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OPTICS MEASUREMENTS IN STORAGE RINGS BASED ON SIMULTANEOUS 3-DIMENSIONAL BEAM EXCITATION

L. Malina[1], J. Coello de Portugal, CERN, Geneva 23, Switzerland
[1] also at University of Oslo, 0316 Oslo, Norway

Abstract

Optics measurements in storage rings usually employ excitation in both transverse directions. This needs to be repeated at several different beam energies and is time-consuming. In this paper, we develop a new optics measurement technique, which excites the beam in all three spatial dimensions simultaneously. It allows measuring the linear optics and chromatic properties at the same time, leading to speed up of the optics measurements. The measurement method has been successfully demonstrated in the LHC using AC-dipoles and RF frequency modulation. Analysis methods have been derived for the 3-dimensional beam excitation case. We quantify the resolution of the measured optical quantities. The first results suggest that the added complexity does not deteriorate the resolution of the linear optics measurement. In the future, this method can serve as an operational tool to check the optics or even to correct it.

INTRODUCTION

One of the ways to perform optics measurements in a storage ring is to excite the beam and acquire turn-by-turn (TbT) beam position monitor (BPM) data showing the coherent betatron motion [1]. The beam is excited using either kickers or AC-dipoles [2]. AC-Dipoles can ramp up and down the oscillation adiabatically [3], i.e. without any measurable emittance growth. Typical optics measurement consist of several kicks at different beam energies, in order to measure the linear optics as well as the chromatic properties.

Based on the experience with optics measurements in the LHC, there are two main sources of delay during the measurements. First, the human intervention to change beam energy by adjusting the RF frequency and check other beam parameters for the new set of measurements usually takes up to 15 minutes. Second, the AC-dipole needs about 70 seconds to cool down after every single excitation. Addition of longitudinal excitation [4] can be used to speed up the measurement, when performed adiabatically.

BEAM EXCITATION

In the LHC, the beam is excited using AC-dipoles in both transverse directions simultaneously. This gives the BPM reading as shown in Figure 1, for one of the planes. Once the beam energy is changed the measurement is repeated. This time-consuming process can be avoided by fast modulation of RF-frequency. RF-frequency change is normally used to adjust the beam energy, or it is modulated in order to measure the chromaticity. However, the frequency of the modulation for the chromaticity measurement is typically about 0.1 Hz, such that Base-Band Tune (BBQ) system can measure the tune.

We employ the same system at its maximal frequency of 5 Hz, which is still far from the natural synchrotron frequency of about 20 Hz. The RF-frequency modulation is ramped up before the actual AC-dipole excitation starts. Three periods of adiabatic energy variation (forced synchrotron oscillation) fit within 6600 turns acquired (with LHC's revolution frequency of 11.3 kHz). The sample TbT reading at dispersive BPM is shown in Figure 2.

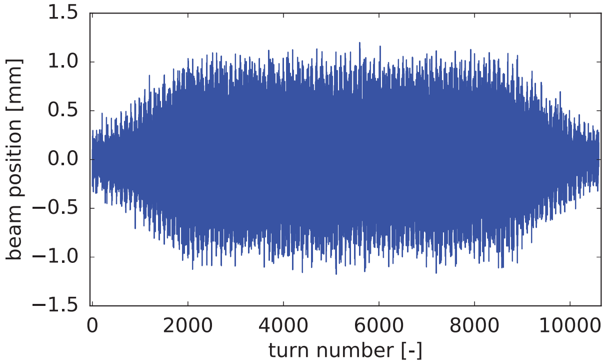

Figure 1: Sample BPM TbT data of beam excited by AC-dipole performing the driven coherent betatron oscillation. Note the ramp-up and ramp-down of the oscillation amplitude, which is important to avoid emittance growth [3] (in hadron machines).

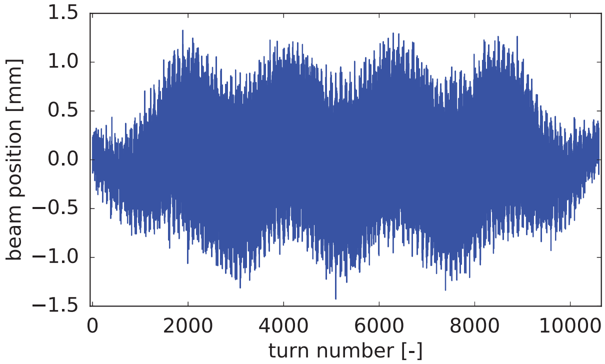

Figure 2: Sample of TbT data at dispersive BPM of beam excited by AC-dipole when the frequency of RF system has been simultaneously modulated. The beam performs the driven coherent betatron oscillations and the beam energy is adiabatically varied.

The adiabaticity of this mode of excitation has been experimentally demonstrated in the LHC, as it can be seen from the beam size measurement from Beam Synchrotron Radiation Telescope (BSRT) during the 3-dimensional (3D) excitations shown in Figure 3.

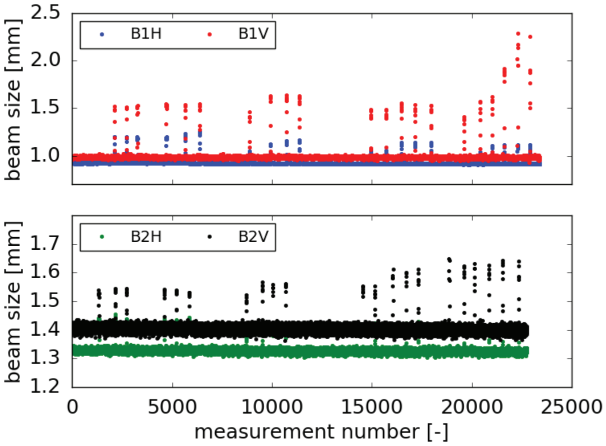

Figure 3: The beam size measurement using BSRT during the 3D excitations, in case the measurement is not fully adiabatic a step-like beam size increase would appear. The spikes refer to AC-dipole excitations.

CHROMATIC PROPERTIES ANALYSIS

The largest advantage of simultaneous 3D excitation is that the chromatic properties, such as normalized dispersion $D_x/\sqrt{\beta}$ [5] or the W-function [6] can be a ratio of certain spectral lines amplitudes. A new dedicated harmonic analysis framework [7] searches for resonances originating from all three spatial dimensions (x, y and s, namely, horizontal, vertical and longitudinal). The following notation of the driven spectral lines has been adopted, for example H(2,0,1) being at frequency $2 \cdot Q_x^F + 0 \cdot Q_y^F + 1 \cdot Q_s^F$ in the horizontal plane ($Q_{x,y,s}^F$ denotes fractional forced tunes).

Relative Beam Momentum Change

Under the assumption of linear dispersion and of beam oscillation around stable orbit (closed orbit), the amplitude of relative beam momentum variation Δp_{amp} is measured. The closed orbit change in the arc BPMs (with larger dispersion) in the horizontal plane is used at the extremes of beam momentum variation. The extremes are identified from frequency and phase of synchrotron spectral line H(0,0,1), i.e. where $|\cos(Q_s n_{turns} + \phi_s)| > 0.9$. A model dispersion is assumed in the calculation of relative beam momentum variation, for measurements in the LHC a variation of 10^{-4} is utilized.

Normalised Dispersion

Using the above-mentioned spectral line notation the normalised dispersion [5] is proportional to the ratio of spectral line amplitudes corresponding to dispersion and $\sqrt{\beta}$:

$$D/\sqrt{\beta} = C\frac{H(0,0,1)}{H(1,0,0)}, \tag{1}$$

where C is a global multiplication factor (related to excitation amplitudes) obtained as a ratio of average measured and average model normalised dispersions in the arc BPMs:

$$C = \frac{\sum_{arcBPMs} \frac{H(0,0,1)}{H(1,0,0)}}{\sum_{arcBPMs} \left(\frac{D}{\sqrt{\beta}}\right)_{model}}, \tag{2}$$

As the spectral line amplitude is always positive, we need to compare the phase of H(0,0,1) at the given BPM with the average phase in the arc BPMs, i.e. if the phases are opposite the dispersion is negative.

OPTICS MEASUREMENT PRECISION

In this section, we compare the precision of the normalised dispersion and the linear optics measurements [8] using 3D and 2D driven beam excitation. The analysis of linear optics quantities is the same as in the 2D case, i.e. N-BPM method [9, 10] is applied. In terms of driven motion, the TbT BPM data differs only in presence of spectral lines related to adiabatic energy variation. The normalised dispersion measurements in high β optics at injection energy (with fractional natural tunes of 0.305 and 0.315 in the horizontal and the vertical plane) were performed by the two methods, one right after the other. Their comparison is shown in Figure 4. In the 3D driven excitation based measurement, TbT data from 6 acquisitions are combined, while 11 acquisitions are combined in 2D case. The measurement error distributions are shown in Figure 5 including the mean errors. The residuals scaled by the errors of measurements combined in quadratures are shown in Figure 6. The mean value of such distribution close to zero demonstrates no systematic bias. The standard deviation shows the agreement within the measurement errors (i.e. smaller than 1). The two methods are in excellent agreement.

The agreement of linear optics quantities, measured the same way using both types of beam excitation (except for normalised dispersion) is summarized in Table 1. As a drift of betatron tunes and coupling was observed during the measurement, the linear coupling is not included. However, impact of tune drift on measured phase advances and β-functions is assumed to be negligible compared to measurement errors. No statistically significant bias, nor precision loss were observed in any of the quantities (phase advances, β-functions from phase and from amplitude, and already mentioned normalised dispersion).

In ESRF [11] the transverse 2D kicks were performed, however a residual synchrotron oscillation corresponding to a relative beam energy variation of $5 \cdot 10^{-5}$ was visible in the data. The normalised dispersion can also be measured by the 3D method from the residual synchrotron motion of bunch centroids using transverse kicks only. The obtained normalised dispersion, shown in Figure 7, is only 4 times less precise, even though the amplitude of residual synchrotron motion is only 3 % of relative beam energy changes of 0.16% applied for the standard measurement.

Table 1: Comparison of Linear Optics Quantities (measured using the 2D AC-Dipole excitation with or without RF-frequency modulation at the same time)

Quantity	**Mean Norm. Residuals**	**Std Norm. Residuals**	**Avg. Error 3D / Avg. Error 2D**
Horizontal phase advance	0.003	0.52	1.22
Vertical phase advance	-0.003	0.51	1.11
Horizontal β-beating from phase	0.003	0.87	1.12
Vertical β-beating from phase	0.019	0.76	1.04
Horizontal β-beating from amplitude	0.049	0.95	0.98
Vertical β-beating from amplitude	0.020	0.84	0.90
$\Delta D_x/\sqrt{\beta_x}[m^{1/2}]$	0.006	0.42	0.75

The RF-modulation does not seem to disturb neither the precision nor the accuracy of phase advances and β-functions.

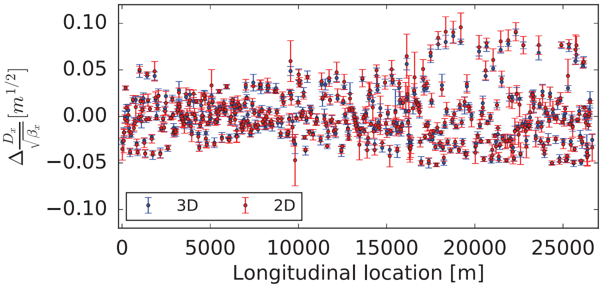

Figure 4: Comparison of LHC normalized dispersion difference to the LHC lattice model measured from TbT data using simultaneous 3D driven excitation (in blue) and 2D driven beam excitation at multiple beam energies (in red).

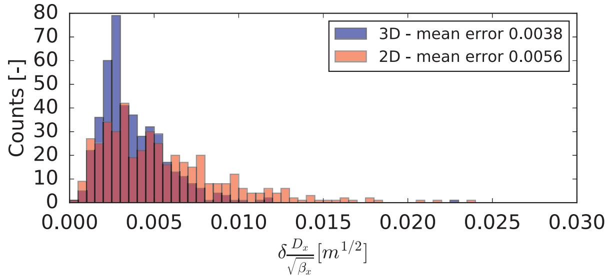

Figure 5: Distributions of the normalised dispersion measurement errors from (Figure 4) for both methods: 3D excitation (in blue) and 2D excitation (in red).

CONCLUSIONS AND OUTLOOK

The optics measurement method based on simultaneous 3D beam excitation allows measuring linear beam optics quantities simultaneously with chromatic properties. The employed beam excitation does not deteriorate the beam quality. The precision of measured quantities is not deteriorated comparing to standard optics measurements based on 2D excitation. A new normalised dispersion measurement technique has been developed, demonstrating faster measurement (fewer beam excitations) with the same or better precision. This represents an important step towards fast online optics measurements or even corrections. TbT data from 3D excitation contains more information than the 2D case. Synchro-betatron lines observed in the spectra are being studied with the aim to measure W-function, or potentially chromatic coupling.

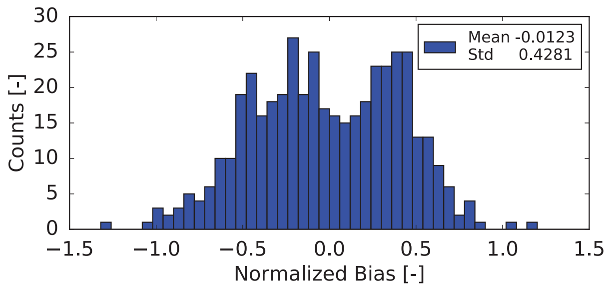

Figure 6: Distribution of differences between the two normalised dispersion measurements from (Figure 4), normalised by their errors combined in quadrature.

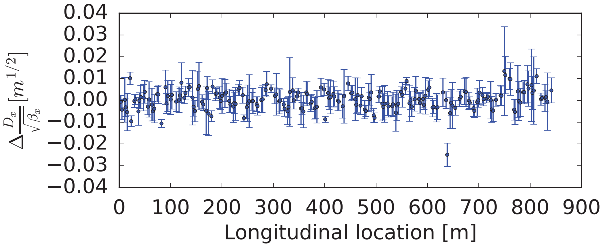

Figure 7: Normalized dispersion (diference to the model) measured in ESRF using the 3D method for TbT data recorded from transverse 2D beam excitation exploiting only the residual synchrotron motion.

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