LHC DAMPER BEAM COMMISSIONING IN 2010

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Abstract

The LHC transverse dampers were commissioned in 2010 with beam and their use at injection energy of 450 GeV, during the ramp and in collisions at 3.5 TeV for Physics has become part of the standard operations procedure. The system proved important to limit emittance blow-up at injection and to maintain smaller than nominal emittances throughout the accelerating cycle. We describe the commissioning of the system step-by-step as done in 2010 and summarize its performance as achieved for proton as well as ion beams in 2010. Although its principle function is to keep transverse oscillations under control, the system has also been used as an exciter for abort gap cleaning and tune measurement. The dedicated beam position measurement system with its low noise properties provides additional possibilities for diagnostics.

INTRODUCTION

The main aim of the LHC transverse damping system [1, 2] is to provide stability for coupled bunch oscillations and to damp injection oscillations caused by steering errors and ripples from the SPS to LHC beam transport systems such as the LHC injection kickers and the SPS extraction kickers. The minimum bunch spacing of 25 ns in LHC calls for a feedback bandwidth of at least 20 MHz. As most of the injection error is contained within a bandwidth of $\simeq$ 1 MHz equal to the inverse of the batch spacing, 1 μs, the high gain regime is limited to 1 MHz. In the following we will describe the crucial steps for the setting-up of the transverse feedback loop and summarize the performance achieved with beam.

SYSTEM OVERVIEW

The hardware of the transverse damper system and the first results from commissioning have been previously reported [3, 4] along with detailed explanations of the block diagram of the system, reproduced in Fig. 1. In LHC there are four independent transverse damper systems, one per beam and transverse plane. Each of these four systems uses two dedicated pick-ups (PU) that provide bunch by bunch and turn by turn information of the beam position. This data stream is treated by the signal processing to compute a drive signal for the power system such that oscillations are correctly damped and beam stability is assured.

The high rigidity of the beam at the 450 GeV injection energy calls for a high kick strength (2 μrad). The power system was therefore split into four units, with two units forming a pair with common drive signal and DC powering. This scheme provides a certain redundancy protecting against beam loss due to an instability developing on the beam, should one of the two power systems per beam and plane trip. Figure 1 shows the layout with the damper kickers (DK), the tetrode power amplifiers (PA) and 100 W solid state driver amplifiers (DA), all installed underground at point 4 of the LHC. The signal processing with combline filter (CF), down conversion to baseband, and filtering using FPGA technology is all installed on the surface. This layout eases beam commissioning as the underground areas are not accessible with beam circulating in LHC.

INITIAL COMMISSIONING

Description of Signal Processing

To achieve the desired damping the kicks applied to the beam have to be correctly phased with respect to the detected oscillation and then sufficiently amplified. In order to provide the necessary phase adjustments two independent knobs are required, one adjusting the phase independently of the frequency and the second adjusting the timing of the kicks to complement all electronic delays and the beam time of flight between pick-up and kicker to an integer multiple of one turn.

The initial commissioning was carried out with a single bunch circulating in the LHC. Signal levels from the pick-ups can be adapted by means of additional amplifiers and attenuators for optimum performance of the mixers for the down conversion and best use of the range of the ADC. A 16 bit ADC is used for digitization of the baseband signals and a 14 bit DAC to re-convert to the analogue domain. More details on the VME boards designed for the signal treatment can be found in [5, 6]. The phase adjustment in the feedback loop is done by means of a Hilbert Filter [7] on each of the two pick-up signals which are then combined to produce a signal with improved signal-to-noise ratio.

Results of First Tests in April 2010

Commissioning of the feedback loop started in spring 2010 and damping was first achieved in April 2010 [8]. Figure 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 is filamenting (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).

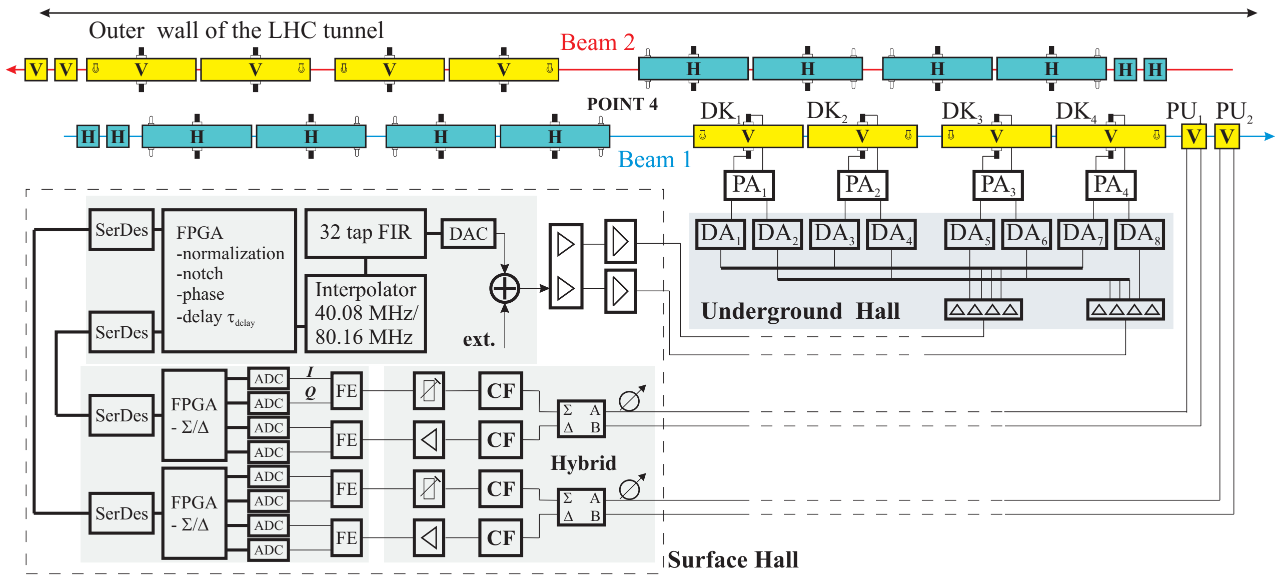

Figure 1: Block diagram of transverse damper system, reproduced from [3, 4].

Adjustment of Feedback Phase

Initial setting-up was done using a network analyzer and measuring the open loop beam transfer function [8]. 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 ΔQ introduced by the feedback as a function of the phase setting difference from optimal damping $\Delta\phi$

$$\Delta Q = -\frac{g}{4\pi}\Delta\phi \; , \qquad (1)$$

where g denotes the feedback gain. Optimal damping is achieved when the tune shift introduced by the feedback is zero when compared with the tune with damping loop open.

Due to the limited time allocated for setting-up the damper the more precise tune shift method was not used on all dampers. The residual phase errors are estimated to be smaller than 20° at 450 GeV (by comparing with values expected from the theoretical optics). The phase settings are being re-visited in the framework of the currently on-going setting-up for 25 ns bunch spacing which calls for more margin allocated for delay errors and therefore requires tighter control of all other errors.

Time Alignment of Kicks in Multi-bunch Mode

The kicker structure is equipped with a capacitive pick-up terminated externally in 50 Ω. It serves on the one hand to damp any higher order modes of the kicker structure and on the other hand to permit a beam based time alignment of the feedback kicks with the passage of the bunch in each of the 16 kicker structures. The damper systems were set-up and used for different bunch spacings: 500 ns (also called ”signal bunch mode”), 150 ns, 75 ns, 50 ns, all used and commissioned in 2010, and most recently 25 ns during machine development periods in 2011. For each of these bunch spacings the FPGA f rmware was conf gured to maintain the sampled beam positions of the individual bunches for a period equal to the used bunch spacing. The resulting kicks where then time aligned with their center to match the passage of the bunch in the kicker using a digital f ne delay.

Comparison with Design Goals

The principle design goals for the transverse feedback system were damping times of 40 turns at 450 GeV [2] 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 locations, the capabilities exceed expectations with respect to the maximum possible kick.

Typical damping times achieved were 20 to 40 turns both at injection energy and at 3.5 TeV. In practice lower gains were used with colliding beams yielding damping times of several hundred turns typically at 3.5 TeV.

From July 2010 onwards the system was operationally used throughout the cycle, from injection onwards and with colliding beams. Commissioning with bunch trains of 50 ns and 75 ns followed towards the end of the proton run in November 2010. During the ion run the damper was set-up for the low intensity of the ion bunches and again used for injection damping and also during Physics with colliding beams. It has contributed both for protons and ions to the excellent machine performance by limiting the transverse emittance growth resulting in the preservation of the

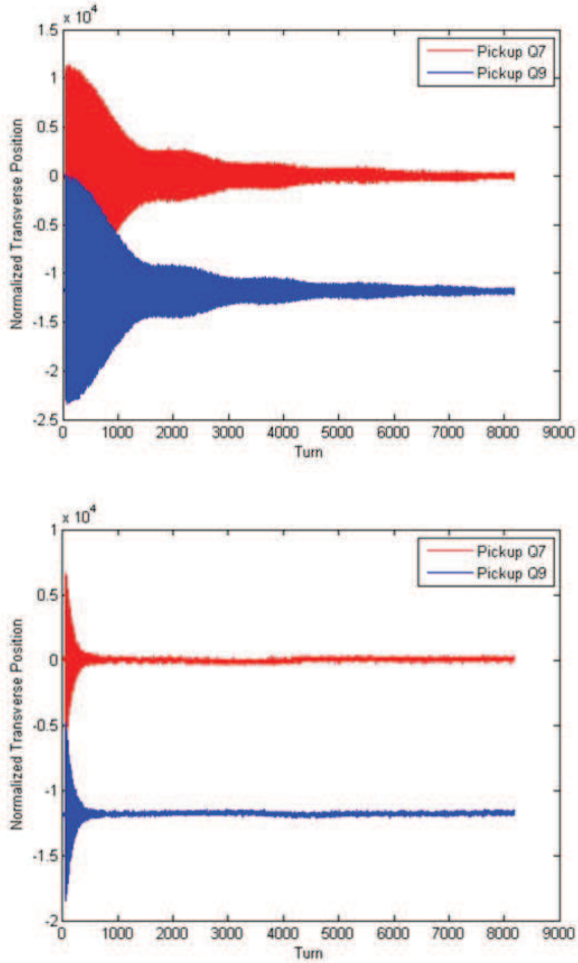

Figure 2: First successful Injection Damping, damper off (a) and damper on (b).

smaller than nominal emittances of the colliding beams.

The system was also used successfully for abort gap cleaning [9]. Aspects related to the high gain operation at 450 GeV to suppress external perturbations are reported elsewhere [10, 11].

SUMMARY AND OUTLOOK

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 future challenge will be to maintain the performance for the nominal LHC parameters with a bunch spacing of 25 ns and an energy of 7 TeV. This calls for a tighter control of delay errors and a reduction of the electronic noise in proportion to the decreased beam size at 7 TeV.

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