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LHC MD 2042: Persistent Injection Oscillations

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Abstract

This MD note summarizes the measurements performed to study persistent longitudinal oscillations after injection into the LHC. It was found that they build up due to mismatch, and can lead to particle losses and uncontrolled bunch lengthening. For the first time, profile measurements and ObsBox data acquisitions were triggered at injection to obtain first-turn data.

The measurements took place on 16th September 2017 between 14:30 and 19:30, and between 27th November 2017 20:00 and 28th November 2017 04:00.

Contents

1 Introduction

During an MD in 2016 [1], bunch phase oscillations at arrival to flat top were observed to depend on the time spent at flat bottom (Fig. 1). It was concluded that undamped injection oscillations survived the controlled emittance blow-up during the ramp and continued at flat top, if the bunches spent less than an hour at flat bottom. In 2017, two MDs were performed with the aim (i) to quantify the dependence of the damping time on bunch intensity and emittance at injection energy, (ii) to study how these oscillations survive the noise injection during ramp, and (iii) to measure the damping time at top energy.

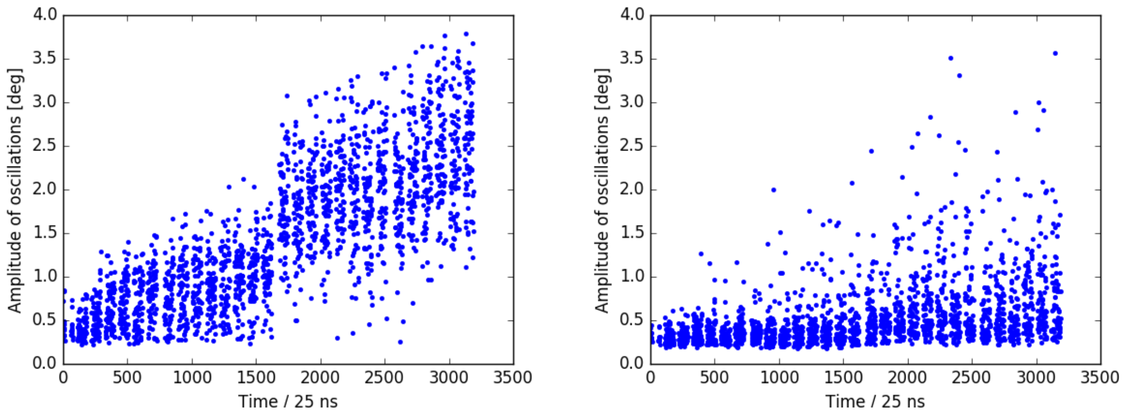


Fig. 1: Amplitude of dipole oscillations, bunch by bunch, at flat bottom (the left-hand side plot) and at arrival to flat top (the right-hand side plot); Fill 5029; data from [1].

2 MD 2042 on 16.09.2017

Fill 1

One batch of 12 and 144 bunches each were injected to reduce the action of the phase loop (PL) on the INDIVs injected later. Their intensity was varied in the PSB, and their emittance in the PSB and SPS. The intensity range was 0.8e11 ppb - 2.2e11 ppb and bunch length was between 1.6 ns - 2.1 ns at SPS extraction. During the MD, bunch profiles and peak-detected Schottky signals were recorded, and ObsBox data was stored every 3 minutes for both beams. Unfortunately, the data of profile measurements and the ObsBox beam pick-up data of high-intensity bunches were saturated. The analysis of the remaining ObsBox data for this fill is still ongoing.

Fill 2

Following a new injection of 12 and 144 bunches, 25 single bunches with an intensity of 2e11 ppb and 25 single bunches with nominal intensity and emittance were injected; all single bunches were spaced by 1.325 µs. For the high-intensity bunches, one of the channels of the ObsBox beam pick-up signal was saturated, which makes it impossible to obtain the correct amplitude of bunch oscillations.

An example of profile measurements of a bunch with an initial intensity of 1.9e11 ppb is shown in Fig. 2. It exhibits large-amplitude non-rigid oscillations (about $\pm 30°$) which still persist 10 minutes after injection. Moreover, the oscillations lead to losses of ~ 5 % and bunch lengthening of ~ 5 %, see Fig. 3.

For this bunch, the peak-detected Schottky spectrum was also recorded, see Fig. 4. It contains a line at 56.7 Hz which is slightly below the central synchrotron frequency of $Q_s = 57.3$ Hz with the 2017 operational gamma transition factor of $\gamma_{\text{tr}} = 53.68$; the small frequency shift is due to the high bunch intensity of 1.9e11 ppb. Further lines are seen at 113.2 Hz, and at the multiples of 50 Hz.

In this MD, it was not possible to trigger the bunch profile observations exactly at injection. The aim of the next MD was to see the first turns of the bunch profiles. This allows us to understand whether the bunch arrives with oscillations from the SPS or whether they develop in the LHC. At the same time,

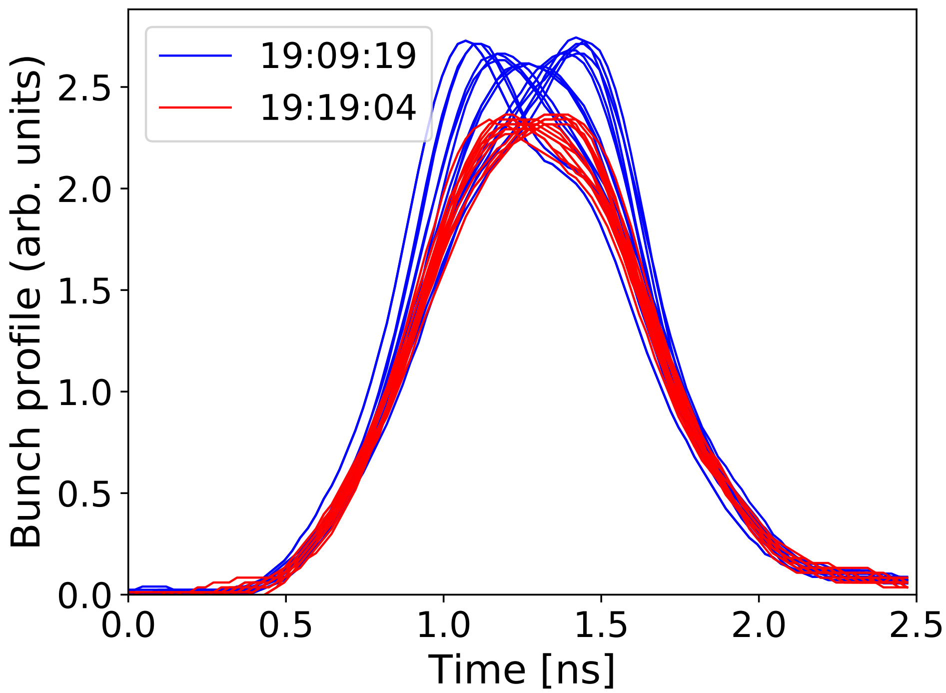


Fig. 2: Non-rigid oscillations of a single bunch in bucket 1088 of B2, in the second fill at different time stamps. Bunch profiles are plotted every 40 turns (1/5$^{\text{th}}$ of the synchrotron period).

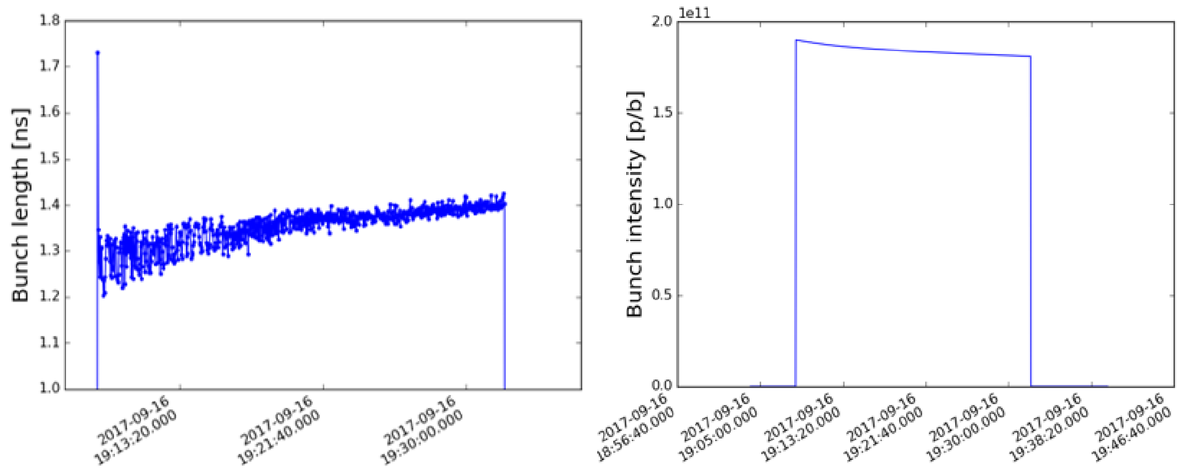


Fig. 3: Bunch lengthening (left) and losses (right) of bunch 1088 of B2 in the first 20 min. after injection.

we aimed to perform more systematic peak-detected Schottky spectra measurements to see the evolution of the oscillation frequency and the damping as a function of time for low- and high-intensity bunches.

3 MD 2042 on 27.11.2017 and 28.11.2017

Fill 1

Single bunches in the range of 6e10 ppb to 2.2e11 ppb were measured. A reference measurement with a single bunch of 6e10 ppb in each ring was taken in order to observe the fast damping due to the PL with a low-intensity bunch and for RF voltage calibration, which is discussed below.

Analyzing the bunch profile data in this MD, we noticed a 30 % bunch (trace) lengthening for data acquired with the scope on B1 w.r.t. the scope on B2, while the bunch lengths measured with the scope of B2 agree with the BQM data (Fig. 5). This problem is being investigated and shall be fixed for the next MDs in 2018.

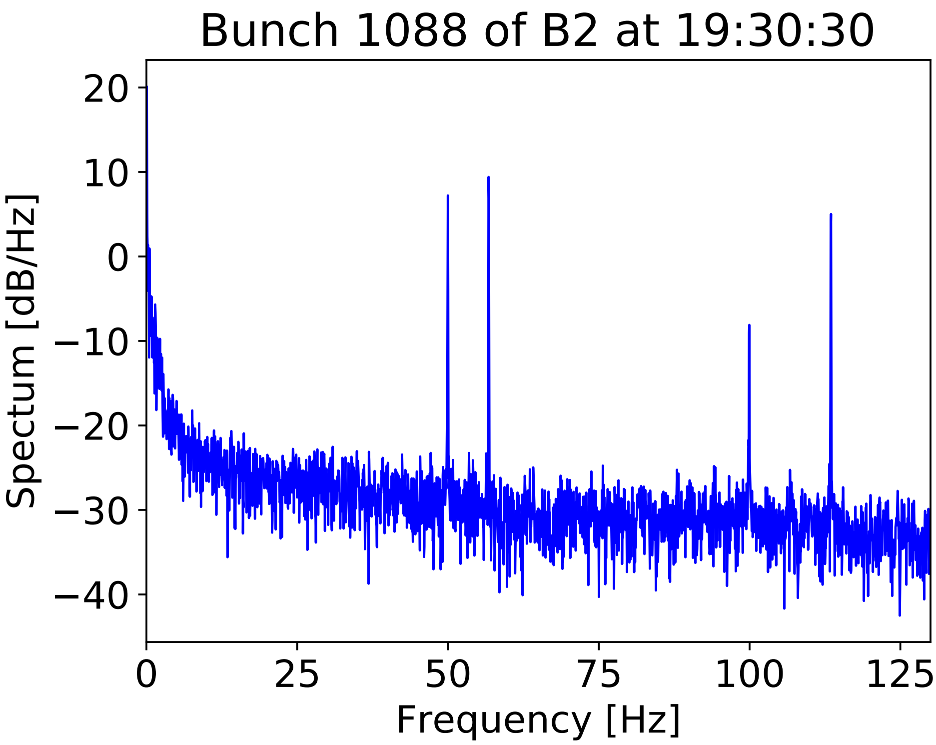


Fig. 4: Peak-detected Schottky spectrum of a high-intensity bunch in bucket 1088 of B2.

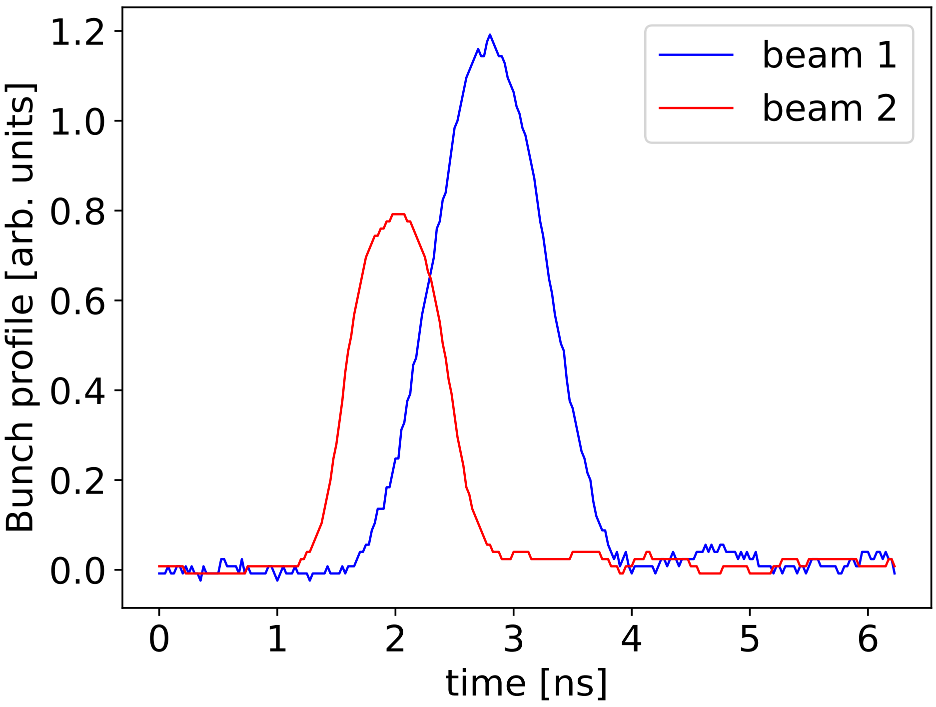


Fig. 5: Comparison of bunch profiles for B1 and B2. The problem of a broadened trace in B1 is still under investigation.

The analyzed profile data for the reference measurement is shown in Fig. 6. From the profiles we can extract the evolution of the beam phase and the bunch length. The former is very noisy due to low bunch intensity and during this measurement the ObsBox data was not available. This makes it difficult to obtain the damping time and amplitude of oscillations for this quickly-damped bunch, and to compare the beam observations with the simulation results. The bunch length oscillates within the first ∼2000 turns and then the quadrupole oscillations are damped.

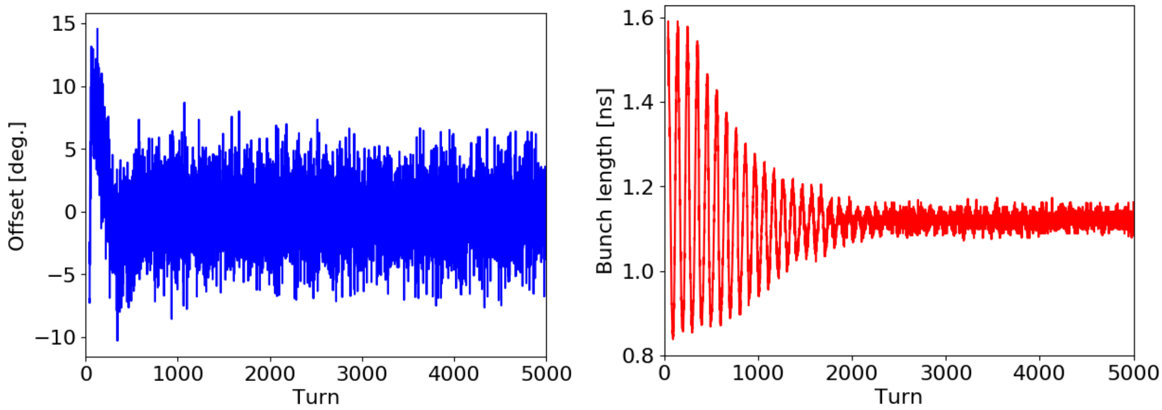


Fig. 6: Time evolution of bunch phase (left) and bunch length (right) of a low-intensity (6e10 ppb) single bunch after injection.

For the subsequent acquisitions, the ObsBox observations were triggered at injection. The 400 MHz beam phase obtained from the ObsBox and the 400 MHz component derived from the profiles agree well (see, Fig. 7). For high-intensity bunches, the ObsBox data was again saturated. During the MD, most of the profile acquisitions were limited to about 1000 turns and could cover only 5 synchrotron oscillation periods. For the ObsBox data, the software trigger for the injection was sent to the hardware with delays, which resulted in slightly asynchronous I and Q data. During the post-processing, the channels were aligned. As expected, the oscillations were damped for both intensities with the help of the PL, for a small number of bunches in the machine.

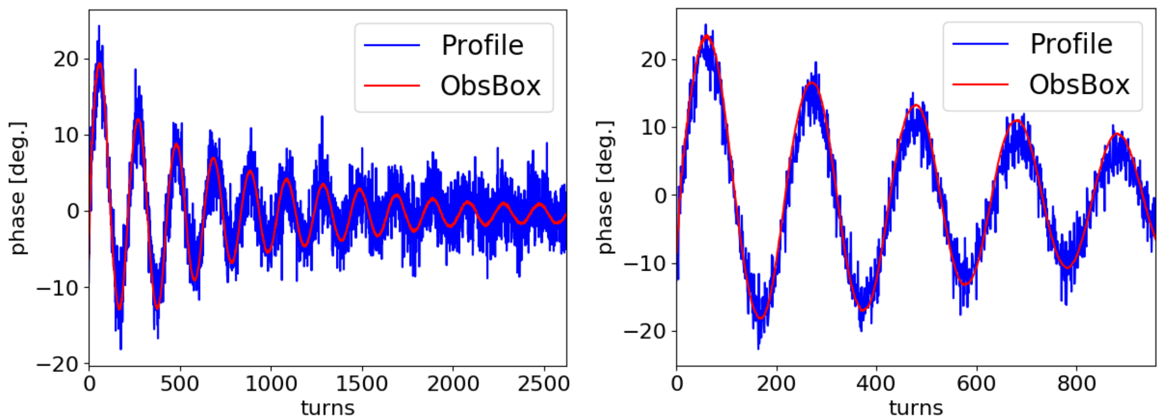


Fig. 7: Comparison of the 400 MHz component of beam phase oscillations obtained from ObsBox and profile data, for bunches with intensities 0.6e11 ppb (left) and 1.1e11 ppb (right).

Schottky measurements were also performed during this part of the MD. In the first fill, the spectrum of a low-intensity bunch injected in the bucket 4521 of B1 is shown on the left-hand side of Fig 8. This bunch oscillates with a large amplitude, see right-hand side of Fig. 8, and due to filamentation, several excited modes in the spectrum appear. The spectrum is dominated by the lines at 57.5 Hz (the dipole line) and 115 Hz (the quadrupole line), which are strongly excited due to the PL that tries to compensate the average offset of all bunches. The peak-detected Schottky spectrum allows to determine the frequency distribution by observing the spectrum around the quadrupole line [2]. As the excited lines range up to the 115 Hz line, one can conclude that the entire range of frequencies is populated and thus the 115 Hz line corresponds indeed to twice the central synchrotron frequency. This can also be shown by comparing the bunch spectrum for different RF voltages, which was done during the MD. For an RF voltage of 8.5 MV, instead of the nominal 6 MV, the dipole frequency is expected to increase by factor of $\sqrt{8.5/6}$, which is consistent with measurements, see (Fig. 9). Long measurements of a single bunch

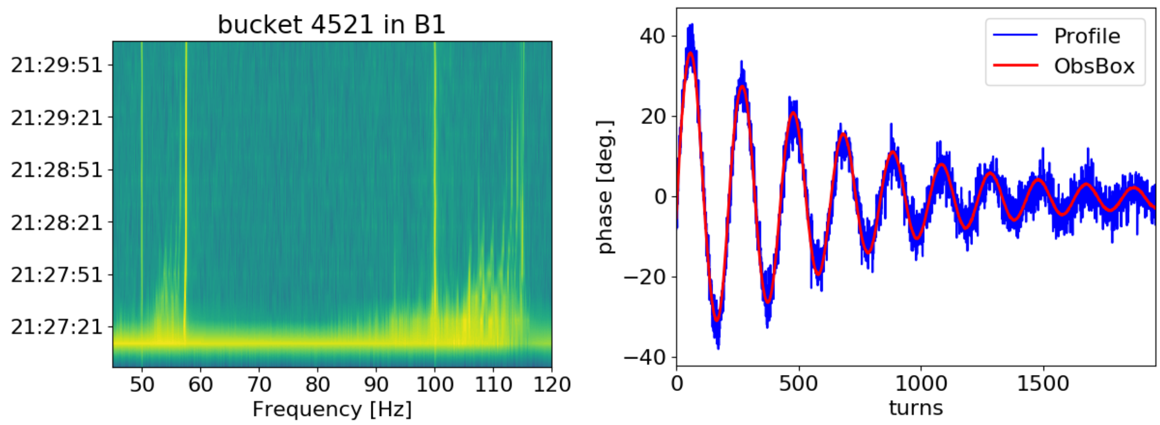


Fig. 8: Evolution of the bunch spectrum (left) and the bunch phase (right) obtained from the ObsBox (red) and profile data (blue) of a single bunch in bucket 4521 of B1 after injection. The bunch intensity is 0.6e11 ppb.

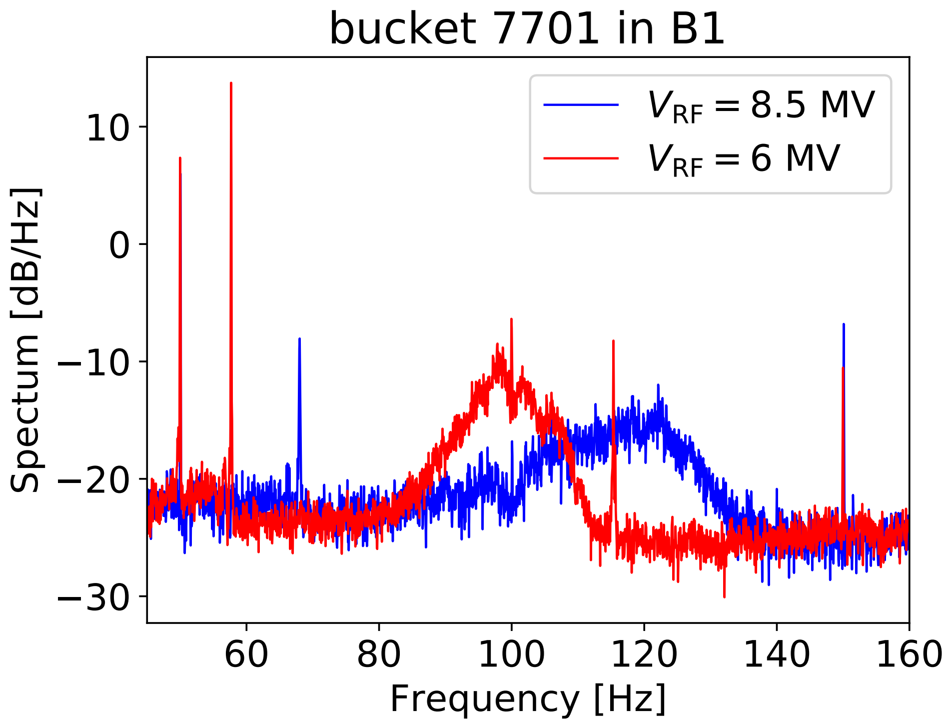


Fig. 9: Peak-detected Schottky spectra for a bunch (bucket 7701, B1) with different RF voltages. For 6 MV, the acquisition is done about one minute after injecting the bunch. For 8.5 MV, the signal was recorded for the same bunch, one minute after injecting another bunch in bucket 8231. In the latter case, the PL excited the bunch oscillations. The signal-to-noise ratio is different for the two acquisitions, because the acquisition length was not identical. The dipole modes are clearly seen for the both spectra and are at 57.5 Hz for 6 MV and 68 Hz for 8.5 MV.

with only two bunches stored in the ring show particle depopulation in the spectrum around 100 Hz (Fig. 10). This implies that the RF noise at 50 Hz, originating from power supplies, can potentially affect the particle distribution, which should be studied further in simulations.

For B2, the peak-detected Schottky signal was very weak because of uncalibrated settings of the gating. The maximum signal level was only 0.3 V with a single channel acquisition regime, whereas normally it should be around 1 V.

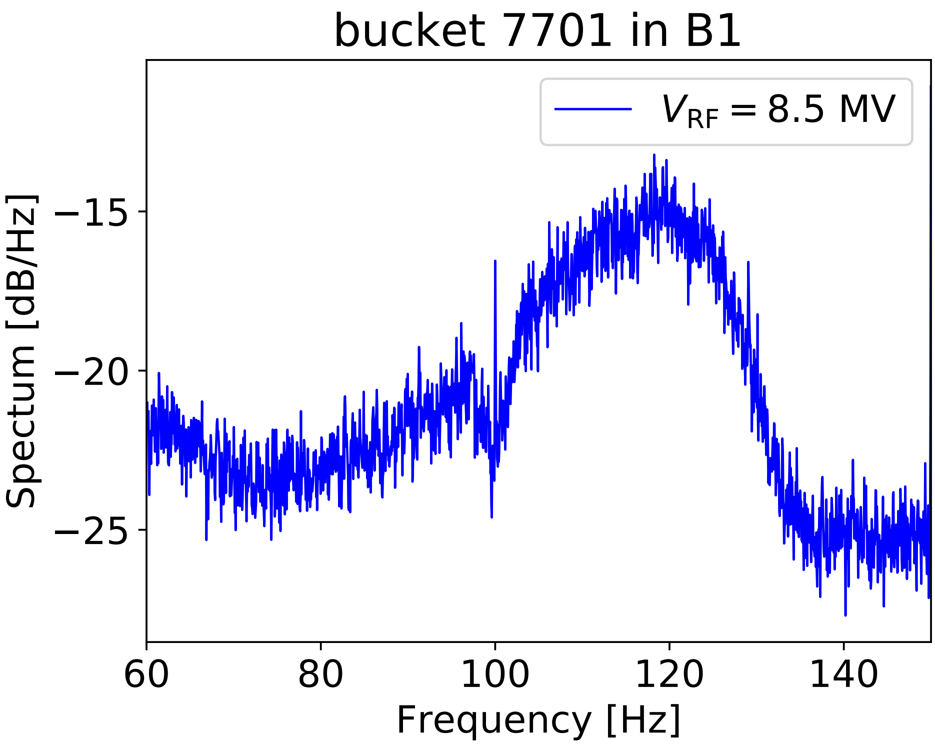
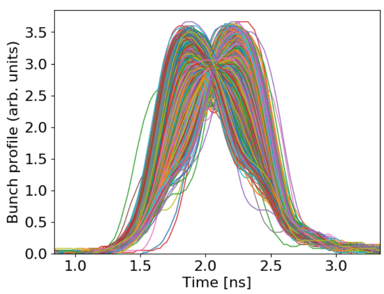


Fig. 10: Peak-detected Schottky spectra for a stable bunch with 8.5 MV RF voltage. The dip around the 100 Hz line corresponds to a depopulation in the particle distribution.

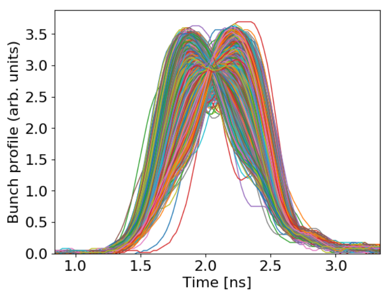
Fill 2

A batch of 12 and 96 bunches each, with nominal intensities were injected, followed by a few single, high-intensity bunches in the range between 1.8e11 ppb and 2.5e11 ppb. The batches were injected so that the PL could virtually not affect the single bunches anymore (as the PL averages over all the bunches).

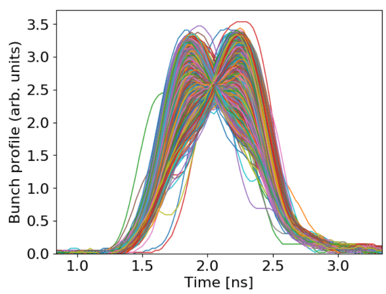
This time, the bunch profiles were recorded every 80 turns to cover a longer period of time, but in this acquisition mode, the first turn data is not available. The bunches were injected in batches of four, equispaced by 1.325 µs, while the data of the first bunch was continuously being recorded. These high-intensity bunches perform non-rigid dipole oscillations (see, Fig. 11) within the first 80000 turns (more than 7 s), but further acquisitions were not performed and the ObsBox data was saturated.



(a) bucket 4521



(b) bucket 6641.



(c) bucket 8761

Fig. 11: Profiles of high-intensity bunches after injection in B2, recorded every 80 turns, during 1000 acquisitions.

These measurements show the formation of an island structure close to the bunch core, which continuously oscillates. To study this phenomenon, simulations of the LHC injection process are ongoing.

First results confirm an island formation following the initial, fast decoherence due to the mismatch of the momentum spread of the injected bunch w.r.t. the LHC bucket height. The damping time of persistent oscillations is yet to be confirmed in simulations.

Fill 3

For the third part of the MD, around 650 bunches of operational 8b4e (BCS) beam were injected in batches of 32 and 128 bunches, in both beams. After injecting the first 300 bunches in each beam, we waited some 10 minutes to damp the oscillations. Then the second part of the beam was injected, and the ramp was started with a small delay of 10 minutes after the last injection.

Figure 12 shows how the PL excites the circulating batch in the machine at each injection of a new batch that has certain initial phase and energy errors. The excitation is larger for longer injected batches. One can also see that the maximum amplitude of bunch oscillations is larger than the initial injection phase (see, for example, the injection of 32 bunches at 03:00:15). This indicates the presence of energy errors that dominate oscillation amplitude after injection.

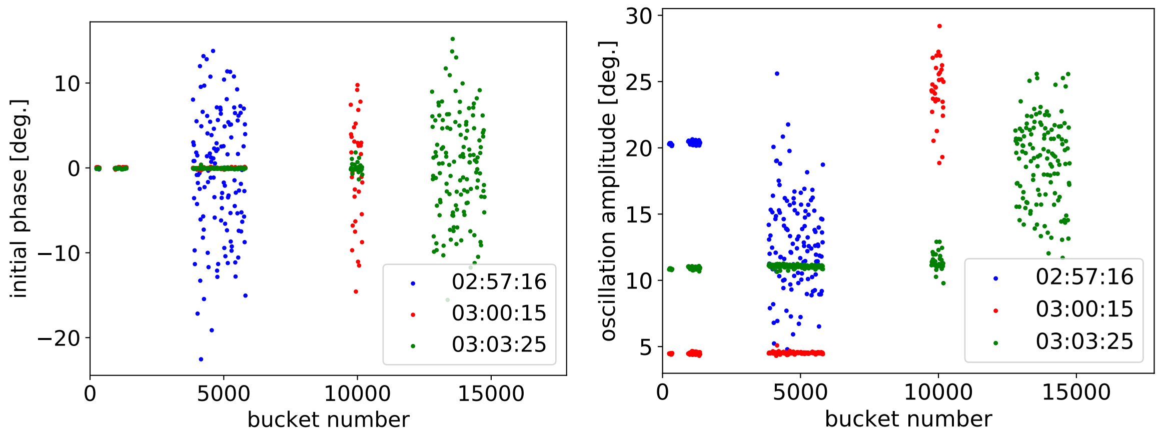
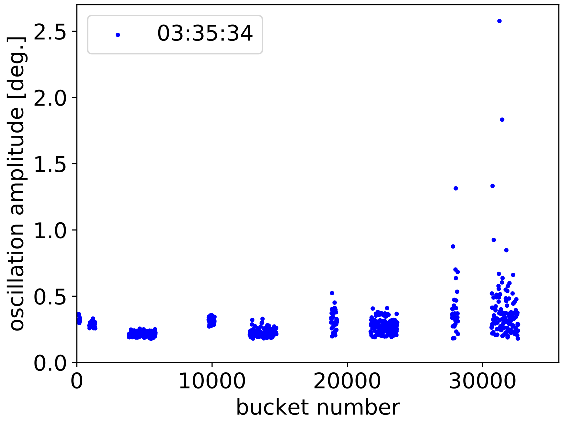


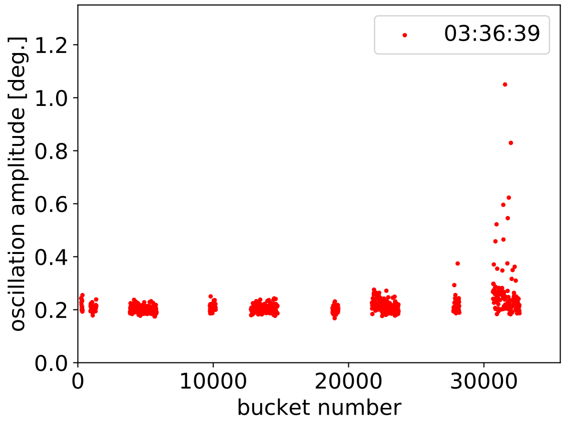
Fig. 12: Bunch-by-bunch data of the 400 MHz component of the bunch phases at the moment of injection of a new batch (left) and the maximum oscillation amplitude within the following 2000 turns (right).

Oscillations were still observed about 5 minutes before the ramp, but unfortunately not at the start of the ramp anymore, neither at the arrival to flat top (Fig. 13). Thus the observations of previous MDs [1] could not be reproduced in this MD; a possible reason could be the different beam used (8b4e BCS instead of 25 ns standard), which could affect the beam parameters at injection. For the same reason, the effect of the long-lasting injection oscillations on the controlled emittance blow-up will have to be studied in further MDs.

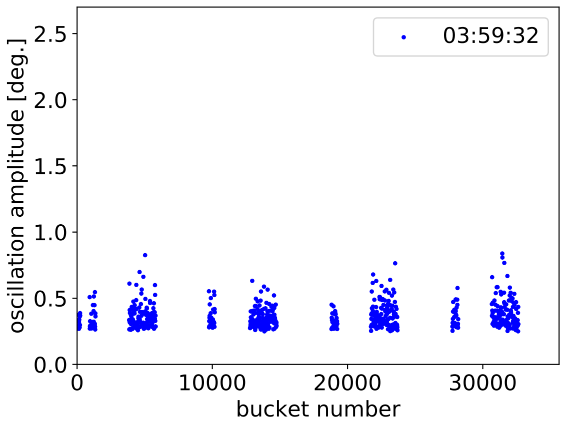
The ObsBox data was also recorded for the both beams during the ramp, with intervals of about two minutes. At the beginning, the bunches were stable, but at 03:43 in B2 and at 03:44 in B1, we observed dipole oscillations of a few degrees for all bunches (Fig. 15). At the same time, the average bunch lengths for the both beams reached their minimum values, see Fig. 15.



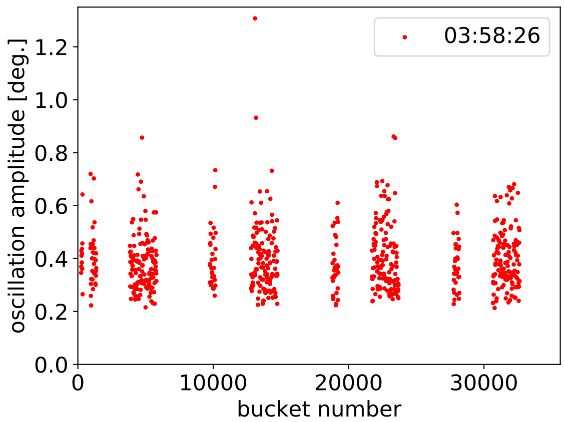
(a) B1, at flat bottom



(b) B2, at flat bottom

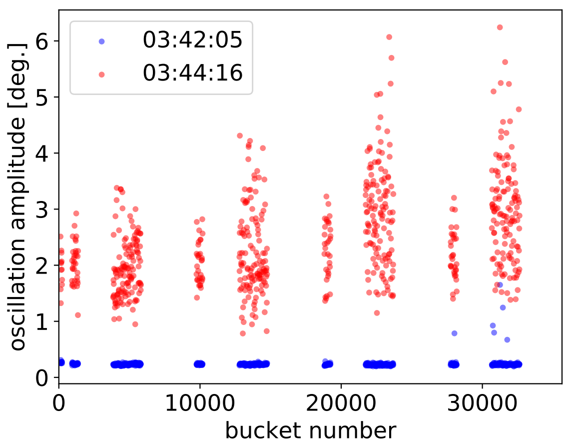


(c) B1, at arrival to flat top



(d) B2, at arrival to flat top

Fig. 13: Bunch-by-bunch amplitude of dipole oscillations along the ring in fill no. 6428.



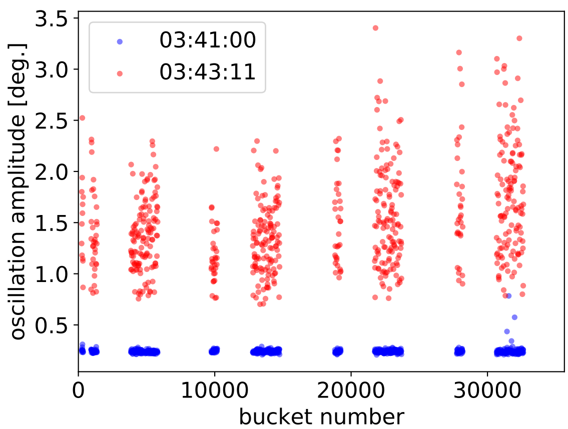


Fig. 14: Bunch-by-bunch oscillation amplitudes during the ramp for B1 (left) and for B2 (right).

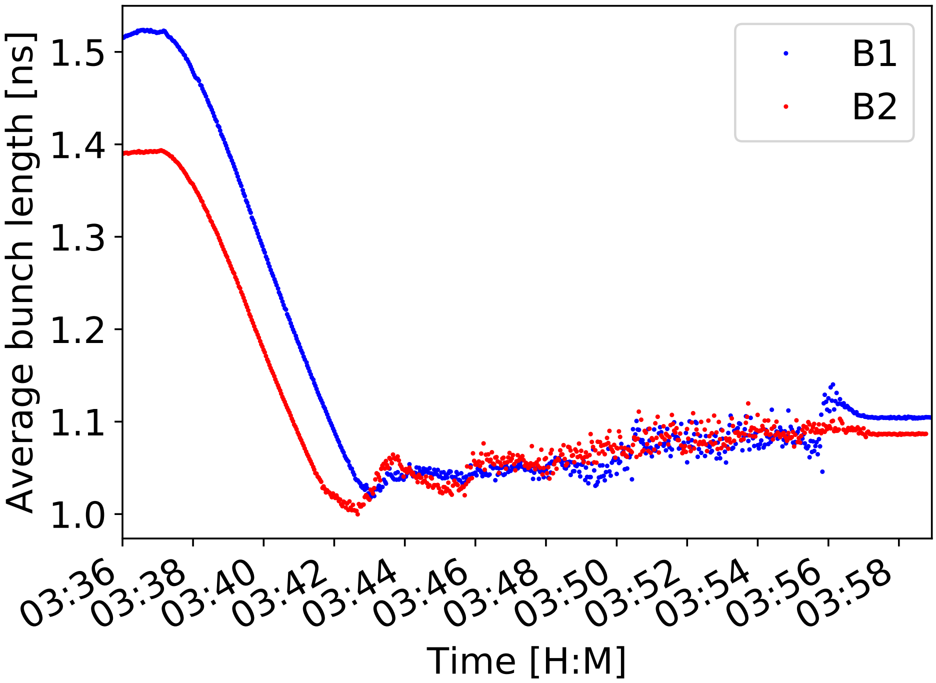


Fig. 15: Evolution of the average bunch length of the beam during the ramp.

4 Conclusions

Two MDs were performed to study the persistent bunch phase oscillations after injection in the LHC. In the first MD, we observed non-rigid dipole oscillations of $\pm 30^{\circ}$ peak-to-peak in the bunch profile measurements. They lead to non-negligible losses and bunch lengthening, about 5 % after 20 minutes, for intensities below 2e11 ppb, and thus below the HL-LHC baseline value.

During the second MD, the profile measurements and ObsBox data acquisitions were triggered at the injection. The observations showed that the oscillations build up in the LHC during a few thousands of turns after injection. Unfortunately, the ObsBox data for high-intensity bunches (about 2e11 ppb) was saturated. Peak-detected Schottky measurements were used to measure the synchrotron frequency and to verify the correct scaling with the RF voltage.

The phase loop can strongly excite the circulating beam when a new batch/bunch is injected, which was observed also on the bunch phase. The maximum amplitude depends on the ratio of the number of circulating to injected bunches. The combination of phase and energy errors at injection can lead to large-amplitude phase oscillations of up to 30°.

In the last fill of the second MD, the initially stable bunches were excited during the ramp and exhibiting up to 5° of phase oscillations at the moment when the average bunch length reached its minimum. Further simulation and measurement studies are necessary to understand the contribution of persistent oscillations to the machine performance, especially in view of future upgrades.

Acknowledgements

We wish to thank the operators of the LHC and its injectors on shift for their kind assistance during the measurements.

5 References

[1] J. Esteban Müller et al., *LHC MD 652: Coupled-Bunch Instability with Smaller Emittance (all HOMs)*, CERN-ACC-NOTE-2017-0017, (2017).

[2] E. Shaposhnikova, *Longitudinal Peak Detected Schottky Spectrum*, CERN-BE-2009-010 RF (2009).