ON THE CONTINUOUS MEASUREMENT OF THE LHC BETA-FUNCTION – PROTOTYPE STUDIES AT THE SPS

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Abstract

Until now, the continuous monitoring of the LHC lattice has been considered impractical due to tight constraints on the maximum allowed beam excitations and acquisition time usually required for betatron function measurements.

As a further exploitation of the Base-Band-Tune (BBQ) detection principle, already widely used for tune diagnostics, a real-time beta-beat measurement prototype has been successfully tested at the CERN SPS and is based on the continuous measurement of the cell-to-cell betatron phase advance. Tests show that the phase resolution is better than a degree corresponding to a peak-to-peak beta-beat resolution of better than a percent. Due to the system's high sensitivity, it required only micrometre-range excitation, making it compatible with nominal LHC operation. This contribution discusses results, measurement systematics and exploitation possibilities that may be used to improve the nominal LHC performance.

INTRODUCTION

Measurement and control of the Large Hadron Collider's (LHC) lattice parameters – beyond being fundamental aspects of luminosity optimisation and general machine operation – have a strong impact on the LHC Cleaning and Machine Protection System performance [1]. In addition to the stability of key beam parameters that is addressed by a comprehensive suite of real-time beam-based feedback systems [2], the correct positioning of protection elements and other aperture bottlenecks fundamentally depends on beam size that may vary during regular machine operation due to time-dependent betatron fluctuations driven by magnetic field imperfections and feed-down effects. Furthermore, while classical methods are limited by the Beam Position Monitor (BPM) resolution and available triplet aperture, the proposed system may allow continuous monitoring of the final-focus squeeze during nominal operation.

MEASUREMENT SETUP

Most optics reconstruction techniques can be grouped into the analysis of dipole corrector-induced beam oscillations (e.g LOCO [3]), utilising the tune dependence due to a known local quadrupole gradient variation on the beta-function (aka. *k-modulation*), or the mutual dependence of the betatron function and lattice phase-advances [4].

The latter method has been tested using LHC-type BPMs at the CERN-SPS as an LHC test-bed. The BPM layout is shown schematically in Fig. 1.

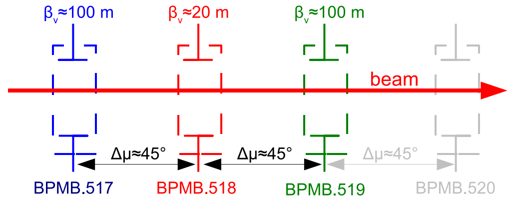


Figure 1: Schematic beta-beat test layout at the CERN-SPS.

With a prospect of its application at the LHC, the signals have been split using a 3 dB splitter, providing more than 30 dB insulation between both systems. This was chosen as the installation of additional BPMs may not be feasible in all locations, and to allow direct cross-comparison of the standard LHC orbit acquisition system [5, 6] with the BBQ-based continuous beta-beat measurement system. The BBQ principle [7] minimises the required beam oscillation amplitudes to the micrometre range, making this type of measurement compatible with nominal emittances and LHC operation. Besides the intrinsic signal loss that raises the minimum trigger threshold of the LHC BPM electronics by 3 dB, no other impact of the signal splitting has been seen in beam- as well as lab-based measurements.

A driven beam oscillation measurement example using the beta-beat acquisition chain and sinusoidal fit is shown in Fig. 2. The characteristic half-cell phase advance of 45 degrees between BPMs and beta-dependent amplitude differences are visible.

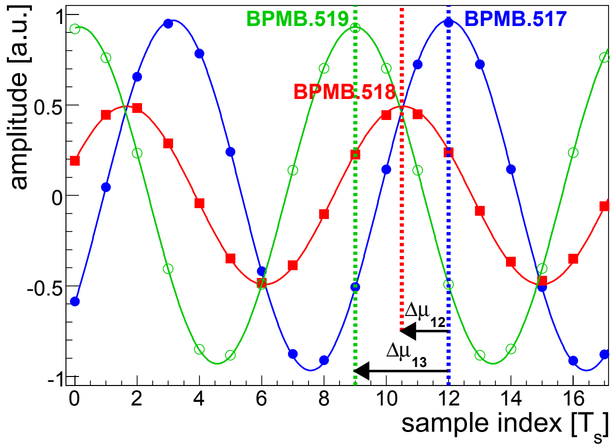


Figure 2: Continuous phase-advance measurement example. Raw measurement data (markers), fits (solid lines), and phase advances between first and second $\Delta\mu_{12}$, and first and third $\Delta\mu_{13}$ are indicated.

The raw-signals were recorded using a consumer-grade 10 channel audio-acquisition card sampling at 96 kHz. While any free or driven excitation can be used for this method, the excitation frequency was fixed at a quarter of the revolution frequency $f_{rev} \approx 43.3\,\text{kHz}$. This choice was motivated by:

- minimising emittance blow-up, by being well off the vertical SPS tune of 0.18 used during the tests;
- limiting excitation amplitudes which would need to be larger in the presence of residual tune oscillations;
- allowing more optimised band-pass filters and simpler phase tracking routines than those required within robust phase-locked-loop (PLL) systems, as the bandwidth of the off-resonance excitation is essentially limited by the width of the revolution carrier.

PRINCIPLE & SPS MEASUREMENTS

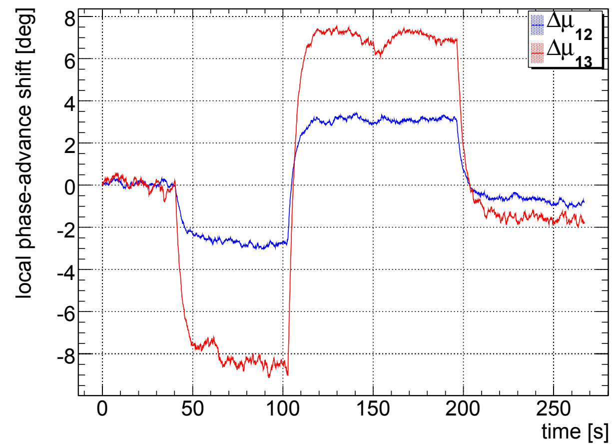
As shown in [4], the dependence of small quadrupole induced betatron function perturbations $\Delta\beta_i$ on the cell-to-cell phase-advances $\Delta\mu_{ij}$ measured at a minimum of three independent locations is in relation to the nominal values β_i^0 given by

$$\frac{\Delta\beta_1}{\beta_1^0} = \frac{cot(\Delta\mu_{12}^{meas.}) - cot(\Delta\mu_{13}^{meas.})}{cot(\Delta\mu_{12}^{nom.}) - cot(\Delta\mu_{13}^{nom.})} \qquad (1)$$

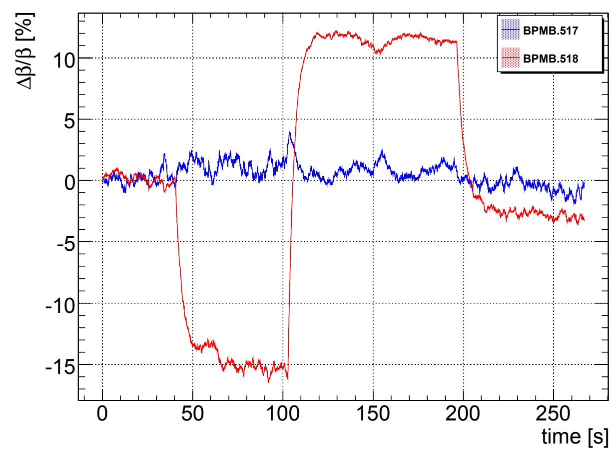
with i and j being the indices of the BPM location, and '$meas.$' and '$nom.$' indicating the measured and nominal lattice phase-advance values. Similar equations can be derived for the other two locations and while not strictly independent, they may nevertheless be combined with neighbouring cells facilitating consistency checks that may identify certain reconstruction errors. Fig. 3(a) and 3(b) show an induced phase-shift and a corresponding reconstructed beta-beat measurement example taken with coasting beam in the CERN-SPS. The known BPM-to-BPM phase advance is subtracted in Fig. 3(a) for better visibility. The phase and corresponding beta-beat has been driven using a single quadrupole, trimmed to change its current from zero, to a first positive then negative value of same absolute amplitude, and then returned to zero amplitude again. The measured beta-beat modulation amplitudes agree with the known optics model and magnet calibration. The beta-beat difference before and after the modulation is due to the known hysteresis of the chosen magnet.

SYSTEM ACCURACY & LIMITATIONS

The accuracy, resolution and noise sensitivity of the measurement depends strongly on the phase advance between BPMs, according to Eq. 1. While this method favours a 45 degree sampling, singularities may occur if the phase-advance is sampled close to or larger than π. This is not an artefact of the reconstruction representation implicitly chosen in Eq. 1, but a fundamental consequence of the betatron function and phase advance definition which, for



(a) beta-beat induced phase shift



(b) induced beta-beat

Figure 3: Quadrupole induced cell-to-cell phase-advance shifts and the corresponding beta-beat.

the simple analytic case of a symmetric final-focus insertion with waist β^*, can be written as:

$$\Delta\mu_{s_1\to s_2} := \int_{s_1}^{s_2} \frac{1}{\beta(s)}\mathrm{d}s = \int_{s_1}^{s_2} \frac{1/\beta^*}{1+(s/\beta^*)^2}\mathrm{d}s = \arctan\left(\frac{s}{\beta^*}\right)\Bigg|_{s_1}^{s_2} \qquad (2)$$

While the phase-advance description is well-behaved with a range of $\pm\frac{\pi}{2}$ around the IP ($s = 0$), the inverse of Eq. 2 has singularities for phase advances which are multiples of π. This is one of the fundamental experimental challenges of final-focus optics measurements and imposes strict limitations on the phase noise and systematic errors of any phase-based optics reconstruction technique. While a 45 degree BPM sampling only requires a phase accuracy of about 5 degrees for a 1 % relative beta-beat resolution, the LHC final optics ($\Delta\mu_{12}^{nom.} \approx 176$ degrees) requires a much tighter phase accuracy of better than 10^{-2} of a degree for the same beta-beat resolution.

In most accelerators phase advances are typically obtained by recording large-amplitude kicks or AC-dipole induced beam oscillations using standard BPMs, followed by classical phase detection techniques. The turn-by-turn noise σ_t intrinsic to all acquisition system with a carrier signal amplitude A add vectorially. Thus the minimum phase resolution or maximum measurement error of any of these techniques is ultimately limited by the achievable signal-to-noise ratio, as expressed by

$$\sigma(\varphi) = arcsin\left(\sqrt{\frac{2}{N}}\frac{\sigma_t}{A}\right) \overset{\frac{\sigma_t}{A}\ll 1}{\approx} \sqrt{\frac{2}{N}}\frac{\sigma_t}{A} \quad (3)$$

with N being the number of turns (or acquisition length) used to compute the phase estimate. Here, σ_t is not only limited to random noise but may also include other residual oscillation amplitudes at the modulation frequency – most importantly self-stimulated tune oscillations. The turn-by-turn resolution of standard BPMs is typically in the order of a few hundred micrometres. With kick excitations typically lasting only a few hundred turns and assuming a 45 degree sampling, the required amplitudes have to be in the order of a few millimetres to achieve a relative betatron measurement resolution of better than one percent. The BBQ with its nanometre resolution is much better adapted for this type of measurement providing large signal-to-noise ratios even with excitation amplitudes below a micrometre. It is ultimately only limited by the trade-off between required precision versus time resolution, the systematic phase components of the acquisition electronics and other externally driven beam excitations.

The measurements shown in Fig. 3 are based on a signal-to-noise ratio of about 60 dB with absolute amplitudes of about $20 - 30\,\mu\text{m}$, and thus provides a phase resolution of about 0.06 degrees, or 0.2 % beta-beat resolution at a measurement bandwidth of 1 Hz. A large amount of the beam signal was lost due to the long cables of the SPS beta-beat installation, and thus the oscillation amplitudes were much larger than those typically required by the BBQ-based tune-meter. The LHC installation will have better and shorter cables which should improve the resolution to well below 0.01 of a degree.

While traditionally the phase noise is typically limited by the available signal-to-noise ratio, in the high-accuracy regime explored by this beta-beat set-up, the measurement accuracy is dominated by systematic phase shifts due to delays and the analogue front-end, all of which may vary on the time-scale of hours to days. For the SPS tests, the systematic phase of the audio-sampler was measured to be about 7 degrees with a medium-term stability of better than 10^{-4} of a degree and about 10 degrees for the analogue front-end with a medium-term stability of about 0.1 of a degree. Since the analogue front-end was not optimised for this type of measurement, it is believed that the latter can be improved by at least one order of magnitude.

The achieved phase stability also indicates that the beta-beat time structure seen in Fig. 3(b) or those shown in Fig. 4 are true optics changes rather than measurement artefacts. While not having been time-resolved, the same effect has been already observed at LEP [4]. Figure 4 shows a measurement example taken during the first two acceleration cycles after returning the SPS from coasting into cycling mode. The injection plateau lasts about 10 seconds followed by a ramp to 270 GeV/c. The systematic optics variation during the ramp and hysteresis between the first and second cycle can be seen, a feature that was supported by the observed tune. While continuously varying the momentum the chromatic beta-beat has been evaluated with time, essentially being limited by the fairly linear SPS optics.

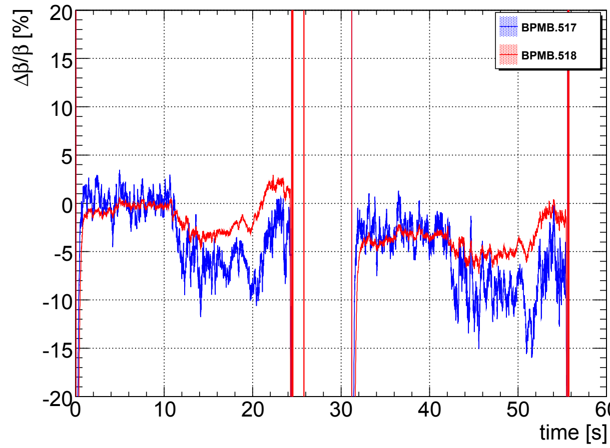


Figure 4: First two beam acceleration cycles after returning from a 270 GeV/c coasting beam mode.

CONCLUSIONS

The aim of the discussed continuous beta-beat measurement system is to provide the means to assess magnitude and time-scale of LHC lattice perturbations, to use the obtained information to improve the protection and other accelerator systems and – if necessary – to locally stabilise the betatron function within a beam-based feedback system.

The SPS tests have shown that the proposed system can achieve 0.1 % resolution at a 1 Hz rate, with excitations kept below $30\,\mu\text{m}$, thus making this type of measurement transparent for nominal LHC operation. Based on these tests, the prototype is being optimised to support non-perturbative final-focus monitoring on the percent level. Such beam diagnostics of higher-order effects have previously been in-accessible, and should facilitate LHC to reach its design performance.

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