SLC BEAM LINE ERROR ANALYSIS USING A MODEL–BASED EXPERT SYSTEM*

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Abstract

Commissioning particle beam lines is usually a very time-consuming and labor-intensive task for accelerator physicists. To aid in commissioning, we developed a model-based expert system that identifies error-free regions, as well as localizing beam line errors. This paper will give examples of the use of our system for the SLC commissioning.

Introduction

To aid in the commissioning of the SLC beam lines, we have used a model-based trajectory simulation system, GOLD [1] (Generic Orbit and Lattice Debugger), to identify the errors in beam line elements and beam position monitors. This system was designed to find beam focus errors, beam kick errors and beam launch errors. It is intended for finding beam kick errors and focus errors that produce large effects on the beam and launch errors that are outside of the operating range of the feedback system to stabilize the launch condition of the beam. It is also useful for finding errors in the beam position monitors (BPM) that are large enough to confuse the SLC Automatic Beam Steering program.

GOLD can be used either manually or automatically. The automatic use of GOLD is done with an expert system, ABLE–GOLD [2] (FORTRAN version). The development of ABLE–GOLD was based on our experience in manual analysis of these problems, using the GOLD Method [3] to first identify the error-free regions and then to localize the beam line errors to a particular element. Numerous cases have been successfully analyzed using the GOLD Method to find errors in the Damping Rings [4], the LINAC and the beam transport system between the damping ring and the LINAC (RTL and LTR). In this paper we will discuss our experiences using GOLD, either manually or automatically, to find element errors in the LINAC, LTR and RTL subsystems of the SLC. A schematic layout of the SLC subsystems is shown in Fig. 1.
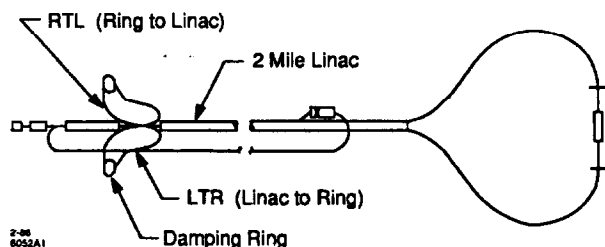

Fig. 1. The subsystems (Damping Rings, RTL, LTR, the LINAC) where we have used GOLD to analyze and to correct trajectory errors, either automatically or manually, during commissioning and operation of SLC.

The GOLD System

For our applications, we assume that the beam line contains only first order uncoupled elements such as drifts, bending magnets, quadrupole magnets, accelerator sections, thin-lens dipole correctors and BPMs. The modeling program COMFORT [5] is used to calculate the transfer matrix element across each individual element. The trajectory simulation program PLUS [6] is used to find the trajectory at every BPM introduced by a kick at a dipole corrector, or due to a change in beam position and angle at a launch point (the launch parameters). The optimization program NPSLAC [7]

is used to adjust either the values of the launching parameters, focus error or kick error at some specific beam line element, to minimize the discrepancy between the predicted trajectory and the measured value. To use the GOLD system manually, the user is required to make successive guesses of the location of the error-free regions and locations of the errors. The values of the errors are found by NPSLAC for each guess. The user can study the result on a graphical display to decide what the next guess should be. This laborious trial-and-error manual procedure can be done automatically by ABLE–GOLD. A block diagram showing the relationship between COMFORT, PLUS, NPSLAC and ABLE–GOLD is given in Fig. 2.
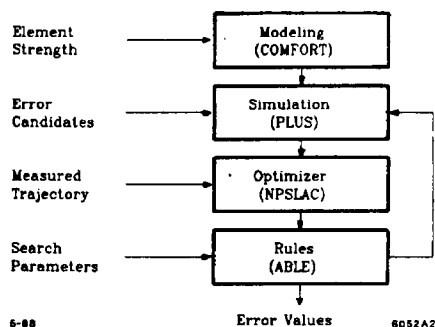

Fig. 2. A block diagram of GOLD consisting of a modeling program, a simulation program, an optimization program and a fixed set of rules. For manual applications, the user specifies the locations of the error candidates (which elements can have errors); GOLD finds the values of the errors. For automatic applications, the user specifies the values of the search parameters for the expert system (ABLE–GOLD); GOLD finds the locations and values of the errors.

The Automated GOLD Method

To find the errors automatically, ABLE–GOLD uses a two-step procedure. It first locates the error-free regions, then finds the location and value of the errors. To find an error-free region, the user needs to specify the values of two search parameters: Max–Discrepancy and Min–Region. Max–Discrepancy is used to define the "error-free" condition and Min–Region is used to define the "minimum" size for an error-free region. The necessary conditions for a segment to be an error-free region are:

1. the number of BPMs within a segment must be larger than or equal to Min–Region;

2. the discrepancy (the absolute value of the difference between the prediction and measurement) must be less than Max–Discrepancy at all of the BPMs.

ABLE–GOLD searches for the largest segments that satisfies these conditions (the error-free regions). The output of this search is the name of the first and last BPM within each error-free region.

To find the location and value of an error, ABLE–GOLD makes the following assumptions: every subregion between two adjacent error-free regions is a possible location for finding an error; there is only one error element within each subregion. To find the error, the user needs to specify the value of Max–Subregion (the number of BPMs in the subregion). The value of Max–Subregion defines the "maximum" size of a subregion. PLUS considers every element within a given subregion to be

a candidate for having an error. For each candidate, NPSLAC finds the value of the error that yields the best match (minimum discrepancy value) between the prediction and measurement over both adjacent error-free regions. ABLE–GOLD interprets these results to find the best candidate with the smallest discrepancy value. The output of this search is the location of the error (name of the element having the smallest discrepancy value) and the value of the error. At the request of the user, ABLE–GOLD can show how it arrives at the result.

Application to Find Focus Error

The GOLD system has been used routinely to check for large errors in the SLC beam line elements. We will describe an example using GOLD to aid the commissioning of RTL (Ring To LINAC beam transport system). Recently, a change in trajectory was measured along RTL that was introduced intentionally using a kick from a corrector at the beginning of the beam line. This change was measured three times, using three different correctors (A, B and C). The results were analyzed, using the GOLD system to check for possible focus errors.

In our analysis, we used ABLE–GOLD to analyze case A automatically. We set Max–Discrepancy = 0.3 mm and Min–Region = 3 BPMs. ABLE–GOLD looked for the error-free regions and reported that it found two: one from BPM 1 to BPM 8; another from BPM 6 to BPM 27 (end of the beam line). This result showed that we may expect to find only one focus error within the subregion between these two error-free regions (around BPM 6).

We then set Max–Subregion = 2 BPMs. ABLE–GOLD looked for the error in the subregion (2 BPMs upstream and 2 BPMs downstream of BPM 6) and reported that it found Quad 184 to be the beam line element with a focus error. The result of this analysis is shown graphically in Fig. 3. The location of each element along the beam line is indicated by a cross (×) in the plot. The error in Quad 184 is shown as a point below the axis. The value of the error is measured on the vertical axis.

To see the effects of this error, we used PLUS to compute the predicted trajectory with the error in Quad 184 removed. The result is shown in Fig. 4.

After finding the error automatically, we decided to check the answer manually. The results from the manual trial-and-error analysis of all three measured BPM data sets (A, B and C) showed that Quad 184 was the best candidate. Approximately the same error value as the value obtained by ABLE–GOLD, was found for all three cases. Based on these results, this quadrupole was inspected carefully to look for mechanical or electrical faults. An "extraneous" bolt was found at the junction of its coils. This could have caused both a dipole field (kick) error and a quadrupole field (focus) error, as a result of a short in the windings on one of its poles. Since the experiment was designed to check for possible focus errors, only a difference trajectory was measured. In this measurement, the effects of dipole errors were subtracted out. Therefore, our analysis did not find the dipole component of the error. [This bolt was subsequently removed.]

Since this analysis was a routine checkup to see if there were any focus errors in RTL, the discovery of this bolt was incidental. Figure 4 shows the model prediction with the error at Quad 184 removed. By comparing Figs. 3 and 4, it can be seen that the discrepancy caused by an error at Quad 184 is small. We were not surprised that the removal of the bolt did not dramatically change the performance of RTL. This example illustrates the sensitivity of our automated method.

To test the automated GOLD method further, we used ABLE–GOLD to analyze cases B and C. In this test, we had to adjust the values of Max–Discrepancy and Max–Subregion, in order to find the same error-free regions as in case A. This result has made us aware of the sensitivity of the search parameters on the automatic solution. The dependence of the solution on the values of the search parameters places a limit on using ABLE–GOLD in its present form.
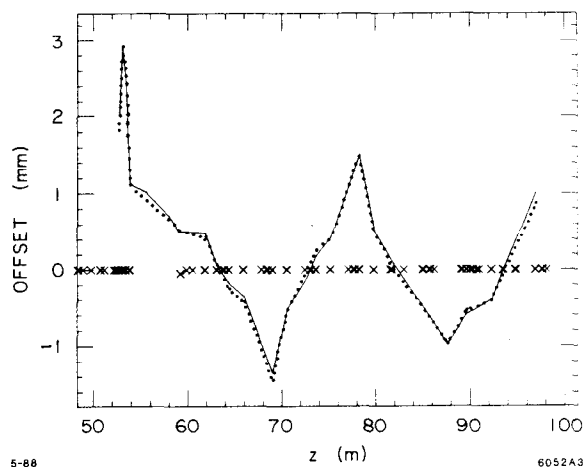

Fig. 3. A typical result of using the expert system to find the error automatically (quadrupole field error in Quad 184 at RTL as indicated by the point "×" off the axis). The solid line is the measured trajectory that was analyzed by GOLD. The dotted line is the "best" match simulated trajectory to the measured data (with the focus error in Quad 184). Every element in the beam line is indicated as a point "×".
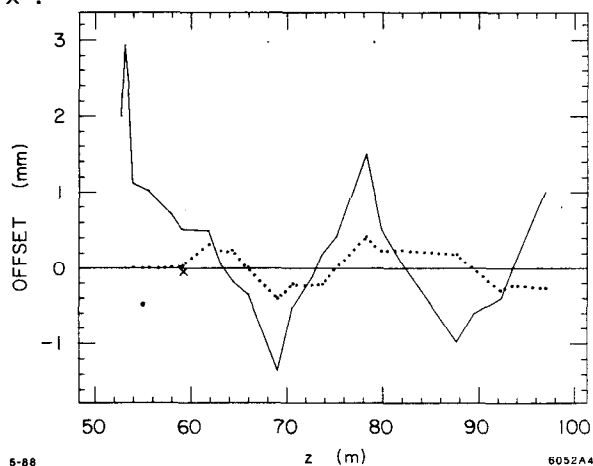

Fig. 4. The simulated trajectory error produced by the quadrupole field error in Quad 184 at RTL (dotted line).

Other Applications

The GOLD system has been successfully used in other SLC subsystems to find focus errors, beam energy gain errors [8], and BPM errors and to correct trajectory errors. In one case, we discovered a focus error in the deflecting magnet (HB0) that kicks the beam into the LINAC (Sector 2) from the end of RTL. After it was found, a thin-lens quadrupole element was added to the entrance pole face of HB0 to model this error. This corrected model is now used in the Launch control feedback system that stabilizes the position and angle of the beam at the beginning of Sector 2. Before this corrected model was used, it was not possible to control the launch condition using the feedback system.

It is also possible to use the GOLD method to identify BPM errors. After an error-free region has been found, a "bad" BPM can be seen as an isolated point with a "bad" fit. For a long period of time, during the commissioning of the LTR, it was noted that the on-line trajectory correction program was not working properly. Several "bad" BPMs were discovered using the GOLD system. After they corrected the cause of the problem (in the electronics), we were able to use the trajectory correction program routinely for the operation of LTR.

After fixing the BPM errors, it was noted that as many as eight correctors were used to steer the beam vertically in LTR; also, many of these correctors were at their strength limits. In order to investigate this problem, the GOLD system was used to look for large kick errors. Trajectory measurements were made under specific conditions for this purpose. The result of our analysis showed that there were only three elements with large kick errors. By choosing three correctors (one near each of the kick errors), we were able to correct the trajectory to the same residual values as before, using eight correctors. In our solution, however, none of the corrections were at their limits. The operators now use only these three correctors to steer the beam vertically.

After we successfully corrected the vertical trajectory errors, we were given a test case to demonstrate the capability of ABLE–GOLD to correct horizontal trajectory errors. For this demonstration, the strengths of three horizontal correctors were intentionally changed by comparable amounts in LTR, and the changes in the BPM values were measured. The measured data were given to us to be analyzed automatically, to see if we could find which correctors were changed. We accepted this challenge enthusiastically. For our analysis, we picked the parameter values; Max–Discrepancy = 0.2 mm, Min–Region = 3 BPMs and Max–Subregion = 3 BPMs. With a "single push of the button," the expert system gave the correct answer. Since the correctors are not considered as candidates for errors in GOLD, it finds the beam line elements closest to the correctors used in making the test, as the "most likely" candidates. The results of this test are shown in Fig. 5. The curves represent trajectory errors in the machine. In this plot, the solid line represents trajectory errors before correction and the dotted line represents the simulated trajectory errors after correction. This plot also shows the position and strength of two correctors (as crosses), with the third corrector located at the launch point. This example illustrates the effectiveness of using GOLD to correct trajectory errors where finding the exact causes of these errors are not required.
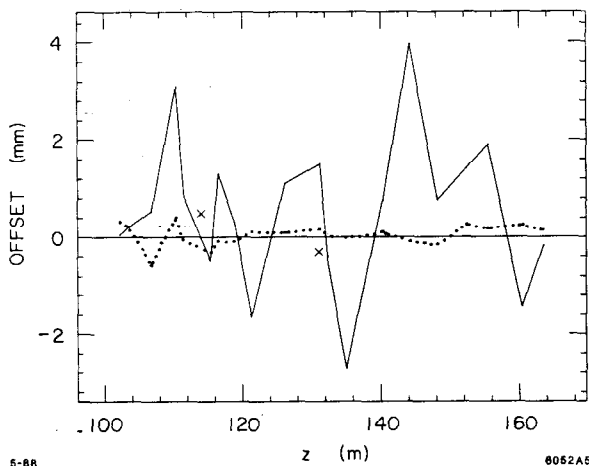

Fig. 5. The result of a demonstration using the expert system to correct the trajectory error automatically in LTR by using correcting elements near the causes of the trajectory errors. The solid line is the measured trajectory error that was analyzed by the expert system. The dotted line is the simulated trajectory error (after corrections). In this test case, the location of two errors are shown as "×"'s in this figure, with the strength of the error given by the value along the vertical axis. The third error is shown at the launch point, with the strength of the error given by the value of the slope of the trajectory at that point.

Summary

Our experience has demonstrated the usefulness of an expert system for data analysis and error correction applications. In its present stage of development, manual usage is still more reliable, although requiring considerably more human effort. In order to make the automatic procedure work consistently, we will need to add more rules to the expert system. Besides the development of rules to interpret the result of analysis, we also will need to develop rules to evaluate the result of these interpretations. However, adding rules in a procedural language like FORTRAN is a difficult task. A convenient way to implement new rules, along with a sophisticated deduction system, can provide a much more flexible and reliable system than is currently available with ABLE–GOLD.

Our experience in using an expert system (with fixed rules) has made us realize some of the usefulness and limitations of the existing method used to find or correct errors in a beam line automatically. The present expert system will need to be improved before it can be used to commission and operate a beam line fully automatically. We believe that an expert system is extremely cost-effective for any complex accelerator facility. The cost of its development is miniscule relative to the expensive beam time saved by automatically finding and correcting errors during commissioning and operation.

References

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