PERFORMANCE OF EXPONENTIAL COUPLER IN THE SPS WITH LHC TYPE BEAM FOR TRANSVERSE BROADBAND INSTABILITY ANALYSIS*

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Abstract

We present the performance and limitations of the SPS exponential coupler [1] for transverse instability measurements with LHC type beam. Data were acquired in 2008 in the SPS in the time domain with a bandwidth of up to 2.5 GHz. The data were filtered to extract the time evolution of transverse oscillations within the less than 5 ns long LHC type bunches. We describe the data filtering techniques and show the limitations of the pick-up due to propagating modes.

INTRODUCTION

Two types of transverse instabilities limit the single bunch intensity of proton beams in the SPS. On the one hand with multi-bunch beams such as the LHC nominal beam with 25 ns bunch spacing the electron-cloud instability limits the maximum intensity per bunch [2]. On the other hand for very high bunch intensities the single bunch transverse mode coupling instability (TMCI) is a limitation as well [3]. Common to both instabilities is the appearance of high frequency signals caused by oscillations within the bunch. Diagnostics to probe the nature of the instabilities, their spectral components and time evolution must be able to resolve oscillations within the bunch.

Due to the relevance of the electron cloud driven instability and its adverse effect on the transverse emittance (blow-up) and because some of the LHC upgrade scenarios beyond ultimate luminosity call for bunch intensities higher than the LHC ultimate bunch intensity of 1.7×10^{11} protons per bunch where the TMCI may limit performance, an R&D program was launched to optimally diagnose and possibly cure these transverse single bunch instabilities by a wide band transverse feedback system [4].

The quest to adequately diagnose the instabilities motivated the analysis of existing pickup/kicker structures in the SPS and to evaluate their performance.

Exponential couplers were built and installed in the SPS [1] and are readily available. A fast digital oscilloscope was used to acquire the data from the pick-up with offline post processing to correct for imperfections, in order to evaluate the pick-up performance and provide the means to accurate diagnose the instabilities.

In the following we present the results of these activities, explain the elements of the acquisition chain, show some sample measurements and discuss the post processing methods. Conclusions are drawn and future plans outlined.

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EXPONENTIAL PICKUP AND ACQUISITION CHAIN

The main component of the acquisition chain is a stripline pickup where the stripline has s-dependent (s being the coordinate in beam direction) width that translates in an s-dependent coupling constant. The distance of the stripline from the vacuum chamber diminishes as the width decreases such as to preserve a constant line impedance of 50 Ω. If the coupling, i.e. the electrode shape, is exponential the resulting transfer function is almost flat in amplitude instead of having the typical notches of a constant width stripline pick-up. The absolute value of the transfer function in frequency domain is [1]

$$|F(\omega)| = \frac{K\omega l/c}{\sqrt{a^2 + \frac{4\omega^2 l^2}{c^2}}} \sqrt{1 + e^{-2a} - 2e^{-a}\cos(2l\omega/c)} \tag{1}$$

and the phase is

$$\mathrm{Arg}\{F(\omega)\} = \arctan\left[\frac{2\frac{\omega l}{c}\sin\frac{2\omega l}{c} + a\left(e^a - \cos\frac{2\omega l}{c}\right)}{2\frac{\omega l}{c}\left(e^a - \cos\frac{2\omega l}{c}\right) - a\sin\frac{2\omega l}{c}}\right] \tag{2}$$

where l is the kicker length, K a coupling constant and a is describe the exponential tapering ([1]). We assumed ultra-relativistic beams, $v = c$. Normally the pick-up is installed with the beam passing the wide end of the strip first, we will call this *forward* installed. A backward installed coupler has the beam interacting the narrow end of the strip first. Note that the coupler is directional and signals are always extracted at the upstream ports.

A drawback of the exponential coupler is its nonlinear phase response, but it can either be corrected by numerically filtering the data or in the case of a pickup-kicker combination one can take advantage of the mirrored phase response for a backwards installed coupler. With one coupler (kicker or pick-up) installed backward and the other forward we expect to compensate for an overall linear phase response.

The pickup has four electrodes at ± 45 degrees to the horizontal plane which allow to measure both bunch intensity, as well as horizontal and vertical displacement. In the SPS there are a total of four such pickups installed, two usually cabled for horizontal operation and two for vertical operation. The tests concentrated on the vertical observations, plane in which the electron cloud effect causes a high frequency instability.

The pickup could not be tested on a bench, but we measured with a network analyzer the properties of the electrodes, cables and hybrids. The installation orientation of the pickup cannot be tested without beam, the stripline being a matched 50 Ω system. A dedicated experiment with short bunches showed that one of the four pickups under test was installed backwards, opposite of what would be the expected default orientation, a relict from past operation with anti-protons, see Fig. 1. Another critical part

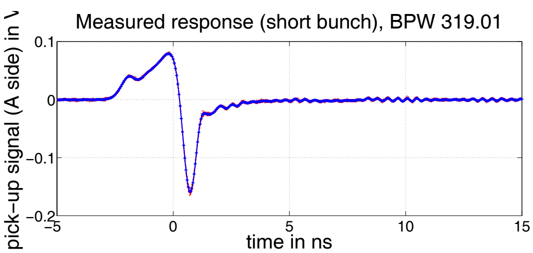

Figure 1: Measured pick-up response to single short bunch (backward installation).

are the long cables that bring the signals to the surface. While the attenuation was as expected and not a major concern, we found, rather unexpected, the nonlinear dependence of phase with frequency in these corrugated cables [5] to further spoil the performance of the pick-up when signals were observed in the time domain: with short bunches and long cables a "ringing" can be observed. This is illustrated in Fig. 2 where we compare the calculated time domain response of the pick-up to a gaussian bunch of length $4\sigma = 1$ ns, in forward (solid blue line) and backward (dashed) installation direction with and without the required cable, as actually installed. The bunch is shown for comparison (red curve) and the responses have been normalised to have a peak value of 1.

Resistive combiners were used to sum signals from the two pairs of electrodes and an Anzac H-9 hybrid was used to produce sum and delta signals. Care must be taken not to saturate the hybrid. In the final set-up used the hybrid was installed on the surface, with cables from the tunnel precisely matched in length. The attenuation from the cables (5 dB to 20 dB in the frequency region of interest) gives additional protection to avoid saturation of the hybrid—the attenuation is in any case in the signal chain. 6 db and 3 dB attenuators were further installed at the cable ends and 20 dB for the sum signal to equalize the voltage level to the delta signal in the scope. With this setup the signal levels were oscillating between 10 mV to 1 V depending on the bunch intensity.

For data acquisition we used a Tektronix DPO7254 digital oscilloscope capable of a maximum sampling rate of 40 GS/s. For most of the measurements two channels (sum and delta) were recorded reducing the maximum sampling rate to 20 GS/s. Bunch synchronous triggering was available (each turn) allowing efficient use of the memory of the oscilloscope. With the installed memory of 20 M samples per channel, one batch of LHC beam ($\simeq 8\mu$s) could be recorded for hundreds of turns or a single bunch for $\simeq 20'000$ turns.

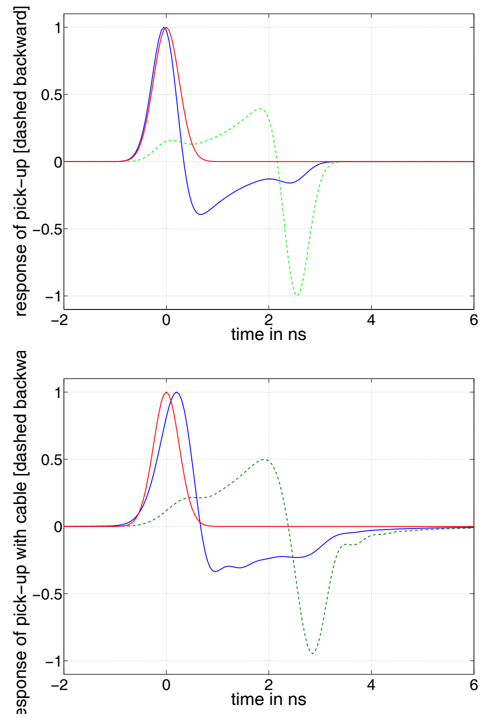

Figure 2: Pick-up response to gaussian bunch without and with cable. Red line represents the bunch intensity, blue and dashed line the signal distorsion of a forward and backward pickup installation respectively.

MEASUREMENTS

We acquired data during machine development study sessions in the SPS in 2008 at injection with LHC beam and up to nominal LHC beam intensity ($> 1 \times 10^{11}$ protons per bunch) subject to the electron cloud instability (Fig. 5) and single bunch beam with and without RF (Fig. 3-4) for TMCI diagnostics and to search for machine impedance [6].

Figure 4 shows the frequency content of one single bunch demonstrating the flatness of the response compared to a traditional stripline. A multi bunch measurement shows that the stripline picks up in the delta signal experiences high Q resonances above $\simeq$1.6 GHz. The frequency of 1.6 GHz can be associated with the TE_{11} mode cut-off frequency of 1.64 GHz (calculated for a vacuum pipe diameter of 107 mm). For the sum signal the signals of the related resonance in the pick-up cancel due to the symmetry of the mode. Careful inspection of the sum signals reveals the presence of spectral components close to the TM_{01} mode (2.1 GHz calculated, 2.2 GHz observed) and the TE_{21} mode (2.7 GHz calculated, 2.4 GHz observed). Analysis of delta signals from a single captured bunch show the absence of a line at the TM_{01}, as expected (monopole mode), but the 2.4 GHz signal is again observed. Note that the TE_{21} is of quadrupolar symmetry and both, delta and sum signals can be excited with the beam not centered in the pick-up.

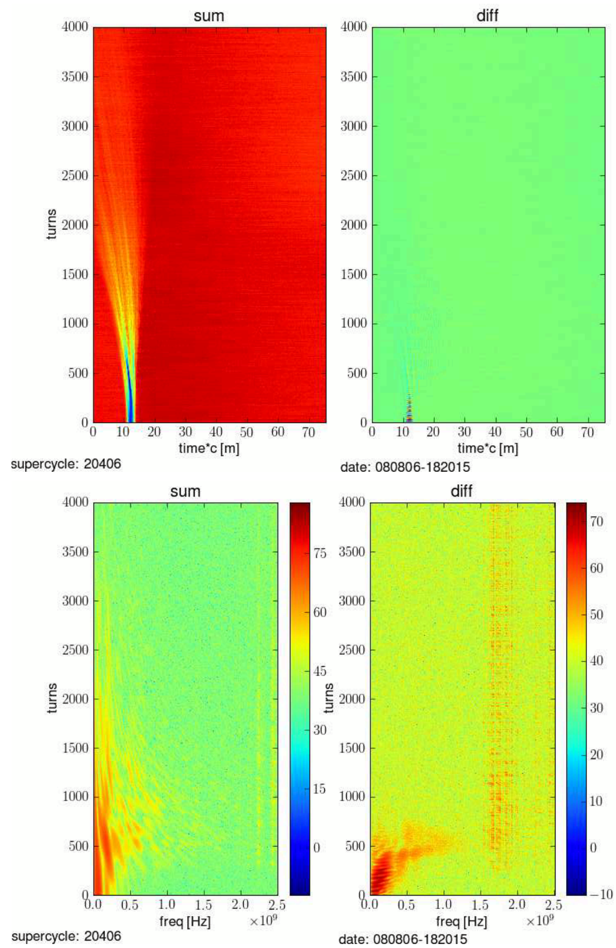

Figure 3: Debunching in the SPS, time domain data reconstructed and spectrum of sum and difference signal from a vertical pick-up. Bunch is unstable and lost.

Delta signals show some distortions, which are supposedly due to strip line imperfections. In order to extract the interesting oscillatory part these distortions can be removed by a comb filter (1-tap notch).

CONCLUSIONS

We demonstrated the performance of the available wide band exponential couplers in the SPS and outlined the signal processing necessary to extract the relevant bunch oscillations. The pick-up worked as expected, but a number of shortcomings such as a systematic distortion of the delta signal due to non-equal electrodes remains to be understood and efficiently removed from the data through calibration. During the 2009 SPS run we plan to continue the measurements for instability analysis. One of the couplers will also be equipped with high power hybrids and loads (200W range) allowing it to be used for excitation purposes and to measure beam transfer functions.

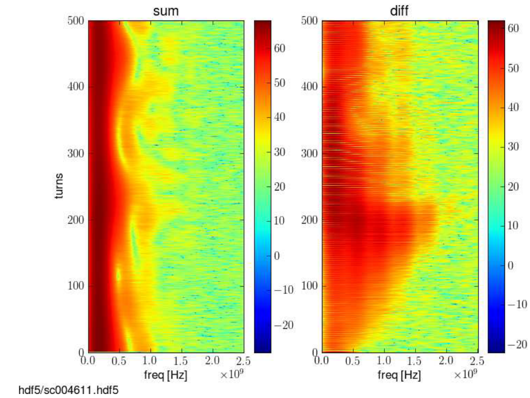

Figure 4: Evolution of spectra (sum and difference) for captured single bunch, transversely unstable.

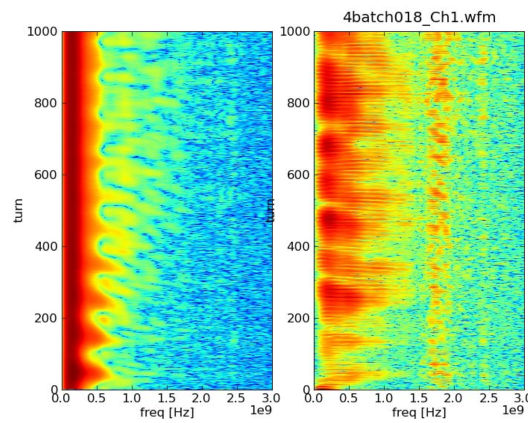

Figure 5: Evolution of spectra (sum and difference) for one LHC bunch in a bunch train subject to e-cloud transverse instability.

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