CURES FOR BEAM INSTABILITIES IN THE CERN SPS AND THEIR LIMITATIONS

E. Shaposhnikova, CERN, Geneva, Switzerland

Abstract

The LHC beam in the SPS is unstable with a threshold almost an order of magnitude below the nominal intensity. The cures used to stabilise this beam against coupled bunch instabilities apart from RF feedback, feed-forward and longitudinal damping, include a fourth harmonic RF system and controlled emittance blow-up. The limitations of the two last methods were studied experimentally and are analysed here from the point of view of beam quality requirements at extraction and future intensity increases up to ultimate value.

LHC BEAM INSTABILITIES

The nominal LHC beam which consists of 4 batches, each of 72 bunches spaced by 25 ns with 1.2×10^{11}/bunch, was obtained at the SPS top energy 450 GeV [1]. This beam sufferers from both single and multi-bunch instabilities, which are cured by different methods. The longitudinal microwave instability is not observed up to the highest injected intensities following the shielding of different machine elements (2001). The vertical single bunch instability due to e-cloud is cured by a scrubbing run and high chromaticity. Transverse mode coupling instability, observed recently at injection (26 GeV/c) with small longitudinal emittance ε, is expected to have a threshold below the ultimate LHC intensity of 1.7×10^{11}/bunch for nominal $\varepsilon = 0.35$ eVs. Horizontal multi-bunch instabilities are damped by the transverse feedback system.

The longitudinal coupled bunch instability observed at the end of the acceleration ramp has the lowest threshold: one batch with 2×10^{10}/bunch is unstable with the RF feedback, feed-forward and longitudinal damper (low modes) in operation. Possible sources of this instability are the fundamental and HOMs (629 MHz and 912 MHz) of the main 200 MHz RF system. This beam is finally stabilised by increased synchrotron frequency spread using a fourth harmonic RF system and controlled emittance blow-up.

CURES AND THEIR LIMITATIONS

High harmonic RF system

The 800 MHz RF system is used from injection through the cycle. The total external voltage seen by the particle is

$$V_{ext}(\phi) = V_1 \sin\phi + V_2 \sin(h_2\phi/h_1 + \Phi_2), \qquad (1)$$

where above transition (the case considered below) and for a non-accelerating bucket, $\Phi_2 = \pi$ in bunch-shortening (BS) mode and $\Phi_2 = 0$ in bunch-lengthening (BL). The main limitations of BL mode (which is attractive due to reduced peak line density) for beam stabilisation in the SPS have been studied [2], [3] and are believed to be (1) very tight requirements on the accuracy of Φ_2, difficult to fulfill during the ramp in the presence of strong beam loading; (2) the region with zero derivative of the synchrotron frequency reducing the instability threshold; (3) absence of self-stabilisation for long bunches. The second limitation also should appear in the BS mode for sufficiently long bunches; studies continue [3].

Controlled emittance blow-up

The controlled emittance blow-up is needed in addition to the high harmonic RF system to stabilise the nominal LHC beam on the flat top (the instability threshold $\propto \varepsilon^2$). This blow-up should be minimal due to the following injection into the 400 MHz bucket in the LHC and without losses, tails and bunch to bunch emittance variation.

Mismatched voltage at injection leads to emittance blow-up from 0.35 to 0.42 eVs. The technique using band-limited noise [4] introduced through the phase loop of the 200 MHz RF system at 260 GeV gives 0.6 eVs. The nominal settings for emittance blow-up [5] (excitation at 15.5 s during 500 ms with $f_c = 190 \pm 15$ Hz) are shown in Fig. 1.

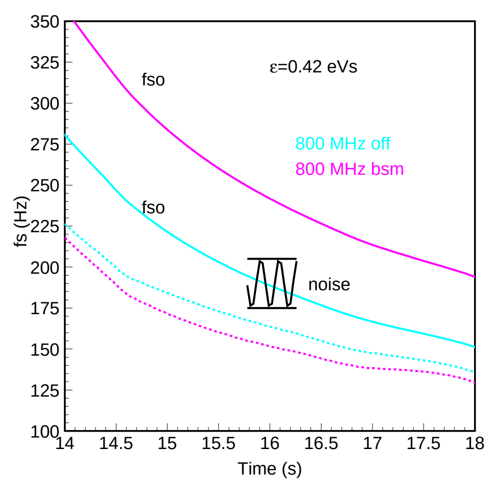

Figure 1: Noise excitation and synchrotron frequency spread (low intensity case) at the end of the cycle for bunch of 0.42 eVs with 800 MHz RF system off (two internal curves) and on ($V_2 = 700$ kV) in BS mode.

For nominal intensity beam the settings found at low intensity should be reduced by $\sim$ 10 Hz due to an incoherent frequency shift produced by the SPS inductive impedance $\mathrm{Im}Z/n \simeq 7$ Ohm. The problem, which has been discovered at the end of 2004 and is analysed below, is the non-uniform emittance blow-up leading sometimes to the instability on the flat top with nominal settings or to particle losses with increased excitation amplitude or bandwidth. Bunch to bunch variation of the incoherent synchrotron frequency due to the residual beam loading can explain these observations. The incoherent frequency shift due to inductive impedance being a function of bunch distribution also varies from bunch to bunch but, even for bunch length variation along the batch of 10%, the effect is much smaller.

The bunch position variation along the batch Δt which corresponds in the stable situation to the synchronous phase displacement $\Delta\phi_s = h_1\omega_0\Delta t$, found from bunch profiles at the start of the controlled emittance blow-up [6], is shown in Fig. 2 for two different cycles. Measurements were done at 15.5 s (260 GeV/c) for 72 bunches of the first batch with nominal intensity. Bunch positions are mainly defined by the residual beam loading in the 200 MHz Travelling Wave RF system in the SPS with feedback and feed-forward system in operation. Patterns only slightly vary through the cycle and from shot to shot.

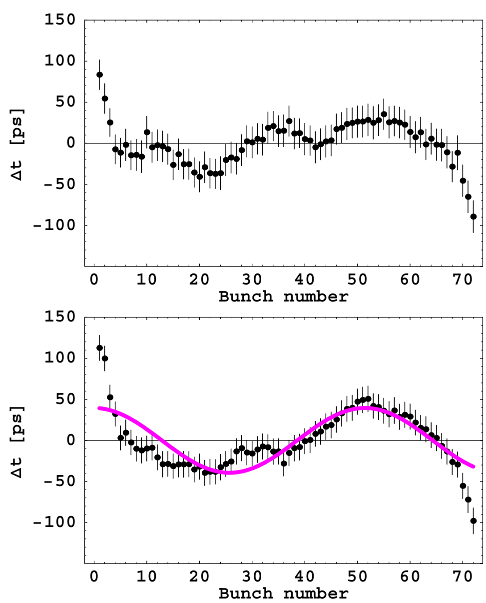

Figure 2: Bunch positions along the batch before emittance blow-up at 260 GeV/s for two different cycles. Solid line - mode $n = 18$ used for calculation of V_{ind}.

A zero-amplitude synchrotron frequency for the k-th bunch $\omega_{sk}^2 = \omega_{sk}^2(0)$, $k = 1, ...72$, is

$$\omega_{sk}^2 = \omega_{s0}^2 \cdot V'_{tot}(\phi_{sk})/(V_1 \cos\phi_{s0}), \tag{2}$$

where ω_{s0} and ϕ_{s0} are the linear synchrotron frequency and synchronous phase in the single RF system with a voltage V_1. In a double RF system, with intensity effects included, the frequency is defined by the slope of the total voltage

$$V_{tot}(\phi) = V_{ext}(\phi) + V_{ind}(\phi), \tag{3}$$

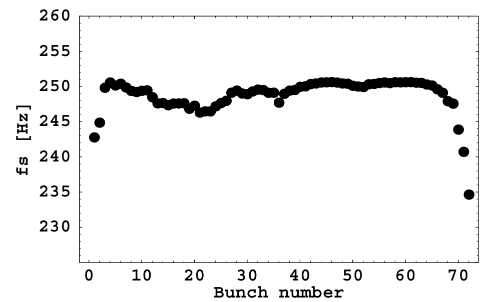

Figure 3: Synchrotron frequency variation along the batch found from the measured bunch position variation shown in Fig. 2 (bottom) using Eq. (4).

at bunch positions $\phi_{sk} = \phi_s + \Delta\phi_{sk}$. The change in synchronous phase $\Delta\phi_{sk}$ from its zero-intensity value ϕ_s, defined by voltage V_{ext}, see Eq. (1), is due to to the induced voltage V_{ind}.

Let us first estimate the change in frequency due to bunch displacement in a double RF system. For the phase between the two RF systems $\Phi_2 = -\phi_{s0}h_2/h_1 + \pi$, the synchronous phase in a double RF system $\phi_s = \phi_{s0}$. This value was used in the SPS to programme the phase between the 2 RF systems during the ramp. Then the synchrotron frequency become

$$\frac{\omega_{sk}^{2ext}}{\omega_{s0}^2} = 1 + \Delta\phi_{sk}\tan\phi_{s0} + \frac{h_2V_2}{h_1V_1}\frac{\cos\left(\frac{h_2}{h_1}\Delta\phi_{sk} + \delta\Phi_2\right)}{\cos\phi_{s0}}. \tag{4}$$

The main contribution is from the high harmonic RF system, in the single RF system the frequency change would be much smaller. The values $f_s = \omega_{sk}^{ext}/(2\pi)$ found from Eq. (4) with phase offset $\delta\Phi_2 = 0$ for bunch positions from Fig. 2 (bottom) are shown in Fig. 3.

This synchrotron frequency variation inside the batch already can explain the observed problems with controlled emittance blow-up. However it could be additionally affected by the fact that the phase Φ_2 most probably had nonzero offset $\delta\Phi_2$ from the programmed value due to the lack of an absolute phase calibration, aggravated by the beam loading in the 800 MHz RF system, making phase control even more difficult. This offset leads (for $\delta\Phi_2 \ll 1$) to change in ϕ_s with opposite sign

$$\delta\phi_s \simeq \frac{\delta\Phi_2 V_2 h_1}{V_1 h_1 \cos\phi_{s0} - V_2 h_2}, \tag{5}$$

reducing slightly the total effect on ω_s variation. The examples for $\delta\Phi_2 = \pm 0.3$ are shown in Fig. 4.

The induced voltage V_{ind} not only displaces bunches from their zero intensity positions, but also affects the synchrotron frequency by a change in the voltage slope. Let us now try and estimate this effect. The measured $\Delta\phi_{sk} \ll 1$ are connected with values of induced voltage by

$$\Delta\phi_{sk} \simeq -\frac{V_{ind}(\phi_s)}{V'_{ext}(\phi_s) + V'_{ind}(\phi_s)} \tag{6}$$

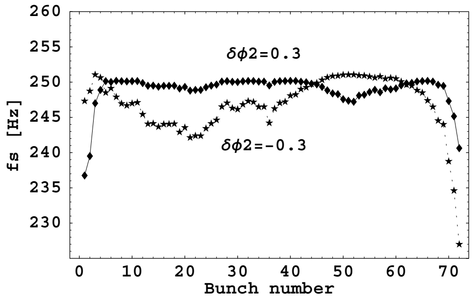

Figure 4: Effect of additional constant phase offsets $\delta\Phi_2 = \pm 0.3$ on synchrotron frequency variation along the batch.

Assuming that this voltage is determined by the beam loading in the main RF system, we can write

$$V_{ind}(\phi) = \sum_n \tilde{V}_n \cos(\phi + n\phi/h_1 + \phi_{n0}). \quad (7)$$

The comparison of (7) with the Fourier transform of measured synchronous phase shifts at positions $\phi_s + 2\pi k n_{bb}$, $k = 1, ...72$,

$$\Delta\phi_{sk} = \sum_n \Delta\tilde{\phi}_n \cos(2\pi k n_{bb} n/h_1 + \psi_{n0}) \quad (8)$$

for $\tilde{V}_n \ll V_{1,2}$ gives for induced voltage an estimation of amplitudes $\tilde{V}_n \simeq -\Delta\tilde{\phi}_n V'_{ext}(\phi_{s0})$ and phases $\phi_{n0} = \psi_{n0} - \phi_{s0}$. Note that due to the bunch spacing $n_{bb} = 5$, the revolution frequency harmonics higher than h_1/n_{bb} can not be resolved by these measurements. Then the change in synchrotron frequency due to the induced voltage is defined by the expression

$$\frac{\omega_{sk}^{2ind}}{\omega_{s0}^2} = \frac{V'_{ext}(\phi_{s0})}{V_1 \cos\phi_{s0}}[1 + \sum_n \alpha_n \sin(\frac{2\pi k n}{h_1/n_{bb}} + \psi_{n0}), \quad (9)$$

where $\alpha_n = (1 + n/h_1)\Delta\tilde{\phi}_n$. The example for contribution from the single harmonic $n = 18$ is shown in Fig. 5 (top).

In reality the frequency variation is the result of all effects analysed above. The example corresponding to measured $\Delta\phi_s$, assumed offset $\delta\Phi_2 = -0.3$ and induced voltage with a single harmonic $n = 18$ is shown in Fig. 5 (bottom).

Unfortunately this bunch-to-bunch synchrotron frequency variation is not sufficient itself for beam stability on the flat top, but being comparable to the noise bandwidth it can lead to the nonuniform emittance blow-up with tails or even losses, as observed in the SPS experiments. Since the induced voltage depends on injected batch structure, the pattern can vary from shot to shot (see Figs. 2). It can be estimated but it would be difficult to take into account in beam control for blow-up. As can be seen from expressions (4) and (9) the frequency variation along the batch during emittance blow-up can be reduced by operating at the minimum 800 MHz and maximum 200 MHz voltages, by careful programming of the phase between the two RF systems Φ_2 during the ramp and in the longer term by a full feedback around 800 MHz which should provide better beam-loading compensation.

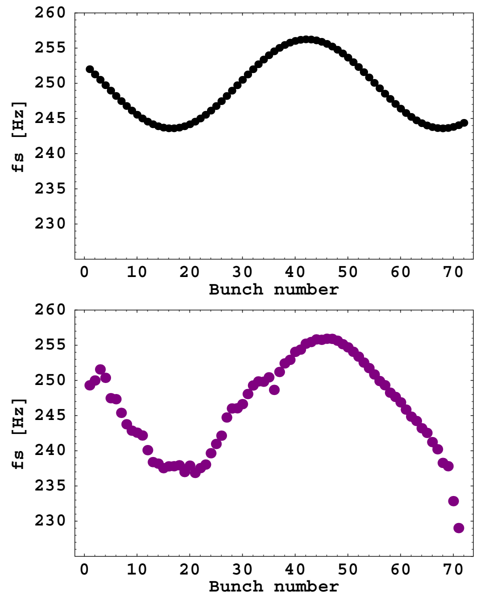

Figure 5: Top: change in the synchrotron frequency due to the induced voltage with a single harmonic $n = 18$. Bottom: the total frequency change corresponding to measured $\Delta\phi_s$, assumed $\delta\Phi_2 = -0.3$ and a single harmonic $n = 18$ from induced voltage.

Summary. The limitations of operating the high harmonic RF system, essential for beam stabilisation in the SPS, have been studied both theoretically and experimentally [2], [3]. The nonuniform controlled emittance blow-up can be explained by the effect of the residual beam loading which creates in a double RF system a significant variation of the incoherent synchrotron frequency from bunch to bunch. Measurements of relative bunch positions at the moment of blow-up allow both the effect from external RF and induced voltage to frequency change to be estimated. Some of the ideas to reduce this effect can be tested with the LHC beam already this (2006) year.

All measurements were done together with T. Bohl, T. Linnecar and J. Tuckmantel. The author is also grateful to T. Bohl for providing the data for bunch positions and to T. Linnecar for useful comments.

REFERENCES

[1] P. Baudrenghien at al., Proc. PAC 2003.

[2] T. Bohl et al., Proc. EPAC 1998, p. 978.

[3] E. Shaposhnikova, T. Bohl, T. Linnecar, Proc. PAC 2005.

[4] T. Toyama, NIM-A 447 (2000), p. 317.

[5] J. Tuckmantel et al., Proc. EPAC 2004.

[6] T. Bohl, private communication.