TRANSVERSE RIGID DIPOLE AND INTRA-BUNCH OSCILLATION DETECTION USING THE TRANSVERSE FEEDBACK BEAM POSITION DETECTION SCHEME IN SPS AND LHC

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Abstract

The LHC and SPS transverse dampers use beam position electronics with I,Q detection at 400 MHz and 200 MHz, of the sum and difference signals from a strip-line pick-up. Digitization is performed to give synchronous bunch-by-bunch data at the rate of 40 MHz corresponding to the bunch spacing of 25 ns. A performance in the µm range is achieved with beams in LHC and has contributed to the high performance of the essential transverse feedback during the LHC run 1. In the present paper we review the systems deployed and their performance as well as the potential of the I,Q detection to also detect intra-bunch motion. The principle is illustrated using data from LHC injection tests in which intra-bunch motion is expected and has been observed due to electron cloud instabilities. The potential use of this signal to drive a transverse intra-bunch feedback system is outlined.

INTRODUCTION

The CERN LHC transverse feedback system, fully commissioned in 2010 [1] uses strip-line beam position monitors to detect bunch oscillations [2] around the closed orbit and provides feedback to damp these oscillations and keep the beam stable. Kickers operate in baseband and cover betatron frequencies up to 20 MHz, half the bunch repetition frequency to be able to damp all coupled bunch dipole oscillations. The power system of the LHC transverse feedback system uses the same technology as used in the CERN SPS transverse feedback system having operated for many years. Kickers use the electric field only with kicker plates ranging from 1.5 m length to 2.4 m length (1.5 m for the LHC and the SPS vertical systems and 2.4 m for the SPS horizontal systems) driven by tetrode tube amplifiers directly installed in the accelerator tunnel under the kicker structure. The SPS transverse feedback system has been upgraded during the long shutdown 1 (LS1, 2013-2014) as part of the LHC Injector Upgrade Project (LIU) [3] to use the same analogue and digital signal processing techniques as already used successfully since 2010 in the LHC.

In the following we describe the signal processing, analogue and digital, used to compute the bunch position (symmetric mode component) as well as the headtail oscillation amplitude (asymmetric mode component).

POSITION DETECTION IN THE SPS AND LHC TRANSVERSE DAMPERS

The stripline pick-ups are optimized in length to have the maximum response around the RF frequency of the main RF system in these accelerators, 400 MHz in case of the LHC and 200 MHz in the SPS case. The SPS system also includes a variant of hardware for the doublet scrubbing beam, a beam that is split at SPS injection to form two bunches spaced 5 ns every 25 ns [3]. The hardware dedicated to this type of beam takes the beam-pick-up signal at a band centered around 40 MHz directly sampling it with 120 MS/s without analogue down conversion. This ensures proper operation during the splitting process.

LHC Transverse Damper (ADT)

The LHC pick-up signal processing scheme [2] is depicted in Fig. 1. The signals from the strip-line pick-up plates pass through a hybrid and both the sum signal (proportional to bunch intensity) and the delta signal (difference of PU plates, proportional to bunch intensity and position) are taken into account in the further processing. A band-pass filter selects the frequency components around the RF frequency of 400 MHz. The filter is shaped to give in time domain a burst of nine pulses from each bunch, at 400 MHz. Each of the signal bursts from the individual bunches is then separated by one RF period, 2.5 ns , for the canonical bunch spacing of 25 ns. After analogue down conversion a 15 ns to 20 ns wide pulse is obtained that is sampled synchronously using a 40 MHz sampling clock. Digitization is done with a 16 bit ADC and four numerical values are obtained for each bunch, the in-phase (I) and quadrature components (Q) — with respect to the RF frequency — of the Σ and Δ signals.

Within an FPGA the absolute value of the bunch position can be calculated by division of the magnitude of the (I, Q) vector of the Δ and Σ signals

$$x = \frac{\sqrt{\Delta_{\mathrm{I}}^2 + \Delta_{\mathrm{Q}}^2}}{\sqrt{\Sigma_{\mathrm{I}}^2 + \Sigma_{\mathrm{Q}}^2}} c_{\mathrm{cal}} \,. \quad (1)$$

The sign for the beam position has to be correctly chosen and depends on the exact phasing of the beam RF signal with the 400 MHz reference RF used for the demodulation. A calibration factor ($\mathrm{mm/counts_{ADC}}$) is determined when the damper is set-up using the orbit measurement system and making closed orbit bumps at the location of the damper pick-ups. In practice, on the FPGA in the damper feedback system, a different algorithm is used to compute the normalised position which takes into account the measured angle between sum and delta signal with respect to the (I,Q) coordinates defined by the 400 MHz RF. This algorithm is using the relation

$$\frac{\Delta_{\mathrm{I}}\Sigma_{\mathrm{I}} + \Delta_{\mathrm{Q}}\Sigma_{\mathrm{Q}}}{\Sigma_{\mathrm{I}}^2 + \Sigma_{\mathrm{Q}}^2} = \frac{|\Delta|}{|\Sigma|} \cos(\phi_\Delta - \phi_\Sigma) \quad (2)$$

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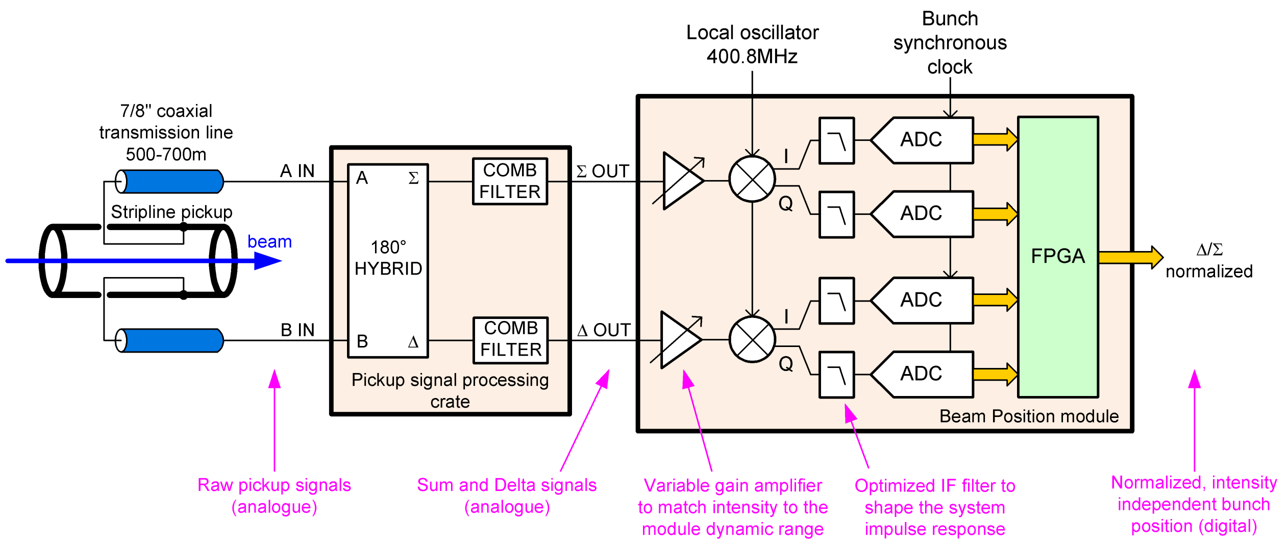

Figure 1: Pick-up front-end processing for LHC transverse feedback system (ADT).

where ϕ_Δ and ϕ_Σ are the phases of the delta and sum signals with respect to the RF signal at the mixer. It can be seen that, if the signals are aligned on the mixers (Δ and Σ vectors parallel in (I,Q) space) the expression yields readily the normalised beam position with the sign coded in the difference angle between sum and delta $\Delta\phi = \phi_\Delta - \phi_\Sigma$. In this case, $\Delta\phi$ is 0 for positive position and π for negative positions as calibrated by comparison with the orbit system. In practice the vectorial alignment of the sum and delta signals is not done in the analog domain, but digitally by applying a standard rotation matrix to the Δ signal

$$\begin{pmatrix}\Delta_I \\ \Delta_Q\end{pmatrix} = \begin{pmatrix}\cos\psi & -\sin\psi \\ \sin\psi & \cos\psi\end{pmatrix} \begin{pmatrix}\Delta'_I \\ \Delta'_Q\end{pmatrix} \tag{3}$$

where ψ is the required rotation angle to align sum and delta signals correctly in the (I,Q) space and the dashes apply to the raw digitized delta I and Q components. The angles ψ for each pick-up are determined during a beam-based calibration.

Provided both channels, sum (Σ) and difference signal (Δ) are equal in transmission characteristics from the pick-up through the hybrid and amplification chain as well as the down conversion, the resultant position is independent of both bunch intensity and bunch length. This is still true for a bunch with an asymmetric longitudinal shape as can be the case in the double harmonic system of the SPS with 200 MHz and 800 MHz RF. If bunches oscillate longitudinally the difference phase $\phi_\Delta - \phi_\Sigma$ remains equal and the computed bunch position is not affected by this oscillation.

SPS Transverse Damper

Within the SPS-LIU Project the lowlevel system of the SPS transverse damper was upgraded [3] and the system fitted with dedicated pick-ups and processing matched to the requirements of the specific beams. In total the upgrade is foreseeing four parallel signal processing paths, one for the fixed target beam (5 ns bunch spacing) using electrostatic pick-ups, and three for the LHC type beams using signals from two strip-line coupler pick-ups.

The three systems for the LHC type beams serve the standard LHC proton beams with a bunch spacing of a multiple of 25 ns, the special scrubbing doublet beam with two bunchlets spaced by 5 ns every 25 ns, and a special set of electronics foreseen for the LHC ion beam injection damping with unique requirements for the clocking scheme due to the FSK modulation of the RF [3].

Three out of the four transverse damper lowlevel systems for the SPS transverse damper were completed in long shutdown 1 (LS1) — all but the system foreseen for ions, which is still under development. All beams were re-commissioned in 2014/2015 with the SPS system now offering similar diagnostics for instabilities as the LHC transverse feedback system since 2010.

In the case of the SPS system a sampling frequency of 120 MHz was chosen at 16 bit, using a Dual ADC from Linear Technology (LTC 2185). The sampling is synchronous with the bunch repetition frequency of 40 MHz and allows two samples to be placed on the pulse from a single bunch meant to enhancing the signal/noise ratio. The choice of sampling rate also allows direct digitization of the RF signal for the scrubbing doublet beam from a band at 40 MHz.

The fact that the Δ signal is proportional to the bunch longitudinal profile and the bunch oscillation pattern can be viewed as a mixing process. This is illustrated in Fig. 2 for a symmtric osillation $x(t) = \cos(2\pi f t)$ at $f = 1$ GHz, on a guassian bunch with $4\sigma = 1.5$ ns. The resultant spectrum is the convolution of the complex spectra and also depicted in Fig. 2. The detected beam position will depend on the value of this spectrum at 400 MHz in the LHC case, the frequency of detection used for the transverse feedback system. For a given bunch profile $\lambda(t)$ we can now plot the sensitivity of the detected position on the intra-bunch frequency and

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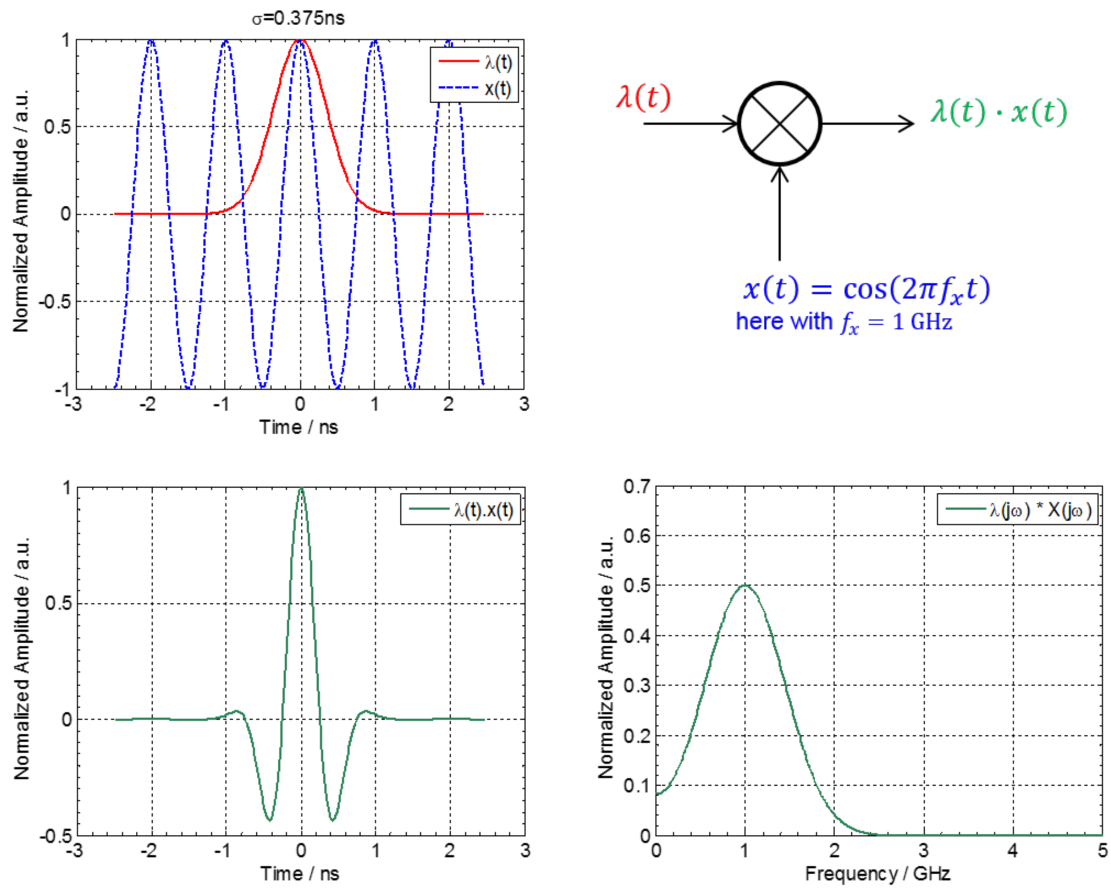

Figure 2: Illustration of internal bunch oscillation pattern multiplied by bunch shape function (top) with resulting time domain pick-up Δ signal and spectrum (bottom).

compare it with the average weighted bunch position (see Fig. 4).

$$\bar{x} = \int_{\text{bucket}} x(t)\lambda(t)\mathrm{d}t \;. \tag{4}$$

SENSITIVITY TO INTRA BUNCH MOTION

In the presence of intra-bunch transverse motion the 400 MHz component of the transverse signal will carry information of this oscillation in its amplitude and phase when compared to the 400 MHz component of the longitudinal signal. This fact is explored in the Multiband-Instability-Monitor being developed at CERN [4]. In this monitor system a bank of band-pass filtered spaced in frequency at the inverse of the bucket-length is used to track down in which frequency range instability occurs. The combination of direct diode detection from the BBQ system [5] is combined to give a very sensitive instrument that can indicate that beam instability occurs in a certain range of frequencies within a multi-bunch beam. However, using gating on the BBQ type of detector reduces its signal-to-noise ratio that can be achieved, making it difficult to track down within a bunch train the instability to a specific bunch. The scheme proposed here in this paper overcomes this limitation and is well adapted to diagnose intra-bunch motion on a bunch-by-bunch basis.

Rigid Dipole Oscillation and Symmetric Component

Taking an actual, non-gaussian profile, as has been measured for LHC with notches in the spectra at 1.5 GHz [6] can reveal some subtleties in the following example of the spectrum of Fig. 3 approximating the LHC spectra of LHC Run 1 [6]. The spectral sensitivity of the detected oscillation for this spectrum is shown in Fig. 4. For a rigid dipole oscillation ($f = 0$) the algorithm (1) exactly gives the average bunch position. For higher symmetric oscillations within the bunch the algorithm used in the feedback gives a signal slightly larger for this type of bunch shape. At 1.5 GHz, the first zero in the spectrum the sign changes for the computed position. This means if an oscillation develops at such a high frequency the feedback system does no longer damp directly the oscillation of the average bunch position that results from this oscillation. However, as the beam then will coherently oscillate also in baseband where a large feedback gain is available this phenomenon is not expected to lead to instability but thought to merely represent an additional mechanism that injects noise into the system.

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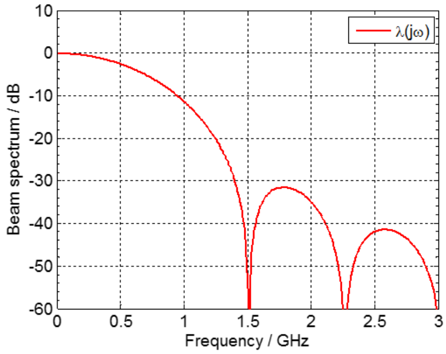

Figure 3: Approximated spectrum of bunch from LHC run 1 [6].

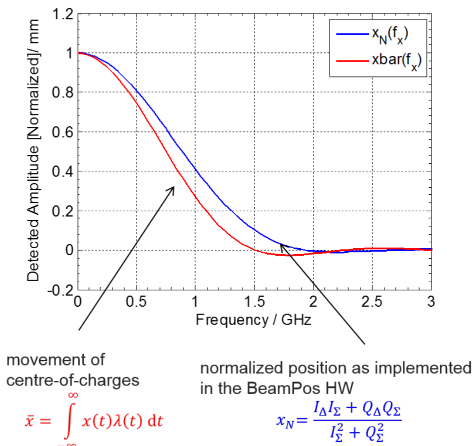

Figure 4: Computed bunch position for symmetric component of oscillation within bunch compared to bunch position weighted with line density.

Headtail Oscillation and Asymmetric Component

The I and Q components of Σ and Δ can be combined in a different way to give a single quantity indicating the presence of asymmetric oscillations within the bunch. Again the sensitivity of this cross term

$$x_{\mathrm{HT}} = \frac{\Delta_{\mathrm{Q}}\Sigma_{\mathrm{I}} - \Delta_{\mathrm{I}}\Sigma_{\mathrm{Q}}}{\Sigma_{\mathrm{I}}^2 + \Sigma_{\mathrm{Q}}^2} \tag{5}$$

can be computed as a function of frequency (Fig. 5).

Equation (5) assumes correct alignment in (I, Q) space. Using 400 MHz for the down conversion as in the LHC shows a broad range of frequencies up to close to 2 GHz that the algorithm is sensitive to. Since this quantity x_{HT} can be computed on a bunch-by-bunch basis, this presents an excellent possibility to diagnose intra-bunch headtail oscillations pointing to the unstable bunches in a train. Deploying this type of detection scheme on the Multi-Band-Instability Monitor would add additional possibilities to track down the frequency band of instability.

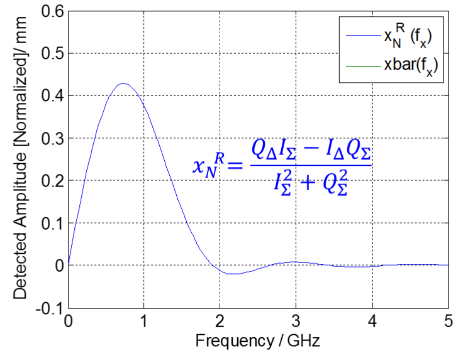

Figure 5: Computed bunch position for asymmetric component of oscillation within bunch; the weighted position for an asymmetric oscillation is always zero for a symmetric line density.

EXAMPLE FROM BEAM OPERATION

Trains of 48 bunches with 25 ns bunch spacing were for the first time injected into LHC in run 1 in 2011. As an example we will show results from a particular beam dump on August 26, 2011 with transverse feedback off. Following injection a transverse instability developed, interpreted as being driven by the electron effect [7, 8]. The data from the postmortem system of the LHC transverse damper for this dump were already analyzed in depth with respect to the rigid bunch motion using Eq. (1) [7]. Applying the algorithm (5) to the raw data reveals that in addition to the rigid bunch dipole oscillation there is also a headtail oscillation present. The two oscillation patterns dipole and headtail, are compared with their bunch-by-bunch amplitudes plotted in Fig. 6. Shown are the injected batch of 48 bunches for the last 73 turns before the beam dump. Clearly the instability, both rigid dipole and headtail develop along the batch and are similar in order of magnitude.

POTENTIAL OF HEADTAIL SIGNAL FOR USE IN A FEEDBACK SYSTEM

The headtail signal has a potential to be used in a feedback system. Similar to the approach of the SPS High Bandwidth Transvserse Feedback system [9], the signal could drive a kicker to damp the oscillation. Up-conversion to the RF frequency is needed as well as a signal processing that creates a signal in quadrature to the oscillation which can be achieved by digital processing using FIR filters similar to the standard coupled bunch feedbacks used at CERN. The up-conversion will create a signal that varies across the bunch and can drive a set of wideband kickers. The technique is particularly interesting for LHC where the shorter bunch length may limit the use of direct digitization of the signal. Moreover, resolution is more important for LHC where keeping noise levels low in any operating transverse feedback system is of great importance. The sampling in baseband of the proposed system offers the advantage of a large number of bit available

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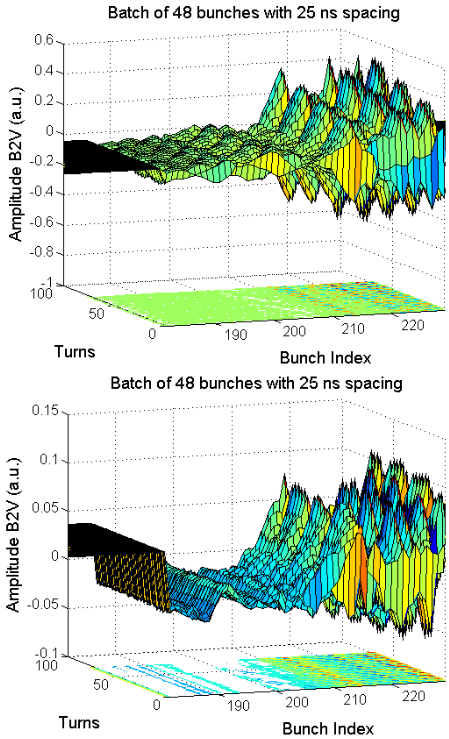

Figure 6: Symmetric (top) [7,8] and asymmetric (headtail, bottom) bunch oscillation pattern along batch before beam dump; LHC, 26.08.2011, transverse feedback off.

compared to direct sampling of the GHz analog signals and consequently a better resolution.

SUMMARY AND CONCLUSION

We have shown how in addition to the bunch position headtail oscillations can be detected using the existing hardware of the LHC and upgraded SPS transverse dampers. The method is promising as it can point to instabilities within a bunch train and identify which bunches are unstable. The potential use of the headtail signal to drive a feedback system to damp the fundamental lowest order asymmetric mode within a bunch has been outlined and represents a promising path to follow in simulation and experiment.

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