LHC TRANSVERSE DAMPER OBSERVATIONS VERSUS EXPECTATIONS

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Abstract

As part of the 2010 LHC start-up the LHC transverse feedback system was successfully commissioned with beam. Damping times better than nominal were achieved and the system was run at high gain on the 450 GeV plateau. Following successful tests during the ramp and with colliding beams, operation of the LHC with the transverse feedback system on rapidly became the standard procedure. This included operation with Pb-ions, but excluded the squeeze and periods of chromaticity measurements. The transverse feedback system contributed to the preservation of the smaller than nominal emittances by limiting emittance increase due to injection errors, the impact of external perturbations ("hump") and curing instabilities observed with chromaticity close to zero. Interferences observed with the tune measurement system will be addressed in a number of ways: In the long term a tune measurement based on the analysis of the residual oscillations in the damper feedback loop seems feasible, but short term improvements for the tune measurement system will be prepared for the 2011 LHC run. Further improvements foreseen for 2011 and beyond address controllability, diagnostics, data acquisition and interlocking as well as the frequency response of the system.

INTRODUCTION

Hardware commissioning of the transverse damper power system had finished in time for the 2008 LHC start-up [1] and the system was regularly used during the brief period of operation in 2008 as an exciter for the tune measurement system [2]. Beam commissioning of the transverse damper system also started in 2008 [3] with observation of the pick-up signals, setting-up of the electronics for demodulating the wide band signals and digitizing these bunch-by-bunch with the aim of resolving oscillations of the individual bunches at the micrometer level. Such a high resolution is necessary as the feedback loop gain will amplify any noise from the pick-up system thus setting a lower limit for the rate of emittance increase achievable with the feedback loop closed. The short 2009 LHC run served to gain further experience, in particular a first test of the abort gap cleaning was carried out [4]. Issues with electromagnetic interferences were identified and corrected [5]. Two sections of 7/8" cable between pick-ups and surface were changed due to damage in the vertical access shaft. More cables are planned to be changed for the same reason during the next long shutdown.

EXPECTATIONS AND LIMITATIONS

System overview

Fig. 1 shows a block diagram of the transverse damper system reproduced and explained in detail in [2, 6]. There are a total of 16 power amplifiers installed directly under the kicker tanks in point 4 of LHC. Per plane and beam a set of two coupler pick-ups is available to detect the transverse oscillations. Pick-ups and kickers are installed at locations with high beta function in order to have a high signal and a large impact of the correcting kicks on the beam normalised oscillation. In point 4, at the relevant locations for the damper system the optics functions (version 6.503) do not change from 450 GeV to 3.5 TeV collisions with $\beta^\star = 3.5$ m. This eased setting-up the system throughout the cycle, as only the change of fractional tune during the squeeze has to be taken into account in the damper signal processing.

The signal processing comprises an FIR filter to shape the response of the system with frequency in amplitude and phase as well as a scheme to combine the signals from the set of two pick-ups as vectorial sum either directly or after shifting them in phase using an FIR filter (Hilbert filter) [7, 8]. In 2010 the system was run at the full available bandwidth (20 MHz low pass filter in the digital part) and with a phase compensating filter adjusting for the *theoretical* phase response of the power amplifiers with a 3 dB point of 1 MHz. The phase response of the 3/8" drive cables has been corrected by an analogue filter at the end of the cables in UX45 which was added in the shutdown 2009/2010. In particular this filter improves the pulse shape for the abort gap cleaning [1].

The pick-up signals are normalised to the bunch intensity in the digital part of the processing. The gain of the analogue front-end before the mixers can be adjusted to optimize the use of the dynamic range of the ADC located after the mixer and digitizing the base-band signal at a rate of 40 MS/s synchronously with the bunch repetition frequency of 40 MHz.

[1] The phase response of a lossy cable (skin effect) leads in time domain to a long trailing edge when a pulse is transmitted. This response cannot be corrected perfectly as the tail has an infinite length surpassing with significant parts the 32-tap (at 40 MS/s) FIR filter implemented in the damper signal processing.

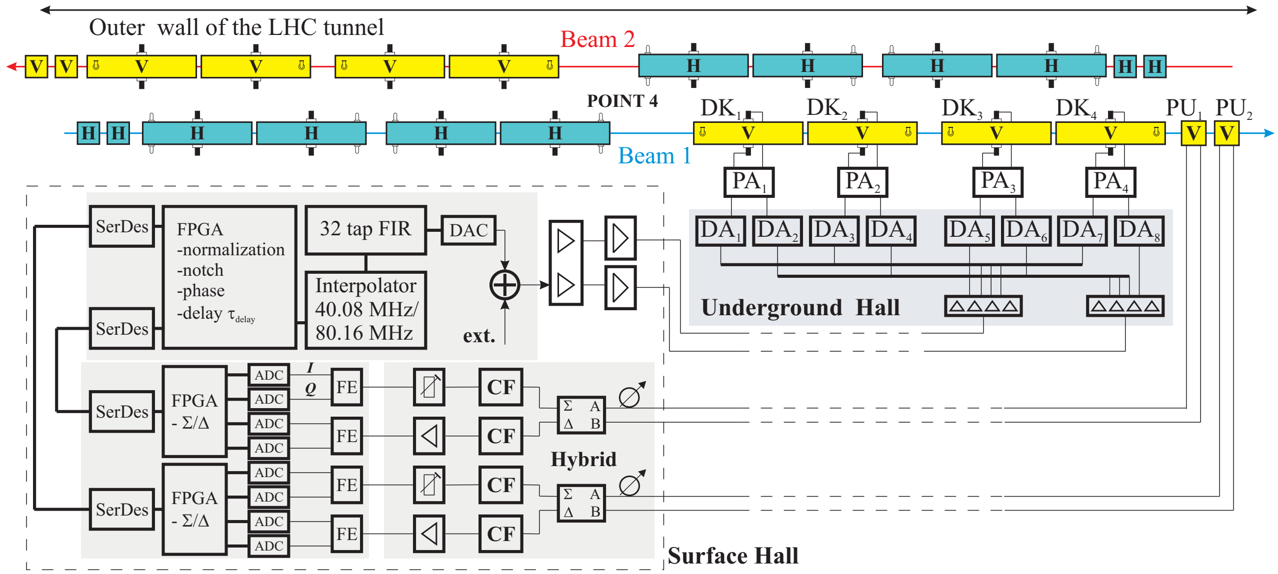

Figure 1: Block diagram of transverse damper system, reproduced from [2, 6].

Design goals

The principle design goals for the transverse feedback system were damping times of 40 turns at 450 GeV [9] and a resolution at the micrometer level in order to permit the feedback to be used with stored beams. The maximum kick strength at low frequency of 7.5 kV per kicker leads to a total combined kick angle (4 kickers) of maximally 2 μrad. Due to beta functions higher than the assumed 100 m at the design stage for the kicker location, the capabilities exceed expectations with respect to the maximum possible kick.

Limitations

A known limitation of the principle underlying the power system (tetrode amplifier driving directly a set of kicker plates), is the relatively low 3 dB bandwidth of 1 MHz defined by the kicker capacity and the resistance in the tetrode anode circuit [10]. This type of system permits a large kick strength at low frequency as needed for batch by batch damping of injection errors and would also be adapted to the frequency dependence of the resistive wall impedance which falls off with frequency and is thought to be one of the main driving impedances of coupled bunch instabilities that the feedback should cure. Digital signal processing permits the system to be used up to 20 MHz, albeit at reduced power. During the design stage, when it became apparent that higher frequencies were present in the injection kicker wave form, the consequence of the reduced power bandwidth was investigated and was found adequate for injection damping [11]. Further modification of the signal processing to boost the gain at frequencies between 1 MHz and 20 MHz may be necessary to match the damping rate with requirements given by the dependence with frequency of the impedance driving instabilities. More studies with bunch trains are required to optimise the signal processing.

For the 2010 run a sample hold scheme was used optimised for different bunch spacings. For the single bunch mode the hold time was 625 ns, for bunch trains with spacings of 150 ns, 75 ns and 50 ns the sample hold time was chosen to be equal to the bunch spacing. This reduces the overall gain for the same electronic gain setting in LSA, as the bunch spacing is reduced.

COMMISSIONING OF THE FEEDBACK LOOP

Procedure and results

Commissioning of the feedback loop started in spring 2010 and damping was first achieved in April 2010. Fig. 2 shows a comparison of the turn by turn injection oscillation recorded with the damper system, with the damper feedback loop open and closed. With the loop open the injection error filaments (top picture), depending on tune spread, due to non-linearities in the optics as well as collective (space charge) effects. In contrast to this the injection error is very quickly damped with the feedback loop closed (bottom).

In the SPS the adjustment of phase in the feedback loop is done using a vector sum of both available pick-ups spaced at 90° in betatron phase space and measuring the open loop transfer function with a network analyser [12]. This method was also tried in the LHC. However, due to the different absolute values of the beta function at the pick-ups and a phase advance considerably different from 90°, it proved easier to use the pick-ups one by one together with the digital phase shifters (Hilbert filter) to adjust the phase individually for each pick-up and then combine both signals digitally. This gives also a better-signal-to-noise ratio at the expense of additional turns of loop delay. This additional loop delay limits the range of tunes for which the

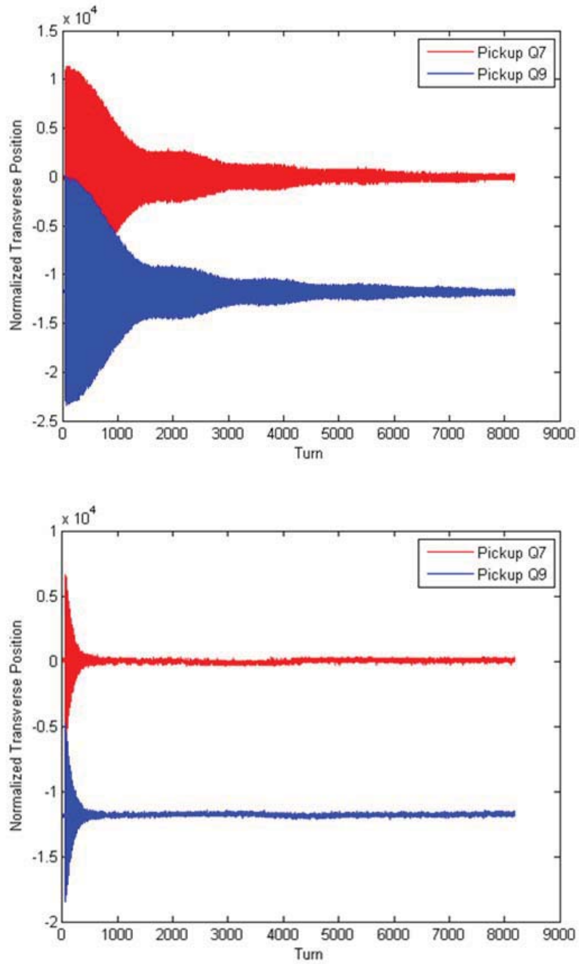

Figure 2: First successful Injection Damping, damper off (a) and damper on (b).

feedback works correctly.

Fig. 3 shows a network analyser open loop transfer function measurement around a betatron side band. For perfect damping the circle has to be orientated to the negative real axis, i.e. the phase setting is wrong by approximately 135 ° in this example. Feedbacks were roughly set-up using the network analyser. In a second pass the feedback phase adjustment was improved by scanning the phase setting for each pick-up individually and looking for the peak damping rate.

Peak damping is not very sensitive to the phase setting. A better setting of the phase can be achieved by looking at the tune shift introduced by the feedback as a function of the phase setting. Fig. 4 compares measured tune shift and damping rate as a function of the phase shift that is applied to the pick-up signal. The correct adjustment for resistive feedback is at the maximum damping rate which coincides with zero tune shift when compared with the case of the feedback loop open.

Due to the limited time allocated for setting-up the damper the more precise tune shift method was not used

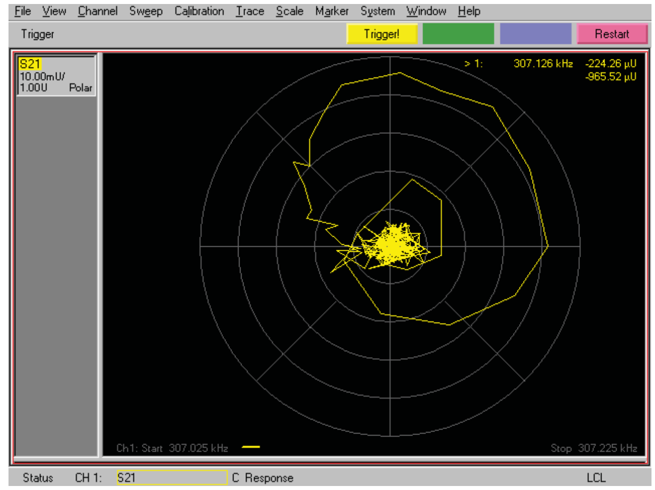

Figure 3: Network analyser measurement of open loop beam transfer function; single pilot bunch — the measurement leads to a loss of beam intensity.

on all dampers resulting in phase errors that are estimated as up to 25° (by comparing with values expected from the theoretical optics). The phase settings should be re-visited during the 2011 start-up. Moreover, the set-up of the direct vector sum should be completed. The 1-turn delay (time

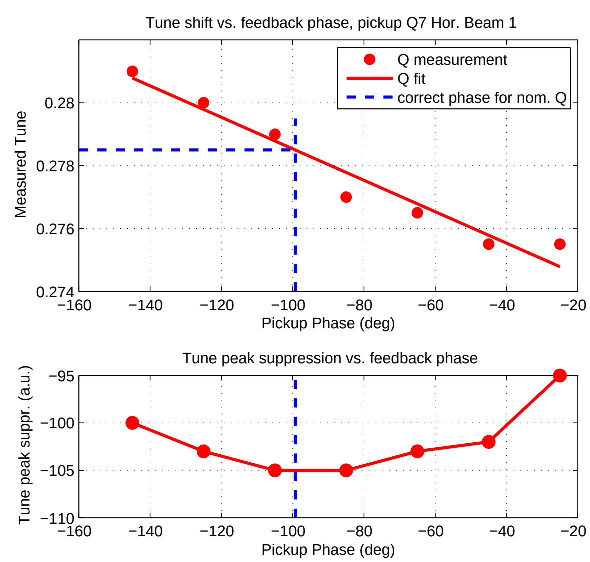

Figure 4: Damping rate and tune shift introduced by the feedback as function of phase setting [13].

alignment of kicks and beam) was adjusted by looking at the damper higher order mode (HOM) ports and observing the signal from the passing bunches and the applied kicks. This method worked quite well, but adjustments need refinement for the short bunch spacings of 50 ns and 25 ns — the latter has not been tested in 2010.

Summary of time line

In the following, a brief history of the 2010 time line for the damper commissioning and operation is given with the important milestones listed:

22.04.	first damping loop successfully closed
17.06.	full operation for nominal bunch intensity at 450 GeV with attenuators and ”low intensity” settings
30.06.	new firmware fully operational with automatic synchronization for the digital links
04.07.	damper becomes operational with colliding beams; standard gain settings documented as in [15,16] with damping times of approximately 40 turns at 450 GeV and 880 turns at 3.5 TeV
05.09.	signal-to-noise improvement by a factor 2; operation with higher gain from 06.09. onwards
17.11.	”scrubbing run” with bunch trains of 50 ns and 75 ns, optimization of sample hold for different bunch spacings
21.11.	Commissioning for ions at 450 GeV completed
23.11.	Following tests at 3.5 TeV damper operationally used with colliding ion beams.

DIAGNOSTICS USING DAMPER SIGNALS

The data present in the damper system can be used to evaluate not only the transverse injection errors and their damping but it also gives an abundant amount of information that can be used for beam diagnostics purposes. From summer 2010 onwards data from all eight pick-ups used by the damper system was stored in the logging data base for the first 8192 turns after each injection, and also visualized with the injection oscillation display. Data from the first bunch of each injected batch is recorded and displayed. Dynamic gain switching between pilot and nominal intensity remains to be implemented for a full exploitation of the data — usually damping was inhibited for the pilot and the threshold set such that the acquisition did not trigger for pilot intensity, in absence of the dynamic gain switching.

Fig. 5 shows the filamentation of an injection error of a pilot bunch with damper off. By comparing with a numerical simulation as in [14] an estimate of the chromaticity (5.5), synchrotron tune (0.0056) and non-linear detuning (6×10^{-5}) can be extracted from the measurement.

Fig. 6 shows the injection oscillation display for beam 1 (top) and beam 2 (bottom) for a pilot beam injection. The horizontal injection oscillations (top set of plots for both beams) with a modulation at the synchrotron frequency points to a non-zero chromaticity while for the vertical plane the chromaticity is close to zero and the filamentation smooth without beating. One of the horizontal pick-ups (Q9) has about 1 m of dispersion while the other (Q7) is installed at a dispersion close to zero. This dispersion makes visible an injection error in energy (bottom plot, top right quarter).

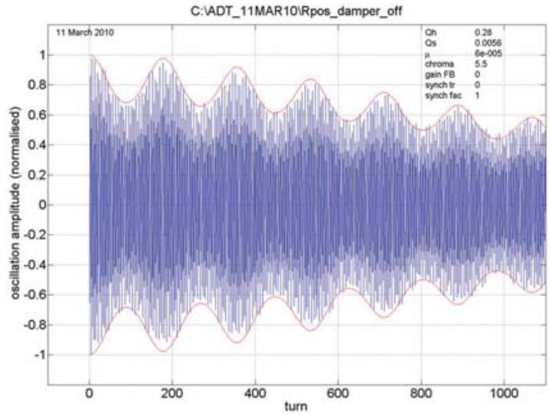

Figure 5: Filamention of injection error without damper.

An example of the injection oscillation display with feedback on is shown for ions in Fig. 7. The top plot shows the first ion injection and the bottom plot the last. Again a small energy transient is visible as oscillation in the top right quarter where pick-up Q9 horizontal is displayed. For the first injection (the top plot), the phase loop locks the RF onto the beam and the synchro-loop transient quickly brings the beam to the correct energy, while for the last injection (bottom plot) the oscillation in energy of the last injected bunch persists for many synchrotron periods. Moreover, bunch by bunch oscillation data has also been made available with an on-demand trigger as part of the MultiQ application. The examples presented demonstrate the high quality of the data available within the damper feedback system. A joint effort between the RF and OP teams is needed to develop the software tools to fully exploit the data.

HUMP CONTROL, GAIN AND TUNE MEASUREMENT

During the stable operating period in August, the feedback system was always used both for injection oscillation damping and during stable beams. Fig. 8 shows an analysis of the damping for fill 1268 where the average damping time was 44.6 turns for beam 1 horizontal oscillations. More plots can be found in [15] where the fit method employed is described in more detail.

Damping times at 3.5 TeV were measured using a non-colliding bunch in an end of fill study (August 20, 2010) at different electronic gains [16]. This exemplary data analysis done permits estimation of damping times for other fills using the stored values of the electronic gain in the logging.

In order to further reduce the impact of external perturbation found to induce beam oscillations, such as the ”hump” the gain of the damper system was pushed to its limits and

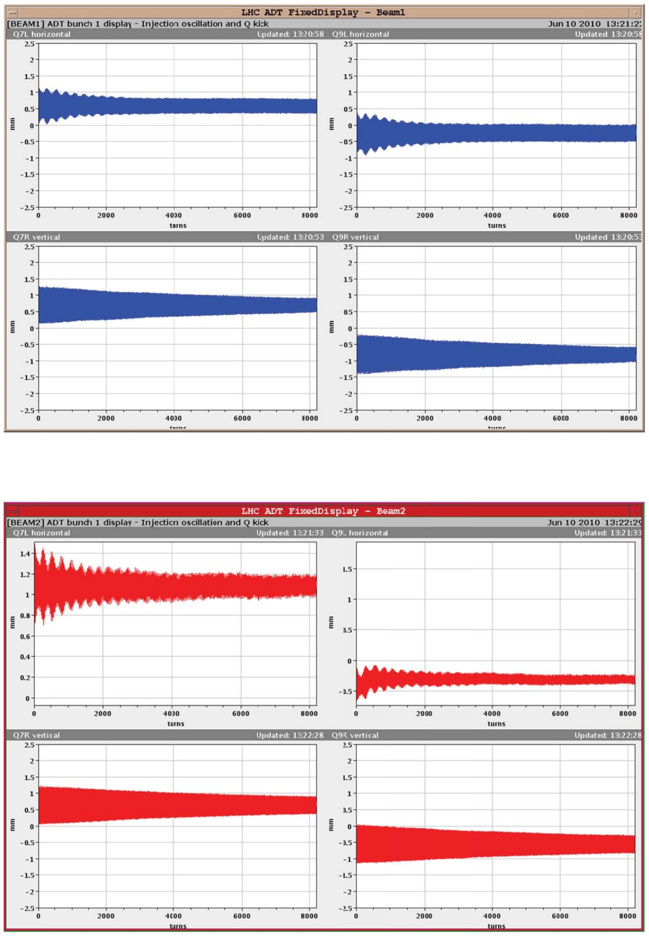

Figure 6: Example of injection oscillations without damper for beam 1 (top plot) and beam 2 with energy error (bottom plot).

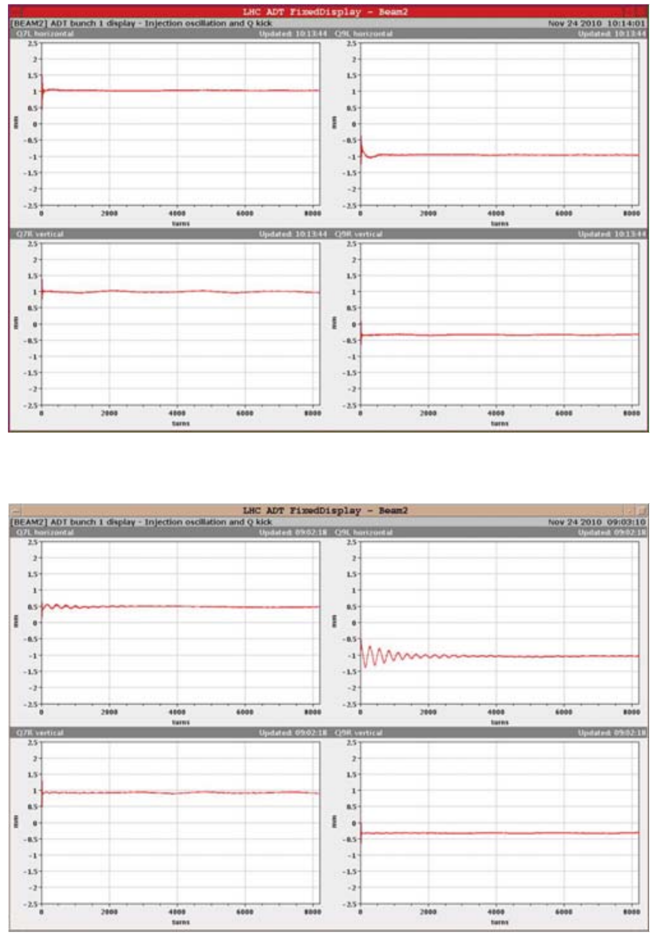

Figure 7: Example of injection oscillations for the first injection (top plot) and last injection (bottom plot) with damper on for beam 2 with an energy error (ions).

running with increased gain at 450 GeV became standard practice, for details see [17]. The operation at high gain interferes with the tune measurement system.

Fig. 9 shows an FFT of 8192 turns of damper data of a single bunch, clearly exhibiting a notch in the noise floor at the betatron frequency where beam response and feedback interact to create the dip. This observation together with simulations started [18] seem to indicate that it should be possible to extract the tune information from the damper signals with feedback loop closed. The question is if a sufficiently large measurement bandwidth and a high precision can be obtained at the same time.

A better tune precision can be reached if FFT spectra are averaged. Fig. 10 shows the average over 999 spectra for three different electronic gains . Clearly the 8 kHz sharp line (perturbation on beam) is reduced proportional to the feedback gain, but at very high gain lobes develop at the tune values limiting the range in which the feedback works in a stable regime. The figure also shows how by averaging 999 spectra it is possible to more accurately locate the tune, however this takes a very long time, consequently the measurement bandwidth is small. As only data from one bunch was recorded a similar result should be obtainable by looking at the data of all bunches and averaging the spectra of the individual bunches. This would lead to a higher measurement bandwidth. A considerable hardware and software development effort is required to build a system that could provide an on-line tune measurement due to the high data throughput (in excess of 1 GBit/s). A first step that will be undertaken in 2011 is to show the feasibility by off-line analysis of multi-bunch data.

IMPROVEMENTS FOR 2011 AND BEYOND

Abort gap cleaning pulse shape

Since the first abort gap cleaning tests in 2009 [4] it is clear that trailing bunches located after the abort gap will suffer small residual kicks. An improvement was intro-

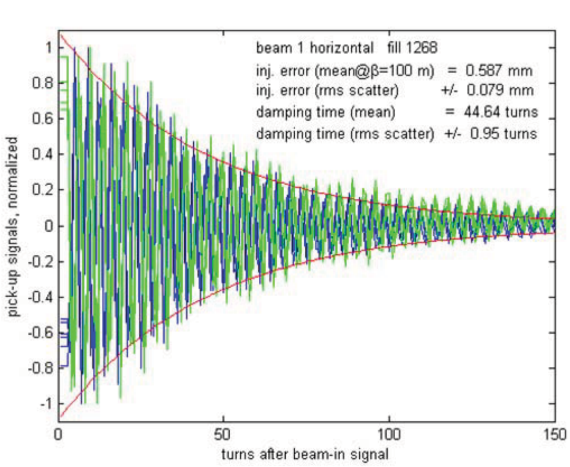

Figure 8: Injection oscillating of all injections of fill 1268 (August 9, 2010) with average damping fitted [15].

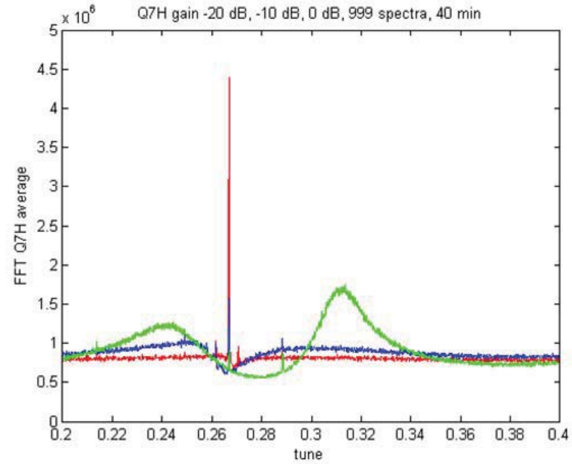

Figure 10: Average of 999 spectra with different gains of the damper feedback.

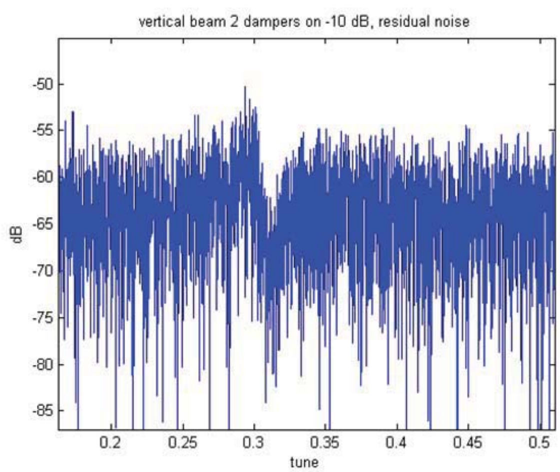

Figure 9: Feedback on, residual damper signal, FFT of 8192 turns.

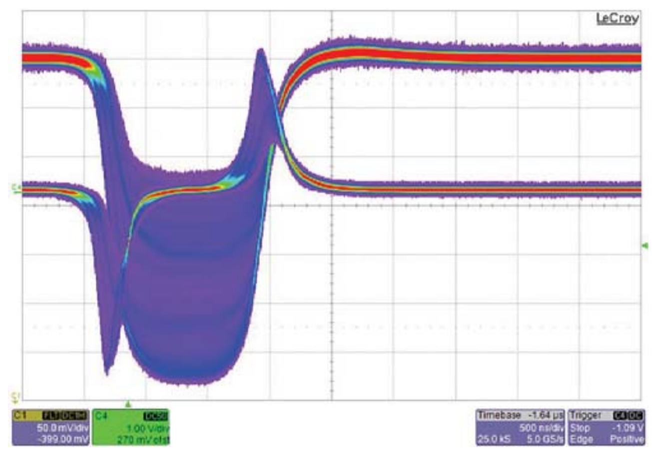

Figure 11: abort gap cleaning pulse directly measured in tunnel inside the amplifier and via the HOM ports; the latter signal is differentiated due to the capacitive coupling at the HOM ports.

duced in the 2009/2010 shutdown in the form of an analogue filter compensating the phase response of cables used to transmit damper signals from the surface building to the underground cavern. This improvement has permitted operation with abort gap cleaning in 2010, although a perturbation of the tune measurement remains. Inspection of the kick wave form in Fig. 11 shows that the filter may slightly over correct and may possibly be further improved in a long shutdown. Moreover, as part of the improvements for the pulse shape, tetrodes in the power amplifiers were regularly checked in 2010 and in a campaign during the summer sorted to have matching pairs of tetrodes in the individual power amplifiers. Note that these power amplifiers are running in class AB in push-pull mode and consequently will only produce an undistorted output pulse if the two tetrodes employed in each amplifier are identical.

List of improvements for 2011 and beyond

The 2010 run identified a number of improvements and extensions of the operating mode that can be planned for 2011:

- automatic loading of settings to adapt to different bunch intensities and spacings
- improving the frequency response and adapting the bandwidth to what is required for a given bunch spacing
- fine adjustment of phase and delay to a higher precision than in 2010
- commissioning of the vector sum as a more robust scheme with respect to tune variations
- programming of the damper gain via a normalised

function (scale with energy), in physical units, e.g. damping time τ
- extending the multi-bunch acquisition to more than eight bunches
- definition of what should be logged for "post mortem" analysis followed by implementation
- move the beam cleaning (abort gap / injection) functionality to standard operation
- further improve the abort gap cleaning pulse shape
- commission the damper during the squeeze
- study the noise properties of the system and propose improvements to be implemented in a future long shutdown
- work on a scheme to restore acceptable compatibility with the tune measurement system (sacrificial bunch?)
- study the feasibility to extract an on-line tune signal from the damper data
- develop and test a scheme for a controlled emittance increase to be used for example to generate loss maps for the collimation set-up and verification

Most of the above require small software or firmware changes that can be implemented without change of hardware. Some of the optimisations require input from the Chamonix workshop, such as the range of bunch intensities at which LHC will run, bunch spacings for trains as well as the energy. Certain items involve finding better parameter sets for the damper requiring dedicated study time with beam. Due to the shortness of the present shutdown it is not realistic to implement all modifications that can be envisioned. The emphasis will be to guarantee an operation with as low as possible down time while still permitting an evolution to more functionality in 2011.

SUMMARY AND CONCLUSIONS

The transverse feedback system in LHC has been successfully commissioned in 2010 with beam for all planes and beams. With the system being used operationally with colliding beams the performance has exceeded expectations. Damping times better than nominal were achieved at 450 GeV and operation at high gain was successfully used to reduce residual oscillations of the beam induced by external perturbations. The system was also used with ions, initially for injection damping and during the last part of the ion run also with colliding beams. The abort gap cleaning will be extended to provide a cleaning of the "injection slot" in 2011. Main changes for 2011 concern software for better operability and the use of the abundant data present in the damper feedback loop. The evaluation and reduction of the noise remains a priority as an improvement is needed to maintain the same performance at 7 TeV as has been achieved at 3.5 TeV due to the smaller beam size at the higher energy. The issue of compatibility with the tune measurement system will be addressed, with a short term solution as well as a long term option that aims at extracting the tune from the damper data itself. To investigate the feasibility of the latter will be one of the priorities of 2011.

ACKNOWLEDGEMENTS

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