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COMMISSIONING OF A NEW DIGITAL TRANSVERSE DAMPER SYSTEM AT THE PSB

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Abstract

At the CERN Proton Synchrotron Booster, PSB, an analog transverse damper system has been in operation since 1999, providing satisfactory operational results with the proton beam supplied by Linac2. As a consequence of the LHC Injectors Upgrade, the PSB will face new challenges imposed by higher intensity, injection and extraction energy. In this framework, the transverse feedback system is subject to an upgrade to adapt to the expected Linac4 beam and to the demands for new features including transverse blow-up, beam excitation for optics measurements and new remote control and monitoring capabilities. The replacement of the aging electronic hardware is also recommended to improve the system maintainability for future years. During 2018 a new digital transverse feedback electronics was installed in the PSB, in parallel with the current operational one, offering for the first time the occasion to demonstrate its performance with beam. Encouraging results were obtained such as the suppression of beam instabilities at all PSB energies and intensities. In this paper we describe the steps undertaken in 2018 in order to commission the system with the main goal to accelerate and extract the highest intensity beams produced at the PSB.

INTRODUCTION

The CERN Proton Synchrotron Booster (PSB) is the first circular accelerator in the proton injector chain of the LHC and it is composed of 4 superposed rings that have a common injection and extraction beamline [1]. The PSB presently receives protons from the linear accelerator Linac2 at an energy of 50 MeV and accelerates them to 1.4 GeV. A transverse damper system has been successfully operated since 1999, allowing to accelerate proton beams with an intensity up to 1.1×10^{13} protons−per−ring (ppr) for the CERN fixed target physics program. The main source of coherent transverse instability in the PSB is currently observed in the horizontal plane, appearing around the kinetic energy of 160 MeV, for an intensity typically above 200×10^{10} ppr and with a tune ranging from 4.22 to 4.30. Recent studies in 2018 isolated the source of the impedance to the unmatched termination in the PSB extraction kicker [2].

In the context of the LHC Injectors Upgrade (LIU) project [3], the present Transverse Feedback system (TFB) is subject to an upgrade, using digital signal processing hardware together with new power amplifiers. The new system has been designed to adapt to the expected Linac4 beam [4]. The updated TFB has been specified to damp transverse instabilities from 160 MeV to 2.0 GeV, with an intensity up to 2.5×10^{13} ppr and a bandwidth up to 20 MHz. Another important reason for the upgrade was the replacement of the aging electronics hardware, an intervention which was advisable because of maintenance considerations.

This paper describes the procedure followed in 2018 to commission the new digital system, together with the results achieved.

TFB HARDWARE

The PSB TFB system consists of independent feedbacks per ring and plane, and is composed of an electrostatic pick-up in the straight section 4L5 and a stripline kicker located in the straight section 3L1, as outlined in Fig. 1. The working principle is as follows. Two opposing pick-up electrodes sense the electric field of the traversing beam and pass the signal to a head amplifier. Then a Beam Orbit Signal Suppressor (BOSS) actively removes the closed orbit beam position. A separate switch allows to select between the analog system or to use the new digital TFB, as during the 2018 run the analog system was still used for operation. Finally, a power amplifier stage provides the required voltage per kicker electrode fed back to the beam as a corrective force.

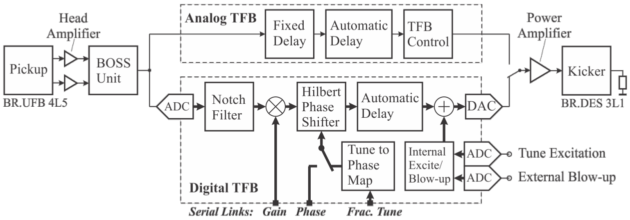

Figure 1: Simplified block diagram of the PSB TFB.

Following the signal path at the output of the BOSS unit through the analog hardware, one finds a fixed delay together with an automatic delay compensating for the time of flight between pick-up and kicker. In this scheme the TFB control module provides configurable gain, loop switching and a low pass filter limiting the bandwidth to 13 MHz.

For the new digital hardware, a VME card [5] is used for processing the sampled BOSS output generated by an on-board 14 bit analog-to-digital converter (ADC). The sampling clock as well as the FPGA clocking of the signal processing chain is synchronous to the beam revolution frequency (harmonic h=64). In the firmware a notch filter first digitally eliminates revolution harmonics, followed by a digital multiplication for controlling the closed loop gain.

At this point it is worth noting that, in the analog hardware, the betatron phase is not adjusted, leading to a feedback phase error over 0.8917 machine turns of [-34; 62] degrees

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for a tune in the range of [4.1; 4.4]. This potential mismatch in betatron phase is addressed in the new digital TFB by introducing a parametric Hilbert phase shifter. Thereby, the requested feedback phase can be configured either directly, or by proving the tune as input using a predetermined mapping of tune to phase, which takes into account the advance between pick-up and kicker, the inherent phase shift of notch filter and signal processing delay, as well as systematic phase errors of the 3-taps Hilbert filter. As a result, the feedback phase deviates by less than 10 deg from its ideal value if the provided tune differs by ±0.01 from the actual machine tune.

The integrated Automatic Delay block ensures that the corrected beam slice at the kicker location corresponds to the measured slice at the pick-up location, by compensating for the incompressible delay in the electronic path, T_{FIX}, (cables, amplifiers). In fact, the PSB revolution frequency changes by a factor 3 from the initial injection at 50 MeV up to extraction at 1.4 GeV during the 1.2 s PSB cycle, a swing in the revolution frequency to be covered by the Automatic Delay block.

Furthermore, the new digital system allows for controlled beam excitation from arbitrary sources. The internal source has been implemented as a sum of up to 9 sine wave vectors whose harmonic numbers and amplitudes can be set independently, providing high flexibility in the configuration. Internal and digitized external sources, e.g. for Tune Excitation or Blow-up, are combined internally with the feedback correction signal and are truncated if necessary, thereby guaranteeing that signal levels generated by the DAC remain below the saturation limit of the power amplifier stage.

During the End-of-Year Technical Stop 2017-2018 an upgrade of the former 100 W amplifiers took place, now offering 800 W per electrode [6] with a bandwidth up to 20 MHz. This required the installation and cabling of 16 new 4 W drivers [7], 16 new amplifiers with 8 power supplies (40 V at 125 A), as well as 16 new power loads. The new PLC control system handles the safe remote management of the water cooling system, power supplies and power amplifiers, and raises an interlock if critical thresholds are exceeded.

COMMISSIONING WITHOUT BEAM

As a first step, systematic measurements using a Vector Network Analyzer (VNA) were carried out for every power stage driving one kicker electrode, to verify the correct cabling and revealing improper connections. In addition, supplementary assessments realized with a waveform generator injecting a bi-polar triangular waveform in each power system revealed peak voltage limitations caused by unwanted saturation effects.

The new Open Analog Signal Information System (OASIS) [8] for remote signal monitoring was extremely useful and extensively used to commission the correct configuration of all serial links, as well as signal propagation from the digital hardware towards the power system, and for passive beam observations revealing proper reception of beam position signals in the new hardware.

COMMISSIONING WITH BEAM

In order to achieve stable closed loop operation with the TFB, these are the main parameters to adjust: the loop gain, the feedback phase and the fixed time delay, T_{FIX}.

Preparation of the Machine Development Cycles

A special machine development (MD) cycle was prepared to accelerate the beam from the present 50 MeV injection energy up to 160 MeV, where the beam was then kept on the measurement plateau for about 200 ms. The beam was injected after 275 ms from the beginning of the cycle and extracted at 805 ms, as for any operational PSB cycle. The measurements reported in this paper were performed along the 160 MeV intermediate flat-top. The design of the cycle was motivated by the appearance of the main coherent instability in the horizontal plane in the PSB at around 160 MeV. Incidentally, 160 MeV will also be the new injection kinetic energy of the H^- beam coming from Linac4. Similarly, another cycle with a measurement plateau at 320 MeV was prepared and exploited to verify the validity of the same hardware setting at different energies.

TFB Settings

Due to time restriction, the commissioning of the TFB with beam focused solely on the horizontal plane, as no instability was ever observed in the PSB in the vertical plane. The first part of the commissioning with beam was then dedicated to the setting-up of the TFB in the horizontal plane. In order to proceed, the beam response to excitation was measured with a VNA. The principle of the measurement works as follows. The TFB was set to work in open loop, i.e. not acting on the observed beam motion. The beam was excited by means of a sinusoidal excitation at constant power and with the frequency sweeping over two adjacent fractional tune lines. The open loop response was recorded for each frequency and both the magnitude and the phase of the transfer function were measured. Two parameters were adjusted with the VNA: the feedback phase, which in turns depends on the tune, and the fixed time delay.

The beam was set with a constant tune along the measurement plateau. Therefore, when sweeping the frequency, two circles could be identified in the polar coordinates, one corresponding to the fractional tune q and the other one at the mirrored tune $1 - q$. When the TFB is properly set up, the two circles should lie one inside the other and be aligned at a phase of -180 degrees. An incorrect setting of the feedback phase would result in the two circles showing a phase shift one with respect to each other. An incorrect setting of the fixed time delay would manifest itself as a global phase shift of both circles from the targeted phase of -180 degrees. An example of the analysis possible with the VNA is shown in Fig. 2. For the PSB, the time required to perform a meaningful measurement at flat top was at least 100 ms.

With this approach T_{FIX} was adjusted in an iterative fashion for all rings and then verified for different tunes,

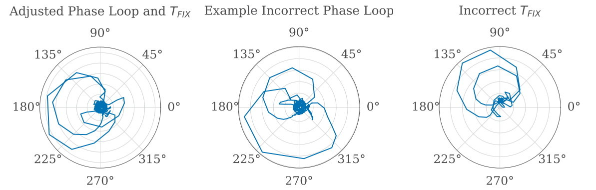

Figure 2: Example of setting up and possible misconfiguration diagnosis attainable with the VNA. Left: example of adjusted setting-up of the feedback phase and T_{FIX}. Center: example of the effect of non-adjusted feedback phase. Right: example of the effect of non-adjusted T_{FIX}.

i.e. phases, and with a range of sweeping frequency from 1 to 10 MHz. The validity of the found setting at 160 MeV was confirmed at higher energy, using the additional special cycle prepared with the flat-top at 320 MeV. This commissioning step allowed to validate at the same time the proper implementation of automatic delay.

Phase Scans

Phase scan measurements at 160 MeV in the horizontal plane were later carried out to evaluate the performance of the TFB system. The bunch population for each ring was usually around 4.0×10^{12} protons, in order to be above the intensity instability threshold. The TFB was set in closed loop mode at the beginning of the flat-top and a few ms before the instability would manifest. As for the measurements with the VNA, the horizontal tune Q_H was set to be constant along the measurement plateau. For a given tune, the feedback phase was scanned for the full range and the beam transmission measured over the plateau.

Phase scans allowed to identify an optimal loop gain, as well as to evaluate the feedback phase margin, which would actively correct undesired transverse motions. An example of the performance insight obtained is shown in Fig. 3. It visually illustrates how an incorrect T_{FIX} could result in a reduced phase margin and therefore sub-optimal performance of the TFB system, evaluated by measuring the beam transmission.

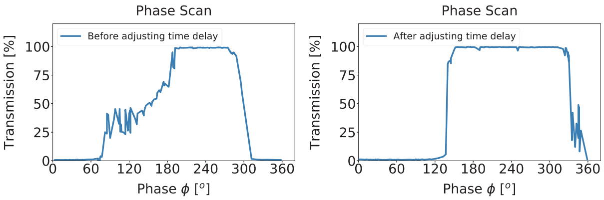

Figure 3: Example of the beam transmission recorded over the measurement plateau as a function of the phase between the TFB pickup and the TFB kicker. Left: initial setting. Right: after T_{FIX} adjustment with the VNA.

In order to produce high intensity beams, the PSB accumulates charge with a multi-turn injection schema, while filling the horizontal phase space to increase the overall injected intensity. This process leads to large incoherent space charge tune spreads associated with high intensity and high brightness beams, especially at injection. Thus, the tune is moved towards higher values to prevent particles from crossing the integer resonances $Q_{\mathrm{H,V}} = 4$. The working point is then lowered towards an area clear of resonances along the acceleration cycle.

Because the tune in the PSB is dynamically changed during the cycle, the new digital TFB system has been equipped with the possibility to program the betatron phase advance along the cycle using the fractional tune values provided by a function generator. Depending on the precision of the precalculated tune this guarantees optimum performance at any point in the cycle.

Phase scans were repeated for several horizontal tunes spanning the current PSB operation working range, from $Q_{\mathrm{H}} = 4.10$ to 4.40. An excellent match between the measurements and the simulation was observed, see Fig. 4.

At the end of the setting up, the new TFB was finally tested to accelerate the highest intensity beam in the PSB in the 4 rings with the nominal operational cycle. The new digital TFB system was able to systematically suppress the PSB beam instabilities along the full cycle and for intensities up to 1050×10^{10} ppr. This was a major milestone, as the updated TFB will replace the old analog system in the physics run after the 2018-2021 long shutdown.

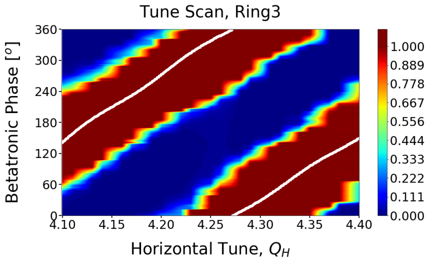

Figure 4: Phase scan for Ring 3 in the horizontal plane at 160 MeV. The color map represents the transmission over the measurement plateau. The white trace corresponds to the mapped horizontal tune as a function of the phase.

CONCLUSION

The commissioning steps of the new digital TFB in the PSB with and without proton beam were presented. The internal settings were validated and means to determine the programmable ones were discussed. The upgraded TFB was used at the end of the year 2018 to successfully and systematically accelerate clones of the highest intensity operational PSB beams. Encouraging results were obtained such as the suppression of beam instabilities at all PSB energies and intensities currently achieved.

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