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Bunch Length along the Batch of the LHC Beam at Extraction from the PS

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Summary

During machine development experiments with multi-bunch LHC beams in the PS, it has been observed that the bunch length at extraction increases slightly towards the end of the batch. This effect does not only get stronger with increasing intensity, but it is also strongly amplified when instead of the usual two all three 80 MHz cavities are operated to produce bunches significantly shorter than nominal. Systematic measurements show that the bunch length gradient along the batch can be attributed to the effect of the impedance of the 80 MHz cavities.

1 Introduction

During MDs with multi-bunch LHC beams in the PS and SPS [1], it has been observed that the bunch length increases towards the end of a batch of 72 bunches. Especially, when so-called short bunches were produced in the PS by operating all three 80 MHz cavities for the bunch rotation prior to extraction, this effect has been clearly measurable.

Prior to extraction of the LHC beam from the PS to the SPS during normal operation, the bunches are rotated in the longitudinal phase space to reduce their bunch lengths from about 11.5 ns to less than 4 ns [2]. Around 280 μs before extraction, the RF voltage at harmonic $h = 84$ (40 MHz) is rapidly switched from 100 kV to 300 kV, causing a longitudinal mismatch which starts the bunch rotation. Finally, 110 μs before extraction, an additional RF system at $h = 168$ (80 MHz), producing 600 kV RF voltage in total, kicks in to further increase the voltage gradient around the bunches to further reduce the bunch length. The bunches are extracted when they are shortest, which means oriented to the vertical position in the longitudinal phase space.

The 80 MHz system for the bunch rotation consists of three cavities [3], each of them capable to deliver about 300 kV to the beam. For the production of LHC beam with nominal bunch parameters, two of these cavities are sufficient to generate the 600 kV required for the second part of the bunch rotation. The third cavity should normally remain available as a hot spare, but can also be used for tests during MDs. Each of the 80 MHz cavities is equipped with a mechanical gap short circuit that fully shields them from the beam when not in use [4]. The short circuit is a slow device that cannot be opened or closed in pulse-to-pulse mode (PPM). A fast feedback is installed around each amplifier to lower the impedance of the cavities seen by the beam [5]. Additionally, higher-order mode dampers reduce the cavity impedance at frequencies other than 80 MHz [6].

Systematic measurements of the bunch length at extraction from the PS using different configurations of the 80 MHz RF system for the bunch rotation have been recorded. This note presents the results, analyzed with respect to a gradient of the bunch length along the batch. It is shown that the increased bunch length towards the end of the batch is caused by the impedance of the 80 MHz cavities. However, the measurements do not allow to disentangle if the observed bunch lengthening is induced by the residual impedance at the fundamental frequency or by a higher-order mode.

2 Experimental conditions and settings

All measurements presented in this note have been taken with a well optimized multi-bunch LHC-type beam with 25 ns bunch spacing. Despite cycle-to-cycle fluctuations, the beam intensity remained unchanged at about $9.6 \cdot 10^{12}$ ppp, corresponding to $1.3 \cdot 10^{11}$ ppb, the nominal intensity required for LHC beam at PS extraction. If not stated otherwise, the coupled-bunch feedback was switched on shortly after transition crossing and kept on until the gaps of the 10 MHz cavities (C86 and C96) used as longitudinal kickers are closed on the flat-top. The bunch profiles of the batch of 72 bunches during the last turn before extraction have been measured for different settings (see below) of the 80 MHz cavities using the bunch shape measurement (BSM) program. This application is connected to an oscilloscope that records the signal from the wideband wall-current monitor WCM3 with a sampling rate of 5 GS/s. The influence of the transfer function of the low-loss coaxial cable to the oscilloscope can be neglected, as this cable is only about 35 m long. The analysis of the data was performed off-line. For each setting, at least ten different cycles were recorded for sufficient statistics.

Each of the three 80 MHz cavities can be set to three states:

1. Switched off with its acceleration gap short-circuited.
2. Switched on delivering voltage to the beam according to a given program and the fast feedback activated.
3. Switched on, but with a voltage program at zero so that no voltage is produced except the voltage induced by the beam. The feedback is active, trying to compensate the induced voltage.

A cavity in the first state is fully invisible to the beam, since it is short-circuited by a pneumatically movable section of beam-pipe which gives an excellent RF contact and fully shields the cavity from the beam. In the second state the cavity gap is obviously open and, together with the voltage produced according to the program, the beam may be influenced by a residual impedance at the fundamental frequency or insufficiently damped higher-order modes. The third case is very interesting as it can be directly compared to the first case.

An ideal fast feedback loop around the amplifier would result in a negligible longitudinal impedance at 80 MHz. Together with perfectly damped higher order modes no measurable difference between open and closed cavity gap would be expected. It will be shown that this is not the case. Either the residual impedance of about 6 kΩ at 80 MHz per cavity [5] or higher order modes cause the bunch lengthening along the batch described in this note.

As an additional cross-check, the voltage program of the 80 MHz system can be reduced to 200 kV per cavity, so that the total voltage of three cavities amounts to the same value as with two cavities at their maximum voltage of 300 kV.

3 Comparison between cavity off and zero voltage program

The 4σ bunch length (Gaussian fit) along the batch at extraction averaged over some ten cycles is shown in Fig. 1 for two cases: The first set of measurements has been taken with one of the 80 MHz cavities completely switched off and the gap short-circuited (normal operation). The second set was recorded with all three cavities switched on, but one cavity receiving a zero voltage program. In both cases

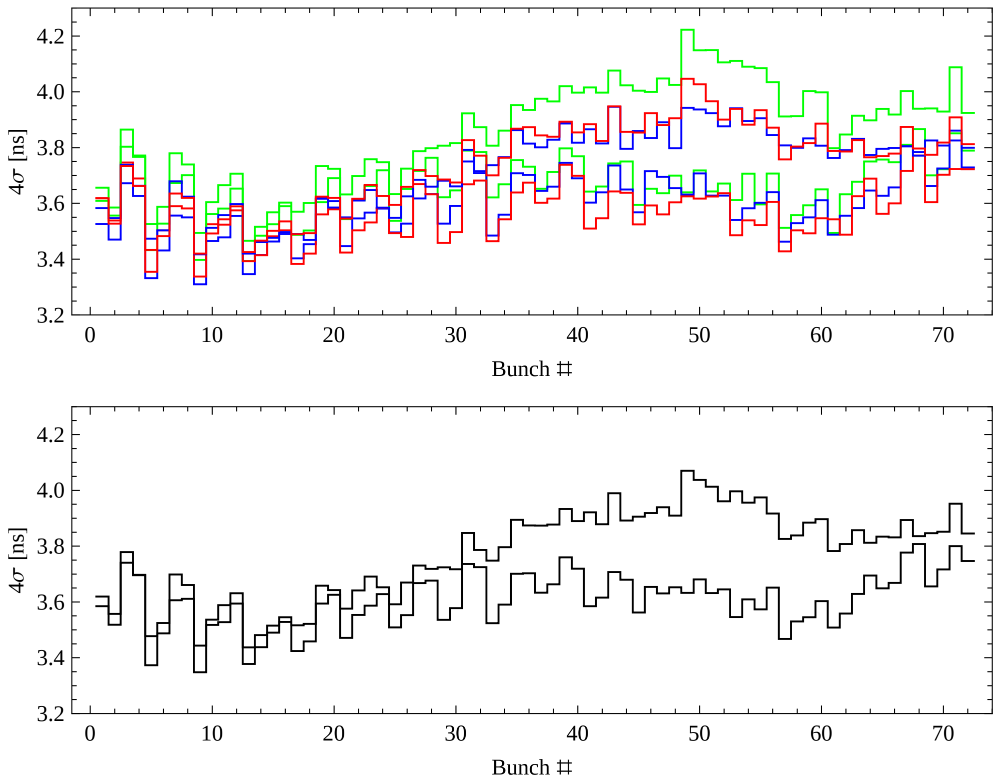

Fig. 1: Top: Bunch length along the batch at extraction averaged over ten cycles with one $80\ \mathrm{MHz}$ cavity (C08: green, C88: blue, C89: red) short-circuited (lower set of traces green, red and blue). For the upper three traces, all cavities have been switched on, but the voltage program was cut for one of them. Bottom: The two traces are averaged over all three cavities (lower trace: two cavities on and the third cavity short-circuited, upper trace: all cavities on, but one of them with zero voltage program).

$2 \cdot 300\ \mathrm{kV}$ are delivered for the bunch rotation. To exclude a technical problem with the fast feedback of one of the cavities, the measurements have been repeated for all three cavities (C08: green, C88: blue, C89: red). The lower plot of Fig. 1 illustrates the average over all cavities.

There is a significant difference in the bunch length along the batch between two active cavities keeping the third one off and three cavities switched on with two of them producing $300\ \mathrm{kV}$ each: From bunch number 30 onwards, the bunches are longer if all three cavity gaps are open. The maximum difference in 4σ bunch length can be observed for bunch numbers around 50, which are $0.4\ \mathrm{ns}$ longer.

Ignoring the detailed shape of the bunch length development along the batch, a linear fit can be applied to the bunch length data to analyze the average bunch lengthening from the head to the tail of the batch. The results, together with the average bunch length of the batch are given in Table 1 for both cases: Firstly, one of the $80\ \mathrm{MHz}$ cavities is completely off and secondly, all cavities are on but with a zero voltage program to one of them. It does not matter which cavity is chosen, the resulting average bunch lengths and bunch length gradients are very similar. However, a difference in length and gradient is clearly visible in between both cases. Switching the third $80\ \mathrm{MHz}$ cavity on, even without a voltage program, has a significant effect on the observed bunch lengthening towards the end of the batch.

3.1 Three cavities with reduced voltage

As a crosscheck for the measurements with three $80\ \mathrm{MHz}$ cavities on, with only two of them delivering $300\ \mathrm{kV}$, measurements with all three cavities with a reduced voltage of $200\ \mathrm{kV}$ each have been recorded. The total voltage of $600\ \mathrm{kV}$ corresponds to what is normally produced by two cavities, but again all three

Bunch rotation with			Average bunch length	Bunch length gradient
C08	C88	C89	4σ [ns]	$\Delta 4\sigma$ [ps/bunch]
off	on	on	3.65	2.1
on	off	on	3.59	3.0
on	on	off	3.57	1.7
Average, two cavities on:			**3.60**	**2.3**
on, $0\ \mathrm{kV}$	on	on	3.86	6.6
on	on, $0\ \mathrm{kV}$	on	3.72	5.4
on	on	on, $0\ \mathrm{kV}$	3.74	5.7
Average, 2 $\times$ on, 1 $\times$ 0 kV:			**3.77**	**5.9**

Tab. 1: Average bunch length at extraction and average bunch length increase from one bunch to the next, measured with one of the $80\ \mathrm{MHz}$ off or on but with zero voltage program. At least ten cycles have been recorded for each setting.

cavities with their fast feedback systems are visible to the beam (Fig. 2) .

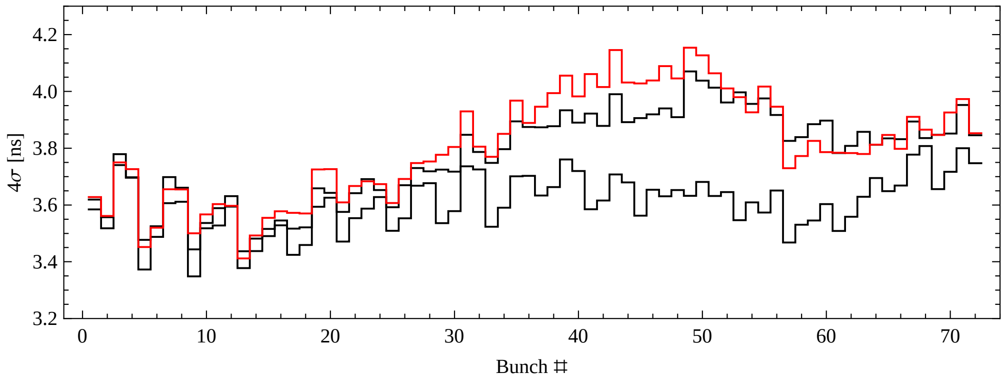

Fig. 2: Bunch length along the batch at extraction averaged over ten cycles using all three $80\ \mathrm{MHz}$ cavities for the bunch rotation, but with reduced voltage of $200\ \mathrm{kV}$ each (red trace). The two black traces are the averaged bunch lengths as in the lower plot of Fig. 1.

The bunch length development for three cavities with reduced voltage (red) follows clearly the trace for three cavities on, but two delivering the full voltage. Apparently, the influence on the beam depends only on the number of $80\ \mathrm{MHz}$ cavities with open gap. The voltage program (0, $200\ \mathrm{kV}$ or $300\ \mathrm{kV}$) does not influence the bunch length distribution at extraction in first order, as long as the total voltage remains the same ($600\ \mathrm{kV}$).

From the bunch length development shown in Fig. 2, an average bunch length of $4\sigma = 3.8\ \mathrm{ns}$ and an average gradient of $\Delta 4\sigma = 5.9\ \mathrm{ps/bunch}$ can be derived. Both parameters thus agree very well with the first case with three open cavities (Tab. 1).

3.2 Effect of Coupled-Bunch Feedback

The benefit of the coupled-bunch feedback can be illustrated best with very short bunches, using all three $80\ \mathrm{MHz}$ at full voltage of $900\ \mathrm{kV}$ in total. This feedback suppresses the spectral components of the longitudinal beam signal at $n = h - 2 = 19$ and $h - 1 = 20$ for acceleration at $h = 21$, using two out of the ten $10\ \mathrm{MHz}$ cavities as longitudinal kickers [7]. The two components may appear from coupled-bunch oscillations of mode 19 and 20.

The effect of this feedback on the bunch length distribution along the batch at extraction is shown in Fig. 3. All bunches are slightly shorter with the coupled-bunch feedback on (blue trace) and, towards

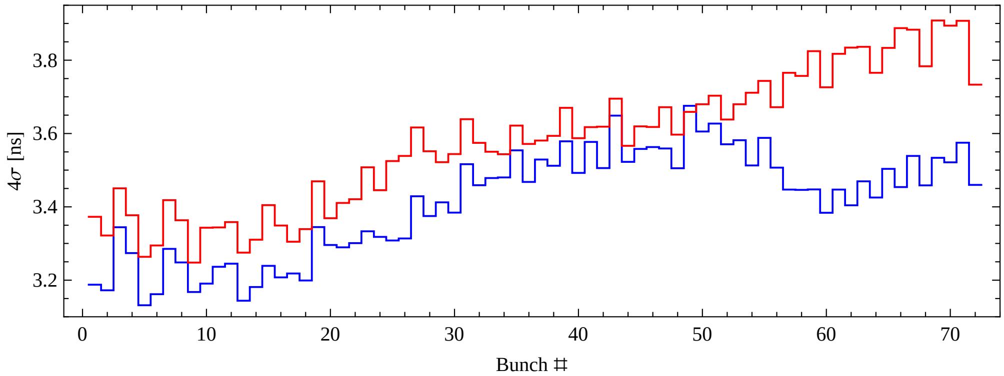

Fig. 3: Bunch length along the batch at extraction averaged over ten cycles using all three $80\ \mathrm{MHz}$ cavities at their maximum voltage of $300\ \mathrm{kV}$. Blue trace: Coupled-bunch feedback on (as during all other measurements presented in this note). Red trace: Coupled-bunch feedback off.

the end of the batch, the bunch length continues to increase when the feedback is off (red trace). With the feedback on, the bunch length shrinks again, as also observed in all bunch length measurements shown above (Figs. 1, 2). The last ten bunches of the batch may be up to $0.4\ \mathrm{ns}$ longer without the coupled-bunch feedback.

As summarized in Table 2, bunches are about $0.2\ \mathrm{ns}$ shorter on average when the coupled-bunch feedback is switched on. Additionally, the average gradient of the bunch length along the batch is

Coupled bunch feedback	Average bunch length 4σ [ns]	Bunch length gradient $\Delta 4\sigma$ [ps/bunch]
off	3.58	8.3
on	3.41	5.3

Tab. 2: Average bunch length and gradient for all three $80\ \mathrm{MHz}$ cavities delivering full voltage, with and without coupled-bunch feedback.

smaller in this case. It is interesting to note that, even for the short bunch case where all three cavities deliver maximum voltage, the average gradient of the bunch length increase of $5.3\ \mathrm{ps/bunch}$ is still consistent with all other cases where the gap of all three cavities is open.

4 Conclusions

Analyzing the bunch length along the batch of a multi-bunch LHC type beam with $25\ \mathrm{ns}$ spacing at extraction from the PS, it has been shown that the observed bunch length growth towards the end of the batch can be attributed to the residual impedance of the $80\ \mathrm{MHz}$ cavities. These cavities are needed for the bunch rotation, allowing to produce bunches shorter than $4\ \mathrm{ns}$ for the SPS. Since the behavior is nearly identical for all three cavities, a technical problem with one of them can be excluded. The observed bunch lengthening effect towards the end of the batch, starting around bunch number 30, depends only on the number of $80\ \mathrm{MHz}$ cavities with an open gap. In addition, there is no significant difference between a cavity delivering voltage or keeping the gap voltage close to zero with the fast feedback around the power amplifier. However, the measurements do not allow to disentangle whether the effect is caused by the residual impedance at the fundamental resonance or a higher-order mode that is not sufficiently damped.

Since the bunch length measurements have been taken at extraction only, the observed bunch lengthening takes place either during acceleration or bunch rotation. Most probably the bunches towards the end of the batch are already blowing up during acceleration. If the bunch lengthening would occur during the fast bunch rotation it could have two sources: Firstly, the RF voltage acting on the beam may vary due to beam loading. For a bunch length deviation of 0.4 ns with respect to a 3.6 ns long bunch an RF voltage error exceeding $\Delta V/V \simeq 2\Delta\sigma/\sigma \simeq 0.2$ would be required. Such a voltage deviation has not been measured. Secondly, due to bunch position errors, not all bunches might be rotated around their center of gravity. This should not be the case, since no significant differences of the bunch position errors along the batch have been observed for all settings described above. Further measurements of the precise bunch length before the bunch rotation and also before the splitting process at flat-top energy must be done to confirm a bunch lengthening during acceleration due to three 80 MHz cavities with open gaps.

The coupled-bunch feedback, damping oscillations at the harmonic 19 and 20, reduces the bunch lengthening towards the end of the batch and allows to produce bunches that are in average 0.2 ns shorter than without the feedback.

For the machine run in 2008, the feedback gain of the three 80 MHz systems will be increased. Repeating the measurements under such conditions might reveal whether the impedance at the fundamental resonance of the cavities or a higher-order mode causes the bunch lengthening. Since the feedback gain only decreases the coupling impedance at the fundamental frequency, this allows to distinguish it from other cavity resonances. Additionally, it should be checked in which way the 40 MHz cavities contribute to the bunch lengthening along the batch, since they are very similar to the 80 MHz cavities.

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