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Automatic Beamline Calibration Procedures*

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Abstract

Recent experience with the SLC and SPEAR accelerators have led to a well-defined set of procedures for calibration of the beamline model using the orbit fitting program, RESOLVE. Difference orbit analysis is used to calibrate quadrupole strengths, BPM sensitivities, corrector strengths, focusing effects from insertion devices, and to determine the source of dispersion and coupling errors. Absolute orbit analysis is used to locate quadrupole misalignments, BPM offsets, or beam loss. For light source applications, the photon beam source coordinates can be found. The result is an accurate model of the accelerator which can be used for machine control. In this paper, automatable beamline calibration procedures are outlined and illustrated with recent examples.

I. INTRODUCTION

The initial commissioning phase of an accelerator typically involves both trial-and-error manipulation of steering magnets (correctors) and application of model-based beam steering algorithms. Accelerator operators look at the beam orbit using beam position monitors (BPM), typically including pick-up electrodes or profile monitors which are like the "eyes" of the operators. The "Model" of an accelerator is based on knowledge of accelerator component positions and calibration factors. When the beam is mis-steered or optically mismatched, operators respond by using the BPM system to see the effects of the errors, and take corrective measures based on the Model. Unfortunately, calibration errors can exist in the BPM system and in the Model which invariably complicates accelerator commissioning and operations. Thus, without well-defined calibration procedures, often the errors persist and valuable beam-time is lost.

To remedy this situation, we have developed two simple beamline (Model and BPM) calibration procedures based on RESOLVE [1]. In these procedures, the beam launch parameters $(x,x',y,y',dl,dp/p)$, are least-squares fitted to sections of the measured orbits to identify "good" regions where the model predicted orbit agrees with the measured data. These "good" regions are used to help identify additional fitting parameters (such as quadrupole strengths or alignment errors) required to calibrate the model. BPM readback parameters (such as sensitivity and offset) can be calibrated as well.

Although this technique has been under development for many years [2,3], the most recent advances are due to the development of RESOLVE. RESOLVE combines second-order beam transport principles with a numerical fitting routine and a user-friendly "point-and-shoot" environment for fitting model-predicted orbits to the measured data. The beamline calibration procedures which were developed using RESOLVE manually are adaptable to automation, and are intended to become a part of the Generic Lattice Debugger (GLAD [4,5]) system. These procedures and examples of these procedures recently applied to the SLC and SPEAR are described in this paper.

II. BEAMLINE CALIBRATION PROCEDURES

The most important part in the calibration of the beamline is preparation. The first step is to develop software for easy access to accelerator parameters residing in the database. For RESOLVE applications, an ASCII Beamline file (including magnets, cavities, kickers, insertion devices, beam energy, etc.) and Orbit files (correctors, BPM's) must be generated. As a second part of the preparation, the beamline file is used to simulate orbit perturbations before any measurements are made. For example, quadrupoles or correctors with the appropriate phase advance relative to a BPM or insertion device can be selected.

Another important step is to turn off all "nonessential" beamline components (solenoids, skew quads, bunch compressors, correctors, beam scrapers) in the region under analysis to obtain a "bare" machine. In some cases, it may be useful to turn off sextupoles or accelerating cavities. The beam is then kicked with the preselected correctors or the energy is changed to produce absolute and difference orbits.

Analysis Procedure for Difference Orbits

Analysis of difference orbits yields a calibrated BPM system and a calibrated optics model which can be used for machine control. The principle steps of an automatable difference orbit analysis procedure include:

(1) Identify BPM readback errors by looking for large readback values in the plane orthogonal to the kick.
(2) Identify the "good" regions in the beamline where model-based trajectory simulations agree with the measured data.
(3) Fit quadrupole strengths and BPM sensitivities to calibrate the model.
(4) Fit "kick" strengths to calibrate the correctors.

For storage rings, the location of quadrupole strength errors can be located by analyzing the closed orbit as a single-pass trajectory before finding the value

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of the errors by imposing the closure conditions. Since errors in a string of quadrupole magnets (powered by a common supply) do not produce discrete discontinuities, they require analyzing multiple trajectories simultaneously to produce a multitrack "correlated" result. Dispersion orbits are analyzed by adding the energy deviation, *dp/p*, to the fit. In SPEAR, for instance, dispersion fitting indicated that a single spurious "kick" caused an asymmetry in the dispersion function. The fitted value of *dp/p* can be used to estimate the momentum compaction factor.

Example I: Beam-Envelope Matching—In a section of the SLC where a transfer line connects the positron beam to a damping ring (SLTR), pole faces were installed backward on a bending magnet. Using the calibration procedure, an equivalent strength error of –4% was predicted at a nearby quadrupole magnet. By adjusting this quadrupole, the beam transmission through the damping ring was found to reach its maximum at the predicted value (–0.4%) yielding an increase of more than 20% beam throughput [4].

Example II: Quadrupole String Calibration—In SPEAR, the measured vertical tune is 0.1 higher for the "bare" lattice than the model predicts. Using RESOLVE, several difference orbits were fitted simultaneously (imposing the closure conditions) and a strength error of +1% was predicted on a single quadrupole string. When the current was lowered by 1%, the measured and model tunes agreed. In the process of calibrating the correctors, an automatable rule was discovered—"The most accurate model produces the least RMS spread on the fitted corrector values."

Example III: Insertion Device Calibration—To calibrate coupling elements, sextupoles, cavities, or insertion devices, the bare lattice optics model should first be established. Components are then turned on one at a time and their model parameters fitted by analyzing the measured data. An example of the calibration of the focusing effects from a wiggler magnet in SPEAR is shown in Figure 1.

Example IV: Photon Beam Steering—While commissioning SPEAR to operate in a new low-emittance optics configuration, two different solutions for photon beam steering were found. One orbit solution produced photon beams in the North Arc with acceptable corrector strengths, but no light in the South Arc beamlines #3 and #4. The other orbit solution produced beams only in the South Arc. The two orbits were subtracted and RESOLVE was used to make a "closed bump" utilizing 14 vertical correctors to match the difference orbit in the South Arc. See Figure 2. SPEAR was then set to the "North Arc" configuration, and the 14-corrector solution was assigned to a control panel knob. When 100% of the "knob" was applied, light appeared in beamlines #3 and #4, without losing signal at the other 7 photon beamlines. The initial commissioning phase of the new SPEAR high-brightness lattice was completed.

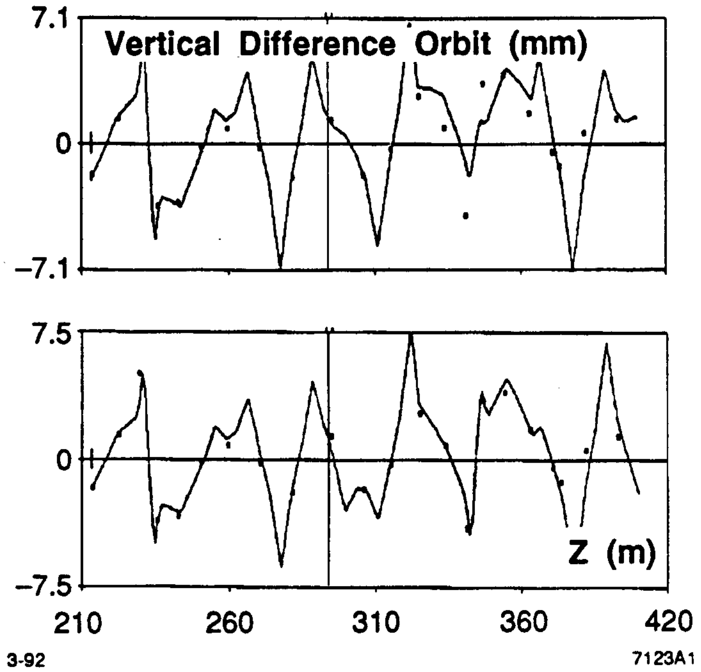

Figure 1. Predicted vertical difference orbit before and after calibration of a wiggler magnet in SPEAR.

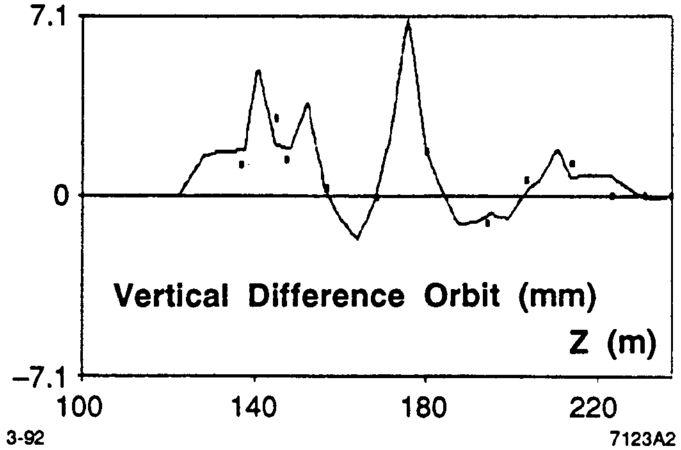

Figure 2. A 14 corrector orbit bump used to steer SPEAR photon beamlines in the South Arc.

Analysis Procedure for Absolute Orbits

The analysis procedure for the absolute orbit is similar to the procedure for difference orbits. The primary fitting parameters are now BPM offsets, quadrupole misalignments or dipole field errors. However, the discontinuities between the "good" regions are generally better defined because alignment errors tend to be discrete. The principle steps of an automatable absolute orbit analysis procedure include:

(1) Identify the "good" regions where model-based trajectory simulations agree with the measured data.

(2) Fit quadrupole alignment and/or BPM offset errors.

Once quadrupole alignment errors have been identified, nearby correctors can be used to compensate the cause of the orbit perturbation locally.

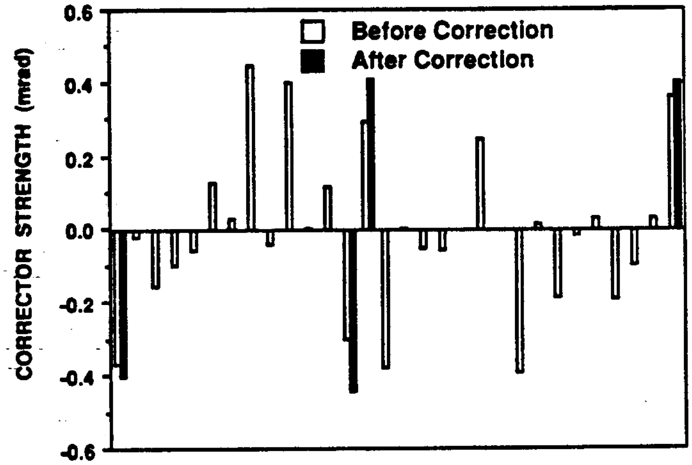

Figure 3. Vertical corrector pattern in SPEAR before and after correcting for misalignment errors at the Interaction Regions.

Example I: Orbit Correction at Misaligned Quadrupoles—In SPEAR, all insertion devices and all horizontal correctors were removed to measure the orbit of the bare lattice. Analysis indicated the main sources of both horizontal and vertical orbit distortion were in the Interaction Regions between the North and South Arcs. Several BPM offset errors were also identified. The online orbit control program was then used to minimize the RMS orbit with correctors located only in the Interaction Regions. In the vertical plane, the RMS orbit remained essentially constant (<2 mm), but no correctors were used in the arcs. See Figure 3. In the horizontal plane the RMS orbit distortion was reduced by a factor of 3.

Example II: Photon Beamline Source Coordinates—Since RESOLVE calculates the beam trajectory at every point along the beamline, it can be used to determine the values of *(x,x',y,y')* at the photon beamline source points. The vertical orbit in the South Arc of SPEAR is shown in Figure 4 with coordinates *(y,y')* indicated.

III. Automation

We are now ready to automate the procedures outlined in Section II by direct integration into RESOLVE. The new system would automatically identify "good" regions of the beamline where the machine and Model agree, and perform fitting to find calibration and alignment errors. The results could then be automatically verified by adjusting beamline components (strengths, correctors, etc.) to the calibrated values.

For example, imagine commissioning a synchrotron light source automatically. The control system could vary correctors, measure the difference orbits, and pass the data to RESOLVE for automatic calibration of the Model and BPM system. The optics model could then be used to automatically analyze the absolute orbits, and adjust the orbit with correctors suitably chosen to compensate alignment errors locally. Finally, insertion devices could be brought in and calibrated as a function of field strength.

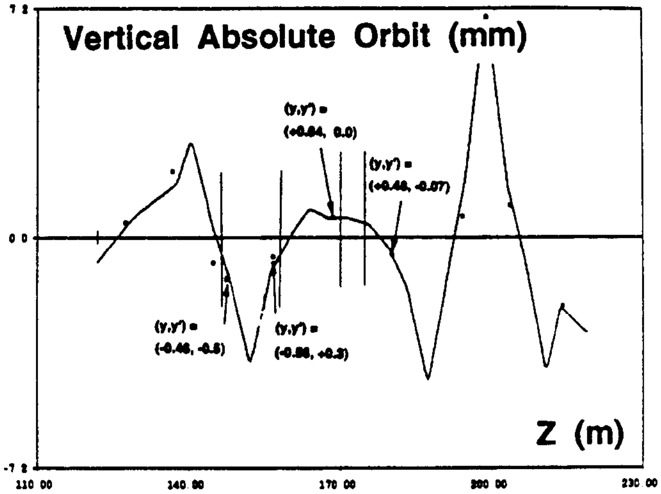

Figure 4. Fit to vertical BPM's in the South Arc of SPEAR showing *(y,y')* at the photon beamline source points.

For linear accelerators, the goal is to match the beam phase ellipse to the design value and to steer the beam on-axis. Since the beam phase ellipse measurement and matching depends on quadrupole calibrations, the automatic calibration procedures should be applied before making these measurements. It is not hard to imagine a system which automatically calibrates quadrupoles prior to measuring the beam phase ellipse and performing the match.

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