EXPERIMENTAL STUDIES OF CONTROLLED LONGITUDINAL EMITTANCE BLOW-UP IN THE SPS AS LHC INJECTOR AND LHC TEST-BED

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Abstract

The longitudinal emittance of the LHC beam must be increased in a controlled way in both the SPS and the LHC itself. In the first case a small increase is sufficient to help prevent coupled-bunch instabilities but in the second a factor three is required to also reduce intra-beam scattering effects. This has been achieved in the SPS by exciting the beam at the synchrotron frequency through the phase loop of the main RF system using bandwidth-limited noise, a method that is particularly suitable for the LHC which will have only one RF system. We describe the tests that have been done in the SPS both for low- and high-intensity beams, the hardware used and the influence of parameters such as time of excitation, bandwidth, frequency and amplitude on the resulting blow-up. After taking into account intensity effects it was possible to achieve a controlled emittance increase by a factor of about 2.5 without particle loss or the creation of visible tails in the distribution.

MOTIVATION

There are two distinct reasons to study controlled longitudinal emittance blow-up in the SPS. First, the LHC beam becomes unstable at high energy in the SPS and suffers unacceptable emittance increase if no counter-measures are taken [1]. One necessary measure is to produce a small controlled blow-up on the ramp before instability occurs. The existing higher harmonic 800 MHz RF system, whose primary purpose is Landau damping, was used for resonant excitation [2]. An alternative technique is application of band-limited RF noise [3], [4].

Secondly, the SPS can be used as test-bed to study LHC requirements. To obtain the specified beam lifetime in coast in the LHC the longitudinal emittance has to be increased from 0.7 eVs (450 GeV) to 2.5 eVs (7 TeV) to reduce intra-beam scattering [5]. In addition, to avoid a decrease in beam stability the emittance should increase with the square root of energy E. There is no higher harmonic RF system in the LHC so techniques using RF noise are particularly interesting.

In both applications, whose study [6] we report here, the blow-up should not produce beam-loss or even tails in the bunch distribution.

NOISE CREATION

To avoid particle losses, the beam should only be excited on frequencies corresponding to the region within the final bunch spectrum required. Therefore a band-limited noise spectrum tracking the linear synchrotron frequency, f_{s0}, is required.

The required spectrum was produced by up-converting a base-band noise spectrum, (0 - f_n), with a carrier of frequency $f_c > f_n$, (in general $f_c \sim f_{s0}$, see Fig. 1), using an analogue multiplier, to give a symmetric spectrum between f_c-f_n and f_c+f_n, and zero at all other frequencies. A programmable synthesizer, driven by a function generator synchronous with the SPS cycle, produces f_c.

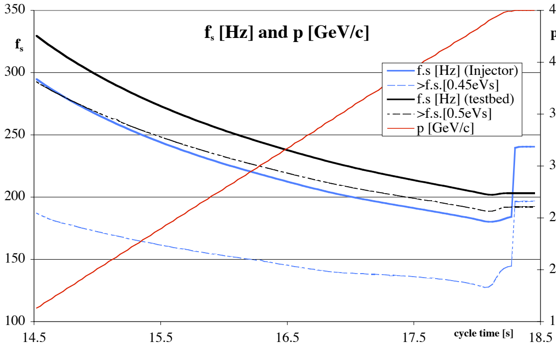

Figure 1: Momentum (red) and linear synchrotron frequency f_{s0} for 1) the SPS as LHC injector, constant bucket, (blue) and 2) the SPS as LHC test-bed, 7 MV constant at 200 MHz (black). In both cases the synchrotron frequency for particles at the bunch edge is also given (dashed).

Due to the shape of the base-band spectrum, the spectrum obtained at f_c has a symmetric trapezoidal shape. The nominal base-band generator setting '5 Hz' produced a ±10 Hz flat-topped spectrum with a linear decrease to zero over ±15 Hz on each side. Other base-band settings behaved similarly.

The beam was excited by injecting noise, at varying amplitudes and gated by the SPS timing system, into the beam phase loop. We used only phase noise excitation.

BEAM TESTS

Two beam conditions were tested: *low intensity* with one or two bunches of 4-5·10^9 p/bunch, below beam instability thresholds, and *nominal intensity* with batches of 24 bunches of nominal intensity (~ 1.1·10^{11} p/bunch), at 75 ns bunch spacing.

Longitudinal bunch profiles from a fast wall current pick-up were observed, the behaviour of one bunch being continuously monitored on a sampling scope with 30 ps rise time. In addition, the profiles of a small set of consecutive bunches could be acquired with a 1 GHz bandwidth oscilloscope, data being taken along the ramp at ~ 60 ms (2500 turns) intervals. The raw bunch profile data were corrected for the pick-up transfer function and a Gaussian fit was used to obtain the 4σ bunch length τ_L.

Beam losses were monitored via the beam current transformer.

The SPS as LHC injector

An 800 MHz higher harmonic RF system produces increased synchrotron frequency spread in order to stabilise the high-intensity LHC beam in the SPS. Even with this system in operation coupled-bunch instabilities develop on the 450 GeV flat-top at nominal intensities and a small preventive blow-up is necessary. This has been achieved using resonant excitation, also with the 800 MHz system, but as this 4th harmonic gives maximum effect in the bunch tails [1], the process is always accompanied by small losses.

Better results were observed with band-limited noise. Optimum performance was obtained with constant f_c = 190 Hz, and either the '5 Hz' or '10 Hz' setting, the noise being applied for 0.5 s starting at 15.8 s. Figure 1 shows the variation of f_{s0} and the frequency at the bunch edge with cycle time for constant emittance. The noise always sits inside the bunch spectrum during the 0.5 s, effectively sweeping across the central region. This is true even with the ~ 10 Hz downward shift of f_{s0} which can be due to interaction with the machine impedance (see next section). The noise reduces the peak intensity and gives a small increase in bunch length, the two together preventing instability without particle loss.

LHC related studies

A factor 4 emittance increase is required between injection at 450 GeV and coast at 7 TeV in the LHC.

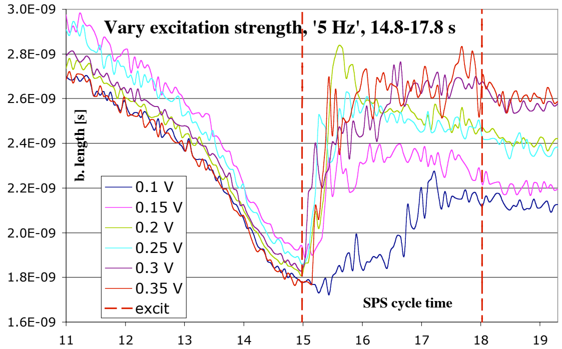

Figure 2: *Absolute* bunch length (versus time) for various excitation amplitudes and '5 Hz' noise setting. The vertical (dashed) bars limit the 3 s period during which the excitation was applied.

The standard RF voltage program was modified by increasing the voltage adiabatically, from 4 MV to 7 MV before the excitation time, and then keeping it constant to provide the largest available bucket area. The corresponding variation in f_{s0} is also shown in Fig. 1. For these test-bed measurements the 800 MHz RF system is off (no higher harmonic in the LHC).

For the first series of measurements we used *low intensity* bunches to avoid intensity related effects.

Different noise spectra amplitudes were applied. The maximum amplitude, 0.35, just avoids the appearance of small beam loss. Figure 2 shows the bunch length along the ramp for different amplitudes, Figure 3 for different excitation times. The blow-up occurs over 0.5 s to 2 s according to the amplitude and then stops, the final bunch length increasing with excitation level. This can be explained by an effective increase in noise bandwidth as the amplitude of the trapezoidal spectrum increases.

Table 1: Examples of excitation conditions and resulting relative blow-up, excitation duration 3s. Excitation amplitudes are expressed in arbitrary units; relations to absolute values can be found in [6].

ampl. (a.u.)	f_c-f_{s0}	type	ρ
0.1	5 Hz	10 Hz	1.34
0.1	5 Hz	5 Hz	1.41
0.15	5 Hz	5 Hz	1.35
0.15	0	5 Hz	1.34
0.2	0	5 Hz	1.56
0.25	0	5 Hz	1.47
0.3	0	5 Hz	1.65
0.35	0	5 Hz	1.73
0.35	0	2.5 Hz	1.50

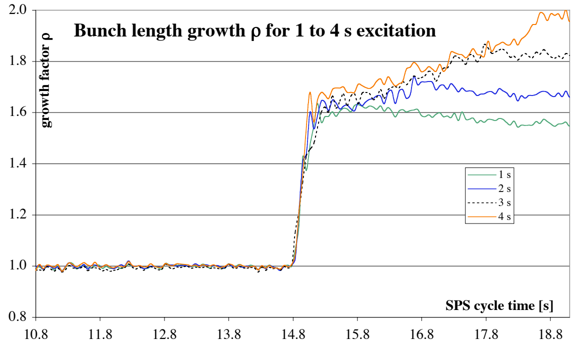

Figure 3: *Relative* bunch length ρ for 1 s, 2 s, 3 s and 4 s excitation, data *averaged* over 5-10 individual sets.

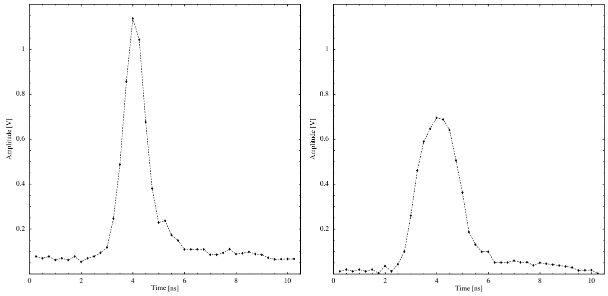

Figure 4: Typical low intensity bunches before ejection without (left) and with (right) phase noise for 3 s.

The final bunch length depends on the injected bunch length, which varies ~ ±5%, (see Fig. 2). We calculated the ratio ρ between the *measured* bunch length and that *expected* without noise excitation, the latter being scaled from reference measurements using the measured injected bunch-length. Furthermore we averaged over several (5-10) data sets measured under the same conditions. Table 1 gives examples of the ρ obtained. The largest blow-up achieved without beam loss in this series gives ρ=1.73 and τ_L = 2.6 ns at ejection. An even larger blow-up, ρ=2, was obtained by delaying the start of excitation by 2 s. An explanation may be that the bunch was shorter at the onset of excitation than for the previous start-time.

Figure 4 shows two typical bunches taken with the 1 GHz scope on the flat top, where the profile should be symmetric, with and without excitation. There are no visible tails to the left. The apparent tail to the right is a signal reflection.

At *nominal intensity*, in the absence of the 800 MHz, the beam becomes unstable without blow-up when the RF voltage is raised. This can be seen in Fig. 5 from the lower curve where the measurement indicates an oscillating bunch from about 15.8 s. When the noise with low-intensity settings was applied no significant blow-up was seen. This could be explained by a reduction in f_{s0} due to the interaction of the bunch with the inductive machine impedance.

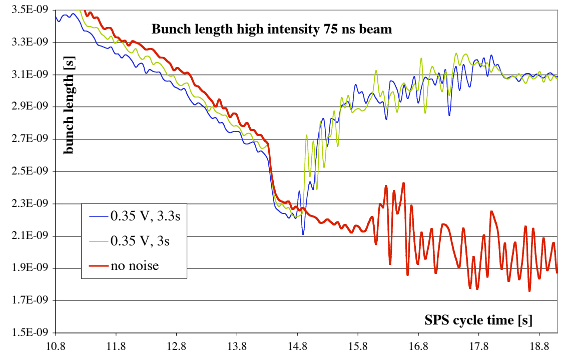

Figure 5: Blow-up tests with nominal intensity (75 ns) beam, bunch length τ. The lower thick trace presents the 'reference' measurement without excitation, showing an unstable beam. The applied excitation frequency is the low-intensity one globally lowered by 10 Hz.

Tests with fixed noise bands at different f_c suggested a coarse average synchrotron frequency shift down by about 10 Hz, which agrees with measurements of quadrupole frequency shift as given in [7]. Applying this constant offset to the low-intensity settings, an increase in bunch length to 3.1 ns was achieved (Fig. 5). For a stable beam and initial bunch-length 3.5 ns, τ_L=1.9 ns is expected at ejection. Thus a blow-up of about ρ=1.6 is obtained, slightly less than for the low-intensity case. Note that the offset should decrease as $1/\tau_L^3$, otherwise the noise spectrum moves with respect to the bunch.

CONCLUSION

The nominal LHC beam in the SPS can be stabilized at 450 GeV by the small emittance increase and peak line-density reduction produced by RF band-limited phase noise at constant frequency, without incurring beam-loss. This provides an alternative to resonant excitation using the 800 MHz higher harmonic system.

Studies in the SPS as LHC test-bed showed that the bunch length of *low-intensity* bunches could be increased without loss or creation of tails by a factor approaching 2, (emittance blow-up about four times), using band-limited noise whose central frequency follows f_{s0}. Most of the blow-up occurs during the first second of excitation, independent of the excitation start-time. Bunches at *nominal intensity* could be increased in length by a factor of about 1.5 (emittance blow-up by two) when intensity dependent corrections were introduced.

Open issues for the LHC are:

- The excitation spectrum, especially for high intensity, should be more carefully controlled, in particular by taking into account the blow-up previously achieved in the cycle.
- Bunches do not necessarily have the same intensity distribution (we expect up to ±10%, causing differences in f_{s0}) and the blow-up may be different from bunch to bunch. Means to control and counteract this, if necessary, have to be found and tested.
- In LHC the blow-up should be applied smoothly over the ~20 minutes of ramp, ($\propto\sqrt{E}$), not in one second. A possible approach is to slowly increase the voltage as blow-up proceeds, keeping the spread in the bunch constant.

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REFERENCES

[1] E. Shaposhnikova, Ph. Baudrenghien, T. Bohl, T. Linnecar, J. Tuckmantel, Proc. PAC 2003, Portland.

[2] T. Bohl, T. Linnecar, E. Shaposhnikova, J. Tuckmantel, CERN SL-MD-Note 221, (1996).

[3] T. Toyama, NIM-A 447 (2000) 317-327 and T. Toyama et al, KEK-99-154 (1999).

[4] S. Ivanov, O. Lebedev, IHEP, report C1-36 to RUPAC2002, Obnisk, Oct. 2002.

[5] CERN LHC Design Report, Vol. I, CERN-2004-003 (2004) and http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/

[6] T. Bohl, T. Linnecar, E. Shaposhnikova, J. Tuckmantel, CERN, AB-Note-2003-084-MD.

[7] E. Shaposhnikova, Proc. LHC Project Workshop, Chamonix XIII, Page 44, Jan. 2004, CERN-AB-2004-014 –ADM.