ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THXA07

DRIVEN 3D BEAM OSCILLATIONS FOR OPTICS MEASUREMENTS IN SYNCHROTRONS

L. Malina, J. Coello de Portugal, H. Timko, R. Tomás, CERN, Geneva, Switzerland

Abstract

Optics measurements in storage rings employ turn-by-turn data of transversely excited beams. Traditionally, to measure chromatic properties, the relative momentum is changed step-wise, which is time-consuming and almost impractical during the energy ramp. We present an optics measurement method based on adiabatic simultaneous 3-dimensional beam excitation, which is more time-efficient and well fitted for the energy ramp. This method was successfully demonstrated in the LHC utilising AC-dipoles in combination either with a slow RF-frequency modulation or a driven RF-phase modulation close to the synchrotron frequency. Faster longitudinal oscillations improve the accuracy of optics parameters inferred from the synchro-betatron sidebands. This paper reports on the experimental demonstration of optics measurements based on 3D driven beam excitations and the plans for LHC Run 3.

INTRODUCTION

One way to perform optics measurements in storage rings is to excite the beam and acquire turn-by-turn (TbT) beam position monitor (BPM) data showing the coherent betatron motion [1,2]. The beam is excited using either kickers or AC-dipoles [3]. AC-dipoles can ramp up and down the oscillation adiabatically [4], i.e. without any measurable emittance growth. Whenever dispersion or other chromatic properties need to be measured, in addition to on-momentum linear optics, the relative momentum of the beam is changed step-wise, and the beam is excited few times at each of the momenta. Based on the experience with optics measurements in the Large Hadron Collider (LHC), such a process is time-consuming. Roughly, about 10 minutes are needed per momentum change, and at least one minute is needed between consecutive beam excitations [5]. Moreover, such an approach is impractical during the beam energy ramp. To significantly speed up the measurements, we utilise 3D beam excitation, a combination of transverse excitation driven by AC-dipoles and longitudinal excitation by RF system modulation. The prominent use case is when optics corrections are to be calculated or verified. The 3D excitation comes in two flavours:

- Excitation by means of AC-dipoles together with slow 5 Hz RF-frequency modulation (compared to natural synchrotron frequency ranging between 20-50 Hz), which was well established during Run 2 [5]. It allows for a precise measurement of dispersion simultaneously with linear optics at constant energy as well as during the energy ramp (reported herein and in [6]), which would be otherwise impractical. Due to the small separation between synchrotron sidebands in the frequency spectra, chromaticity and potentially chromatic beatings are not measured with sufficient accuracy.
- Fully forced 3D excitation, which excites the beam by means of AC-dipoles close to the betatron tunes and by RF-phase modulation close to the synchrotron tune [7]. The driven frequency needs to be higher than the central synchrotron frequency $Q_{s,0}$, which is necessary to preserve the longitudinal beam emittance. The other condition to preserve the emittance (both transverse and longitudinal) is adiabatic ramp-up and ramp-down of oscillation amplitudes. We demonstrated the fully forced 3D excitation with long RF-phase modulation (90 s in total), which is usually performed to manipulate the longitudinal bunch shapes. Figure 1 schematically shows the timing and envelopes of excitation amplitudes.

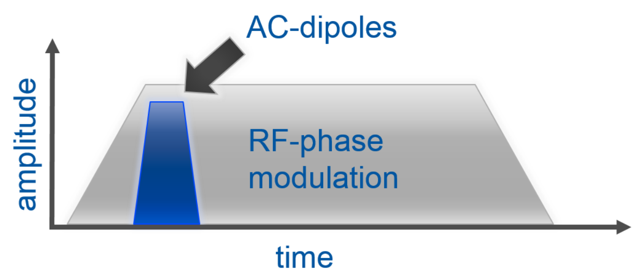

Figure 1: Schematic excitation amplitude of AC-dipoles and RF-phase modulation. In both cases, the amplitude of modulation is trapezoidal in time; with ramp up, constant plateau and ramp down. The excitation time scales are very different: for AC-dipoles 0.2 s + 0.6 s + 0.2 s were used, while for RF-phase modulation 10 s + 70 s + 10 s were used.

In the following, we first introduce the chromatic properties measured from TbT BPM data, then we present the results of the experimental demonstration of 3D excitation in the energy ramp and of fully forced 3D excitation. Finally, we discuss the future development, most notably for the LHC Run 3.

CHROMATIC PROPERTIES

In this section, we summarise the chromatic properties calculated from the frequency spectra of TbT BPM data. These spectra acquired during 3D excitation are calculated, for instance, by Harpy [8]. We utilise the following notation for amplitudes A and phases ϕ of spectral lines: A_s and ϕ_s correspond to driven longitudinal (synchrotron) motion, A_0 and ϕ_0 correspond to driven betatron motion and $A_\pm$ and $\phi_\pm$ are amplitudes and phases of its first synchrotron sidebands. The amplitude of relative beam momentum modulation $|dp/p|$ is measured directly as follows (in the LHC

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THXA07

using only arc BPMs):

$$|dp/p| = \frac{\langle A_s \cdot D_{\text{x,model}} \rangle}{\langle D^2_{\text{x,model}} \rangle}, \quad (1)$$

where $D_{\text{x,model}}$ is the nominal (design) horizontal dispersion obtained, for instance, using MAD-X [9]. We measure the dispersion in both horizontal and vertical planes and above transition energy as follows:

$$D = \frac{A_s}{|dp/p|} \cdot \text{sgn}(\cos(\phi_s - \overline{\phi_s})), \quad (2)$$

where we define a factor c_{sign} corresponding to the sign of dispersion, i.e. $c_{\text{sign}} = \text{sgn}(\cos(\phi_s - \overline{\phi_s}))$. In the LHC, $\overline{\phi_s}$ is also calculated using only arc BPMs. In the horizontal plane, we also measure dispersion normalised by $\sqrt{\beta_x}$, which is independent of BPM calibration errors [10] and utilised to correct quadrupole errors [2].

$$D_x/\sqrt{\beta_x} = c_{\text{sign}} \sqrt{c_{\text{comp}}} \frac{A_s}{A_0} \cdot \frac{\langle (D_x/\sqrt{\beta_x})_{\text{model}} \rangle}{\langle c_{\text{sign}} \sqrt{c_{\text{comp}}} \frac{A_s}{A_0} \rangle}, \quad (3)$$

where c_{comp} is a ratio of model β-functions with and without AC-Dipoles in the lattice [11].

While the derivation of the quantities mentioned above is straightforward and with a broad range of applicability, the derivation of linear chromaticity deserves more attention. We derive an equation for linear chromaticity from Eq. (23) in [4], which describes a frequency spectrum of an off-momentum particle performing transverse driven motion in the presence of non-zero linear chromaticity. We assume small non-linear chromaticity, and we neglect the third term as it is much smaller than the second term for fractional tunes not far from 0.25 (it is the case for the LHC). We also approximate Bessel functions $J_0(x) = 1$, $J_{\pm 1}(x) = \pm x/2$ and higher-order Bessel function with zero, which holds for small x. Then we can express chromaticity (in both planes) using either left (Q'_-) or right (Q'_+) sideband as:

$$Q'_{\pm} = \frac{2A_{\pm}}{A_0} \cdot \frac{Q_{\text{drv}} - Q_{\text{nat}} \pm Q_s}{|dp/p|} \cdot \text{sgn}(\cos(\phi_0 - \phi_{\pm} \pm \phi_s)), \quad (4)$$

where $Q_{\text{drv}} - Q_{\text{nat}}$ is the difference between driven and natural betatron tunes and Q_s is a driven synchrotron tune. A more detailed derivation can be found in the Appendix of [7].

The analysis of linear optics quantities is the same as in the 2D case [2, 12], e.g. N-BPM method [13, 14] is applied.

ENERGY RAMP MEASUREMENTS

We utilised the 3D excitation during the LHC energy ramp during the 2018 optics commissioning. The slow RF-frequency modulation was started at injection energy and kept on throughout the ramp. Measurements were taken at multiple energies through the ramp, synchronously with AC-dipole excitations. The RF-frequency modulation corresponded to a $|dp/p|$ of 10^{-4}. Figure 2 shows the maximal peak and rms normalised dispersion beating of both Beam 1 and Beam 2 through the energy ramp.

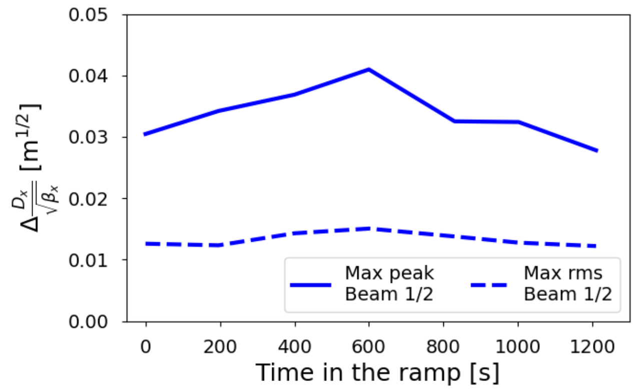

Figure 2: Normalised dispersion beating with respect to nominal model measured along the LHC energy ramp. The beam was excited by AC-dipoles when the frequency of the RF system has been simultaneously modulated at 5 Hz.

FULLY FORCED 3D EXCITATION

Driven longitudinal excitation (at a frequency close to the central synchrotron tune) is better suited for the chromaticity measurement than the slow RF-frequency modulation mentioned above. The higher beam-momentum modulation frequency introduces a larger separation between the driven betatron spectral line and its synchrotron sidebands, therefore, allows for more accurate signal processing (reduces spectral leakage). Another way to reduce spectral leakage could be an upgrade of the AC-dipole's hardware to extend the excitation plateau from 6600 turns to about 20000 turns (approximately from 0.6 s to 1.8 s).

In the LHC, we have experimentally demonstrated a fully driven 3D beam excitation using a transverse excitation by AC-dipoles common to optics measurements combined with RF-phase modulation at a single frequency injected in one RF cavity, during machine development time (MD). We operated with one to three pilot bunches of LHC Beam 1 at the beam energy of 450 GeV and the RF voltage of 4 MV. The central synchrotron frequency in such conditions is $Q_{s,0} = 4.15 \cdot 10^{-3}$. As the synchrotron frequency spreads only to lower values than $Q_{s,0}$, we chose the RF-phase modulation frequency above $Q_{s,0}$ to avoid a longitudinal blow-up.

We optimised the parameters of RF-phase modulation for optics measurements with two main constraints: avoid longitudinal emittance blow-up and provide sufficient resolution in the measurement of normalised dispersion (using Eq. (3)) from TbT BPM data. We used the amplitude of 9.6 degrees (corresponding to 1.2 degrees in each of eight cavities) at a frequency corresponding to $Q_s = Q_{s,0} + 8 \cdot 10^{-5}$. In the measurements, such an excitation corresponds to an amplitude of the relative beam momentum variation of $5 \cdot 10^{-5}$, obtained independently from RF parameters and TbT data analysis Eq. (1). With the further shortening of RF-phase modulation, the optimal RF parameters may change. We also scanned both horizontal and vertical chromaticities to measure the transverse frequency spectra of the beam response. Towards the end of the MD, we measured the beam

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THXA07

optics with three pilot bunches as a proof of principle to probe lattice changes on shorter time scales.

Figure 3 displays the frequency spectra of TbT data showing the driven betatron line with its synchrotron sidebands and natural betatron line in the low and high chromaticity cases. All the observed beam spectra qualitatively agree with simulations of a proton bunch as a driven oscillator in three dimensions [7]. For the chromaticity up to 10 units, there is a good quantitative agreement with tracking in MAD-X.

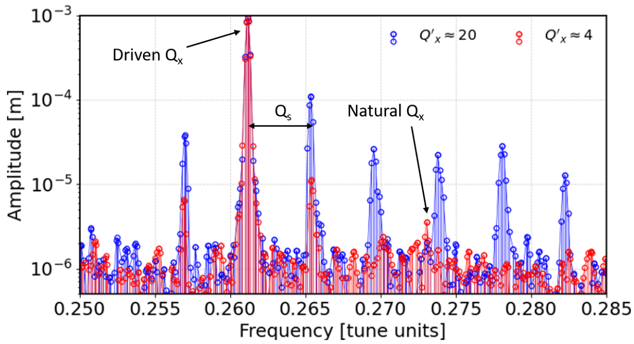

Figure 3: Frequency spectra of turn-by-turn data recorded by BPMs in the low chromaticity case (Q' = 4) and high chromaticity case (Q' ≈ 20).

From the frequency spectra, we measure chromaticity using Eq. (4) with a precision of 0.1 units based on the statistical uncertainty of chromaticities measured for three simultaneously excited bunches. Figure 4 shows all chromaticity measurements during the MD compared to the standard method (or best estimate for a given time). The two methods differ by 0.2 ± 0.7 units and 0.2 ± 0.4 units, when excluding the high chromaticity measurements ($Q' \approx 20$).

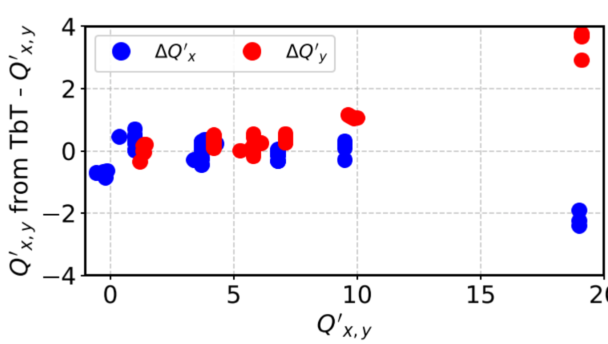

Figure 4: Comparison of chromaticities measured from turn-by-turn data with the estimate based on the standard measurement with assumed accuracy of 1 to 2 units.

We also compare normalised dispersion obtained using driven longitudinal excitation to the reference measurement performed with slow RF-frequency modulation validated [5] against the standard measurement. Figure 5 shows a very good agreement of measured normalised dispersion from the two methods (within errors bars and without bias).

CONCLUSIONS AND OUTLOOK

The 3D beam excitation allows measuring linear beam optics parameters simultaneously with chromatic properties, decreasing the necessary number of excitations and time needed for measurements. We successfully utilised 3D beam excitation (with slow beam momentum modulation) during the LHC energy ramp, allowing the first dispersion measurement while accelerating the beam. With the increasing importance of optics control in the energy ramp, the additional dispersion measurement is a step forward. With the slow longitudinal excitation and a short time for which AC-dipoles can excite the beam, spectral leakage limits the accuracy of synchro-betatron spectral lines. In turn, this poses a limit, for example, on accuracy and automation of chromaticity measurement.

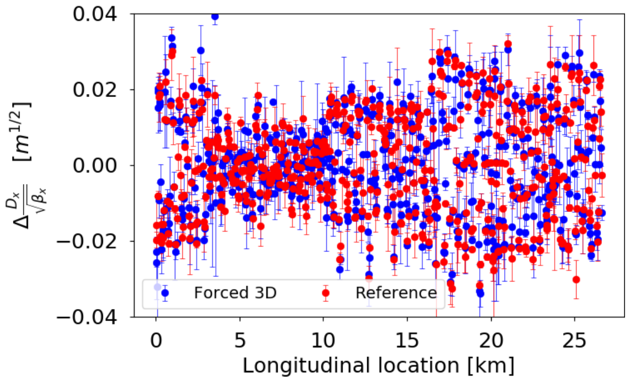

Figure 5: Comparison of normalised dispersion measurements based on forced 3D excitation with a reference measurement performed with slow RF-frequency modulation (driven oscillations in transverse plane only).

Consequently, the fully forced 3D beam excitation, featuring a longitudinal oscillation close to synchrotron tune, has been simulated and experimentally demonstrated in the LHC at injection energy. The amplitude and frequency of longitudinal excitation were optimised for optics measurements and to avoid longitudinal emittance blow-up. The chromaticity should remain below five units to avoid transverse emittance blow-up. For low and intermediate chromaticities, the measured frequency spectra agree with simulations. For high chromaticity ($Q' \approx 20$), the agreement is only qualitative. We developed and tested new methods to measure dispersion and chromaticity with very promising first results.

Simulations of the underlying beam dynamics processes will continue to develop a robust chromatic beta-beating measurement and optimise the ramping time of the RF-phase modulation. The work on overall measurement automation will allow the routine use of these methods during the LHC Run 3 commissioning. Experience with the beam excitation in other machine conditions, at flattop energy, and during the energy ramp will be needed. Moreover, a reasonably safe solution for excitation of three pilot bunches also at higher beam energies has been found [15]. We foresee 3D excitation of three bunches throughout the machine cycle as it can remove some sources of systematic errors or probe larger parameter space efficiently. These techniques combined can speed up significantly the future HL–LHC commissioning, where β^*-levelling will be used and will require commissioning of up to 50 different optics configurations.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THXA07

REFERENCES

[1] R. Tomás, M. Aiba, A. Franchi, and U. Iriso, "Review of linear optics measurement and correction for charged particle accelerators", *Phys. Rev. Accel. Beams*, vol. 20, p. 054801, 2017. doi:10.1103/physrevaccelbeams.20.054801

[2] T. Persson *et al.*, "LHC optics commissioning: A journey towards 1% optics control", *Phys. Rev. Accel. Beams*, vol. 20, p. 061002, 2017. doi:10.1103/physrevaccelbeams.20.061002

[3] M. Bai *et al.*, "Experimental test of coherent betatron resonance excitations", *Phys. Rev. E*, vol. 56, p. 6002, 1997. doi:10.2172/1149841

[4] R. Tomás, "Adiabaticity of the ramping process of an ac dipole", *Phys. Rev. ST Accel. Beams*, vol. 8, p. 024401, 2005. doi:10.1103/physrevstab.8.024401

[5] L. Malina and J. Coello de Portugal,"Optics measurements in storage rings based on simultaneous 3-dimensional beam excitation", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, paper THPAF046, pp. 3068-3071.

[6] L. Malina and R. Tomás, "Optics measurements in the ramp and impact on emittance", presented at 377th LHC Machine Committee (LMC), May 2019. https://indico.cern.ch/event/819410/.

[7] L. Malina, R. Tomás, H. Timko, D. Louro Alves, and J. Coello de Portugal, "LHC MD 4505: Forced 3D beam oscillations", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2020-0065, Nov. 2020.

[8] L. Malina, Harpy, https://github.com/pylhc/omc3/tree/master/omc3/harpy

[9] MAD-X, mad.web.cern.ch/mad

[10] R. Calaga, R. Tomás and F. Zimmermann, "BPM calibration independent LHC optics correction", in *Proc. PAC'07*, Albuquerque, New Mexico, USA, Jun. 2007, paper THPAS091, pp. 3693-3695.

[11] S. Peggs and C. Tang, "Nonlinear diagnostics using an AC Dipole", RHIC-AP-159, Oct. 1998. https://www.agsrhichome.bnl.gov//AP/ap_notes/RHIC_AP_159.pdf

[12] L. Malina *et al.*, OMC3, https://github.com/pylhc/omc3

[13] A. Langner and R. Tomás, "Optics measurement algorithms and error analysis for the proton energy frontier", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 031002, 2015. doi:10.1103/PhysRevSTAB.18.031002

[14] A. Wegscheider, A. Langner, R. Tomás, and A. Franchi, "Analytical N-beam position monitor method", *Phys. Rev. ST Accel. Beams*, vol. 20, p. 111002, 2017. doi:10.1103/PhysRevAccelBeams.20.111002

[15] L. Malina and R. Tomás, "AC-dipole operation with three bunches", presented at 191st Machine Protection Panel Meeting (LHC), May 2020. https://indico.cern.ch/event/918007/.