STABILIZING EFFECT OF A DOUBLE-HARMONIC RF SYSTEM IN THE CERN PS

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Abstract

Motivated by the discussions on scenarios for LHC upgrades, beam studies on the stability of flat bunches in a double-harmonic RF system have been conducted in the CERN Proton Synchrotron (PS). Injecting nearly nominal LHC beam intensity per cycle, 18 bunches are accelerated on harmonic $h = 21$ to 26 GeV with the 10 MHz RF system. On the flat-top, all bunches are then transformed to flat bunches by adiabatically adding RF voltage at $h = 42$ from a 20 MHz cavity in anti-phase to the $h = 21$ system. The voltage ratio $V(h42)/V(h21)$ of about 0.5 was set according to simulations. For the next 140 ms, longitudinal profiles show stable bunches in the double-harmonic RF bucket until extraction. Without the second harmonic component, coupled-bunch oscillations are observed. The flatness of the bunches along the batch is analyzed as a measure of the relative phase error between the RF systems due to beam loading. The results of beam dynamics simulations and their comparison with the measured data are presented.

INTRODUCTION

Large Piwinski angle scenarios as a luminosity upgrade path for the Large Hadron Collider (LHC) [1, 2, 3] may require longitudinally flat bunches at collision. In this framework, beam studies have been initiated in the CERN PS to address the stability of flat bunches in a double-harmonic (DH) RF system. Considerable progress has been made in the past, both in theory and experiments [4, 5, 6] to explore the underlying phenomenology of longitudinal instabilities in DH RF systems in hadron machines under various conditions. Small amplitude synchrotron oscillations of beam particles in a DH RF system with the harmonic ratio of two and a voltage ratio of ≈ 0.5 can provide large synchrotron tune spread and thus improved Landau damping. Consequently, this may lead to very stable bunches, as the threshold of multi-bunch instabilities is increased.

The CERN PS, as one of the accelerators in the injector chain to the LHC, is equipped with several RF systems from 2.8 MHz to 200 MHz to perform the required RF manipulations. The bunches required for the LHC injection are prepared in the PS by splitting twice at the flat-top energy using the RF systems with harmonic number ratios of two and four ($h = 21$, 42 and 84 corresponding to 10, 20 and 40 MHz, respectively); hence, the PS is ideal for experiments with flat bunches with DH RF systems. The RF parameters for the experiment were chosen based on longitudinal beam dynamics simulations using the tracking code ESME [7]. Both, experiment and simulations were carried out at 26 GeV, reasonably far away from the transition energy (5.7GeV).

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SINGLE AND DOUBLE HARMONIC RF ON THE FLAT-TOP

During the production of nominal LHC-type beam [8], flat bunches in a DH RF system can be produced on the flat-top by adiabatically a) reducing the 10 MHz RF voltage from 200 kV (used for acceleration) to 32 kV and b) increasing the 20 MHz RF voltage to its maximum value of 16 kV in anti-phase (bunch lengthening mode) to the 10 MHz RF. The unused eight cavities out of ten of the 2.8–10 MHz RF system are switched off and short circuited in a sequence to reduce beam loading effects. From 140 ms before ejection the beam is kept in the DH $h = 21/42$ RF sytem with constant voltages of $V_{\mathrm{h21}}/V_{\mathrm{h42}} = 32\,\mathrm{kV}/16\,\mathrm{kV}$. It is worth noting that the RF signals at the two harmonics were directly derived by frequency division from a common master oscillator. The phase loop, thus moving the phase of $h = 21/42$ synchronously, was kept closed on the phase of the $h = 21$ component of beam and the cavity return vector sum. The intensity was about $8.5 \cdot 10^{12}$ ppp corresponding to $4.7 \cdot 10^{11}$ ppb.

The development of the longitudinal bunch profile during the formation of the flat bunches is compared to the single-harmonic (SH) case in Fig. 1. While the DH case is

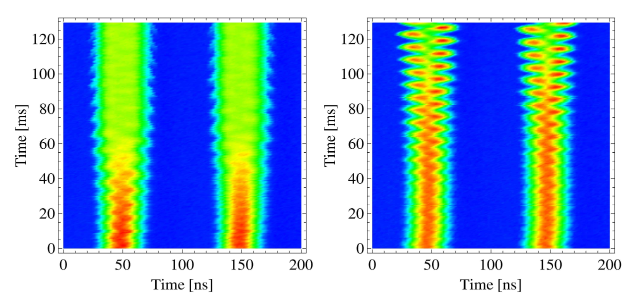

Figure 1: Last two bunches of the 18 bunch batch on the flat-top. The second harmonic ($h = 42$) is increased to 16 kV within the first 70 ms (left). The SH case ($h = 21$ only) is shown on the right plot.

stable, strong coupled-bunch mode oscillations are excited within $\simeq 100$ ms in the SH RF system.

SIMULATIONS

The ESME simulations are carried out in two steps. Firstly, the general features of the necessary beam manipulations within the single particle beam dynamics applied to the PS were examined. In this case, a single bunch is populated with a longitudinal emittance in the range of $1-2$ eVs ($\approx 4\sigma$ emittance) in the RF buckets of the 10 MHz system and transformed to a flat bunch by turning on the 20 MHz RF system adiabatically. The simulations showed that one can generate flat bunches from standard bunches in $h = 21$ in ≈ 35 ms (≈ 5 synchrotron periods) without blowing up their longitudinal emittance. These simulations provided the initial operational parameters for the experiment.

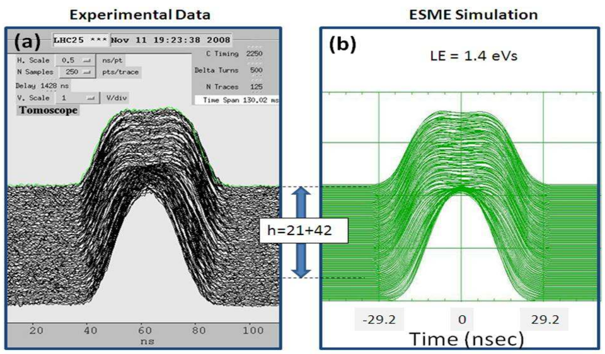

Figure 2: Comparison between (a) measured and (b) simulated mountain range pictures during flat bunch formation.

Fig. 2 shows the simulated mountain range plots for a single bunch and its comparison with the measurements for the 12th bunch of a train of 18 bunches. The general features of the mountain range are well reproduced by the simulations.

In the second step the simulations are performed including space-charge effects, broad-band impedance arising from the beam pipe and known cavity impedances for the 10 MHz and 20 MHz RF systems. The calculations are carried out for a range of bunch intensities starting from $5 \cdot 10^{11}$ ppb. Simulations show that the above mentioned single-bunch effects play a detrimental role only at intensities which are more than an order of magnitude larger than the present operating intensities in the PS.

LONGITUDINAL BEAM STABILITY

The synchrotron frequency versus single particle emittance for SH and DH cases is illustrated in Fig. 3 for different phase errors between $h = 21$ and 42. Compared to the SH case, the synchrotron frequency distribution is not decreasing monotonically toward the separatrix, which might cause loss of Landau damping when $d\omega_s(\varepsilon_l)/d\varepsilon_l = 0$ and $df(\varepsilon_l)/d\varepsilon_l \neq 0$ [9]; $f(\varepsilon_l)$ is the longitudinal particle distribution. The measured $\varepsilon_l = 1.4$ eVs is well below the 2.55 eVs (Fig. 3) needed to reach the limit of instability. Furthermore, the relative synchrotron frequency spread is significantly larger in the DH RF system (> 0.6 compared to $\simeq 0.1$), even taking a phase error between the two RF systems into account [10]. As expected, the beam is thus more stable in the DH RF system.

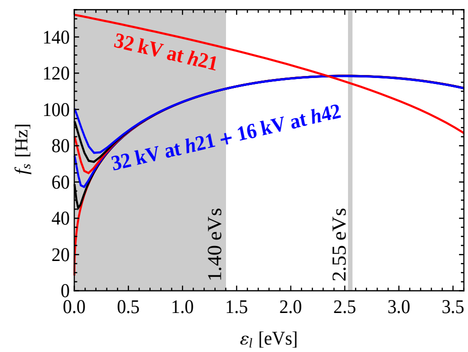

Figure 3: Synchrotron frequency versus single particle emittance for single and DH RF system (voltage ratio 0.5). A bunch of $\varepsilon_l = 1.4$ eVs covers the gray shaded area. A phase error of 0^0, 2^0, 4^0, 6^0, 8^0, 10^0 (from bottom to top trace) has been assumed between the two RF systems.

To identify a possible source of impedance, a dipole oscillation mode analysis has been performed [11]. The position error of each bunch was extracted from Gaussian fits to the traces of the mountain range data from SH measurements. Subsequently, a sinusoidal function is fit to the dipole motion of each bunch, resulting in oscillation amplitude and phase per bunch. A discrete Fourier transform can then be applied to convert amplitudes and phases per bunch to mode amplitudes and relative phases. The relative mode amplitudes are shown in Fig. 4. It is important to point out

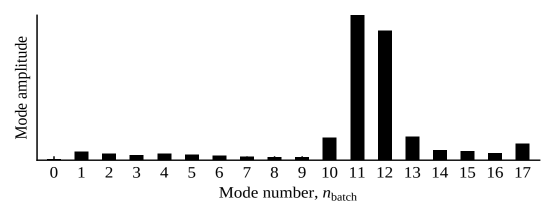

Figure 4: Mode spectrum of the coupled-bunch oscillations observed on the flat-top.

that mode numbers refer to the batch of 18 bunches only, and do not directly correspond to integer harmonics of f_{rev}; each batch mode number n_{batch} shows up as a spectrum around with the strongest harmonics at $\lfloor 7/6 \cdot n_{\mathrm{batch}} \rfloor$ and $\lceil 7/6 \cdot n_{\mathrm{batch}} \rceil$ ($21/18 = 7/6$, 18 bunches at $h = 21$). The excitation resulting in the observed spectrum is therefore around 6.4 MHz $\pm\, p f_{\mathrm{bunch}}$, $f_{\mathrm{bunch}} = h f_{\mathrm{rev}}$ is the bunch frequency and p an integer. Aliasing occurs since the field of the impedance source is sampled with f_{bunch}. Since no coupling between tail and head of the batch across the gap ($\tau_{\mathrm{gap}} = 350$ ns) has been observed, the quality factor Q of the impedance candidate can be estimated to be $Q \leq 2\pi f_{\mathrm{res}} \tau_{\mathrm{gap}}/2$ ($Q \simeq 7$ at $f_{\mathrm{res}} = 6.4$ MHz, $Q \simeq 4$ at $f_{\mathrm{res}} = 3.6$ MHz, $Q \simeq 15$ at $f_{\mathrm{res}} = 13.6$ MHz, etc.).

None of the RF cavities in the the PS have correct frequency and quality factors that would explain the observed coupled-bunch instability. A similar coupled-bunch instability was observed for the first time in 2008 during the first splitting of the nominal 25 ns beam for LHC with new kickers in the PS [12]. Therefore, these kickers are suspected as a possible source of impedance.

TRANSIENT BEAM LOADING

During the experiment, the relative phase between the two RF systems has been adjusted such that the arbitrarily chosen bunch 12 was well flattened. However, the bunches at head and tail of the batch become noticeably asymmetric as shown in Fig. 5. Obviously, this is due to the relative

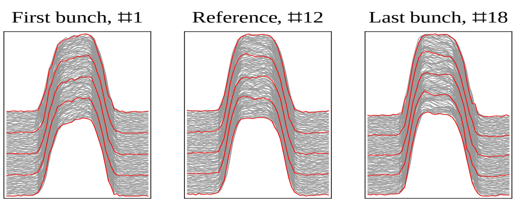

Figure 5: First, reference and last bunch of the batch (recorded on the same cycle, time span: 21 ms).

phase changes along the batch due to transient beam loading. Since the relative phase of the gap voltages $h = 21/42$ has not been measured, an estimation of the phase error based on the asymmetry of the bunch profiles has been performed. Starting from a Hofmann-Pedersen distribution in longitudinal phase space [13], bunch profiles for various longitudinal emittances and relative phase errors have been calculated. Selecting those profiles with the measured (tomographic reconstruction for the SH case) longitudinal emittance results in a set of profiles with the correct ε_l and various phase errors. Comparing them with the measured profiles, estimates on phase errors are done that give the best representation of the data.

Fig. 6 illustrates the estimated phase error along the batch. A relative phase slippage of $h = 21/42$ RF com-

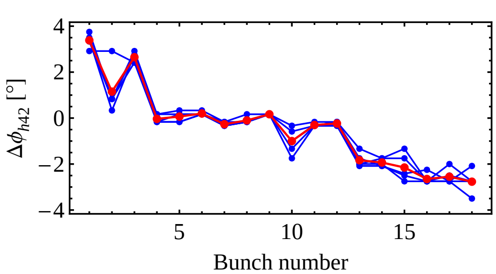

Figure 6: Estimated phase offset along the batch for five individual cycles (blue) and averaged (red).

ponents along the batch of the order of $\pm 2^0$ can be estimated. It should be mentioned that the measurement does not allow to disentangle which of the RF systems (10 MHz, 20 MHz or both) is the major contributor. It is thus planned to measure the RF phases along the batch directly.

CONCLUSIONS

Beam experiments in the CERN PS to address the longitudinal beam stability in the DH RF system with $h = 21/42$ and a voltage ratio of 0.5 have been performed. As expected, the flat bunches in DH RF buckets are more stable compared to bunches in SH RF buckets where strong coupled-bunch oscillations have been observed. The symmetry of flat bunches turned out to be very sensitive to small phase errors of the two RF harmonics applied. A beam-loading induced phase error of a few degrees is sufficient to produce significantly asymmetric bunches at the head and tail of the batch. Any effect of electron cloud, which is normally observed close to extraction of 72 short bunches spaced by 25 ns, could not be detected with normal or flat bunches spaced by 100 ns.

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