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ON-LINE CONTROL MODELS FOR THE STANFORD LINEAR COLLIDER*

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Models for computer control of the SLAC three-kilometer linear accelerator and damping rings have been developed as part of the control system for the Stanford Linear Collider. Some of these models have been tested experimentally and implemented in the control program for routine linac operations. This paper will describe the development and implementation of these models, as well as some of the operational results.

Introduction

More than a dozen mathematical models[1] will be needed for on-line computer calculation of the strengths of the magnetic components in the Linac, Damping Rings, the Bending Arcs, the Final Focus Region, and the transport beamlines connecting these systems in the Stanford Linear Collider (SLC). At least as many computer models will be required to correct the effects of errors in these systems. This work will call for the close collaboration of many accelerator physicists and programmers to develop and test these models, and to implement them into the SLC control program. Because of the complexities of this task, it is necessary that everyone involved follows the same procedure in the design and implementation of models into the control program.

Over the past eighteen months, we have developed and installed models for the first 10 sectors of the Linac, the Damping Ring, and the transport beamline between the Linac and the Damping Ring (LTR). In all of our work, we have followed a simple three part procedure: (1) define the design objectives; (2) choose a method of modeling to achieve these objectives; (3) apply the method to specific cases. Since all of the existing models have been found to be satisfactory, we will follow this procedure in the design and implementation of the future models required for other systems in the SLC. The purpose of this paper is to describe our design and implementation procedure, and to discuss some of the operational experiences associated with the models that we have completed.

Design Objectives

We have learned from our experience in maintaining and modifying the modeling codes in the PEP and SPEAR control programs that we must define our design objectives for the SLC modeling codes carefully. Some of the design requirements are:

1. Each of the off-line codes used in the design of an SLC system should be an on-line model.
2. Each of the off-line codes used in the study of such a system should also be an on-line model.
3. Each model should be a self-contained module which calculates the value of an output vector for a given value of an input vector.
4. The values of the input and output vectors should be obtained from the database of the control program.
5. Streamlined modeling codes should be used only after the accelerator system is throughly debugged and understood.

For initial operation of machines under computer control, it is very important that the on-line models of the systems are the same as those used in the design calculations and error studies. Thus, all those codes used for the final beamline design of the SLC will be included in the control program. The primary reason for initially incorporating the off-line programs is to eliminate the errors associated with reprogramming and restructuring of the models. Since the control model is the design model, the models work by definition albeit a system may not perform as predicted by the modeling. If such an event occurs, it would be reasonable to investigate errors in the other areas (design, fabrication, installation, or calibration) but not to be concerned with the accuracies of the modeling. Inclusion of design codes should encourage the machine designers to participate in the initial operation of the systems as well as in the experimental verification of the design models.

A drawback to putting the designer's models on-line is that such programs are typically large, general purpose routines which require relatively large amounts of computer memory and are not as fast as one would like for an automated control system. Once a new system has been brought up and understood, new streamlined and speedier models should be developed and installed in place of the original design codes. To ease the process of model modification and replacement it is important that modeling codes are modular in nature. This is accomplished by requiring the specific modeling codes to accept input vectors and to return output vectors of information to appropriate driver programs. Model replacement then becomes a minor localized perturbation to the control system.

Communication through the database is a tool by which modularity of modeling can be insured. Use of the database also allows simultaneous development of interacting models by several different people. Database communication provides a well structured method by which modeling can communicate with those portions of the control program associated with the actual adjustments of power supplies while also isolating the task of modeling from the remainder of the control system. The details of power supply control become transparent to the modeler.

Models

From a modeling point of view, it is considered to be poor practice to operate the accelerator by tweaking power supplies. Using a model, it is possible to adjust the value of any of the beam parameters which are elements in an input vector. However, given that a power supply output has changed, models enable a user to predict the effects on the beam. This corresponds to finding the value of an input vector, given known values of an output vector in terms of power supply settings. A model is useful in the study of a system without actually adjusting the system itself. Such an "ignore hardware" feature allows a user to read the extant system settings, to calculate a change, and to predict the results of such a change before implementing the changes. In addition, models enable one to study the effects of errors in a system and the subsequent effectiveness of schemes designed to compensate for such errors.

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SLC models can be divided into three broad categories according to the functions they perform: (A) to compute the strengths of system elements which correspond to a set of desired parameters; (B) to calculate the strengths of correcting elements to reduce the effects caused by errors in a particular system; and (C) to facilitate normal machine operations with miscellaneous application codes which perform sundry specific tasks. Each region of the SLC will be characterized by a single type A model. Type A models are used for lattice design and for computation of machine functions (e.g. beam sizes, machine tunes, transfer matrices, etc.) corresponding to a specified machine configuration. Based on the system parameter values determined from the type A model, error corrections will be computed by as many type B models as there are kinds of errors to be corrected. Type B models include programs to steer the beam to the centers of the linac irises or correct the closed orbit of a stored beam and to refocus the beam in compensation for changes in beam energy. Type C models comprise the remainder of the modeling type calculations. An important example of type C modeling is the case of models which predict the behavior of the beam in response to the variation of a single parameter or element in a system. While such models can be short lived in nature, they are indispensable for diagnosing hardware problems during the machine turn-on phase.

In general, each of the models can be considered to be a stand alone computer code which computes the value of an output vector corresponding to the value of a desired input vector. Input vectors to the models include the users's specifications, usually entered from options selected using a touch panel, as well as other necessary data which is stored in the computer database. The information in the output vector is in turn saved in the database or on library files. Database entries have been reserved for information relating to the state of elements in the accelerator. This includes, for example: the locations, lengths, current settings and integrated field strengths of magnets; the beam energy gain associated with each klystron; and the locations of beam position monitors. Information resulting from a modeling calculation that is not involved with the setting of power supplies (such as the calculated machine functions or the results of calculations which will appear on a graphics display) is not included in the database but is stored in local data files.

TRANSPORT[2] was used to develop the focusing for the Linac and to design the beam transport system which connects the Damping Ring and the Linac (LTR). Subsequently, the system models (type A) describing these regions are represented by the respective TRANSPORT datasets that were used in the system design studies. Similarly, COMFORT[3] was used in the case of the Damping Ring; the design COMFORT dataset represents the present control model of the Damping Ring. Examples of type B models for these regions are the trajectory correction codes. The models communicate with the database in physical units (e.g. meters for longitudinal position in the accelerator, GeV for beam energy, kG-m for dipole magnet settings, kG for integrated quadrupole gradient, etc.). The conversions of the magnet field values to power supply settings are considered to be type C modeling.

Applications

At present, the first 10 sectors of the Linac, the Injector, the Damping Ring, and the Linac to Damping Ring transport line (LTR) have been fully instrumented with SLC type quadrupoles, corrector dipoles, and beam position monitors. Only those beam position monitors in the first sector of the Linac have the associated electronics to allow them to be readout using the control computer.

Since September 1982, the SLC type magnetic elements have been controlled using recently developed software. Modeling for these regions consists primarily of the type A lattice design programs and sundry machine function displays. In addition, several applications codes have been written and tested. A brief description of the modeling for the instrumented regions is given below in order to illustrate our modeling procedure.

Linac Type A system design models for Linac control consist of TRANSPORT datasets which describe the beamline elements in each of the linac sectors. These datasets are updated according to initial beam properties, klystron gain settings, and desired betatron phase advance in the SLC F0D0 array. TRANSPORT is used to accomplish the mathematical fitting of magnet strengths and the determination of machine functions. The output vector, consisting of calculated quadrupole strengths and selected transfer matrix elements, is saved in the database for use by magnet supply control programs and by type B and C models. A group of displays and diagnostic routines have been written to aid in both the normal operation of the Linac and during the weekly SLC machine physics experiments. Perhaps the most useful of such models is a display of the predicted beam size along the length of the Linac, given the operating values of quadrupole strengths and klystron powers. This beam simulator is used to help determine the effects of arbitrary changes in the complement of beamline elements and to explain observed changes in the beam. This routine is used to decide whether additional adjustment and calculation are required when operating conditions change. A similar program predicts the position of the beam in the Linac, subject to launching conditions, corrector dipole settings, quadrupole values, and beam energy. Once the beam position monitors have come on-line, the position simulator will be used extensively in the development of automated beam steering algorithms. Locations of the magnetic centers of linac quadrupoles have been explored using a quadrupole shunting program; the generation of calculated beam trajectory distortions have been used to diagnose dipole calibration errors. An emittance measuring model has been used to determine the phase space orientation of the beam injected into the Linac.[4]

Damping Ring The type A design model for the Damping Ring lattice consists of a COMFORT dataset which describes the quadrupole and bending magnets in the ring lattice. This dataset is updated to reflect the periodicity conditions of the machine functions in the repeated cells and the desired betatron tunes in the ring. COMFORT determines the strengths of the quadrupole magnets as required by the values of fitting conditions in the dataset. The output vector, consisting of calculated quadrupole strengths and selected transfer matrix elements is saved in the database for use by the magnet supply control programs and by type B and C models, such as models for closed orbit and eta correction. The values of the machine functions at the point of injection from the LTR are also saved in the database as a matching condition for the LTR.

LTR The TRANSPORT dataset used to design the LTR has been incorporated into the control program. This design dataset is updated with respect to the beam leaving the Linac along with the required Damping Ring machine functions, as determined by the Damping Ring models, and then used with TRANSPORT to find the desired set of magnet strengths. Calculated magnet strengths are saved in the database. Displays of beam sizes and eta functions corresponding to the current magnet settings enable users to study the effects of tweaking individual power supplies. It has been obvious from the onset of Linac and LTR modeling that TRANSPORT is too slow and memory intensive for use in the control system. At present, some of the functional tasks of TRANSPORT are being accomplished with the use of COMFORT. In the case of the Linac, COMFORT is being used to determine machine functions for a given set of element strengths. Eventually, COMFORT will be used for the lattice design calculations. The replacement of TRANSPORT by COMFORT is expected to be transparent to the user because of the modularity of the modeling system. In addition to the usual lattice and error correction programs, we have found the beam simulators to be extremely important models. They have been used to diagnose energy errors, magnet calibrations, broken power supplies and to successfully design focusing lattices when there has been insufficient knowledge, time, or desire to perform an analytical calculation.

Conclusions

We have developed a procedure of design and implementation of mathematical accelerator models which are used in the computer control system of the SLC. These models are used to generate magnet strengths which are on-line solutions to the beam dynamics problems. In addition, such models allow the users to tweak beam parameters and to study the effects of changes in individual beamline elements. The models are dataset driven to simplify the process of implementation, modification, and replacement (by improved modeling schemes). To a large degree, we believe that any measure of success in the modeling can be attributed to the careful selection of design procedure and strict adherence to the procedure. The uniform structure of our modeling keeps the system flexible by facilitating the process of modifying and replacing specific model algorithms.

The task of developing and implementing the on-line control models has been assigned to a group of accelerator physicists and programmers, who are members of the Accelerator Physics department and the Instrumentation and Control department at SLAC. Accelerator physicists worked out the design and correction procedures and then turned the codes over to the programmers for implementation into the control system. The accelerator physicists also specified the input/output vectors to be saved in the database/files, as well as the information for the displays and data entries. The programmers participated with the machine physicists in the operation of the accelerator systems under the computer model control. This close collaboration between the accelerator physicists and programmers has turned out to be an important factor in our success.

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