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xavier.buffat@cern.ch

Limitations due to strong head-on beam-beam interactions (MD 1434)

X. Buffat, S.V. Furuseth, G. Iadarola, S. Papadopoulou, Y. Pappaphilipou, D. Pellegrini, M. Pojer, G. Crockford, B. Salvachua, G. Trad (CERN, CH-1211 Geneva 23, Switzerland), J. Barranco, T. Pieloni (EPFL, CH-1015 Lausanne), C. Tambasco (EPFL, CH-1015 Lausanne, Switzerland;CERN, CH-1211 Geneva 23, Switzerland)

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Summary

The results of an experiment aiming at probing the limitations due to strong head on beam-beam interactions are reported. It is shown that the loss rates significantly increase when moving the working point up and down the diagonal, possibly due to effects of the 10th and/or 14th order resonances. Those limitations are tighter for bunches with larger beam-beam parameters, a maximum total beam-beam tune shift just below 0.02 could be reached.

Contents

1 Introduction

The electromagnetic interaction between the beams at the interaction point (IP) has been the main performance limitation in most high energy hadron colliders [1–3]. Yet, the LHC has been operated with tune shift much larger than design without significant impact on the beam quality. Different hypothesis have been proposed to explain this behaviour, mainly the remarkably low transverse jitter at the IP, RF noise and tune ripple. A proper understanding of the mechanisms limiting the performance with

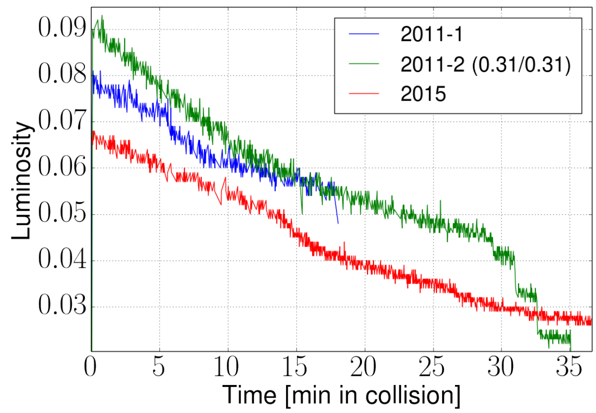


Figure 1: Luminosity evolution during different MDs with high brightness bunches colliding at 450 GeV [4, 5].

Parameter	Value
Energy	6.5 TeV
β^*	40 cm
Full crossing angle	280 μrad
Octupole current [A]	570 A
ADT damping time	50 turns
chromaticity	≈15

Table 1: Machine and beam parameters at start of the test.

higher tune shift is crucial in view of operation with higher brightness in the LHC, HL-LHC and FCC-hh. Dedicated experiments at injection energy (450 GeV) revealed severe lifetime degradation when colliding bunches with large beam-beam tune shifts (Fig. 1), that could not entirely be attributed to intrabeam scattering. The noise level as well as tune ripple being stronger at injection energy with respect to top energy (6.5 TeV), different mechanisms are expected.

2 Experimental setup

The main machine and beam parameters are summarized in Tab. 1. Three bunches were injected in each beam, the first two are regular bunches, one is non-colliding and the other collides in IPs 1 and 5. The third bunch has a larger intensity and collides in IPs 1 and 5. The regular physics cycle was executed up to the establishment of collision in IPs 1 and 5, with a larger octupole current from flat top on. The attenuator of the transverse feedback (ADT) were set to high intensity settings, reducing their resolution for the low intensity bunches.
Once in collision, the octupole current, damper gain and tunes were varied in steps. The bunches intensities, emittances and luminosity were monitored in each steady configuration for about 10 minutes.

3 Results

3.1 Evolution of the beam parameters

During the first fill (5453) the beams were affected by RF noise, resulting in the slow increase of the bunch length visible in Fig. 2. Beam 2 was affected all along the fill, while beam 1 was affected only during tests aiming at solving the issue with the phase loop. While the RF issue was under investigation by the piquet, the beams were kept for tests, the results are reported here, but it is clear that the data

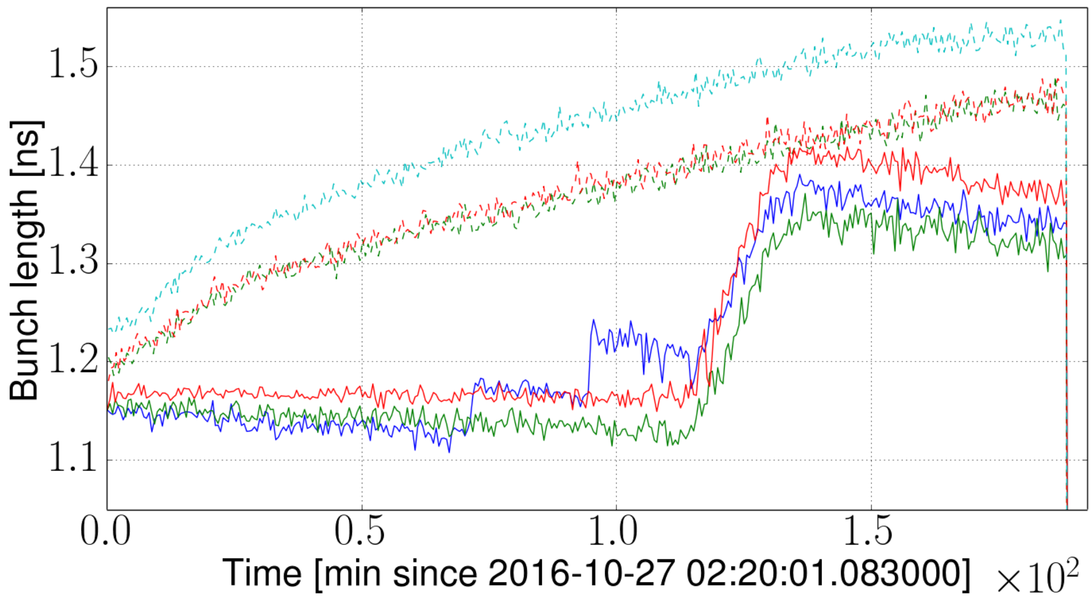
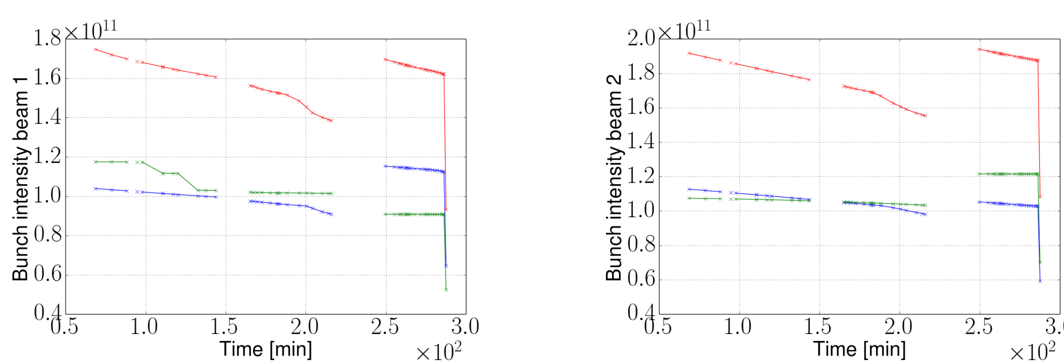


Figure 2: Length of the bunches of beam 1 (solid lines) and beam 2 (dashed lines) during fill 5453, starting at the end of the energy ramp. The witness, low intensity and high intensity bunches are represented by green, blue and red curves respectively.

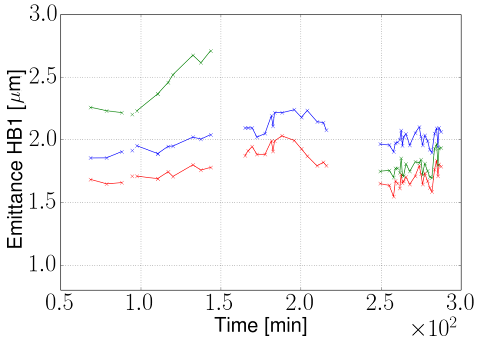
obtained during this fill are difficult to extrapolate to more realistic conditions. The beams were dumped when implementing a solution for the RF noise. After recycling the machine, 40 minutes were left for data tacking in good conditions (Fill 5454). Due to this time constraints, the length of the steps was limited to 5 minutes, allowing for a good estimation of the beam lifetime, but prevents a good estimation of the emittance growth rates. This change of strategy is also motivated by previous tests in similar conditions suggesting that the emittance growth is significant with the ADT setup with unoptimised high intensity settings [6]. Future tests with high intensity bunches will therefore require that some beam time is dedicated to a better setup of the ADT with high intensity bunches in order to fully assess the emittance effects in the presence of strong head-on beam-beam interactions.
Only the tune of beam 1 was varied in the second fill, in an attempt to understand its lower lifetime with respect to the one of beam 2.

The measured beam intensities and emittances at each step of the experiements are shown in Figs. 3

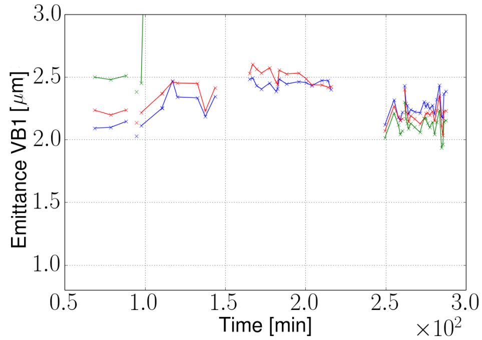


(a) Beam 1 (b) Beam 2

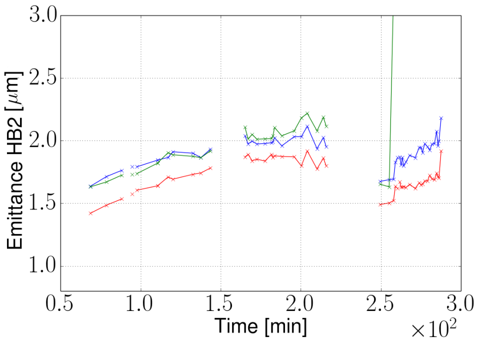
Figure 3: Bunch by bunch intensities during the tests. The witness, low intensity and high intensity bunches are represented by green, blue and red curves respectively.



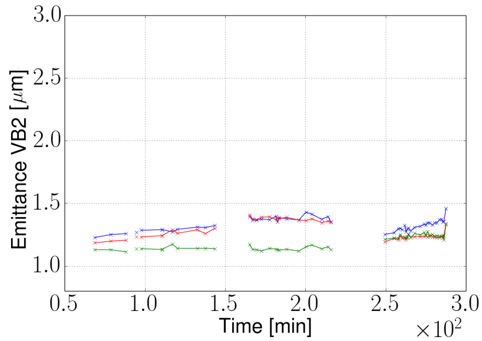
(a) Horizontal, beam 1



(b) Vertical, beam 1

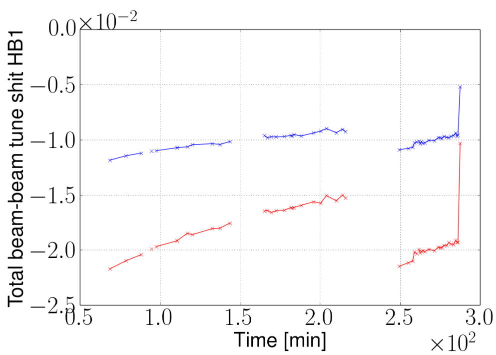


(c) Horizontal, beam 2

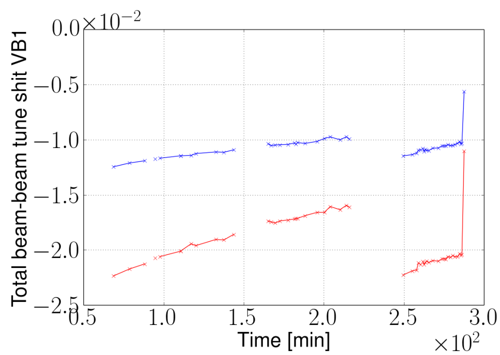


(d) Vertical, beam 2

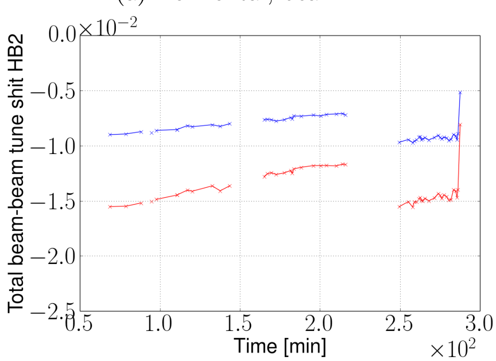
Figure 4: Bunch by bunch emittances during the tests. The witness, low intensity and high intensity bunches are represented by green, blue and red curves respectively.



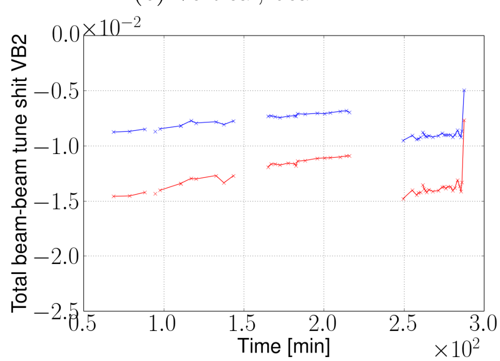
(a) Horizontal, beam 1



(b) Vertical, beam 1

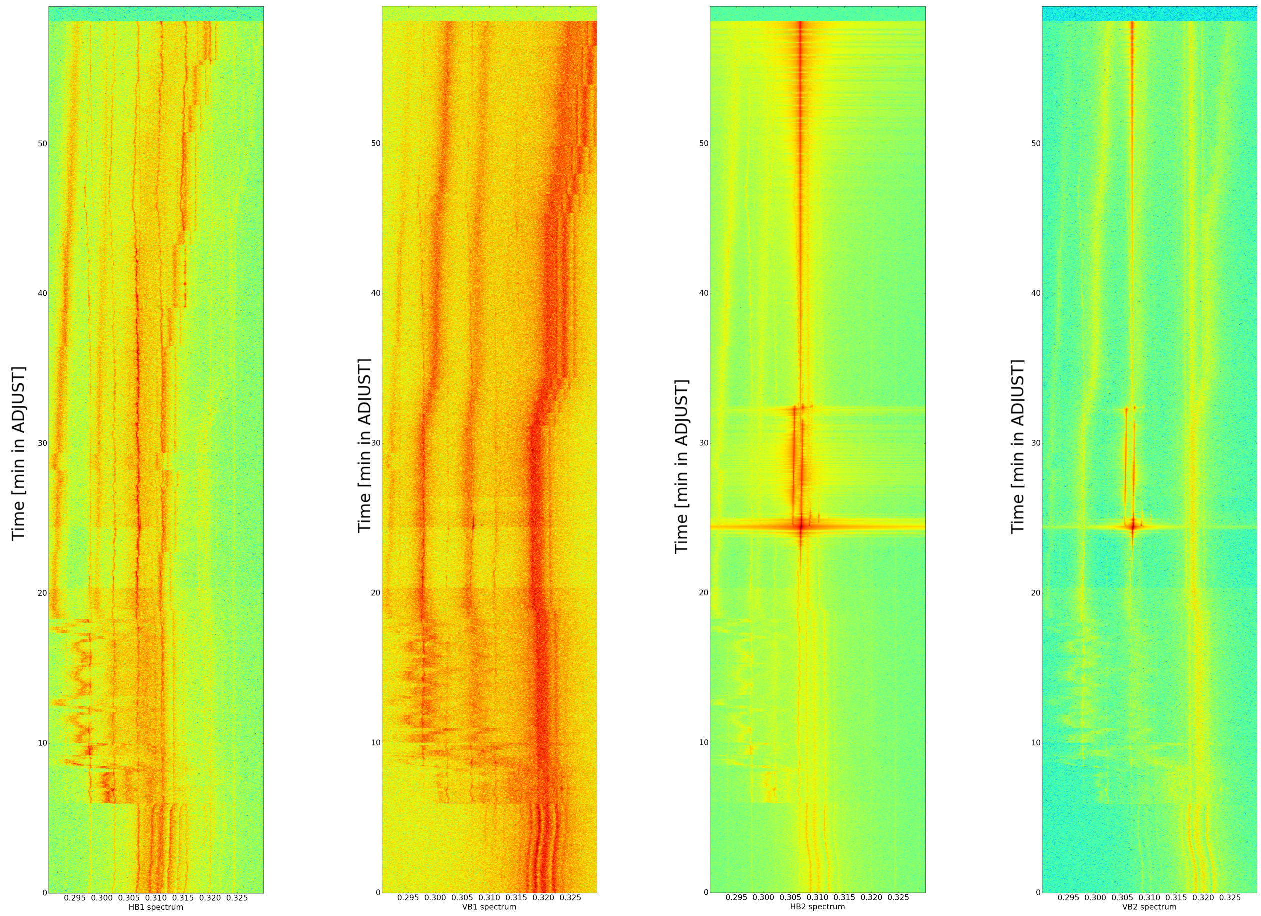


(c) Horizontal, beam 2



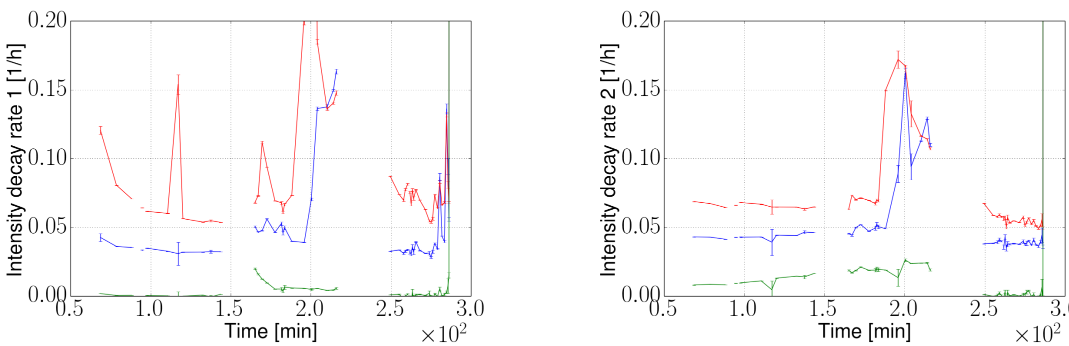
(d) Vertical, beam 2

Figure 5: Total beam-beam tune shifts deduced from machine and beam parameters during the MD. The low intensity and high intensity bunches are represented by blue and red curves respectively.



(a) Horizontal, beam 1 (b) Vertical, beam 1 (c) Horizontal, beam 2 (d) Vertical, beam 2

Figure 6: BBQ spectrograms during the second fill. Since the BBQ mixes the signal of all bunches, different frequency shifts are measured when bringing the beams into collision (between minute 6 and minute 18). The maximum shift is just below 0.02 in all planes and beams. The strong signal in beam 2 correspond to a coherent instability of the witness bunch.



(a) Beam 1 (b) Beam 2

Figure 7: Bunch by bunch loss rate during the tests. The witness, low intensity and high intensity bunches are represented by green, blue and red curves respectively.

and 4, along with the estimated total beam-beam tune shift resulting from head-on collision with alternating crossing angle in IPs 1 and 5 in Fig. 5 using :

$$\Delta Q_i = \frac{r_0 N \beta}{2\pi\gamma}\left(\frac{1}{\sigma_{i,\mathrm{eff}}(\sigma_{i,\mathrm{eff}}+\sigma_j)} + \frac{1}{\sigma_i(\sigma_i+\sigma_{j,\mathrm{eff}})}\right), \tag{3.1}$$

where i refers to a given plane, j to its counterpart, N is the number of protons per bunch and r_0 the classical proton radius. σ_i is the beam size in plane i at the IP and the corresponding effective beam size due to the crossing angle θ is given by :

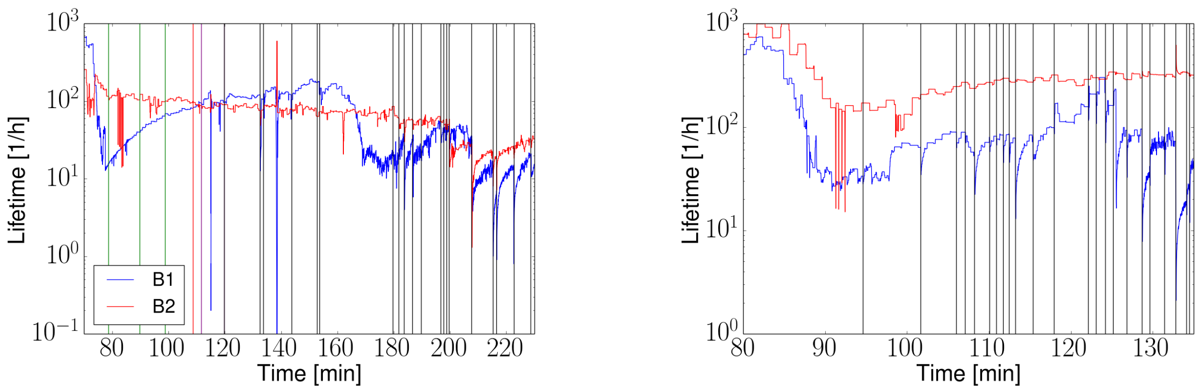
$$\sigma_{i,\mathrm{eff}} = \sigma_i\sqrt{1+\left(\frac{\sigma_s}{\sigma_i}tan(\theta/2)\right)^2}, \tag{3.2}$$

where σ_s is the r.m.s. bunch length. All quantities used to compute the tune shift refer to the bunches with which the one under consideration is colliding. The discrepancy with the measured luminosities is discussed in [6]. Similarly to the experiment reported there, the comparison of the estimated total tune shifts (Fig. 5) with respect to measured ones with the BBQ (Fig. 6) suggests that the emittances of beam 2 are underestimated by 20 to 30%, leading to an overestimation of the beam-beam tune shifts of beam 1.

During the second fill, a coherent instability of the non-colliding bunch was observed in the horizontal plane of beam 2, 5 minutes after the establishment of head-on collisions in IPs 1 and 5 (Fig. 6). The parameters of beam 2 were unchanged during this period. The resulting emittance increase is visible in Fig. 4d. After this instability, the oscillation of the witness bunch seemed to increase slowly in the horizontal plane up to the end of the fill.

3.2 Optimisation of the ADT gain, octupole and chromaticity

The first three steps (first three points in Figs. 3, 4, 5 and 7) represent a scan in ADT gains corresponding to an increase of the damping time from 50 to 100 and 200 turns respectively. The loss rate of the high intensity bunch of beam 1 was significantly reduced when decreasing the damper gain. This effect is also visible with a smaller amplitude on the low intensity bunch of beam 1, beam 2 seemed unaffected by the change of ADT gain. The fourth step corresponds to a reduction of the octupole strength from 570 A to 414 A. Again during those steps the loss rate was reduced for the colliding bunches of beam 1, beam 2 remained unaffected. The fifth and sixth steps correspond to a reduction of the chromaticity by 5 units (from ≈ 15 to ≈ 10) and by 3 units. The reduction of chromaticity seemed to reduce the loss rate of the high intensity bunch of beam 1. The link between the observations of improvement of the beam lifetime and the modifications of the machine settings is however doubtful, since no clear correlation with the steps are found. This effect is better visible in the beam lifetime computed based on measured beam losses shown in Fig. 8b. The modification of the ADT gain (marked with green vertical lines), octupole (red) and chromaticity (purple) did not have a significant impact on the beam lifetime, as the latter seems dominated by a low recovery of the drop generated when the beams are brought into collision. An important reduction of the beam lifetime is however visible between minutes 160 to 175, correlated with the involuntary increase of the bunch length of beam 1 shown in Fig. 2. The fact that the lifetime remains low once the issue with the RF noise was solved for beam 1, suggests that the bunch length plays an important role in the dynamic of the losses. An increased bunch length, in the presence of a significant crossing angle reduces the total beam-beam tune shift (Eq. **??**), but increases the Piwinski angle possibly leading to an increase of the effect of some specific resonances driven by the beam-beam interaction. This effect will be further discussed in the next section.
The decay rate of the non-colliding bunches was not affected by the changes of configuration. Yet, the non-colliding bunch of beam 2 experiences significant losses that are no longer present in the second fill (Fig. 7), suggesting an important impact of the extra RF noise on the beam lifetime.



(a) Fill 5453

(b) Fill 5454

Figure 8: Beam lifetime reconstructed based on beam losses at the primary collimators. The vertical lines mark the different steps of ADT gain (green), octupole (red), chromaticity (purple) and tune (black).

3.3 Tune scan

The first tune scan was performed before the involuntary increase of the bunch length of beam 1 (black lines before minute 160 in Fig. 8b). The tune was moved by $\pm 10^{-3}$ around the working point, without significant effect on the beam lifetime. The large peak of loss rate observed in Fig. 3 during this scan is an artefact due to a too short integration time, as confirmed by the lifetime reconstructed based on beam losses.
The second tune scans was performed after the increase of the bunch length of beam 1 (black line after minute 180 in Fig. 8b). While the RF noise issue was solved in beam 1, the lifetime of beam 2 is still affected by the RF noise during this phase. During this scan the tunes were decreased simultaneously in both planes, thus moving the working point along the diagonal. The change of working point resulted in an important increase of the loss rates, reported on a tune diagram in Fig. 9 (dots). One observes that the losses occur when the bare tune approaches the tenth and fourteenth order resonance. Since the single particles' tunes are shifted to lower frequencies with respect to the machine tune due to the beam-beam interactions, the particles in the core of the beam moved across these resonances during the scan with a limited impact on the loss rate. The losses are therefore observed when the tail particles are on the resonances. This observation is in qualitative agreement with expectations, as the corresponding resonance driving terms are stronger for particles oscillating with a large amplitude. Consistently, the high intensity bunch, experiencing a larger beam-beam tune shift, starts losing earlier in the scan, i.e. at higher tunes. The increase of the loss rate is clearly visible in the lifetime reconstructed based on beam losses (Fig. 8b), nevertheless this method does not allow to distinguish losses from the different bunches. The decompostion of the losses at the different collimators show that more than 90% of the losses in this configuration occurred in the horizontal plane.

During the fill 5454, the tune scan aimed towards the third order resonance, along the diagonal. The lifetime during the steps are reported in Fig. 9 as stars. An increase of the decay rates were observed when increasing the vertical tune, which could be mitigated by increasing the horizontal tune. These observations are in qualitative agreement with an impact of the tenth and/or the fourteenth order resonances. The increase of the loss rate is also visible in the lifetime computed based on measured beam losses (Fig. 8b). As opposed to the previous scan down the diagonal, the losses during this scan up the diagonal were entirely in the vertical plane.

4 Beam profiles

Bunch by bunch transverse and longitudinal beam profiles were acquired during the fill 5454, using the BSRT and BSRL. Figure 10 shows the q-Gaussian factor obtained with a fit of the measured profile with

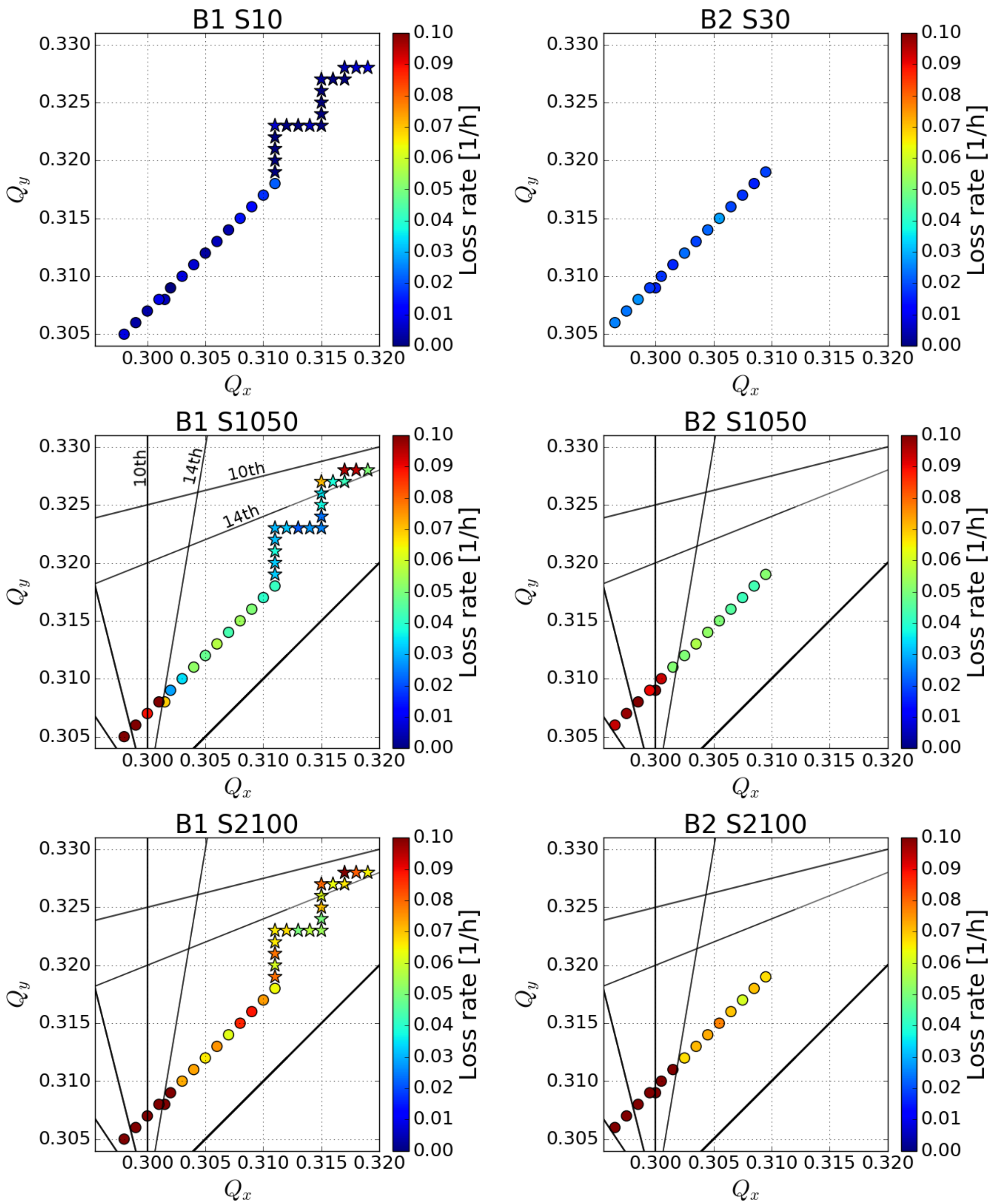
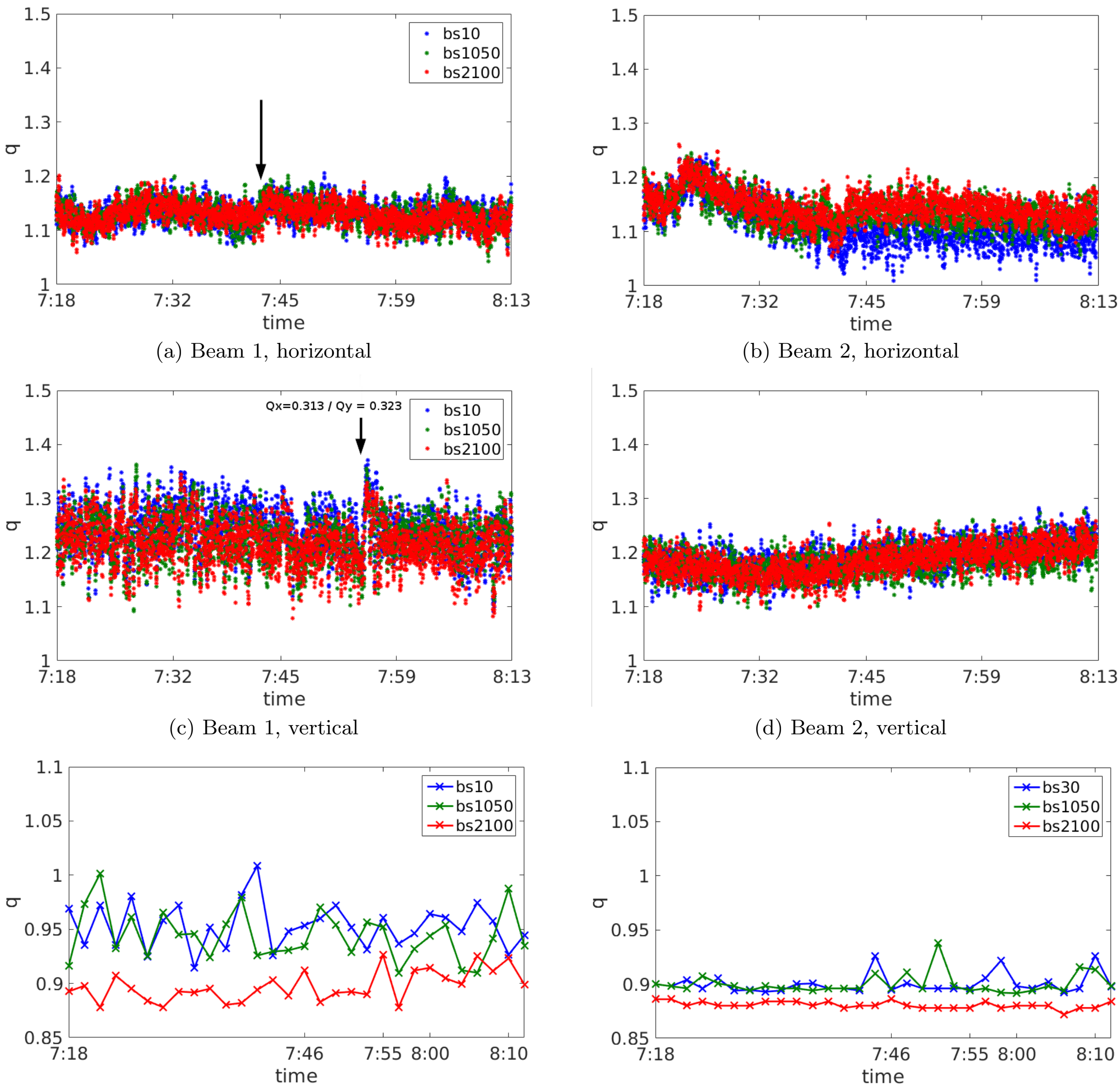


Figure 9: Measured loss rate as a function of the working point for the different bunches of the two beams. Resonance lines up to order 14 are drawn, with a width according to the amplitude of the driving terms from the head-on beam-beam interaction [7].



(a) Beam 1, horizontal
(b) Beam 2, horizontal
(c) Beam 1, vertical
(d) Beam 2, vertical
(e) Beam 1, longitudinal
(f) Beam 2, longitudinal

Figure 10: q-Gaussian parameter measured based on the measured beam distribution with the BSRT and BSRL, during fill 5454. The blue dots corresponds to the non-colliding bunch, the green to the colliding low intensity bunch and the red to the high intensity colliding bunch. The black arrow on the upper left plots marks the moment when the beams are brought into collision. The one on the middle right shows a step in tune scan when a significant variation of the q parameter is observed.

the following distribution function [8] :

$$\Psi(u) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta u^2) \quad (4.1)$$

with C_q a normalisation factor and β a parameter analogue to the measured beam emittance. $e_q(x)$ corresponds to the regular exponential if $q = 1$ and otherwise :

$$e_q(x) = (1 + (1-q)x)^{\frac{1}{1-q}} \quad (4.2)$$

The factor q allows for an estimation of the tail population, as a factor lower or higher than 1 corresponds to depleted or overpopulated tails respectively. This parameter does not vary significantly during the fill in any of the degrees of freedom, despite the important losses that were observed in some of the steps. In the transverse planes, the variations of the tail population are probably masked by the effect of diffraction in the BSRT signal. Small variations are observed when the beams are brought into collision and at a given step of the tune scan corresponding to Q_x=0.313, Q_y=0.323. As shown in Fig. 9, no significant losses were observed during this step.
In the longitudinal plane, the tail of the high intensity bunches with respect to the two others seems less populated in both beams. The evolution in beam 1 exhibits a slow trend upwards, i.e. a mechanism populating the tails with a time scale much slower than the one of this experiment.

5 Conclusion

A quantitative comparison of the observations with models is difficult due to an issue with the longitudinal phase-loop which led to a significant RF noise during most of the MD. Nevertheless, it seems that the effect of the 10th and 14th order resonance are limiting the tune space available with bunches colliding head-on with large beam-beam tune shifts. The effect of the reduction of the ADT gain, chromaticity and octupole strength is unclear since the beam lifetime of beam 1 seems improving independently of the machine settings variations in the first 40 minutes after the beams are brought into collision. The lifetime of beam 2 was also not affected by the changes.
The reduction of the beam lifetime of beam 1 when its bunch length was artificially increased suggests that the presence of a crossing angle has an impact on the loss mechanism, comparison with simulations are required to understand the mechanisms.
While promising in terms of tune space available for the HL-LHC era, a validation with larger total beam-beam tune shift is still required for a full assessment of the limits, e.g. by operating in similar conditions removing the crossing angle. Most importantly, due to time constraints the emittance effects could not be addressed. A similar experiment should be repeated to fully validate the possibility to run with large beam-beam tune shift, but dedicating beam time for the ADT setup with high intensity bunches. The observation steps will need to be longer during the experiment in order to allow for a estimation of the growth rate variations with a sufficient precision.

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