BEAM-BASED PERFORMANCE OF THE CERN PS TRANSVERSE FEEDBACK

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Abstract

The CERN PS transverse damper is a flexible wideband system to damp injection coherent oscillations, inter and intra-bunch transverse instabilities at different energies along the cycle, to perform controlled emittance blow-up and to serve as abort cleaning device. In this paper we summarise some beam-based observations of the CERN PS transverse feedback performance and compare them with the expected results.

INTRODUCTION

The CERN PS has to cope with several beam dynamic challenges to produce the present and the future high brightness and high intensity beams [1]. The PS Transverse Feedback (TFB) will be used mainly to address three aspects of the PS beam dynamics to reach the required performance:

- *The injection misteering* due to an injection error. This is expected to be an important source of the emittance growth [2] which drove the specifications of the TFB system. The system has been designed to damp a 3 mm_p oscillation with a time constant < 50 turns at injection energy (E_k=1.4 GeV) while its bandwidth should cover from the first betatron line at Q=6.1 (40 kHz) up to 23 MHz corresponding to the ripple observed on the injection kicker bending field. Given the TFB kicker design, this translates into the power specifications for the present driving amplifiers of 3 kW per kicker plate. Considering a E_k=2 GeV injection and maintaining the same requirements of the 1.4 GeV case, the amplifier power should be increased to 5 kW. The new amplifiers are presently under construction and will be commissioned during the 2015 in the framework of the LHC Injectors Upgrade project [3].
- *The head-tail instability*. This effect is due to the interplay between the machine transverse impedance, its chromaticity and the bunch longitudinal motion [4–6]. It can have a detrimental effect of the beam characteristics up to prevent the beam transmission or to degrade the beam emittance to unacceptable level. The TFB proved to be a valuable tool against this issue.
- *The transverse coupled instability at extraction*. In specific, not yet operational, conditions it has been observed a coupled bunch instabilities at the PS extraction flattop with the 25 ns bunch train. Investigations are ongoing to understand if a similar instabilities will be present with the production LIU beams. Measurements demonstrate that the PS TFB can delay by 10 ms the the instability rise [7]. This result may indicate that an increase of the loop gain should cure the instability.

In addition to that, the TFB can perform controlled emittance blow-up, serve as abort cleaning device, excite the beam for tune measurement and machine development studies.

THE SYSTEM AND ITS PERFORMANCE

A description of the present system is provided in the following, highlighting its performance and limits. A more detailed description can be found in [8–10]. The envisaged upgrade for 2015 will also be discussed. A simplified block diagram of the present system from the pick-up to the kicker is shown in Fig. 1 (only the horizontal plane is depicted).The transverse pick-up [9, 11], PU, feeding the TFB is positioned in section 98. The PU signal is amplified to match the input dynamic of the digital card (DSPU). The output of the digital card is amplified, combined with the Q-meter signal and splitted on the input of the two power amplifiers that drives the two horizontal plates of the kicker. The matching between the output impedance of the power amplifier (50 Ω) and the kicker impedance (100 Ω) is performed with a transformer. The transverse kicker is positioned in section 97. The TFB is composed of the subsystems described in the following sections.

The Pick-up Pre-amplifier

The PU preamplifier is a critical subsystem for the TFB since it is used to set the feedback loop gain and to adjust the ΔH and ΔV signals to the 1 V_p input dynamics of the DSPU ADC. It is a low-noise pre-amplifier with a gain range of −60 to +40 dB (down to −60 dB provided by an attenuator in 3 steps of -20 dB and up to +40 dB provided by an amplifier in 255 steps of ≈ 0.155 dB) that allows to adjust it to the different PS beam flavours [9]. The pre-amplifier has a global attenuation block shared by all three channels (Σ, ΔH and ΔV) together with an analog gain separately adjustable on each single channel. Attenuation and gain can vary from cycle to cycle but not within a cycle. This implies that if the TFB has to address different problems within one cycle (e.g. damping injection oscillation, head-tail instability, coupled bunches instabilities at extraction) the loop gain cannot be adjusted and optimised for each physical process. The −10 dB bandwidth of the PU amplifier is 60 MHz with less than 10 degrees of non-linear phase error on the entire amplification and attenuation range. Presently the transverse signals are not normalised therefore the gain of the feedback loop varies along the bunch for not uniform longitudinal distributions.

The Digital Signal Processing Unit

There is one digital signal processing unit (DSPU) for each plane, clocked with harmonic 200 of the beam revolution

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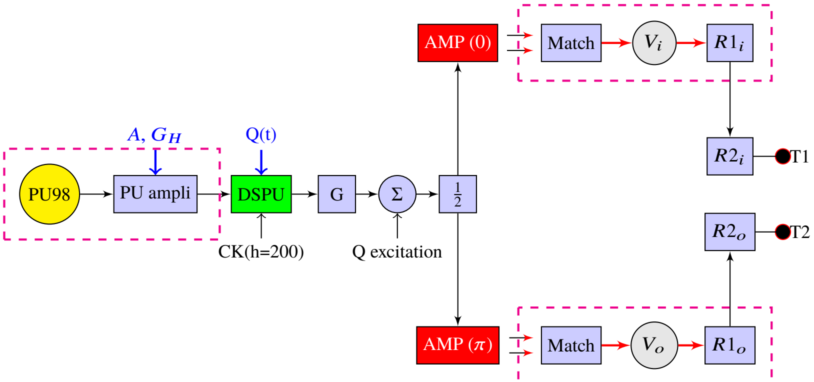

Figure 1: The block diagram of the PS Transverse Feedback. The magenta rectangles indicate the devices installed in the tunnel. Let us assume to have a bunch of 160e10 proton with a 4σ length of 180 ns with and injection error of 3 mm_p. The pre-amplifier can be set to a gain of 0.3 V/mm to match the 3 mm_p to the 1 V_p dynamic of the DSPU. We assume that the DSPU will not add any gain (1 V/V). From the exit of the DSPU to the entry of the power amplifier, AMP, the gain as to be fixed at 0.3 V/V (chain of post-amplifier, G, combiner and splitter). Each amplifier has two modules of 62 dB gain (1.5 kW RMS on 50 Ω), the two modules will be summed in power (+3 dB) and then the matching network will increase by 3 dB the voltage (68 dB) to adapt the amplifier output impedance (50 Ω) to the kicker plate input impedance (100 Ω). The total voltage gain from the amplifier input to the kicker (2 plates, V_i and V_o) is 74 dB. The kicker will deliver 7.9 10^{-9} rad/V and the angle form the kicker will be transported in variation of position on the PU with 17 m/rad at injection energy. Summing all contributions and considering 1.5 dB losses for the cable attenuation the total gain the loop is G=0.05 mm/mm that is 40 turns of damping time in the centre of the system bandwidth and for the peak density of the bunch.

frequency. As discussed later this choice introduces the first limit to the bandwidth of the system .

The DSPU is responsible for

1. Adding the fixed (due to the cable length) and variable (due to the decreasing time-of-flight along the acceleration of the beam between the section 98 PU and the section 97 kicker) time delay to the PU signal.
2. Suppressing the revolution line harmonics, related to the closed orbit, using a notch filter.
3. De-phasing the error signal feeding the kicker by the correct betatron angle using the measured machine-tune information supplied by a function generator. Once the delay of the TFB are set correctly the only source of dephasing between PU and kicker is assumed to be the notch filter transfer function, N, and the Hilbert filter transverse function, H. The phase of the Hilbert filter has to be chosen to satisfy the equation

$$\angle H(\phi_H,Q)+\angle N(Q)=2\pi Q+\Delta\mu(Q)+\frac{3\pi}{2}+\arctan\alpha(Q). \tag{1}$$

where Q is the machine tune, μ is the phase advance between the pick-up and the kicker and α is the α-Twiss function at the position of the kicker. A look-up table provides the Hilbert phase angle versus the machine tune.

Due to circuitry constraints, the maximum clock rate of the present DSPU is limited to ≈ 105 MHz while the h=200 clock ranges from 87.4 MHz up to 96 MHz for protons. After the digital treatment the signal is converted by a DAC and sent to an additional programmable amplifier before being input to a combiner and a splitter feeding the pair of power amplifiers used for the H or V plane. The programmable amplifier is used to adjust further the output voltage of the DSPU (1 V_p) to the input saturation value of the final stage (300 mV_p), taking into account the attenuation of the combiner and the splitter. At the moment for an optimal exploitation of the DSPU dynamic, the closed orbit at the PU should be minimised all along the beam cycle.

The Power Amplifiers

There is one 3 kW power amplifier driving each kicker plate. The two face-to-face kicker plates, for a given H or V plan, work in push-pull mode with their rf signal in opposite phase. These devices are designed for a -3 dB bandwidth of 23 MHz thus representing the bandwidth bottleneck of the entire system. During the damping of the injection oscillations the final stage can work at maximum power. These amplifiers provide 62 dB voltage gain on each of the 2×1.5 kW RMS outputs to be combined. This RMS power can be provided only for a limited duration (3 ms) and afterwards the amplifier provides 0.8 kW CW. In addition to this limit, the power amplifier output is not back-matched to 50 Ω: this implies that the signal induced on the kicker by the beam will reach the amplifier and be reflected back to the kicker,potentially causing a cross talk between the different bunches. From preliminary investigations this cross talk appears to have a negligible effect. The new power amplifiers will have a 50 Ω output impedance.

The Strip-line Kicker

The TFB kicker installed in section 97 is a strip-line kicker. It is a combined horizontal and vertical kicker (the optics in section 97 privileges the horizontal plane in term of kick effectiveness). The kicker as a characteristic impedance

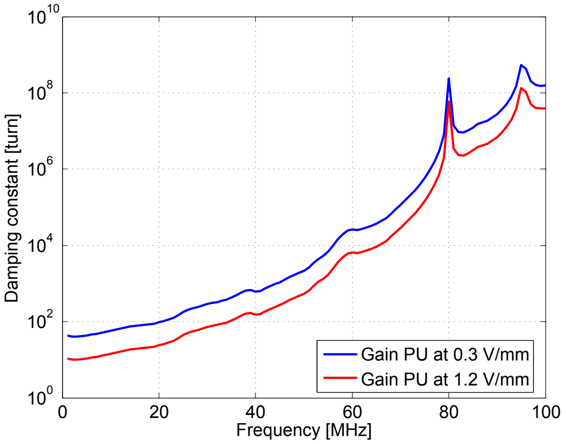

Figure 2: The TFB damping constant of the TFB as function of the frequency with the loop gain set for saturation with a 3 mm_p beam position error at low frequency. Increasing further the gain is presently limited by the PS RMS closed orbit.

of 100 Ω in both planes. The 2 power amplifier signals conveyed on 50 Ω lines are matched to the 100 Ω kicker using a power transformer.

Upgrade of the TFB Power Amplifiers

To cope with the 2 GeV injection energy while preserving the same performance, the power amplifiers of the system have to be upgraded to 5 kW CW (3 kW peak down to 800 W CW presently). The commissioning of the new power amplifiers is expected by 2015. With the new power amplifiers the problem of the matching of the output and the consequent reflection signals will be addressed. As explained the power amplifiers are presently bandwidth bottleneck of the system. For this reason the new devices will provide a 3 dB bandwidth at 100 MHz. The full power available in CW will allow more flexibility for transverse blow-up purposes

By combining the measured frequency responses of the main components of the TFB one can compute the damping constant of the system as function of the frequency (Fig.2). By increasing the pre-amplifier gain from 0.3 V/mm to 1.2 V/mm one would use the amplifier in “bang-bang” mode for the injection oscillations (that provides the maximum efficiency in extracting the beam transverse energy) and would gain in TFB damping time for the beam instabilities. Increasing the gain of the loop will increase also the noise excitation of the TFB but this problem is not relevant for relatively short PS cycle. It is worth noting that due to the Nyquist sampling criteria, only a total bandwidth of half the sampling frequency can be effective. Selecting the right frequency offset by steps of half the sampling frequency, is left to the choice of the user who should then apply the adequate band-pass analogue filtering. Presently there is no such an interest since all the transverse instabilities observed fall below 40 MHz with the exception of the the fast instability at transition that lies anyhow far beyond the limit of the system (≈700 MHz, [12]).

BEAM-BASED PERFORMANCE

In this section the following examples of beam-based performance of the PS TFB are reported

- damping of intra-bunch oscillation at the injection,
- damping of head-tail instabilities,
- some preliminaries results on the use the damper as TFB as abort cleaning device.

Damping of Intra-bunch Oscillation at Injection

As explained in [13], for high intensity bunches a missteering at injection can evolve in high frequency intra-bunch oscillations due to the transverse tune difference along the longitudinal position of the bunch. This phenomena is very rapid (much less than a synchrotron period) and it is an ideal check case for testing the PS TFB performance. The TFB was tested with 4 LHC-type bunches at the PS injection (160e10 ppb). In Fig. 3 we can compare observe the first 50 turns of the beam without (*top*) and with the TFB (*bottom*).

Figure 3: LHC-type bunches injection oscillation without (*top*) and with (*bottom*) the TFB. Σ (yellow), ΔH (green), ΔV (magenta) (200 ns/div, 200 mV/div). On the plots 50 consecutive turns of 4 LHC-type bunches in the PS are overlapped.

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The oscillation evolved mostly on the vertical plane (magenta line) and could be successfully damped by the TFB. It is important to note that the closed orbit at the position of the PU was not minimised so the loop gain could not be maximised. Even in this non optimal condition, the TFB could damp this intra-bunch oscillation.

Damping of Head-tail Instabilities

In the PS, head-tail instabilities (HT) were systematically observed during the early commissioning and studies of the LHC beam [14] on the 1.2 s injection plateau needed for the double batch injection. It was a horizontal instability with a growth time in the order of 100-200 ms for a bunch injected in h=8, 4 σ bunch length of 200 ns, $N_b = 200\ 10^{10}$ ppb at $E_k = 1$ GeV injection. Depending on the chromaticity the number of observed modes varied between m=3 and m=8. The beam loss was between 20-30%.The main responsible of the instability has been associated with the machine resistive wall impedance. In general there are three possible solutions to cure this instability:

- transverse coupling,
- Landau damping using non linear element (octuples),
- and transverse feedback.

Starting from 1996 this instability was addressed by using transverse coupling [15, 16] to avoid strong non linear elements in the optics and because, at that time, PS Transverse Feedback could not cope with it. Since then the HT was successfully suppressed in the PS using the machine natural coupling, introducing additional coupling using the skew quadrupoles, setting the working points close to the main diagonal the HT and exploiting the asymmetry between the two planes (in terms of impedances and chromaticities). The drawback of this approach is that it restricts the machine operability to a confined space of parameters, restricting thus its flexibility. For example, with the new space-charge regime expected for the LIU the choice of the working point needs as much freedom as possible in order to better accommodate the tune footprint. For these reasons, in the LIU perspective, the coupling solution becomes problematic. The TFB system appears as the natural candidate to cure the HT: one of its goal is to address the HT issue at the injection energy in the LIU parameter space, for a wide range of working points and without any residual coupling. In [17] a comparison of the PS case between Sacherer's theory and direct simulation is presented. The results show that varying the horizontal chromaticity between -1 and -0.1 with an uncouple machine the theory and the simulations results are in good agreement. The faster HT instability predicted has $\tau = 32$ ms with $N_b = 1.6e12$ and $E_k = 1.4$ GeV. Doubling the bunch population we expect to halve the rise time constant ($\tau = 16$ ms). This corresponds to ≈ 7000 turns and can be qualitatively comparesto the damping capability of Fig. 2. Assuming, parabolic bunches and a full length of the bunch of 180 ns from the bunch spectrum computation with m=10, most of the power spectrum is confined below 50 MHz. This lead us to the conclusion that the present system PS TFB can successfully stabilise the PS HT instability at $E_k = 1.4$ GeV. At $E_k = 2$ GeV the maximum feedback loop gain will remain constant thanks to the new amplifiers. On the other hand being closer to the transition will increase significantly the frequency of the instability spectrum. The improvement of the TFB power is justified by the damping of the injection errors at the higher energy and to allow for a more efficient blow-up for applications like the Multi-Turn Extraction [18]. Its increase in bandwidth is needed for curing the HT and the instability at flattop. In the following we will present some results of beam based measurements in the PS. In the space of parameters explored (varying chromaticity with an uncoupled machine) the TFB proved to be always capable to cure the instability. In Figs. 4 we show an example of HT instability without (*top*) and with the TFB (*bottom*) .

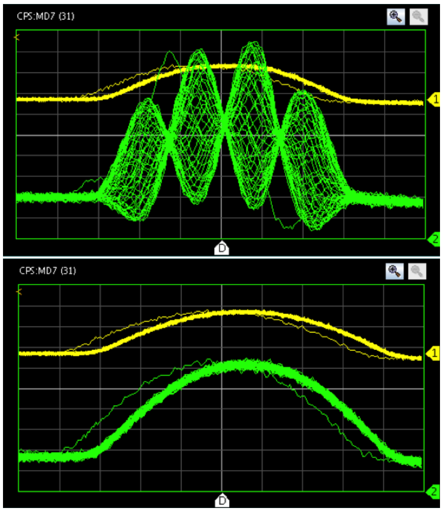

Figure 4: Head-tail instabilities (*above*) cure by the TFB (*below*). Σ (yellow) and ΔH (green) signals with 10 ns/div. On the plot 100 turns are overlapped. The frequency of the shown instability is about 20 MHz. Natural chromaticity and fully uncoupled machine.

The TFB as Abort Cleaning Device

Recently it was proposed to use the TFB as abort cleaning device [19]. This would add flexibility in the filling scheme of the SPS and the LHC. As a proof of principle a test has been prepared to verify that an open loop excitation at the beam tune frequency could make the bunch unstable until its complete loss. In order to achieve this result it is important to correct the nominal chromaticity of the machine. Since the plane of excitation was the horizontal one, the ξ_H was increase from -0.8 to -0.1 in absolute unit. The result can be observed in Fig. 5. With the reduced chromaticity the beam is almost unstable (slow losses on the beam current, cyan curve). When the excitation of the TFB is switched on, almost the 90% of the beam is lost in few milliseconds. The rationale behind this abort cleaning approach is to push the beam towards and instability (by reducing the chromaticity) and, by using convenient gating intervals, stabilise the bunches that have to be accelerated while exciting those that

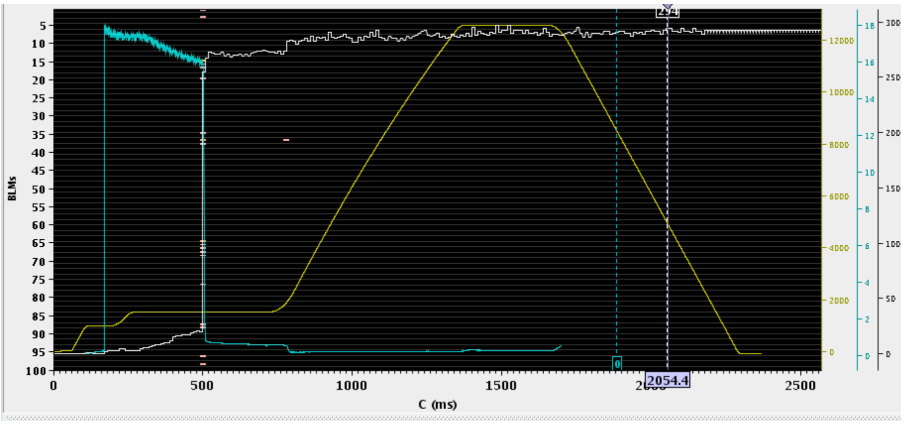

Figure 5: Proof of principle of using the TFB as abort gap cleaner. A single bunch is excited and lost in the machine at 2.5 GeV using the present TFB. The cyan curve represent the beam intensity in 10^{10} protons (scale on the right), the yellow curve is the magnetic cycle in Gauss and the white curve is proportional to the losses in the ring is in arbitrary units.

have to be lost. The losses can be localised to specific location of the machine by close orbit distortion. The firmware needed for the gating capability of the TFB is presently under preparation and will be commissioned during the end of the 2014 and the beginning of the 2015.

CONCLUSIONS

The CERN PS transverse damper proved to be a flexible system to damp injection coherent oscillations, inter and intra-bunch transverse instabilities. After an introduction of the system and a prediction of its performance some significant examples of beam-based observations were discussed. The measurements are consistent with the expectations.

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REFERENCES

[1] S Gilardoni et al. Long-term beam losses in the CERN Injector Chain. THO1LR01, HB2013, East Lansing, MI, USA (2014).

[2] A. Chao and M. Tigner. Handbook of accelerator physics and engineering, 3rd Printing, Chapter 4.5.6, 2006.

[3] LHC Injector Upgrade Project. `https://espace.cern.ch/liu-project/default.aspx`

[4] C. Pellegrini. On a new instability in electron-positron storage rings (The head-tail effect) Nuovo Cimento, LXIV, 1969.

[5] F. J. Sacherer. Transverse bunched beam instabilities: theory. 9th Inter. Conference on High-energy Accelerators, 1974.

[6] F. J. Sacherer. Theoretical aspects of the behaviour of beams in accelerators and storage rings. In First Course of the In-

[6] F. J. Sacherer. Theoretical aspects of the behaviour of beams in accelerators and storage rings. In First Course of the International School of Particle Accelerators of the "Ettore Majorana" Centre for Scientific Culture, Erice, 1977.

[7] A. Blas et al. Beam tests and plans for the CERN PS transverse damper system. IPAC13, Shanghai, 2013.

[8] J. Belleman et al. PS transverse damping system for the LHC beams. AB/RF-Note-2005-027,CERN,2005.

[9] J. Belleman. PS Transverse Feedback pick-up, `http://jeroen.home.cern.ch/jeroen/tfpu/overview.shtml`

[10] A. Blas et al. The new CERN PS transverse damper. PAC09, Vancouver, 2009.

[11] J. Belleman. A proposal for new head electronics for the PS orbit measurement system. AB-Note-2005-057, CERN, 2003.

[12] S. Aumon. HIgh Intensity Beam Issue in the CERN Proton Synchrotron, CERN-THESIS-2012-261.

[13] A. Huschauer et al. paper submitted to PRSTAB.

[14] R. Cappi. Observation of high-order head-tail instabilities at the CERN-PS, CERN/PS 95-02, CERN, 1994.

[15] E. Métral. Coupled Landau Damping of Transverse Coherent Instabilities in Particle Accelerators, PhD Thesis, CERN, 1999.

[16] R. Cappi et al. Control of Coherent Instabilities by Linear Coupling, 18th International Conference on High Energy Accelerators, 2001.

[17] E. Métral et al. Simulation Study of the Horizontal Head-Tail Instability Observed at Injection of the CERN Proton Synchrotron, PAC07, Albuquerque, 2007.

[18] Multi-Turn Extraction. `http://ab-project-mte.web.cern.ch/AB-Project-MTE/`

[19] H. Bartosik et al. Other Means to increase the SPS 25 ns Performance. LHC performance workshop, Chamonix, 2014.