A STATISTICAL ANALYSIS OF THE BEAM POSITION MEASUREMENT IN THE LOS ALAMOS PROTON STORAGE RING*

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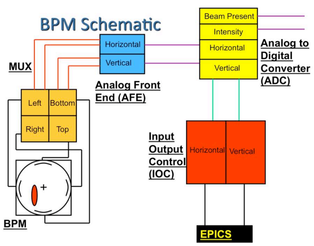
Abstract

The beam position monitors (BPMs) are the main diagnostic in the Los Alamos Proton Storage Ring (PSR). They are used in several applications during operations and tuning including orbit bumps and measurements of the tune, closed orbit (CO), and injection offset. However, the BPM data acquisition system makes use of older technologies, such as matrix switches, that could lead to faulty measurements. This is the first statistical study of the PSR BPM performance using BPM measurements. In this study, 101 consecutive CO measurements are analyzed. Reported here are the results of the statistical analysis, tune and CO measurement spreads, the BPM single turn measurement error, and examples of observed data acquisition errors.



Introduction

A PSR BPM is a collection of four stripline electrodes located in the beam pipe and situated top, bottom, left, and right. The BPM diameters are 4″ and 6″. They are tuned to the 201.25 MHz longitudinal structure of the beam and are a 201.25 MHz quarter wavelength long, ~37 cm. A mechanical relay matrix switch (MUX) selects the BPM for measurement. There are four MUXs to interface with each of the four BPM electrodes. Beam signals from the selected BPM pass to the analog front end (AFE) where the signals are converted from AM to PM. The AFE outputs a voltage proportional to the power ratio deposited on opposing BPM electrodes. The voltages are digitized by a 12-bit analog to digital converter (ADC). The intrinsic BPM resolutions, $d/2^b$, are .0124 mm and 0.0186 mm for the 4″ and 6″ BPM respectively. The ADC is triggered to digitize data by a beam present trigger. The digitized voltages are read to the input/output controller (IOC) where they are converted back to beam positions using geometric coefficients and AM-PM theory. The position data is lastly read by EPICS.

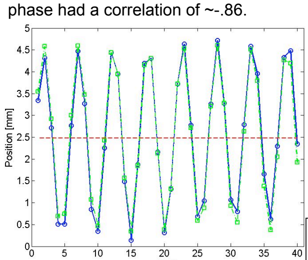
Measurement Setup and Data Analysis

101 consecutive CO measurements were taken for the same PSR configuration. Each CO measurement consists of 40 turns of turn-by-turn beam position data at each BPM. Since a MUX is employed to select the BPMs, data from only one BPM can be recorded per machine cycle. The CO is measured at each BPM on a different pulse with different central momentum (different CO) due to the pulse-to-pulse momentum variations.

The beam circulates around the ring performing harmonic (betatron) oscillation about the CO. So the turn-by-turn BPM data is then fit to a cosine wave,

$$y_n = A\cos(2\pi\nu n + \phi) + O_{ffset} \qquad (1)$$

where y_n is the turn-by-turn BPM data, n ranges from 1 to N = 40; A, ν, ϕ, and O_{ffset} are the amplitude, betatron tune, phase, and CO respectively. A nonlinear least squares fitting routine was used to fit for A, ν, ϕ, and O_{ffset}. The sum of squares of residuals per degree of freedom (SSR/DOF) was used as the goodness of fit quality factor. A maximum likelihood (ML) error analysis was applied to calculate the fitting error on the fitting parameters, the single turn BPM measurement error, and the covariance and correlation matrices relating the fitting parameters. Aside from the tune and the phase, the fitting parameters were found to be uncorrelated. The tune and the phase had a correlation of ~-.86.



A typical scan. The blue circles are the BPM data, the green squares are the cosine wave fit, and the red line is the value of the extracted CO from the cosine wave fit of Eq. (1). The SSR/DOF for this scan is very good, ~.03 mm^2.

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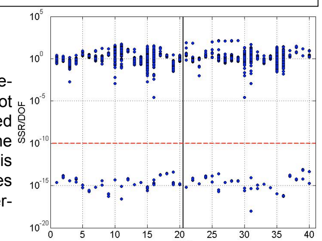
Data Acquisition Errors

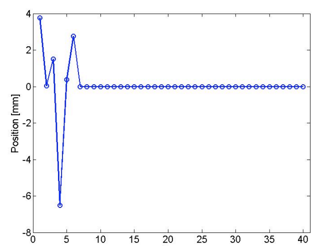
BPM Selection Errors



Normally the ADC buffer is cleared between machine cycles. When it does not clear, the IOC reads the same digitized voltages multiple times. The IOC "thinks" the data is from the MUX selected BPM which is not where the data originated, and analyzes the same digitized voltages using the different coefficients of the MUX selected BPM.

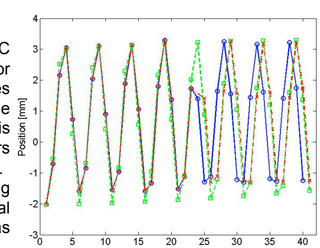
BPM selection errors are identified and removed from the data set by comparing the power ratios of a scan with the scan taken immediately before it. The repeated digitized voltages will calculate the same power ratios for both scans. A SSR/DOF of the difference of the power ratios for both scans can be computed. An SSR/DOF less than 10^{-10} indicates a BPM selection error.

Flat Line Errors



Flat line errors are only observed in BPMs immediately after the missing BPMs. Data from the missing BPMs always consists of one or two points of random noise. The power ratios of the first (and/or second) points from the missing BPM are the same as the power ratios of the first one or two points of the scan with the flat line error. The addition of five points of random noise to the data from the missing BPM is presumably a digitization from the ADC arm trigger and disarm trigger and three points from flushing the pipeline. The IOC will "fill" the scan with zeros if it receives less digitized turns than the user requested number of turns.

Missed Turn Errors

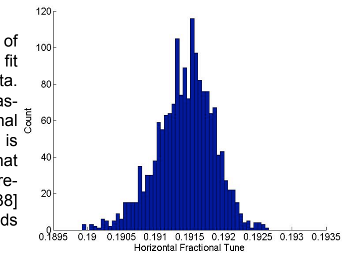


Missing turn errors occur when the ADC digitizes the AFE voltage as normal, but for some turn, the beam present trigger does not trigger the ADC to digitize data. The beam passes by the BPM and no data is taken. The following beam present triggers prompt the ADC to digitize data like normal.

The missed turn is observed by comparing the BPM data (blue circles) with the initial guess, green squares. The initial guess has a constant frequency that in the beginning of the scan matches the BPM data. At turn 24, the guess is maximum, but the BPM data goes down. From turn 24 on, the BPM data is one turn ahead of the initial guess. If the BPM data were delayed a turn for turns after 24 (red x's), then the BPM data with the added turn and the initial cosine guess match for the entire scan.

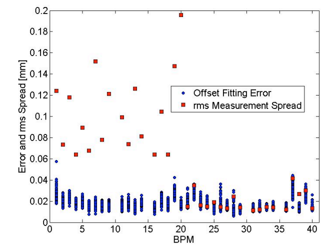
Results

Fitted Tune

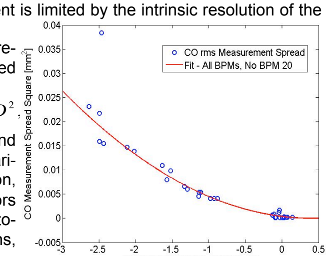


The tune is the frequency of the cosine wave fit. The tune fit is better with more turns of data. All BPMs in one direction measure the same tune, so the final quoted tune measurement is the average of all scans in that direction. The tune measurement was [0.191432, 0.197938] with *rms* measurement spreads [4.2e-4 (.22%), 3.4e-4 (.17%)]

Fitted Offset



The fitting error on the offset calculated from the ML error analysis is fairly constant across all BPMs (blue circles). The fitting error on the offset is only slightly larger than the intrinsic resolution of the BPM. The the measurement spreads (red squares) for the vertical BPMs match fitting errors. Thus the precision of vertical CO measurement is limited by the resolution of the BPM measurement. The error on the average CO for 101 CO measurements is less than the intrinsic resolution of the BPMs. The accuracy of the CO measurement is limited by the intrinsic resolution of the BPM measurement.

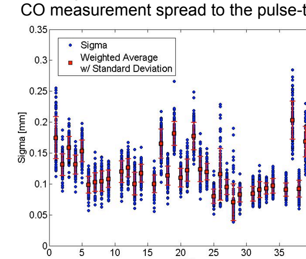


The square of the CO measurement spread (blue circles) fit (red line) to

$$\sigma^2_{CO} = \sigma^2_{BPM} + 2\langle\varepsilon_\delta\ \varepsilon_{BPM}\rangle D + \sigma^2_\delta D^2,$$

where σ and ε are the *rms* and absolute error, <...> is a covariance, D is the dispersion function, and BPM and δ indicate errors due to the BPM and pulse-to-pulse momentum variations, showing the dependence of the CO measurement spread to the pulse-to-pulse momentum variations.

Fitted Sigma



Sigma is the single turn measurement error, the *rms* standard deviation of the residual distribution. The measurement error is the same for all BPMs, between 0.1 and .2 mm. Analyzing the residuals as a function of turn it becomes apparent that the main contributor to sigma is a constant offset drift across all averaging .4 mm.

Conclusion

101 consecutive CO measurements, 40 turns of turn-by-turn BPM data, were taken for the same PSR configuration. The turn-by-turn data was fit to a cosine wave, Eq. (1). 11 data acquisition errors were found. 264 scans of the 3636 scans in the CO reproducibility measurement had data acquisition errors, 7.26%. But 62 CO measurements of the possessed a data acquisition error, 61.38%. After the errors were removed, the fitted parameters from the good scans were analyzed.

All scans of one dimension were used to calculate the tune value [.191432, .197938] with *rms* measurement spread [4.2e-4 (.22%), 3.4e-4 (.17%)].

The CO measurement spread was found to be [.1, .02] mm. The vertical CO measurement spread is minimum and limited by the intrinsic resolution of the BPM measurement. The pulse-to-pulse momentum variations cause the much larger horizontal CO measurement spread. The error on the average CO for 101 CO measurements is less than the intrinsic resolution of the BPM. The accuracy of the CO measurement is limited by the intrinsic resolution of the BPM measurement.

The single turn measurement error (sigma) was found to be between .1 and .2 mm. A constant offset drift in each scan is the main contributing factor to sigma.