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MD2490 – Measurement of the TMCI threshold at flat-top in the LHC

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Summary

This report summarizes the results of MD2490 on the measurement of the intensity threshold of the Transverse Mode Coupling Instability (TMCI) in the LHC at flat top. The measurement took place during MD block 3 of 2017, on the night between 15$^{\text{th}}$ and 16$^{\text{th}}$ September. The betatron tune of bunches with different intensities was measured via ADT excitation and for different collimator settings, thus changing the machine impedance. The tune shift versus intensity measurement allowed to infer the intensity threshold of the TMCI. Relaxing the collimator settings to mimic the HL-LHC impedance reduction also showed the beneficial effect of the collimator upgrade planned for HL-LHC.

1 Introduction

In the HL-LHC era, brighter beams will be used in operation. The impact of these beams on collective effects must therefore be studied. Among those, the TMCI might become a limitation for operation at low chromaticity (few units). An accurate measurement of the TMCI in the LHC allows to evaluate the accuracy of the LHC stability predictions and to project to the future HL-LHC scenario of operation. In the following, we will summarise the procedure and main results of the TMCI measurement in the LHC.

2 Procedure and Beam Conditions

A transverse mode coupling instability (TMCI) can occur when two transverse oscillation modes couple when $Q' \sim 0$ [1]. In the LHC case, the coupling of azimuthal mode 0 (tune) with mode -1 is expected to drive the TMCI if the transverse damper was deactivated [2]. The TMCI threshold can be estimated by measuring the tune shift of bunches as a function of their intensities at low chromaticity and extrapolating the crossing point with the mode -1. To improve the measurement resolution, the coherent beam excitation method developed and used in previous collimation and impedance MDs was used [3, 4, 5, 6]. The beam was coherently kicked by the transverse damper (ADT): this method allows for a flexible control of the excitation gain and time profile, and allows to kick individual bunches [7]. The coherent oscillations were recorded with the ADT ObsBox [8], the tune shift of each bunch was then reconstructed from the coherent oscillation signal.

The MD activity was performed on the night between 15th and 16th September [9] 2017 during fills 6210 and 6212 where the beams were brought to the top energy of 6.5 TeV. The measurements were performed at flat-top, after the "combined ramp and squeeze" sequence. The octupole current was increased to 564 A to ensure beam stability.

The injection scheme used for the activity was the `Single_3b_0_0_0_CollimationImpedance`, used during previous collimation and impedance MDs [4, 6]. Up to three nominal bunches were injected in each ring, buckets 1, 361 and 721 in B1, and 71, 431 and 791 in B2. Figure 1 shows an overview of the MD.

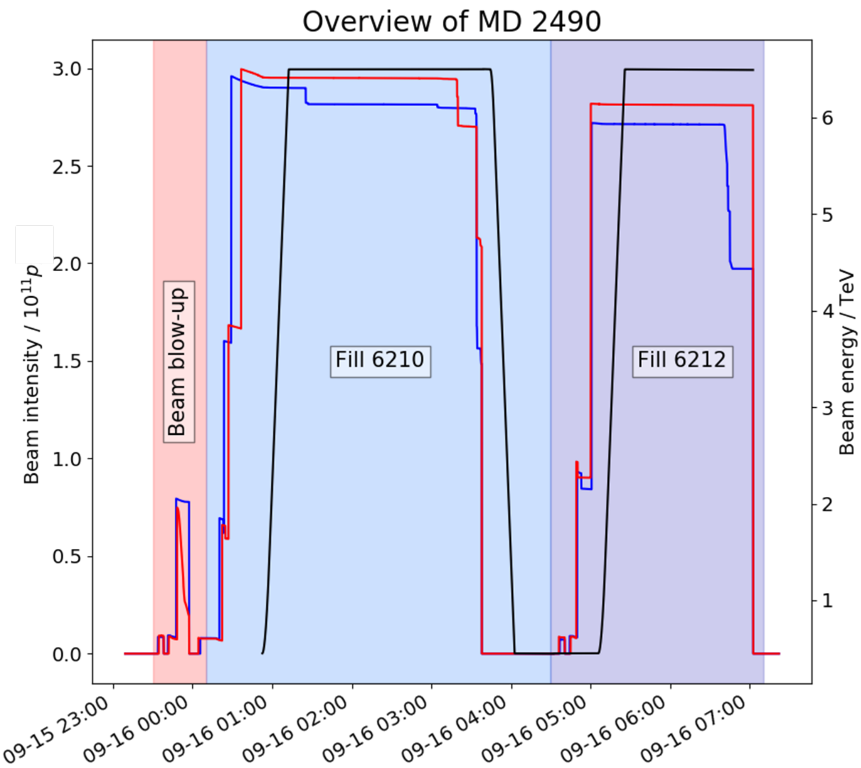

Figure 1: Beam 1 intensity (blue curve) and Beam 2 intensity (red curve), alongside beam energy (black curve) during the MD activity. The relevant fill numbers are reported as well.

At first, the nominal bunch injected in B2 suffered heavy losses. It was found that the ADT continuous blow-up was still active despite the application being closed. The issue was solved by relaunching the application and closing it back.

In the following, a first ramp was carried out with three nominal bunches in each beam. Their intensities at injection were 0.6×10^{11} protons per bunch (p.p.b), 1×10^{11} p.p.b and 1.2×10^{11} p.p.b so that the total beam intensity remained below the limit imposed by the Setup Beam flag (i.e. 3×10^{11} protons), necessary to mask collimator movements from the interlock system. Once at top energy, the chromaticity was reduced from 15 units to approximately 5 units for both beams and planes. The damper gain was reduced in order to improve the acquisition signal, but the trim was reverted as an instability developed in B1. After the set-up of the ADT, the bunches were coherently excited ~ 10 times. The primary and secondary collimators in IR7 were then brought closer to the beam in order to increase the machine impedance. The different steps taken in the collimators settings are detailed in Tab. 1.

Scenario	TCP setting	TCSG setting	Fill
1	5	14	6212
2	5	6.5	6210 & 6212
3	5	6	6210 & 6212
4	4.5	6	6210 & 6212

Table 1: IR7 collimator settings in σ_{coll}[1] Scenario 1 corresponds to relaxed settings reproducing the expected HL-LHC impedance. Scenario 2 is the operational collimator setting in 2017, scenarios 3 and 4 are tighter settings used to increase the overall machine impedance. The last column indicates in which fill the scenarios were used.
[1] With a reference emittance of 3.5 µm used for the measurements.

A second ramp was performed with two bunches in each beam, their intensities being 0.8×10^{11} p.p.b and 1.9×10^{11} p.p.b. The chromaticity was also reduced to 5 units in two steps. It was planned to profit from the high intensity bunch in B2 to perform:

1. A tune shift versus intensity measurement with an equivalent HL-LHC impedance [2];
2. A complementary impedance measurement of the TCSPM collimator [5, 10].

To perform the first item, the secondary collimators in IR7 were first set to relaxed settings chosen to emulate the impedance expected in the HL-LHC era. The tune shift measurement was performed with these settings and with 2017 operational settings for comparison. As an instability developed on the high intensity bunch in B2 with the 2017 operational collimator settings, the secondary collimators were relaxed again in order to preserve the bunch for the TCSPM impedance measurement. However the tune shifts measurements on B1 were carried out with the same procedure as in the first fill.

3 Data Treatment and Results

The turn-by-turn transverse position of each excited bunch was recorded with the ADT ObsBox [8]. The individual tune for each bunch was reconstructed using PySUSSIX [11], a Python wrapper of the SUSSIX code [12]. Due to decoherence, only the first 500 turns after the bunch excitation were used for the spectral analysis.

Results were compared to DELPHI [13] simulations performed using the measured collimator settings. These gaps were retrieved using PyTimber [14], the python wrapper of the CALS Java API. The simulations results were corrected to account for the quadrupolar impedance contribution to the tune shift [2]: Sacherer formula is used to compute the dipolar tune shift ΔQ_{dip} and the quadrupolar tune shift ΔQ_{quad}. The correction factor to account for the quadrupolar impedance is then the ratio $\left(\Delta Q_{dip} + \Delta Q_{quad}\right)/\Delta Q_{dip}$. Figures 2 and 3 show the measured tune shifts for the 2017 operational (scenario 2) and tighter collimators (scenarios 3 and 4) settings. Dots represent the measurement and dashed lines DELPHI simulations.

As predicted, the tighter collimators settings increase the tune shift, particularly in the horizontal plane. Figures 2 and 3 also show the results for the relaxed collimator settings (scenario 1, red curves) used to reproduce the impedance expected in the HL-LHC era. A clear

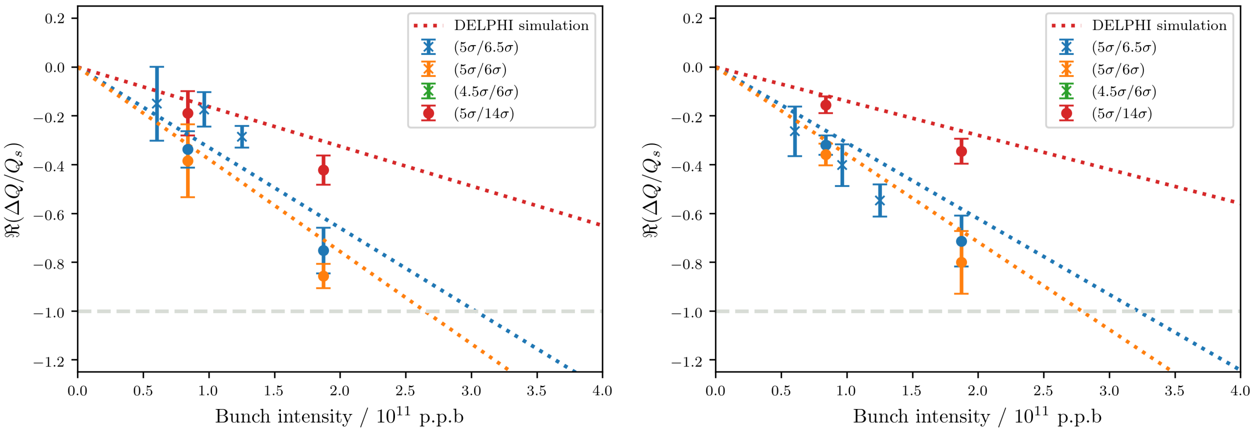

Figure 2: Measurement of the beam 1 tune shift versus intensity for different sets of collimator settings compared to DELPHI simulations (dashed lines). Fill 6210 data is represented with crosses and fill 6212 data with dots. On the left the horizontal plane is shown, on the right the vertical plane.

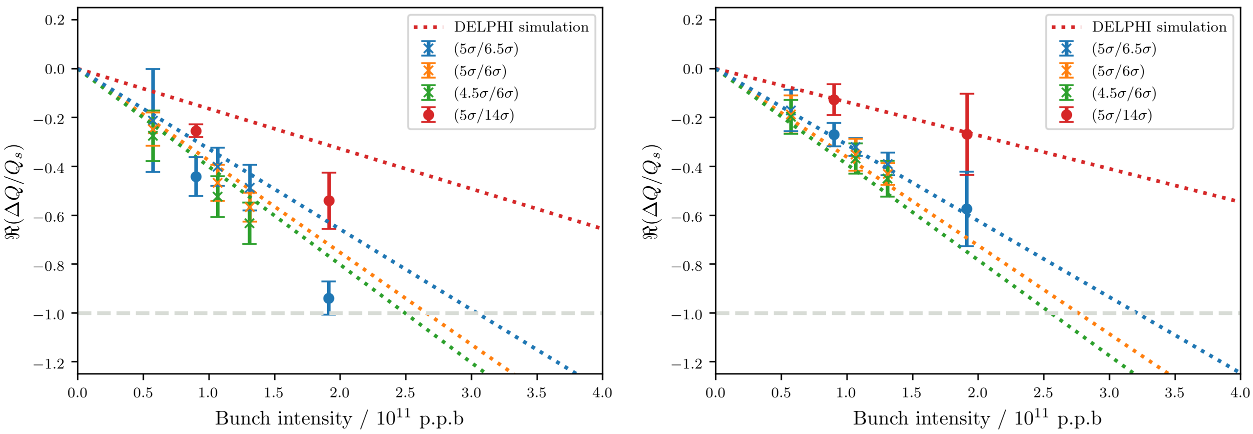

Figure 3: Measurement of the beam 2 tune shift versus intensity for different sets of collimator settings compared to DELPHI simulations (dashed lines). Fill 6210 data is represented with crosses and fill 6212 data with dots. On the left the horizontal plane is shown, on the right the vertical plane.

reduction of the tune shift is achieved in this configuration, which is particularly visible with the high intensity bunch.

The tune shift slopes deduced from the measurement are reported in Tab. 2. For the measurement, the slope was obtained by performing a linear regression on the data points shown in Figs. 2 and 3, accounting for the errors for each point. The covariance matrix of the fit gave the error on the fit parameter. To be able to merge the data from the two fills, the base tune value fitted for each fill was substracted from the data points. From the measured and simulated tune shifts, the TMCI intensity threshold can be extrapolated [2].

Simulation results obtained with DELPHI (for a chromaticity $Q' = 4$) are given, as well as the correction factor applied to account for the quadrupolar impedance contribution to the tune shift [2].

Table 2: Measured and simulated tune shifts for the LHC relaxed, 2017 operational and tighter collimator settings. The "Scenario" column gives the scenario from Tab. 1 and the corresponding TCP/TCSG setting in σ_{coll}. The following columns report the tune shift slope values normalised to the synchrotron tune $Q_s = 1.9 \times 10^{-3}$ and a bunch intensity of 10^{12} p.p.b computed with DELPHI ("Sim."), the correction factor to account for the quadrupolar impedance effect ("Corr. factor") and the tune shift accounting for the correction factor ("Sim. w/ quad."). The "Measured" column is the measurement result obtained by linear regression of the tune shifts measured at different intensities, with the corresponding errorbar. The "Ratio" column computes the ratio between tune shift from simulation (with quadrupolar impedance) and the average measured one.

Fill	Plane	Scenario	Tune shift / 10^{-12} p.p.b $\times Q_s$				
			Sim.	Corr. factor	Sim. w/ quad.	Measured	Ratio
6210	B1H	2 (5/6.5)	−4.1	0.81	−3.3	-2.2 ± 0.3	1.50
	B1V	2 (5/6.5)	−3.4	0.92	−3.1	-4.3 ± 0.4	0.72
	B2H	2 (5/6.5)	−4.0	0.82	−3.3	-3.8 ± 0.5	0.86
		3 (5/6.0)	−4.7	0.81	−3.9	-4.4 ± 0.4	0.89
		4 (4.5/6.0)	−5.0	0.81	−4.0	-4.9 ± 0.5	0.81
	B2V	2 (5/6.5)	−3.4	0.92	−3.1	-3.0 ± 0.2	1.03
		3 (5/6.0)	−3.9	0.93	−3.6	-3.3 ± 0.3	1.09
		4 (4.5/6.0)	−4.2	0.93	−3.9	-3.5 ± 0.4	1.11
6212	B1H	1 (5/14)	−1.9	0.86	−1.6	-2.3 ± 0.3	0.70
		2 (5/6.5)	−4.1	0.81	−3.3	-4.0 ± 0.4	0.82
		3 (5/6.0)	−4.7	0.81	−3.8	-4.6 ± 0.3	0.83
	B1V	1 (5/14)	−1.6	0.85	−1.4	-1.8 ± 0.2	0.77
		2 (5/6.5)	−3.4	0.92	−3.1	-3.8 ± 0.4	0.82
		3 (5/6.0)	−3.9	0.92	−3.6	-4.3 ± 0.4	0.83
	B2H	1 (5/14)	−1.9	0.86	−1.6	-2.8 ± 0.3	0.57
		2 (5/6.5)	−4.0	0.82	−3.3	-4.9 ± 0.3	0.67
	B2V	1 (5/14)	−1.6	0.85	−1.4	-1.4 ± 0.5	1.0
		2 (5/6.5)	−3.4	0.92	−3.1	-3.0 ± 0.4	1.03

The results reported in Tab. 2 clearly show that for the relaxed collimators settings, the tune shift is decreased and therefore the TMCI threshold increased. In the low impedance configuration of the collimators (scenario (5/14) in Tab. 2), the TMCI threshold can be estimated as 4.3×10^{11} p.p.b and 5.5×10^{11} p.p.b for B1H and B1V respectively. In the operational configuration (scenario (5/6.5) in Tab. 2), these thresholds are inferred to be at about 2.4×10^{11} p.p.b for both planes of B1.

For B2, in the low impedance configuration the TMCI threshold can be estimated at 3.6×10^{11} p.p.b and 7.1×10^{11} p.p.b for the horizontal and vertical plane respectively. In the operational configuration it can be estimated (averaging measurements from the first and second fill) as 2.3×10^{11} p.p.b and 3.3×10^{11} p.p.b for the horizontal and vertical plane respectively.

This highlights the beneficial effect of the collimators impedance reduction planned for HL-LHC.

For completeness, we report in appendix the evolution of the bunch emittance, intensity and length, for each beam, plane and fill, as well as the gaps in two of the IR7 collimators, a TCP and a TCSG.

4 Conclusion

The tune shift measurements performed during the MD showed the clear impact of the collimators on the LHC impedance.

An increase in tune shift with intensity could be observed with tighter collimator settings. From these measurements we observe that the model might be underestimated by 30% to 60% with respect to the measurements results.

For the equivalent HL-LHC impedance reproduced using relaxed collimator settings, the model is also underestimated by 20% to 60%. However a clear reduction of the tune shift was observed in measurements with this configuration. Given the same order of magnitude of the discrepancy, a systematic error in the collimator impedance could be investigated.

In the equivalent HL-LHC impedance configuration of the collimators, the TMCI threshold can be estimated as 4.3×10^{11} p.p.b and 5.5×10^{11} p.p.b for B1H and B1V respectively. For B2, the TMCI threshold is at 3.6×10^{11} p.p.b and 7.1×10^{11} p.p.b for the horizontal and vertical plane respectively.

In the 2017 operational collimators configuration, the TMCI threshold is estimated to be at about 2.4×10^{11} p.p.b for both planes of B1 and at 2.3×10^{11} p.p.b and 3.3×10^{11} p.p.b respectively for the horizontal and vertical plane of B2.

The tune shift reduction and the subsequent TMCI threshold increase observed with the relaxed collimator settings support the collimators impedance reduction planned for HL-LHC.

Acknowledgements

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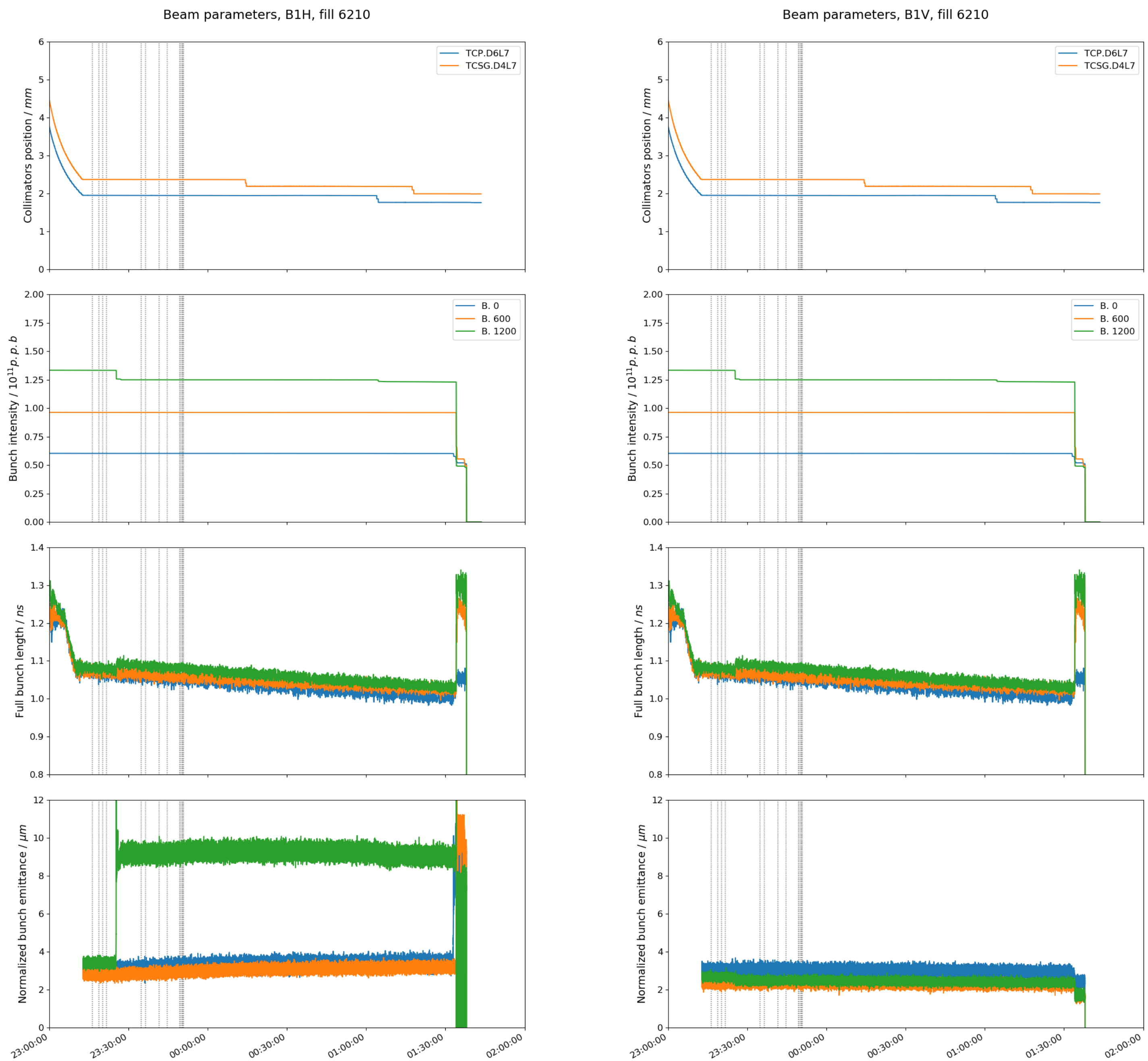

Figure 4: Beam 1 bunch-by-bunch parameters for both horizontal and vertical planes during the first fill (6210) of the MD activity.

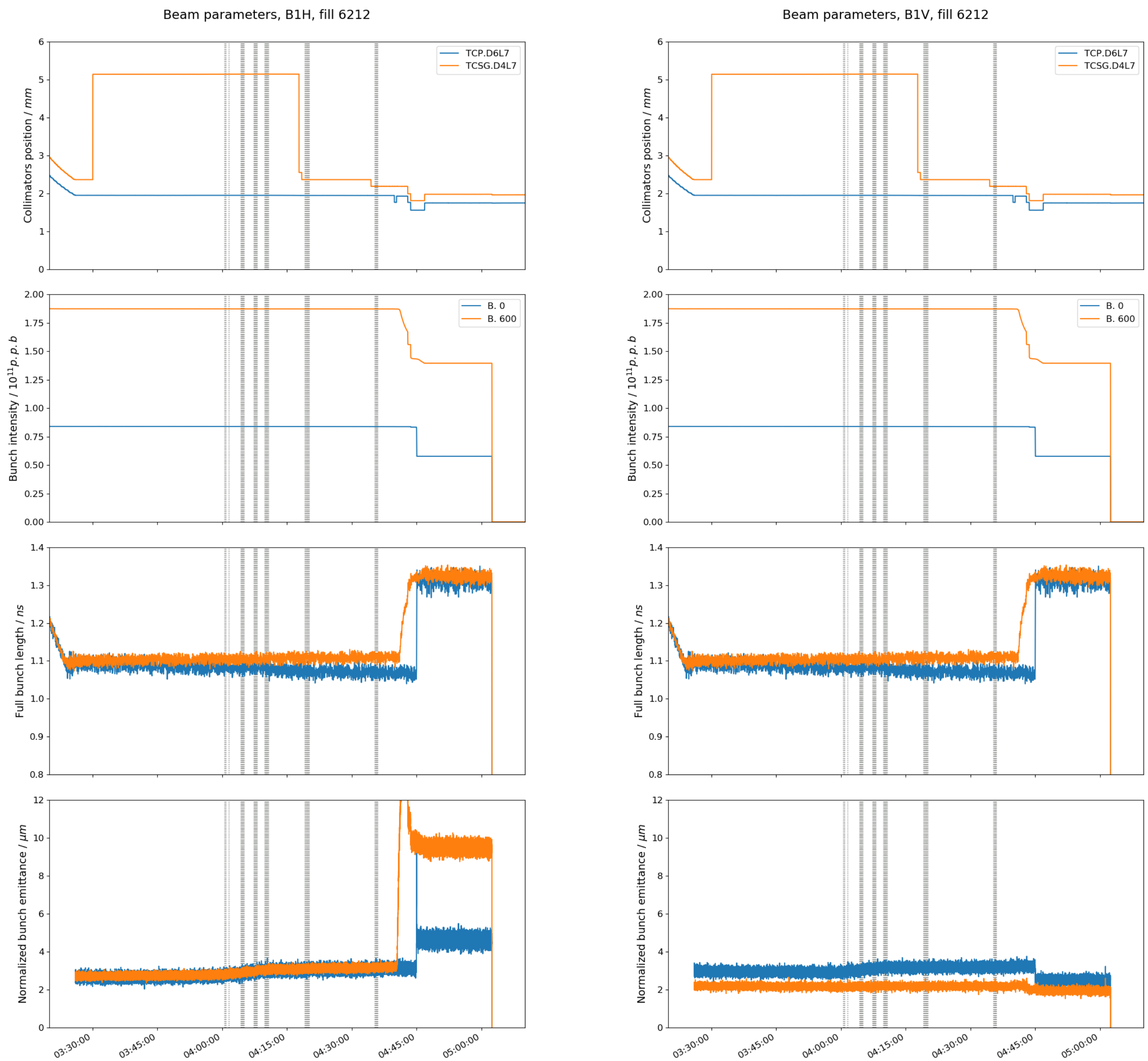

Figure 5: Beam 1 bunch-by-bunch parameters for both horizontal and vertical planes during the second fill (6212) of the MD activity.

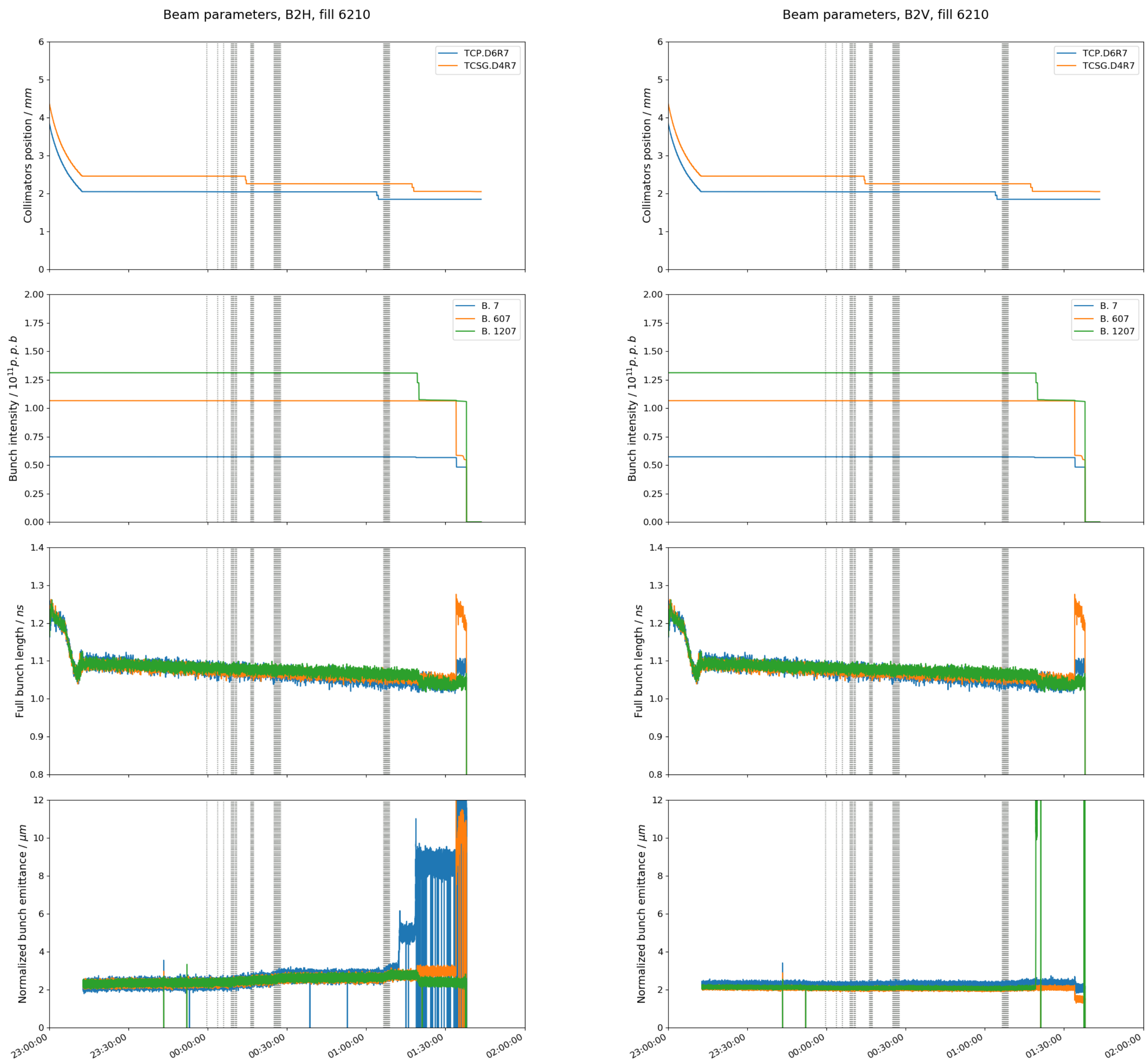

Figure 6: Beam 2 bunch-by-bunch parameters for both horizontal and vertical planes during the first fill (6210) of the MD activity.

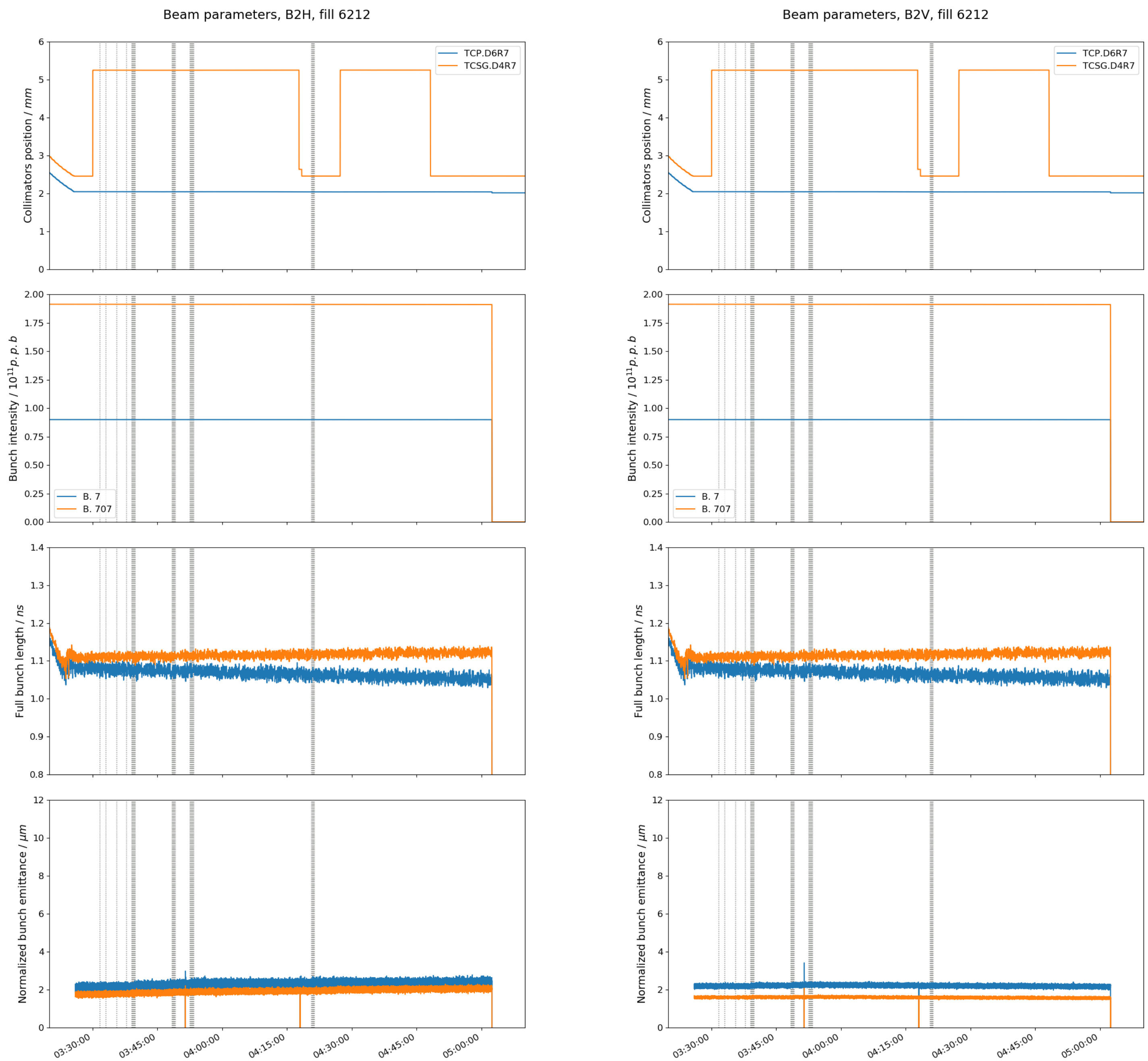

Figure 7: Beam 2 bunch-by-bunch parameters for both horizontal and vertical planes during the second fill (6212) of the MD activity.