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BEAM-BASED MEASUREMENT OF THE SKEW-SEXTUPOLAR COMPONENT OF THE RADIO FREQUENCY FIELD OF A HL-LHC-TYPE CRAB-CAVITY

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Abstract

Two High Luminosity Large Hadron Collider (LHC) type crab-cavities have been installed in the CERN SPS for testing purposes. An attempt to characterize the skew-sextupolar component of the radio frequency field of the crab-cavity (a_3) has been carried out by means of beam-based techniques using turn-by-turn monitoring of the betatron motion. The skew nature of a_3 couples the horizontal and vertical betatron motions through a non-linear term. Therefore by exciting the horizontal betatron motion it was possible to observe a spectral line in the vertical beam motion driven by the non-linear coupling at the characteristic frequency $2Q_x$. A measurement of the magnitude of a_3 was thus obtained by characterizing amplitude and phase of such line. The results of the measurements are discussed here.

INTRODUCTION

Crab cavities will contribute to an increase in the LHC luminosity output as part of the the High-Luminosity LHC upgrade [1–4]. The transverse radio frequency electric field of the crab cavity is synchronized with the circulating bunches such that the head and tail of the bunches receive an opposite transverse kick while the central part of the bunch stays unperturbed. This condition "tilts" the bunch in the transverse plane and produces head-on collision. Space constraints, mainly due to the limited separation between the two counter-rotating beams, required the crab cavities to be shaped accordingly, resulting in a non-perfect transverse profile of the dipolar electric field. From simulations [4], a quadratic term has been identified as the main contributor beyond the purely dipolar field. Due to the potential beam dynamics implications of such a non-linear field, it was found necessary to verify experimentally the results of the crab-cavity electromagnetic model simulation. The radio-frequency (RF) nature of the crab-cavity field makes it very hard to measure precisely such a non-linear field component in an RF test bench, therefore a beam based measurement was attempted.

During 2018, a prototype set of the LHC cavity has been installed in the SPS [5] for test and validation purposes, providing an opportunity to carry out the measurement. The method selected to carry out the experiment is based on the turn-by-turn observation of the non-linear betatron motion. The cavities were installed in a vertical kick configuration, turning the quadratic field distortion into a skew-sextupolar field. A skew sextupole provides a non-linear coupling force between horizontal and vertical planes. By approaching the problem in a perturbative fashion, where the linear betatron motion dominates over the small non-linear perturbation, the betatron motion can be decomposed into small set of modes with characteristic frequencies. The measurement has been carried out by exciting the horizontal betatron motion and observing with a turn-by-turn technique [6] the spectral lines V_{20} and V_{00}, where V_{nm} stands for a vertical mode with frequency $n \cdot Q_x + m \cdot Q_y$ with Q_x and Q_y representing respectively the horizontal and vertical tunes (V_{00} has frequency zero and therefore is a static orbit distortion). Other modes are found by exciting the vertical betatron motion (or both planes at the same time) but have not been considered in this work because of experimental limitations explained in the next section.

SPS TURN-BY-TURN OPTIMIZATION

Ideally, a single low intensity bunch provides the best possible approximation of the single particle dynamics and therefore is the preferred condition to carry out turn-by-turn measurements. However, this condition is far from the optimal working point of the SPS beam position monitors (BPM) [7], resulting in very noisy read-out. Increasing the bunch intensity is not an option, because of the strong decoherence due to collective effects and beam instabilities observed at low chromaticity. Instead, by employing a train of low intensity bunches with low chromaticity setting of the machine, it was possible to obtain clear signals with low decoherence in the horizontal plane. Unfortunately this was not possible in the vertical plane. Figure 1 shows the bunch-by-bunch detuning in the horizontal and vertical planes for a train of 72 bunches. Due to transverse coupling impedances, the vertical plane is subject to a strong tune-shift along the train, resulting when observed with a standard BPM, in a strong decoherence of the vertical betatron motion. This is not the case for the horizontal plane, where no major detuning is observed until a threshold of ~5e12 protons is reached, triggering the build-up of electron-cloud. Operating below this threshold allowed the clear observation of the spectral lines V_{00} and V_{20}. The maximum kick strength to be used to excite the horizontal betatron motion instead was set by the safety margins required to operate the crab-cavity that imposed a maximum trajectory excursion of 10 mm.

SKEW-SEXTUPOLE MEASUREMENT

The ability to change the crab-cavity field amplitude allows for a differential measurement, where data-sets are acquired in two configurations: cavity on and cavity off,

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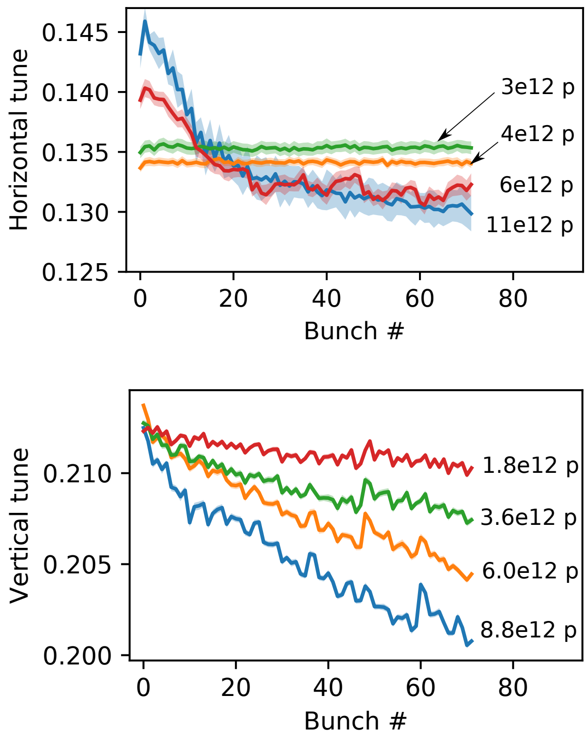

Figure 1: Horizontal (top) and vertical (bottom) bunch by bunch detuning measured in the SPS for trains of 72 bunches of various intensity. The measurement was carried out using a special BPM with single bunch capability. In the horizontal plane no detuning is observed until a threshold is reached. This strongly non-linear behavior is the fingerprint of electron-cloud, that requires a certain beam intensity in order for the cloud to build-up. The linear detuning observed in the vertical plane instead can be attributed to transverse impedance.

allowing to infer a_3 from the change of the spectral lines V_{20} and V_{00}. This approach removes any contribution from any other skew-sextupolar term in the SPS optics, due for example to alignment errors in the normal sextupoles.

The steps operated on each data-set required to carry out the analysis are the following:

- Several BPMs are subject to a strong 50 Hz noise (Fig. 2), to alleviate the problem the turn-by-turn acquisition is started 3000 turns before exciting the horizontal betatron motion. This early acquisition allows to establish the phase and amplitude of the 50 Hz spectral line and to remove it from the data.

- Q_x is searched applying Laskar's approach [8–10] individually for every BPM and averaged. Subsequently the amplitude and phase of H_{10} (horizontal mode with frequency Q_x) are evaluated at each BPM (assuming no damping). Those values are used as the starting condition for a least squares fit of H_{10} that includes as fitting parameters amplitude and damping. τ_x is obtained by averaging the damping over all the BPMs.

- The horizontal betatron action J_x is evaluated by fitting the H_{10} amplitude at each BPM with a model of the SPS optics.

- The amplitude and phase of V_{20} are evaluated after having renormalized the data by an exponential damping law with damping rate $2\tau_x$ and by J_x.

- V_{00} is evaluated from the orbit change observed before and after the horizontal kick. Also in this case a proper renormalization by J_x is applied.

The evaluation of phase and amplitude of every spectral line is obtained again by using the NAFF method developed by Laskar [8].

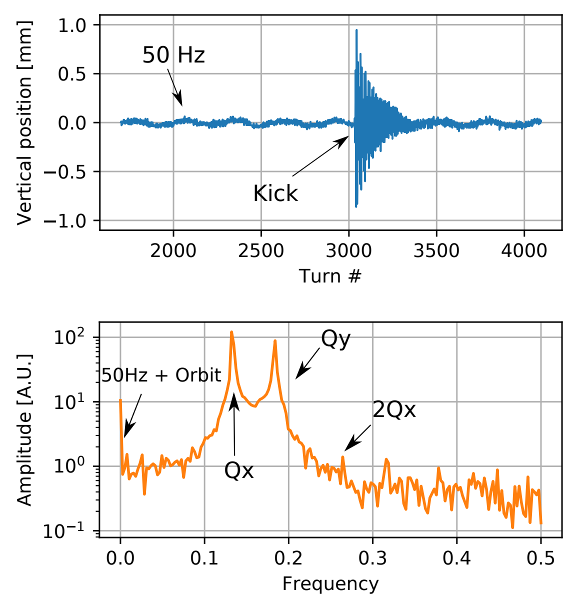

Figure 2: Example of the vertical betatron motion (top) measured by one BPM and spectrum (bottom). In the time domain the 50 Hz noise appears as a steady oscillation with ~866 turns period and overlaps the V_{00} line in the frequency domain.

STATIC SKEW-SEXTUPOLE TEST

In order to verify the data acquisition and analysis chain, a test was performed by using a static skew sextupolar field. Since no skew-sextupole magnets are installed in the SPS, the feed-down produced by a vertical orbit bump in an octupole was used instead to produce a skew sextupolar field. Several data-sets have been acquired for a vertical orbit bump of ±5 mm and an integrated octupole strength of K=0 and ±5 $\mathrm{m^{-3}}$. Figure 3 shows the measured variations of the spectral lines V_{20} and V_{00} as observed by the BPMs around the ring when changing the octupole strength from K=0 $\mathrm{m^{-3}}$ to K=5 $\mathrm{m^{-3}}$. The skew-sextupole strength is inferred by fitting

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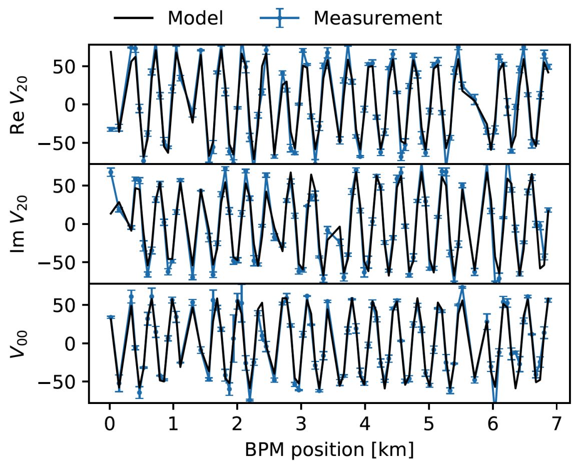

Figure 3: Variation (blue) of the real and imaginary part of the V_{20} spectral line and the V_{00} orbit distortion induced by switching on the static sextupolar field. The analytical model (black) is fitted to the data to obtain the skew-sextupole strength.

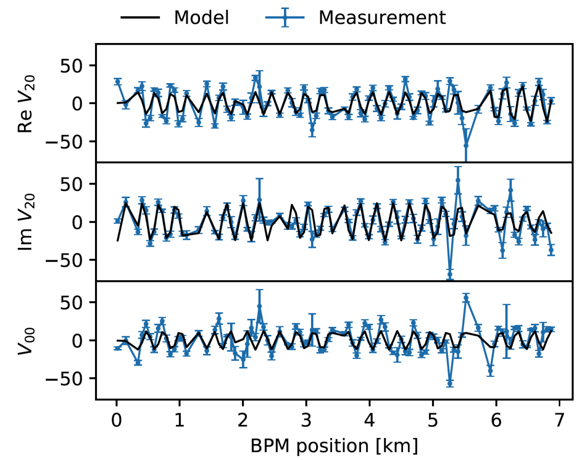

Figure 4: Variation (blue) of the real and imaginary part of the V_{20} spectral line and the V_{00} orbit distortion induced by changing the crab cavity voltage from 100 kV to ~1 MV. The analytical model (black) is fitted to the data to obtain the crab cavity skew-sextupolar field strength.

the experimental points with an analytical model obtained with a perturbative approach. While in the case of the V_{00} fit, the skew-sextupole strength is constrained to a real value, for V_{20} complex strength values are allowed. The complex strength angle $\psi = \arctan(\frac{Im(V_{20})}{Re(V_{20})})$ provides an indication of the fit, a large angle indicates a mismatch between model and measurements produced for example if the skew-sextupole is assumed at the wrong location. The two independent fits for V_{20} and V_{00} provide respectively a strength of a_3: $2.3 \times 10^{-2}\,\mathrm{m}^{-2}$, ψ: -0.11 rad and a_3: $2.1 \times 10^{-2}\,\mathrm{m}^{-2}$ to be compared with the expected value of $2.5 \times 10^{-2}\,\mathrm{m}^{-2}$.

CRAB CAVITY MEASUREMENTS

A short time span was assigned for crab cavity tests in October 2018 during which the measurement was carried out. The time limitation constrained the attempts to a minimum and forced to keep the setup as simple as possible. Three data sets were acquired, two with the maximum allowed crab cavity voltage (only one cavity was available during the measurement) but opposite phase (±1 MV) and one with the cavity set to the minimum voltage (the system in fact did not allow to bring the cavity voltage below 100 kV). In order to induce the strongest possible effect on the beam the crab cavity phase was set such that the beam would pass through the cavity on crest: the center of the beam was synchronized with the maximum cavity voltage. Figure 4 shows the measured variations of the spectral lines V_{20} and V_{00} using two of the acquired data-sets with the crab cavity field set to 100 kV and ~1 MV. A similar result is obtained using the data-sets 100 kV and −1 MV. The fitting procedure is the same as the one applied to the previous case of a static skew-sextupolar field. The two independent fits for V_{20} and V_{00} provide respectively a strength of a_3: $1.1 \times 10^{-2}\,\mathrm{m}^{-2}$, ψ: -1.4 rad and a_3: $1.0 \times 10^{-2}\,\mathrm{m}^{-2}$. Those values are consistent but disconcertingly larger than what predicted by simulation ($2.7 \times 10^{-3}\,\mathrm{m}^{-2}$). Furthermore the large value of ψ is the clear signature of an inconcistency betweem measurement and model.

CONCLUSIONS AND OUTLOOK

The values of the skew-sextupolar field distortion that have been observed in the crab-cavity experimental test are over one order of magnitude higher than what predicted by simulation. The analysis attempted so far considered the quadratic field distortion of the crab cavity as the only contributor to the shift in the V_{20} and V_{00} observed when changing the cavity field. On the other hand it is known that the strong vertical orbit produced by the crab cavity itself induces effects that could potentially dominate compared to the small direct contribution of the crab cavity skew-sextupolar field to the spectral lines V_{20} and V_{00}. As already discussed a vertical orbit in a normal octupole results in an effective skew-sextupolar field due to the feed-down effect. Even if all the octupoles in the SPS were switched off during the measurement it was found that a residual magnetization, due to magnetic hysteresis, can not be excluded. Also normal sextupoles in the presence of a vertical orbit, play a role through a second order effect. At first order a strong linear coupling is produced through feed-down by the vertical orbit in the sextupoles, inducing a large vertical motion with frequency Q_x. Such a motion is now "mixed" by the sextupoles with the horizontal betatron motion producing the two modes V_{20} and V_{00}. Further work to include those two effects in the analysis is in progress.

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