PERFORMANCE OF THE LHC TRANSVERSE DAMPER WITH BUNCH TRAINS

W. Höfle*, F. Dubouchet, G. Kotzian, D. Valuch, CERN, Geneva, Switzerland

Abstract

In 2012 the LHC was operated for Physics with bunch trains at 50 ns spacing. Tests have been performed with the nominal design bunch spacing of 25 ns. The transverse damper has been an essential element to provide beam stability for the multi-bunch beam with up to 1380 bunches used at 50 ns spacing. We report on the experience gained with 50 ns spacing and the improvements in the signal processing tested for the future 25 ns operation. The increase in bandwidth required for 25 ns spacing constituted a particular challenge. The response of the system was carefully measured and the results used to digitally pre-distort the drive signal to compensate for a drop in gain of the power system for higher frequencies. The bunch-by-bunch data collected from the feedback signal path provided valuable information during the 2012 Physics run that can be further explored for beam diagnostics purposes and instability analysis in the future. Performance estimates are given for the 7 TeV run planned for 2015, at 25 ns bunch spacing.

INTRODUCTION

The LHC requires a strong transverse feedback system to keep the transverse emittance increase at injection small and to provide stability against coupled bunch instabilities. Initially commissioned in 2010 for injection oscillation damping [1] with individually injected single bunches, the system rapidly became indispensable for operation during the ramp and with colliding beams.

In the LHC the RF frequency is 400.8 MHz and the minimum bunch spacing used is 25 ns, i.e. every 10^{th} RF bucket can be occupied by a bunch. After the initial commissioning the luminosity of the LHC was rapidly ramped up, first by increasing the intensity per bunch, followed by filling the LHC with ever more bunches. During the different stages of commissioning the bunch spacing was reduced in steps down to the nominal 25 ns. Operationally the luminosity accumulation in 2012 of more than 23 fb^{-1} was carried out at 50 ns bunch spacing.

In particular the occurrence of single bunch instabilities motivated the development of signal processing for the transverse damper to achieve a true bunch-by-bunch treatment at 25 ns spacing as described in the following.

BANDWIDTH LIMITATION

The final amplifier and kicker of the LHC transverse damper form a RC low pass with a 3 dB cut-off frequency defined by the capacitance of the kicker plates and the resistor internal to the power amplifier in the anode circuit [2]. This configuration is most economic and has been optimized to provide a large kick strength at low frequency.

Transfer function measurements of the power systems performed in 2008 showed good agreement up to 10 MHz with the theoretical response of a first order low pass,

$$H_{\mathrm{k}}(j\Omega) = g_{\mathrm{k}} \frac{1}{1 + j\,\Omega/\Omega_{\mathrm{c}}}, \quad (1)$$

with the 3 dB cutoff frequency $\Omega_{\mathrm{c}}/2\pi$ at 1 MHz and a nominal voltage of $\mathrm{V}_{\max} \pm 7.5$ kV [2].

Fig. 1 shows a frequency plot of amplitude and phase for the 1-pole roll-off following the dependance of Eqn. (1).

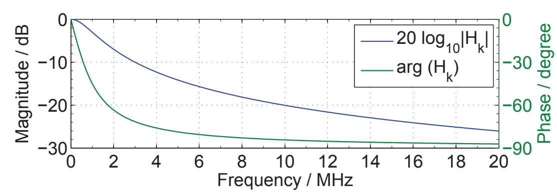

Figure 1: Amplitude and phase response in frequency domain (1-pole roll-off at 1 MHz).

Between 10 MHz and 20 MHz the actual power amplifiers have more gain than suggested by the 1-pole roll-off [2]. Nonetheless they represent the main limitation in bandwidth in the system.

The acquisition of bunch oscillations is bunch-by-bunch [3] and does not represent a limitation of the bandwidth of the system. Furthermore, the transfer functions of coaxial cables for the drive signals have been compensated by analog filters and do not represent a bandwidth limitation either.

SHAPING THE TIME DOMAIN RESPONSE

Measurement Technique

A capacitively coupled pick-up directly senses the voltage on the kicker. Electrically terminated in 50 Ω a high pass of ≃500 MHz bandwidth is formed. Measured in time domain with an oscilloscope, signals appear then differentiated. In the following all measured responses have been corrected for by integration of the raw signals. A single non-zero sample in the digital part was used as a probe function.

Response without Digital Correction

The backend damper signal and amplification chain is depicted in Fig. 2. In the digital part the phase equalizer, a 32-tap FIR, is clocked at 40 MHz. The DAC and the pulse

* Wolfgang.Hofle@cern.ch

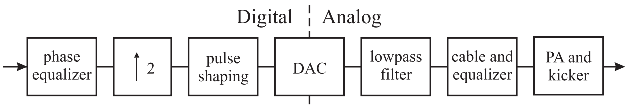

Figure 2: Feedback backend digital and analogue chain.

shaping low pass filter are clocked at 80 MHz with zeros inserted every other sample.

The signal is shaped in the analog domain by a 27 MHz low pass filter (Minicircuits SCLF-27) which introduces some unwanted ripple in time domain.

In a first test the digital phase equalizer and the digital pulse shaping filter were switched off. The expected response (Fig. 3, green curve) is a step up, followed by an exponential decay with time constant RC of the power-amplifier-kicker low pass. The measured response (blue) deviates mainly due to a peak in group delay of the analog reconstruction filter after the DAC. The red curve represents the measured response after digital corrections applied as described in the next section.

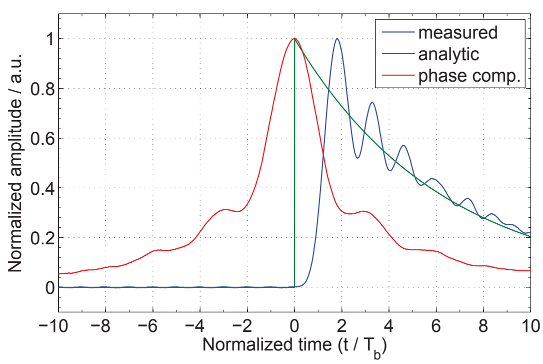

Figure 3: Ideal response (green), actual measured response, without digital correction (blue) and with digital phase correction and digital ≃15 MHz low pass (red).

Digital Phase Equalization

In "standard bandwidth" operation a digital phase equalizer compensates for the phase change with frequency of the ideal 1-pole roll-off at 1 MHz [4]. The system can then be used up to 20 MHz, the maximum coupled bunch mode oscillation frequency occurring with 25 ns bunch spacing. A digital low pass filter starts to roll-off at ≃15 MHz. Overall the measured response (Fig. 3, red curve) is symmetric due to the linear phase response resulting in frequency independent group delay as required for damping all frequencies of interest.

Bunch-by-Bunch Operation for 25 ns Spacing

Instabilities observed with 25 ns as well as with 50 ns motivated in 2012 the improvement of the signal processing to approach a truly independent treatment of individual bunches spaced 25 ns or 50 ns. In the ideal case an oscillation detected on one bunch is damped independently and is not propagated to adjacent bunches. The symmetry condition to achieve this is illustrated in Fig. 4, where $\Omega = 2\pi/T_b$ and T_b denotes the bunch spacing.

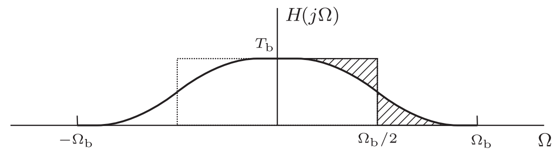

Figure 4: Schematic of ideal response in frequency domain for bunch-by-bunch operation.

A limitation of 25 MHz maximum imposed by the 200 W driver amplifier before the final tetrode amplifiers guided the development of a digital pulse shaping filter to taper the loop gain starting at 15 MHz in the symmetric fashion sketched in Fig. 4, with a gain of 0.5 at 20 MHz and reaching zero at 25 MHz. The resulting ideal time domain impulse response (red) is compared in Fig. 5

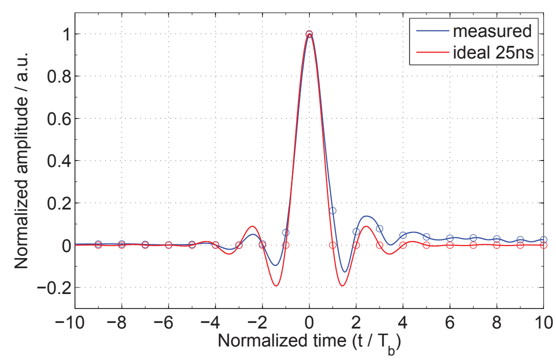

Figure 5: Impulse response for 25 ns operation in 2012.

with the measured response (blue). Some improvement is still possible as not all zero crossings of the measured response coincide exactly with bunch crossings, especially in the trailing part. The settings described here are referred to as "enhanced bandwidth" (EB) settings compared to the "standard bandwidth" settings (SB) of Fig. 3, red curve.

Standard Operation with 50 ns Bunch Spacing

For bunch spacings larger than 25 ns a digital hold circuit is used. To obtain the overall response in time domain the impulse response of the system must then be convoluted with a rectangular function representing the hold mechanism. For large bunch spacings, independent treatment of bunches and high feedback gain is easily obtained by the hold mechanism.

For 50 ns bunch spacing the SB settings were used in combination with a hold of one sample, except for the second half of the 2012 run during the squeeze for which the EB settings were used, without the hold function activated. Figure 6 compares the impulse responses obtained using these two different settings.

The curves in Fig. 6 have been scaled to show the difference of a factor two in gain introduced by the hold mech-

ISBN 978-3-95450-122-9

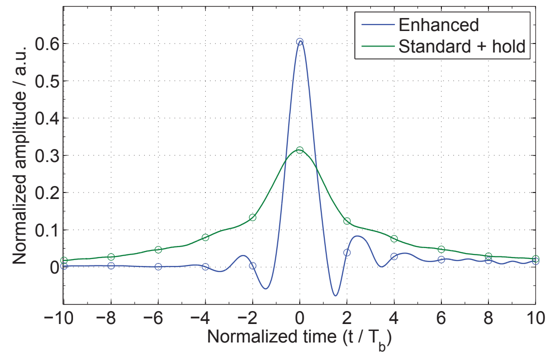

Figure 6: Impulse responses for 50 ns operation in 2012.

anism. In practice the operationally requested gain is adjusted in the analogue part of the feedback loop in combination with a shifting of the bit pattern in the digital part.

PERFORMANCE IN OPERATION

As an example of operational performance the damping of injection oscillations (vertical plane, beam 1) is illustrated in Fig. 7 for injections with batches of 50 ns (four batches of 36 bunches) and for 25 ns bunch spacing (two batches of 72 bunches).

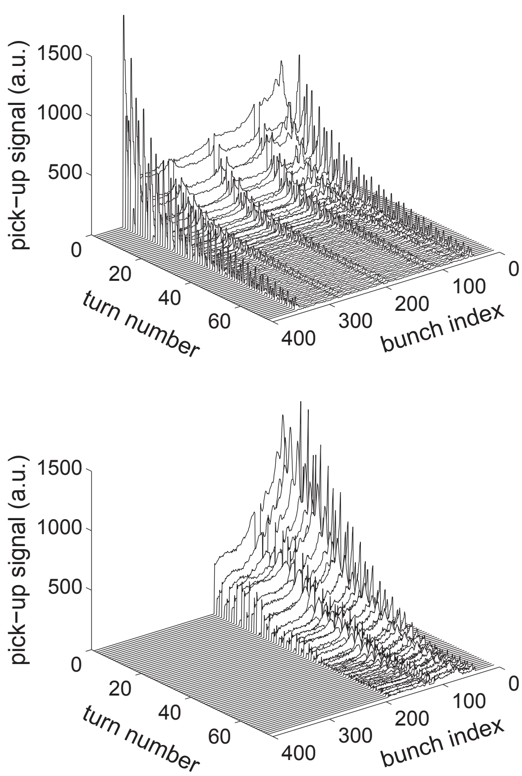

Figure 7: Injection damping (vertical plane, beam 1) with 50 ns (top) and 25 ns (bottom) bunch spacing.

The data were acquired using the transverse damper internal acquisition memory, the offset removed in the post processing and the absolute value of the pick-up signal displayed. Oscillations are well damped in both cases, with damping times of about $\simeq$10 turns with SB settings for 50 ns spacing (operational beam) and $\simeq$20 turns with EB settings for 25 ns spacing (Machine Development). The difference in damping time is attributed to the effect of the hold function.

The effect of the limited bandwidth in the 50 ns case can be clearly seen in the oscillations of the bunches at the edge of the injected batch: the oscillation persists for many more turns. In the 25 ns case with EB settings, the oscillation of the bunch at the leading edge is much better damped, similar to the rest of the batch.

Tests with EB settings in 2012 during Physics showed that the luminosity lifetime is decreased. This is attributed to the lack of the beneficial effect of the lower bandwidth in the SB case that rejects part of the noise in the feedback loop. Operation with the EB settings was therefore limited in 2012 to tests with 25 ns beams and the squeeze of the standard Physics beam for which a higher bandwidth was desirable to optimally fight single bunch instabilities.

It should be noted that the observed luminosity reduction is due to an emittance increase caused by the damper noise in combination with the high tune spread present with colliding beams. EB settings could be beneficial also during the ramp and flat bottom, where at lower tune spread the effect on the emittance increase is small compared to colliding beams. Further tests and developments are planned for 2015 to explore this.

SUMMARY AND OUTLOOK

Improvements in the signal processing have permitted to overcome limitations of bandwidth in the transverse damper of LHC. Excellent damping, both for 50 ns and 25 ns spaced bunches in nominal trains has been achieved. The increased noise level of the new EB settings will be improved by measures planned for the LHC long shutdown: more pick-ups will be used with newly developed electronics optimized for yet better noise performance. The ability to act on individual bunches also opens up the possibility to excite individual bunches in a train for the purpose of damper setting-up, loss maps, tune measurement or other beam based diagnostics even during a store with full beam. The full potential of these new functionalities will be explored in the LHC run 2 starting in 2015.

REFERENCES

[1] W. Höfle et al., IPAC'11, San Sebastián, September 2011, MOPO012, p. 505–507.

[2] E. Gorbachev et al., LHC-Project-Report-1165, CERN, Geneva, Switzerland, 2008.

[3] D. Valuch et al., LLRF'07, Knoxville TN, October 2007, https://edms.cern.ch/file/929563/1/llrf07_poster.pdf

[4] W. Höfle et al., EPAC'08, Genoa, June 2008, THPC122, p. 3269–3262.