Summary of MD on nominal collimator settings


Keywords: Collimator settings, collimator impedance

1 Summary

The presently installed Phase 1 LHC collimators (1), were moved in the betatron cleaning insertion (IR7) from relaxed to nominal settings at 3.5TeV and further in. The collimator performance and impedance were measured. The local cleaning inefficiency improved from \( \sim 3e^{-4} \) (average relaxed settings) to \( 1e^{-4} \) (nominal settings), and \( 4e^{-5} \) (tight settings).

In parallel, measurements of transverse betatron tune shifts during collimator movements were carried out to verify the transverse impedance model. Despite very large noise, preliminary analysis shows that the measured effective impedance may be slightly larger than expected. Dedicated measurements without transverse dampers are needed to improve the tune signal to noise ratio and conclude on the effective impedance of the collimators at 3.5 TeV.

The significant performance improvement with tight settings could be used to allow for a higher intensity in the machine. Tighter collimator settings could allow operations with smaller \( \beta^* \) in the experimental insertion regions.

2 Introduction and motivation

During the runs in 2010 and 2011, the LHC has been operating with relaxed collimator settings. These settings, presented in Table 1, provide more margins than the nominal design settings (2) (3) between the different steps in the cleaning hierarchy. This allows maintaining the cleaning hierarchy despite a larger uncertainty on the orbit and the beta beating but also limits the performance.

The minimum aperture that can be protected must be well outside the last step in the cleaning hierarchy. In a squeezed optics the limiting aperture is found in the inner triplets in the interaction regions, meaning that if the outermost tertiary collimator can be moved closer to the beam, a smaller \( \beta^* \) can be used. The calculation procedure is explained in Ref. (4).

The local cleaning efficiency in the cold parts of the machine is also dependent on the distance between the different steps in the hierarchy and a significant efficiency increase can be
expected when moving from intermediate to nominal settings (5). Therefore, a higher intensity can be used in operation with tighter settings (6).

Because of the possible gains in performance, it is preferable to operate at tighter collimator gaps, provided that the machine imperfections do not break the cleaning hierarchy. This motivates our MD, where the goal was to investigate the cleaning performance through loss maps at nominal collimator settings at 3.5 TeV and even tighter settings, taking into account the smaller beam emittance. These settings are close to the settings in mm foreseen for 7 TeV operations.

In parallel, as the collimators were moved, the impedance of the machine was investigated through tune measurements.

**Table 1**

Different collimator settings used at 3.5 TeV, in nominal beam σ. Only collimators in IR7 and IR6 are shown – other groups of collimators (TCTs and IR3) were not moved and stayed at their standard settings. The settings quoted as nominal are the same as in Ref. (2), except that all stages are closer to the beam by 0.3 σ.

<table>
<thead>
<tr>
<th></th>
<th>TCP IR7</th>
<th>TCSG IR7</th>
<th>TCLA IR7</th>
<th>TCSG IR6</th>
<th>TCDQ IR6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 settings</td>
<td>5.7</td>
<td>8.5</td>
<td>17.7</td>
<td>9.3</td>
<td>10. - 10.6</td>
</tr>
<tr>
<td>Nominal</td>
<td>5.7</td>
<td>6.7</td>
<td>9.7</td>
<td>7.2</td>
<td>7.7</td>
</tr>
<tr>
<td>Tight B1</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
<td>7.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Tight B2</td>
<td>4.0</td>
<td>5.0</td>
<td>7.2</td>
<td>6.2</td>
<td>6.7</td>
</tr>
</tbody>
</table>

3 Procedure and beam conditions

The foreseen MD procedure, to be carried out on each beam, was:

- Drive in all IR7 secondary collimators (TCSG) to nominal position (see Table 1), keeping the primaries (TCP) at 5.7 σ.
- Drive in the dump protection TCSG/TCDQ in IR6 to their nominal position
- Drive in IR7 absorbers (TCLA) to have all IR7 collimators at their nominal position.
- Verify the cleaning performance through beam losses provoked by a crossing of the third order resonance. Loss maps should be performed for:
  - The nominal configuration presented in Table 1
If possible, settings tighter than nominal, with a target setting in mm corresponding to the nominal 7 TeV scheme. These settings should be found empirically by provoking losses with a primary collimator. Although this is not a full loss map, observations of the downstream BLM signals provide information on the hierarchy.

- Do parasitic impedance measurements by observing the tune shifts induced by collimator movements.

The collimator centre was taken from the last beam-based alignment. Beams at 3.5 TeV were used in an unsqueezed optics during two fills. After a first ramp and subsequent measurements, described in Section 4, the beams were dumped and reinjected before a second ramp and new measurements, described in Section 0, were performed. The emittances from wire scanner measurements are shown for both beams in Table 2. The chromaticity was measured to 2-3 units and two bunches with nominal intensity were used in each ring.

<table>
<thead>
<tr>
<th></th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1</td>
<td>2.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Beam 2</td>
<td>2.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>

4 Results from first fill

Beam 1:

For the first fill, the collimators in beam 1 were set as described in Section 2 to nominal 3.5 TeV settings (Table 1 and Figure 1). A small loss was observed when moving the secondary collimators. The horizontal and vertical primary collimators (TCP.C6L7.B1 and TCP.D6L7.B1) were then moved to touch the beam. It should be noted that when moving left and right jaws, a different number of motor steps were necessary to touch the beam halo, indicating that the collimators were not perfectly centered on the beam. An offset of 230 µm could be inferred by the difference in motor steps in the horizontal plane, 110 µm in the vertical plane and 130 µm in the skew plane.

The recorded losses for the horizontal TCP show a correct hierarchy but the cleaning inefficiency cannot be estimated since the overall losses are so low that the BLM signals from the cold magnets downstream of IR7 do not exceed the noise level. As no hierarchy problem was observed, the primary collimators were driven further in to the nominal 7 TeV settings (5.7/√2=4 nominal σ units at 3.5 TeV).
The secondary collimators in beam 1 were subsequently moved in towards 7 TeV nominal settings (6.7/√2), i.e. going to ~ 4.7 nominal σ. In order to avoid large losses, the settings were changed in steps: at 5.7 nominal σ units, clear losses were observed, indicating a break-down in hierarchy. The TCSG7 were therefore retracted to 6σ. The TCLA7 were set with the same retraction and the TCGS6/TCDQ6 to intermediate values as shown in Table 1 as tight settings for beam 1. The settings in mm are shown in Figure 2.

Figure 1: The settings in mm for nominal collimator settings at 3.5 TeV, B1 (see Table 1).

Figure 2: The tight B1 settings, as defined in Table 1, given in mm.
Figure 3: Horizontal betatron loss map with tight collimator settings for B1 (see Table 1).

Figure 4: Horizontal betatron loss map with tight collimator settings for B1, zoom in IR7.
These tight settings were qualified with loss maps as described in Ref. (7) (horizontal, vertical and off-momentum). The horizontal loss map is shown in Figure 3). No indications of a hierarchy breakdown were observed. The obtained local cleaning inefficiencies, and the cold elements where they were observed, are shown in Table 3 and the development of the inefficiency with time over one year is shown in Figure 5. The inefficiencies measured with the tight settings for B1 are lower than recently observed in the last loss maps by a factor 8-12. This is a significant improvement, which could be used to allow for a higher intensity in the machine.

Figure 5: Beam 1 and Beam 2 maximum local cleaning inefficiency in the cold parts of the LHC at 3.5TeV over about one year operation. The results from this MD are contained in the second and third sets of points from the right, where a clear decrease can be observed.

**Beam 2:**

In beam 2, the collimators were driven in directly to their nominal 3.5 TeV settings, which are shown in mm in Figure 6. No losses were observed during the collimator movement\(^1\). Pushing to tighter settings was saved for the second fill. Instead, the nominal settings were qualified directly with a full set of loss maps. As an example the horizontal betatron loss map is show in Figure 7. The loss maps showed a good hierarchy and therefore nominal settings for 3.5 TeV has been fully qualified for beam 2.

As can be seen in Table 3 and Figure 5 the measured local cleaning inefficiencies in the cold parts of the machine are better than recent loss maps. However, the observed improvement of a factor 2-4 with nominal settings is not as drastic as for the tight settings.

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\(^1\) The offsets of the horizontal (TCP.C6R7.B2 ) and vertical (TCP.D6R7.B2 ) primary collimators were 310 um and 60um respectively.
Finally, off-momentum loss maps were performed with the B1 collimators at tight settings and the B2 collimators at nominal settings. The maximum observed local cleaning inefficiency in the cold part of the machine was $1.63 \times 10^{-4}$.

Figure 6: Nominal collimator settings in mm at 3.5 TeV, B2 (see Table 1).

![Figure 6](image)

Figure 7: Horizontal betatron loss map with nominal collimator settings for B2.
5 Results from second fill

The scope of the second fill was to set to reach 7TeV nominal settings with beam 2 and to characterize 3.5TeV nominal settings with beam 1 with complete loss maps in order to check if the break down in hierarchy previously found could be observed already at these more relaxed settings.

Due to problems encountered during the second filling, very little time was left to complete the program.

Beam 2:

After the energy ramp, all collimators: TCSG7, TCSG6/TCDQ6 and TCLA6, were moved to 3.5 TeV nominal settings in one go. As for the first fill, no losses were observed. The 3 TCP7 were moved to 4 nominal σ units, without re-centering them, due to lack of time. The TCGS7 were moved in steps, and could be stopped at 5 nominal σ units, since at 4.7 the hierarchy broke down (see Figure 8 where the BLM signals from the secondary collimators are larger than from the primary ones). The retraction of the TCLA7 was chosen to be proportional to that at nominal settings, giving ~ 7.2 nominal σ units. The TCGS6/TCDQ6 were then moved (prior the TCLA7) to 6.7 and 6.2 σ respectively. An example of normalized loss maps on the vertical plane are shown in Figure 9 and Figure 11. As in the previous fill, the beam was first blown up in the vertical plane because the vertical tune was closer to the 3rd integer resonance than the horizontal one.

Figure 8: BLM signals when moving TCGS7 collimators from 5 to 4.7 nominal σ units. Evidence of breakdown of hierarchy is highlighted.
Figure 9: Vertical betatron loss map with tight collimator settings for B2, data taken one second after the maximum value reached in IR7.

It should be noted that the losses in Q9.R1 observed in the vertical loss maps (highlighted with a dashed green circle in Figure 10), did not appear a second later (see Figure 10), while the absolute losses in IR7 stayed almost identical. These spikes have yet to be understood.

Furthermore, an increase in local cleaning inefficiency was observed in the Q7.L7 by a factor of ~ 5 compared to previous loss maps with intermediate settings. The BLM in this case is located very close behind a TCLA, and therefore the higher signal may be caused by showers from the collimator. Several BLM’s in IR6 show higher relative signal than normal. Further investigation is ongoing.

The ratio between losses at the primary collimators and the DS magnets in IR7 is improved by a factor of about 4 with respect to the 3.5TeV nominal settings.

Table 3
The highest local cleaning inefficiencies in the cold regions, as measured with loss maps, and the elements where they were observed (Q7 downstream of IR7 is not included because BLM signal may be due to showers from nearby collimators). The different settings are defined in Table 1. The nominal settings for beam 1 could not be qualified due to hierarchy breakdown.

<table>
<thead>
<tr>
<th></th>
<th>B1 hor</th>
<th>B1 ver</th>
<th>B2 hor</th>
<th>B2 ver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>-</td>
<td>-</td>
<td>Q8L7: 1.5e-4</td>
<td>Q8L7: 5.4e-5</td>
</tr>
<tr>
<td>Tight</td>
<td>Q11R7: 3.8e-5</td>
<td>Q11R7 :4.7e-5</td>
<td>Q8L7: 7.81e-5</td>
<td>Q8L7: 6.85e-5</td>
</tr>
</tbody>
</table>
Beam 1:

The collimators in beam 1 were moved from 2010 to nominal beam settings in one go. These settings were characterized with loss maps. A clear breakdown of hierarchy can be
observed (see from Figure 12 to Figure 15). The reason for the breakdown is not yet understood.

Figure 12: Vertical betatron loss map with nominal 3.5 TeV collimator settings for B1.

Figure 13: Vertical betatron loss map with nominal 3.5 TeV collimator settings for B1. Zoom in IR7.
Figure 14: Horizontal betatron loss map with nominal 3.5 TeV collimator settings for B1.

Figure 15: Horizontal betatron loss map with nominal 3.5 TeV collimator settings for B1. Zoom in IR7
6 Transverse impedance studies

As the collimators are moved towards the beam from relaxed settings to nominal settings and then tight settings at 3.5 TeV, the transverse impedance of the collimators is expected to increase causing a negative tune shift. In order to estimate these quantities, the horizontal and vertical tunes were monitored during the whole MD. However, due to large noise and tune drifts, no clear tune change could be measured.

As a consequence, as it was done last year at injection energy, it was decided to take some time to abruptly move back and forth some of the B2 collimators to facilitate the identification of a tune change correlated with collimator movements (see Figure 16 and Figure 17). From 23:18 to 23:23, moving TCSG7 collimators (from 6.7 to 8.5 nominal σ) and TCLA7 collimators (from 9.7 to 17.7 nominal σ) back and forth twice lead to a tune shift of ΔQy≈1e-4. From 23:30 to 23:40, moving TCP7 (from 5.7 to 9.7 sigma), TCSG6 (from 7.2 to 11.2 sigma), TCSG7 (from 6.7 to 10.7 sigma), TCLA7 (from 9.7 to 13.7 nominal σ), TCDQ (from 7.7 to 11.7 nominal σ) back and forth twice lead to a tune shift of ΔQy≈2.5e-4. The effective transverse impedances corresponding to these tune jumps are respectively 4 MOhm/m and 9 MOhm/m, which is of the same order of magnitude but still larger than predictions. Work is ongoing to crosscheck the collimator and machine settings between the impedance model and the MD.

![Figure 16: B2 vertical tune (green curve) while some of the B2 collimators were moved back and forth (orange curve) from nominal settings. Despite the large noise, it can be seen that moving collimators back and forth leads to a tune shift, at least for the larger movements between 23:30 and 23:40, but it is not obvious to quantify it.](image-url)
In the horizontal plane of B2, no correlation between collimator movement and tune could be observed. This is probably because the BBQ signal is locking on the wrong peak, given the large drift observed: $\sim$1e-3 peak to peak, even after averaging. BBQ 2D spectra from the hump buster confirmed that the BBQ signal was locked on a perturbation peak that lies on top of the horizontal tune. At the time of the measurements, the conditions for Beam 2 were: 3.5 TeV/c, Nb=0.9e11 and 1.1e11p/b and 4 sigma bunch length=1.2ns.

Figure 17: B2 vertical tune (green curve) while some of the B2 collimators were moved back and forth (orange curve) from nominal settings. Compared to Figure 16, averaging the tune over 5 s enables to clean the signal and to observe that also the first collimator movements between 23:18 and 23:23 can be correlated with a small tune jump of $\Delta Q \sim$1e-4. The second larger collimator movements between 23:30 and 23:40 can be correlated to a tune jump of about $\Delta Q \sim$2.5e-4.

During the second filling, only IR7 secondary collimators were moved back and forth for beam 1 from 7.2 to 11.2 $\sigma$. Issues with the actual trim prevented us from getting all the other collimators to move together. As it can be seen in Figure 18 and Figure 19, a $\Delta Q_y \sim$1e-4 tune shift was observed in the vertical plane, and a hint of a $\sim$1e-4 tune shift in the horizontal plane could be guessed (much less obvious than in the vertical plane due to drift and noise).
Figure 18: B1 horizontal tune (green curve, averaged over 3 s) while some of the B1 collimators were moved back and forth (orange curve) from nominal settings. It can be noted that the retraction of the collimators from 7 to 8.7 $\sigma$ did not lead to any tune shift, while a tune jump of $\sim$1e-4 could be guessed when moving the collimators to smaller gaps.

Figure 19: B1 vertical tune (green curve, averaged over 3 s) while some of the B1 collimators were moved back and forth (orange curve) from nominal settings. A tune jump of $\sim$1e-4 can be guessed when moving the collimators to smaller gaps.
7 Conclusion

The LHC collimators performance and impedance were measured with 3.5TeV beams, and two bunches of nominal intensity per beam, for nominal and tight settings.

Nominal 3.5TeV settings in the betatron cleaning insertion (IR7) could be qualified for beam 2 and show a slight improvement (a factor between 2 and 4) with respect to the relaxed settings. In beam 1, the observed breakdown in hierarchy is under investigation. A local inefficiency at Q7 in IR7 was noted to be higher than with relaxed settings, but this could be due to showers from the close-by TCLA upstream.

Tight settings, with primary collimators at 4 nominal \( \sigma \) (half gap), i.e. close to the 7TeV opening in mm, could be achieved with retractions of the secondary collimators and absorbers set to maintain collimator hierarchy (2 nominal \( \sigma \) for beam 1 and 1.2 for beam 2). The performance measured with loss maps show an improvement of about a factor of 10. Such significant improvement could allow for a higher intensity in the machine, and tighter collimator settings for operation with smaller \( \beta^\ast \) in the experimental insertion regions.

Measurements of transverse betatron tune shifts during collimator movements were carried out to verify the transverse impedance model. Despite very large noise, preliminary analysis shows that the measured effective impedance may be slightly larger than expected. Dedicated measurements without transverse dampers are needed to improve the tune signal to noise ratio and conclude on the effective impedance of the collimators at 3.5 TeV.

8 Bibliography


