

TRANSVERSE DAMPER

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Abstract

Plans for the operation of the transverse damper in 2012 at bunch spacings of 50 ns and 25 ns and at increased collision energy will be reviewed. The increased energy and the experience that will be gained at 25 ns are very important to define any upgrades that may be necessary for the high luminosity operation at 7 TeV after LS1. This means that the available parameter space must be probed in 2012 which in particular includes a higher feedback gain in the ramp and with colliding beams. Limits for the feedback gain for the current system will be outlined. The potential benefits of running with higher feedback gain for a better emittance preservation will be stressed and weighed against the operational difficulties and the potential impact of noise in the damper system. A plan for re-commissioning at 50 ns and 25 ns for operation at 4 TeV will be outlined.

INTRODUCTION AND HIGHLIGHTS IN 2011

The LHC transverse damper (ADT) has become indispensable not only for beam stability, but also as a tool to excite beam oscillations, and to observe instabilities with its turn-by-turn and bunch-by-bunch observation capabilities. Highlights of 2011 include the operational use of the abort gap and injection gap cleaning at 450 GeV and successful tests of the abort gap cleaning at 3.5 TeV. These applications are reviewed in more detail in [1].

Controlled Transverse Blow-up

Inspired by the successful gating used for the abort gap and injection gap cleaning, a new method for selective blow-up was developed during 2011 and successfully tested in an MD [2]. It could be shown that loss maps for the qualification of the collimation system can be efficiently generated. Fig. 1 shows as an example a comparison of a loss map by the 3rd order resonance method (bottom) and the excitation by the damper (top). The transverse blow-up can also be used to produce larger emittance bunches, both for machine studies and to probe the LHC aperture limit. Fig. 2 shows as an example the selective blow-up of a bunch of beam 2 in the vertical plane up to 18 μm normalised emittance while the bunch not targeted remains at 2 μm emittance.

Following these successful tests in 2011 it is planned to develop a user friendly application for the 2012 run for the extensive use of the transverse damper blow-up for loss

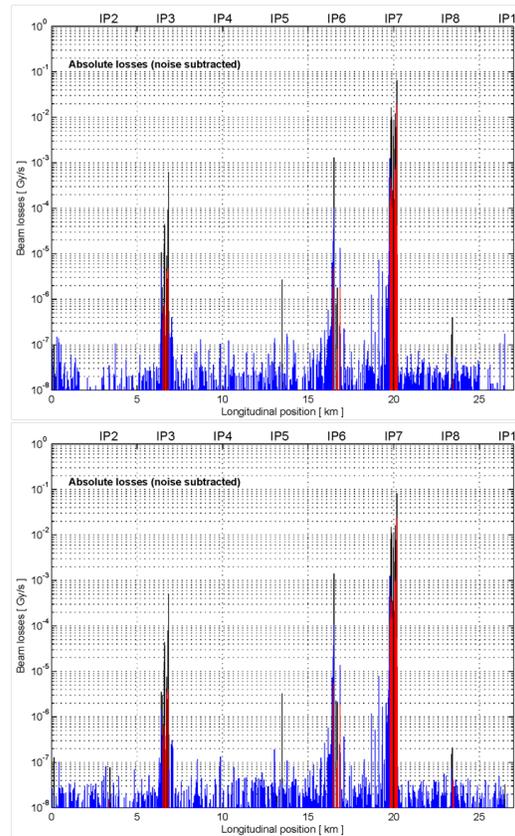


Figure 1: Comparison of Loss maps with ADT blow-up (top) and 3rd order resonance method (bottom), reproduced from [2].

maps, aperture measurements and studies requiring larger transverse emittances.

Operation with 50 ns Bunch Spacing

Operation at 50 ns bunch spacing with 1380 bunches has been the standard mode of operation for Physics in 2011. The transverse dampers were operated at high gain during the injection plateau at 450 GeV, during which injection damping with short damping times is particularly important in order to preserve the small emittances available from the injectors. The feedback gain is reduced before the start of the ramp and the damping time remains larger throughout the ramp. Before the beams are brought into collision at top energy the gain is again increased, as described in [1].

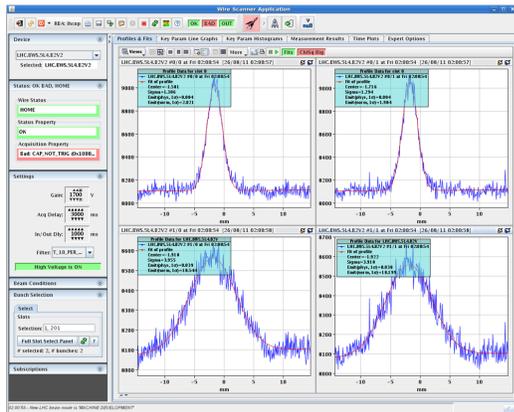


Figure 2: Selective blow-up by applying gated noise in vertical plane (beam 2): bunch not blown-up (top) with $2 \mu\text{m}$ emittance, bunch blown-up to $18 \mu\text{m}$ emittance (bottom).

The reduction in gain during the ramp had been introduced in order to enable the tune feedback to lock on a clear signal from the BBQ tune measurement system. With too high damper gain the signal-to-noise ratio of the BBQ system becomes too small for a reliable operation of the tune feedback. Fig. 3 shows the BBQ signal amplitude (in

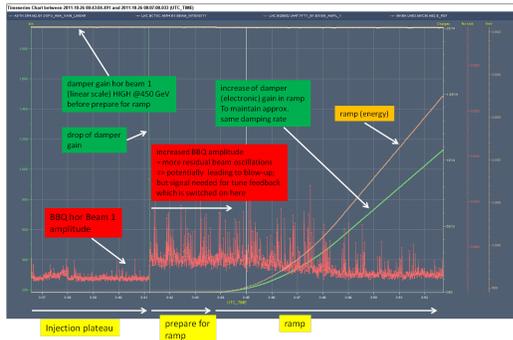


Figure 3: BBQ signal amplitude (red), damper gain and beam energy (beam 1 horizontal plane, 26.10.2011).

red) as it increases as the damper gain is reduced.

It should be noted that the increased amplitude of the BBQ signal is a result of increased transverse oscillatory activity on the beam which should, according to theory, inevitable lead to emittance blow-up [3]. Indeed emittance blow-up in the ramp has been observed [4], but no time was dedicated in 2011 to systematically study the effects of the damper gain setting on the blow-up. In 2012 the study of the dependence of the emittance increase on the damper gain will be a priority. Running at higher damper gain requires a viable solution for the compatibility with the tune feedback.

Observations with 25 ns Bunch Spacing

At 25 ns bunch spacing the required bandwidth in order to damp bunch-by-bunch oscillations is 20 MHz. Towards 20 MHz the damper system has a very much reduced kick strength and without compensating for this only a fraction of the feedback gain will be active at this frequency when compared with the low-frequency gain. In addition the overall phase response and loop delay must be carefully corrected to achieve damping at 20 MHz.

A first MD with injection of bunch trains with 48 bunches spaced at 25 ns on August 26, 2011, carried out before the completion of the setting-up of the damper fine-delays, illustrates this very well [5]. It had been the first attempt of injection of 48 bunches spaced 25 ns into the LHC. On two occasions beam was injected, but circulated only for 500 turns (damper off), and 1000 turns (damper on), respectively. It also has been the only attempt to inject with low chromaticity into an unscrubbed LHC machine in 2011. Figs. 4 and 5 show the analysed bunch-by-bunch data from the damper post-mortem system. With

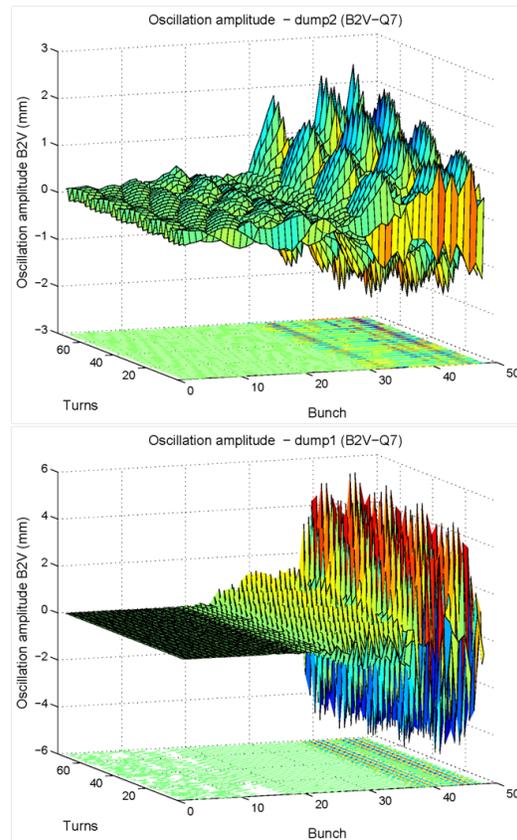


Figure 4: Injection with damper off (top) and damper on (bottom) of a bunch train of 48 bunches spaced 25 ns; shown is the reconstructed vertical oscillation amplitude, bunch-by-bunch for approximately 70 turns as an instability develops, following which beams were dumped (courtesy H. Bartosik [5]).

damper off (top pictures of Figs. 4 and Figs. 5) the beam

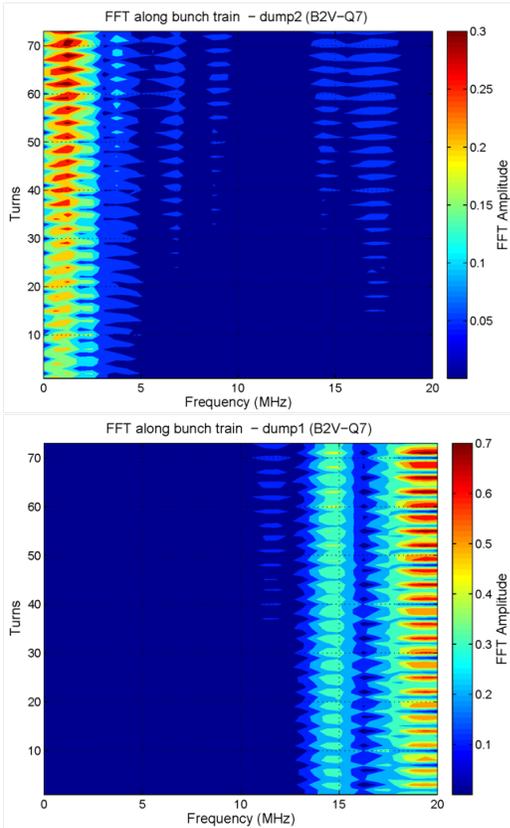


Figure 5: Turn-by-turn spectrum from data of Figs. 4; low frequency instability with dampers on (top) and high frequency instability with dampers off (bottom).

was dumped after 500 turns as a low frequency instability develops; most of the frequency contents (Fig. 5 top) is contained within and band up to 2 MHz approximately. With damper off the beam survived longer, 1000 turns, and instabilities now developed for frequencies larger than 15 MHz. These high frequency instabilities may be due to the electron cloud effect or the incomplete setting-up of the damper (delay), or a combination of both. Subsequent MDs were carried out with a high chromaticity ($Q' > 10$) and an improved setting-up of the damper (fine delay) with the beam then surviving. For a complete discussion of the data of this first injection test with 25 ns bunch spacing see [5].

BEAM STABILITY, NOISE AND FEEDBACK GAIN

Damper and Instability Control

Instability growth rates were calculated for 50 ns bunch spacing using the current knowledge of the LHC impedance and the operational parameters of the LHC in 2011 [6]. The fastest coupled bunch mode growth rate at low frequency is approximately $1/650$ 1/turns [6], and much slower than the nominal damping time of the trans-

verse feedback of 40 turns. The transverse feedback gain falls off towards higher frequency as a result of the design principle of the power amplifiers [7]. However, the damping by feedback remains faster than the instability growth rates at all frequencies of coupled bunch modes because the impedance, dominated by the resistive wall effect, is also diminishing with increasing frequency. This is depicted in Fig. 6 where growth rates and damping times are compared

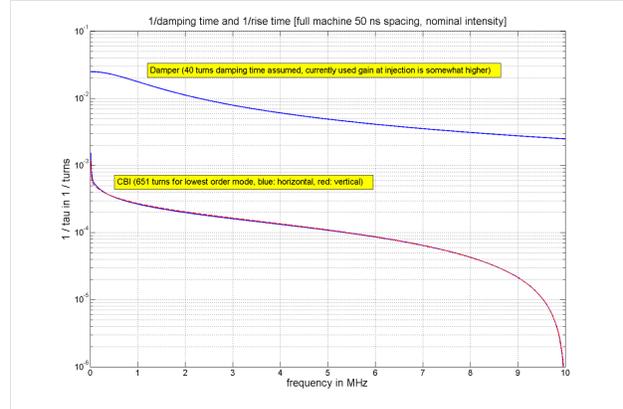


Figure 6: Time constants of damping and instability growth rates [6] as a function of coupled bunch mode frequency for 2011 LHC operational parameters with 50 ns bunch spacing.

for operational parameters in 2011.

Damper Signal Processing

A higher than nominal feedback gain is in theory desirable to reduce the impact of external transverse excitations on the beam transverse emittance. On the other hand, noise and interferences applied to the beam by the damper system itself are undesirable effects and can lead to emittance increase.

In order to study the impact of noise from the damper system the exact signal processing of the turn-by-turn samples must be taken into account. The 2011 algorithms for the signal processing are therefore reproduced here with values for the exact phase shifts as programmed in LSA summarized in [8]. Strictly speaking this analysis is only correct for the single bunch case as the frequency roll-off for the multi-bunch case is not taken into account.

In the following the notation of [3] is used and the essential ingredients for a turn-by-turn simulation reproduced: The transverse damper signal processing starts from a notch filter, subtracting two successive turns and eliminating the closed orbit offset, followed by a FIR filter with 7 taps in order to adjust for the correct phase in the feedback. It can be described by the following turn-by-turn map:

$$z_{n+1} = e^{i\mu_3} \left(e^{i(\mu_2 + \mu_1)} z_n - i\delta\hat{\theta}_n \right),$$

$$\delta\hat{\theta}_n = g_1 \sum_{k=0}^{K-1} A_k^{(1)} X_{n-k-n_d} \quad (1)$$

$$\begin{aligned}
& + g_2 \sum_{k=0}^{K-1} A_k^{(2)} Y_{n-k-n_d}, \\
X_n & = \operatorname{Re}\{z_n - z_{n-1}\} + \frac{\delta x_n^{(1)} - \delta x_{n-1}^{(1)}}{\sqrt{\beta_{p1}}}, \\
Y_n & = \operatorname{Re}\{e^{i\mu_1}(z_n - z_{n-1})\} + \frac{\delta x_n^{(2)} - \delta x_{n-1}^{(2)}}{\sqrt{\beta_{p2}}},
\end{aligned}$$

where $z = x/\sqrt{\beta} - i(\sqrt{\beta}\theta + \alpha x/\sqrt{\beta})$ is the complex bunch coordinate with x and θ being actual bunch position and angle; n enumerates turns so that the beam coordinates are referenced to pickup 1, β is the beta-function which is equal to β_{p1} and β_{p2} in pickups 1 and 2; $\alpha = -\beta'/2$; μ_1 is the betatron-phase advance between pickups 1 and 2, μ_2 between pickup 2 and kicker, and μ_3 between kicker and pickup 1; g_1 and g_2 are the gains of the system for pickups 1 and 2, $A_k^{(1,2)}$ are the coefficients of the digital filters for the pickups, $K = 7$ is the order of the digital filter, and $\delta x_n^{(1,2)}$ are the measurement errors for pickups 1 and 2, so that the entire noise in the damper is referenced to the errors of the pickup position measurements. For each transverse plane and beam the signals from the two available pickups are treated independently and the processed signals added to provide the input to the power chain of the feedback system.

For the signal processing a Hilbert filter is chosen, which can be parametrized by a single angle φ ($S = \sin \varphi$, $C = \cos \varphi$)

$$A_k = \left[-\frac{2}{3\pi}S, 0, -\frac{2}{\pi}S, C, \frac{2}{\pi}S, 0, \frac{2}{3\pi}S \right]^T \quad (2)$$

which effectively is a phase shift that needs to be applied to the pickup signal and is programmed as function in LSA. The phase shift for optimal damping, i.e. for a purely resistive damping and minimised damping time, depends on the overall machine tune and the optics parameters at the pickups and kickers.

The signal processing takes into account the beam signal on past turns. Consequently, the region of stability and fast damping is influenced by the machine tune. During the 2011 run the parameter $n_d = 2$ in (1) and samples from a history of 7 turns had been taken into account. The region of stability (range of tunes the feedback achieves damping) is relatively limited. Figs. 7 show the range of stability in a gain versus phase shift (top) and gain versus tune diagram (bottom) for the vertical dampers of beam 2 using the pickup Q7 only. More details can be found in [8]. The operational values for the phase shift, experimentally found, are close to the theoretical values derived from the optics model of the LHC.

It should be noted that for the LHC damper the figure of merit for the signal processing is *not* the range of stability but rather *the impact of noise* on the emittance. For 2012, as it is transparent with respect to the impact of noise, the synchronisation of data within the digital part of the system can be modified to save a single turn delay leading

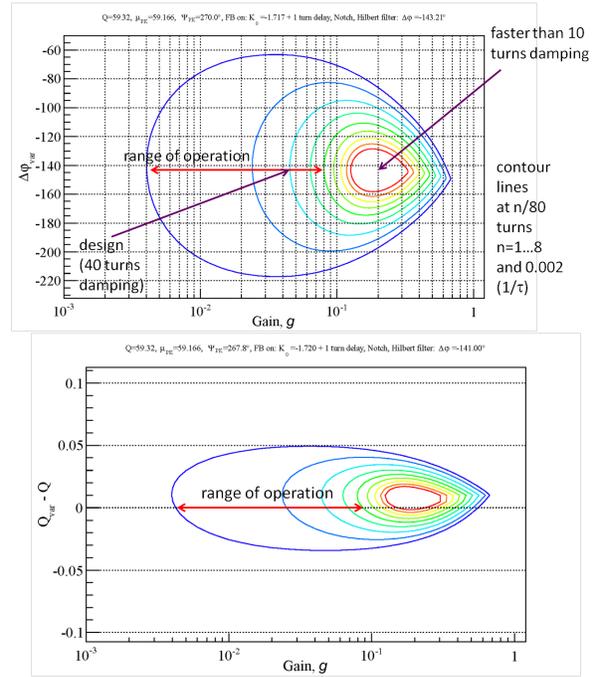


Figure 7: Stability and lines of equal damping for the vertical damper module 2 of beam 2 with use of pickup Q7, at collision settings, for fixed tune as a function of gain and phase shift (top) and for fixed phase shift (operational value from 2011) as a function of gain and tune deviation from nominal tune (59.32); courtesy V. Zhabitsky [8].

to a slightly larger stability region. Any further modification of the signal processing needs to be compared with the current scheme and modifications must be clearly justified, and improve or be transparent in terms of their impact on the emittance.

Beam Response to Noise

Fig. 8 (top) shows the signal of a pickup in simulation with the feedback loop closed and an initial error of 1 mm. The oscillation is quickly damped and the envelop follows, as expected, an exponential. In the simulation the pickup signals have been assumed to be polluted by gaussian noise (errors not correlated turn-by-turn, taken from a gaussian distribution), such that the rms fluctuations at the pickups agree between simulation and experiment. The residual rms fluctuation amounts to $2 \mu\text{m}$ rms when the slow variations corresponding to orbit movements that are present in measured data are removed.

In principle, the simulations demonstrate that it is possible to extract the tune information from the residual damper in-loop data, by looking at the valley visible at the tune location in the spectra, see Fig. 8 bottom plot. A practical difficulty is the required averaging taking into account more than one bunch and a number of successive acquisitions per bunch. Real-time averaging, as needed to generate a signal for the tune feedback, requires the fast computation

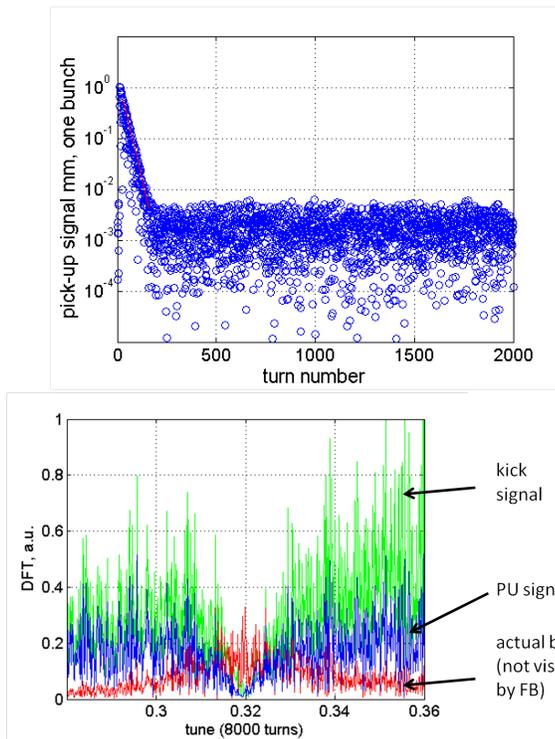


Figure 8: Simulated damping in the presence of noise with gain and noise level adjusted to mimic observed damping time and residual beam position fluctuation; turn-by-turn data (top) and spectra of pickup signal, kicker signal and actual beam movement (bottom, only data after completion of damping of simulated injection error of 1 mm are taken into account).

of spectra and the handling of a large number of data. For 2012 it is foreseen to implement additional memory on the FPGA treating the ADT feedback signal and a fast access by software to extract these data. Following a successful off-line analysis of these data it can be envisaged to specify at what rate and with what precision the tune can be extracted from the damper signals. An upgrade of the signal processing hard- and software may be required in particular should averaging over a large number of bunches be necessary for an accurate tune determination.

The simulations have also revealed a peculiarity: If the transverse damper is not adjusted for perfect resistive damping the valley in the spectra stay at the original unperturbed tune while the actual beam tune is shifted by the feedback. This is illustrated in Fig. 9 where the top plot shows the situation with perfectly adjusted feedback phase and the bottom plot shows signals with a 30° phase error applied. The phase error leads to a shift of the actual beam tune (peak of red trace). However, this signal is not observable in the damper loop. The fft spectra of the pickup signal and the kick signal observed in the damper loop do *not* show this shift. This can be explained by the fact that the valley in the spectra is essentially due to the peak of

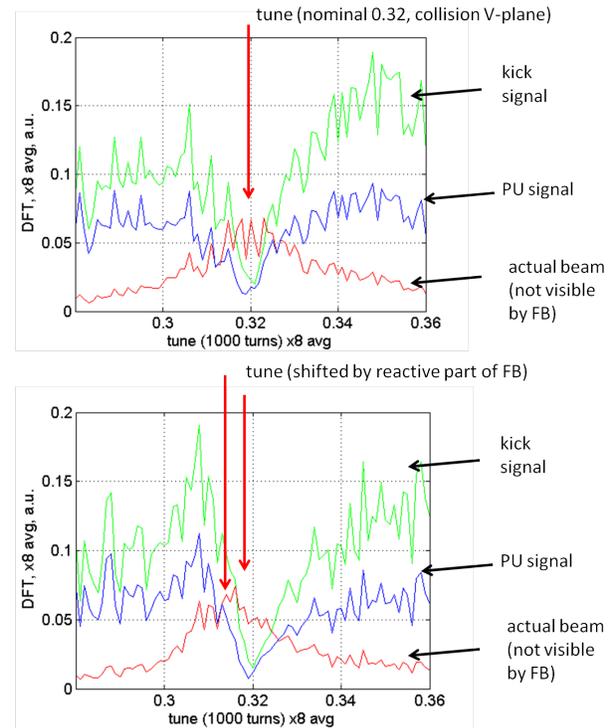


Figure 9: Comparison of spectra (data from simulation) with feedback phase correctly adjusted (top: pure resistive damping, no tune shift) and with phase error in feedback (bottom: tune of beam shifted).

the beam transfer function *without* feedback which is *not* shifted in frequency.

In summary, the valley will only coincide with the tune for a perfectly adjusted feedback which can be considered as a certain limitation to use this signal for a tune feedback. On the other hand the difference in location of the valley and the actual tune (which can be measured by the BBQ system) could potentially serve as a tool to correctly adjust the feedback phase to its optimal value, i.e. to a value where the feedback is not introducing any tune shift.

Improvements to Compatibility of ADT and BBQ Tune Measurement System

Machine studies will be carried out in 2012 to study whether the tune can also be extracted in *practice* from the data as described above.

In the short-term, an improvement of the BBQ signal can be put in place that relies on larger oscillations of the 12 leading bunches of the standard filling pattern. To this end the damper gain will be modulated to have different values for the different batches. The leading 12 bunches can thus be allowed to make larger oscillations, better visible to the BBQ system (at the expense of a possible emittance increase). Possibly this method requires a higher intensity for the leading bunches or a gating of the BBQ signal to achieve a real improvement.

The feasibility of this method will be checked in MDs in 2012. Beyond the simple modulation of the gain it can also be envisaged to put in place a mechanism in the damper signal processing that maintains a certain oscillation amplitude for the leading 12 bunches at all times ("dead band/excitation"). The oscillations that then are building up will also be visible on the ADT pickup signals and open up another possibility to use the leading 12 bunches for a tune measurement, should the BBQ continue to not give a satisfactory signal for the tune feedback at high damper gain.

SUMMARY AND PRIORITIES FOR 2012 AND TOWARDS A HIGHER BEAM ENERGY

Priorities for the operation in 2012 are

- deployment and commissioning of an application for the transverse blow-up
- new observation memory for fast collection and analysis of data in view of a tune measurement
- batch-by-batch modulation of the damper gain

The latter can be used to study the impact of damper gain on the emittance and on the quality of the BBQ signal, in view of a short-term improvement in the ADT-tune feedback compatibility.

In the quest for a higher beam energy with a physically smaller beam, it is desirable to improve the noise level in the ADT systems. Means to do this include improvement of cabling, electronics, signal processing and the use of more than the present set of two pickups per plane and beam. While there are no limitations expected to come from ADT for the target beam energy of 4 TeV for 2012, studies must be carried out in 2012 to define the improvements needed for after LS1 for operation towards 7 TeV design energy.

ACKNOWLEDGEMENTS

The 2012 ADT results have been the achievement of a large number of people. The Author wishes to thank in particular D. Valuch and the members of the RF group that have contributed to the smooth running of the ADT system and the numerous upgrades in 2012. Results from machine studies have been quoted in this report which are again the result of larger teams and the operations group of BE department. The Author wishes to thank them for the fruitful collaboration in these studies.

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