CONTINUOUS MEASUREMENT AND CONTROL OF BETA-BEATING IN THE LHC

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Abstract

The beta function has a fundamental impact on the LHC performance and on the functioning of its machine protection and collimation systems. A new beta-beat diagnostic system, prototyped at the SPS, has been used to verify the time-dependent variations of the LHC lattice with unprecedented 1% beta-beta resolution and at a measurement bandwidth of about 1 Hz.

This contribution discusses the first results of local continuous beta-function measurements in the LHC collimation region, the systematic measurement errors and their compensation. The impact on nominal LHC operation and the potential to provide an input for an automated local feedback control of the beta-function are presented.

INTRODUCTION

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]. The Cleaning System relies on a hierarchy of primary, secondary and tertiary collimators as schematically illustrated in Figure 1. In addition to the orbit stability that is addressed by a real-time beam-based feedback system [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. In the example given in Figure 1, the hierarchy is broken by the secondary collimator due to local beta-beating (failure scenario 'A)') or the tertiary collimators protecting the triplets due to global beta-beating (failure case 'B)') becoming the primary aperture bottleneck instead of cleaning the secondary and tertiary halo particles.

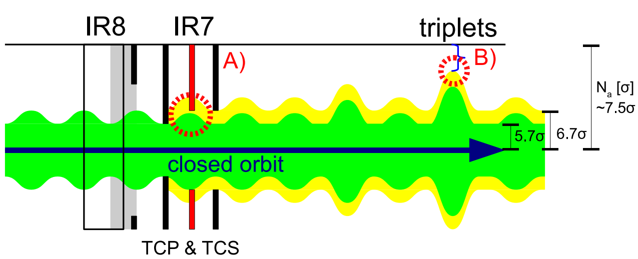


Figure 1: Schematic layout of the LHC beta-beat setup showing the hierarchy between primary (TCP) and secondary (TCS) collimators. Two failure scenarios where the secondary or tertiary collimators become primary aperture bottle-necks are indicated.

The global variation of the beta-function has been successfully measured and corrected at the LHC early on via the classic phase-beating method using an AC-dipole based excitation and recording of turn-by turn data using the standard Beam Position Monitor (BPM) System [3]. While essentially only limited by the available BPM resolution and machine aperture, due to machine protection considerations in view of potential beam losses caused by the required large excitations, these measurements were however restricted to dedicated fill studies with low intensity beam.

In order to access the impact of beam size variations that may compromise the Cleaning System's hierarchy, a Continuous Beta-Beat Measurement System, prototyped at the CERN-SPS [4], has been installed in the vicinity of the primary Beam 1 collimators. It allows the monitoring of the beta-function at selected locations in the ring with 0.1 % resolution at a 1 Hz bandwidth. The required micro-meter-level excitations make this type of measurement transparent for nominal operation. This contribution describes the first results obtained with a LHC test installation in the vicinity of the LHC collimators during the energy ramp and β^*-squeeze.

MEASUREMENT SETUP

The Continuous Beta-Beat Measurement System, an exploitation of the Base-Band-Tune (BBQ) principle, is based on the reconstruction of the cell-to-cell phase-beating [5,6]. For the small-scale tests, the system has been installed in in the vicinity of the betatron cleaning insertion (LHC Point 7). The system uses three button-type pick-ups, each equipped with an independent BBQ front-end, and the phase advance between the chosen pickups being about $\mu_{12} = 38\,^\circ$ and $\mu_{13} = 81\,^\circ$ for the nominal optics.

The pickups are shared with the standard LHC orbit acquisition system [7, 8] which allowed a direct cross-comparison with the BBQ-based continuous beta-beat measurement system. The signals have been split using a 3 dB splitter, providing more than 30 dB insulation between both systems. 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 with beam during day-to-day operation. Compared to the BBQ system that is used for tune (Q) and chromaticity (Q') diagnostic, the signals were much smaller and the achieved signal-to-noise ratio about 6-10 dB less due to using 24 (34) mm buttons and relatively long cables compared to the Q/Q' BBQ diagnostics installation that uses a 30 cm strip-lines. Similar to the SPS setup, the raw-signals were recorded using a consumer-grade 10-channel audio-acquisition card sampling at 96 kHz.

While the accuracy of the BPM-based phase-beating reconstruction is essentially limited by the available signal-to-noise ratio of the turn-by-turn measurement, for an absolute estimate of the beta-beating the accuracy of the BBQ-based phase reconstruction – due to working in base-band (< 11245 kHz) – is dominated by systematic phase shifts caused by cable length and analogue filters differences – particularly since each pick-up was processed by an independent BBQ front-ends with slightly different filter characteristics. However, these systematic delays can be calibrated using beam-based measurements using e.g. a constant tone excitation on the beam while either slightly shifting the revolution or sampling clock frequency, or cross-calibrated against the BPM-based phase measurement. Here, the presented data has been corrected using the latter method.

RAMP MEASUREMENTS

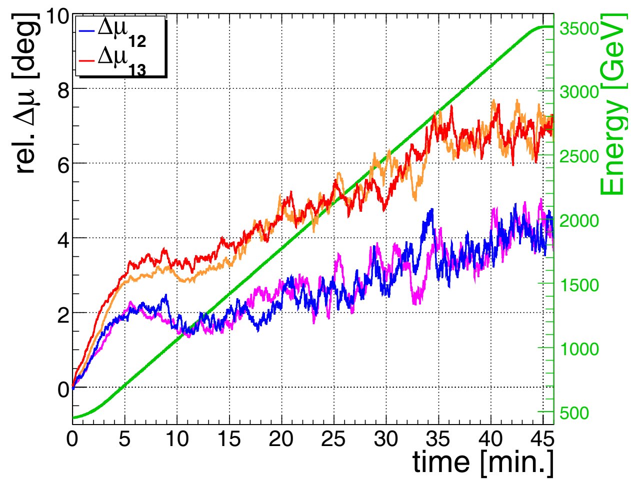
The measurements were done with micro-metre level excitation in the order or smaller than the residual tune oscillations. While both on- and off-tune resonance excitation have been tested, most of the measurements were done using the transverse damper in and AC-dipole-type configuration with excitation frequencies at 0.18 for the horizontal and a quarter of the revolution frequency for the vertical plane compared to the nominal tunes of $q_h = 0.28$ and $q_v = 0.13$ during the ramp.

While there some additional constant systematics that need to be calibrated, the Off-resonance excitation were chosen to minimise

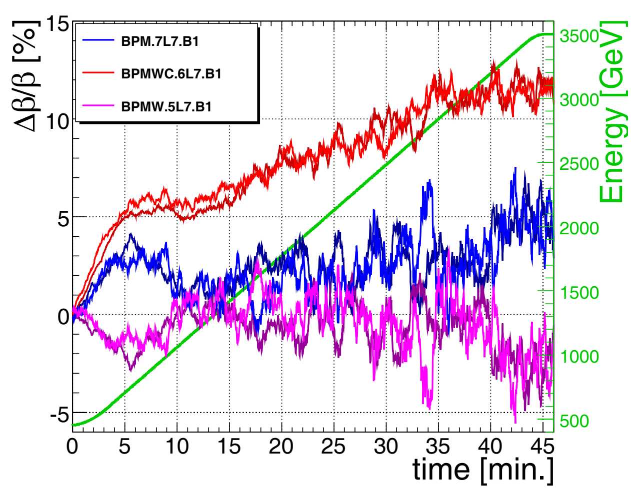
- the phase dependence on tune, chromaticity and synchrotron tune shifts during the ramp,
- any resonant excitation of the nominal (synchrotron-) tunes and potential emittance blow-up or losses,
- the impact of and on the transverse damper feedback within its operational frequency range, and
- the impact of the – compared to the used um-level excitations – strong residual tune oscillations on the phase measurement noise.

Attempts have been made to also reconstruct the phase information using the residual tune oscillations. While the measured phase seemed to agree, due to the short coherence time of these oscillations the achieved signal-to-noise ratios was usually poor compared to the driven oscillations in the vicinity or far off the tune resonance with typically long coherence times. For the ramp measurements, the damper excitation amplitude was kept constant at the given available maximum. The signal-to-noise ratio reduced by about 20 dB due energy dependence of the kick strength during the ramp. Despite the low signal levels, typical signal-to-noise ratio of 30 to 40 dB could be achieved with a bandwidth of 1 Hz. In order to achieve better signal-to-noise ratio at top energy with the limited excitation, the phase measurements were averaged over a minute yielding a 17 dB gain – assuming that phase-advance does not change on these time-scale. The phase resolution was about 0.7 degrees, corresponding to a 1 % beta-beat resolution during the ramp. While this may seem large, it is noteworthy to point out that these measurements were done during regular operation with excitations not larger than a micrometer.

Figure 2(a) and 2(b) show the phase-shift and a corresponding reconstructed beta-beat measurements taken during two ramps that were about three weeks apart. The known BPM-to-BPM phase advance is subtracted in Figure 2(a) for better visibility.



(a) beta-beat induced phase shift



(b) beta-beat

Figure 2: Ramp induced cell-to-cell phase-advance shifts and the corresponding beta-beat.

The fast beta-beat change caused by the snap-back during the first five minutes as well as beating with an opposite sign for BPM.7L7.B1 and BPMW.5L7.B1 that have an approximate phase difference of 90 degree are visible. Part of the beta-beating is assumed to be caused by calibration errors of the warm quadrupole magnets in the collimation region. For two given ramps, the measured beta-beat was reproducible on the level of 1% which demonstrates the good magnetic field reproducible – provided the machine underwent the same magnetic pre-cycle history. These fill-to-fill- and pre-cycle-dependent variation have been also been apparent for the tune perturbations during the ramp [9–11]).

For comparison, Figure 3 shows the beta-beat evolution during a successive ramp, for a case where three out of the eight main dipole circuits were pre-cycled to 2 kA instead of the default 6 kA. It included also a percent-level correction of the transfer function of one of the warm quadrupole magnet in the vicinity of the test setup has been supplied. This measurement had a similar signal-to-noise ratio and variations of the beta functions compared to the one shown in Figure 2 in the order of 4% are visible.

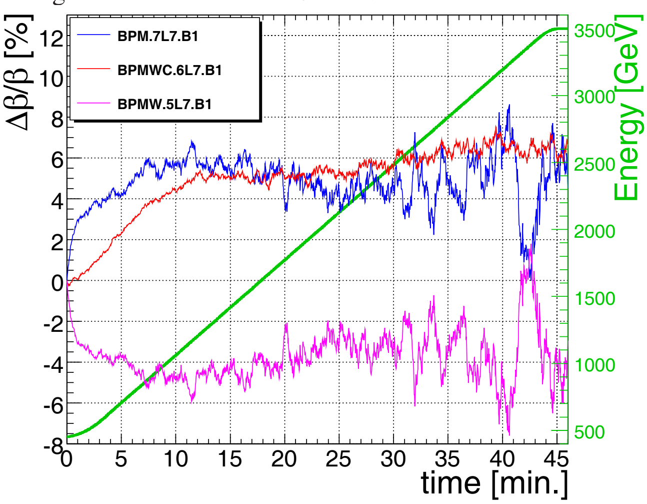


Figure 3: Beta-beat during the ramp after a non-standard magnetic pre-cycle.

MEASUREMENTS DURING β^*-SQUEEZE

Figure 4 shows the evolution of the beta-function during the β^*-squeeze in all four interaction points. Since these optics changes are designed to be local confined to the given interaction point, this measurement gives an estimate of the closure of this procedure under operational conditions and actual quadrupole field imperfections.

The beta-function at the given pick-up locations in the IR7 Cleaning Insertion seem to change in the order of about 5% between the individual squeeze matching points (seen as zeros in the beta-beat evolution). However, compared to the measurements taken during the ramp that had signal to noise ranges in the order of 40 dB, the measurement is much noisier due the reduced signal-to-noise ratio during the β^*-squeeze of only 16 dB due to the reduced excitation strength at top energy and small bunch intensity (half the intensity was lost during the preceeding ramp). Further measurements with possibly larger excitations are required to asses this effect more precisely.

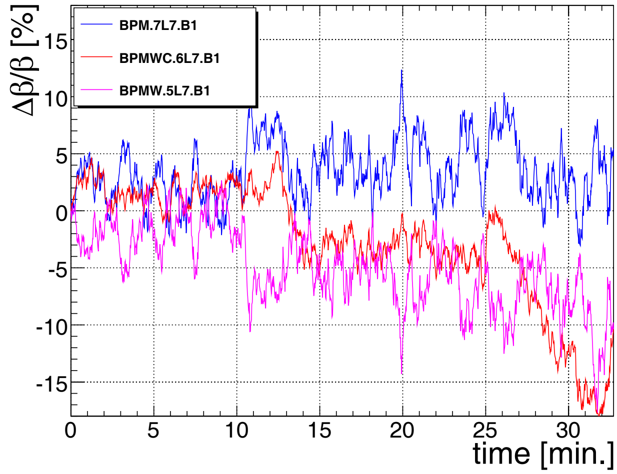


Figure 4: Beta-Beating in the collimation region during the β^*-squeeze.

CONCLUSIONS

The aim of the presented studies was to provide a proof-of-feasibility and to assess magnitude and time-scale of the LHC lattice changes during the energy ramp for a selected location in the ring. Limited by the maximum power of the chosen exciter, the continuous beta-beat measurement system could achieve a 1 % resolution, with excitations kept below a micro-meter, thus making this type of measurement transparent for nominal LHC operation. These preliminary measurements seem to confirm that beta-beating evolution is reproducible within 1% for the measured LHC ramps which is a tribute to the magnetic field stability of the LHC – provided the machine underwent a nominal pre-cycle.

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