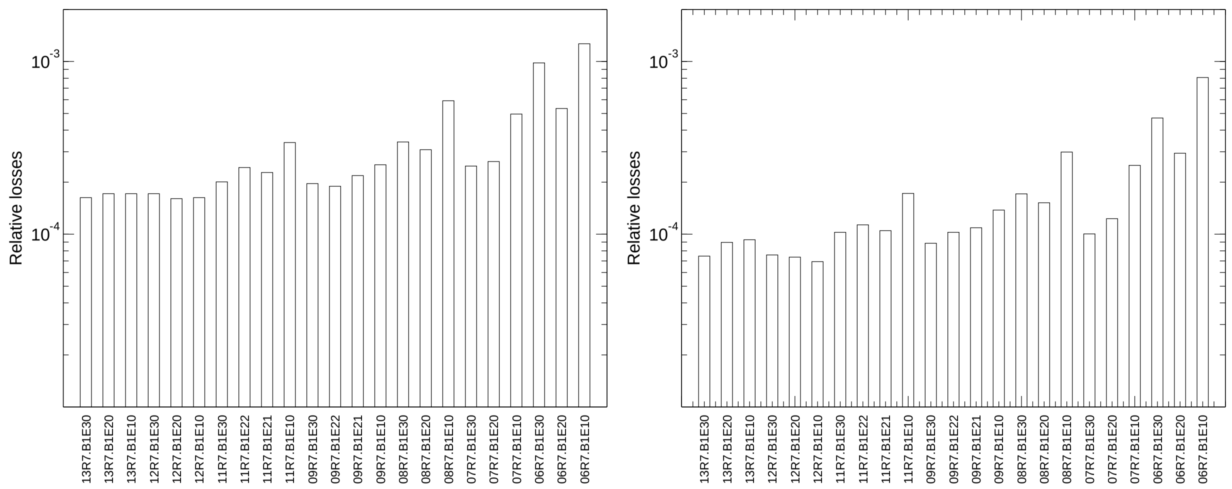

Figure 12: Normalised losses in the recorded in the quadrupoles of the dispersion suppressor on the right side of IP7, with relaxed (left) and tight (right) B1 collimator settings.

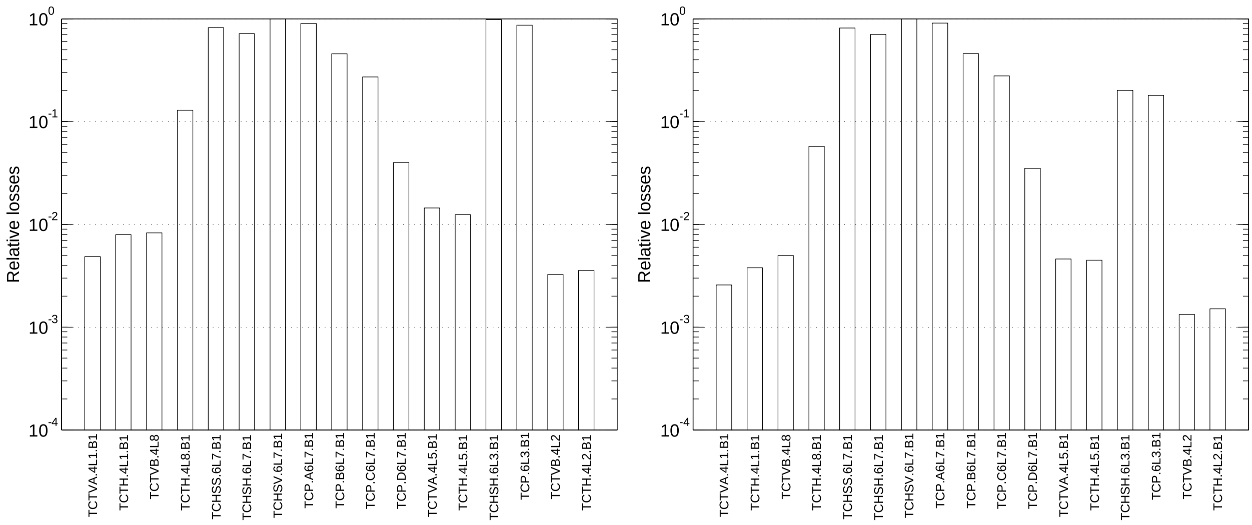

Figure 13: Normalised losses at a selection of collimators in different IRs with standard (left) and tight (right) settings.

5 Acknowledgments

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