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AN IMPROVED BEAM-BASED METHOD TO CALIBRATE THE RELATIVE GAINS OF THE BEAM POSITION MONITOR PICK-UP ELECTRODES AT THE CORNELL ELECTRON STORAGE RING*

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Abstract

An improved beam-based method to measure the relative gains of the beam position monitor pick-up electrodes at the Cornell Electron Storage Ring (CESR) has been developed and validated using Monte Carlo simulation. We report on that work as well as on the successful deployment of the method at CESR.

INTRODUCTION

The Cornell Electron Storage Ring (CESR) beam position monitor (BPM) consists of four button-shaped pick-up electrodes, each individually instrumented with readout electronics [1, 2]. The electronics does a peak-sampling measurement that allow acquisition of turn-by-turn data. The beam position is reconstructed using the measured signal amplitude from the four electrodes. CESR currently has two BPM configurations. The first one corresponds to about 75% of the ring and has a larger aperture vacuum chamber (90 mm wide by 45 mm tall). The second configuration has a smaller aperture (52 mm wide by 22 mm tall) that was introduced as part of the Cornell High Energy Synchrotron Source upgrade [1, 3].

Systematic effects such as physical differences between the electrodes (displacement, tilt) and differences between the readout electronics bias the measured amplitudes, thus the accuracy on the measured beam position. Monte Carlo simulation shows that without gain calibration, the expected absolute position accuracy on the horizontal and vertical beam positions are 150 µm and 300 µm for the smaller and larger apertures, respectively. In other words: without calibrating for the gains, the measured beam position would be off by hundreds of microns at the 1 standard deviation level. Figure 1 shows the results from the Monte Carlo simulation for the smaller CESR aperture.

An improved beam-based method to measure the relative gains has been developed and validated using Monte Carlo simulation, and has been successfully deployed at CESR.

METHOD OVERVIEW

The new gain calibration method relies on solving a system of equations for different beam positions and simultaneously for the relative gains, knowing the response map of the pick-up electrodes as a function of the beam position [4]. The nonlinear response map relates the electrodes signal amplitude to the beam positions. Figure 2 shows that the

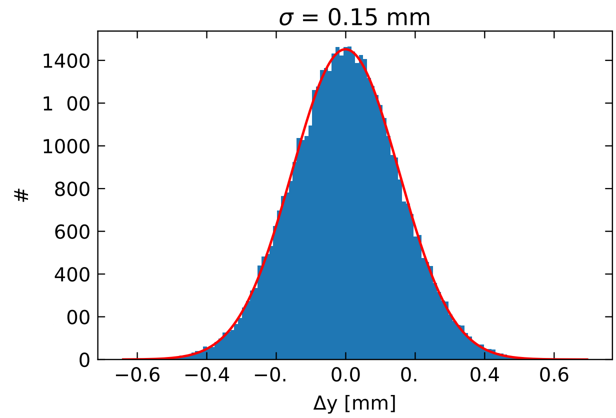

Figure 1: Expected accuracy on the measured vertical beam position without gain calibration in pseudo-data, for x and y both limited to within ±5 mm in CESR smaller aperture. Pseudo-data was generated using a BPM Monte Carlo simulation for normally distributed gain values with a width of 3% in order to mimic CESR gain measurements.

deviation between the linear and nonlinear beam position reconstruction can easily reach hundreds of microns, thus demonstrating the importance of including the nonlinearities. Including the nonlinear response map in the new gain calibration method is an important improvement over the previous method that is limited to second order [5]. The two methods are independent in their approach and effort is going into improving [5] to account for higher orders.

The nonlinear beam position reconstruction from a set of 4 pick-up electrode amplitudes is done minimizing the following system of equations for the horizontal x and vertical y beam positions:

$$\begin{aligned} A_1 - f_{A_1}(x,y) &= \epsilon_1 \to 0, \\ A_2 - f_{A_2}(x,y) &= \epsilon_2 \to 0, \\ A_3 - f_{A_3}(x,y) &= \epsilon_3 \to 0, \\ A_4 - f_{A_4}(x,y) &= \epsilon_4 \to 0, \end{aligned} \tag{1}$$

where A_i are the observed (measured or simulated) electrode amplitudes and $f_{A_i}(x,y)$ are the expected ones from the electrode response map. The minimization finds the x and y positions corresponding to the best match between observed and expected signal amplitudes.

If we inject 4 extra parameters to account for the relative gains, the system becomes underdetermined and a solution cannot be found. To overcome that problem, we fit simultaneously more than one system of equations, meaning that

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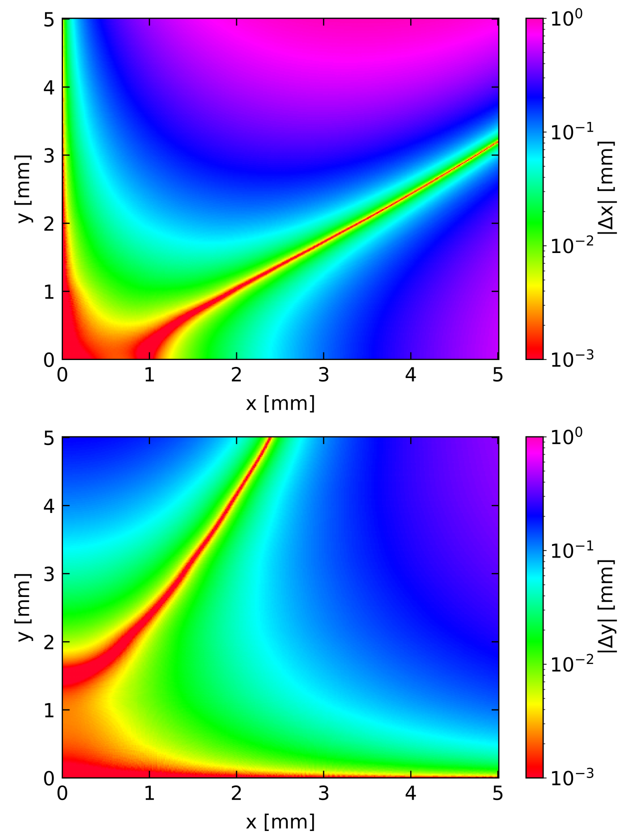

Figure 2: Difference for the horizontal (top) and vertical (bottom) beam positions between the linear and nonlinear (response map) calculations. The pick-up electrode response map is close to being linear only around $(x, y) = (0, 0)$. The linear position reconstruction is done as follow: $x = k_x(A_2 + A_4 - A_1 - A_3)/\sum_i^4 A_i$, $y = k_y(A_3 + A_4 - A_1 - A_2)/\sum_i^4 A_i$, where $i = 1$ is the lower left $(x < 0, y < 0)$ electrode, $i = 2$ the lower right, $i = 3$ the upper left and $i = 4$ the upper right. k_x and k_y are geometric factors accounting for the vacuum chamber geometry.

we fit for several independent beam positions minimizing the objective function:

$$\text{obj. fun.} = \sum_{i=1}^{n}\Big[\sum_{j=1}^{4}\big[A_{ij} - \frac{f_{A_{ij}}(x_i, y_i)}{g_j}\big]^2\Big], \qquad (2)$$

where i corresponds to the i^{th} beam position, j to a given pick-up electrode and g to the electrode gains. When fitting for 4 different x, y beam positions, we have 8 position parameters but only 4 gain parameters given that they are position-independent, for a total of 16 equations. The system is overdetermined and solvable via standard global minimum search algorithms. For our case, we have identified the Basin-Hopping algorithm [6] as implemented in SciPy [7] to be the most suitable in term of both how well it finds the solutions and how long it takes to get there.

PERFORMANCE EVALUATION

The performance (precision) of the method has been evaluated in pseudo-data generated with a Monte Carlo simulation that uses the pick-up electrode response map to generate signal amplitudes. One pseudo-data corresponds to a set of 9 beam positions sampled on a grid with a spatial separation greater than 500 μm. The position of the center of the grid is randomly selected but limited within ±5 mm in both x and y to mimic the actual data collected at CESR.

An ensemble of pseudo-data (typically several 1,000s) is generated to define a pseudo-dataset. Many pseudo-dataset have been generated, each to study the impact from a set of BPM systematic effects by varying the signal amplitudes accordingly [2]. Figure 3 shows the expected precision on the gain measurements, when including all the measured BPM systematic effects (sampling clock jitter, peak-sampling offset, noise RMS and pedestal variation), to be 0.3% for gain values typically in the ±10% range.

More recently, we studied the impact of the quality of the response map. We have not measured the actual response map and rely on simulation. If the map is not close enough to the real one, it degrades the precision of the method. An alternative map has recently been generated in a 3D dynamic fashion running wakefield simulation with CST Studio Suite [8]. It contrasts with the map we have been using until now which solves Poisson's equation to generate the map in a 2D static fashion [4]. When generating the pseudo-data with one map and reconstructing the gains with the other map, the precision of the method degrades to 1%. In the future, we plan on using the newly generated map for beam position measurement. More work is planned to study how sensitive the map is to the pick-up electrodes being misaligned or tilted.

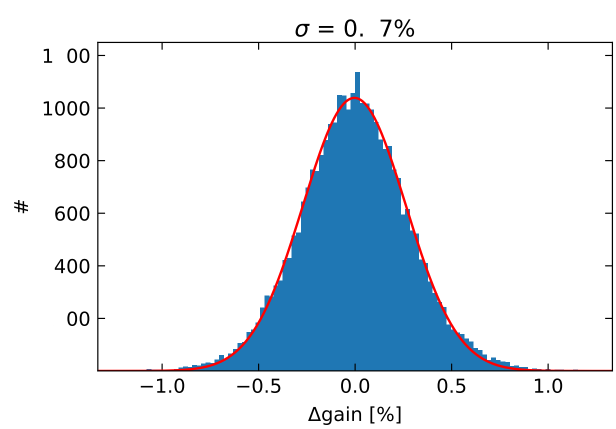

Figure 3: Distribution of the generated minus reconstructed gain values (all 4 electrodes combined) for the case of including all the known BPM systematic effects in the simulation. The red line is a normal distribution fit to the data from which the precision of 0.27% is extracted.

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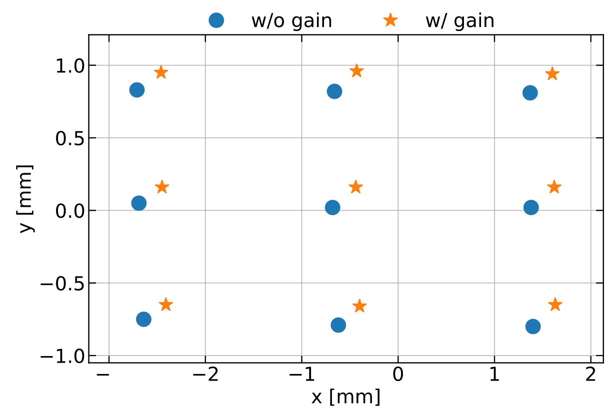

Figure 4: Blue: data for the 9 beam positions collected to measure the gain values at a specific BPM location, therefore without gain calibration applied. Orange: same 9 beam positions data but after calibrating for the gains. The BPM is part of the smaller CESR aperture.

MEASUREMENTS AT CESR

Method Deployment

After thoroughly validating the method using Monte Carlo simulation, we deployed it at CESR. As shown in Fig. 4, the typical implementation uses 9 beam positions at a given BPM with horizontal and vertical spatial separation greater than 500 microns. The beam is bumped locally using steering magnets and for each position, more than 200,000 consecutive turns are collected. The average of all those turns is used in order to decrease the uncertainty on the pick-up electrode signal amplitudes to a negligible level. Out of the 100 CESR BPMs, more than 60 have been gain calibrated. The improved position accuracy has led to improvement in tuning the orbit and performing global fit to it. Figure 5 shows the impact of the gain calibration on the absolute horizontal and vertical beam positions for the BPM locations that have recently been calibrated at CESR.

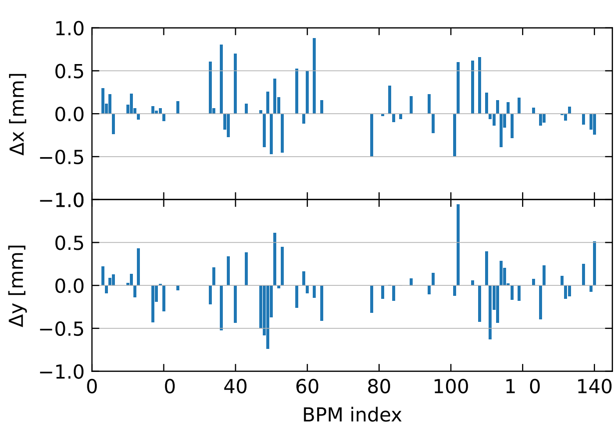

Figure 5: Difference for the horizontal and vertical orbits with and without gain calibration for the recently calibrated BPMs at CESR. The smaller aperture BPMs are located at indices ≤ 20 and ≥ 123.

Current Work

One of the limitations of the new method is time; it takes about 15 minutes to collect data for a single/few BPMs, making it impractical to quickly calibrate all the 100 BPMs. We are working on using a transverse resonance island buckets (TRBIS) [9] lattice demonstrated at CESR to allow collecting 9 beam positions at all the BPM locations at once in a matter of minutes. We are also currently working on understanding the method repeatability in CESR data. We are observing it to be at the 1% level without a proven origin yet. One possibility is temperature dependence. The air temperature in the tunnel varies depending on the stored current and other operating events. The BPMs are currently not temperature controlled and the electronics response will vary with air temperature and workload, thus changing the gain values. The air temperature variation could also mechanically affect the pick-up electrode, thus affecting the gain calibration. This effect matters since the gain calibration data is collected during dedicated shift where CESR runs 0.7 mA in a single bunch. The tunnel air temperature varies up to 5°F from when CESR runs high-current for X-ray production for the Cornell High-Energy Synchrotron Source [3].

CONCLUSION

We presented an improved beam-based method to calibrate the relative gains of the pick-up electrodes of the CESR BPM. The method has been studied and validated in Monte Carlo simulation, and successfully deployed at CESR with more than 60% of the BPMs calibrated. Current work focuses on understanding better the method repeatability and limitation when applied to CESR. The focus is also on speeding up the data collection in the hope of making gain calibration part of the regular CESR BPM maintenance.

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