STUDY OF CONTROLLED LONGITUDINAL EMITTANCE BLOW-UP FOR HIGH INTENSITY LHC BEAMS IN THE CERN SPS

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Abstract

Preventive longitudinal emittance blow-up, in addition to a fourth harmonic Landau damping RF system, is required to keep the LHC beam in the SPS stable up to extraction. The beam is blown-up in a controlled way during the acceleration ramp by using band-limited phase noise targeted to act inside the synchrotron frequency spread, which is itself modified both by the second RF system and by intensity effects (beam loading and others). For a high intensity beam these latter effects can lead to a non-uniform emittance blow-up and even loss of stability for certain bunches in the batch. In this paper we present studies of the emittance blow-up achieved with high intensity beams under different conditions of both RF and noise parameters.

MOTIVATION

The longitudinal coupled-bunch instability threshold for the LHC beam in the SPS is $\sim 2 \times 10^{10}$ p/bunch, while the nominal beam intensity is $\sim 1.2 \times 10^{11}$ p/bunch. The second RF system guarantees stability until $\sim 9 \times 10^{10}$ p/bunch, while above this value controlled emittance blow-up is needed to keep the beam stable. Both the second RF system and the controlled emittance blow-up increase the synchrotron frequency spread inside the bunch, effectively increasing Landau damping.

The second RF system is a fourth harmonic system (800 MHz, with the main RF system running at 200 MHz). It is used in bunch shortening mode [1].

Emittance blow-up is needed to stabilize the beam on the Flat Top, FT (threshold of the instability is inversely proportional to the energy of the beam). The blow-up is done in a controlled way as it should be minimal for the extracted bunches to be captured in the 2.5 ns LHC buckets (acceptable losses for $\tau_{4\sigma} < 1.7$ ns from simulation [2]).

RF NOISE FOR BLOW-UP

The nominal LHC beam in the SPS consists of up to four batches, each of 72 bunches spaced by 25 ns. The beam is accelerated from 26 GeV/c to 450 GeV/c and extracted to the LHC at around 18.9 s in the cycle. During the ramp the voltage initially maintains a constant bucket area, then is fixed to 4.5 MV; in the last 0.3 s of the cycle (end of the FT) the voltage is raised to 7 MV. In 2007, the 800 MHz voltage was set to 340 kV along the flat bottom and to 500 kV along the ramp and the FT. It is worth noting that beam loading effects on the 800 MHz cavities are not sufficiently compensated by the existing beam control system (upgrade foreseen in the near future).

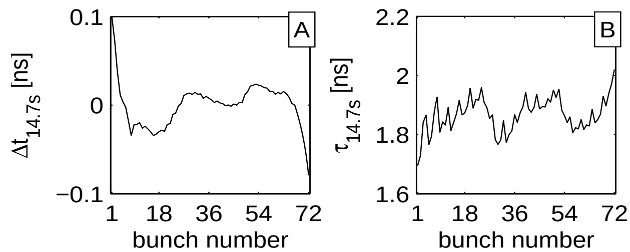

Figure 1: Bunch position (A) and length (B) along the batch before controlled blow up, at 14.7 s in the cycle (180 GeV/c), average across different cycles.

The controlled emittance blow-up is achieved by applying band-limited noise on the phase loop of the 200 MHz RF system. The RF noise is applied for a period of 3 s starting at 14.8 s in the cycle (from 185 GeV/c to 420 GeV/c). This is during the energy ramping while the 200 MHz voltage is 4.5 MV.

The generation of the noise spectra is described in [3]. White noise is generated as numeric samples and is then filtered to obtain a triangular spectrum with width matched to the bunch synchrotron frequency spread and with maximum amplitude at the center of the bunch. The noise high and low cutoff frequencies ($f_{\rm high}$ and $f_{\rm low}$) correspond respectively to the synchrotron frequency at the center of the bunch and at 0.5 eVs. They are calculated by taking into account the voltage programs from both the RF systems and the phase shift between the two. As the synchrotron frequencies in the bunch vary during the energy ramp, the noise spectrum has to follow to maximise the excitation, and is scaled accordingly. The values indicated in this paper for $f_{\rm high}$ and the noise bandwidth are the initial values, at 14.8 s in the cycle [3]. The noise spectrum is calculated for zero intensity ($f_{\rm high} = 294$ Hz and $f_{\rm low} = 194$ Hz) and very good results were obtained for the blow-up of a low intensity single bunch [4].

In reality though, the SPS broadband inductive impedance shifts down (above transition) the synchrotron frequencies as a function of beam intensity. As this shift is uniform across the batch for identical bunches, it can be taken into account in the choice of the noise frequency program. Additionally the beam intensity, through beam loading, produces a displacement of the bunches from the design stable phase which is not uniform across the batch and affects the synchrotron frequency, making it different from bunch to bunch in a double RF system [5]. The displacement is shown in Figure 1 (A), along with bunch length, Figure 1 (B), before the noise excitation is applied.

Due to the many different effects and uncertainties that have to be taken into account, an analytical estimation of optimum noise parameters (choice of a common noise bandwidth to be applied to the whole batch) is problematic. Hence, experimental study of the performance of settings is necessary, and is described in this paper.

EXPERIMENTAL SETUP

The results presented in this paper are derived from data acquired during the 2007 SPS Machine Run. The acquired data consists of longitudinal Bunch Profiles (BP) obtained at different times in the cycle (altogether: Mountain Range data, MR). For each BP, the bunch peaks are identified and a Gaussian fit is used to derive the bunch length, defined as $\tau = 4\sigma_{\rm fit}$, and the bunch position (the mean of the fit).

Due to software limitations, the BP are acquired at the four injections, before the noise excitation is applied and after it is finished (14.7 s and 18.2 s). Moreover, eight BP are acquired at the FT (18.7 s) at one eighth of a synchrotron period to evaluate the amplitude of dipole and quadrupole oscillation [6]. In the plots that follow, an average bunch length of the 8 BPs at the FT ($\tau_{\rm avg}$) or a maximum deviation in bunch length ($\tau_{\rm max} - \tau_{\rm min}$) will be used to indicate uniformity of blow-up across the batch and the amplitude of oscillation of unstable bunches.

Different settings for the noise excitation are applied. The frequency $f_{\rm high}$ is scanned down from the 0 intensity value by 40 Hz in 10 Hz steps through the cycle. The noise is applied through an Artificial Waveform Generator to the SPS phase loop at three values of amplitude $\rm A_n$ (100 mV, 200 mV and 400 mV).

The total external voltage seen by the particle is:

$$V_{tot} = V_{200}\ \sin\phi + V_{800}\ \sin(4\phi + 4\Phi_2), \qquad (1)$$

where Φ_2 is programmed to be $(45^o - \phi_s)$ in bunch shortening mode (ϕ_s is the stable phase). We use a phase offset, $\phi_{\rm offset}$, to compensate a hardware-related offset between the 200 MHz and 800 MHz RF systems and operate in bunch shortening mode. The phase $\phi_{\rm offset}$ is scanned between $213°$ and $233°$.

RESULTS

In the following, results are presented for a one batch beam with $\sim 1.15 \times 10^{11}$ p/bunch, unless otherwise noted. Studies on 2–4 batch beam were also carried out but are not presented here.

In Figure 2, $\tau_{\rm avg}$ for the first batch is plotted with a solid line, while dotted lines indicate $\tau_{\rm min}$ and $\tau_{\rm max}$. In (A) the noise excitation is not applied, and the beam is unstable at flat top, especially in the middle of the batch. A closer inspection reveals a mixture of dipole and quadrupole oscillations. In (B), the noise excitation is applied ($f_{\rm high} = 254$ Hz and $\rm A_n = 400$ mV). The bunches are longer than in (A), with quite uniform length across the batch, and very stable, proving the emittance blow-up successful in obtaining beam stabilization.

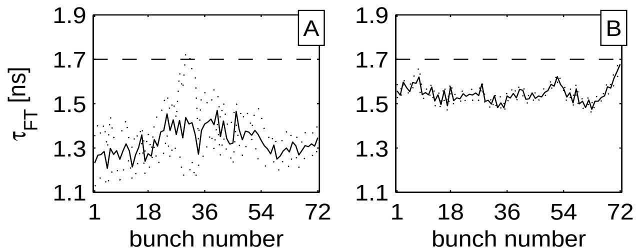

Figure 2: $\tau_{\rm avg}$ (solid line), $\tau_{\rm max}$ and $\tau_{\rm min}$ (dotted lines) at the FT, with noise off (A) and noise on (B, $f_{\rm high} = 254$ Hz and $\rm A_n = 400$ mV). All with $\phi_{\rm offset} = 223°$.

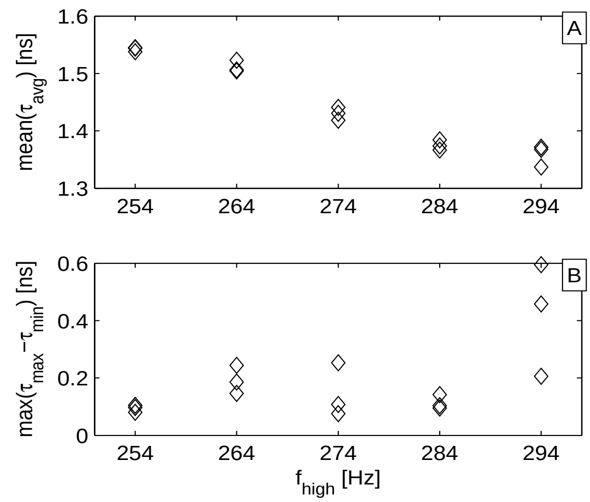

Figure 3: Average bunch length (A) and maximum oscillation across the batch at the FT (B), each point a different MR, plotted versus noise high cutoff frequency ($\rm f_{high}$). All with $\rm A_n = 400$ mV and $\phi_{\rm offset} = 223°$.

In Figure 3, a comparison between data acquired with different $f_{\rm high}$ settings is carried out. Each symbol in (A) represents the average bunch length across the batch in a different MR, i.e. the average of the solid line in Figure 2. Each symbol in (B) represents the maximum deviation between the two dotted lines in Figure 2. For lower $f_{\rm high}$, the average bunch length is higher and the amplitude of oscillation is lower. In other words, the noise excitation is more effective in obtaining bunch blow-up and stabilization for $f_{\rm high} = 254$ Hz. This can be explained by assuming that lower noise spectra (e.g. 154–254 Hz, opposed to 194–294 Hz calculated for zero intensity) better matched the synchrotron frequency spread in the bunches for this intensity. To explain this incoherent frequency shift one would need a constant inductive impedance of Im Z/n = 7.5 Ohm. Using the effective SPS machine impedance gives a relative frequency shift of 5% for a single bunch. However multi-bunch effects give a larger contribution.

Figure 4 highlights the effect of $\rm A_n$. The average bunch length across the batch, as in Figure 3 (A), is plotted for different MRs. A higher $\rm A_n$ results in increased blow-up. Dif-

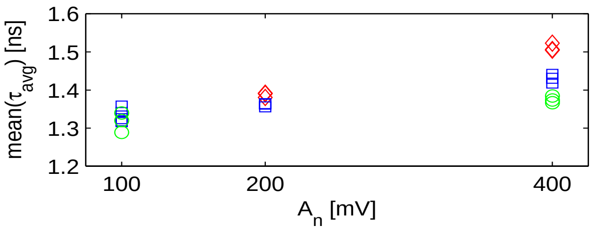

Figure 4: Average bunch length across the batch, each point a different MR: for $f_{\mathrm{high}} = 264$ Hz (◇), 274 Hz (□), 284 Hz (○). All with $\phi_{\mathrm{offset}} = 223°$.

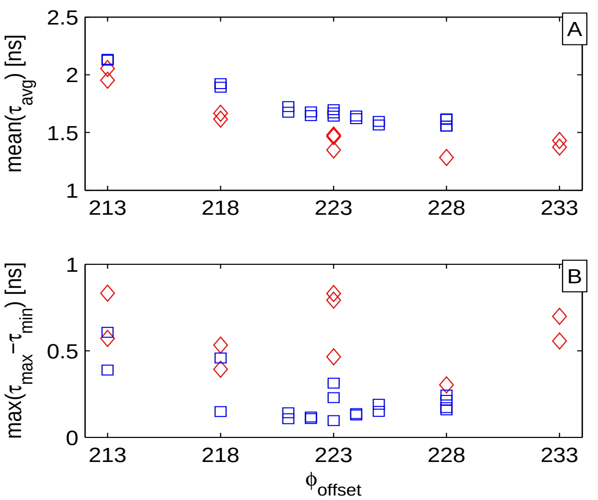

Figure 5: Average τ_{avg} (A) and maximum oscillation across the batch at the FT (B), each point a different MR. Scan of ϕ_{offset} with noise excitation off (◇) or on (□), with $f_{\mathrm{high}} = 254$ Hz and $A_n = 400$ mV.

ferent symbols are used for different f_{high}, stressing once more that lower frequency spectra resulted in more efficient blow-up.

Figure 5 emphasizes the dependence of beam average blow-up (A) and stability (B) on the setting of ϕ_{offset}, with the noise excitation applied or not. The optimum setting for ϕ_{offset} is in the range $225°$–$228°$, where the beam is more stable and less blown up even in the absence of the noise excitation. In (A) the measurements acquired while applying the noise are characterized by larger bunch length than without noise; at the same time, in (B), they are characterized by improved stability.

Figure 2 can be compared to Figure 6: the latter shows data from a four batch beam with $\sim 0.9 \times 10^{11}$ p/bunch (reduced intensity). Only the results for the first batch are shown here, but it is observed that batches 2–4 are in general more difficult to stabilize than the first one. Average, minimum and maximum bunch length (τ_{avg}, τ_{max}, τ_{min}) are reported for two different cases: (A) for noise excitation off; (B) for noise applied, with $f_{\mathrm{high}} = 274$ Hz and $A_n = 400$ mV. For reduced intensity, the best results are obtained with no noise excitation applied, Figure 6 (A), as shorter and stable bunches are observed: for this intensity

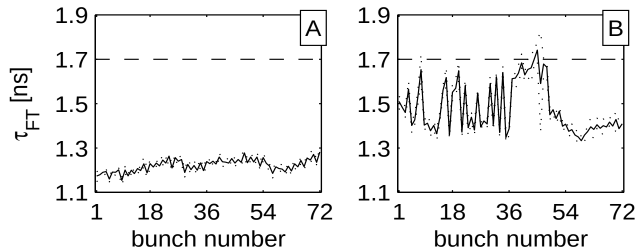

Figure 6: τ_{avg} (solid line), τ_{max} and τ_{min} (dotted lines) at the FT for noise off (A) and noise on (B). Intensity at injection $\sim 0.9 \times 10^{11}$ p/bunch, $\phi_{\mathrm{offset}} = 223°$.

emittance blow-up is not necessary for beam stability at the FT. For unstable beam, e.g. Figure 6 (B), non-rigid dipole and quadrupole oscillations are observed at the FT. More studies will follow in the 2008 Machine Run when scans are planned to assess the dependence of the optimum noise settings on beam intensity.

CONCLUSIONS AND FUTURE PLANS

The use of RF phase noise effectively increases the bunch lengths and improves the stability of the nominal LHC beam in the SPS. In this paper, the dependence of emittance blow-up and beam stability on settings such as noise bandwidth and amplitude are measured, and optima are highlighted. More data need to be gathered to assess the dependence of the optimum settings on the beam intensity, and in general more statistics are needed to be able to guarantee the reproducibility of the results and make the procedure operational for LHC operation.

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