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## Abstract

The LHC transverse dampers initially built to control transverse instabilities are also a good remedy to suppress the oscillations causing emittance growth excited by electro-magnetic noise at the frequencies of betatron sidebands. To prevent the emittance growth excited by the damper itself, it has to have extremely low noise. The paper presents experimental results obtained during the 2010 LHC run and their comparison with simulations of the suppression of these externally excited oscillations and subsequent emittance growth suppression. Recent analysis of emittance growth in LHC shows that there is a missing contribution that cannot be explained by IBS and for which the interplay of the transverse damper with its intrinsic noise and external sources of noise may be the cause. A further reduction of the noise in the damper system is highly desirable. Possible improvements in the damper system to enhance its effectiveness with respect to the suppression of emittance blow-up are also discussed.

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*Abstract*

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## INTRODUCTION

In 2010 the successful beam commissioning of the LHC damper [1] resulted in a suppression of transverse emittance growth so that emittances smaller than 2.5 $\mu$m (well below the design value of 3.75 $\mu$m [2]) could be brought in collision. The noise intrinsic to the damper system was sufficiently low, and it has allowed to keep the feedback running during the Physics fills with beam lifetimes of 100 hours and emittance growth time constants in excess of 20 hours for nominal bunch intensities of $\simeq 1 \times 10^{11}$ protons per bunch.

If the damper is off any external source of dipolar excitation can drive the beam motion at betatron frequencies leading to measurable coherent oscillations. The tune spread of particle betatron motion leads to a decoherence of particle motion in a bunch and limits its coherent betatron amplitude. However, this decoherence leads to emittance growth [3]. Abnormal high excitation, particularly in the vertical plane and for beam 2, of the betatron motion was observed in 2010. This excitation was not constant in frequency and amplitude. Observations showed that it has a comparatively narrow spectrum with slowly changing frequency [4]. When the excitation frequencies overlap with the betatron frequencies a fast transverse emittance blow-up was observed. Without resolving this issue a normal operation of the LHC in a collider mode would be impossible. This phenomenon motivated the present study which was focused on the suppression of external noise using the transverse feedback system. Following successful tests it was decided during the run 2010 to operate the transverse feedback system at values of gain higher than originally anticipated.

## OBSERVATIONS

### *Effect of feedback on moving perturbation*

Results from the tests with variable gain of the transverse feedback system are summarized in Fig. 1. It shows a spectogram of the vertical oscillations of beam 1 at injection energy of 450 GeV in the range of 0.2 to 0.4 of tune over time [4]. The spectogram was acquired using the damper pickups.

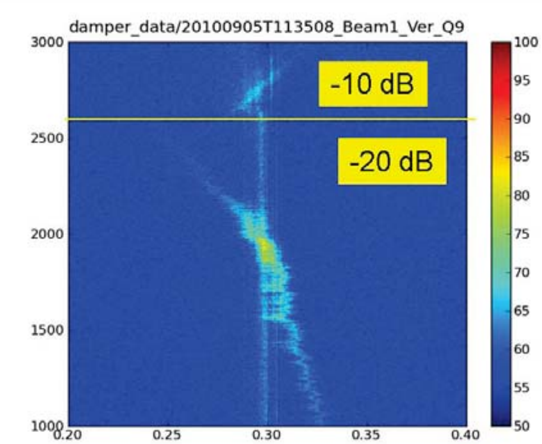


Figure 1: Effect of damper with different gain settings on the tune spectrum, vertical plane beam 1 at injection plateau of 450 GeV; the effect on a moving perturbation (”hump”) can be seen [4].

By probing with a single bunch or by averaging spectra over all bunches present in the machine, one cannot distinguish if a perturbation observed at a normalised frequency $\nu = f/f_{\rm rev}$ is caused by a low frequency below $f < f_{\rm rev}$ or if the exciter is located at a frequency offset by an integer multiple of the revolution frequency $f_{\rm rev}$. Moreover, due to aliasing the effect on the beam of an exciter at a normalised frequency of $\nu$ will also be visible in the beam spectrum at $1 - \nu$. For the case of a sufficiently coherent exciter frequency its exact frequency can be located by observing the oscillation pattern of many bunches. The analysis from data collected using the damper pickups during the 2010 LHC ion run with 500 ns bunch spacing points to exciter frequencies in the range of several hundred kHz [6].

### *Narrow band perturbations*

In addition to the moving perturbations described in the previous section fixed frequency narrow band perturbations of the beam in LHC can be observed causing small transverse oscillations. The battery backed-up 400 V power distribution system for critical systems is suspected to cause the 8 kHz and 5 kHz lines, although the entire set of equipments injecting these perturbations onto the beam could not be identified. A contribution caused by the transverse damper system itself had already been identified in 2009 and corrected by means of suppressing the 8 kHz interference penetrating coaxial links. Fig. 2 shows a zoom of the

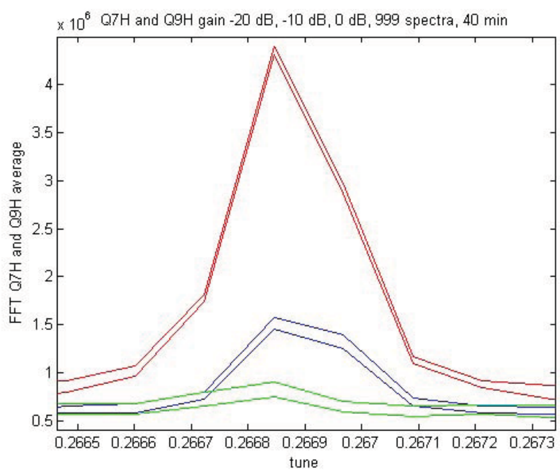


Figure 2: Effect of damper gain increase (10 dB steps, lowest gain: red, highest gain: green) on spectrum observed with damper pickups, horizontal plane beam 1 (top); reduction of a 3 kHz perturbation.

horizontal beam 1 spectra (with different feedback gains) as acquired by the two damper pickups using the electronics of the feedback system [7]. The narrowband perturbation is reduced by increasing the gain in 10 dB steps. The displayed perturbation is observed at 0.2669 in normalised frequency, likely to be caused by an equipment operating at 3 kHz exact (the line is likely due to 12-pole thysristor bridge power converters as those powering the main bend circuits and some warm dipoles).

## COMPARISON WITH THEORY

### *Single versus multi-bunch case*

In the following we will restrict the analysis to the single bunch case. In practice the LHC damper "power" bandwidth, i.e. the regime in which we can operate at high gain and high kick strength, is limited to 1 MHz with gains at 20 MHz reduced to $\simeq 10$ % of the low frequency gain. Filling schemes for the protons Physics run in 2010 featured bunch spacings larger or equal to 1 $\mu$s until mid September 2010, such that all bunches can be considered treated separately by the LHC transverse feedback system, justifying the "single bunch" approach taken in the following. We also expect magnet noise and external perturbation to have large amplitudes mainly in the lower frequency range. Should there be higher frequency perturbations well beyond the 1 MHz power bandwidth of the transverse feedback system, then these will be less efficiently suppressed. For the operation with bunch trains which started end of September 2010, the frequency characteristics of the feedback must be duly taken into account.

In order to correctly predict the effectiveness of the transverse feedback system to suppress external noise on the beam, simulations are required that take into account the actual implementation of the signal processing chain. Conveniently accessible by measurement are the residual oscillations of bunches as recorded by the digital part of the feedback loop in the damper system.

### *Turn-by-turn simulation of the Damper system*

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 loop [7]. It can be described by the following turn-by-turn map [8]:

$$\begin{aligned} z_{n+1} &= \mathrm{e}^{i\mu_3}\left(\mathrm{e}^{i(\mu_2+\mu_1)}z_n - i\delta\hat{\theta}_n\right) \ , \\ \delta\hat{\theta}_n &= g_1 \sum_{k=0}^{K-1} A_k^{(1)} X_{n-k-n_\mathrm{d}} \\ &+ g_2 \sum_{k=0}^{K-1} A_k^{(2)} Y_{n-k-n_\mathrm{d}} \ , \\ X_n &= \mathrm{Re}\{z_n - z_{n-1}\} + \frac{\delta x_n^{(1)} - \delta x_{n-1}^{(1)}}{\sqrt{\beta_\mathrm{p1}}} \ , \\ Y_n &= \mathrm{Re}\{\mathrm{e}^{i\mu_1}(z_n - z_{n-1})\} + \frac{\delta x_n^{(2)} - \delta x_{n-1}^{(2)}}{\sqrt{\beta_\mathrm{p2}}} \ , \end{aligned} \tag{1}$$

where $z = x/\sqrt{\beta} - i(\sqrt{\beta}\theta + \alpha x/\sqrt{\beta})$ is the complex bunch coordinate with $x$ and $\theta$ being actual bunch position and angle; $n$ enumerates turns so that the beam coordinates are referenced to pickup 1, $\beta$ is the beta-function which is equal to $\beta_\mathrm{p1}$ and $\beta_\mathrm{p2}$ in pickups 1 and 2; $\alpha = -\beta'/2$; $\mu_1$ is the betatron-phase advance between pickups 1 and 2, $\mu_2$ between pickup 2 and kicker, and $\mu_3$ 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. Pickups and kickers are closely spaced in the tunnel, however the electronic signal delay and the synchronization delays require a total lead loop delay of $n_{\rm d} = 2$ turns, i.e. the first non-zero value appears two turns after beam injection at the output of the digital filter chain. For small gains, $g_{1,2} \ll 1$, the damping rate (expressed in the inverse number of turns) is:

$$\begin{aligned} g_{\rm d} &= && g_{\rm d1} + g_{\rm d2} \qquad (2)\\ g_{\rm d1} &= &-& g_1 \sin(\mu_0/2) \\ && \times & \; {\rm e}^{-i(\mu_1+\mu_2+\mu_0(n_{\rm d}+1/2))} \sum_{k=0}^{K-1} A_k^{(1)} {\rm e}^{-i\mu_0 k} \\ g_{\rm d2} &= &-& g_2 \sin(\mu_0/2) \\ && \times & \; {\rm e}^{-i(\mu_2+\mu_0(n_{\rm d}+1/2))} \sum_{k=0}^{K-1} A_k^{(2)} {\rm e}^{-i\mu_0 k} \; , \end{aligned}$$

where $\mu_0 = \mu_1 + \mu_2 + \mu_3$. For the optimal system, i.e. the one with minimized impact of the pickup noise on the emittance growth, the coefficients of both digital filters have to be chosen such that the imaginary parts of $g_{d1}$ and $g_{d2}$ are equal to zero. For this case the susceptibility to pickup noise does not depend on the choice of coefficients, i.e. filtering. We used a Hilbert filter, ($S = \sin\psi$, $C = \cos\psi$)

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

which is parametrized by a single angle, $\psi$. For both systems $\psi$ was chosen so as to minimize ${\rm Im}\{g_{\rm d1,2}\}$. Rewriting Eq. (51) of Ref. [3] one obtains that the emittance growth is:

$$\begin{aligned} \frac{{\rm d}\varepsilon}{{\rm d}t} &= \frac{16\pi^2\overline{\Delta\nu^2}}{\left({\rm Re}\{g_{\rm d}\}\right)^2 + 16\pi^2\overline{\Delta\nu^2}} \qquad (4)\\ &\times \left[ \left(\frac{{\rm d}\varepsilon}{{\rm d}t}\right)_0 + f_0 \left( |g_{\rm d1}|^2 \frac{\overline{\delta x_1^2}}{\beta_{\rm p1}} + |g_{\rm d2}|^2 \frac{\overline{\delta x_2^2}}{\beta_{\rm p2}} \right) \right] , \end{aligned}$$

where $f_0$ is the revolution frequency, and $\sqrt{\overline{\Delta\nu^2}}$ is the rms spread of betatron tunes. As one can see an increase of the gain reduces the emittance growth as long as the second term is smaller than the first one. With further gain increase the dependence on the gain disappears and the emittance growth is proportional to $\overline{\delta x^2}$. Numerical simulations on the propagation of noise from the damper pickups in the feedback loop showed good agreement with observations as depicted in Fig. 3.

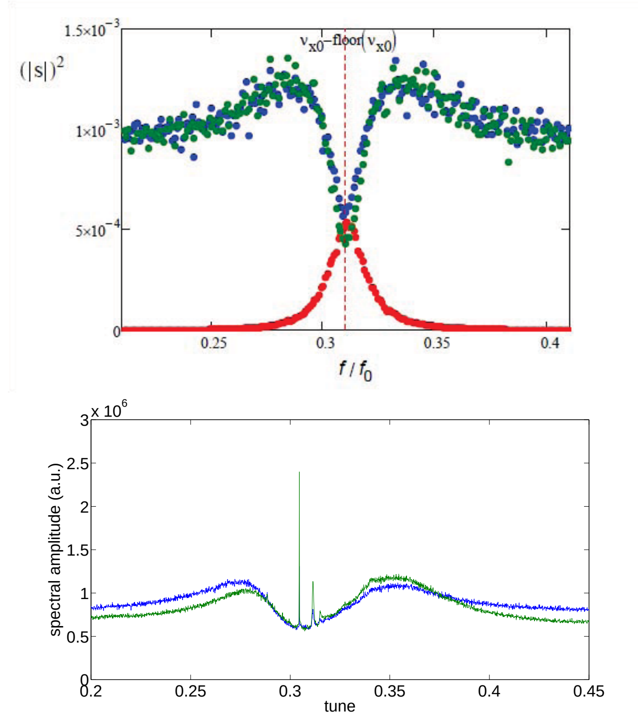


Figure 3: Simulated spectra of the feedback noise floor from two pickups of a damper (top, green and blue dots) and residual beam oscillation below detection limit of feedback (top, red dots); measured spectra of two pickups (bottom, averaged over 800 spectra); narrow band perturbations visible.

## SUMMARY AND OUTLOOK

The LHC run in 2010 has shown that the transverse feedback system is an indispensable ingredient to limit the transverse blow-up by external noise. In order to be most efficient the feedback itself must be low noise and adjusted to act purely as a resistive feedback. Further improvements in the noise floor of the feedback system are advised in particular in view of operation at 7 TeV.

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