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STATUS OF THE 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. A first partially successful attempt to characterize the skew-sextupolar component (a_3) of the radio frequency field of the crab-cavity by means of beam-based techniques has been carried out in 2018. The large orbit distortion produced by the crab cavity dipolar field combined with the multipolar errors in the SPS optics resulted in some systematic errors that cannot be easily accounted for. After a major overhaul of the SPS turn-by-turn BPM system a second attempt was carried out in 2022. In the attempt to keep under control systematic errors, orbit correctors have been used to compensate the large orbit excursion produced otherwise by the crab cavity. The results of the new measurement are here discussed.

INTRODUCTION

During 2018, a prototype of the LHC crab cavity [1–5] has been installed in the SPS [6, 7] for test and validation purposes, providing an opportunity to carry out, among other studies, the measurement of the sextupolar field error. The cavities were installed in a vertical kick configuration, turning the quadratic field distortion into a skew-sextupolar field. In 2017, before installing the cavities, a simulated measurement using a skew sextupolar field equivalent to the one of the crab-cavity but generated with a static magnet gave very encouraging results. Following the success of the just mentioned test, the same procedure was employed in 2018 to carry out the first attempt at measuring the a_3 of the newly installed crab cavity, unfortunately producing only deceiving results [8]. Data analysis has shown that two effects were probably at the root of the issue:

1. The skew sextupolar field produced in octupoles by the feed down effect due to the large vertical closed orbit distortion induced by the crab cavity.

2. A second order effect created by the joint action of sextupoles and the large coupling due to the skew quadrupolar field produced in the same sextupoles again by the feed down effect.

The strength of such unexpected effects together with the absence of an accurate non-linear model for the SPS optics made it very difficult to discern the actual crab cavity field.

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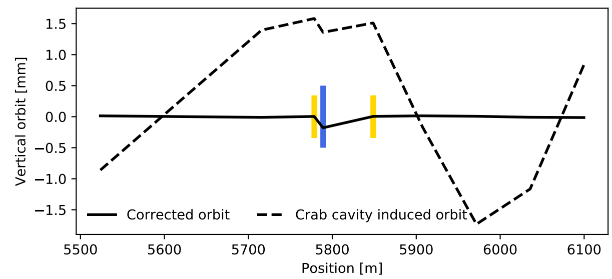

Figure 1: The vertical closed orbit induced by the crab cavity (dashed line) gets drastically reduced when properly driving the two designated vertical orbit correctors. The position of correctors and crab cavity is also marked by yellow and blue stripes respectively

Based on the previous experience, a new measurement strategy immune to the aforementioned spurious effects was laid down: Two correctors close to the crab cavity were selected to compensate for the large vertical closed orbit distortion induced by the crab cavity. The rationale being that by correcting the large vertical orbit as close as possible to the crab cavity, the orbit would be ideally not affected in the most part of the machine, as shown in Fig. 1, inhibiting any orbit and feed-down related effect. It could be objected that the kick induced by the crab cavity has a non negligible time dependency compared to the SPS bunch length due to the RF curvature of the crab cavity, resulting in a longitudinally varying orbit. This effect makes it impossible to zero the orbit for each and any particle in the beam by means of a static orbit corrector. Nonetheless, correcting the orbit of the electric-charge center of the bunch as measured by the BPMs ensures that also any first order orbit induced effect would average to zero when measured through the very same BPM system.

NEW MEASUREMENT

During September 2022 a short time window was assigned to repeat the measurement. Experimental conditions have been replicated as close as possible to the ones used during the attempt in 2018 [8], although in the meantime several upgrades, including a complete renovation of the SPS BPMs electronics has been carried out. The limited time allowed to acquire only one dataset for a positive and one for a negative crab cavity voltage of ~1MV plus a reference dataset with the cavity off. Each dataset includes about 10 identical

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measurements repetitions during different SPS injections. Before proceeding to collect the turn-by-turn data the crab cavity induced vertical closed orbit was corrected to the nominal one by driving the two designated correctors. As shown in Fig. 2 the achieved orbit correction is only partial and the crab cavity induced orbit distortion is suppressed by a factor 2.4. Nevertheless the difference orbit between the two cavity field settings is as low as 36μm rms, ensuring no other sources of a_3 around the SPS than the one from the crab cavity.

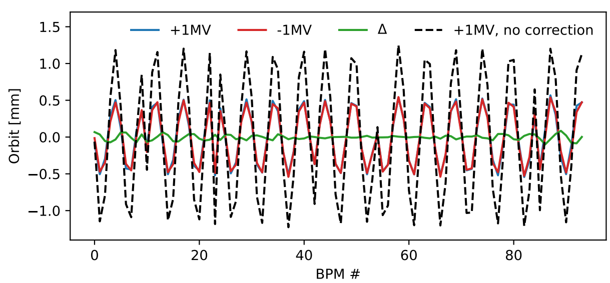

Figure 2: After measuring the reference closed orbit the crab cavity is switched to +1MV, resulting in a vertical orbit distortion (dashed line) with respect to the reference. The orbit correctors are driven to bring back the orbit towards the reference value (blue). When the cavity voltage is inverted to -1MV (i.e. changing the crab cavity phase by π), the orbit correction is repeated (red). The achieved correction is only partial, but the difference orbit between the two field settings is very good (green).

ANALYSIS AND RESULTS

Following the data analysis path as described in [8], the very first step consists in removing the 50 Hz noise from the BPM data. As a result of the BPM's upgrade this step is not anymore necessary, in fact as shown in Fig. 3 the new electronics has a much lower noise. Next, spectral analysis is used to extract from the turn by turn data amplitude and

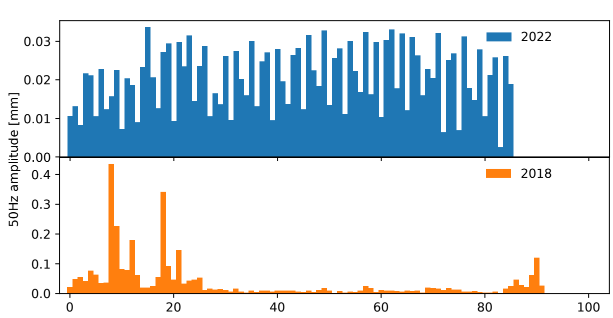

Figure 3: The amplitude of the 50 Hz noise measured by each vertical BPM measured in 2022 with the new electronics shows a substantial reduction respect to the previous measurement in 2018.

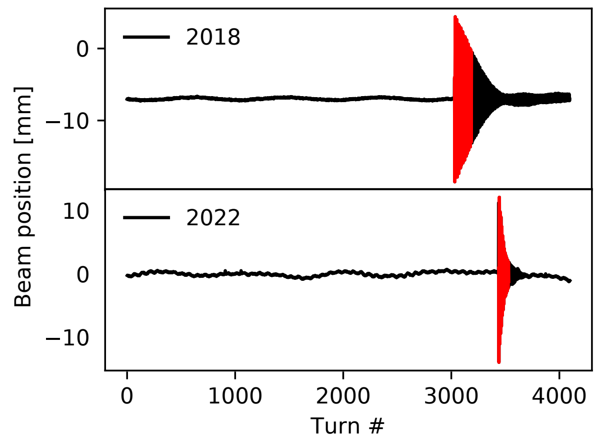

Figure 4: Comparison of the horizontal turn-by-turn signal acquired in 2018 and 2022. The damping in 2022 has been estimated at 51 turns, while more than 200 turns was observed in 2018. The strong reduction was attributed to the SPS transverse damper.

phase of the vertical mode with frequency two times the horizontal tune (V_{20}), which is excited by skew sextupolar fields. Figure 4 shows a comparison of the new measurements with the one collected in 2018. While the structure of the signal is pretty much the same, the damping time of the betatron motion in the newly collected data is substantially shorter. During the MD an unexpected beam instability required to pursue this MD with an active transverse feedback resulting in a premature damping of the betatron oscillation. The spectral analysis is carried out for each one of the three datasets, and the difference between any two datasets of the three available can be used to derive the strength of a_3. Figure 5 shows the measured real and imaginary part of the V_{20} mode obtained as difference from two of the available datasets. The a_3 of the crab cavity is then obtained by fitting the observed difference with an analytical model calculated with a first order perturbative approach. The fit includes two free parameters: an amplitude, which represents the strength of the skew sextupolar term and a phase which takes into account for an error in the phase advance between the crab cavity and the BPMs. In other words this angle should be zero if the source of a_3 is located at the crab cavity, while a non-zero angle shows a mismatch between the model and measurements. The results of the fit obtained from the difference of the datasets acquired with +1MV and -1MV with respect to the zero voltage one are shown in Fig. 6 as a yellow and a red arrow, along with the measurements from 2018 (blue arrows). The sign flip of a_3 between the two voltage settings in the newly acquired data could be the symptom of a systematic error affecting in a similar way both measurements not driven by the crab cavity field settings. While

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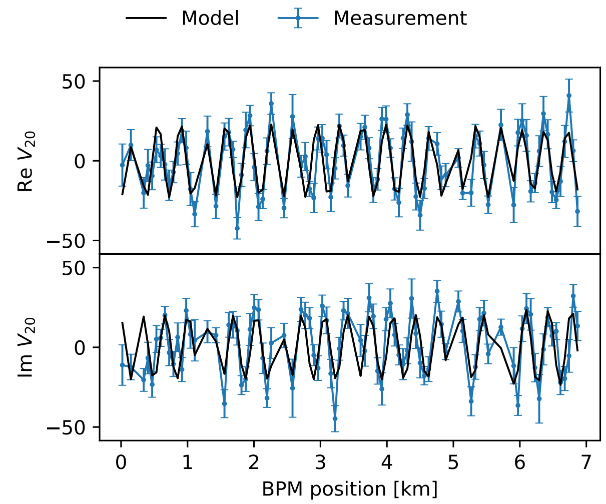

Figure 5: Real and imaginary part of the V_{20} mode obtained from the spectral analysis of the turn-by-turn data (blue). The error bars are derived from the distribution of the analysis carried out over several kicks. The a_3 of the crab cavity is obtained by fitting the experimental data with an analytical (black).

an opposite behavior was observed in 2018, where a large angle (roughly -90°) and the absence of a sign change between the two measurements testify the presence of some additional effect which instead depends on the crab cavity voltage. Such as the aforementioned effects induced by the vertical closed orbit, which indeed depends proportionally on the field of the cavity. A systematic error is removed when considering the difference of two measurements, and indeed the result of the difference analysis (green) comes much closer to the expected value (black) obtained from electro-magnetic simulations [5, 9] than any previous result.

CONCLUSIONS AND OUTLOOK

The first attempt at measuring the skew sextupolar component of an LHC type crab cavity was carried in 2018 in the SPS, resulting in some puzzling result. A posteriori it was shown how shortcomings of the employed technique were undermining the analysis, making it impossible to draw a definitive conclusion from the collected experimental data. The measurement procedure was therefore modified and a new attempt was carried out in 2022. The newly collected data comes a step closer to quantify the skew sextupolar component of a crab cavity, producing results more consistent with the expected values. The differential analysis of the two datasets collected with a crab cavity voltage of +/- 1MV estimates of a_3 to 0.20 T m^{-1} MV^{-1} value to be compared to the 0.15T m^{-1} MV^{-1} provided by electro-magnetic simulations [5, 9]. Due to the limited amount of time available and the complexity of the setup, two major issues limited the quality of the collected data:

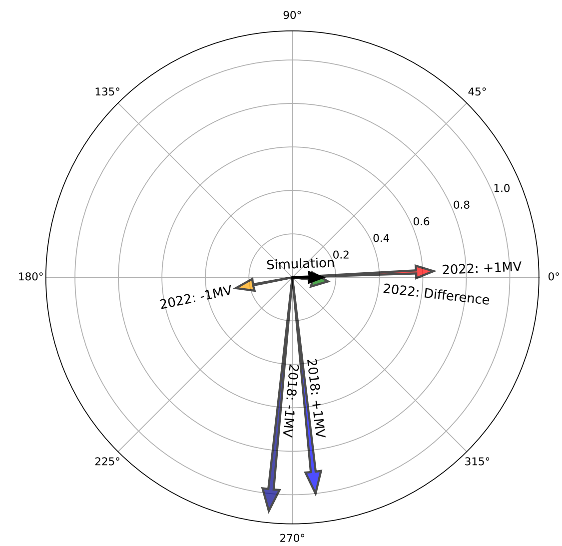

Figure 6: The value of a_3 inferred from the fit of the V_{20} mode is shown as a complex vector. The yellow and red arrows show the result of the analysis for the datasets acquired at +/- 1MV where the dataset acquired with the crab cavity off was used as reference. When the analysis is instead repeated on the the difference of the +1MV and -1MV datasets the green arrow is obtained. The blue arrows represent results from 2018. Finally the black arrows shows the expected a_3 from simulation.

1. The action of the SPS transverse damper required to counteract a not fully understood beam instability, resulting in a drastic reduction of the quality of the collected turn-by-turn data.
2. Only two of the three collected datasets exhibit a good orbit reproducibility, limiting to those two datasets the analysis.

Even though it is still hard to draw a definitive conclusion from the experimental data collected up to date, it appears that the problematic which affected the previous measurement attempt in 2018 have been overcome and no fundamental limit to the technique described here has been made evident. This opens the possibility to an even more accurate characterization in the future.

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REFERENCES

[1] G. Apollinari, I. Béjar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi and L. Tavian, CERN Yellow Rep. Monogr. **4**, 1 (2017). doi:10.23731/CYRM-2017-004

[2] R. Tomás *et al.*, "Operational scenario of first high luminosity LHC run", *J. Phys.: Conf. Ser.* 2420, p. 012003, 2023

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL001

[3] L. Rossi and O. S. Brüning, "Progress with the High Luminosity LHC Project at CERN", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 17–22. doi:10.18429/JACoW-IPAC2019-MOYPLM3

[4] Y. P. Sun, R. Assmann, J. Barranco, R. Tomas, T. Weiler, F. Zimmermann, R. Calaga and A. Morita, "Beam dynamics aspects of crab cavities in the CERN Large Hadron Collider" *Phys. Rev. ST Accel. Beams* **12**, 101002 (2009). doi:10.1103/PhysRevSTAB.12.101002

[5] J. Barranco García, R. De Maria, A. Grudiev, R. Tomás García, R. B. Appleby and D. R. Brett, "Long term dynamics of the high luminosity Large Hadron Collider with crab cavities", *Phys. Rev. Accel. Beams* **19**, no. 10, 101003 (2016). doi:10.1103/PhysRevAccelBeams.19.101003

[6] L. R. Carver *et al.*, "First Machine Developments Result with HL-LHC Crab Cavities in the SPS", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 338–341. doi:10.18429/JACoW-IPAC2019-MOPGW094

[7] R. Calaga *et al.*, "First demonstration of the use of crab cavities on hadron beams" *Phys. Rev. Accel. Beams* **24**, 062001 (2021).

[8] M.Carla', A.Alekou, H.Bartosik and L.R. Carver, "Beam-based measurements of the skew-sextupolar component of the radio frequency field of a HL-LHC-type crab-cavity", 2020, https://cds.cern.ch/record/2715376

[9] James Alexander Mitchell, Ph.D. dissertation