THE NEW CERN PS TRANSVERSE DAMPER

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Abstract

A new transverse feedback system for the CERN PS accelerator has been commissioned [1]. The main highlights of the signal processing are the automatic delay, adapting itself to the varying revolution frequency, and the programmable betatron phase adjustment along the cycle.

For the power system, a compact design of a wideband high-power solid state amplifier has been realised, as well as an impedance matching transformer to apply the signal to the strip-line kicker.

Pick-ups were re-furbished with new electronics covering the very low frequency of the first betatron line.

Since 1999 the PS has been operated without active transverse damping thanks to an increase of the coupling between the transverse planes [2] and the reduction of injection steering errors. Although the LHC requirements are fulfilled by these means, the new transverse feedback system will reinforce the robustness of the operation and avoid the blow-up generated by the always remaining injection steering errors. It could also allow the reduction of the chromaticity which might reduce the slow incoherent losses during the long PS injection plateau. Another potential application is to try stabilizing the high energy instabilities that appear occasionally with the LHC nominal beam and may be a limiting factor for ultimate LHC beams. The overall system is described together with experimental results.

INTRODUCTION

The Transverse feedback system was first dimensioned in terms of power and bandwidth. Power is crucial to damp injection errors before decoherence (6 kW per plane), and the larger bandwidth is required to cover the ripple of the injection kicker (25 MHz) at one end and the first betatron line at the other (40 kHz).

The transverse feedback was also specified in terms of adaptation to the varying revolution frequency, wide range of intensities, wide range of beam harmonics and ring filling pattern and change of transverse machine tune along the cycle. The resulting system is described below.

ARCHITECTURE

Power Requirements

Power requirements are dictated by the decoherence time of injection errors. As not all foreseen beams were available at the project starting time, the decisions were taken upon simulation results. The simulations using the "HEADTAIL" code are plotted in Fig. 1 and show how the beam decoheres at the PS injection with different types of beams. Space charge effects prolong the coherent motion, while non-linearity and chromaticity tends to damp it. Nevertheless, with small intensities (non effective space charge) and a linear lattice, the motion decoheres and then fully recoheres at the synchrotron rate indefinitely under the effect of chromaticity (ξ=-1 in the simulations). Due to amplitude-dependent non-linearities, there is no full re-coherence but a decay of the envelope. The safe approach taken here asks for the damping to be completed before the end of first natural decay.

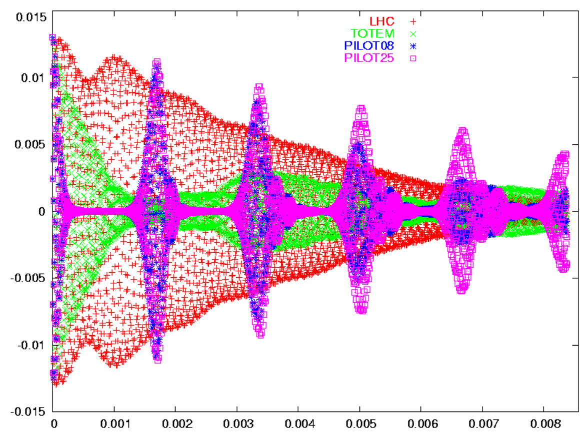

Figure 1: Transverse decoherence as simulated.

The required power of each of the two amplifiers per plane mounted in push-pull can be expressed [1] as:

$$P_{strip-line} \geq \frac{68^2 \cdot d^2}{\eta_K^2 \cdot 8 \cdot L^2 \cdot Z_C} \cdot \left(\frac{\Delta u}{T_d}\right)^2$$

This formula takes into account $\beta_{H\,Kicker}$ = 22 m, η_K = 0.5 is the efficiency of the kick (includes the non ideal Betatron phase at each turn and the effective field strength), d = 0.35 m is the distance between opposite kicker plates, L = 0.9m is the kicker length, Z_C =112 Ω is the characteristic impedance of the kicker, Δu = 3 mm is the maximum injection error and T_d = 50 μs is the most demanding damping time (LHC pilot beam). The resulting required power is 1764 W minimum per strip.

Power Equipment

The actual power setup with 3kW per strip-line kicker plate and a [2.5 kHz, 25 MHz] bandwidth, is a very compact and economical design. The solid state power amplifier, [3kW for 2ms, 800W-CW], [2.5 kHz, 25 MHz], [43x40x17cm], water cooled and fed by a 55V, 55A power supply has a gain of 60 dB. A custom designed 3 kW transformer, Fig. 2, [2 kHz, 40 MHz], [8x24x30cm] adapts the 50 Ω line to the 100Ω (112 Ω actually) strip-line kicker.

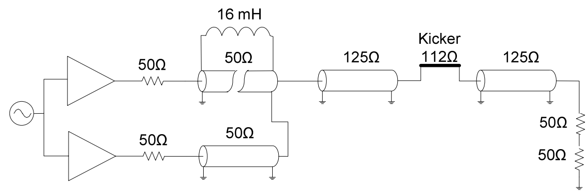

Figure 2: Impedance matching transformer diagram.

The final matching load is composed of a 50Ω, 190 MHz, 1.6 kW-CW series resistor in line with a 50Ω cable feeding the final 50Ω power attenuator [1 GHz, 1 kW-CW].

Pick-Up Amplifiers

The pick-up amplifiers are 5 meters away from the ring to avoid irradiation. The equivalent 70 pF of the pick-ups driving a 50Ω matched line would create a high-pass cut-off pole at 45 MHz (70pF/50Ω), which means a 60 dB attenuation at the lower Betatron band. Therefore, a compensating network, Fig. 3, has been added to decrease the impedance loading at the lower frequency end. The coaxial cable drives a high impedance load at low frequencies - below the natural cut-off – and it is matched for higher frequencies. The reflections at high frequencies are damped by the series resistor at the pick-up level. The cable has been chosen with a characteristic impedance of 75 Ω to ease the design (lower natural cut-off). The obtained bandwidth is [20 kHz, 40 MHz].

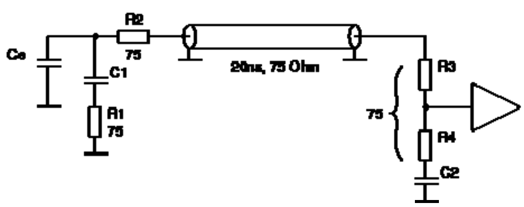

Figure 3: Pick-up amplifier input network.

The variable gain amplifier and the programmable attenuation network within the device allows for a 80 dB gain range compatible with all the beam intensities including ions.

PS TFB Digital Signal Processing

The Digital Signal Processor [3, 4] will take care 1) of the equalisation of the loop delay with the beam time of flight, 2) of the adaptation of the betatron phase to the machine tune and 3) of the removal of the unwanted revolution frequency lines corresponding to an orbit offset. The entire circuit is clocked at harmonic 160 of the revolution frequency which stays within the 80 MHz limits of the ADC's clock. The clock is obtained from a 1GHz clocked DDS driven by the PS digital frequency program.

Betatron Phase Adjustment

The betatron phase offset can be obtained in two ways: 1) vector sum of the signals from two pick-ups having a different betatron phase (PU98 and PU02) or 2) insertion of a Hilbert digital filter. The first method can be used when the present module, originally developed for the LHC cavity 1TFB will be upgraded. The present tests were accomplished with an m=1 Hilbert filter [figure 4] at the expense of an additional 1-turn delay in the electronic path. With the kicker in section 97/100 and the PU in 98/100, this makes a total loop delay of 199/100 revolutions over which the betatron phase is integrated. Taking into account the phase response of the notch filter, the phase offset in the electronic path needs to be set to the following value: $\Delta\varphi_{Hilbert} = 158^o + 896^o * q$, where q is the decimal part of the transverse machine tune; the integer part Q being equal to 6. $\Delta\varphi_{Hilbert}$ will be programmed in accordance with the measurement of Q, with a sensitivity towards the q value $d(\Delta\varphi_{Hilbert})/dq = 896^o$. With a tolerated Betatron phase error of 10^o, the error on the measurement of q should not exceed 0.011, which is 11 times more than the precision estimated for the tune measurement system (BBQ) and therefore within reach.

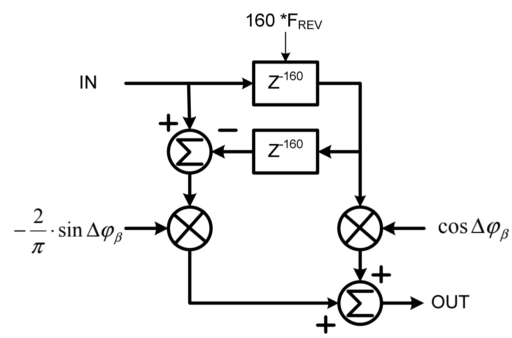

Figure 4: m=1 Hilbert filter.

Suppression of the Revolution Harmonics

The removal of the revolution frequency lines is obtained by the use of a simple notch filter, Fig 5.

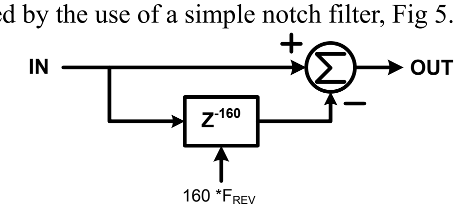

Figure 5: Notch filter.

Automatic Delay Adjustment

A circuit has been designed to automatically adjust the delay of the loop to the beam time of flight [5]. To the fixed delay (T_{FIX}) and to the digital pipeline delay ($K_{FIX\ CLK}$ clock periods) present in the loop it adds a variable amount. This variable delay has two consecutive components: a wide range variable pipeline delay ($K_{VAR\ CLK}$ clock periods) and a fine programmable delay ($T_{VAR\ FINE}$), with a maximum value equal to the clock period. The resolution and the precision of the system were chosen to be equal to 1ns. The expression to be fulfilled is: $K_{FLIGHT} * T_{REV} = T_{FIX} + K_{FIX\ CLK} * T_{REV} + T_{VAR}$, where $K_{FLIGHT} * T_{REV}$ is the beam flight time from PU to kicker. This expression can be rewritten as:

$$(T_{VAR} / T_{CLK}) = (K_{FLIGHT} - K_{FIX\ CLK}) * h_{CLK} - (T_{FIX} / T_{CLK})$$

The circuit depicted in figure 6 shows how this equation is translated into hardware. The obtained T_{VAR}/T_{CLK} is split into integer and decimal subsets to control the pipeline and fine delays. Apart from arithmetics, there is a transformation of the T_{FIX} register value into T_{FIX}/T_{CLK} and of the decimal value T_{VAR}/T_{CLK} into nano-seconds by means of a window creation with one clock and its length measurement with another.

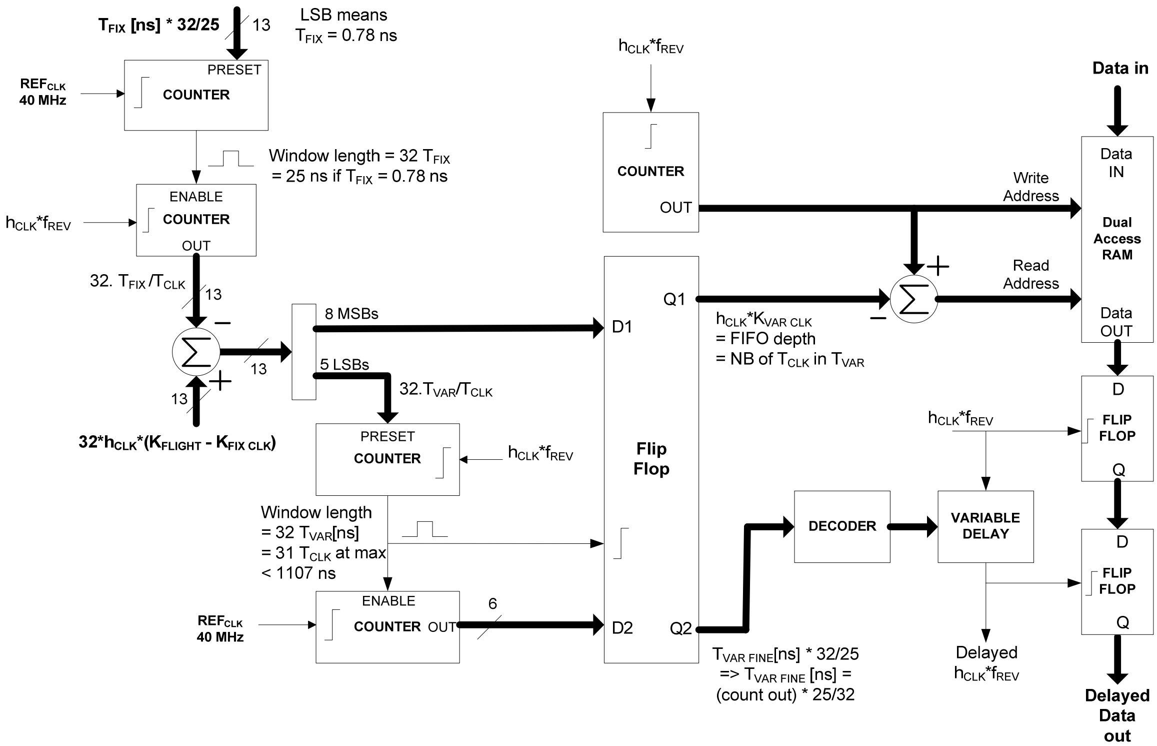

Figure 6: Architecture of the automatic delay circuit.

MACHINE RESULTS

The described setup could be tested late in the 2008 beam run. The system was first parameterised during a session with measurements of the open loop response at different energies. K_{FLIGHT} and K_{FIX} were known and could be programmed straight forward. T_{FIX} had to be found from the phase deviation along the different betatron lines. These parameters being set at one energy (1.4 GeV) were used at another (3.5, 14 and 26 GeV) to check the proper behaviour of the automatic delay. At these different energies the betatron phase was set manually to adapt to the existing machine tune. The efficiency of the injection damping was tested at 1.4 GeV. Figure 7 shows how the 30mm p-p initial injection is damped with a rate of 20mm/ms (21mm/ms required at max) with the TFB (horizontal scale = 500 µs /div).

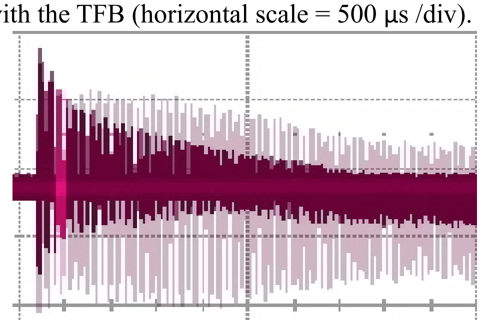

Figure 7: Horizontal decoherence time, w or w/o TFB.

CONCLUSION

The new PS TFB has shown its capability in terms of kick efficiency and adaptation to the varying parameters during acceleration. The automatic delay, the Hilbert and Notch filters behave as expected together with the power equipment and the control system. Taking full advantage of the PS tune measurement along the cycle and carefully adjusting the phase accordingly, the 2009 run will allow the test of the equipment with full capabilities.

ACKNOWLEDGMENTS

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