ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK041

MAGNETIC FIELD NOISE SEARCH USING TURN-BY-TURN DATA AT CESR*

V. A. Khachatryan†, J. J. Barley, M. H. Berry, A. T. Chapelain, D. L. Rubin, J. P. Shanks, S. T. Wang
CLASSE, Cornell University, Ithaca, New York, USA

Abstract

A method for locating for magnetic field noise has been developed using the CESR beam turn-by-turn beam position data. The technique was validated using Monte-Carlo samples and turn-by-turn real data with induced noise in one of the CESR dipole magnets. We estimate the analysis sensitivity for the noise sources slower than 4 kHz (or 100 CESR turns) with the current CESR BPM system on the level of 1 μrad or 0.2 Gs×m field integral. In this work we report the observed noise sources and the improvements achieved by applying this technique. Long-term, several hours, beam stability analysis is also performed using the same method.

INTRODUCTION

Cornell Electron Storage Ring (CESR) [1], was constructed as an electron-positron collider operating at a center-of-mass energy in the range of 3.5-8 GeV. CESR is now used as an x-ray source for a state-of-the-art x-ray facility, known as the Cornell High Energy Synchrotron Source (CHESS, or CHESS-U after the recent upgrade).

CHESS-U beams are considered fully “stable” in the vertical plane if the vertical position of the centroid at the light observation points drift less than 3 μm over all time scales, and the beam trajectory simultaneously varied by less than 1 μrad. The equivalent numbers in the horizontal direction would be 60 μm and 5 μrad. These stability requirements come from the 10% stability requirement standard used at many light sources.

Our aim is to develop methods to improve the CESR beam stability. In this paper we will discuss one of the techniques based on turn-by-turn beam data analysis, its sensitivity, and the stability improvements achieved by applying the technique.

ANALYSIS METHOD, SIMULATIONS AND VALIDATION

The positron beam stability depends on the stability of the magnetic fields and positions of the ring magnets. The beam is also sensitive to the environment where the beam components are installed.

For the beam coordinate measurements CESR Beam Position Monitors (BPM) [2] are used. Along the CESR ring there are 110 BPMs, their four-electrode design allows measurements of both the horizontal and vertical coordinates with 10 μm single-turn precision. The BPM system data acquisition (DAQ) allows accumulation of data for up to 300k turns from each BPM.

In this work the noise frequency is divided into three ranges:

- high – periodicity corresponds to several turns (tens of kHz);
- medium – from several tens of turns to thousands of turns (~ 10 kHz to a few Hz);
- low – from minutes to days.

This division important since the method being discussed can only be applied to the medium and low frequency ranges. For the medium frequency noise search the input is CESR BPM turn-by-turn data files, while for the low frequency noise, the data is averaged over 1024 turns.

The inductance of the magnets, as well as the vacuum chambers will prevent the high frequency noises from penetration into the beam pipe. Previous studies showed that frequencies above 360 Hz are suppressed significantly by the CESR aluminum vacuum chamber which cover most of the CESR ring. Noise suppression by the stainless steel vacuum chamber is not observed for the frequencies up to 720 Hz. However, only a few short (no more than 5-10 m) CESR sections are covered by stainless steel chambers. Therefore, the medium and low frequency magnetic noise searches are prioritized. For such frequency ranges, the orbit distortion due to localized kicks can be described by the following formula [3]

$$f(s) = \sum_{i=1}^{N} \theta_i \frac{\sqrt{\beta(s)\beta(s_i)}}{2sin(\pi Q)} cos(|\phi(s) - \phi(s_i)| - \pi Q), \quad (1)$$

where $f(s)$ is the closed orbit function for N kicks, i is the index of kicks, θ_i is the beam deflection angle by the i-th kick, $\beta(s)$ and $\beta(s_i)$ are the ring lattice beta functions at location s and at the kick location s_i, the CESR betatron tunes are 16.556 and 12.636 for horizontal and vertical planes respectively, $\phi(s)$ and $\phi(s_i)$ are the lattice betatron phase advances at locations s and at the location of the kicker s_i.

The analysis code is written using the ROOT package [4], and it uses Minuit-Migrad [5] minimization method to fit the data with (1) formula. The fit parameters are the kick s-coordinates and angles θ. We allow the code to increase the number of kicks as far as the fit χ^2 improvement is more than the specified threshold (default is 15). And it stops adding more kicks when the total number of the kicks reaches the maximum number (default is 8), or if there is no χ^2 improvement more than the threshold. A fit example is shown on Fig 1.

In the analysis each consecutive group of 50 turns is averaged and a fit is performed for them (50 turns is just an

* Work supported by NSF PHYS-1416318 and DMR-1829070
† vk348@cornell.edu

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK041

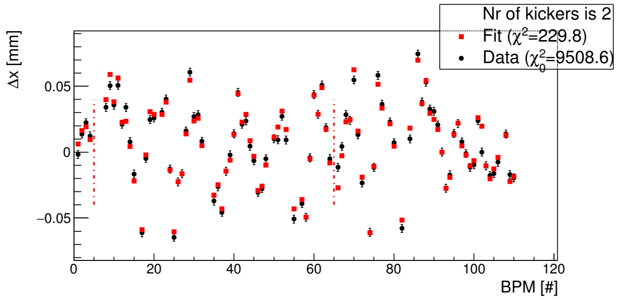

Figure 1: A fit example: During this data taking 300 Hz sinusoidal horizontal magnetic field is induced at s=510.2 m (at BPM 65). The black markers are the difference between reference and i-th orbit, where the reference orbit is the average over 65k turns and the i-th orbit is the average over 50 turns starting turn 22800. The red markers represent fit results using formula (1). In this example the analyzer found two kicks, one is at s_1=511.1 m (at BPM 65), θ_1=3.5 μrad, and s_2=53.6 m, θ_2=-0.57 μrad.

example, details see below). Figure 2 (top) shows the distribution of all the kick angles that the analyzer found in a data set with 65000 turns, the kick angle dependence on the turn number can be seen on the Fig. 2 bottom plot.

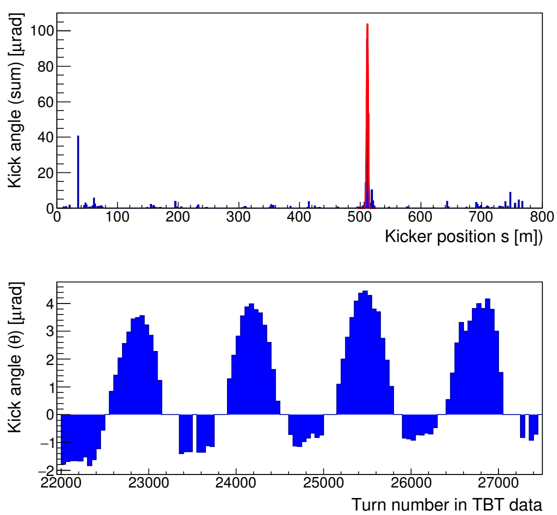

Figure 2: Fit summary distribution (top) is the sum of absolute values of the kick angles. Horizontal axis show the s-coordinate, where kicks were found. vs kick s-coordinate. The red curve on the graph is a Gaussian fit with peak at 511.6 m, and σ=1.27 m. The bottom graph shows the kick angle vs turn number. The induced noise frequency is 300 Hz (1300 turns). The power supply is unipolar, therefore the angle distribution is not completely sinusoidal.

To study the sensitivity of the method, Monte-Carlo (MC) samples with different amplitudes of sinusoidal kick angles were produced using BMAD [6] simulation package.

The i-th orbit is calculated using the average coordinates of N number of turns. The resulting method sensitivity for the current CESR BPM system, which depends on the number of turns being averaged, is summarized in Table1. The more turns are averaged for the orbit calculation the better are the results, however, using more turns weakens the sensitivity for higher frequency noises. The sensitivity also depends on the beta function at the noise location. In the MC simulations the noise is located half way around the ring (s=384 m, β=11 m), which was one of the anticipated noise sources after the preliminary data analyses of the horizontal orbit.

Table 1: The table shows the minimum detectable kick angle depending the number of turns averaged for each orbit extraction. The kick is considered detected if its s-coordinate, Gaussian fit mean value, is found better than 5 m.

Number of averaged turns	**Sensitivity for 10 μm single shot BPM resolution [rad]**
1	5E-5
10	1E-5
25	5E-6
100	2E-6

DATA ANALYSIS

Horizontal orbit analysis, medium frequency range: In the following data analyses 100-turn averaging is used for the orbit calculations. The horizontal orbit analysis summary distribution Fig.3 (top) has a sharp peak at $s \approx 385.6$ m, the width of the peak is about 1.7 m. Figure 3 (bottom) shows the kick angle dependence on the turn number. The average distance between two positive peaks is 2170 turns, which corresponds to 180 Hz (CESR revolution frequency is 390.14 kHz). This observation later was confirmed during magnetic field direct measurements using hall probes, and the source of the 180 Hz field was determined to be a power supply located nearby the CESR beam pipe, which was upgraded later to reduce its magnetic noise. After the power supply upgrade the horizontal orbit modulation average (over all the BPMs) RMS goes down from 6.9 μm to 5.0 μm. Worth mentioning that in this location the CESR beam pipe is stainless steel and not aluminum.

Vertical orbit analysis, medium frequency range: A similar analysis is performed for the vertical plane. The analysis results helped to identify and mitigate several 60 Hz noise sources:

- a power supply output 60 Hz noise at s ~ 0 m;
- magnet cooling fans at the electron transfer line (s ~ 510 m), which were very close to the beam pipe.
- also the synchrotron, which is in a few feet distance from CESR beam pipe induce some 60 Hz noise. The synchrotron 60 Hz is stronger at the locations, where the CESR pipe is not covered by any magnet, there are several such straight sections on the CESR ring.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK041

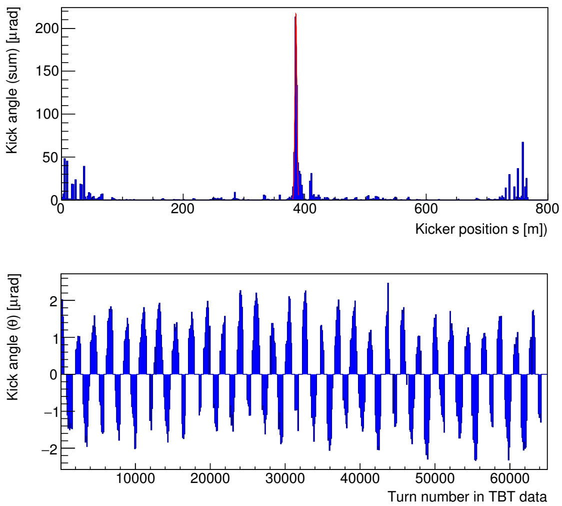

Figure 3: The horizontal kick angle summary distribution (top) is the sum of absolute values of the kick angles vs kick s-coordinate. The red curve on the top graph is a Gaussian fit with peak at 385.6 m, and σ=1.7 m. The bottom graph shows the kick angle vs turn number. the distance between peaks is 2170 turns which correspond to 180 Hz.

Eliminating all the above mentioned 60 Hz noise sources the vertical orbit modulation average (over all the BPMs) RMS goes down from 7 μm to 3.5 μm.

Slow noise search: During nominal CHESS operation, 1-minute interval 1024-turn averaged data files are recorded instead of turn-by-turn data. The same technique was used to analyze these orbits, and the results pointed to two locations where the beam gets vertical kicks. The kick angles change for about 12 hours, and later stabilize as long as the CESR magnets are turned on. Further investigations showed that this is a warming effect which moves two quadrupoles vertically. These quadrupoles are installed on relatively long stands which are impacted by thermal expansion (3° − 5°C temperature rise), the quadrupole position change is estimated about 150 μm. The kick angle summary distribution is shown on Fig.4 (top). Middle and bottom distributions correspond to the kick angle change as a function of orbit number at s~260 m and s~500 m respectively.

CONCLUSION

A method has been developed for magnetic field noise search using CESR turn-by-turn data. The sensitivity of the method was studied using simulated samples, and we found that 1 μrad kicks should be detectable.

Data analyses have been performed, and several locations with magnetic field noise were identified in the horizontal and vertical planes with the frequencies 180 Hz and 60 Hz respectively. After the noise sources were removed the beam looks significantly stable. Eliminating the observed noise sources the vertical orbit modulation average RMS goes down from 7 μm to 3.5 μm, and the horizontal RMS from 6.9 μm to 5.0 μm.

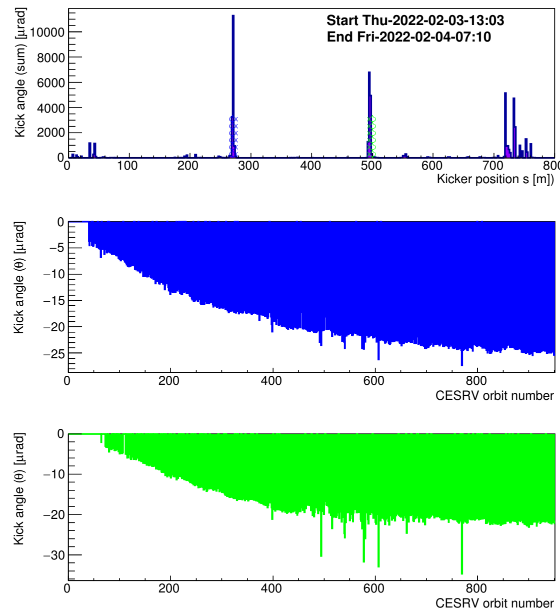

Figure 4: The kick angle summary distribution (top) points two locations where the beam gets the strongest kicks. The middle and bottom distributions correspond to kick angle dependence on the orbit number at s~270 m and s~500 m respectively.

The same method has been applied on 1024-turn averaged orbit data files recorded with 1 minute intervals, and identified two locations on the CESR ring, where the beam gets vertical kicks.

ACKNOWLEDGEMENTS

The authors thank Michael Forster for the help with experimental setup, Bogdan Wojtsekhowski and David Sagan for the discussions and recommendations on the analysis code development.

We also thank the U.S. National Science Foundation under Award No. PHYS-1416318 and DMR-1829070 for supporting the work.

REFERENCES

[1] https://www.classe.cornell.edu/Research/CESR/WebHome.html

[2] M.G. Billing, *et al.*, "Beam position monitoring system at CESR", *J. Instrum.*, vol. 12, p. T09005, 2017.

[3] W. Bergan, *et al.*, "Limit on the anisotropy of the one-way maximum attainable speed of the electron", *Physical Review D*, vol. 101, p. 032004, 2020. doi:10.1103/PhysRevD.101.032004

[4] ROOT Data Analysis Framework, https://root.cern.ch

[5] J. Fred and W. Matthias, "MINUIT User's Guide", CERN, Geneva, 2004.

[6] D. Sagan, "Bmad: A relativistic charged particle simulation library" Nucl. Instrum. Methods Phys. Res. A 558, p. 356 (2006).