Studies of longitudinal single bunch stability


Keywords: Beam dynamics, Longitudinal, Instability, RF, LHC

Summary

The goal of this MD was to study a single bunch longitudinal instability observed during the acceleration ramp in the LHC in 2010 for bunches with nominal intensity and small injected longitudinal emittance. During this MD there were two fills, the first without acceleration and the second with acceleration. In the first each ring was filled with 8 high intensity bunches with small longitudinal emittance. During the second 8 high intensity bunches were injected into each ring with longitudinal emittances varying from 0.9 eVs to 0.3 eVs. Two longitudinal instability modes (dipole and quadrupole) were observed in different parts of the cycle with both beams. Measurements of phase and bunch length oscillations, as well as data extracted from bunch profile acquisitions during the cycle, are presented in this Note together with an analysis of the growth rate dependence on bunch emittances and intensity.

1 Experimental conditions

The MD fill number is 1759. According to planning this MD session was supposed to take place on 5.05.2011 from 8:00 till 14:00 (flat top). We started later, around 11:00, due to access (till 9:45) and due to tests done by J. Uythoven (change in interlocked BPM configurations in IP6) which should allow us to have oscillating bunches with particle losses equivalent to 2 pilot bunches.

Around 10:15 we asked PSB to increase bunch intensity from \(1.4 \times 10^{11}\) to \(1.6 \times 10^{11}\). We applied transverse emittance blow-up in the SPS to obtain 3-3.5 \(\mu\)m in both planes. After a few tests we disabled transverse scraping in the SPS. For details of setting for the controlled longitudinal emittance blow-up in the SPS see [2]. Voltage at extraction in the SPS was 7.0 MV at 200 MHz and 640 kV at 800 MHz. Voltage at injection in the LHC was 6 MV. It was increased linearly to 12 MV during a 680 s long acceleration ramp (nominal operation voltage program in 2011).

1.1 Filling pattern

Using more than one bunch gave us possibility to have more data from one ramp. However we didn’t want to have too many bunches since we were looking for single bunch effects and therefore bunches should be sufficiently spaced. Filling LHC with too many single bunches could take a long time leading to the significant change in beam parameters (in particular longitudinal emittance) due to the IBS. This is especially true for bunches with smallest longitudinal emittances, this is why they were injected at the end. This was also the reason why we applied controlled transverse emittance blow-up in the SPS. It has been chosen to have 8 bunches in 9 equally spaced buckets (for bunch profile acquisitions, see below).

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The following filling pattern has been used in both fills. The bucket number 1 was filled by
a pilot bunch. The first high intensity bunch was injected in bucket 401 and bunch number \( k \) into the position
\[
\text{bucket} = 401 + (k - 1) \times 3960, \quad k = 1, \ldots, 9.
\]
The 9-th bunch (at the bucket 32081) could not be injected due to limitation from the AGK
(Abort Gap Keeper), the last allowed bucket being 31161.

1.2 Bunch profile acquisition

For the bunch profile acquisition with the 2.5 GHz bandwidth oscilloscope a new triggering
scheme was used in order to keep the total amount of data within the limit given by software
(maximum 4 MPoints). A burst of triggers was generated which allowed to acquire 2.5 ns long
frame centered on the bunch with a sampling interval of 50 ps. Each bunch was acquired 20 times
with a time interval of 1.7 ms. This sequence was repeated every 2 s and allowed 860 s (duration
of the ramp plus 3 min on the flat top) to be covered by measurements without interruption.

Due to the fact that only one experimental set-up (scope) is available, all measurements
presented below were done on one beam, Beam1.

1.3 Phase loop

During both fills the phase loop settings were different from the normal operation. Only
pilot and the first bunch were used for the reference. The bunch mask for other bunches was
programmed accordingly in the RF Beam Phase Module. In the first fill the first high intensity
bunch was similar to others. In the second fill the first bunch was the most stable (with the
largest longitudinal emittance). At the end of each fill this mask had been disabled to see the
effect of the setting used in normal operation on beam stability.

2 First MD fill

The goal of the first part of this MD was to study single bunch longitudinal instabilities
on the flat bottom for smallest longitudinal emittances available from the SPS at this high
intensity. Note that no single bunch quadrupole instability was observed (from bunch length
measurements by BQM) on the flat bottom in 2010 for nominal intensity bunches and emittance
of 0.35 eVs with \( V = 5 \text{ MV} \).

During the first fill we didn’t plan to ramp and all measurements were done on the flat
bottom. We started by injecting 8 high intensity bunches with small, similar, longitudinal
emittances varying between 0.35 eVs and 0.4 eVs (without emittance blow-up in the SPS) to
test bunch stability on the flat bottom before acceleration. The summary of bunch parameters
at extraction from the SPS and at injection into the LHC is given in Table 1. Note that two
bunches (one per each beam) had lower intensity (shown in bold).

From the BQM measurements we didn’t see any quadrupole instability developing on the flat
bottom. On the other hand the amplitude of phase error oscillations for Beam1 were growing
after injection and for Beam2 even they were not growing, but their damping took a long time
(~ 20 min), Fig. 1. From bunch length evolution, also shown in this Figure, we see also that
for Beam1 phase oscillations were growing for some time, together with bunch length, till bunch
length was reaching some value between 1.2 and 1.25 ns. For Beam1 one can clearly see the effect
of changing of phase loop setting (mask) at 12:14 which led to the phase oscillation damping.
This effect is less visible on Beam2 since at this time phase oscillations were already well damped
(below 1 deg). On average the bunch length of injected bunches was slightly larger for Beam2
than for Beam1. Another observation is that for Beam2 the amplitude of injection phase error
was reducing with time as a function of injection (bunch) number. The signals from Beam2 are
also more noisy than from Beam1.
Table 1: Fill 1: injection time and bunch length as measured with the BQM at extraction in the SPS and at injection in the LHC (the first BQM value) together with bunch intensity measured after injection into LHC (BCT) for all 8 bunches of Beam 1 and Beam 2. The average values are shown in the last row.

Note that in the case of Beam 1 both the pilot bunch and the first high intensity bunch were used as a reference for the phase loop while for Beam 2 only high intensity bunch was used due to too low intensity of the pilot bunch (below $5 \times 10^9$).

For Beam 1 the growth rates of dipole oscillations seem to depend both on bunch intensity and on bunch length (which were very similar for most of bunches in any case), see Fig. 2.

3 Second MD fill with ramp

The aim of the second part of this MD was to study a single bunch longitudinal instability observed during the acceleration ramp in the LHC in 2010 for bunches with nominal intensity and small injected longitudinal emittance [1].

3.1 Injected bunch parameters

For this fill injected bunch emittances were varied between 0.3 eVs and 0.9 eVs by applying different emittance blow-up in the SPS [2]. The summary of bunch parameters at extraction from the SPS and at injection to the LHC is given in Table 2.

Transverse emittances were measured in the LHC at the end of the filling during 21 min, starting at 13:38. They are plotted in Fig. 3 as functions of bunch intensity, bunch length and bunch number for Beam 1 and Beam 2. Taking into account that injected emittances were supposed to be in the range (3.0-3.5) $\mu$m it looks like significant transverse emittance blow-up occurred in the LHC, mostly dependent on bunch intensity. There is no visible dependence on bunch length or bunch number (time spent on flat bottom).

3.2 Phase measurements

For this fill it looks like an injection error was slightly increasing with time, being on average smaller than in the first fill, see Fig. 4. One can see that for the first bunches, having larger emittances, phase error oscillations are being damped after injection while for later coming bunches, with smaller emittances, they grow first and then start to decay. Due to the IBS effect (especially for small emittance bunches) and undamped phase oscillations the bunch length is
Table 2: Fill 2: injection time and bunch length $\tau_{sps}$ as measured with the BQM at extraction in the SPS and $\tau_{lhc}$, at injection in the LHC (the first BQM value) together with bunch intensity measured after injection into LHC (BCT) for all 8 bunches of Beam 1 and Beam 2. The average values are shown in the last row.

growing after injection for all bunches but with a different rate. The time when decay starts is probably correlated with bunch length reached at this moment.

Measurements of phase error during the cycle are shown in Fig. 5. During the ramp bunches with the smallest longitudinal emittances became unstable earlier and had larger amplitude of phase oscillations later on, including the flat top, see Table 3. In Fig. 6 the energy at which the phase oscillations start to grow during the ramp is plotted as a function of bunch length at the end of the flat bottom for all 8 bunches in both beams. Bunches with smaller emittances became unstable during acceleration ramp earlier. The amplitude of phase oscillations as a function of bunch length at the end of flat bottom is shown in Fig. 7 (top). The linear fit to the amplitude of the dipole oscillations as a function of time on the flat top gives growth rates presented in Fig. 7 (bottom) as functions of bunch length at the beginning of the flat top. The growth rates of dipole oscillations seem to depend both on bunch length and intensity.

3.3 BQM data

Bunch length during the cycle as measured by the BQM for all 8 bunches in Beam 1 and Beam2 is shown in Figs. 8-9.

Only dipole instability was observed during the acceleration ramp. The bunch length oscillations start to grow on the flat top. One can clearly see that the first bunches with larger emittances are more stable. The growth time and growth rate of quadrupole oscillations found from the exponential fit to the maximum and mean bunch length evolution during the first 25 min at the beginning of the flat top are shown in Table 4 and Fig. 10. Note that bunch number 8 in Beam1 with lowest intensity and emittance is more unstable than higher intensity bunches with larger emittances.

One can also notice the change in the phase loop settings (all bunches used for reference) at the end of the flat top data, after which more unstable bunches were slightly damped and stable started to oscillate.
Table 3: Fill 2: bunch intensity, bunch length $\tau_{fb}$ measured with the BQM at the end of the flat bottom before the ramp in the LHC, amplitude of phase oscillations at the end of ramp $\phi_{ft}$, bunch length $\tau_{ft}$ at the beginning of the flat top together with growth rate $\gamma_{ft}$ obtained from linear fit $\phi = \phi_{fb} + \gamma_{ft} t$ for all 8 bunches in Beam 1 and Beam 2.

### 3.4 Bunch profile data

Bunch profiles acquired for Beam1 5 min after the start of the flat top and 860 s later are shown in Figs. 11-12. One can clearly see that in addition to dipole oscillations observed during the ramp now quadrupole oscillations are also present. One can also see (as in the BQM data) that the first bunches with larger emittances are more stable.

### 4 Conclusions

During the first fill with 8 bunches with low emittances (no blow-up in the SPS) the phase oscillations were growing for some time for Beam1 and were being damped from injection for Beam2. The only difference in experimental conditions for both beams which could be identified is presence of the pilot bunch in addition to bunch number 1 in the phase loop reference for Beam1. For Beam1 the growth rate of dipole oscillations was larger for higher intensity bunches.

No quadrupole instability was observed on the flat bottom and during acceleration ramp for bunches with injected average intensity of $1.53 \times 10^{11}$ and emittance of 0.39 eVs during the first fill as well as for all bunches during the second fill.

During the second fill phase oscillations of the last injected bunches with smaller emittances were growing for some time on the flat bottom for both Beam1 and Beam2. Dipole instability was observed during the acceleration ramp. Bunches with the smallest longitudinal emittances became unstable earlier and had larger amplitude of phase oscillations at the end of the ramp and flat top.

On the flat top quadrupole oscillations started to develop in addition to dipole oscillations already growing during the ramp, again with larger amplitude for bunches with smaller emittance.

### 5 Acknowledgments

We are grateful to J. Uythoven (LHC machine coordinator during our MD) and to A. Rey for transverse emittance measurements as well as to the SPS OP shift for their help.
Table 4: Fill 2: bunch intensity measured after injection into LHC (BCT), bunch length measured with the BQM at the beginning of the flat top in the LHC and growth time of quadrupole oscillations at the beginning of the flat top (during 25 min) for all 8 bunches of Beam 1 and Beam 2.

References

[1] E. Shaposhnikova, First measurements of longitudinal impedance and single bunch effects in LHC, talk at LHCC WG.

Figure 1: Fill 1. Evolution of amplitude of the phase error oscillations and of the bunch length on the flat bottom for each of 8 bunches in Beam1 (top) and Beam2 (bottom). Note change in phase loop setting (mask) at 12:14 leading for Beam1 to the phase oscillation damping.
Figure 2: Fill 1. Growth rate of the amplitude of the phase error oscillations (linear fit) as a function of the bunch length (top) and bunch intensity (bottom) for Beam1. Bunch N1 (phase loop reference) is stable and has the smallest bunch length.
Figure 3: Fill 2. Horizontal (left) and vertical (right) normalised emittances (µm) measured before the ramp (average of two measurements per bunch) as a function of the injected bunch intensity (top), bunch number (middle) and bunch length (bottom) for Beam1 (blue circles) and Beam2 (red circles).
Figure 4: Fill 2. Evolution of amplitude of the phase error oscillations and of the bunch length on the flat bottom for each of 8 bunches in Beam1 (top) and Beam2 (bottom).
Figure 5: Fill 2. Amplitude of the phase error oscillations with time for each of 8 bunches in Beam1 (left) and Beam2 (right) during whole cycle (top) and zoomed-in during the ramp (bottom).
Figure 6: Energy at which the phase oscillations start to grow during the ramp (2nd MD fill) as a function of bunch length at the end of the flat bottom for all 8 bunches in Beam1 (top) and Beam2 (bottom).

Figure 7: Amplitude of the phase oscillations at the end of the ramp) as a function of bunch length at the end of the flat bottom (top) and growth rate $\gamma$ as a function of bunch length at the beginning of the flat top for all 8 bunches in Beam1 (left) and Beam2 (right).
Figure 8: Beam1. Bunch length during the cycle for all 8 bunches as measured by the LHC BQM. Change of the phase loop settings at 14:42 min.
Figure 9: Beam2. Bunch length during the cycle for all 8 bunches as measured by the LHC BQM. Change of the phase loop settings at 14:42 min.
Figure 10: Growth rate (top) and growth time (bottom) of the maximum and mean bunch length during first 25 min of the flat top as a function of initial (average, flat top) bunch length for 8 bunches of both beams (B1 and B2) measured by the LHC BQM. Based on data presented in Figs. 8-9. Note lower intensity bunches from Table 2.
Figure 11: Mountain range and contour plot as function of time during one acquisition period for the first 4 bunches (out of 8) in Beam1 at the beginning of the flat top (left) and 860 s later (right).
Figure 12: Mountain range and contour plot as function of time during one acquisition period for the last 4 bunches (out of 8) in Beam1 at the beginning of the flat top (left) and 860 s later (right).