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MEASUREMENT OF TRANSVERSE IMPEDANCE OF SPECIFIC COMPONENTS IN CESR USING BPM MEASUREMENTS OF PINGED BUNCHES *

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Abstract

A beam-based technique is applied to determine the quadrupole impedance of large-impedance components of the CESR storage ring. Two bunches separated by 1/3 of the ring circumference are charged to 1.44×10^{10} and 0.48×10^{10} N/bunch (0.9 and 0.3 mA). Both bunches are given a single kick of the same amplitude. Turn-by-turn, bunch-by-bunch position information is recorded for 16 k turns. BPM-by-BPM phase is calculated using the All-phase FFT method of spectral analysis. The difference in the BPM-to-BPM phase advance between the two bunches is a measurement of the local transverse impedance. The impedances of a small-aperture in-vacuum undulator, collimators, scrapers, RF cavities, electrostatic separators, and bulk impedance of the remaining ring are determined in this manner.

INTRODUCTION

We utilize the bunch-by-bunch capability of the Cornell Electron Storage Ring (CESR) BPM system to measure the BPM-to-BPM phase advance of two bunches at different currents [1]. The difference in the phase advance is a measure of the local impedance.

This technique presented here is similar to that published in [2]. The main difference being that a bunch-by-bunch BPM system is utilized to measure the two different bunch currents simultaneously.

This work is motivated by the CHESS-U upgrade to CESR, which will reduce the ring emittance from 100 nm to 30 nm and install an additional 3 canted undulator pairs (bringing the total to 4 pairs while retaining an existing 24-pole device) [3]. Understanding the impedance of the undulators is important for establishing the current limit of the upgraded CESR.

The results of this experiment are compared to before-and-after measurements of the current dependent tune shift taken when the first undulator was installed.

Because of limited machine studies time, experiments have focused on the vertical impedance. Only vertical results are shown here.

EXPERIMENT & PHASE MEASUREMENT TECHNIQUE

For this experiment, CESR is configured for single-beam operation. Two bunches, separated by 1/3 of the ring circumference, are filled to 0.9 mA and 0.3 mA. Beam lifetime is several hours and the current does not decay appreciably during the experiment. A pinger with a pulse shorter than that of one machine revolution applies the same kick to each bunch once per second [4]. After each ping the bunches oscillate freely and damp by synchrotron radiation. The radiation damping time of CESR at 5.3 GeV is 23.3 ms. Feedback attenuator is attenuated. The BPM trigger is synchronized to the pinger. Following a ping, 16384 turns of data is recorded by the BPM system and written to disk for post-processing. Data from 75 pings is recorded in each set of conditions.

Relevant conditions include the state of large impedance components: the position of scrapers and insertion state of a small aperture collimator. Additionally, the beam trajectory through a narrow gap undulator is varied.

The following considerations improve the signal-to-noise ratio and thus the precision of the phase measurement (described in following section):

1. To avoid chromatic damping and maximize the number of turns following the ping during which the particles oscillate coherently, chromaticity is set to zero in both planes.
2. The bunch currents are chosen such that the BPM system can operate in high-precision gain mode.
3. The synchrotron ramp cycle is turned off, as it generates cross-talk that can be observed in the stored beam.
4. The feedback amplifier input is attenuated.
5. The ping repetition rate is set to 1 Hz, so that the oscillations from the previous ping damp completely before the next ping is applied.
6. Vertically pinged data is taken separately from horizontally pinged data.

The following are among the systematics that have been checked for and found to be negligible or mitigated by experiment setup:

1. Current dependence of damping time of oscillations.
2. Ordering of the two bunches and their gap, to check for long-range wakes.
3. Dependence of measurement on the ping amplitude.

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Phase Measurement

The phase of the betatron oscillation at each BPM is calculated by applying the All-Phase FFT (ApFFT) algorithm to the turn-by-turn, bunch-by-bunch, BPM-by-BPM coordinates of a pinged beam.

ApFFT is a straightforward algorithm for extracting phase information from signal data [5]. It is better at inhibiting spectral leakage than traditional FFT. It is also 'phase invariant,' in that no corrections are made to the phase after taking the argument of the spectral peak.

Begin with a vector $\mathbf{x}$ containing $2N-1$ data points,

$$\mathbf{x} = \{x_{-N+1}, ..., x_0, ..., x_{N-1}\}, \tag{1}$$

and apply a window (commonly a convolution of two Hann or rectangular windows). Call the windowed data $\mathbf{y}$.

Next, form the length N "All-Phase" vector $\mathbf{v}_{ap}$,

$$\mathbf{v}_{ap} = \{y_0, y_{-N+1} + y_1, y_{-N+2} + y_2, ..., y_{-1} + y_{N-1}\}. \tag{2}$$

Finally, take an ordinary FFT $\mathcal{V} = \mathcal{F}(\mathbf{v}_{ap})$. Locate the peak i in abs$\mathcal{V}$ and calculate the phase as $\phi_{ap} = \arg \mathcal{V}_i$. ϕ_{ap} is the phase of the peak relative to data point x_0

With a Hanning window and no noise, ϕ_{ap} converges to the real signal phase of a strong isolated peak as $1/N^4$. This is a dramatic improvement over the $1/N$ convergence of an ordinary FFT analysis on noiseless data. In the presence of a noise background that is 1% of the signal peak, the ApFFT convergence diminishes to $1/N$.

At each BPM for each ping, the phase of the betatron oscillation is computed for each bunch using ApFFT. Then at each BPM take the difference in the phase of the betatron oscillation between the two bunches. Finally, the mean and standard error of the mean are taken over these individual differences. The mean phase differece at each BPM divided by the current difference is the signal to which the simulation is fit.

SIMULATION

A quadrupole error ΔK_{1i} at location i generates phase beating throughout the storage ring. The effect of the impedance source on the betatron phase is simulated using `Bmad`. In the lattice file, current-dependent quadrupole moments (K_1/mA) are superimposed at the locations of known impedance sources [6]. The short scraper and collimator are each represented by single thin K_1 moments. The longer elements (RF cavities, undulators, and electrostatic separators) are represented by a several K_1 moments distributed along the length of the element. The four RF cavities are treated as if they have the same K_1. Similarly for the four electrostatic separators.

The remaining impedance, consisting of resistive wall and the combined effect of many small-impedance vacuum components, is simulated by distributing 100 current-dependent quadrupole moments evenly throughout the ring. Each of these 100 moments has the same K_1/mA

The resulting simulation contains 7 variables: the K_1/mA of the scraper, collimator, narrow-gap undulator, separator, RF cavities, bulk global impedance, and an offset. The simulation is also given the bunch currents. For each BPM, the simulation outputs the difference in the betatron phase of the two bunches.

FIT

The fit is the solution to the weighted least squares problem

$$\min f = \sum_i \left(\frac{\Delta\phi_{data,i} - \Delta\phi_{sim,i}\,(\mathbf{K_1}/\mathrm{mA})}{\sigma^2_{\phi,data,i}} \right)^2, \tag{3}$$

where $\Delta\phi_{data,i}$ is the measured difference in the phase advance of the two bunches at BPM i, σ_i is the standard error of the mean for $\Delta\phi_{data,i}$, $\Delta\phi_{sim,i}$ is the simulated phase advance at BPM i that depends on $\mathbf{K_1}$/mA, the vector of current-dependent quadrupole moments.

The fit usually unproblematic; a local optimizer, such as Levenburg-Marquardt, and global optimizers such as differential evolution or simulated annealing consistently converge to the same result.

The uncertainty in the fitted model parameters $\mathbf{K_1}$ is obtained from the inverse of a numerically determined Hessian of f with respect to $\mathbf{K_1}$.

Results

In the experiment reported here, we average over 75 individual measurements (pings), each with 10k turns of data. This yields a standard error of the mean, averaged over all bpms, of 173 μrad.

The results of fitting $\mathbf{K_1}$/mA to the data are shown in Fig. 1, along with the simulated phase beating induced by each impedance source.

Results for 5 different machine configurations are shown in Fig. 2. With the trajectory through the undulator centered, symmetric scrapers were inserted and retracted, and a collimator was inserted and retracted. With the scrapers and collimator retracted, the vertical offset through the undulator was adjusted to near the top and bottom of the undulator. The K_1/mA are expressed in Hz/mA by normalizing by the vertical β-function at the impedance source.

When the narrow gap undulator was installed Feb. 2014, before and after measurements of CESR's global vertical tune shift were measured to be −93 Hz/mA where $\beta_{y,und}$ = 9.38 m. $\beta_{y,und}$ was reduced to 3.4 m after installation [7]. Scaling this result for the new β_y yields −33.7 Hz/mA. A similar global tune shift measurement using the collimator yielded −34.4 Hz/mA. These measurements are included on Fig. 2.

CONCLUSIONS

We have demonstrated a technique for measuring transverse local impedance by simultaneously measuring the phase of betatron oscillations of two bunches at different currents. The results here compare well with global tune

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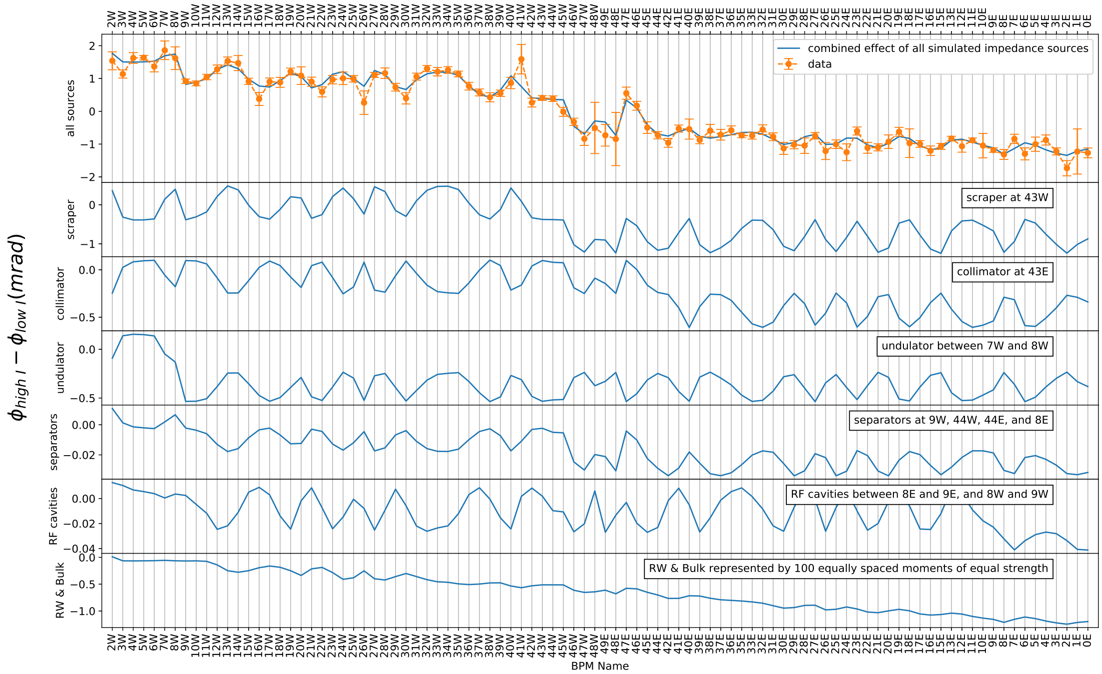

Figure 1: Phase of vertical betatron signal at each BPM of high current bunch, minus that of low current bunch. Top plot is data with uncertainty and fitted simulation. Reduced-χ^2 of the fit is 1.14. Bottom 6 plots break out the individual contributions to the phase beating from each simulated impedance source at its fitted strength.

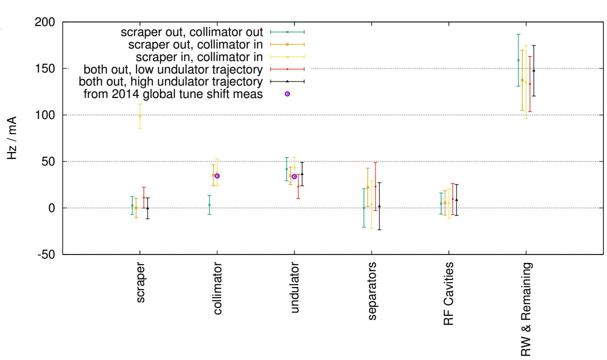

Figure 2: Impedance for 5 sets of conditions. Notice that the fitter correctly attributes zero impedance to the scraper and collimator when they were in a retracted state.

shift measurements taken before and after undulator installation, and similarly for the collimator when it was in position and retracted.

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