LHC TRANSVERSE FEEDBACK SYSTEM: FIRST RESULTS OF COMMISSIONING

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Abstract

A powerful transverse feedback system ("Damper") has been installed in LHC. It will stabilise the high intensity beam against coupled bunch transverse instabilities in a frequency range from 3 kHz to 20 MHz and at the same time damp injection oscillations originating from steering errors and injection kicker ripple. The LHC Damper can also be used as means of exciting transverse oscillations for the purposes of abort gap cleaning and tune measurement. The LHC Damper includes 4 feedback systems on 2 circulating beams. The feedback system is described along with first results of the LHC Damper commissioning.

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]. To a large extent this project is based on the system in the SPS [2] which has operated successfully for many years, facing in recent years, the additional challenge from the electron cloud effect [3].

The LHC will provide high intensity proton and lead ion beams. The ultimate intensities after injection into the LHC will be about $4.8 \cdot 10^{14}$ particles for the proton beam with an energy of 450 GeV and $4.1 \cdot 10^{10}$ 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 [4] at injection energy, and a significant contribution of the LHC collimators at collision energy to τ_{inst} is also predicted [5]. 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 [6] and for abort gap cleaning [7].

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 (TFS, see Fig. 1) [8]. 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 phase advance and the correction of the 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 signal to match the bunch arrival time. It equals τ_{PK}, the particle flight of time from PU to DK, plus an additional delay of q turns:

$$\tau_{\mathrm{delay}} = \tau_{\text{PK}} + qT_{\mathrm{rev}}\,, \tag{1}$$

where T_{rev} is the revolution period of a particle in the synchrotron. The PU and DK are installed at locations with high β-functions. For vertical oscillations in the LHC (see Fig. 1), the delay τ_{delay} is slightly *shorter* than one beam revolution period $T_{\mathrm{rev}} = 88.93\ \mu$s and $q_{\text{V}} = 0$. For the horizontal systems, kicker *downstream* of the PU, an additional delay of one turn ($q_{\text{H}} = 1$) is added. The delay τ_{delay} is then slightly *longer* than one turn.

The damping time $\tau_{\mathrm{d}} = 40\ T_{\mathrm{rev}}$ of the LHC feedback was chosen to limit the emittance growth due to injection errors [9, 10]:

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

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

The gain g and the maximum injection error e_{inj} yield the maximum deflection $\theta_{\max} = 2\ \mu$rad required for the proton beam with energy 450 GeV and the location of the kickers at $\beta_{\text{K}} \gtrsim 100$ m. The deflection $\theta_{\max}$ is delivered by a set of 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 up to 1 MHz is $V_{\max} \pm 7.5$ kV.

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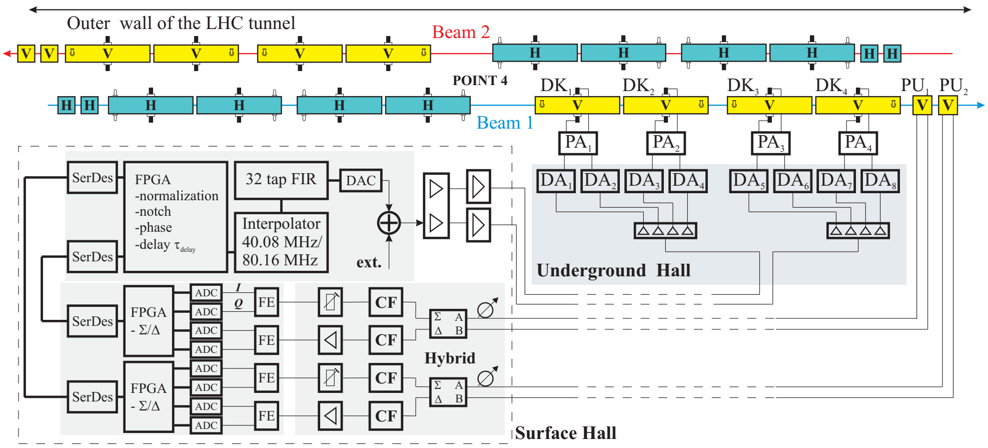


Figure 1: Layout of the LHC Damper and block diagram of the transverse feedback system for vertical oscillations.

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 ($Q_{\rm H} = 64.28$ and $Q_{\rm V} = 59.31$). 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 $f_{\rm max} = 20$ MHz for the nominal bunch spacing of 25 ns. Coherent oscillations at higher frequencies are assumed to be suppressed by Landau damping.

FEEDBACK LOOP

The feedback loop contains all functionalities for transverse damping and controlled bunch excitation as well as many built-in features allowing the user full remote operation and diagnostics.

Two 50 Ω strip-line pick-ups ($f_{\rm centre} = 500$ MHz) [11] are used to detect the betatron oscillations (see Fig. 1). Signals from each PU are transmitted by coaxial lines ($570-650$ m, $7/8''$ coaxial cable) to the surface hall where after delay calibration (by a cable delay of $\lesssim 5$ ns and a mechanically tuneable fine delay of $\lesssim 2.7$ ns) signals are combined and subtracted by a wideband hybrid ($\sim$1 GHz) providing Σ and Δ signals. Strip-line comb filters (CF) designed at CERN 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 first VME module, the Beam Position Unit (BPU) [12]. Its RF front-end (FE) converts the Σ and Δ signals to the I (In-phase) and Q (Quadrature phase) baseband signals (I/Q demodulator at 400.8 MHz reference clock and Gaussian type low-pass filter with a cut-off of $f_{\rm c} \simeq 40$ MHz). I and Q signals are digitized (16 bit ADCs) using a 40.08 MHz beam-synchronous clock needed for 20 MHz feedback bandwidth. The digitized I and Q values are used to compute for each bunch the normalised transverse beam position Δ/Σ at 40 MS/s rate on a FPGA semiconductor device.

The normalised position signal is serialized (SerDes) and transmitted via a 1 Gbps serial link to the second VME module, the Digital Signal Processing Unit (DSPU) [13]. After the deserializer (SerDes) the data stream is processed by an FPGA clocked at 40.08 MHz with the following functionalities: a) normalization of signals proportional to $\sqrt{\beta}$ at the corresponding PU locations; b) closed orbit rejection (notch filter); c) phase adjustment by mixing of PU signals to obtain the "virtual" pick-up signal; d) delay (with 10 ps resolution). A faster clock rate of 80.16 MHz is used for the further processing. The data at the 80.16 MHz sampling rate is obtained from expanding the 40.08 MHz data stream by inserting zeros between the original samples and applying an interpolating FIR filter. A second, 32 tap FIR filter, is then 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 a splitter after the DAC are passed to 1 W predriver amplifiers, are then transmitted via coaxial lines ($\sim$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 200 W driver amplifiers (DA). The signals are finally transmitted to the 4 power amplifiers (PA) and 4 kickers (DK) located in the LHC tunnel.

RF POWER SYSTEM

The RF power system of the LHC Damper was designed at JINR in collaboration with CERN. The wideband power amplifiers and electrostatic kickers were made by Russian industry and JINR. Final assembly and tests of the amplifiers and kickers were done at CERN.

The electrostatic kicker [1] consists of: a) a vacuum tank of stainless steel 304 L, 1.6 m length, $\varnothing$100 mm internal diameter and 14 mm wall thickness for optimal shielding of electromagnetic fields at low frequency and for mechanical stability; b) an electrode module with two electrodes (shaped from copper strips as 90° arcs) and 3 ceramic-metal rings (metallization by a thin layer of rhenium to evacuate any charges) to hold the electrodes and align of the electrode module inside the vacuum tank; c) two high voltage feedthroughs; d) two couplers capacitively coupled to the electrodes to damp high order modes which can be excited by the beam and lead to instability.

The estimated power loss to each electrode from circulating ultimate LHC beam current is $\sim$2 W/m. Tests under vacuum have shown that the temperature reaches 70°C when the electrodes are heated with 10 W/m [1].

Tests of the kickers confirmed their compliance with design specifications. Tolerances on the 100 mm tank internal diameter are in the range of $0\ldots+0.054$ mm, camming actions of main flanges ($\oslash 152$ mm) do not exceed 0.016 mm, the internal surface smoothness obtained is $R_\mathrm{a} = 0.4$ μm.

Standard vacuum cleaning procedures were used with a bake-out limited to <200°C due to the copper electrodes. NEG pumps [14] are used around the kickers in the LHC tunnel. During hardware and beam commissioning the vacuum at the kickers was better than 10^{-11} mbar.

16 power amplifiers (PA) are installed directly under the 16 electrostatic kickers (DK) (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. Simulations of possible variants of the power amplifier electrical circuit were made using MicroSim® PSpice® software [15].

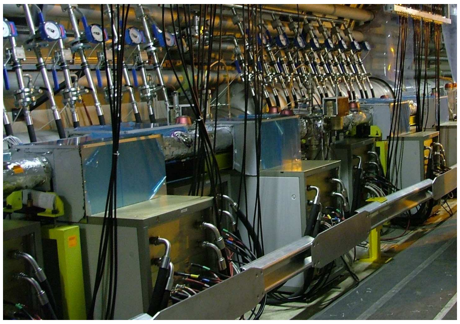


Figure 2: Kickers and amplifiers in the LHC tunnel.

HARDWARE COMMISSIONING

Beam stability is achieved for a damping rate

$$\frac{T_\mathrm{rev}}{\tau_\mathrm{d}} = \frac{1}{2} g(\omega) \cos\left(\varphi(\omega)\right) > \frac{T_\mathrm{rev}}{\tau_\mathrm{inst}},$$

where $g(\omega)$ and $\varphi(\omega)$ are gain and phase transfer characteristics of the feedback loop. The maximum gain of the power amplifier $g_\mathrm{a}(\omega)$ has been measured to be between 39 dB with an RF voltage divider sensing the tetrode anode RF voltage. The higher order mode couplers (HOM) can also be used to measure accurately the voltage at the kicker plates and spectrum of this signal $g_\mathrm{H}(\omega)$. The HOM couplers consist of a 50 Ω vacuum feedthrough with a small plate attached that capacitively couples to the kicker deflecting plates. The coupling capacitance of 6.4 pF and the 50 Ω loading at the HOM form a high pass with a cut-off of $f_\mathrm{HP} = 500$ MHz. The transfer function from kicker voltage to the voltage measured at the HOM port when loaded with 50 Ω is $\widetilde{F} = \mathrm{j}f/f_\mathrm{HP}/(1+\mathrm{j}f/f_\mathrm{HP})$.

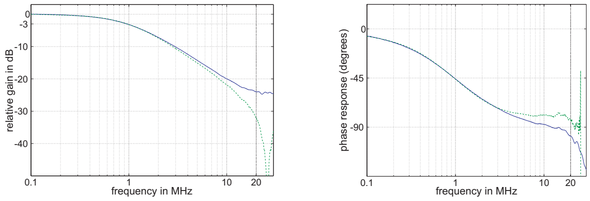


Figure 3: Gain (on the left) and phase response (on the right) characteristics for kicker voltage (solid) and tetrode anode voltage (dashed).

Fig. 3 shows the relative gain g_a and phase response φ_a versus frequency measured at the anode of the tetrode (dashed) and at the HOM port, corrected for the high pass response (solid). The latter represents $g(\omega)$ and $\varphi(\omega)$ or the voltage seen by the beam as a function of frequency. At the anode of the tetrode the gain characteristics exhibit a resonance at $\sim$25 MHz caused by the inductance of the connection to the kicker and the kicker capacitance. This resonance (notch in gain curve) is not seen on the kicker voltage transfer function $g(\omega)$. Below 3 MHz the phase responses measured via the HOM ports and on the anode voltage dividers perfectly match. The mismatch above 3 MHz is again caused by the resonance. The phase response will be compensated by FIR filters in the digital signal processing unit by adding phase at higher frequency in order to achieve an overall linear phase and constant group delay [13].

The performance specifications and obtained parameters of the power amplifiers in conjunction with the driver amplifiers are shown in Tab. 1.

Table 1: Parameters of amplifiers

Parameter	Required	Achieved
nominal voltage up to 1 MHz	±7.5 kV	±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

Power amplifiers and kickers were extensively tested in the run-up for beam commissioning. The design specifications have all been met, the available peak voltage of 11 kV at up to 100 kHz has exceeded the design value 10.5 kV.

FIRST RESULTS OF BEAM COMMISSIONING

The LHC Damper kickers at Point 4 were passed by beam 1 in ring 1 of the LHC on 7th September 2008 and by beam 2 in ring 2 on 10th September 2008. Signals from the LHC Damper pick-up for the first shot of beam 2 (about $2 \cdot 10^9$ protons in a single bunch) are shown in Fig. 4.

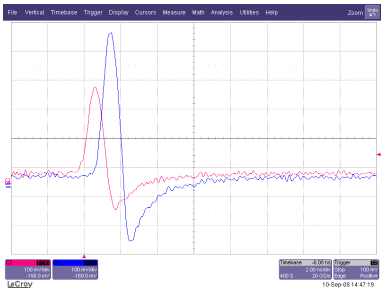
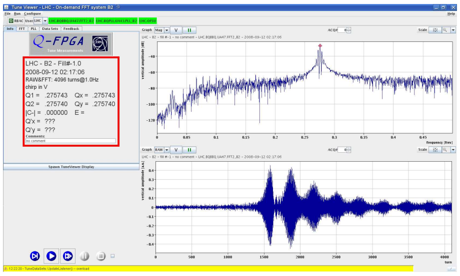


Figure 4: Signals from the LHC Damper pick-up for the first shot of beam 2. 10th September 2008.

Tune measurements [16] were the first operational task for the LHC Damper when it was used as an exciter after obtaining captured and circulating beam 2 on the 11th September 2008. The tune measurement system uses



LHC - B2 - Fill#-1.0
2008-09-12 02:17:06
RAW&FFT: 4096 turns@1.0Hz
chirp in V
Q1 = .275743 Qx = .275743
Q2 = .275740 Qy = .275740
|C-| = .000000 E =
Q'x = ???
Q'y = ???
Comments:
no comment

12:22:20 - TuneDataSets::UpdateListener() -- overload

Figure 5: A Tune Measurement using "Chirp" Excitation (courtesy of the AB/BI Group). The bottom trace shows the vertical beam response and the top trace is the spectrum of the signal with the vertical tune peak.

a direct input to the amplifiers in the tunnel to provide a swept frequency sinusoidal excitation to the beam. Fig. 5 shows the results of such a scan, with the applied amplitude of the wideband power amplifiers at only 10% of their maximum.

For damping of single bunch oscillations a special programming has been developed that holds the transverse position value in FPGA memory for one machine turn in order to produce a long output pulse that renders the set-up of the delays easy and operates the power amplifiers in the easier low frequency range up to 1 MHz. The LHC Damper is ready for commissioning with beam.

CONCLUSIONS

The hardware commissioning of the LHC transverse damper system has been successfully completed. 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. The commissioning with beam for the damping of transverse oscillations has started, pick-up signals verified and the low-level modules set-up for closing the feedback loop. Full operation is planned for the 2009 LHC run.

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