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MODERN APPROACHES TO ACCELERATOR SIMULATION AND ON-LINE CONTROL*

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1. Introduction

The use of modeling programs for accelerator beamline control and commissioning is becoming an accepted practice. For *control* applications, the goal in using these programs is to *correct* deviations in the beam measurements or to change the machine parameters. Since these programs are used for operation of the machine, they are a part of the on-line control system. For *commissioning*, the goal is to *find* the errors in the machine which cause deviations from the predicted beam measurements. Since these latter programs are needed only occasionally during commissioning of a new beamline or starting up an old one, many of these programs are off-line and not integrated into the control system.

This conventional approach has many shortcomings. Since the on-line modeling programs are usually an integral part of the control system, new correction programs must be written for new control systems. For example, error correction programs have been developed three times at caps slac: the first time for SPEAR, the second time for PEP, and the third time for SLC. Also, since the off-line modeling programs are not intended for general use, they remain the special province of their authors. Thus new off-line programs also have to be developed from scratch rather than by modifying existing programs.

The redevelopment of both the on-line and off-line programs is labor intensive, and in many instances the same methods are used in the on-line system for correcting beam errors and in the off-line programs for finding the machine errors (the causes of the beam errors). It makes sense, therefore, to combine on-line and off-line programs into a single stand-alone modeling application program which can be easily transported from one control system to another.

The use of a dedicated workstation offers an ideal setting for the implementation of these stand-alone *high-level* modeling programs. With its high resolution graphics, windows, and menus, the workstation can provide a truly user-friendly environment, and many have the computing power required for modeling calculations. Furthermore, their networking capabilities make it particularly easy to *plug* them into a control system.[1]

As a demonstration of the viability of this idea, the COMFORT–PLUS package has been developed on a SUN–3 workstation. This paper describes this project in detail and presents an example of the use of the package.

2. Overview of COMFORT–PLUS

COMFORT–PLUS consists of three pieces: (a) COMFORT (Control Of Machine Function, ORbits, and Trajectories),[2] which computes the machine lattice functions and transport matrices along a beamline; (b) PLUS (Prediction from Lattice Using Simulation) which finds or compensates for errors in the beam parameters or machine elements; (c) a highly graphical interface to PLUS.[3]

COMFORT–PLUS performs two closely related functions: (1) it can calculate the effects on the beam parameters due to specific errors in the machine elements, enabling it to generate simulated trajectories; (2) given trajectory data, either a set of actual measurements or a simulated trajectory, it can find the cause of the trajectory errors or calculate the strengths of the correctors needed to compensate these errors. Thus COMFORT–PLUS can be used both for commissioning and routine operation. In addition, with its graphical interface COMFORT–PLUS provides a novel way for training operators in the high-level control of the machine. Because it can simulate errors off-line, the training does not require expensive beam-time.

Four basic tasks have been included in the initial version of COMFORT–PLUS: (1) Finding focus errors; (2) Finding kick errors; (3) Finding launch errors; and (4) Beam-steering.

The first three are particularly suited for commissioning, beam-steering for day-to-day operations.

The basic error finding and correcting algorithms have recently been verified in the commissioning and operation of the SLC system at SLAC. Encouraged by this success, we have further developed these algorithms and automated their use in COMFORT–PLUS.[4]

3. Structure of COMFORT–PLUS

To use COMFORT–PLUS, the strength and location of every element in a beamline lattice is described in a COMFORT dataset. This dataset is read by COMFORT and it generates as output an ASCII file listing the elements in the beamline, their position, type, and associated transport matrices. This is the entire role of COMFORT in COMFORT–PLUS, with two important consequences: (1) COMFORT need only be run when the lattice is changed; and (2) COMFORT may be replaced with any modeling program capable of producing the same output.

The PLUS program is separate from COMFORT. PLUS uses the transport matrices generated by COMFORT to represent an ideal accelerator. Given these matrices, which transform the values of x (beam trajectory deviation), x' (the slope of the trajectory deviation), and dE/E (beam energy deviation) along the accelerator, PLUS generates the ideal trajectory to any point of interest. Because PLUS has the transport matrices for every element in the beamline, it can calculate the predicted beam parameters at each element, not only at monitors.

PLUS models errors in the machine by inserting additional transport matrices into the beamline. For example, to simulate focus errors, PLUS inserts the transport matrix for a thin-lens quadrupole magnet at each quadrupole. To simulate kick errors, PLUS inserts thin-lens dipole elements at each bend magnet (for bend-field errors) and at each quadrupole (for quadrupole-alignment errors). Using thin-lens elements enables PLUS to run quite fast, aiding the interactive response when PLUS is used as a simulation for training, and significantly improving the speed at which PLUS finds element errors (see below). We have performed sensitivity analyses to verify that the thin-lens approximations are valid.

PLUS is not inherently limited to these three problems: with minor modifications it can simulate any other machine error which can be expressed in terms of transport matrices.

After generating a trajectory, PLUS can add noise and offsets to the resultant monitor readings, filter the noisy readings over a number of trajectory scans to throw out particularly bad readings, and use the final average of the readings to simulate an actual, measured trajectory. For training purposes, these simulated orbits can be used in lieu of actual measurements, obviating the need for beam-time during training. The simulated orbits also provide the ability to develop new control algorithms off-line. For on-line use, PLUS can read in a file containing actual beam measurements.

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Given a trajectory, PLUS uses its ability to rapidly generate simulated trajectories, coupled with a powerful optimization package, NPSLAC[5] (also used by COMFORT), to find the settings of the thin-lens elements which will yield beam readings matching the trajectory. When the trajectory has been matched, each thin-lens element with a nonzero strength will be the site of an error. From its strength PLUS can help identify the exact nature of the error.

With the graphical interface, the user can also search for errors manually, by *knobbing* individual lattice elements and observing their effects on the trajectory. This method of finding errors is illustrated in the figures below.

With its trajectory-matching capabilities, PLUS is also well suited for day-to-day tasks such as beam-steering. Given a trajectory to be achieved, PLUS will search a group of correctors to find the necessary settings. PLUS can then show the effects of the corrector at every element along the beam-line before the solution is implemented. Because the optimization package allows for elaborate constraints, limits such as maximum corrector strengths and maximum beam trajectory values can easily be implemented.

PLUS has a simple, keyboard-oriented operator-interface, in which elements are referred to by name or number and trajectories are displayed as a table of numbers. Built on top of PLUS is a highly graphical operator-interface which greatly eases its use for both training and actual operation. The display shows a plot of the current beam trajectory. Along the bottom of the trajectory are shown each of the possible elements of error (if the operator is looking for errors) or control (if doing beam-steering). By clicking the mouse over an element the operator can control it and any other elements it is ganged with. The operator can summon a pop-up menu to attach a knob to adjust the element's strength or upper or lower limits, or to add the element to or delete it from the list of elements to vary when doing trajectory matching.

4. Using COMFORT–PLUS

When running PLUS, the user chooses the type of error to be found. The user then can select any element as an error candidate and try *knobbing* it in an attempt to match the simulated trajectory with the measured trajectory. This procedure can become untenable as the combinatorics of multiple errors comes into play. A more time- and labor-saving method of finding errors is for the accelerator physicist to select a set of likelyerror candidates to be varied when PLUS searches for a solution. This procedure can be used iteratively to find the errors. One successful technique we have used allows all the elements in the beamline section to vary. The resulting fit of this *global* search shows regions where errors are likely to be located. In fact, simulation studies have shown that individual errors show up in the global fit as smeared out regions of interest and the sum of the errors in the fit is approximately equal to the actual individual error.

An illustration of using COMFORT–PLUS to find errors by hand is shown in Figs. 1–5. Figure 1 shows the initial problem loaded into PLUS (the trajectory is simulated for a beamline in the SLC system). The beam clearly is running into some sort of error and later scraping the beampipe. In Fig. 2, an upstream corrector has been knobbed enough to get the beam all the way down the pipe. The dotted plot shows the ideal, model-based trajectory for the given corrector setting. The user then instructs PLUS to plot the differences between the two orbits (Fig. 3). It is clear that the error originates in the region where the differences grow large. By attaching a knob to the quadrupole in that region and introducing an alignment error, the user further matches the model trajectory to the measured one (Fig. 4). Now another alignment error is apparent further downstream. The user introduces another error into the model at the downstream location, and knobs it until the trajectories match (Fig. 5). At this point, the two major errors in the beamline have been uncovered.

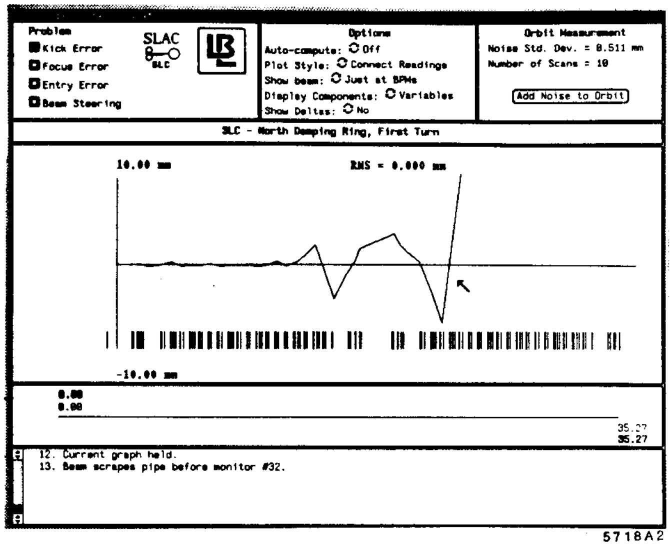

Fig. 1. COMFORT–PLUS display showing the initial, measured trajectory.

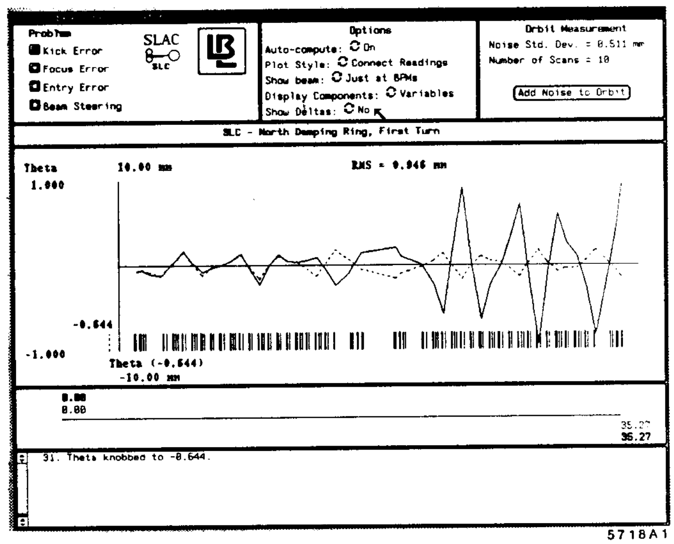

Fig. 2. An upstream corrector has been knobbed to get the beam all the way down the beamline (solid). Also shown is the predicted beam trajectory for the same launch condition (dotted).

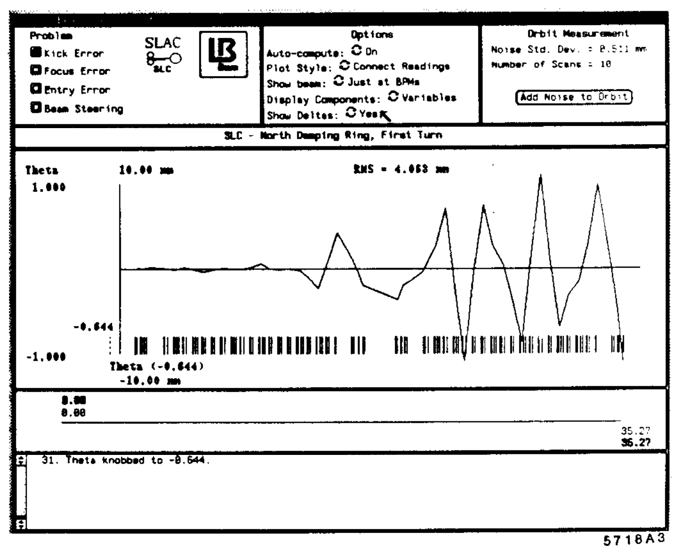

Fig. 3. Plot of the trajectory differences between the measurement and the prediction shown in Fig. 2.

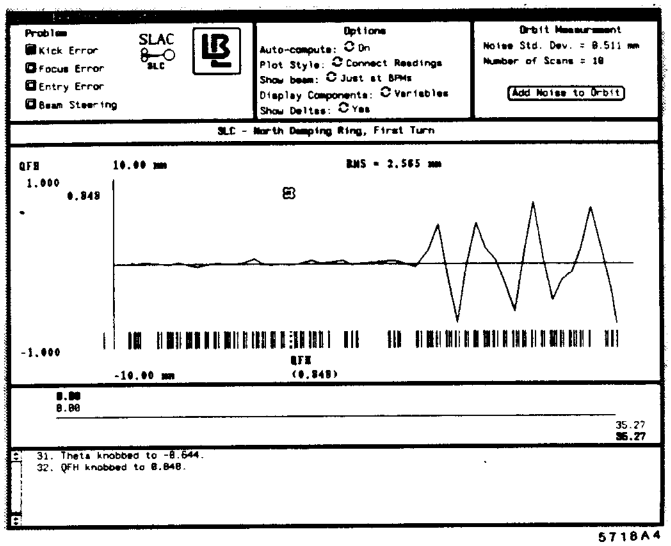

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Fig. 4. Plot of the trajectory differences after knobbing an error in the region where the trajectories first diverge.

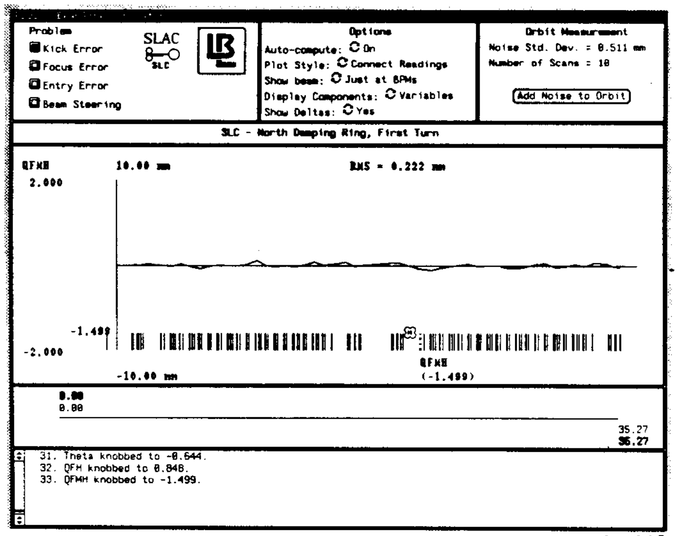

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Fig. 5. Plot of the trajectory differences after knobbing of a second error in the region where the trajectories in Fig. 4 diverge.

The ultimate time- and labor-saving method is to automate all the above procedures, usually done by an accelerator physicist expert, into a computer program called an expert system. A prototype expert system, ABLE,[6] that automatically finds beam-kick errors has been built and successfully tested. The expert system requires orders of magnitude less time to find errors than required in the past using *manual* methods.

5. Summary

For transportability, COMFORT and PLUS are both written in FORTRAN-77 and are intended to be in full compliance with the Standard. COMFORT has been successfully run on VAX, IBM, and SUN computers; PLUS on VAX, SUN, and Symbolics computers. For ease of integration into any control system a keyboard interface has been provided. The present SUN-specific graphical interface can be used directly, or serve as a guide for implementing other graphical interface systems. The low cost of workstations makes the former an attractive option.

The program has been used to train novice users to solve problems that, until now, have involved tedious numerical calculations and considerable expertise. In addition, it can be used by accelerator physicists to further their understanding of the beamline system . Also, PLUS has been used to develop rules for the ABLE expert system.

COMFORT-PLUS has been written in a modular fashion that will allow us to add new methods with a minimum of effort. The major benefit of the simulation is that studies can be done off-line without having to waste expensive beam time.

PLUS, with its graphical interface, allows the effects of a *trial and error* solution to be seen quickly and conveniently on-line without risking possible damage to the machine. The graphics interface makes solving lattice error problems easier and more intuitive.

The development of PLUS and its graphical interface took only a few months. Inspired by its success, we are planning to expand the capabilities of the programs to include other accelerator control algorithms and features. Because the major development of the basic program is complete, further enhancements should be a straight-forward and easy task.

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References

1. E. Theil, V. Jacobson, V. Paxson, "The Impact of New Computer Technology on Accelerator Control," these Proceedings.
2. M. D. Woodley, M. J. Lee, J. Jaeger, and A. S. King, "COMFORT, Control Of Machine Functions OR Transport Systems", 1983 Particle Accelerator Conf., Santa Fe, New Mexico, March 21-23, 1983.
3. V. Paxson, V. Jacobson, E. Theil, "A Scientific Workstation Operator-Interface for Accelerator Control", these Proceedings.
4. Martin J. Lee, Scott H. Clearwater, Stephen D. Kleban and Lawrence J. Selig, "Error-Finding and Error-Correcting Methods for the Start-Up of the SLC," these Proceedings.
5. A special purpose optimization program developed for SLAC by the Stanford University Systems Optimization Laboratory.
6. S. H. Clearwater and M. J. Lee, "Prototype Development of a Beamline Expert System," these Proceedings.