5th International Particle Accelerator Conference IPAC2014, Dresden, Germany JACoW Publishing
ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPME028

FLAT BUNCHES IN THE LHC

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Abstract

A high harmonic RF system which could serve multiple purposes was proposed for the LHC. Possible applications of the second harmonic RF system include beam stabilisation in the longitudinal plane in the absence of wide-band longitudinal feedback and reduction of bunch peak line density. Apart from other useful features, flat bunches are expected to produce less beam-induced heating below 1 GHz, the frequency region critical for some LHC equipment. The latter however can also be achieved by de-populating the bunch center. This was demonstrated during the dedicated machine development session in the LHC using RF phase modulation. In this paper the results of tests with single bunches and nominal LHC beams are presented and possible use of this technique in LHC operation is discussed.

INTRODUCTION

The LHC RF system has a frequency of 400 MHz and is designed to provide during nominal operation a voltage of 16 MV per beam. The installation of an additional, higher harmonic RF system in the LHC is under consideration since a quite long time. The first proposals were related to the LHC upgrade scenarios using very short or long and flat bunches [1]. Later it was also proposed for an eventual improvement of longitudinal beam stability, in particular in absence of a bunch-by-bunch longitudinal feedback.

The first LHC run has demonstrated the existence of some margin in longitudinal beam stability [2] due to controlled emittance blow-up [3]. This margin is most probably sufficient for operation at 7 TeV even with much higher beam intensities, required for future upgrade scenarios. At the same time, issues related to short bunches were seen in both the accelerator itself and the detectors, due to beam-induced heating in the first case and high pile-up density in the second. As a remedy, the average bunch length at the beginning of the coast was increased from the nominal value of 1.05 ns ($4\sigma_t$, Gaussian fit) to 1.3 ns. Further increase of bunch length leads to particle loss and lifetime degradation as well as to reduction of luminosity (through the geometric factor). In fact, during physics the average bunch length of colliding bunches only slightly grows above this value.

More recently a higher harmonic RF system was considered for creating “flat" bunches, to further reduce beam induced heating and also useful for some HL-LHC scenarios [4]. However, due to the transient beam loading in the main RF system with limited power, bunches will have some phase modulation along each PS and SPS batch as well as along the whole bunch train. This will lead to tilt in bunch shape unless the higher harmonic RF system will have enough power to follow these bunch displacements. On the other hand, flatter bunches can be produced in a single RF system by applying phase modulation. This technique was first used in the CERN PS [5]. This test was also performed recently in the LHC and the results are presented below.

BUNCH SPECTRUM AND BEAM INDUCED HEATING

In beam operation the longitudinal emittance is significantly increased during the acceleration ramp by applying a band-limited noise via the phase loop in such way that the average FWHM (full-width half-maximum) bunch length of each beam is kept approximately constant [3].

A gradual increase of bunch length (emittance) in physics during the LHC run1 was mainly dictated by issues with beam induced heating in the different machine elements [6], associated with the increase of bunch intensity. For example, in one fill, when the controlled blow-up was not working, the beam was dumped by the interlock related to the temperature increase in one of the tertiary collimators (TCTVB). The heating of the ferrite yoke of the injector kickers (MKI) was a serious limitation for filling the LHC with high intensity beams. Critical heating of the ferrite damper ring was measured in the ATLAS-ALFA roman pot. The extraction mirror in the beam synchrotron radiation telescope (BSRT) was overheated and partially destroyed. Primary collimators (TCP) caused a few beam dumps due to jaw temperature increase. Two beam screens of the injection protection collimator (TDI) were damaged already in 2011. Many improvements (new design, impedance reduction, improved cooling and temperature monitoring) are expected for the next LHC run, however the total beam current will be also higher due to operation with 25 ns spaced bunches.

The power dissipated in the machine element with a longitudinal impedance $Z(\omega)$ by a bunch train of M bunches spaced by t_{bb} can be presented in the form

$$P = \sum_{k=-\infty}^{\infty} j_k^2 \,\mathrm{Re} Z(\omega_k) \left[\frac{\sin\left(M\omega_k t_{bb}/2\right)}{\sin\left(\omega_k t_{bb}/2\right)} \right]^2, \qquad (1)$$

where $\omega_k = k\omega_0$ and $\omega_0 = 2\pi/T_0$ is the revolution frequency. This power loss strongly depends on the harmonics of the single bunch spectrum j_k, proportional to the average bunch current $J_b = eN_b/T_0$, where N_b is the bunch intensity. Longer bunches usually help to reduce heating for broad-band impedances. For narrow-band impedances,

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPME028

bunches of different shape or length τ can lead to different results, unless these impedances have relatively low resonant frequency f_r, below $1/\tau$, when longer bunches are also always better. In the 400 MHz RF system of the LHC the maximum $4\sigma_t$ bunch length during physics is limited to ~ 1.3 ns. Then flatter bunches with the same maximum bunch length potentially can help. Indeed, in the extreme case of a rectangular line density, bunch spectrum (Fig. 1)

$$j_k = J_b \frac{\sin \omega_k \tau/2}{\omega_k \tau/2} \tag{2}$$

has the first zero $f_1 = 1/\tau$, to be compared with the spectrum of a triangular bunch

$$j_k = J_b \frac{\sin^2 \omega_k \tau}{(\omega_k \tau)^2}, \tag{3}$$

where $f_1 = 2/\tau$, or with an intermediate case of a parabolic bunch, also shown in Fig. 1. Note that the high frequency spectrum envelope of a triangular bunch decays $1/(f\tau)$ faster than that of a rectangular one.

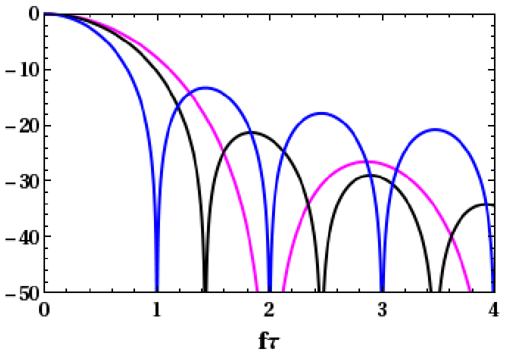

Figure 1: Envelope of bunch spectrum power $20 \log (j_k/J_b)$ for parabolic (black), triangular (magenta) and rectangular (blue) line density.

As one can see from Fig. 1, flatter bunches can reduce heating only at frequencies below $\sim 1.2/\tau$. This is the case for practically all known critical machine elements in the LHC discussed above, except the TDI [6]. Indeed measurements performed in the LHC confirmed the expected improvement for all monitored devices.

PHASE MODULATION TESTS IN LHC

The RF phase modulation has been widely used in accelerators for particle redistribution with various aims: to reduce space charge effect [5], to improve bunch stability [7] or beam lifetime in electron machines.

Bunches can be made flatter without increasing their maximum emittance by using a sine-modulation of the RF phase at frequency slightly below the linear synchrotron frequency f_s. The effect can be described by theory of non-linear resonance [8], see also [9]. To obtain the desired results, it is important that the modulation is switched on and off adiabatically [7].

At the end of the LHC run1 in 2012 one Machine Development (MD) session was devoted to studies of the effect of the phase modulation on bunch distribution and beam-induced heating [10]. The first tests were made on the 450 GeV flat bottom with phase loop (PL) off using 8 single bunches with similar bunch length and intensity varying in the range $(0.7 - 2.1) \times 10^{11}$. In order to find an optimum modulation frequency f_m for high intensity bunches the applied frequency was reduced in 0.1 Hz steps from 55.3 Hz (for $V_{RF} = 6$ MV a zero-intensity frequency $f_{s0} = 55.09$ Hz). During this test the incoherent synchrotron frequency shift Δf_s with intensity due to the LHC reactive impedance could also be estimated [2]. From the difference in bunch reaction (the 400 MHz signal) on RF excitation this shift was found to be less than 1 Hz for $\Delta N_b = 10^{11}$. All 8 bunches were successfully flattened by applying the phase modulation with $f_m \sim 0.97 f_{s0}$ and an amplitude of 1 deg, similar to the parameters used in Tevatron [7]. The change of the bunch profile could also be observed from measurements of the bunch spectrum and, as expected, the first zero moved down in frequency.

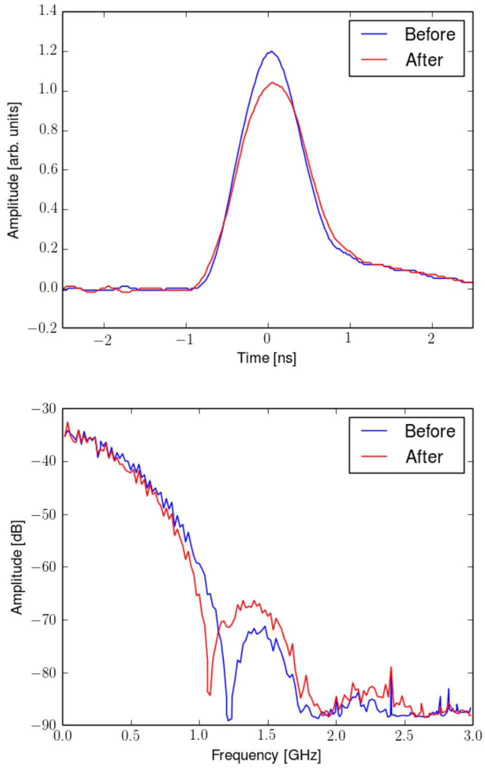

Figure 2: Bunch profile of bunch 1 in Beam 1 at 4 TeV (top) and corresponding spectrum in logarithmic scale (bottom) before and after excitation. The profile asymmetry is caused by non-compensated cable transmission.

As the next step during the MD a phase modulation was applied to the operational beams (Beam 1 and Beam 2) with bunches spaced at 50 ns (1374 bunches per ring), first at 450 GeV and then at 4 TeV (following the operational controlled emittance blow-up by a factor 5 during the ramp which eliminated the effect of the first excitation).

The excitation used at 4 TeV was 10 s long (80 synchrotron periods or 3.3 s for rise, fall and top of trapezoid) and had $f_m = 0.965 f_{s0}$ (at 4 TeV $f_{s0} = 24.01$ Hz for the operational voltage of $V_{RF} = 10$ MV). Initially, for Beam 1, the PL was on to decrease unexpected particle losses and therefore the phase modulation had to be applied at the revolution frequency sidebands $f_0 \pm f_m$ to avoid interference with the PL. Nevertheless, due to the existence of the abort gap the PL still sampled an excitation and tried to act on it resulting in a bunch length modulation along the ring at $2f_0$ ($\sim$ 250 ps peak-to-peak). For Beam 2 the amplitude was reduced from 2.5 deg used for Beam 1 to 1.25 deg, the PL was switched off and then no bunch length modulation could be detected in this case. The change in bunch profile and corresponding spectrum can be seen in Fig. 2. It is similar to that obtained in the first test at 450 GeV as well as in particle simulations for 4 TeV (without intensity effects) for the same excitation and beam and machine parameters, Fig. 3.

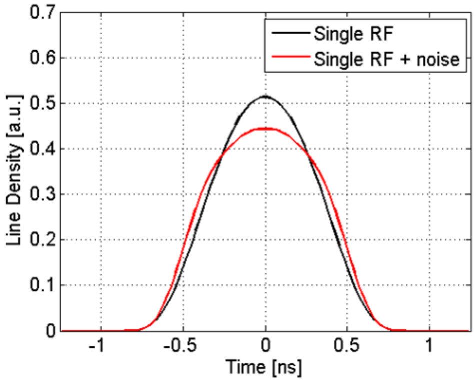

Figure 3: Effect of phase modulation on bunch profile from particle simulations under experimental conditions.

The beam-induced heating was monitored for several devices during the last test with operational beams. A sharp decrease of the temperature was observed for the ALFA Roman Pot and the TCTVB collimators after the RF phase modulation had been applied (vertical line in Fig. 4). One can also see the temperature reduction during the period when the 400 MHz voltage was reduced from 10 MV to 6 MV and bunches were longer. A reduction (of the slope) in temperature increase of the BSRT was also observed after the phase modulation was applied. No effect could be detected on MKI kickers due to their large inertia. During this MD there was no sign of an excessive heating due to bunch flattening in any other devices.

Note that the bunch length shown in Fig. 4 is calculated by the Beam Quality Monitor from the FWHM as a $4\sigma_t$ value, assuming a Gaussian bunch. Indeed, after the excitation the bunch widens by $\sim$ 100 ps (Fig. 2).

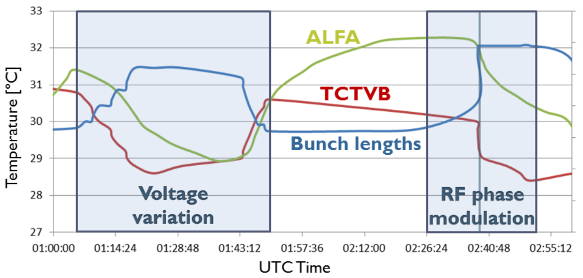

Figure 4: Temperature of ALFA and the TCTVB collimators during the 2nd fill and average bunch length evolution.

SUMMARY

In the absence of a higher harmonic RF system in the LHC flatter bunches were produced by applying the RF phase modulation. These bunches have a spectrum favorable for a reduction of beam-induced heating in some critical equipment, and can be interesting for the LHC experiments due to a potential reduction of the pile-up density in the luminosity regions. The main uncertainty of this scheme is related to the evolution of the “flat" distribution during physics which will be studied in future experiments.

ACKNOWLEDGMENTS

We would like to thank J. Molendjik, S. Jakobsen and the OP shift crew for their help during MD. We are grateful to E. Metral, N. Mounet and T. Pieloni for useful discussions.

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