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Longitudinal emittance blowup in the large hadron collider

P. Baudrenghien [1], T. Mastoridis *

BE-RF, CERN, Geneva, Switzerland

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ABSTRACT

The Large Hadron Collider (LHC) relies on Landau damping for longitudinal stability. To avoid decreasing the stability margin at high energy, the longitudinal emittance must be continuously increased during the acceleration ramp. Longitudinal blowup provides the required emittance growth. The method was implemented through the summer of 2010. Band-limited RF phase-noise is injected in the main accelerating cavities during the whole ramp of about 11 min. Synchrotron frequencies change along the energy ramp, but the digitally created noise tracks the frequency change. The position of the noise-band, relative to the nominal synchrotron frequency, and the bandwidth of the spectrum are set by pre-defined constants, making the diffusion stop at the edges of the demanded distribution. The noise amplitude is controlled by feedback using the measurement of the average bunch length. This algorithm reproducibly achieves the programmed bunch length of about 1.2 ns[2], at flat top with low bunch-to-bunch scatter and provides a stable beam for physics coast. The noise can be injected either in the beam phase loop or directly in the cavity voltage set point. These two different technical implementations are presented and their respective advantages analyzed. The performance of the algorithm and its further applications are also presented in this paper.

1. Introduction

The longitudinal emittance blowup is necessary to achieve the desired levels of Landau damping for longitudinal stability in the LHC. This fundamental motivation for the system development is presented in Section 2. A description of the algorithm, the choices of excitation noise spectrum, and the actual technical implementation are presented in Section 3. Section 4 presents the original blowup implementation through the LHC beam phase loop, its performance and limitations. Section 5 presents an alternative implementation through the LHC cavity controller, which allows for further applications of the longitudinal emittance blowup, especially selective excitation along the ring. Finally, Section 6 suggests possible future improvements for the system.

This paper follows the work previously presented by the authors in Ref. [1]. The LHC stability thresholds have been estimated in Ref. [2]. A theoretical treatment of the beam diffusion in the LHC has been presented in Ref. [3]. Using this treatment, a comparison of the estimated and measured longitudinal emittance growth rates was presented in Ref. [4].

2. Motivation for blowup

The first attempt to ramp single bunch, close to nominal intensity ($\approx 1.1\times 10^{11}$ protons) took place on May 15th, 2010. At injection, the bunch was 1.2–1.3 ns long with about 0.4 eVs longitudinal emittance[3] and this emittance was preserved during capture. Ramping was done with a constant 8 MV. Towards the end of the ramp, as the bunch length shrank down below 600 ps, a violent longitudinal instability developed as seen in Fig. 1, due to loss of Landau damping [2]. This behavior did not come as a surprise; it was consistent with LHC longitudinal stability studies done in 2000 [5]. At the time of the LHC design, the options of emittance blowup or an active longitudinal feedback system were considered to mitigate these instabilities [6]. The former solution was chosen for the LHC. The alternative option of distorting the longitudinal profile was not considered, but in this case periodic action on the bunch would be necessary during the long LHC coast, with implications for the physics program.

During acceleration, the threshold for loss of Landau damping scales as

$$\frac{\mathrm{Im}(Z^{thr})}{n} < \frac{|\eta|E}{eI_b\beta^2}\left(\frac{\Delta E}{E}\right)^2\frac{\Delta\Omega_s}{\Omega_s}f_o\tau \tag{1}$$

[1] Tel.: +41 22 767 5581

* Corresponding author. Tel.: +41 764 8790 68.
E-mail addresses: Philippe.Baudrenghien@cern.ch (P. Baudrenghien), tmastoridis@gmail.com (T. Mastoridis).

[2] Bunch length is defined as the 4σ value in this paper.

[3] At CERN it is customary to quote the longitudinal emittance as $4\pi\sigma_\tau\sigma_E$. Note that, for a Gaussian distribution, 95% of the particles are within a $6\pi\sigma_\tau\sigma_E$ area. The $4\pi\sigma_\tau\sigma_E$ area contains 86.5% of the particles.

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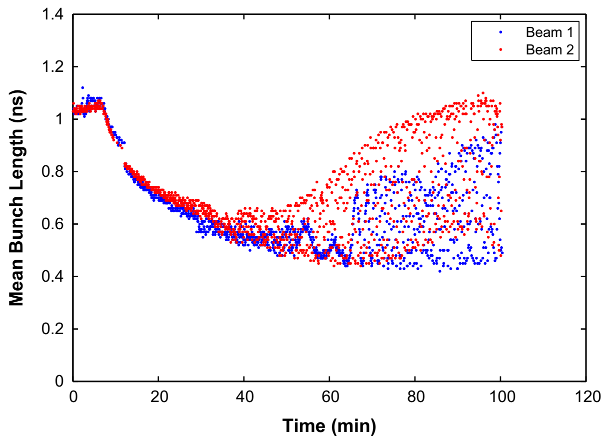

Fig. 1. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (< 0.4 eVs). The bunch becomes unstable. The bunch length measurement implies an oscillation with quadrupole components.

where $\mathrm{Im}(Z^{thr})/n$ is the inductive impedance divided by the azimuthal bunch shape mode number n ($n=1$ dipole, $n=2$ quadrupole, etc.), η is the slip factor, E is the particle energy, e is the proton charge, I_b is the bunch current, $\beta = v/c$ with v the particle speed, Ω_s is the synchrotron frequency, f_o is the revolution frequency, τ is the bunch length, and $\Delta\Omega_s$ is the synchrotron tune spread [2]. The LHC values for these parameters are available in the Appendix.

Eq. (1) can be rearranged to

$$\frac{\mathrm{Im}(Z^{thr})}{n} \propto \frac{\epsilon^{5/2}}{E^{5/4}V^{1/4}} \tag{2}$$

where ϵ is the longitudinal emittance and V is the total RF voltage. Since the LHC is always well above transition, η is approximately constant.

For a constant emittance the threshold quickly drops with energy, explaining the instability observed in the first ramp. The energy for the observed onset of instability is consistent with the 0.06Ω estimate for the inductive impedance divided by mode n for the LHC [2]. Since the bunches are stable at 450 GeV, it is sufficient to sustain a constant threshold to achieve stability throughout the LHC cycle, assuming that the longitudinal impedance is only marginally increased due to the collimator motion closer to the beam with energy increase. By inspection of Eq. (2), the stability margin is preserved if the emittance grows according to

$$\epsilon \propto E^{1/2}V^{1/10} \tag{3}$$

In the operational LHC blowup implementation, the bunch length τ is kept constant during the ramp. The emittance then grows as the bucket area (the bucket filling factor is constant)

$$\epsilon \propto E^{1/2}V^{1/2} \tag{4}$$

As the voltage increases during the ramp, the fixed bunch length blowup actually improves the stability margin during the acceleration.

The narrow-band impedance threshold was also studied in the RF design [5]. It is shown that, to avoid decreasing the threshold during the cycle, the emittance should be increased with energy at least as

$$\epsilon \propto \frac{E^{1/2}}{V^{1/6}} \tag{5}$$

Again the constant bunch length blowup results in a faster than strictly necessary emittance increase.

3. Longitudinal emittance blowup

The LHC blowup is inspired by the SPS system [7] but the LHC case is different: the much longer ramp makes the process smoother, there are short bunches in a single RF system with small synchrotron frequency spread, and there is almost no effect of bunch intensity (lower machine inductive impedance and much better compensation of the periodic beam loading). The beam is excited with RF phase noise acting via the fundamental RF system (400.8 MHz). The frequency of a single-particle synchrotron oscillation depends on the peak amplitude of its trajectory ϕ_{pk}

$$\Omega_s(\phi_{pk}) \approx \Omega_{s0}\left[1-\left(\frac{\phi_{pk}}{4}\right)^2\right] \tag{6}$$

with Ω_{s0} the synchrotron frequency of the zero-amplitude oscillation (Fig. 2).

This dependance can be used to selectively excite the particles in a chosen region centered around the core of the bunch. Assume, for example, that the phase noise spectrum extends from Ω_{s0} down to $0.85\Omega_{s0}$ (corresponding to an amplitude of phase oscillation equal to $\pi/2$ in Fig. 2). By exciting with a phase noise spectrum extending between these frequencies, the particles of the core of the bunch are driven in synchrotron resonance, but when the amplitude of their oscillation exceeds $\pi/2$, they would see no more coherent excitation. Diffusion should therefore stabilize around that point. The bunch length can be precisely controlled by fine adjustment of the lower frequency of the phase noise spectrum. For 1.2 ns target bunch length, the excitation is used in the band

$$0.85\Omega_{s0} \le \Omega \le 1.1\Omega_{s0} \tag{7}$$

The upper frequency exceeds Ω_{s0} to guarantee that the core is not missed (the filling factor is sufficiently low that higher modes are not excited). The beam intensity has a negligible impact on the incoherent synchrotron frequency shift in the LHC: the broadband inductive impedance ($\mathrm{Im}(Z^{thr})/n \approx 0.06\ \Omega$) reduces Ω_{s0} by only 1% at maximum bunch intensity, and the periodic beam loading is well below 0.5% in voltage [8]. A flat power spectral density is used. The excitation is applied during the acceleration ramp and the spectrum of the phase noise tracks the changing Ω_{s0} (Fig. 3). An algorithm has been developed for the generation of the phase noise samples with the required time-varying spectrum [9].

3.1. Feedback from measured length

When blowup was first tested in the LHC the bunch would indeed grow quickly till it reached the length corresponding to the lower synchrotron frequency in the excitation spectrum, but diffusion would not come to a complete stop then. The rate would just be reduced. An on-line measurement of the bunch length was

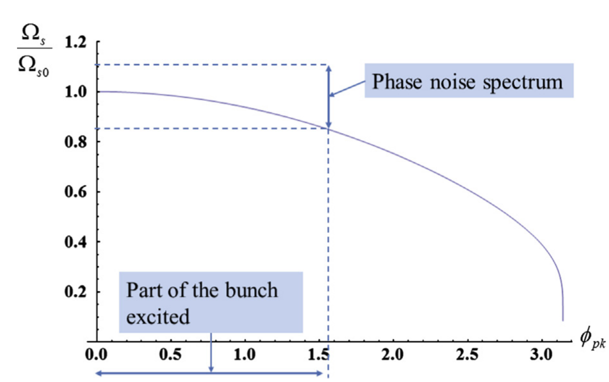

Fig. 2. Ω_s/Ω_{s0} as a function of the maximum phase deviation in radians. Stationary bucket.