BEAM TESTS OF THE LHC TRANSVERSE FEEDBACK SYSTEM

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Abstract

A powerful transverse feedback system ("Damper") has been installed in LHC in order to stabilise the high intensity beams against coupled bunch transverse instabilities in a frequency range from 3 kHz to 20 MHz and at the same time to damp injection oscillations originating from steering errors and injection kicker ripple. The LHC Damper has been also used for exciting transverse oscillations for the purposes of abort gap cleaning and tune measurement. The LHC Damper includes 4 feedback systems on 2 circulating beams (in other words one feedback system per beam and plane). Every feedback system consists of 4 electrostatic kickers, 4 push-pull wide band power amplifiers, 8 preamplifiers, two digital processing units and 2 beam position monitors with low-level electronics. The power and low-level subsystem layout is described along with first results from the beam commissioning of the LHC Damper.

INTRODUCTION

The powerful transverse feedback system ("Damper") for the Large Hadron Collider (LHC) is a joint project of the European Organization for Nuclear Research (CERN) and the Joint Institute for Nuclear Research (JINR) [1, 2]. To a large extent this project is based on the system in the SPS which has operated successfully for many years [3, 4].

The peak luminosity of 1.0×10^{34} cm^{-2}s^{-1} is achieved in the LHC with high intensity beams of low emittance. The ultimate intensities after injection into the LHC will be about 4.8×10^{14} particles for the proton beam with an energy of 450 GeV and 4.1×10^{10} ions for the $^{208}\mathrm{Pb}^{82+}$ beam with an energy of 177 GeV/u. These intensities can lead to coherent transverse instabilities. The theoretical prediction for the instability rise time τ_{inst}, dominated by the resistive wall effect, is about 18.5 ms or 208 turns [5] at injection energy for the proton beam, and a significant contribution of the LHC collimators at collision energy to τ_{inst} is also predicted [6].

The normalised transverse emittance ε is expected to be smaller than 3.75 mm·mrad at collision energy. The damping time τ_{d} of the LHC transverse feedback system (TFS) was chosen to limit the emittance growth due to injection errors [7, 8]:

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{e_{\mathrm{inj}}^2}{2\sigma^2} F_\varepsilon \, ; \qquad F_\varepsilon = \left(1 + \frac{\tau_{\mathrm{dec}}}{\tau_{\mathrm{d}}} - \frac{\tau_{\mathrm{dec}}}{\tau_{\mathrm{inst}}}\right)^{-2} . \quad (1)$$

Here σ is the initial RMS beam size; $e_{\mathrm{inj}} \lesssim 4$ mm $= 3.5\sigma$ is the maximum assumed amplitude of a beam deviation from the closed orbit due to displacement and angular errors at injection where the betatron amplitude function is $\hat{\beta} = 185$ m; $\tau_{\mathrm{dec}} \simeq 750 \times T_{\mathrm{rev}} = 68$ ms is the assumed decoherence time (the revolution period of protons in the LHC is $T_{\mathrm{rev}} = 88.93$ μs after injection). These parameters lead to $\Delta\varepsilon/\varepsilon < 2.5\%$ the maximum admissible emittance blow-up in the LHC allocated to injection dipole errors [5] if $\tau_{\mathrm{d}} = 40 \times T_{\mathrm{rev}}$. Thus, the LHC TFS gain is $g = 2T_{\mathrm{rev}}/\tau_{\mathrm{d}} = 0.05$ and the overall damping time $(1/\tau_{\mathrm{d}} - 1/\tau_{\mathrm{inst}})^{-1}$ of the injection oscillations becomes about 50 turns or 4.4 ms.

The nominal LHC beam represents an unprecedented stored energy of 350 MJ [5]. The extremely high destructive power of such a beam imposes an external dump, where the beam must be extracted completely from the LHC, diluted to reduce the peak energy density and then absorbed in a dedicated system. A gap of 3 μs in the circulating bunch pattern is present to allow the horizontally deflecting extraction kickers to rise up to their nominal field. Since particles transiting the kickers during their field rise will not be dumped properly, the proton population in this interval must always remain below damage and quench limits. The control of the abort gap population is a problem common to high energy machines using superconducting magnets. Cleaning of the abort gap using the LHC transverse dampers should require no more than a few tens of milliseconds [9].

The LHC Damper will stabilize the beam against coupled bunch instabilities as well as damp the transverse oscillations of the beam originating from steering errors and kicker ripple. It will also be used for the purposes of tune measurement similar to the SPS system [10] and for abort gap cleaning.

GENERAL DESCRIPTION

The LHC Damper has 4 independent transverse feedback systems on 2 circulating beams (one feedback system per beam and transverse plane). Each system is a classical bunch-by-bunch transverse feedback system (see Fig. 1) [11]. It consists of 2 pick-ups (PU), a 4 section damper kicker (DK) and an electronic feedback path with appropriate signal processing and transmission from PU to DK. The DK corrects the transverse momentum of a bunch in proportion to its displacement from the closed orbit at the PU location. The digital signal processing unit (DSPU) ensures the adjustment of the feedback to the phase advance and the beam time of flight for optimum damping. The mixing of signals from 2 pick-ups allows adjustment of the betatron oscillation phase advance ψ_{PK} from the "virtual" PU to the DK to an odd multiple of $\pi/2$.

The total delay τ_{delay} in the signal processing of the feedback path from PU to DK adjusts the timing of the

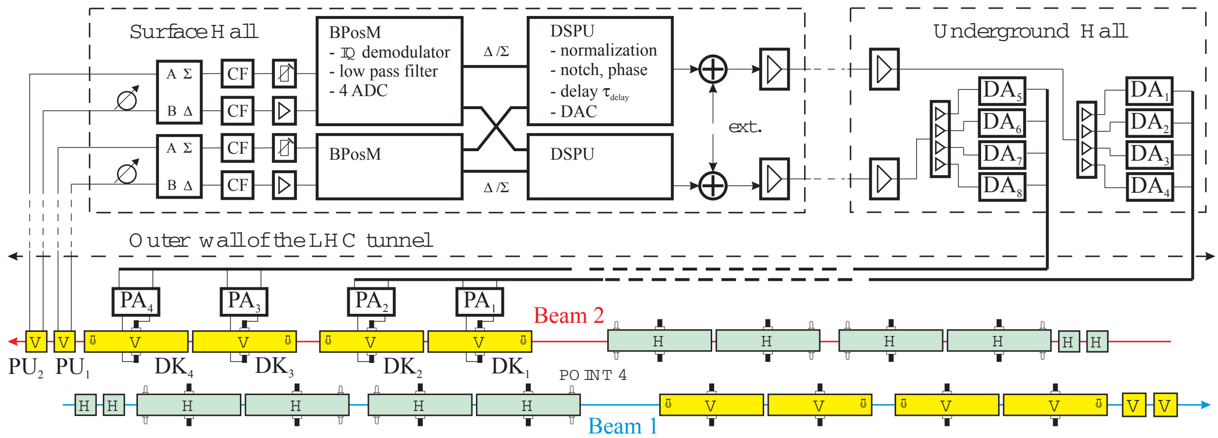

Figure 1: Layout of the LHC Damper and block diagram of the transverse feedback system for vertical oscillations.

signal to match the bunch arrival time. It equals τ_{PK}, the time of flight of the particle from PU to DK, plus an additional delay of $\hat{q}$ turns:

$$\tau_{\text{delay}} = \tau_{\text{PK}} + \hat{q}\,T_{\text{rev}} \,. \quad (2)$$

For vertical oscillations in the LHC (see Fig. 1), the delay τ_{delay} is slightly *shorter* than one beam revolution period $T_{\text{rev}} = 88.93\ \mu$s and $\hat{q}_{\text{V}} = 0$. For the horizontal systems, kicker *downstream* of the PU, an additional delay of one turn ($\hat{q}_{\text{H}} = 1$) is added. The delay τ_{delay} is then slightly *longer* than one turn.

The main instability that the feedback has to handle is the resistive wall instability for which the lowest frequency in the LHC is about 8 kHz ($Q_{\text{H}} = 64.28$ and $Q_{\text{V}} = 59.31$). For purposes of abort gap cleaning the unwanted beam should be coherently excited at frequencies (in accordance with the non-integer parts of the tune) gated in the 3 μs long abort gap. Consequently a lower cut-off frequency of 1 kHz was chosen for the feedback loop. The highest frequency must be sufficient to damp the dipole mode oscillation of two neighbouring bunches which corresponds to $f_{\text{max}} = 20$ MHz for the nominal bunch spacing of 25 ns. Coherent oscillations at higher frequencies are assumed to be suppressed by Landau damping. The pulse response must cope with the minimum gap between batches in the LHC (995 ns). Consequently, a rise time (1–99% V_{max}) of 720 ns was chosen for the power amplifier.

The gain g and the maximum injection error e_{inj} yield the maximum deflection $\theta_{\text{max}} = 2\ \mu$rad required for the proton beam with energy 450 GeV and the location of the kickers at $\hat{\beta}_{\text{K}} \gtrsim 100$ m. The deflection θ_{max} is delivered by electrostatic kickers with an aperture of 52 mm. The total required deflecting length of 6 m is divided into 4 kickers to limit the capacitive loading of the power amplifiers. The nominal voltage at 1 MHz is $V_{\text{max}} = \pm 7.5$ kV [2].

Beam oscillations are measured by eight dedicated coupler type pick-ups (49 mm aperture, 15 cm in length), two per transverse plane and beam (see Fig. 1). Signals from each pick-up are transmitted by coaxial lines of 570 - 650 m length to the surface building where signals after delay equalization are combined and subtracted by a hybrid (2 − 2000 MHz) providing Σ and Δ signals. Strip-line comb filters (CF) generate wavelets at 400.8 MHz lasting for 9 RF periods which are then passed to variable attenuators or low noise amplifiers according to the signal levels.

The signals are then processed by the Beam Position Module (BPosM) where they are IQ-demodulated, low pass filtered, sampled and digitized (16 bit analog-to-digital converter, ADC) to compute for each bunch the normalised transverse beam position Δ/Σ at 40 MS/s rate on an FPGA (field-programmable gate array).

The normalised position signal Δ/Σ is transmitted via a 1 Gbps serial link to the Digital Signal Processing Unit (DSPU) with FPGA operating at 40 MS/s rate with the following functionalities: 1) normalization of signals proportional to $\hat{\beta}^{1/2}$ at the corresponding PU locations, 2) closed orbit rejection (notch filter), 3) sample hold circuit, 4) 7 tap phase shifter, 5) phase adjustment by mixing of PU signals to obtain the "virtual" pick-up signal, 6) delay (with 10 ps resolution), 7) three 32 tap filters, 8) digital-to-analog converter, DAC, plus other built-in features allowing the user full remote operation and diagnostics. The sample hold circuit is used for damping of single bunch oscillations by holding the transverse position value in the FPGA memory for $\lesssim 255$ sampling periods in order to produce a long output pulse that allows the operation of the power amplifiers in the low frequency range up to 1 MHz. The 7 tap phase shifter allows to adjust the phase advance of the feedback loop. The 32 tap FIR (finite impulse response) filters are used to compensate the power amplifier phase response, to optimise the feedback gain for injection error damping and instability control as well as to shape the roll-off beyond 20 MHz. Overall loop gain adjustment is provided via the reference to the 14 bit DAC.

Two output analog signals from the 1 W predriver amplifier after the DACs (see Fig. 1) are transmitted via coaxial lines (∼300 m) to the underground hall in a cavern outside of the LHC ring where the signal is again amplified and split to drive the eight solid state 200 W driver amplifiers (DA) per system. The signals are finally transmitted to the power amplifiers (PA) and kickers (DK).

16 power amplifiers are installed directly under the 16 electrostatic kickers (see Fig. 2) in the LHC tunnel on either side of Point 4 (see Fig. 1). Each pair of electrodes is driven in counter phase by one wideband power amplifier, consisting of two 30 kW grounded cathode tetrodes RS–2048–CJC (Thales®) operated in class AB (push-pull). At low frequency the amplifier works on a relatively large impedance ($\sim$1 kΩ) leading to a large kick voltage. At higher frequency the capacitance of the kicker plates shunts the impedance and consequently less kick strength is available.

Figure 2: Kickers and amplifiers in the LHC tunnel.

The surface building also houses the 56 power converters for the power amplifiers in the tunnel at a distance of about 600 m: 8 converters for the tetrode anode voltage operating at a voltage/current of 12 kV/7 A, 16 converters of 1000 V/1 A, 32 converters of 300 V/0.2 A for the auxiliary voltage.

The hardware commissioning of the LHC transverse damper system has been successfully completed in 2008. The performance specifications and the obtained characteristics of the power amplifiers in conjunction with the 200 W driver amplifiers are shown in Tab. 1.

Table 1: Parameters of amplifiers

Parameter	Required	Achieved
nominal voltage at 1 MHz	$\pm$7.5 kV	$\pm$7.8 kV
nominal –3 dB bandwidth, kHz	3–1000	2–950
rise-time 10–90% $V_{\max}$	350 ns	410 ns
rise-time 1–99% $V_{\max}$	720 ns	760 ns
gain ripple	0.7 dB	0.5 dB

The design specifications were all met and the system has been successfully used with first beam in September 2008, exciting transverse oscillations for the purpose of tune measurement [2].

HARDWARE TUNING

Power Amplifiers

Since 2008, all the sixteen amplifiers have been in operation for, up to date (September 2010), approximately 8500 hours without any major down time. Some modifications have been implemented to the air cooling system to slightly improve it, by adding two extraction blowers, reinforcing the air flow through the critical components.

However, it has been found that tetrodes offer significant different control grid $U_{\rm g1}$ versus anode current $I_{\rm a0}$ characteristics. It has been decided to arrange tetrodes by pairs, with each pair offering as similar as possible characteristics. The rearrangement of tetrodes was done during 2010 in two short technical stops. Fig. 3 shows the differences before (red dashed curves) and after (green solid curves) readjustment on one of the most significantly modified amplifiers.

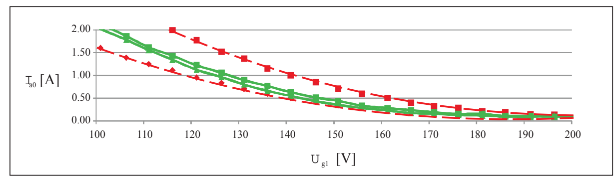

Figure 3: Anode current $I_{\rm a0}$ versus control grid value $U_{\rm g1}$ applied in an amplifier.

Since May 2010, all amplifiers now have similar characteristics, and while changing tetrodes during maintenance, it will be an important parameter to check.

The new settings for maximum operational values have been decided as follows: anode voltage of 12 kV applied with a screen grid voltage of 900 V and a biasing current of 1.2 A per tetrode that leads to peak pulse voltages of $\pm$7.5 kV at 1 MHz on the plates of kickers.

After all corrections have been applied, there were no major breakdowns due to power amplifiers, whilst amplifiers have been extensively used.

Electronics

Coefficients for mixing of pick-up signals in the DSPU were calculated in accordance with measurements of betatron phase advances between pick-ups $Q7$ and $Q9$ (PU$_1$ and PU$_2$ in Fig. 1) in horizontal (H) or vertical (V) planes for all dampers. Transverse oscillations of a bunch were

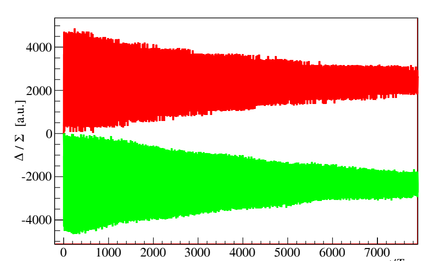

Figure 4: Signals from $Q7$ (top trace) and $Q9$ (bottom trace) pick-ups (vertical oscillations, beam 2).

induced by the Q-kicker with a pulse duration of about one revolution period, and the corresponding data (see Fig. 4) from pick-ups $Q7$ and $Q9$ were recorded at every turn. Then polar plots for the Fourier transform coefficients from the data recorded were used to determine phases at the betatron frequency that correspond to maximal amplitudes (see Fig. 5). Measured betatron phase advances at injec-

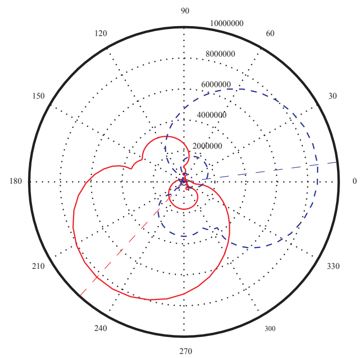

Figure 5: Amplitude–phase plot for signals from $Q7$ (solid curve) and $Q9$ (dashed curve) pick-ups.

tion between pick-ups $Q7$ & $Q9$ for all dampers are shown in Tab. 2. The values in Tab. 2 are in good agreement with data from the corresponding optics version of the LHC machine.

Table 2: Measured phase advances between pick-ups

Position of pick-ups (left or right of point 4) for beam 1 (B1) or beam 2 (B2)	Phase advance, degrees	Delta with respect to 90°
H.B1, left of 4, $Q9 \rightarrow Q7$	115	25
H.B2, right of 4, $Q9 \rightarrow Q7$	107	17
V.B1, right of 4, $Q7 \rightarrow Q9$	56	34
V.B2, left of 4, $Q7 \rightarrow Q9$	137	47

Signals from the higher order mode (HOM) couplers (50 Ω vacuum feedthrough with a small plate attached that capacitively couples to the kicker deflecting plates) was used for tuning the TFS synchronization circuit. Matching of the kick voltage generated by the feedback system and the beam voltage induced by a bunch that passes the kicker was used as a criteria for the synchronization procedure.

LHC Damper pick-ups were calibrated with data from the closed orbit pick-ups located in the same cryomodule. The calibrated pick-ups measure a deviation of the beam centre of gravity from the electrical centre of the pick-up, and data measured can be displayed in millimetres. With the present gain settings in BPosM ($< 1.3 \times 10^{11}$ protons per bunch of length > 1 ns at a saturation of ± 2 mm) an amplitude resolution of about 1 μm was obtained. A further improvement of the S/N ratio and resolution require to improve the analog circuit before digitization.

BEAM TESTS

Single Bunch Operation

First results of active damping with the LHC Damper were obtained for one bunch with an intensity of 1×10^{10} protons at 450 GeV in beam 2 in May 2010. Then all damper systems, for a single bunch injected from the SPS into the LHC, were tuned. The damping effect for injection errors is shown in Fig. 6 for the nominal intensity of $\sim 1 \times 10^{11}$ protons per bunch.

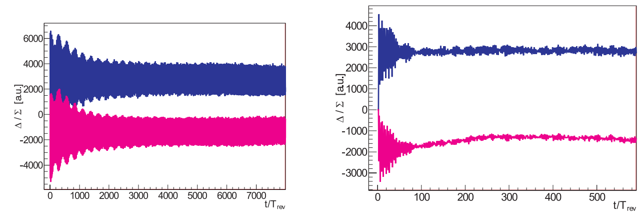

Figure 6: Damping of horizontal injection errors (beam 1): damper OFF (on the left) and ON (on the right); signals from $Q7$ (top trace) and $Q9$ (bottom trace) pick-ups.

Damping times can be modified by the feedback loop gains (see Fig. 7). A damping time of 40 turns was achieved that corresponds to the LHC Damper specification.

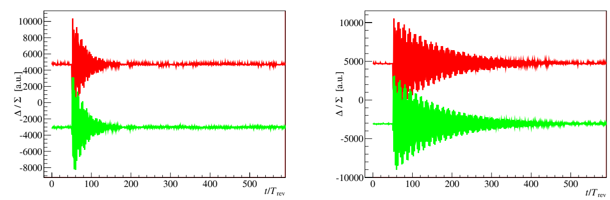

Figure 7: Damping of vertical oscillations (beam 2) induced by the Q-kicker: high (on the left) and lower (on the right) gains; signals from $Q7$ (top trace) and $Q9$ (bottom trace) pick-ups.

Table 3: Emittance measurements (20.05.2010)

Beam	ε_0, μm	ε, μm	Growth, %
H.B1	1.053	1.747	66
H.B2	1.009	1.603	59
V.B1	1.334	1.787	34
V.B2	1.305	1.487	14

Emittance measurements show better preservation for the plane for which the damper was used (V.B2, see Tab. 3, beam lifetime is > 100 hours at energy 3.5 TeV).

With the damper on the transverse emittance blow up at injection had been smaller than without the damper. Emittances of the order of 2.5–2.9 micron after injection were achieved.

The LHC Damper also has been tested during collisions with stable beam and everything worked as expected. The damping time at injection and during the ramp was approximately 70 turns, increasing to about 500 turns during collisions at 3.5 TeV. The damper is currently off during the squeeze (tune change) and for pilot bunches.

Bunch Train Operation

The LHC Damper was also used during beam tests for injection of groups of bunches (trains) from the SPS into the LHC in August–September 2010. Transverse oscillations of a whole train with four bunches (150 ns spacing) were induced by the Q-kicker. The damping effect was measured for different bunches in the train (see Fig. 8). It was observed that the damping time was the same as for single bunch operation.

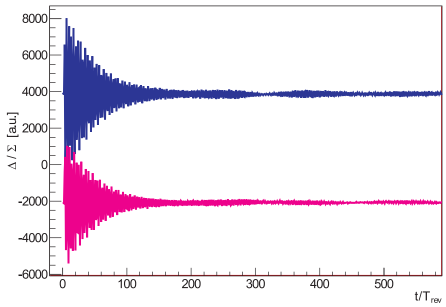

Figure 8: Damping of 150 ns bunch train excited by the Q-kicker (beam 2, horizontal oscillations); signals from Q_7 (top trace) and Q_9 (bottom trace) pick-ups, first bunch of the train.

Abort gap cleaning

The wide band power amplifiers allow the simultaneous use of the kickers for cleaning the abort gap and for feedback purposes. The flat top of the kicker pulse within the abort gap of 3 μs may be modulated as desired (see Fig. 9). Modulating the damper kicker pulse at a frequency corresponding to the transverse tune will resonantly excite transverse oscillations and drive particles to larger and larger amplitudes, until they are intercepted by the betatron collimators. A specific monitor [12] to measure the particle population of this gap has been designed based on the detection of synchrotron radiation produced by protons moving through the superconducting undulator for low beam energies or the superconducting dipole for beam energies higher than 1.5 TeV. The light intensity collected by the monitor changes both in intensity and spectrum as the beam energy is ramped up. Once the cleaning is started the synchrotron light production decreased proportionally to the gap population. During 2009 a first abort gap cleaning test was carried out with encouraging results [9].

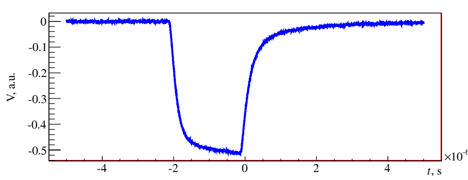

Figure 9: Signal from the kicker plates for abort gap cleaning regime (modulation at 3 kHz gives the slop at flat top).

CONCLUSIONS

Beam tests and commissioning of the LHC transverse feedback system have been successfully completed. All of the 16 damper kickers, 16 wideband power amplifiers and 8 low-level subsystems have been operating continuously since. The LHC Damper is now routinely used during injection, ramping and collisions for active damping.

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