USING TUNE MEASUREMENT SYSTEMS BASED ON DIODE DETECTORS FOR QUADRUPOLAR BEAM OSCILLATION ANALYSIS IN THE FREQUENCY DOMAIN

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Abstract

Requirements for diagnostics of injection matching and beam space charge effects have driven studies at CERN using high sensitivity tune measurement systems based on diode detectors for the observation of quadrupolar beam oscillations in the frequency domain. This has led to an extension of such tune systems to include a channel optimised for quadrupolar oscillation measurements. This paper presents the principles of such measurements, the developed hardware and example measurements.

INTRODUCTION

The unprecedented requirements for the sensitivity of the tune measurement system in the Large Hadron Collider (LHC) triggered an extensive research program, resulting in the development of the direct diode detection technique [1]. Its operational implementation, the Base-Band Tune (BBQ) system, was already proven in several accelerators before the LHC start-up [2]. The large dynamic range of these systems and their complete suppression of beam orbit signals made them excellent candidates for new attempts of obtaining quadrupolar signals from standard four-electrode beam position pick-ups (PUs) for beam diagnostic purposes. The first BBQ system used to observe quadrupolar signals was in the CERN Super Proton Synchrotron (SPS). The system was configured for quadrupolar studies in 2006 and was used for successful observation of beam quadrupolar oscillations during injection matching studies. Following this, a similar setup was used at GSI for studying space charge [3]. In 2014 the BBQ system in the CERN Proton Synchrotron (PS) was upgraded with a sensitive strip-line PU and since then space charge studies based on quadrupolar signals have continued at CERN [4]. Finally, in 2018 these studies led to an extension of the PS BBQ system in order to provide the spectra of beam quadrupolar signals in parallel to regular tune measurement operation. This paper briefly describes the BBQ systems, beam quadrupolar oscillation signals and the setups that have been used for their observation in the frequency domain. Finally, the new BBQ front-end providing both tune and quadrupolar signals is described along with example measurements performed with this setup.

BASE-BAND TUNE SYSTEMS

A simplified block diagram of a BBQ system is shown in Fig. 1. The four signals *L*, *R*, *T* and *B* correspond to the left, right, top and bottom pick-up electrodes, respectively. The signals are first processed by diode detectors (DD) installed directly on the PU output terminals. The detectors provide envelope demodulation around the maxima of the beam pulses. In this process, any modulation carried by the short beam pulses is converted into an envelope signal superimposed on a DC level that is related to the beam pulse amplitude that does not change from one pulse to another. The subsequent analogue front-end (AFE), installed close to the PU in the accelerator tunnel, processes only the envelope signals. The large DC background is suppressed at the input of the AFE by series capacitors, as shown on the block diagram in Fig. 2. The envelope signals are first amplified by low-noise amplifiers (LNA) before going to the inputs of differential amplifiers built in the classical instrumentation configuration with three operational amplifiers (op-amps). Two differential amplifiers provide subtraction of the amplified envelope signals from the opposing PU electrodes for both the horizontal and vertical planes. The subsequent analogue processing (AP) consists of a chain of filters and amplifiers, as described in more detail in [2].

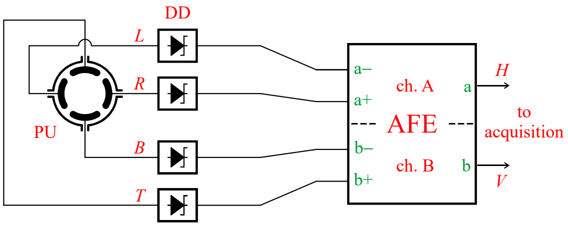

Figure 1: A sketch of a BBQ system in its standard tune measurement configuration.

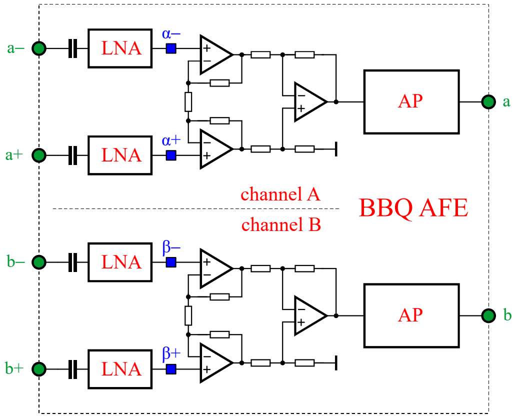

Figure 2: Simplified signal processing of the BBQ analogue front-end (AFE).

The two AFE output signals are base-band signals that are sent over long cables to a dedicated VME acquisition system with 16-bit ADCs sampling synchronously to the beam revolution frequency (f_{rev}). The acquisition system performs spectral analysis of the samples using a fast Fourier transform (FFT) algorithm. The resulting spectra are used to measure the betatron tunes and observe other beam oscillations.

QUADRUPOLAR MEASUREMENTS

The idea of using a classical beam position pick-up with four simple electrodes for observing beam quadrupolar signals is illustrated in Fig. 3. If a probe charge (blue dot) from the beam transverse distribution (green dashed line) is in position P0 in the PU centre, then the signals induced on the four electrodes are equal. In such conditions the quadrupolar signal

$$Q = (R + L) - (T + B) \tag{1}$$

induced by the probe charge is zero, $Q(\mathrm{P0}) = 0$.

If the probe charge moves to position P1 at the extremity of the distribution closest to the R electrode, then the corresponding signal R increases by ΔR as the distance of the charge to the electrode decreases. Similarly, signal L decreases by ΔL and both signals T and B decrease by ΔT and ΔB. The quadrupolar signal for P1 then becomes

$$Q(\mathrm{P1}) = (\Delta R - \Delta L) + (\Delta T + \Delta B) \tag{2}$$

The amplitude of $Q(\mathrm{P1})$ depends on the nonlinearity of the PU sensitivity, that is by how much larger is the signal gain ΔR than the signal loss ΔL when the probe charge moves from P0 to P1. Please note from Eq. (1) that Q does not change if L replaces R, and therefore $Q(\mathrm{P1}) = Q(\mathrm{P2})$. Similarly, Q changes sign if T or B replaces R or L, therefore $Q(\mathrm{P3}) = -Q(\mathrm{P1})$. As the quadrupolar signal Q is sensitive to the position of particular charges inside the beam envelope, the signal is a measure of the beam charge distribution.

Unfortunately, in practice Q is influenced more by the beam position than the beam size, especially if the beam size is small with respect to the distance of the beam to the PU electrodes. This is the case for all CERN circular accelerators, and is why measurements based on quadrupolar signals are very challenging [5]. The large dynamic range of the BBQ systems initiated studies on using these systems for observing changes of the quadrupolar signal related to beam size oscillations, originating for example from a betatron mismatch between an injection line and the following accelerator ring. If such quadrupolar signals are observed in the frequency domain then they can be distinguished from the dipolar position-related signals as the oscillation frequencies are different. The origin of this is explained in Fig. 4, showing a sketch of a beam size envelope (black contours) and trajectories of two probe charges p1 and p2 following two extreme betatron oscillation paths. In this case, the period of the betatron oscillations (T_β) it twice that of the beam envelope oscillations (T_σ).

The output signals H and V of the BBQ setup in the standard tune measurement configuration, shown in Fig. 1, can be described as functions of the difference of the opposing electrode signals

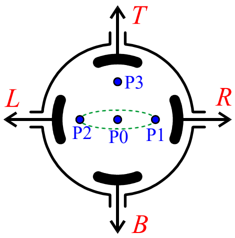

Figure 3: Four-electrode pick-up and positions of a probe charge within a transverse beam charge distribution.

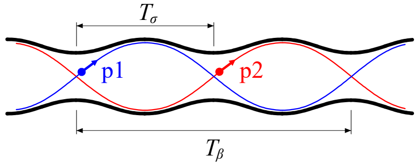

Figure 4: Relationship between periods T_σ and T_β of beam size envelope and betatron oscillations, respectively.

$$H = BSP(R - L) \tag{3a}$$

$$V = BSP(T - B) \tag{3b}$$

where the function $BSP()$ symbolises the BBQ signal processing. A quadrupolar signal similar to that defined in Eq. (1) can hence be obtained by a BBQ setup implementing the function

$$Q_a = BSP(R + L) - BSP(T + B) \tag{4}$$

The initial measurement setup is shown in Fig. 5(a) where the difference of the $BSP()$ functions in Eq. (4) was performed as a mathematical subtraction of the ADC data. Such a setup was used in the SPS in 2006 to demonstrate that a BBQ system using signals from a classical strip-line PU could be used for observing quadrupolar beam oscillations in the frequency domain.

While the separate digitisation of signals $BSP(R+L)$ and $BSP(T+B)$ allowed for easy analysis, in such a setup the two digitised signals are large and the desired quadrupolar signal is only a small fraction of the signal amplitude. This results in a very inefficient use of the ADC dynamic range. For this reason the setup was replaced by the one shown in Fig. 5(b), implementing the function

$$Q_b = BSP\big((R + L) - (T + B)\big) \tag{5}$$

In this case, the subtraction of the large sum signals was performed by the analogue circuits of the BBQ AFE, economising the ADC dynamic range. In addition, the quadrupolar signal was available on one AFE output, which allowed the use of standard BBQ tune measurement acquisition and related control room software.

Once the CERN BBQ quadrupolar studies moved from the SPS to PS, the setup of Fig. 5(b) could no longer be used. The bunches in the PS are quite long, and so the BBQ PU is operated with a high impedance load. The PU signal summation with terminated signal combiners is therefore not possible. Instead, the setup shown in Fig. 5(c) was used, implementing the function

$$Q_c = BSP(R-T) + BSP(L-B) \tag{6}$$

which is analogous to Eq. (1) with the difference of the sums replaced by the sum of the differences.

This setup is very similar to the standard BBQ tune measurement configuration, with some rearranged connections between the PU electrodes and the AFE, and one additional signal combiner. This feature was exploited for quick swapping between the standard and quadrupolar modes of BBQ operation. During quadrupolar operation tune measurements were performed by a second BBQ system using signals from another PU with shoe-box electrodes. This second system performed well with proton beams but the short PU electrodes with large capacitance yielded signals too small for reliable operation with low intensity ion beams. For such beams the quadrupolar BBQ setup, using signals from a PU with long, small-capacitance electrodes, had to be reverted to the regular tune measurement configuration. This inconvenience resulted in a hardware development aimed at a BBQ analogue front-end providing both standard horizontal and vertical tune signals as well as a quadrupolar signal similar to that of Eq. (6).

The developed three-channel analogue front-end with parallel quadrupolar processing (qAFE) was realised by extending the standard tune processing, sketched in Fig. 2, with a third channel, whose simplified signal processing is shown in Fig. 6. The outputs of the LNA amplifiers, marked on the diagrams as $\alpha-$, $\alpha+$, $\beta-$ and $\beta+$, are low impedance nodes, convenient for splitting the amplified detector signals. Given the 20 dB gain of the LNAs, the noise performance of the following stages can be relaxed, which is helpful for the quadrupolar channel containing five op-amps. Their configuration is based on the instrumentation amplifier used in the standard tune channels, extended with a further op-amp pair providing two additional inputs. The quadrupolar channel of the qAFE implements the function

$$Q_{qAFE} = BSP\big((R-T) + (L-B)\big) \tag{7}$$

The analogue processing (AP) block of this quadrupolar channel is very similar to the corresponding blocks used in the tune channels [2].

The three-channel qAFE described in this paper was installed in the PS before the 2018 run, replacing its standard tune AFE predecessor. Other components of the BBQ system, namely the PU with 780 mm long electrodes and 172 mm aperture and the diode detectors with high-impedance 60 MHz low-pass filters were reused. The VME acquisition system was extended to include three symmetric 16-bit ADCs sampling synchronously to the eighth harmonic of the PS f_{rev}. For regular operation eight ADC samples are averaged to achieve the effective sampling at f_{rev} and to improve the dynamic range of the acquisition system.

The qAFE was built in such a way that the new quadrupolar functionality does not degrade the performance of tune measurements, which is the fundamental application of the BBQ systems. A year of beam operation with the new qAFE proved that this is indeed the case.

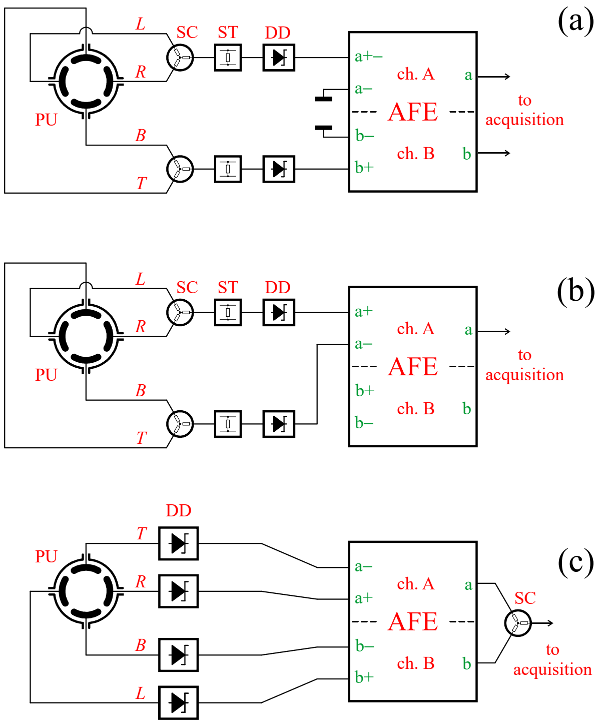

Figure 5: Setups based on BBQ hardware used for quadrupolar oscillation measurements. SC – signal combiners, ST – signal terminators.

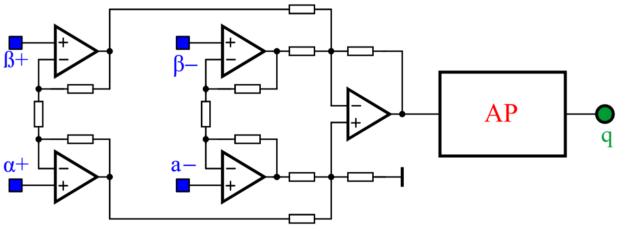

Figure 6: Simplified signal processing in the quadrupolar channel of the qAFE.

EXAMPLE MEASUREMENTS

Example time-domain signals from the quadrupolar (Q), horizontal (H) and vertical (V) channels of the new PS BBQ system are shown in Fig. 7 along with their corresponding spectra. In order to display all three signals on one readable plot, their absolute values are shown with the H and V signals below the time axis. The signals were acquired synchronously to f_{rev} starting at the beam injection for the EAST1 PS user. Despite the minimal system gain used for the measurement, the H signal (blue) is already limited in the qAFE, as the presented injection oscillations are much larger than typical signals used for regular tune measurements. Due to the principle of BBQ operation, this does not prevent reliable tune measurements to be performed, but typically results in odd tune harmonics appearing in the signal spectrum. This can be seen in the H spectrum, with the tune peak q_H around 0.2 f_{rev} and its third harmonic appearing aliased just above 0.4 f_{rev} ($3\,q_H$). The signals in the V spectrum (red) are lower with the V tune peak q_V seen at around 0.28 f_{rev} and the H tune peak appearing due to betatron coupling. The quadrupolar spectrum (green) has two peaks: a large one at the H tune peak, and a smaller one $2\,q_H$, just below 0.4 f_{rev}, related to beam quadrupolar oscillations. The amplitude of the $2\,q_H$ quadrupolar peak was seen to fluctuate depending on the injection matching conditions.

The large low frequency content of all three signals below 0.1 f_{rev} is most likely related to beam motion in the longitudinal plane, with the corresponding spectral content present in f_{rev} sidebands. As in all BBQ systems, the f_{rev} harmonics are downmixed to DC and their sidebands appear as low frequency spectral content, similar to that observed in the measurement.

Results of a measurement performed during beam optimisation are shown in Fig. 8. In this measurement the quadrupolar signal is much stronger and lasted long enough to start the acquisition 1200 turns after injection, once all the beam signals fit into the system dynamic range. This resulted in very clean spectra and distinct peaks in the quadrupolar spectrum, with their origin marked on the plot. The quality of this measurement prove the very good operation of the new PS BBQ system with a dedicated quadrupolar channel.

More information on how the system is used for studying and measuring beam parameters can be found in [4].

SUMMARY

This paper presents the principle of using tune measurement systems based on diode detectors for observing quadrupolar beam oscillations in the frequency domain, along with the setups used for such measurements. A decade of development and beam studies has resulted in an elegant system that allows regular tune measurement and the observation of quadrupolar beam oscillations at the same time. The system uses a single beam position pick-up with a classic arrangement of four simple electrodes.

The good experience with the PS three-channel BBQ system initiated the idea of performing a similar upgrade of the BBQ system of the PS Booster, which is planned for its restart in 2021. The design of the new qAFE is universal and can be adapted for any CERN circular accelerator by soldering suitable components.

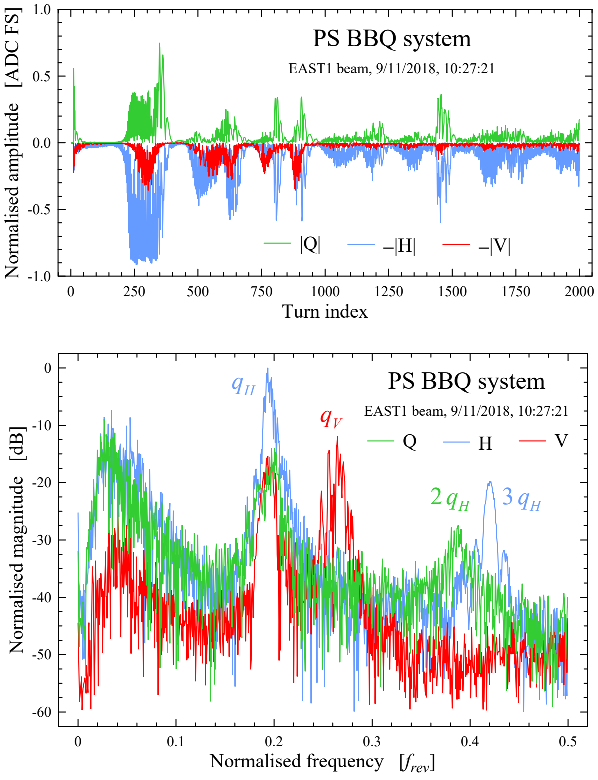

Figure 7: Injection oscillations (top) and the corresponding spectra (bottom) of the EAST1 beam.

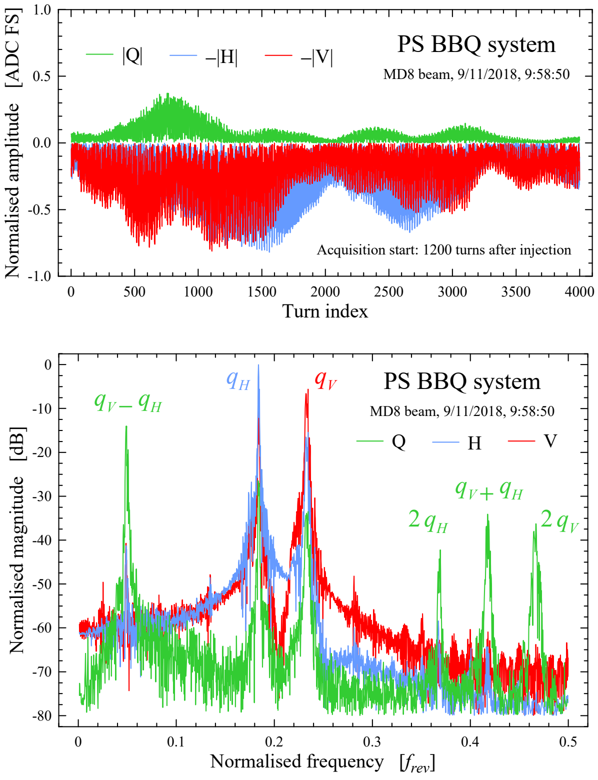

Figure 8: Injection oscillations (top) and the corresponding spectra (bottom) of the MD8 beam.

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