BEAM TESTS AND PLANS FOR THE CERN PS TRANSVERSE DAMPER SYSTEM

A. Blas, S. Gilardoni, G. Sterbini, CERN, Geneva, Switzerland

Abstract

The CERN Proton Synchrotron (CPS) has been running without any transverse damping equipment since 1998, thanks to the stabilizing effect of the linear coupling applied between horizontal and vertical planes.

Lately, the demand for an active damper strongly emerged for two main reasons: to avoid restrictions as imposed on the betatron tune settings by the linear coupling and to cure instabilities appearing with high intensity beams, especially at the extraction energy. Late in 2012, two electronic prototype units, newly developed for the CPS one-turn-feedback, were programmed with a firmware designed to satisfy the transverse feedback (TFB) requirements in both planes. The main achievements were to automatically adapt the loop delay to the particles' time-of-flight variation within a nanosecond precision and to compensate the changing betatron phase advance between pick-up and kicker during the entire accelerating cycle. With the power equipment limited to the modest bandwidth of 23 MHz and 2 x 800 W per plane, encouraging results were obtained such as fast damping of injection oscillations caused by injection errors, reduction of beam losses along the cycle and damping of instabilities at all CPS energies.

INTRODUCTION

The CPS beam is affected by four main sources of transverse perturbation leading to emittance growth and losses, namely: injection kick error, head-tail instability, transition crossing instability and ejection flat-top instability. To cure these problems, an active damper has been foreseen and its power and bandwidth have been specified in 2003, only taking into account the needs related to the injection errors at 1.4 GeV kinetic energy. A 3 mm maximum peak error, an emittance growth budget of 0.05 µm (normalized) for the most demanding LHC beams and a kick ripple in the 23 MHz range motivated for a system with 3 kW on each of the four kicker plates covering the horizontal and vertical planes within a bandwidth from 10 kHz to 23 MHz. The electronic part of the system converts the beam position signal observed on a pick-up into a kick respecting the varying beam time of flight and the betatron phase advance depending on the machine tune. The performance of the system will be explored in the various conditions corresponding to the perturbations listed above.

HARDWARE

Two pick-ups at two different locations in the ring detect the beam position that is transmitted via a 5 m and 75 Ω coaxial cable to an amplifier in a radiation shielded area. The amplifier's input has a specific corrective network pushing the low frequency cut-off down to 20 kHz (enough for the lower betatron line at 40 kHz to be covered) while the first order high frequency cut-off stays at 40 MHz. The gain of this pick-up amplifier can be set for each successive cycle within a 100 dB range, allowing for a wide set of beam intensities to be covered.

The transverse error signal of each plane is then sent to a VME digital signal processing unit that combines three main functions: cancelling of revolution lines (beam orbit offset), adjustment of the betatron phase within one degree and automatic adjustment of the loop delay with a 1 ns precision. This unit is clocked at harmonic 200 of the revolution frequency (87.4 MHz to 96 MHz).

The processed signal of each plane is split to feed two power amplifiers (3 kW pulsed, 800 W CW) of 60 dB voltage gain in opposite phase. Each amplifier has two outputs in-phase providing each 1.5 kW during 2 ms and 800 W CW. The decay from the peak power to the steady state power is almost linear and takes 40 ms. The amplifiers' outputs are not matched to 50 Ω causing an almost total reflection of incoming waves from the beam signal as picked up by the kicker. Their bandwidth ranges from 2.5 kHz to 23 MHz.

After 250 ns of coaxial cables, each of the damper drive signals reaches an impedance transformer matching the 50 Ω line to the 100 Ω strip-line kicker plate impedance. This transformer can stand 3 kW with frequencies ranging from 2 kHz to 40 MHz.

The strip-line kicker is 0.9 m long, which means a first gain notch at 160 MHz due to the transit time factor for relativistic particles. It is terminated by 100 Ω with a series 50 Ω resistor feeding a 50 Ω coaxial cable ending in a 50 Ω power attenuator.

The betatron phase advance is set along the cycle using the fractional tune value provided by a function generator. A look-up table taking into account the optics between PU and kicker and the non-linearities of the notch and Hilbert filters, transforms the tune into a Hilbert phase set point. In order for the phase to stay within ± 10 degrees of precision, the fractional tune needs to be measured with a 1% precision.

BEAM BASED MEASUREMENTS

After its commissioning, the PS TFB was tested with different beam types and machine cycles. In the following we summarize a collection of relevant observations.

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Damping of the Injection Orbit Errors

Compared with the low emittances required for the LHC Injector Upgrade (LIU) [8], the injection orbit errors and jitter can produce significant emittance growth. This can be estimated as [1]

$$\frac{\Delta\varepsilon_n}{\varepsilon_n} = \frac{\beta_r\gamma_r}{\varepsilon_n}\frac{\Delta x^2 + (\beta_{H,V}\Delta x' + \alpha_{H,V}\Delta x)^2}{2\beta_{H,V}} \quad (1)$$

where (Δx, $\Delta x'$) represent the injection errors and all other symbols have the usual meaning. For E_{kin} = 2 GeV, β_H = 20 m, α_H = 0, $\Delta x'$ = 0 and ε_n = 2.2 mm mrad, Eq. 1 yields 34% emittance growth with Δx = 1 mm (to compare with the emittance budget for the whole PS cycle of 5%). The effective damping of these oscillations becomes of paramount importance.

The natural damping time constant of the oscillation, T_u, depends on the machine settings and beam properties. The TFB time constant, T_d, depends on the TFB gain (the subscript 'u' and 'd' refer respectively to the un-damped and damped case). In linear approximation, the residual emittance growth using a TFB can be expressed in the absence of instability as [9]:

$$\left.\frac{\Delta\varepsilon_n}{\varepsilon_n}\right|_d = \left.\frac{\Delta\varepsilon_n}{\varepsilon_n}\right|_u \left(\frac{T_d}{T_d + T_u}\right)^2 \quad (2)$$

The PS TFB has been design for a damping time T_d = 50 µs with Δx = 3 mm at E_{kin} = 1.4 GeV [2] (it can damp 65 µm/turn when the amplifier is saturated). During the 2013 PS program, T_d was estimated by reducing the machine chromaticity ($T_u \gg T_d$).

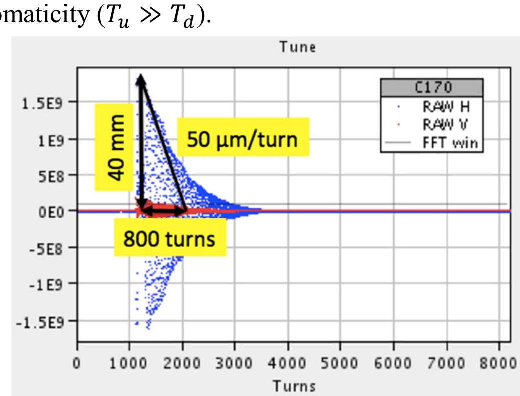

Figure 1: Damping of the injection errors.

The observed slope of the damped oscillation was compatible with the expected 65 µm/turn.

Damping the PS Head-tail Instability

It was shown that the head-tail instability can be cured in the PS by introducing linear coupling between the horizontal and vertical planes and by operating the machine close to the coupling resonance [3]. With the space charge dominated regime of the LIU-PS [4], this constrains the machine operation. A measurement campaign has been conducted during 2012 and 2013 to test the potential of the PS TFB with respect to this head-tail instability.

Typically, the beam used for these studies was a single bunch beam (~25E10 ppb). The working point of the machine was set to (6.1, 6.4), far from the diagonal and the natural coupling was corrected using the machine skew quadrupoles. Without the active feedback a horizontal head-tail instability was systematically observed at the flat-bottom (E_{kin} = 1.4 GeV, Fig. 2) producing ~50% of beam losses (Fig. 3) and ~300% of emittance growth in ~500 ms.

In all tested machine conditions, the PS TFB damped efficiently the head-tail instabilities; within the measurements' precision, no beam losses or emittance growth were visible.

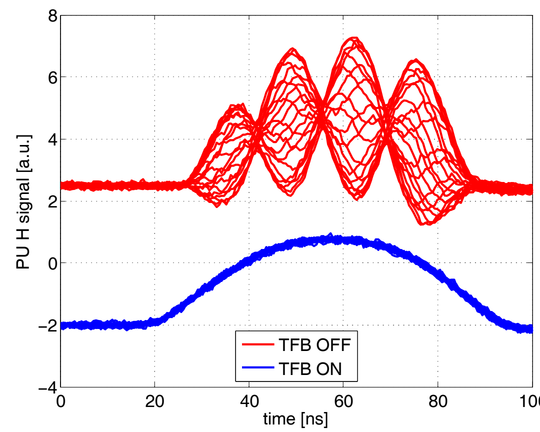

Figure 2: An example of horizontal head-tail instability at injection energy in the PS with and without TFB.

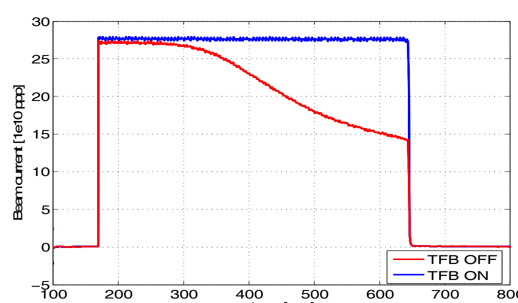

Figure 3: Beam intensity evolution with TFB on and off.

The TMCI Instability at Transition Crossing

During the 2013 MD program the well-known TMCI instability was observed during the PS transition crossing [5][6] (single bunch with 40E10 ppb and ε_l = 0.25 eVs). An exhaustive analysis of the instability has still to be carried out, since for identical beam parameters, the instability was measured having a higher order (660 MHz instead of the present 150 MHz modulation) early in 2012 [6].

The TFB was set up to damp the instability but with no success. It can be seen in Fig. 4 that the spectrum of the instability (>100 MHz) extends beyond the bandwidth capability of the damper system and that the rise time of the instability is a few turns, meaning that the loop gain should be set close to the optimal (very high) gain corresponding to the shortest possible decay time, to cope with it.

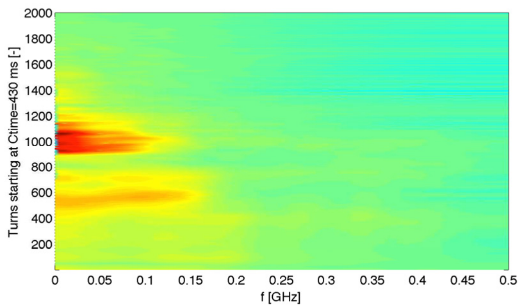

Figure 4: Spectrogram of the TMCI at transition crossing (transition occurs around turn 800). A [200 kHz, 250 MHz] delta PU sampled at 1 GHz was used to observe the beam.

The Transverse CBI Instability at Flattop

At top energy (E_{kin} = 25 GeV) the LHC production beams are split in order to produce the 25 ns spaced 72 bunches batch. Before extraction, the bunches undergo a bunch compression and a final rotation to be accommodated in the 200 MHz SPS bucket. In this condition, even if some electron-cloud activity is noticeable, there are no measurable detrimental effects on the beam quality [7]. To study in more details this mechanism, the extraction of the beam was delayed by ~70 ms and the compressed bunches stored in the machine. In these conditions a strong electron cloud activity is observed and a coupled bunch instability (CBI) develops [7].

Using the TFB at top energy we observed (Fig. 4) that the instability can be delayed by ~10 ms giving an additional margin to the machine operation.

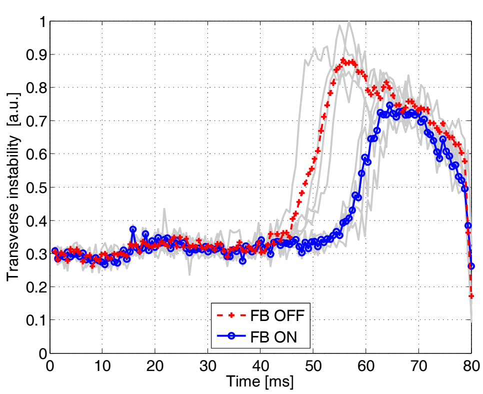

Figure 4: CBI at PS flattop for the 25 ns beam after bunch compression if the beam extraction is delayed.

CONCLUSION

The active transverse damper system has been successfully tested in both planes in the CERN PS using prototype electronic boards just before the long shut-down of 2013. Power, betatron phase setting and automatic delay compensation have proved to meet specifications along the entire accelerating cycle. Rigid oscillations due to injection errors are damped as expected, head-tail instabilities are handled at low-energy up to the highest order (six) observed in the machine and instabilities at the ejection plateau at 26 GeV are delayed although not totally cured yet. There are signs that the latter instability could have been cured with an increase of the feedback gain. For the wide frequency range instability occurring during transition, the active damper did not show any measurable effect but further tests need to be performed with a higher loop gain in order to draw final conclusions. The most important ingredients for beam emittance growth and losses are nevertheless covered. From these preliminary tests having been performed, it seems that even transverse instabilities with a frequency content predominantly above the system bandwidth do benefit from it. Studies are on-going to understand in which circumstances the low-frequency betatron lines hold the information allowing the damping of the entire instability. On the hardware side, there is an evident need for a variable gain amplifier in the loop with different settings along the cycle.

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