ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-WED04

PRECISE ANALYSIS OF BEAM OPTICS AT THE VEPP-4M BY TURN-BY-TURN BETATRON PHASE ADVANCE MEASUREMENT

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Abstract

Turn-by-turn (TbT) beam centroid signals can be used to evaluate various relevant accelerator parameters including betatron frequencies and optical functions. Accurate estimation of parameters and corresponding variances are important to drive accelerator lattice correction. Signals acquired from beam position monitors (BPMs) are limited by beam decoherence and BPM resolution. Therefore, it is important to obtain accurate estimations from available data. Several methods based on harmonic analysis of TbT data are compared and applied to the VEPP-4M experimental signals. The accuracy of betatron frequency, amplitude, and phase measurements are investigated. Optical functions obtained from amplitudes and phases are compared.

INTRODUCTION

The VEPP-4M is an electron-positron collider operating in 1 GeV to 6 GeV beam energy range [1]. The VEPP-4M storage ring is equipped with 54 dual-plane BPMs [2] capable of performing accurate TbT measurements. TbT data is acquired by excitation of the circulating beam with impulse kickers. In Fig. 1 the optical functions of the VEPP-4M ring are shown along with corresponding BPM positions.

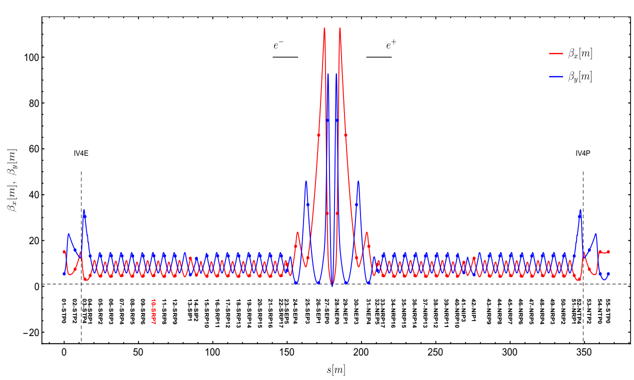

Figure 1: The VEPP-4M lattice functions.

Harmonic analysis [3] can be used to obtain frequency and optics from TbT data. Previously, optics measurements were based only on the computation of β functions from amplitudes. In this paper, the extension of the optics measurement procedure is described. It includes the addition of TbT data processing, anomaly detection and BPM noise estimation. The frequency measurement algorithm has been tuned. Statistical error propagation has been added to the computation of BPM signal parameters. Optics measurement from phase has been performed for the first time at the VEPP-4M. This provides an additional tool to check optics measurement from amplitude and to study BPM calibrations. Both methods with statistical error propagation will allow more accurate lattice correction. Experimental results of optics measurement are reported.

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VEPP-4M TBT PROCESSING LOOP

In Fig. 2 TbT analysis workflow at the VEPP-4M is shown. First, detection of anomalies in TbT signals is performed [4], and anomalies are flagged. After anomaly detection, TbT filtering is performed. Noise estimation using optimal SVD truncation [5] is performed for each BPM signal. The frequency for each BPM is computed from its interpolated spectrum maximum. For known frequencies, amplitudes and phases are computed for each BPM with statistical error propagation. Amplitudes and phases are then used to compute linear optics.

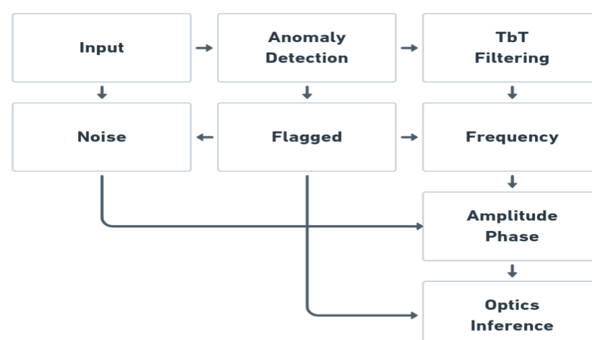

Figure 2: The VEPP-4M TbT processing loop.

We have tested several different techniques for TbT data noise cleaning. One of the common options is to used truncated SVD applied to the full TbT matrix. For the VEPP-4M case, the optimal rank of truncated representation was found to be eight. Another option is to apply Robust PCA [6] to the full TbT matrix. This method was found to introduce a bias for estimated amplitudes and phases, but no bias was observed in frequencies. Both SVD and Robust PCA can be applied to individual BPM signals. In this case each signal $x = [x_1\ x_2\ x_3\ x_4\ x_5\ x_6]$ is represented using Hankel matrix:

$$X = \begin{bmatrix} x_1 & x_2 & x_3 \\ x_2 & x_3 & x_4 \\ x_3 & x_4 & x_5 \\ x_4 & x_5 & x_6 \end{bmatrix}$$

Truncated SVD or Robust PCA can be applied to this signal representation. The filtered signal is then reconstructed as the mean of skew diagonals.

27th Russian Particle Acc. Conf. RuPAC2021, Alushta, Russia JACoW Publishing
ISBN: 978-3-95450-240-0 ISSN: 2673-5539 doi:10.18429/JACoW-RuPAC2021-WED04

BPM NOISE ESTIMATION

BPM noise study was performed for experimental TbT data obtained with impulse kick excitation. Each BPM signal noise was estimated using Hankel matrix representation and optimal SVD truncation. In Fig. 3 the dependence on the beam current of the estimated noise is shown. Top plots show results for 100 successive kicks for two particular BPMs. After each 20 kicks TbT data without excitation were acquired (SOFT). Hollow points correspond to the noise estimation as the standard deviation for these cases. The bottom plots show noise estimation for 10 successive kick measurements for all BPMs. On average, noise is at the level of 40 µm for the horizontal plane and 35 µm for the vertical one. Noise estimations are used for statistical error propagation in amplitude, phase and optics computation.

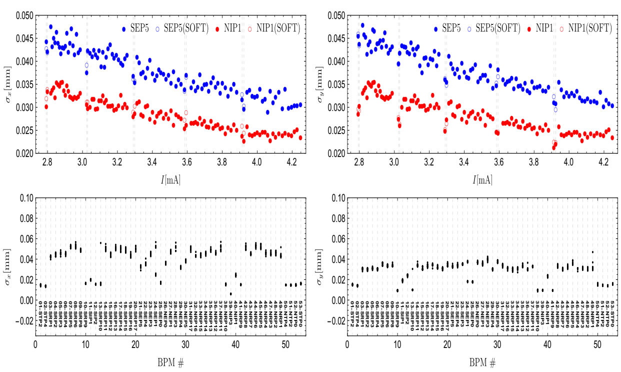

Figure 3: BPM noise estimation. Estimated noise vs the beam current for selected BPMs (top plots). Estimated noise for all BPMs @ 2 mA (bottom plots).

FREQUENCY MEASUREMENT

Previously, frequency measurement was configured to provide accuracy of 10^{-4}. This is related to magnetic system stability and is sufficient for optics measurements. For nonlinear beam dynamics studies, a more accurate measurement was desired. Several methods based on the interpolated spectrum were tested including the effect of windowing.

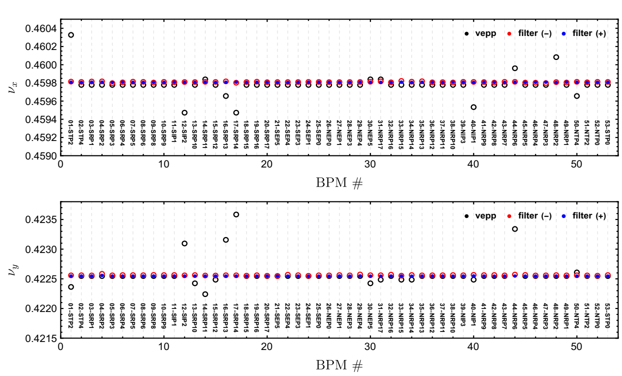

Figure 4: An example of frequency measurement with (blue) and without (red) signal filtering in comparison with the previous system (black).

In Fig. 4 an example of frequency measurement is shown. The spread of frequencies across BPMs is $5 \cdot 10^{-6}$ without filtering and close to 10^{-6} with filtering. Cosine window was used in both cases.

AMPLITUDE AND PHASE MEASUREMENT

For known frequencies, corresponding amplitudes and phases can be computed using convolution. The results of phase measurements are shown in Fig. 5 and Fig. 6. The accuracy of phase measument is better than 5 % and average deviation from the model is 15 %. For amplitude, the accuracy is 2 % and 3 % for horizontal and vertical planes.

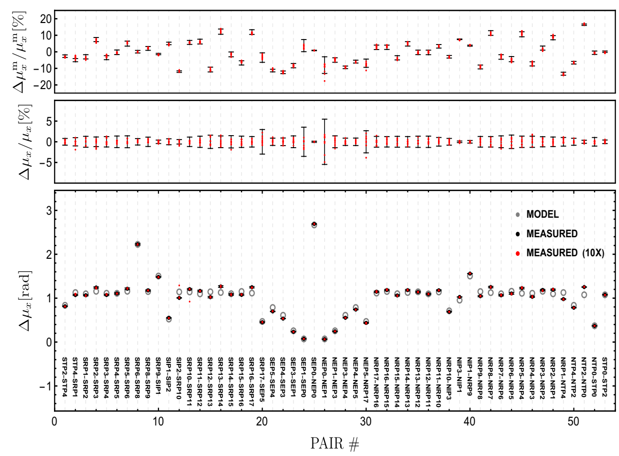

Figure 5: Measured phase advance between successive BPM pairs for the horizontal plane. Deviation from model (top) for a single measurement with statistical errors (black) and 10 successive measurements (red). Spread of phase advance (middle) for 10 measurements (red) and a single measument with statistical errors. Absolute phase advance (bottom) for model (gray), 10 measurements (red) and a single measument (black).

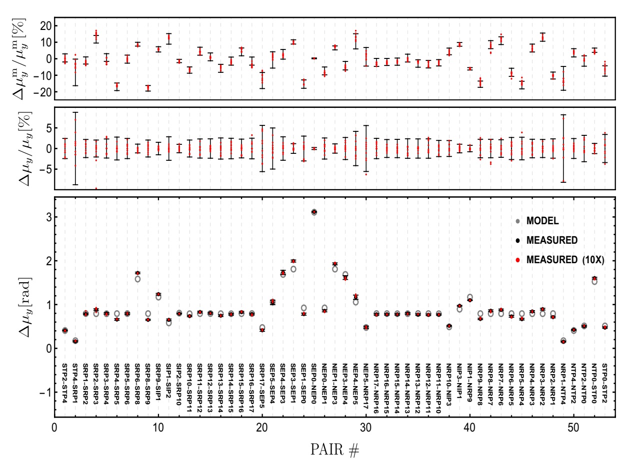

Figure 6: Measured phase advance between successive BPM pairs for the vertical plane.

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OPTICS MEASUREMENT

In Fig. 7 the results of optics measurement from amplitude are shown. The average deviation from the model is around 15 %, and the spread between measurements is 5 %. For measurements from phase (Fig. 8), the average deviation from the model is also around 15 %. Spread in this case is close to 10 %. Here, the best adjacent triplets were used for optics computation. We have also tested using a combination of several different triplets. In this case, the spread from 10 measurements was around 5 %.

Comparison of two methods is shown in Fig. 9. Both methods are around 15 % off from the model. The ratio of β functions is within 15 %.

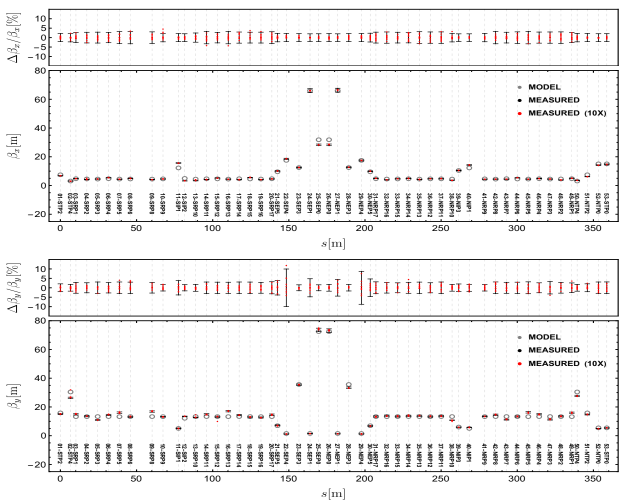

Figure 7: Optics measurement from amplitude. Top plots shows spread from 10 measurements (red) with a single measurement with errors (black). Comparison with model optics (bottom plots).

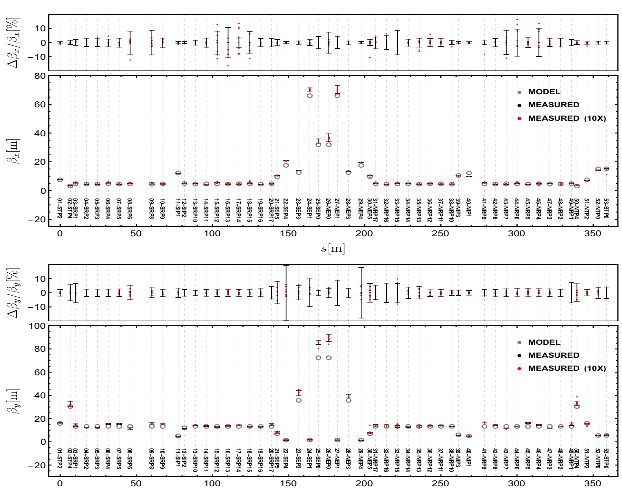

Figure 8: Optics measurement from phase. Top plots shows spread from 10 measurements (red) with a single measurement with errors (black). Comparison with model optics (bottom plots).

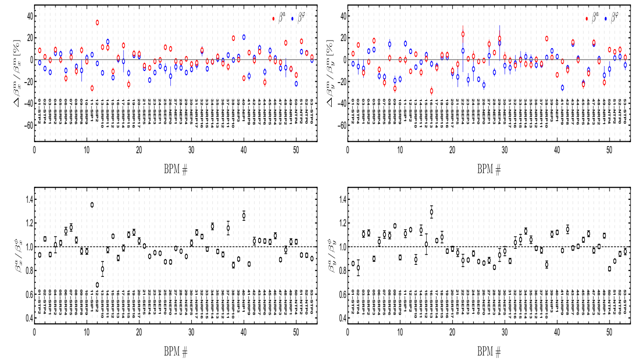

Figure 9: Comparison of optics from amplitude and phase. Deviation from model for optics from amplitude (red) and phase (blue). Ratio of β functions (bottom plots).

CONCLUSION

The improved TbT analysis workflow was verified at the VEPP-4M. An anomaly detection system and TbT data filtering were introduced. BPM noise studies were performed using noise estimation based on optimal SVD truncation. The estimated noise agrees with the results from measurements without excitation. An improved frequency estimation procedure was implemented. The frequency spread close to 10^{-6} was archived across BPMs in a single measurement. This allows a more accurate study of nonlinear dynamics at the VEPP-4M. The spread of amplitudes and phases from successive measurements is less than 5 % and around 5 %. Single measurement statistical errors match the observed spread. Two methods of optics computations were performed and compared. Both methods are around 15 % off from the model. The difference between methods is also close to 15 % on average. Phase advance measurements are planned to be added to the optics correction. A detailed BPM calibration study is scheduled for the new season.

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