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UPGRADED TRANSVERSE FEEDBACK FOR THE CERN PS BOOSTER

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Abstract

A new transverse feedback (TFB) system is being used for the 4 rings of the CERN Proton Synchrotron Booster (PSB). In addition to transverse instabilities mitigation - within the range of 100 kHz to 100 MHz - the system allows for controlled beam emittance blow-up, machine tune measurement and other optic studies. The system was upgraded in order to multiply by 8 its power (800W instead of 100W on each of the 4 kicker electrodes) and in order for its electronic core to employ a digital processing. The transverse feedback adapts automatically to a factor 3 change in the beam revolution period and to any change of the machine tune. It includes an excitation source that combines up to 9 selectable harmonics of the revolution frequency with a selectable amplitude for each. The excitation may be dipolar or quadrupolar. Future possible upgrades will be presented including a setup to tackle half-integer tune values and a digital processing using a fixed clock frequency instead of the revolution frequency clock.

MOTIVATION FOR AN UPGRADE

Table 1: Benefits of the New Hardware

Changes	Benefits
Increased power (1600 W vs 400 W)	Improves S/N in beam transfer function measurement
Extended -3dB bandwidth towards the low frequencies. (10 kHz vs 50 kHz)	Improves the loop phase error at the 1st betatron line and thus the loop damping time
Digital hardware	- Precise loop adjustments along the cycle (phase, gain, delay) - Perfect suppression of the parasitic effect of the beam position offset - Allows for bunch tracking. - Provides an excitation signal tracking automatically the betatron lines. - Provides a quadrupolar excitation on demand - Doesn't required an external adjustable delay using 250 m of cable for each plane. - All the processing on a single VME board instead of 4 different modules - New electronic components available on the market in case of a failure.

The CERN PSB TFB has been successfully used in operation in its original form since 1980 [1]. This initial hardware will remain available, on demand, until 2021 when the PSB will reach its new nominal intensity (1.6 E13 ppp instead of 1E13 as presently). The new hardware installed in 2018 offers some benefits listed above, but comes with a limitation in terms of -3dB upper bandwidth (25 MHz instead of 100 MHz). With the present peak beam intensity a bandwidth of 10 MHz proved to be sufficient, but no reliable prediction can be made with a 60% beam intensity increase and the present coarse impedance model for the PSB ring.

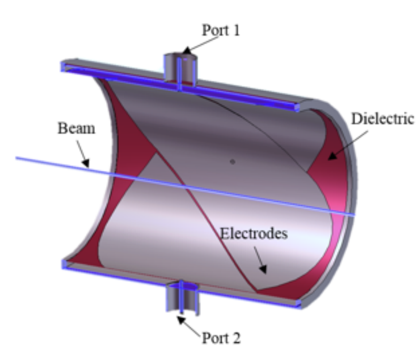
Table 2: Downsides of the New Hardware

Change	Downside
Digital Hardware	Max sampling frequency = 100 MHz which leads to a practical BW of 25 MHz
Digital Betatron phase adjustment	Imposes 2 extra turns delay in the loop-processing path which increases the requirements for a precise estimation of the machine tune (0.01error on tune corresponds to 10 deg error on the betatron phase).
New PU head amplifier	- Does not saturate with the increased beam intensity. - Extended bandwidth in both high and low frequencies. Allows for less phase error on the first betatron line.

DESCRIPTION

Beam Position Monitoring

The beam transverse (H and V) position is sensed using a single "shoe-box" type PU (see Fig. 1) in each of the 4 PSB rings.



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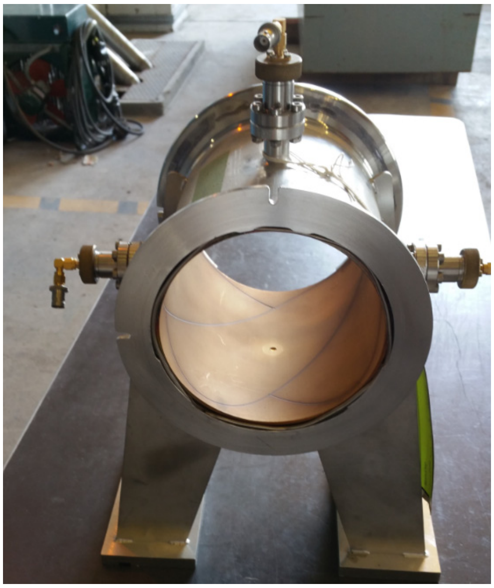

Figure 1: Beam pick-up.

Each PU plate voltage is amplified using a high impedance electronic setup (see Fig. 2) to extend the low frequency cut-off well below the first betatron spectral line. This electronic setup is inspired by what is used with high impedance probes on commercial oscilloscopes.

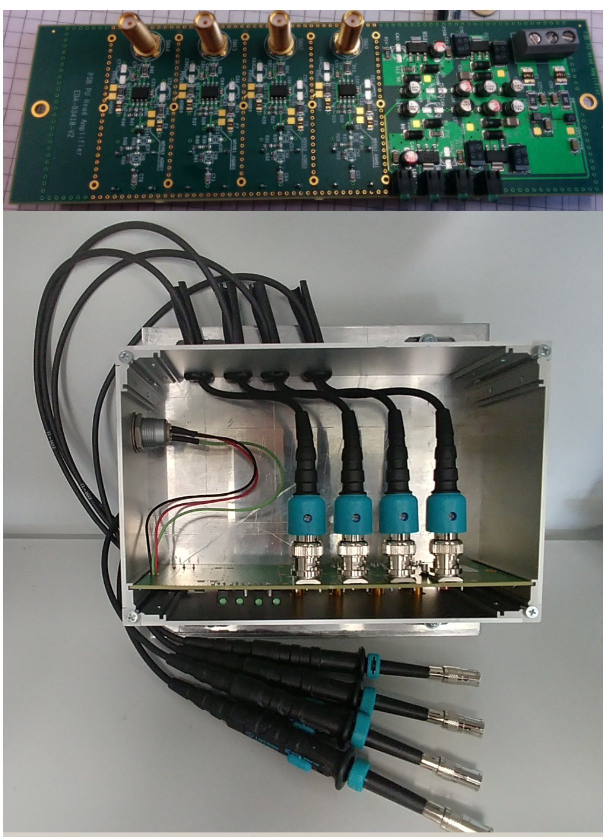

Figure 2: New PU head amplifier.

Beam Offset Suppression

The two amplified signals of a given plane are sent to a so-called Beam-Offset-Suppression System (BOSS) that will first subtract the two voltage values (delta signal) so that a zero is output when the beam travels on the electrical centre of the PU. If a transverse beam position offset is detected, the latter will automatically be cancelled by applying an appropriate gain difference on each of the two PU channels. This analogue BOSS is not strictly required upstream the digital processing, where it could be replaced by a 180 degree combiner, but in case of a beam position offset like during the slow extraction bump, the BOSS should allow for an improved loop gain before saturating the digital input stage and thus improve the system dynamic range.

Digital Processing Unit [2]

The delta signal from the Beam Position Monitor as output by the BOSS is digitized on a Digital Signal Processing Unit (DSPU) using 14 bits converters sampled up to 100 MHz. The transverse feedback loop processing includes four major blocks: gain control, revolution lines mitigation, betatron phase adjustment and automatic delay. Apart from its main features as an instability damper, the DSPU carries also a beam excitation source. The hardware presents itself as VME board (see Fig. 3) with 4 ADCs and 4 DACs connected to a Stratix II FPGA from Altera. One particularity of this board is to have a main sampling clock (at the 64^{th} harmonic of the beam revolution frequency) and its delayed sibling feeding the output DACs. The analogue delay between the two sampling clocks is obtained by a variable delay circuit using selectable sequences of analogue ECL stages.

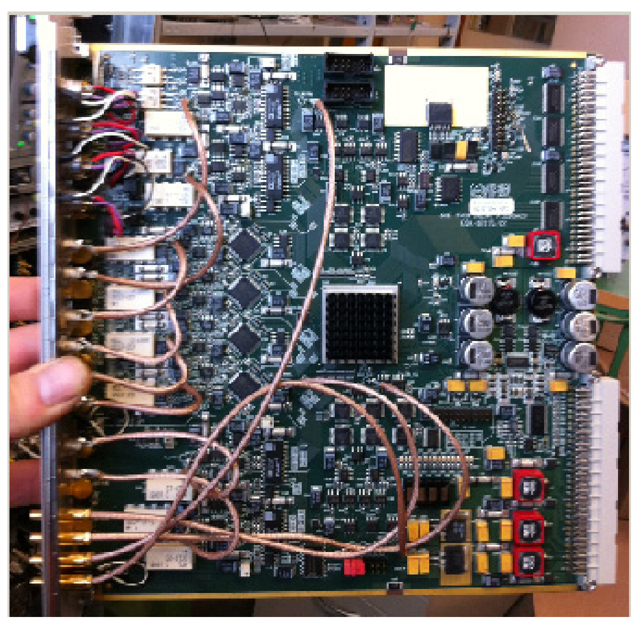

Figure 3: DSPU VME board.

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Revolution Frequency Lines Mitigation

The beam frequency spectrum may show some activity at the harmonics of the revolution frequency. These lines' amplitudes are proportional to the beam position offset that the transverse feedback system is not designed to tackle. These revolution lines are thus parasitic signals that need to be cancelled in order not to saturate uselessly the power stage. When amplified these harmonics of the revolution frequency translate in a local bending dipolar kick with no effect on the beam stability or instability, except when the process leads to a saturation of the system where no superimposed betatron instabilities can manifest themselves anymore.

The analogue BOSS, upstream the digital processing stage, plays the role of suppressing the revolution lines but the actual circuit suffers from some imperfection, and a digital backup was found to be beneficial.

The implementation of the revolution lines' mitigation circuit uses a Notch filter topology (see Fig. 4) subtracting the incoming signal to its sibling delayed by one revolution period (64-samples pipeline-delay clocked at the 64th harmonic of the revolution frequency)

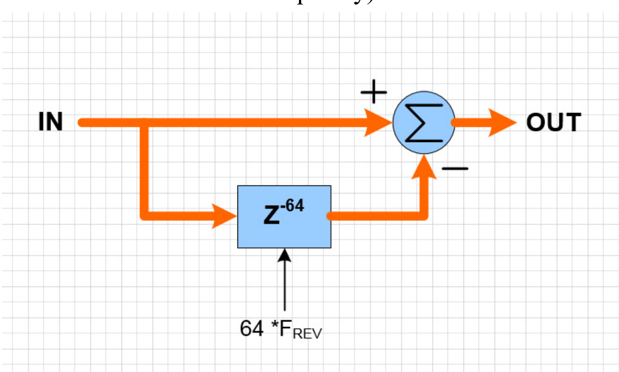

Figure 4: Notch filter.

Betatron Phase Adjustment

The Betatron phase adjustment uses a first order Hilbert filter topology (see Fig. 5). The Hilbert filter frequency response would ideally impose a phase in the form of a square wave, with transitions of the square wave at the multiples of the revolution half-frequency. One side of the revolution line should experience the opposite phase compared to the other side, as expected by signal theory when confronted with a betatron amplitude modulation sampled at the revolution frequency.

The amplitude of the square wave in terms of additional phase within the loop would ideally be set to reach the required value. With a first order implementation, the supposedly square phase-wave looks more like a sinewave for most set values, which means practically that only the peak of the sinewave is at the expected phase-value. This behaviour is nevertheless not harmful as we are dealing with well-defined unique beam betatron lines along the sinewave function. Knowing the betatron tune value and the required phase lag, one needs to select the set-point value of the Hilbert Filter that will provide the appropriate phase lag for the actual betatron line.

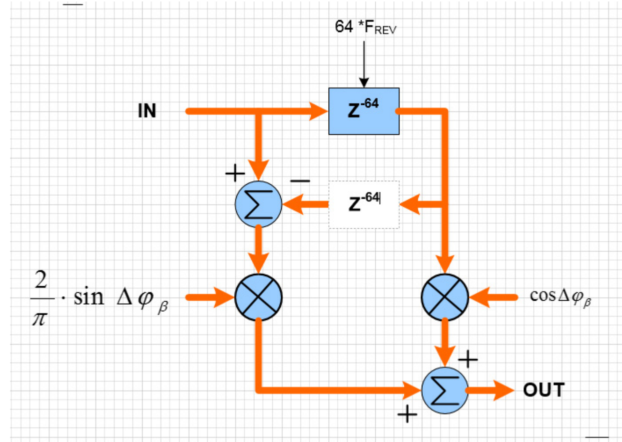

Figure 5: First order Hilbert filter.

Automatic Delay Adjustment

The beam revolution period within the PSB ring evolves from 1666 ns to 546 ns, so by about a factor three. The PU to Kicker distance represents 83% of the circumference and the beam time of flight between these two entities needs to be respected in order to address the appropriate kick to the very particle having been measured. The variable loop delay is obtained by a FIFO (see Fig. 6), using pipelined registers. The number of FIFO registers clocked at 64*Frev represents one part of the delay with a granularity of Tclk. A 10 ps resolution "analogue" delay is then added to enhance the available precision.

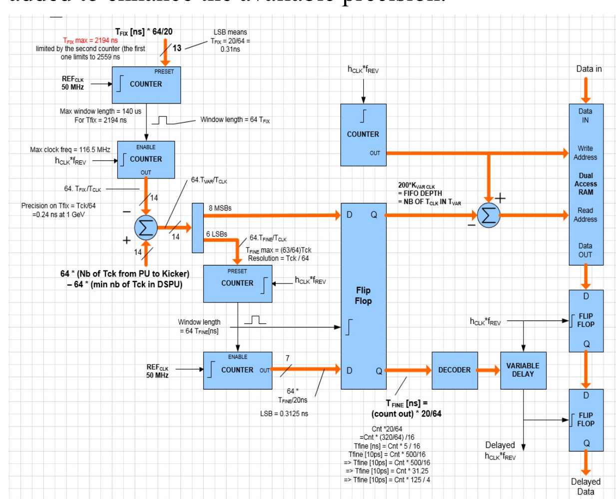

Figure 6: Automatic delay.

The delay is computed first by measuring the revolution time. For this purpose, the 64*Frev ticks are counted within a fixed duration time-window. When the revolution time is known, the real time process need to receive as inputs both the PU-to-kicker distance and the fixed cable delays within the loop. The circuit can then infer the additional delay to add in the feedback loop. The reference window's length for the measurement of the 64*Frev clock sets the precision of the required delay in a context where the revolution frequency would be fixed. During acceleration, a compromise needs to be found, as a too long measurement would induce errors due the varying revolution frequency during the time

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of measurement. The fine "analogue delay" for the loop-processed signal is obtained by inserting the analogue delay between the write and read clock of the variable length FIFO streaming the loop data. The challenge here is to avoid indeterminations when sampling data during their transition phase.

Beam Excitation Signal Generation

The excitation signal can be summed to the main loop signal when required. The excitation signal may have three different sources. One external input from the tune measurement system that requires a transverse excitation of the beam to measure the betatron lines' position, another external input for beam studies and finally an internal source with 9 independent sinewave sources with independent amplitudes, frequencies and relative phases. The 9 sources are designed using Direct Digital Synthesizers (DDS) clocked with an harmonic (64) of the revolution frequency. This allows to set the excitation frequencies as harmonics of the revolution without the hassle of following its progression. Only the progression of the machine tune will need to be accounted for. As an option, up to 3 different programmable windows can be defined within each revolutions in order to excite the beam only partly. Finally, the excitation can be programmed to be either dipolar or quadrupolar. In the latter mode, both kicker plates within the same H or V plans will exhibit the same signal, meaning that the kick force sensed by the particle will be a function of its distance to the centre of the vacuum pipe.

Power Amplifiers [3]

The power stage provides 800 W_{RMS} CW on each 50 Ohms kicker strip-line electrode, instead of 100 W initially. This increase allows for more gain in the loop, thus more headroom for potential high growth rate instabilities. Primarily this increase of power was required to avoid saturation in case of a misbehaviour of the BOSS during the extraction bump (leading to an absence of damping). Then a demand came also from the machine physicists who needed a transverse excitation source, powerful enough during a short time-period, to allow for a beam response with spectral lines popping-out enough from the noise floor. The amplifiers are designed using two stages: one 4 W unit driving a 800 W unit.

Kicker

The kicker in each ring of the PS Booster hosts four 50 Ohms stripline electrodes diametrically opposed in each H and V planes. Each electrode is fed via a 50 Ohm coaxial line that in turn feeds a 50 Ohm cable to a power attenuator.

MEASUREMENTS

The new digital setup with its new amplifiers has been successfully tested in the horizontal plane of the PSB Booster ring 3. This test is not yet backed-up with precise measurements proving the expected benefit on the damping time of beam instabilities but proof has been made that he expected power is sensed by the beam, in excitation mode, as reported by machine physicists during machine optics measurements [4]. As the present highest intensities (1E13 ppp) were accelerated without losses, it proves that all the signal-processing blocks behave as expected. Without a well-set transverse feedback, losses occur repeatedly with all intensities above 0.35E13 ppp (see Fig. 7). The internal excitation source has not yet been tested with beam, but no surprise is expected as the lab results are totally under specifications.

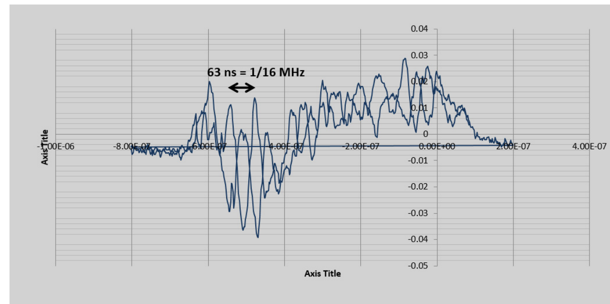

Figure 7: Instabilities cured by the new TFB.

CONCLUSION

A new transverse feedback system has been successfully installed and tested in the CERN PS BOOSTER synchrotron. It offers more power, a sophisticated and previously non-existent transverse beam excitation source, and a new digital processing allowing for an improved damping time, together with more refined control features and tuning capabilities. The new system will also cope with the increased beam intensity expected in 2021 (60% increase). The availability of the transverse feedback with a half integer tune value came lately as a new potential requirement and the latter should be assessed in 2018. A first estimation shows that a second PU and a second kicker would be required for this purpose. The sampling clock of the DSPU is also being scrutinized, as its present varying frequency is not perfectly handled by the FPGA programming applications and its imbedded PLL frequency sources. This inadequacy is even worse when both a clock and its delayed sibling are both used within the same FPGA.

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