

## ERROR-FINDING AND ERROR-CORRECTING METHODS FOR THE START-UP OF THE SLC\*

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### Introduction

During the commissioning of an accelerator, storage ring, or beam transfer line, one of the important tasks of an accelerator physicist is to check the first-order optics of the beam line and to look for errors in the system. Conceptually, it is important to distinguish between techniques for finding the machine errors that are the *cause* of the problem and techniques for correcting the beam errors that are the *result* of the machine errors. In this paper we will limit our presentation to certain applications of these two methods for finding or correcting beam-focus errors and beam-kick errors that affect the profile and trajectory of the beam respectively. Many of these methods have been used successfully in the commissioning of SLC systems. In order not to waste expensive beam time we have developed and used a beam-line simulator to test the ideas that have not been tested experimentally. To save valuable physicist's time we have further automated the beam-kick error-finding procedures by adopting methods from the field of artificial intelligence to develop a prototype expert system.<sup>1</sup> Our experience with this prototype has demonstrated the usefulness of expert systems in solving accelerator control problems. The expert system is able to find the same solutions as an expert physicist but in a more systematic fashion. The methods used in these procedures and some of the recent applications will be described in this paper.

### Defining the Process

We treat any system as a beam line. For an accelerator section or transfer system, the beam line can be treated as a single pass system. In a storage ring, the beam line can be treated as a closed periodic system. In both systems the inputs to the procedures are the measured beam trajectory values at the BPM's (beam position monitors). Let  $\mathbf{x} = (x_1, x_2, \dots, x_i, \dots)$  represent either the horizontal or vertical BPM measurements. Let  $d\mathbf{x} = (dx_1, dx_2, \dots, dx_i, \dots)$  represent the difference in the trajectory or closed orbit measurements, before and after making a specific change to the beam line. The error-finding process requires a sophisticated numerical optimization program that fits the simulated beam trajectory errors from a model of the machine to the input beam trajectory. This is done by varying the machine model errors to obtain a "best match" between the simulation and the measurement. The aim of the process is to find the best possible model to represent the machine. How well the model represents the machine depends on the magnitude of the machine errors and the accuracy of the

measurements. Only after an accurate model is used can the error-correcting programs be used effectively to reduce errors in the beam parameters.

The output of the error-finding processes are the possible beam-focus and beam-kick errors introduced by the beam line elements such as the bending magnets, quadrupole magnets, and RF accelerator sections. The possible beam-focus errors are caused by quadrupole gradient errors or beam energy errors. Here, the focussing strength of a quadrupole magnet is equal to the field gradient divided by the beam energy. The possible beam-kick errors are caused by quadrupole alignment errors, bending magnet field errors, or transverse RF field errors in the accelerator sections. The methods used in these error-finding processes will be described in the following sections.

### Finding Quadrupole Focus Errors

In practice, it is possible to use the "design" model to determine if there are any large errors in the beam line. This is done by comparing  $dx^p$  with  $dx^m$ , where

$$dx_i^p = R_{12}(\text{design})_{i0} \theta_0^p$$

and  $dx^m$  is the measured change in  $x^m$  produced by a specific current change in a corrector element at the "launch" point, denoted by a subscript "0". The superscript  $m$  refers to the measured quantity and the superscript  $p$  refers to the predicted quantity from the model simulation. The predicted value of  $\theta_0^p$  is dependent on the corrector element calibration that converts magnet current to bending angle. In particular, for a single-pass beam line  $R_{12}$  is the 1-2 element of the transport matrix element that transforms the values of  $(x_j, x'_j, \delta_j)$  along the beam line where  $x'_j$  is the slope of the trajectory and  $\delta_j$  is the energy difference equal to  $(E - E_{\text{ref}})_j / E_{\text{ref}}$  where the beam energy is  $E$  and the machine reference energy is  $E_{\text{ref}}$ . This procedure has been implemented on-line as a standard method for checking a beam line. If the corrector calibration is unknown, the value of  $\theta_0^p$  is adjusted to fit  $dx^p$  to  $dx^m$ . By studying the differences between  $dx^p$  and  $dx^m$ , the user can quickly decide if there are any large focus problems. A typical example of a large focus error problem is given in Fig. 1 for the beam line connecting the Damping Ring to the LINAC, as illustrated by the mismatch between the solid and dashed lines.

The program uses a non-linear optimization package to find the focus errors by minimizing the non-linear function,

$$\min \sum (dx_i^m - dx_i^p)^2$$

summed over all  $i$  monitors, where

$$dx_i^p = R_{12}(\text{design} + \text{focus errors})_{i0} \theta_0^p.$$

The value of  $R_{12}$  is computed from the machine functions with the given focus errors in the beam line elements. In addition, if a BPM is located at the launch point, then  $dx_i$  may also include the effects of a non-zero  $dx_0^m$  in the term  $R_{11}^p(\text{design} + \text{focus errors})_{i0} dx_0^m$ . This enables us to fit for the value of  $R_{11}$ . For a single-pass beam line,  $dx_0^m$  can be adjusted experimentally using a corrector upstream of the launch point.

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For this case, the solution,  $\theta_0^p$ , also includes the change in  $x'_0$  introduced by the upstream corrector. The calibration of the corrector at the launch point is given by the ratio of  $\theta_0$  and the measured corrector current change. The values of the focus errors and  $\theta_0$  are adjusted in this minimization procedure by the optimization program, NPSLAC.<sup>2</sup> Figure 1 also shows a typical result, using the above procedures, to find a focus error, as illustrated by the match between the solid and dotted lines. In fact, we have used this procedure successfully several times in the commissioning of a closed system, the SLC Damping Rings.

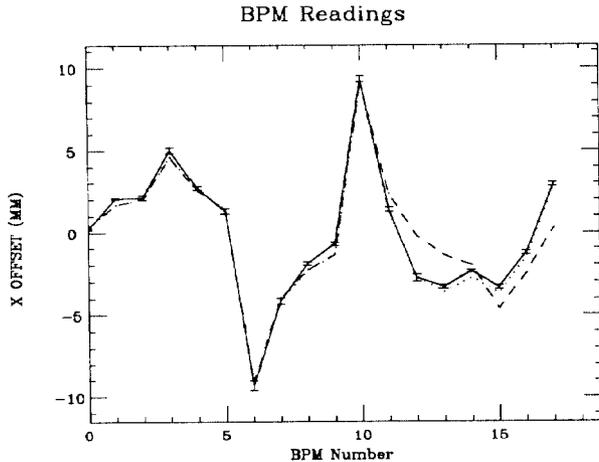


Fig. 1. Checking a single pass system for possible focus errors:  $dx^m$  = solid,  $dx^p$  = dashes, and  $dx^p$  (model with a 2% error in one of the quadrupole magnets) = dots.

### Finding Alignment Errors

In contrast to the beam focus case, it is possible to directly check for any large beam-kick errors due to misalignment of elements directly, without using a model. This can be done by comparing  $x^m$  with  $dx^m$ , both measured experimentally under specific conditions at the launch point:  $x_0 = 0$  and  $x'_0 = \theta_0$ . In practice, any one of the BPM's can be chosen to be a launch point. Correctors upstream of the launch point can then be used to obtain the required launch conditions. In addition, this method requires that all of the correctors downstream from the launch point be turned off. Since the  $x_i^m$  are affected by beam-kick errors and the  $dx_i^m$  are not, a large discrepancy between  $x_i^m$  and  $dx_i^m$  indicates a large beam kick error. In the presence of such errors, it is necessary to vary the value of  $x'_0$  to optimize the range of beam transmission along the beam line. Note that  $dx^m$  is the difference between the trajectories having  $x'_0 = 2\theta_0$  and  $x'_0 = \theta_0$ .

If there is a beam-kick problem due to transverse quadrupole alignment errors, NPSLAC can be used to find the beam-kick errors,  $\theta_k$ , that minimize the sum of the squares of the linear function,

$$\min \sum (x_i^m - x_i^p)^2,$$

where the sum is over all the monitors  $i$ , and

$$x_i^p = \sum R_{12,ik}^p \theta_k$$

with  $k$  denoting the  $k^{\text{th}}$  quadrupole element in the beam line. Unlike the example shown in Fig. 1, there are now up to  $k$

errors in a beam line. Also in the case where  $i$  is less than  $k$  the problem is under-determined making it difficult to locate a few discrete errors out of many possibilities. It is possible to use an expert system to "intelligently" reduce the search space of possible errors so that an error can be found more efficiently. For this application, the expert system first performs a "global" test where it allows all the  $k$  element mis-alignments to vary while fitting to the reference trajectory. The results of this experiment give a smeared out picture of the actual mis-alignments, that is, a single discrete mis-alignment may appear as a region of several smaller mis-alignments in the vicinity of the actual error. To more precisely locate the errors, "local" experiments are performed where only a few errors are allowed over a sub-region containing fewer elements and monitors.

The use of NPSLAC has enabled us to find focus errors automatically given a set of possible mis-focussed elements. The constraint feature of NPSLAC has made it possible to find realistic solutions\* even for cases where the betatron phase shift between correctors is  $n\pi$ . However, it is still possible that the error-correcting procedures may fail to find an acceptable solution to the problem. In this instance, the error is so large that the error-finding programs must be used. To use these methods the physicist first guesses where the errors are to restrict the problem to a reasonable size, bearing in mind the relative phase shift between correctors/errors and monitors.

### Correcting Beam Errors

After the large errors have been located by the error-finding methods they can be fixed on the physical beam line. The beam-focus errors that were found can then be included in the model as correction factors. Any residual problems remaining on the beam-line can be corrected using the error-correcting programs.<sup>3,4</sup> Methods of these programs are similar to those of the error-finding programs, but there is one conceptual difference between the two: *finding* large machine errors is easy; however, *correcting* large beam errors may be impossible because the strength and number of correctors is limited. Furthermore, the solution may also depend on which correctors are used in the model calculations for optimization. As a rule of thumb, the problem region should contain several monitors past the last possible error. For example, NPSLAC may be used for finding the beam-kick at the correctors,  $\theta_k$ , by minimizing the same function as was minimized in the case of finding alignment errors except that the subscript  $k$  now refers to the correctors. Using NPSLAC it may be possible to impose the constraints:  $|\theta_k| \leq \max \theta_k$  and  $|x_i(\text{residual})| \leq \max x_i$ . With this scheme, the user can study the effects of different values of  $\max x_i$  on the solution.

A similar method can be used to restore the trajectory to a reference value by minimizing,  $dx_i^m$ , the change in trajectory from the reference values. This scheme has been applied successfully in the feedback system<sup>5</sup> that restores the launch condition  $(dx_0, dx'_0, \delta_0)$ . The method solves for the values of  $(dx_0, dx'_0, \delta_0)$  by minimizing the same function as was minimized in the focus error case, except that the index  $i$  refers to

\* Care must taken in the choice of the launch point to avoid "ill-conditioning" in the fitting procedure which occurs when the betatron phase shift between the error(s) and the launch point is  $n\pi$ .

specific BPM's used in the feedback system and

$$dx_i^p = R_{11,i0}^p dx_0 + R_{12,i0}^p dx_0' + R_{13,i0}^p \delta_0$$

where  $dx_0'$  is the change in angle, and  $\delta_0$  is the change in energy at the launch point. Since  $dx_0$  is a **measured** quantity, it may not be needed in the fitting. Furthermore, the reference energy,  $E_{ref}$  may also be adjusted using NPSLAC as described in the section on focus errors. In this case, all the focus errors vary inversely as  $E_{ref}$ , a condition that can easily be included in the constrained fitting.

In the presence of noisy monitor data, several iterations of the procedure are sometimes required to reduce the residual errors to an acceptable level. The solution converges when the scaled differences of the fit values between successive iterations are used for the next iteration. Furthermore, it may be possible to improve the signal-to-noise ratio by using multiple scans of the BPM's. In addition, the monitor data can be filtered by throwing out scans that are more than one standard deviation from the mean and using the recomputed mean as the BPM value. Additional improvement may be gained by weighting the BPM values in the optimization by the inverse of its standard deviation.

### Using Simulation Methods

Not all of the ideas described in the previous sections have been implemented and they have been denoted by the bold-faced word **may** throughout the text. It is possible to test the other features without wasting beam time with the use of a beam line simulator. The development of a beam line simulation program requires a lattice modeling code, an optimization code, and a code for simulating fluctuations in the beam parameter data. In our application we have used the lattice code, COMFORT,<sup>6</sup> a sophisticated optimization program, NPSLAC, and a beam simulator, PLUS (Predictions from Lattice Using Simulation). The use of COMFORT-PLUS in finding the focus-errors and kick-errors has saved much valuable beam time while making the difficult task of commissioning the Damping Rings and the LINAC considerably easier. Because of its success, COMFORT-PLUS is being modified to be more transportable<sup>7</sup> so that it can be used for the commissioning and start-up of any accelerator or storage ring system.

The simulator can be used in one of three modes. First, the simulator can be used manually to see directly the effects of errors on the beam, which helps in making guesses about the errors. Second, an optimization program can be used to determine the best fit values of the errors to the beam data. In some cases the error-finding and error-correcting methods may find multiple solutions that must be interpreted to find the "best" answer. Our experience with the simulator shows that there is still a great need for the skills of an experienced accelerator physicist to choose the best answer. Thus, we have taken our methods one step further by using COMFORT-PLUS as the basis for the prototype development of a beam line expert system, ABLE, to automate this task.

## Using an Expert System

In ABLE we have combined simulation methods together with expert heuristics into a unified hybrid expert system. This hybrid approach has allowed us to save beam time as well as physicist's time by automatically performing experiment design and analysis. The use of simulation has permitted the almost simultaneous development of an error-finding methodology and its implementation into the expert system.

Using the methods described in the previous sections, the expert system first performs a global experiment which defines likely problem regions. It then performs a series of local experiments, interpreting the results to plan new experiments that will better model the problem.

For finding alignment errors, the expert system often finds several "acceptable" solutions to a problem. The acceptability is determined by how well the fitted monitor data agrees with the reference data and by the consistency of the solution during the optimization. The acceptable solutions can then be further analyzed to find the "best" candidate solution.

This automated procedure has been tested in simulation and can find errors as well as an expert accelerator physicist. At present, the simulation and expert system are waiting to be applied to the commissioning of the SLC final focus system. The development of the ABLE prototype has demonstrated that the use of a hybrid expert system is a new and viable approach to beam line control, and may be generalized to optimize other functions of a beam line.

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