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OPTICS MEASUREMENTS IN STORAGE RINGS: SIMULTANEOUS 3-DIMENSIONAL BEAM EXCITATION AND NOVEL HARMONIC ANALYSIS

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Abstract

Optics measurements in storage rings employ turn-by-turn data of transversely excited beams. Chromatic parameters need measurements to be repeated at different beam energies, which is time-consuming. We present an optics measurement method based on adiabatic simultaneous 3-dimensional beam excitation, where no repetition at different energies is needed. In the LHC, the method has been successfully demonstrated utilising AC-dipoles combined with RF frequency modulation. It allows measuring the linear optics parameters and chromatic properties at the same time without resolution deterioration. We also present a new accurate harmonic analysis algorithm that exploits the noise cleaning based on singular value decomposition to compress the input data. In the LHC, this sped up harmonic analysis by a factor up to 300. These methods are becoming a "push the button" operational tool to measure the optics.

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 measurements consist of several excitations 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 time-consuming tasks during the measurements. First, the human intervention to change beam energy by adjusting the RF-frequency and check other beam parameters, which 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.

In the analysis process, TbT BPM data is first cleaned of noise using methods [5–7] based on Singular Value Decomposition (SVD). The SVD of a matrix $\mathbf{A}$ is given by: $\mathbf{A} = \mathbf{USV^T}$. Cleaning keeps only the modes corresponding to the largest singular values, in this way it improves precision and accuracy. It also reduces the amount of information without changing the size of the data, typically about a factor 40 larger than the reduced $\mathbf{U}$, $\mathbf{S}$ and $\mathbf{V^T}$ matrices.

Later the harmonic analysis is performed on cleaned TbT data BPM by BPM (further reffered to as "bpm" method). The Discrete Fourier Transform (DFT) is obtained performing Fast Fourier Transform (FFT). The refined frequency of the strongest signal obtained from FFT is found using Jacobsen frequency interpolation with bias correction [8] based on 3 DFT peaks. The refined complex amplitude of the signal is obtained as an inner product of a unit signal corresponding to the refined frequency with the TbT data. This signal is subtracted from the TbT data and the whole procedure starting with FFT is repeated [9], typically 300 times in the LHC. As a result the TbT data is approximated by the sum of the 300 strongest harmonics.

The framework presented here implements new methods to also increase the speed of harmonic analysis by its combination with precedent data cleaning.

ADIABATIC 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 the Base-Band Tune (BBQ) system [10] can measure the tune.

We employ the RF-modulation 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 acquired 6600 turns (with LHC's revolution frequency of 11.3 kHz). A sample of TbT reading at a dispersive BPM is shown in Figure 2.

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.

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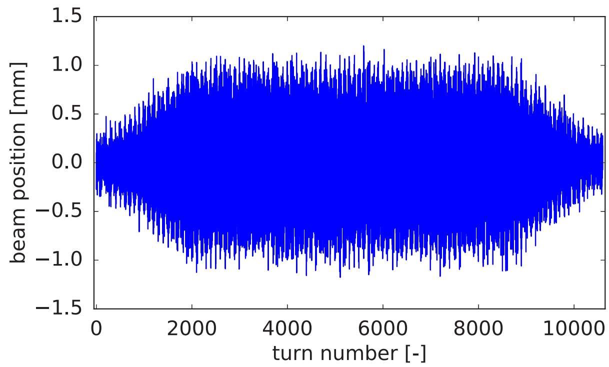

Figure 1: Sample BPM TbT data excited by an AC-dipole performing driven coherent betatron oscillation. Note the ramp-up and ramp-down of the oscillation amplitude, which is important to avoid emittance growth [3] (in hadron machines).

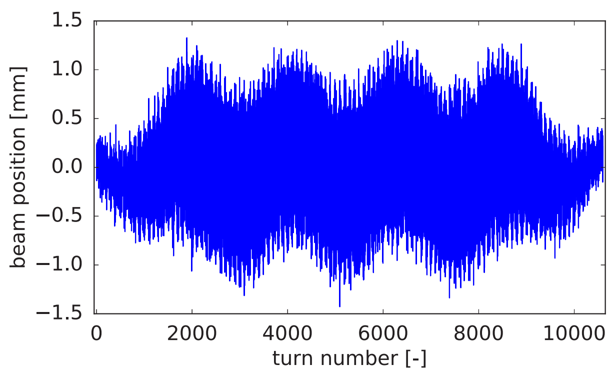

Figure 2: Sample BPM TbT data at a dispersive BPM excited by an AC-dipole when the frequency of the RF system has been simultaneously modulated. The beam performs driven coherent betatron oscillations and the beam energy is adiabatically varied.

HARMONIC ANALYSIS OF DECOMPOSED DATA

As SVD and refined harmonic analysis are both linear operations, they can be combined. The cleaned TbT data can be reconstructed from SVD matrices elements:

$$x_{jn} = \sum_{l=0}^{N_{modes}-1} u_{jl} s_{ll} v_{nl}, \tag{1}$$

where j and n are the BPM index ($j < N_{BPM}$) and the turn number ($n < N$). N_{modes} stands for number of SVD modes used. The complex coefficients X_{ja} corresponding to an arbitrary frequency a/N are given by:

$$X_{ja} = \sum_{n=0}^{N-1} \sum_{l=0}^{N_{modes}-1} u_{jl} s_{ll} v_{nl} e^{i2\pi na/N} = \tag{2}$$

$$= \sum_{l=0}^{N_{modes}-1} u_{jl} \sum_{n=0}^{N-1} s_{ll} v_{nl} e^{i2\pi na/N} = \sum_{l=0}^{N_{modes}-1} u_{jl} X_{la}, \tag{3}$$

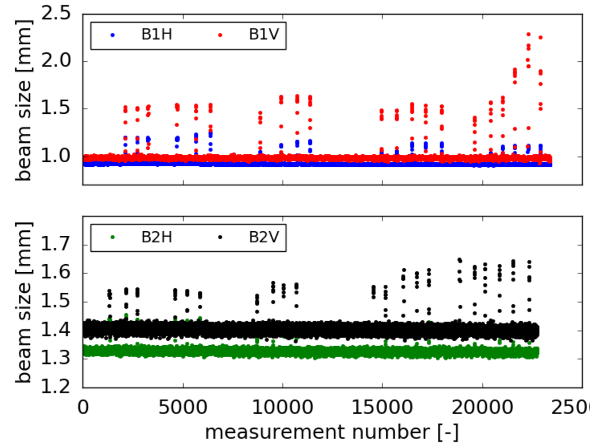

Figure 3: The beam size measurement using BSRT during the 3D excitations, the spikes refer to AC-dipole excitations. No beam size growth is observed after more than 20 3D excitations.

the second summation of Eq. (3) represents the complex coefficient corresponding to frequency a/N in the l^{th} row of $\mathbf{SV^T}$. Putting all this together, we obtain complex coefficients corresponding to frequency a/N in cleaned TbT data from all BPMs as a linear combination of complex coefficients corresponding to the same frequency in the rows of $\mathbf{SV^T}$ with the multiplication factor being the rows of $\mathbf{U}$. Two algorithms were developed, in order to identify the frequencies corresponding to the largest harmonics. The aforementioned harmonic analysis is performed on:

- the sum $\sum_{l=0}^{N_{modes}-1} s_{ll} v_{nl}$ of the rows of reduced $\mathbf{SV^T}$ giving a single set of frequencies, hereafter referred to as "fast" method
- each of the rows of reduced $\mathbf{SV^T}$, giving a union of frequencies, found for every row, hereafter referred to as "svd" method

The complex coefficients, corresponding to resulting frequencies, are calculated for each of the rows of reduced $\mathbf{SV^T}$ matrix by the inner product in the time domain (last sum in Equation (3)). At this point, the vectors in the frequency domain are no longer orthogonal. The perturbation of the orthogonality of the two arbitrary vectors (in the frequency domain) is influenced by two factors:

- the difference (in the time domain) between the vector under study and the vector the harmonic analysis was performed on
- the spectral response of a windowing function, that can be used to filter the signal in the time domain

A rectangular window, which does not change the signal and has the best frequency resolution, is used in the following. On the other hand, in a case of the rectangular window spectral leakage is more pronounced compared to other windowing functions [11], which should be kept in mind.

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The harmonic analysis performed on decomposed TbT BPM data is faster than the "bpm" method by up to a factor of N_{BPM}/N_{modes} using the "svd" method and up to a factor of N_{BPM} in the "fast" method. Computational speed is essential for efficient beam operation, for example, in automatic coupling correction [12], where these methods are used. Harmonic analysis by "fast" method of one set of LHC data set takes about 2 seconds in a single thread compared to about 18 seconds in 32 threads in the "bpm" method.

ACCURACY OF HARMONIC ANALYSIS

The accuracy of the harmonic analysis performed on decomposed TbT data is studied in this section. TbT data of the LHC injection optics was simulated. A realistic noise of about 8 % amplitude compared to coherent betatron motion at focusing quadrupoles was added. Results of the aforementioned analysis corresponding to a given spectral line consist of its frequency $\in (0, 1)$, initial phase in units of 2π and its amplitude. The accuracy is estimated by the root mean square of the difference to the value defined in a simulation in a set of all BPMs. The two methods ("svd" and "fast") are compared to the original harmonic analysis the "bpm" method. The betatron tune is found in the spectra from all three methods.

Both "svd" and "fast" methods have accuracies in frequency and phase comparable or slightly better compared to the "bpm" method. An exception is the "svd" analysis performed on a low number of turns, where it shows less accurate results. The differences in relative amplitude accuracy are negligible. Generally, "svd" and "fast" methods seem to be better suited for a larger number of turns and larger noise levels. For a small number of turns or small noise levels, the situation is the opposite. Additionally, a weaker spectral line with about 14 % amplitude at focusing BPMs and 0.01 away in frequency from the betatron tune was investigated. Here, the methods perform all similar in terms of frequency accuracy. In terms of its phase accuracy, the "bpm" method is better than the other two. The amplitude accuracy shows similar behaviour as the phase accuracy. For more details, see [13].

CHROMATIC PROPERTIES ANALYSIS

The largest advantage of simultaneous 3D excitation is that the chromatic properties, such as normalised dispersion $D_x/\sqrt{\beta}$ [14] or the W-function [15] can be a ratio of certain spectral lines amplitudes. 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 ($Q^F_{x,y,s}$ 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 [14] is proportional to the ratio of spectral line amplitudes corresponding to dispersion and $\sqrt{\beta}$:

$$\left|D/\sqrt{\beta}\right| = C\frac{H(0,0,1)}{H(1,0,0)}, \tag{4}$$

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:

$$C = \frac{\sum_{arcBPMs}\frac{H(0,0,1)}{H(1,0,0)}}{\sum_{arcBPMs}\left|\left(\frac{D}{\sqrt{\beta}}\right)_{model}\right|}, \tag{5}$$

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 [16] using 3D and 2D driven beam excitations. The analysis of linear optics quantities is the same as in the 2D case, i.e. N-BPM method [17, 18] 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 quadrature 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 (except for normalised dispersion) using both types of beam excitation 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, the 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

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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
$\Delta D_x/\sqrt{\beta_x}$	0.006	0.42	0.75

precision loss were observed in any of the quantities (phase advances, β-functions from phase and from amplitude, and already mentioned normalised dispersion). However, slight differences in precision between the horizontal (dispersive) and the vertical planes are visible.

In ESRF [19] 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 is only 4 times less precise, even though the amplitude of residual synchrotron motion is about 30 times smaller than relative beam energy changes of 0.16% applied for the standard measurement.

The RF-modulation seems to disturb neither the precision nor the accuracy of phase advances and β-functions.

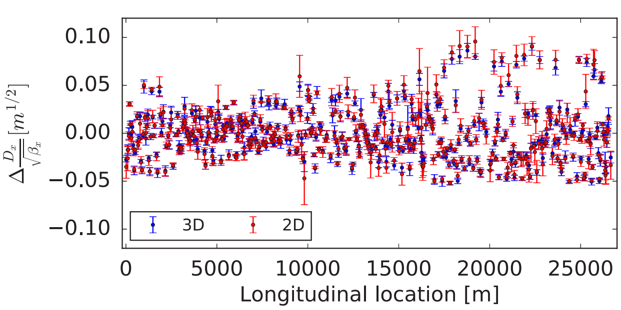

Figure 4: Comparison of LHC normalized dispersion difference to the LHC lattice model measured from TbT data using simultaneous 3D driven excitation (in blue) and 2D driven beam excitation at multiple beam energies (in red).

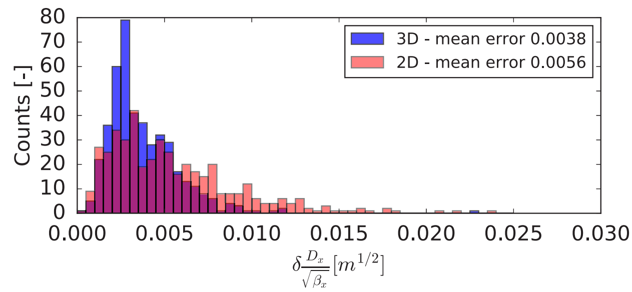

Figure 5: Distributions of the normalised dispersion measurement errors from (Figure 4) for both methods: 3D excitation (in blue) and 2D excitation (in red).

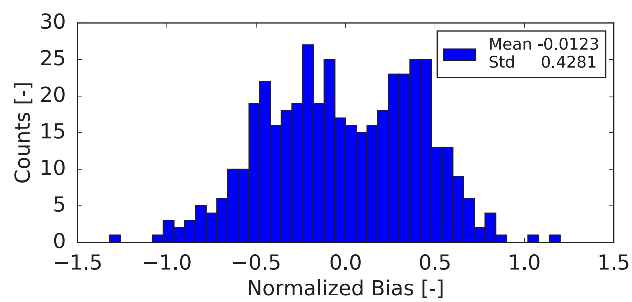

Figure 6: Distribution of differences between the two normalised dispersion measurements from (Figure 4), normalised by their errors combined in quadrature.

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 and corrections. In cases where beam excitation is not a limiting factor, e.g. when a single beam excitation is used the analysis may become a bottleneck, in terms of speed. Tests with a transverse damper as an exciter are foreseen, since its repetition is not limited.

New techniques performing harmonic analysis directly on decomposed data instead of the recomposed data have been developed. When used in LHC, they are up to 300 times faster and are better suited for noisy data, compared to the standard method. The choice of a windowing function and the orthogonality perturbation is being studied to further improve the accuracy. Synchro-betatron lines observed in the beam frequency spectra after 3D excitation are also being studied with the aim to measure W-function or potentially chromatic coupling.

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