HIGH SENSITIVITY TUNE MEASUREMENT BY DIRECT DIODE DETECTION

M. Gasior, R. Jones, CERN, Geneva, Switzerland

Abstract

The fractional part of the betatron tune for a circular accelerator can be measured by observing beam oscillations on a position pick-up. In frequency domain the betatron frequency is seen as sidebands on either side of the revolution harmonics. Usually beam signal pulses from the pick-up are very short with respect to the revolution period, resulting in a broadband spectrum. Classical tune measurement systems filter out just one of the betatron sidebands. As a consequence, most of the betatron energy is lost and only a very small fraction remains for further processing. This paper describes a new method, referred to as Direct Diode Detection (3D). It is based on the idea of time stretching beam pulses from the pick-up in order to increase the betatron frequency content in the baseband. The 3D method was recently tested in the CERN SPS and PS, BNL RHIC and FNAL Tevatron machines. Results from all these machines [1, 2, 3, 4] show that this method can increase the betatron signal level by orders of magnitude as compared to classical systems, making it possible to observe tunes with no explicit excitation. Frequency resolution in the order of 10^{-5} and amplitude sensitivity in the order of 10 nm has been achieved with this very simple hardware.

3D PRINCIPLE AND THE HARDWARE

The crucial part of a 3D-based tune measurement system is the peak detector. Two such detectors connected to opposing electrodes of a beam position pick-up (PU) (see Fig. 1) yield the amplitude modulation envelope of the beam signals. Such signals, depicted in Fig. 2, are superimposed on a DC voltage related to the bunch amplitude (revolution frequency content). The signal difference, shown in Fig. 3 for single bunch in the machine, contains almost the whole bunch modulation amplitude, with a DC component related to the beam offset from the centre of the pick-up. Since the DC content can be easily suppressed by series capacitors, most of the corresponding revolution frequency (f_r) background can be removed by the peak detectors before the first amplifying stage. In Fig. 4 the f_r attenuation characteristic is shown assuming single bunch in the machine, which is the most difficult case to deal with. For a detector time constant $\tau = R_f C_f$, which is larger than the machine revolution period $T=1/f_r$, the suppression of the revolution line goes as $4\tau/T$ [1]. This makes it possible to obtain f_r attenuation in the order of 50 dB for $\tau \approx 100$, which is easily achievable in practice.

The 3D circuit in Fig. 1 can be also understood as two sample-and-hold blocks, sampling bunch signals close to their maxima at the bunch repetition rate, downmixing the wideband bunch spectrum into the baseband.

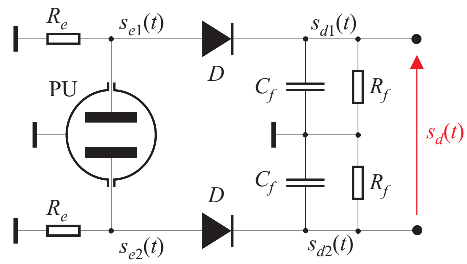

Figure 1: Direct Diode Detection principle.

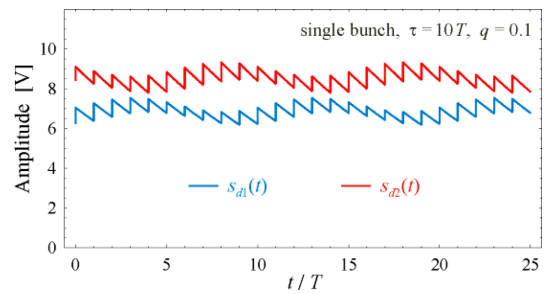

Figure 2: An example of peak detector voltages.

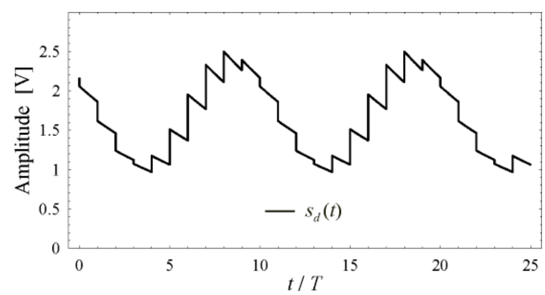

Figure 3: Difference of the signals in Fig. 2.

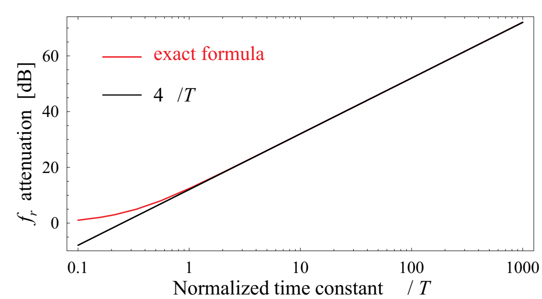

Figure 4: 3D circuitry revolution frequency attenuation.

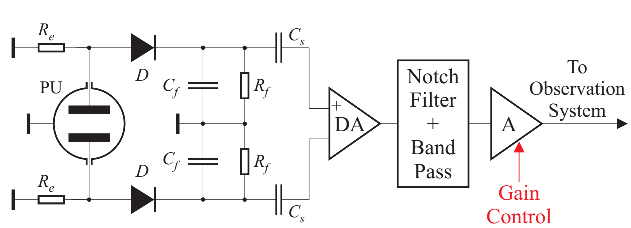

Figure 5: Block diagram of a 3D-BBQ system.

A block diagram of a 3D Base-Band Q (BBQ) measurement system is depicted in Fig. 5. The peak detector voltages with the DC content removed by the series capacitors are subtracted by the differential amplifier (DA), further increasing the suppression of f_r for beams close to the PU centre and improving the interference immunity. A notch filter attenuates f_r by another large factor, in the order of 100 dB [1]. The high cut-off frequency of the band pass filter is $0.5 f_r$, as for all possible tune values one betatron sideband is always present in the band $(0, f_r/2)$. The typical low cut-off is $0.1 f_r$, which means that the observation system only has to process frequencies between 0.1 and $0.5 f_r$. For large machines, therefore, the 3D-BBQ output signal can be digitised with a 24-bit audio ADC at the revolution frequency, requiring relatively little processing power to yield a signal spectrum through an FFT, or to build a tune tracker based on a digital phase-locked loop (PLL) [2].

Notice that a 3D-BBQ system is 'low frequency' only after the detectors, due to the 'time stretching' of the short beam pulses. Before the detectors the processed bandwidth can easily be as high as a few hundred MHz. In the detection process the spectral content from this wide bandwidth is converted to the baseband, resulting in a very high sensitivity.

3D-BBQ prototypes according to the block diagram of Fig. 5 have been installed on four machines, namely SPS ($f_r \approx 43$ kHz), PS ($f_r \approx 477$ kHz), RHIC ($f_r \approx 78$ kHz) and Tevatron ($f_r \approx 48$ kHz) (chronological order). All prototypes were based on very similar hardware, with only the notch and band-pass filters adjusted for the machine f_r.

A detailed comparison of the 3D and classical tune measurement methods are given in [1], together with a quantitative estimate of the signal to noise improvement given by the 3D method operated on a machine with a single bunch. This factor is in the order of 30 dB for the PS, 40 dB for RHIC and Tevatron, 50 dB for the SPS, and 60 dB for the LHC.

RESULTS

All installed prototypes were sensitive enough to observe betatron oscillations with no explicit beam excitation. Such oscillations, with amplitudes in the μm range, were seen to be almost always present in the beam.

Examples of such measurements made with the SPS BBQ prototype and no intentional beam excitation are shown in Fig. 6 and 7. Figure 6 shows the horizontal tune path for the lowest intensity SPS beam of $\approx 5 \cdot 10^9$ protons in a single bunch at 26 GeV, during a programmed tune change of $\approx 5 \cdot 10^{-3}$. Figure 7 shows the SPS horizontal tune variations induced by the jaws of an LHC collimator prototype as it was cycled between a fully opened position and a gap of 1.96 mm. This measurement was performed with a single bunch at 270 GeV and formed part of a series used to evaluate impedance-induced tune changes introduced by LHC collimators [5]. Tune variations as small as a few Hz could be resolved in this

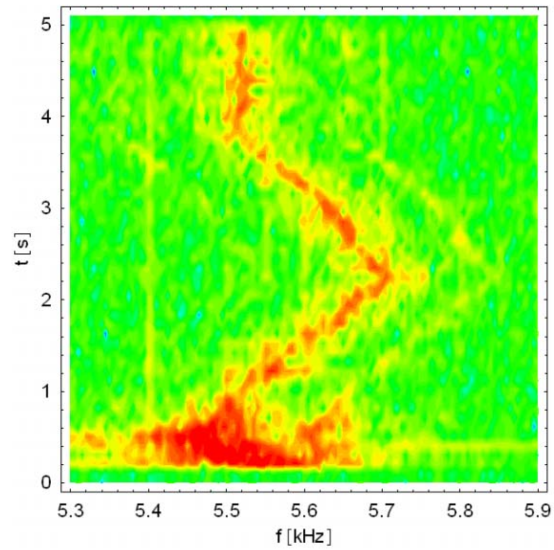

Figure 6: SPS, single bunch LHC pilot beam ($\approx 5 \cdot 10^9$ p^+).

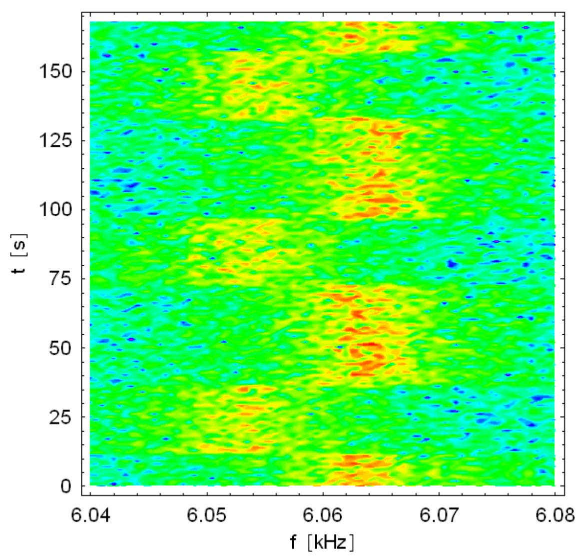

Figure 7: SPS, single bunch LHC beam ($\approx 10^{11}$ p^+).

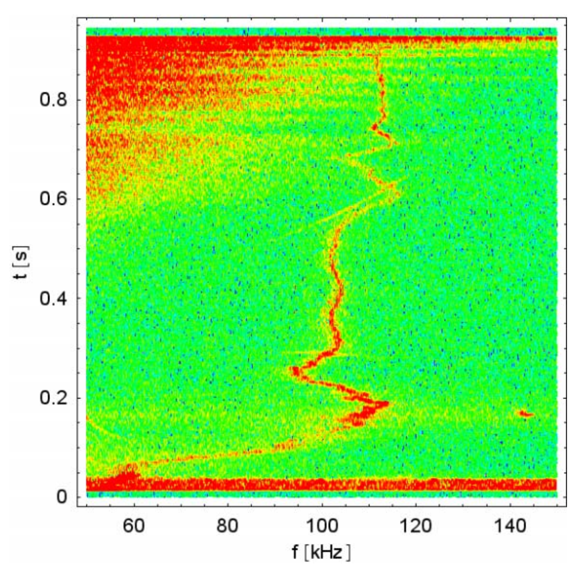

Figure 8: PS, AD beam (4 bunches, $\approx 4 \cdot 10^{12}$ p^+/b).

way, with the tune resolution in the order of 10^{-5}. These SPS measurements were acquired using a low cost 24-bit PC sound card followed by off-line spectral analysis.

Figure 8 shows the horizontal tune evolution measured by the PS BBQ prototype with no explicit excitation for a beam destined for the Antiproton Decelerator (AD), and accelerated from 1.4 to 26 GeV. The noise-like components appearing from the middle of the record onwards result from the RF beam gymnastics performed for this type of PS beam.

Figure 9 shows a vertical plane time record from the RHIC 3D-BBQ prototype, with the corresponding frequency spectra shown in Figure 10. The largest amplitude signals correspond to beam oscillations caused by high voltage sweeps, related to the operation of an Ionization Profile Monitor (IPM). Each excitation consists of a burst of a hundred pulses, applied every 100^{th} revolution. If either of the tunes happen to be a multiple of $f_r/100$, then these kicks resonantly excite the beam, as seen in the spectra for frequencies around 17.1 kHz ($0.22 f_r$, close to the horizontal tune) and 17.9 kHz ($0.23 f_r$, vicinity of the vertical tune).

Mains harmonics are clearly visible around the betatron tune paths throughout the RHIC acceleration cycle. These lines increase considerably once the main ramping power supplies are turned on around 26 s from the beginning of the record. The corresponding increase in the time domain signal can be seen in Figure 9. The presence of mains harmonics in the beam spectrum is reported in detail in [3] and is thought to be caused by magnetic field ripple in the main RHIC dipoles. Similar phenomenon was observed with the 3D-BBQs on the SPS, PS and Tevatron.

A comparison at RHIC between spectra from calibrated, million turn BPM data and that of the 3D-BBQ data has quantified the noise floor of the RHIC BBQ prototype at less than 10 nm. This is an order of magnitude better than most existing tune measurement systems.

CONCLUSIONS

This paper has introduced the principle of tune measurement using Direct Diode Detection. It has been shown to be highly sensitive while using simple, cheap and robust hardware. Prototypes recently installed on four machines, namely the CERN SPS and PS, BNL RHIC and FNAL Tevatron, have given very good results and are in the process of being converted into fully operational systems. Due to the many advantages of this method, 3D baseband tune measurement systems will be gradually introduced on all circular machines at CERN. This includes the LHC, where it is hoped to use the 3D-BBQ as part of a PLL tune tracking system, for the measurement of tune, chromaticity and coupling [5], with the ultimate aim of providing reliable tune feedback.

The 3D method is still under development and its full potential has probably not yet been fully realised. Extensive studies will therefore continue on this technique.

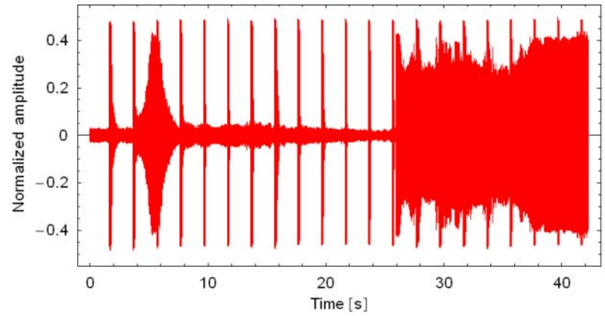

Figure 9: RHIC, a 3D-BBQ signal sound card record.

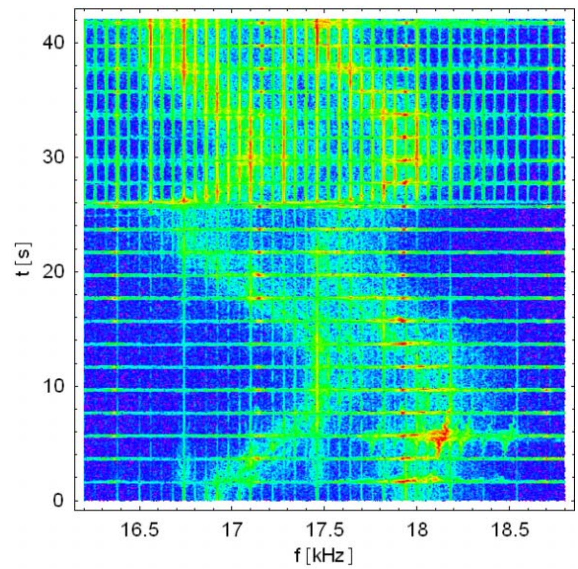

Figure 10: RHIC, spectra of the signal in Fig. 9.

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