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

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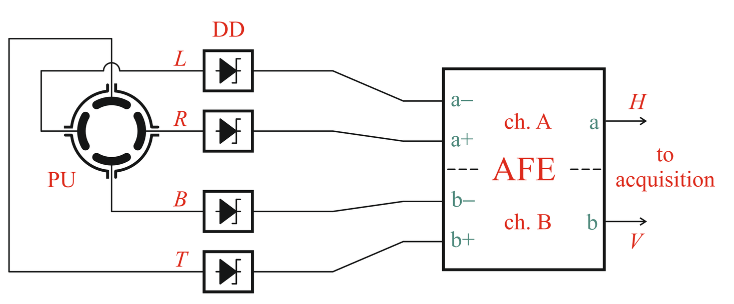
ABSTRACT

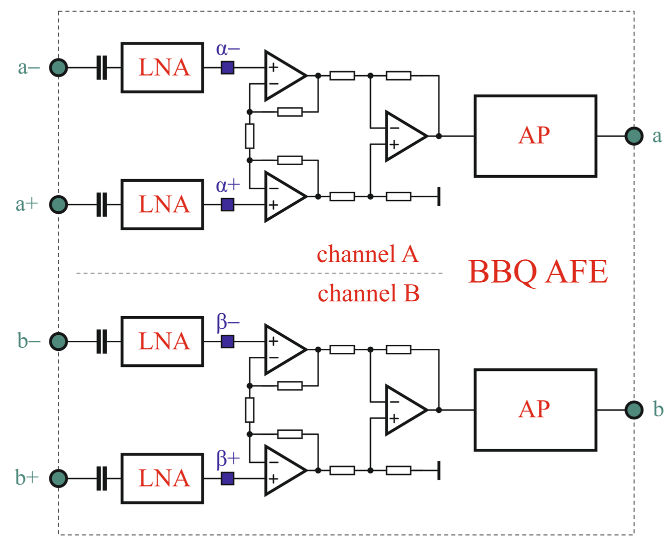
Requirements for diagnostics of injection matching and beam space charge effects have driven studies at CERN using high sensitivity tune measurement systems for the observation of quadrupolar beam oscillations in the frequency domain. This has led to an extension of such tune systems to include a channel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

BASE-BAND TUNE SYSTEMS

BBQ setup for tune measurement



Details of BBQ analogue front-end

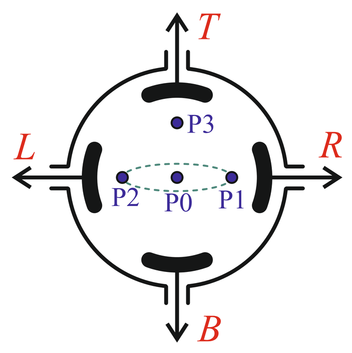


- Base-Band Tune (BBQ) systems are installed in all of CERN's synchrotrons for tune measurement.
- The electrode signals from a BPM are first processed by diode detectors which are mounted directly on the BPM's output terminals.
- The detectors demodulate the betatron envelope carried by the short beam pulses into a low frequency signal superimposed on a DC level.
- Series blocking capacitors at the input of the analogue front-end (AFE) remove the DC level.
- The signals are amplified by low-noise amplifiers (LNAs) before going into differential amplifiers which calculate the two tune signals:

$$Q_h = BSP(R - L)$$
$$Q_v = BSP(T - B)$$

where the function $BSP()$ represents the BBQ analogue signal processing.
- The BBQ AFE is installed in the tunnel beside the pick-up. The base-band signals are transported to a surface building with long cables where they are acquired with a custom VME acquisition system.

QUADRUPOLAR MEASUREMENTS



- If a probe charge P0 from the beam transverse distribution passes through the center of a BPM, the quadrupolar signal

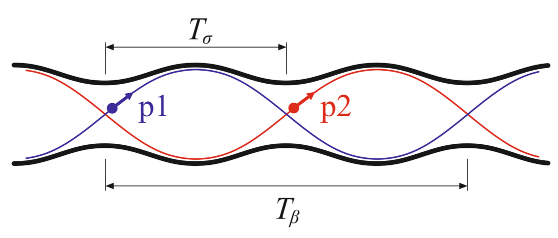
$$Q(P0) = (R + L) - (T + B) = 0$$

- If the charge moves to P1, the signal R increases by ΔR while L decreases by ΔL. Similarly, T and B will decrease by ΔT and ΔB. The quadrupolar signal is then

$$Q(P1) = (\Delta R - \Delta L) + (\Delta T + \Delta B)$$

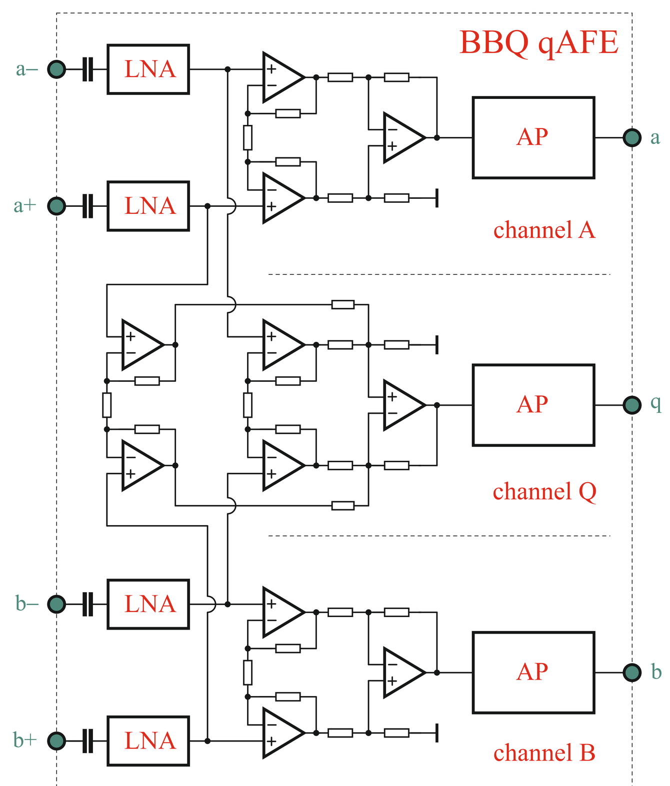
- The amplitude of Q depends on the nonlinearity of the BPM sensitivity, that is how much larger the signal gain ΔR is than the signal loss ΔL. Note, Q does not change if L replaces R, so $Q(P2) = Q(P1)$. Similarly, Q changes sign if T or B replaces L so $Q(P3) = -Q(P1)$.
- In practice, Q is influenced more by the beam position than the beam size, especially if the beam size is small with respect to the BPM size, making quadrupolar measurements extremely challenging, especially absolute measurements in the time domain.
- 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.

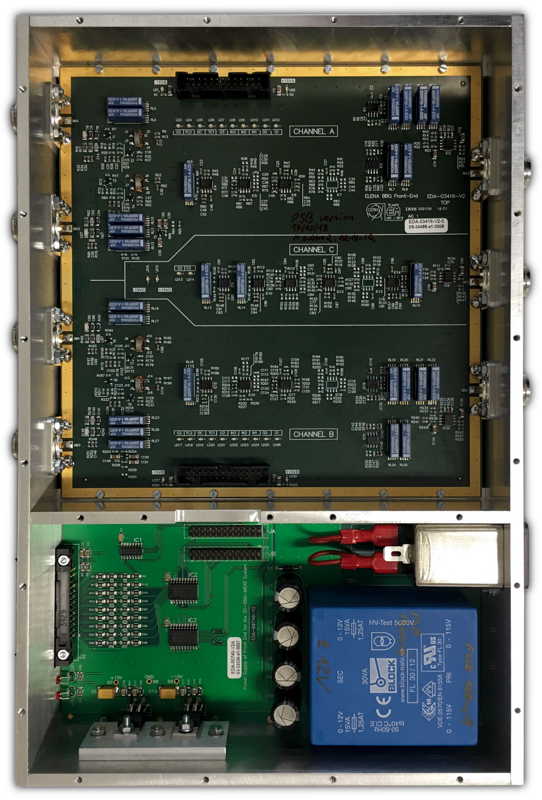
- In the frequency domain, the quadrupolar beam size oscillations can be distinguished from dipolar beam position oscillations due to their distinct frequencies.
- An example of the source of this frequency difference is shown graphically to the right.



- Given two probe charges p1 and p2 following two extreme betatron oscillation paths, it can be seen that the period of the beam envelope oscillation T_σ (black line) is half of the period of each particle's betatron oscillation T_β, so $f_\sigma = 2f_\beta$.

QUADRUPOLAR BBQ ANALOGUE FRONT END

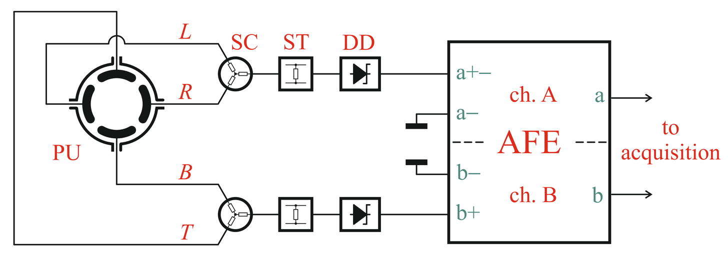




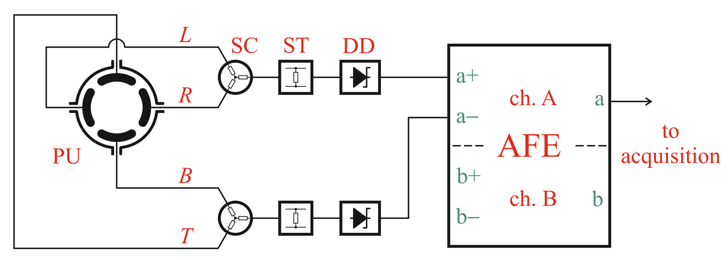
- A new BBQ analogue front-end (AFE) was constructed by extending the standard BBQ AFE with a third channel allowing parallel processing of the quadrupolar signal.
- The outputs of the LNAs are low impedance nodes which is convenient for splitting the amplified detector signals.
- The op-amp configuration is based on the instrumentation amplifier used in the standard tune channels, extended with a further op-amp pair providing two additional inputs.
- The sequence of the analogue operations in is beneficial for the system dynamic range, as first large electrode signals are subtracted and only then the subtraction results are added.

QUADRUPOLAR BBQ DEVELOPMENT IN SPS AND PS

Initial SPS measurement setup



Second SPS measurement setup



- In 2006, a setup was used in the SPS to demonstrate for the very first time that a BBQ system using signals from a classical strip-line pick-up (PU) could be used for observing quadrupolar beam oscillations in the frequency domain.
- The electrode signals were added with passive summation before the diode detectors. The two signals were acquired separately and a mathematical subtraction was performed on the digitised data. This realised the function:

$$Q_c = BSP(R + L) - BSP(T + B)$$

- As a second stage, the analogue subtraction was performed by the AFE to economise the ADC dynamic range. This implemented the equivalent function:

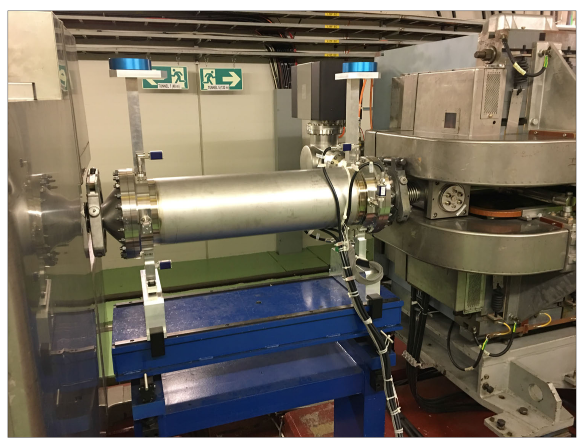
$$Q_c = BSP((R + L) - (T + B))$$

- The PS was equipped with a new 780mm strip-line tune PU in 2014, for the first time offering the sensitivity necessary to study quadrupolar effects.
- As the bunches are long, the PU is operated with a high impedance load to maximise sensitivity and the passive summation of the electrodes could no longer be used.
- Instead, the setup shown to the right was implemented to realise the mathematically equivalent sum of differences of the electrodes:

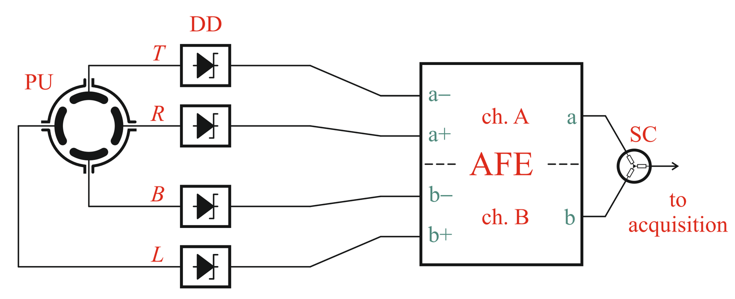
$$Q_c = BSP(R - T) + BSP(L - B)$$

- This setup is very similar to that of the standard tune measurement, with only a rearrangement of the electrodes and an additional summation. This fact was exploited to allow fast changes of the configuration during machine accesses.

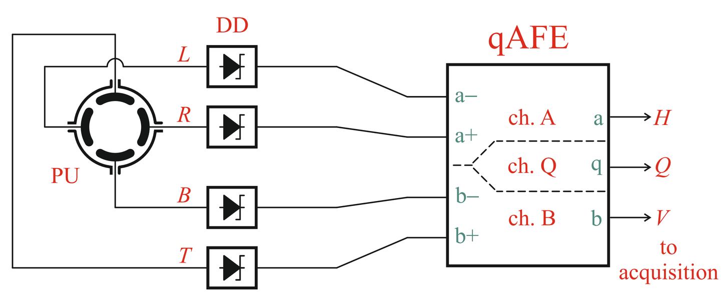
PS 780 mm strip-line tune PU in SS72



PS test setup

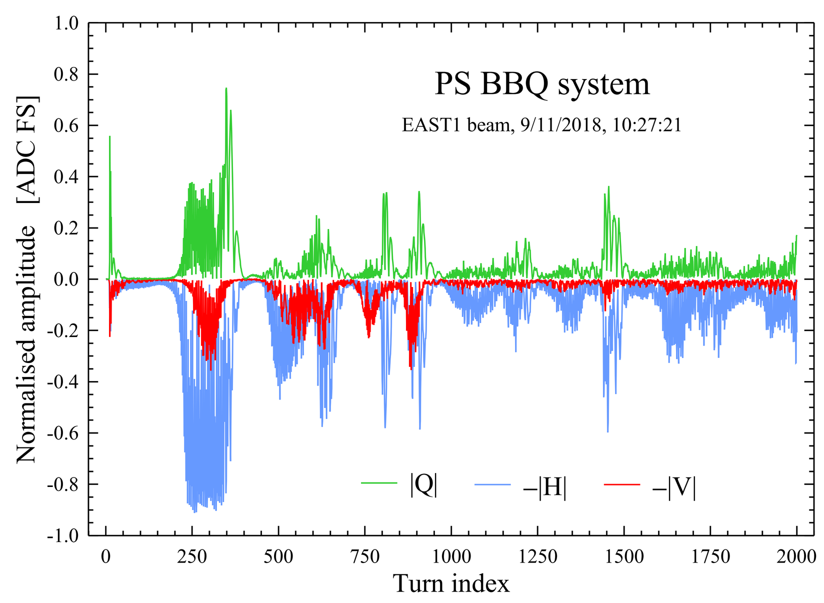


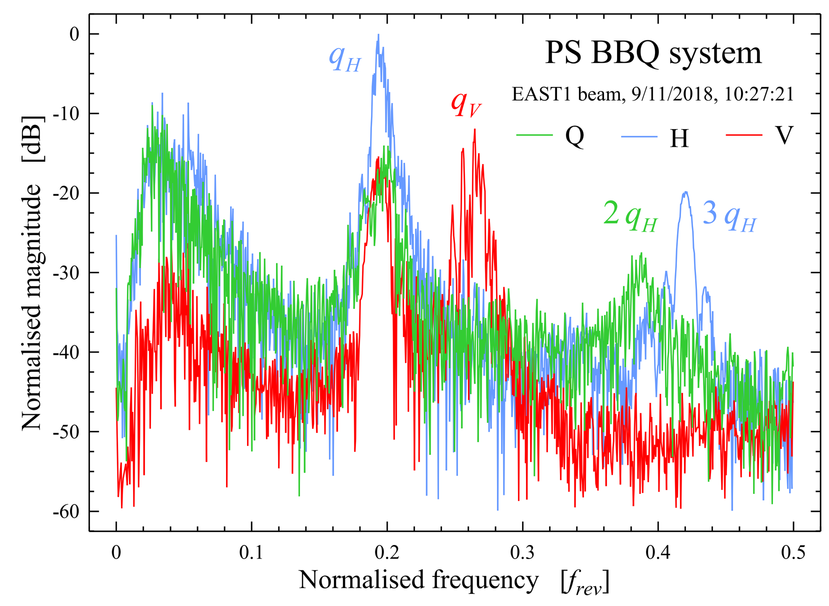
PS final configuration with qAFE



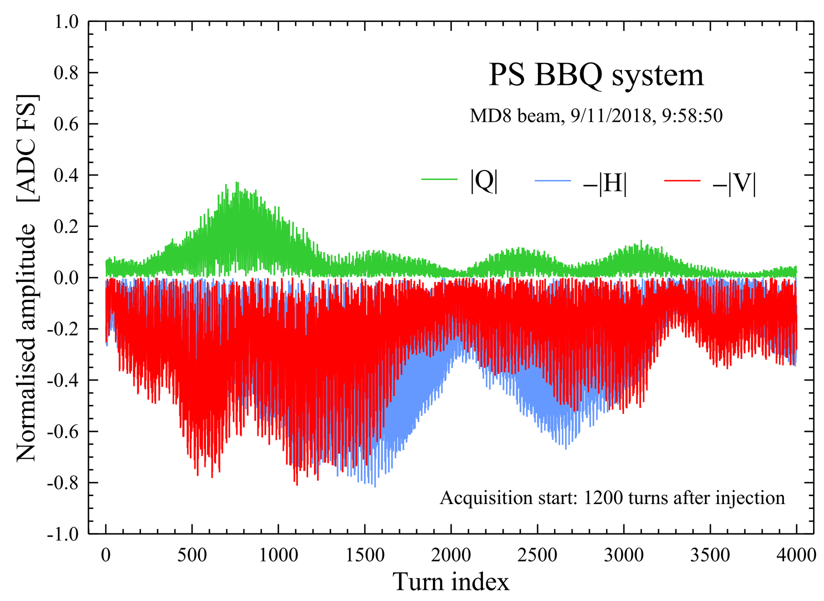
- Since 2018 a qAFE has been installed on the PS strip-line tune pick-up to avoid regular recabling.
- All other system components were reused, including the detectors with high impedance 60 MHz low pass filters.
- The VME acquisition system was extended to have a third 16-bit ADC channel sampling synchronously to f_{rev}.

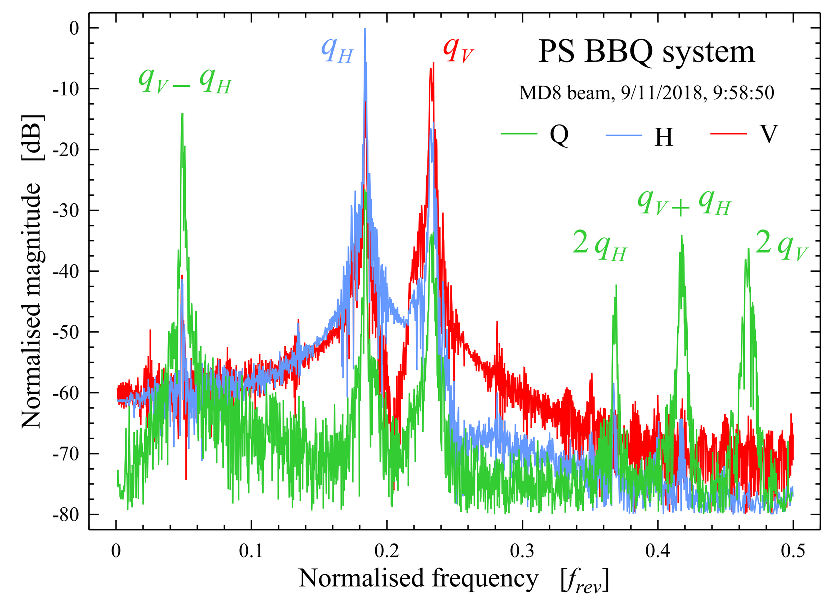
EXAMPLE MEASUREMENTS





- The horizontal signal (blue) is saturated, however this does not affect the tune measurement as it only adds odd harmonic distortion. The 3rd harmonic of q_H can be seen aliased around 0.4.
- The strong q_H signal can be seen clearly in the vertical spectrum (red) indicating a betatron coupling between the planes.
- In the quadrupolar spectrum (green), the $2q_H$ peak, expected with a horizontal betatronic mismatch, and q_H peak, expected with a horizontal dispersive mismatch, are visible.
- As the BBQ downmixes the sidebands of f_{rev} to DC, the large low frequency content in all three signals is most likely related to the longitudinal beam motion.





- In the quadrupolar spectrum, the $2q_H$, $2q_V$, q_H and q_V peaks are clearly visible.
- Additionally, the odd (skew) modes $q_V - q_H$ and $q_V + q_H$, first explained by Chernin, are visible.
- These measurements are simple examples, taken at injection with operational beams, and only scratch the surface of what it is possible to measure in optimised conditions. It is expected that the qBBQ will be a powerful tool for future machine studies in CERN's injectors.

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