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APPLICATION OF ONLINE MODELING TO THE OPERATION OF SLC*

M. D. Woodley, L. Sanchez-Chopitea, H. Shosee
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94305

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Abstract

Online computer models of first order beam optics have been developed for the commissioning, control and operation of the entire SLC including Damping Rings, Linac, Positron Return Line and Collider Arcs. A generalized online environment utilizing these models provides the capability for interactive selection of a desired optics configuration and for the study of its properties. Automated procedures have been developed which calculate and load beamline component set-points and which can scale magnet strengths to achieve desired beam properties for any Linac energy profile. Graphic displays facilitate comparison of design, desired and actual optical characteristics of the beamlines. Measured beam properties, such as beam emittance and dispersion, can be incorporated interactively into the models and used for beamline matching and optimization of injection and extraction efficiencies and beam transmission. The online optics modeling facility also serves as the foundation for many model-driven applications such as autosteering, calculation of beam launch parameters, emittance measurement and dispersion correction.

Introduction

Much of SLAC's Linear Collider (SLC) has been commissioned and is now being routinely operated with the help of online model-driven control algorithms. The software which generates the online models here at SLAC has been evolving for quite some time, and has been discussed in previous papers.¹⁻⁴ This paper discusses the nature of the models as they exist today and the protocols which have been established for their generation and storage online for use by the control system. We will also describe, from an operator's standpoint, how the system is used to set up a model, and how the model thus generated is then used for control.

The Models

The SLAC complex is made up of accelerator sub-systems of several different types: linac, damping rings, storage rings, standard transport lines and the combined-function Collider Arcs (see Figure 1). Daily operations entail delivery of beams of electrons and positrons to various parts of the machine,

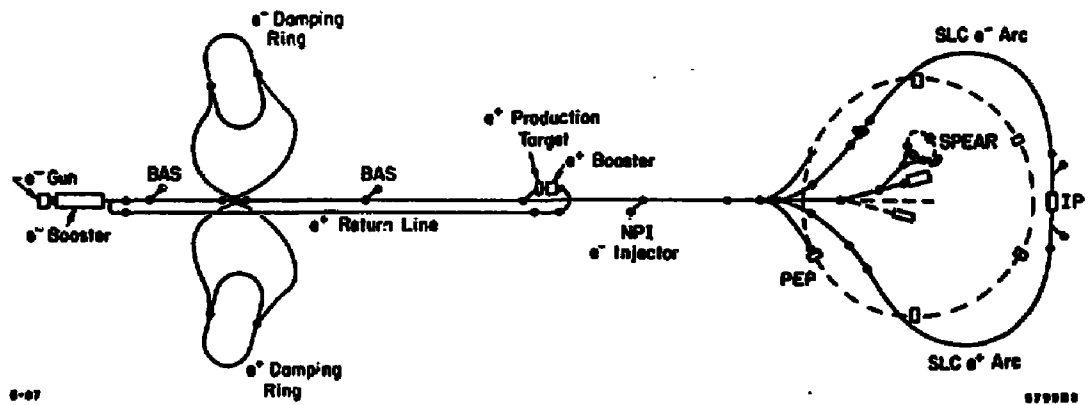


Fig. 1. Schematic layout of SLAC complex showing modeled areas (solid lines) and marker points (dots).

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MASTER

sometimes at very different energies. Integrated models which allow the operators to establish and control any beam, from production to delivery, quickly and easily are essential.

In previous versions of our online modeling system, specialized optics programs were used to generate the model for each different type of accelerator sub-system.² This allowed us to make use of the special features of each optics program that made it appropriate for a given part of the machine and to create the online models using the same programs which were used for the design and study of these areas offline. We soon learned, however, that this philosophy had some drawbacks.

In order to function efficiently in the computing environment of our control system, each optics program had to be modified to allow it to interface directly to our control program and database and to run autonomously. This meant many man-hours spent delving into the internals of each program to perform the interfacing and made implementation of fixes and updates to each program cumbersome. In addition, difficulties were encountered in making these programs interface with each other in order to generate integrated models of entire systems. In order to save time, reduce programming overhead and standardize the models of the various pieces of accelerator, we decided to use a single optics program for all online modeling.

COMFORT³ was chosen for this purpose because it can handle each major type of accelerator sub-system (transport line, linear accelerator and storage ring), it was already integrated into the control system environment⁴ and because, as its authors, we knew its internals intimately and could maintain it easily. The choice of COMFORT as the single optics program for all online modeling necessarily set some bounds on the nature of our models. Since COMFORT is a first order, uncoupled optics program our model of the machine is a linear, uncoupled model. We felt that the limitations of linear, uncoupled models were outweighed by the advantages of standardized models and a single, easily maintained optics program which had been reliably in use for some time.

A "building block" approach to the generation of online models was adopted in order to provide maximum flexibility in the definition, selection and modeling of beamlines. We define a *beamline* as a group of one or more accelerator sub-systems which, when taken together, can transport a beam of particles from a well-defined originating point to another, equally well-defined, destination. This scheme was implemented via a three-tiered selection hierarchy composed of objects which we call model LINES, SECTIONs and REGIONs. At the lowest

level we divided the SLAC complex into the smallest set of unique "atomic" pieces from which any desired beamline could be constructed; these are the model SECTIONs. Figure 1 shows the SLAC complex and illustrates this division. The dots are the division points; they are referred to as *marker points* and, for SLC beams, each has a specific set of desired beam properties associated with it. Some of these points are origins or destinations for beamlines. Each SECTION has its own model which can be generated individually or in series with any other SECTION with which it shares a marker point. A model LINE is a beamline made up of a contiguous sequence of model SECTIONs; a model REGION is a group of one or more SECTIONs within a LINE which is defined so that operators can select geographical regions of the machine regardless of SECTION boundaries. Any defined LINE, REGION or SECTION may be selected via control system touch-panels; we will discuss how these objects are defined and selected in later sections. A model of a selected area can be generated by requesting a COMFORT run which will take extant beam phase ellipse parameters from the originating marker point and translate them through the lattices of the selected SECTIONs.

The Control System Environment

The overall structure of the SLC control system has been discussed in detail elsewhere.^{4,6,7} In brief, one or more copies of the SLC control program (SCP), executing on a VAX 11/785, communicate via a SLAC-developed, broadband-based network known as SLCNET with a number of augmented Intel 86/30 single-board computers ("micros"), which in turn monitor and control the hardware through CAMAC interfaces. A database exists on the VAX which is shared by the SCPs and the micros and which contains information about the state of the components which make up SLC. Figure 2 shows a schematic of the control system, with emphasis on the relationship of modeling to the online computing environment. We will limit the present discussion to the VAX-resident elements of the control system which pertain to online modeling.

The COMFORT optics program has been modified in several ways in order to integrate it into the online computing environment. A preprocessor has been added which gives COMFORT direct access to the SLC database and a set of "front end" routines have been added which effectively make COMFORT a batch process on the VAX which owns a queue to which computation requests may be sent. COMFORT remains

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idle until one or more requests for computation appear in its queue. It then process the requests sequentially until the queue is empty and returns to idle.

Generation of a model begins in the SCP with the selection of an area. The SCP is run via touch-panels. The first touch-panel an operator is presented with at SCP startup is the MASTER INDEX panel. This panel is essentially a gateway to other INDEX panels associated with various functional sub-systems of the control system. The operator selects the MODEL SYSTEM INDEX in order to begin the selection of an area to be modeled. At this level, a model LINE is chosen, as well as a BEAM. A BEAM is basically a time-slot to which triggers for pulsed devices (such as klystrons and kickers) have been assigned. Because the energy profile of the linac for a given beam of particles depends on which BEAM has been assigned to it, this number must be made known to the modeling software.

The selection of a model LINE automatically brings up the next panel, the MODEL APPLICATIONS INDEX. At this level the operator selects the REGIONs of the selected LINE which he wishes to consider. The REGIONs available for selection are displayed on the touch-panel dynamically, based on what has been defined for the selected LINE. The results of this selection are made known to all model-based applications programs which can be called up from this panel, so that any model-driven function that is requested will be performed on the selected area. Figure 3 illustrates the area selection hierarchy.

To generate a model, the operator next selects the OPTICS panel. From the OPTICS panel, the operator may request a COMFORT run to generate the optics for the selected area. A request-for-computation message is deposited in a VMS mailbox which is established for the COMFORT process when it is brought online; in addition, an event flag is set which informs the COMFORT process that its queue is not empty. The COMFORT process responds to the flag by reading the request message from its mailbox and acting upon it. The initial conditions for the run (beam energy and phase ellipse parameters) are contained in the request message itself; COMFORT reads input files for each of the selected model SECTIONS and, if requested, the database, performs the requested computations sequentially on the selected SECTIONS, and generates a group of output files containing the computed optics. The SCP may then read these files and present the results graphically to the operator. If the results of the computation meet with approval, they may then

be deposited into the database and become available to model-driven applications programs. The connections between SCP, COMFORT, the database and the model input and output files is diagrammed in Figure 2.

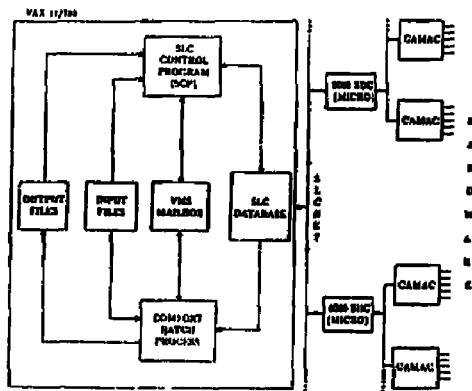


Fig. 2. Functional diagram showing how modeling fits into the SLC control system environment.

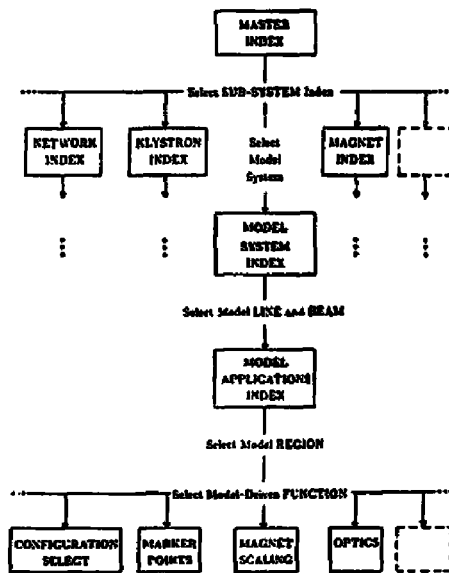


Fig. 3. Functional diagram of the region selection tree.

The Database

As previously stated, the SLC database contains information about the state of machine components. Database quantities of particular interest in a discussion of modeling are the physical attributes and set-points of magnetic beamline elements and the Twiss parameter values which describe a beam at various points throughout the beamline.

Magnet set-points in the database are specified in two ways. Each magnet has an integrated strength control value (BDES) which is given in engineering units:

$$BDES_{dipole} = \int B \, dl \quad (\text{KG} - \text{m})$$

$$BDES_{quadrupole} = \int \left(\frac{\partial B}{\partial x} \right) dl \quad (\text{KG})$$

$$BDES_{sextupole} = \int \left(\frac{\partial^2 B}{\partial x^2} \right) dl \quad (\text{KG} - \text{m}^{-1}).$$

These BDES values correspond directly with magnetic measurements data taken for each magnet. The BDES control values are translated into current values (amps) at the microprocessor level via a polynomial characterization of the measurement data for each magnet and the result used to set that magnet's power supply.

For a variable energy profile machine, however, BDES values alone are not enough to retain desired lattice properties (such as betatron phase advance in FODO cells) for different beam energies. Therefore an additional control value for each magnet that is independent of beam energy is also saved in the database.

These values are known as KMOD values; they are computed from values of BDES and beam energy for each magnet taken from the design for a particular optical lattice:

$$KMOD_{dipole} = \frac{BDES_{dipole}}{(B\rho)l} \quad (\text{m}^{-1})$$

$$KMOD_{quadrupole} = \frac{BDES_{quadrupole}}{(B\rho)l} \quad (\text{m}^{-2})$$

$$KMOD_{sextupole} = \frac{BDES_{sextupole}}{(B\rho)l} \quad (\text{m}^{-3})$$

where $B\rho$ is the magnetic rigidity of the beam at the magnet and l is the effective length of the magnet. From

these defining equations we can see that, for any magnet, the BDES control value needed for any beam energy is related to its KMOD value by:

$$BDES_{magnet} = B\rho \cdot KMOD_{magnet} \cdot l_{magnet}$$

The KMOD value for a dipole magnet is its bend angle per unit length and is a constant determined by local beamline geometry; these values are computed once and stored permanently in the database. The KMOD values for quadrupoles and sextupoles come from optical lattices of which there may be many for any particular part of the machine. Sets of BDES and KMOD values may be saved in named configuration files which may be loaded by the operators at any time.

BDES control values for magnets may be changed by the operators with software knobs, available through the SCP, which operate at the microprocessor level. KMOD values, however, are not automatically updated when a BDES value is changed in this way since KMOD depends not only on the current flowing in a device (which the micro knows), but also on the energy of the beam passing through that device (which the micro is unaware of). Hence the "real" machine may have BDES values which are not in agreement with their corresponding KMOD values for a given beam if adjustments of this kind have been made. In order to allow the operator to generate KMOD values which match the extant BDES values, a facility has been provided which allows KMOD values to be computed from the present BDES values and the extant beam energy profile. Once this computation has been performed, the operator can re-run the optics for the effected area and create a model of the true state of the machine. Conversely, new BDES values may need to be computed from the extant KMOD values when the energy profile of the machine changes as, for instance, in the case of automated klystron replacement. When a klystron becomes inoperative, a different klystron can be brought online automatically in order to recover the same beam energy at the beam delivery point; however, the beam energy profile between the faulted klystron and its replacement will now be different. In this case the same conversion facility may be used to compute new BDES control values from the extant KMOD values and the new energy profile. This magnet strength conversion facility, coupled with the ability to save and restore configurations, gives us a flexible system for establishing and maintaining desired accelerator lattice

properties over varying beam energies and for keeping an up-to-date model of the machine available at all times.

While complete sets of Twiss parameters at every point in a beamline are computed by COMFORT and written to output files, only a small subset of Twiss values that are needed by model-driven applications programs are actually loaded into the database. Twiss parameters are saved in the database at the locations of beam diagnostic elements (beam position monitors, beam width monitors, profile monitors and wire scanners), beam steering elements, and at marker points. In order to allow quick comparison of extant Twiss parameters at marker points to their SLC design values, a second set of Twiss values, the SLC design values, is also saved in the database at all marker points. A facility exists for displaying both sets of Twiss values at any marker point; this same facility provides the capability of entering Twiss parameter values at marker points by hand via a special touch-panel.

Model Input Files

The input files needed for online modeling can be divided into two categories: *model definition* files which are used to define model SECTIONS, REGIONS and LINES and are read by SCP only, and *skeleton desk* files which are special standard input format³ files for each model SECTION which are read by COMFORT.

There are three model definition files containing the definitions of SECTIONS, LINES and REGIONS.

The SECTION definition file contains a SECTION's skeleton desk number, display group name (display groups are basically lists of database devices which can be accessed as a group; each model SECTION has a display group associated with it), beginning and ending marker points, and a flag which indicates whether a SECTION represents a storage ring or a transport line.

The LINE definition file lists, in order, the model SECTIONS that comprise each LINE. In addition, the LINE definition file assigns a unique number to each LINE which allows the software to reference it.

The REGION definition file lists for each defined REGION the identification number of the LINE for which the REGION is defined, the number of SECTIONS in the REGION, and the ordinal numbers of the first and last SECTION of the REGION from the list of SECTIONS defined for the associated LINE. In addition, each REGION is assigned a name that is

to be displayed on touch-panel buttons when that REGION is available for selection.

The model definition files are read once by each SCP at startup time or upon operator request (if, for instance, the files have been changed since SCP startup).

The second type of model input files, model skeleton decks, are augmented standard format input decks for COMFORT. These decks contain a description of the static properties of the elements in each SECTION and give their relative positions. In addition, the skeleton decks contain pointers to the energy contributions of klystrons and to the strengths of quadrupoles and sextupoles in the database. A sample is given here to illustrate the structure of a typical skeleton deck:

```

TITLE
SAMPLE SKELETON DECK
!
! DATABASE POINTERS
!
APOO1 : POINTER, DEFA= 0.105,FRAC= 0.263,&
PRIM= KLYS, MICR= L100, UNIT= 11, SECS= ENLD
QPOO1 : POINTER, DEFA= 4.000,FRAC= -1.000,&
PRIM= QUAD, MICR= L101, UNIT= 111, SECS= KWOD
!
DATABASE
!
! ELEMENT DEFINITIONS
!
K0000111: ACCE,L= 0.802000,EGAIN= APOO1,&
          LABEL= "KLYS L100 11"
B0101351: SBEN,L= 0.101000,ANGLE= 0.105,&
          LABEL= "BND5 L101 135"
Q010111T: QUAD,L= 0.124000,K1= QPOO1,&
          LABEL= "QUAD L101 111"
DRIF0001: DRIF,L= 1.000000
DBMARK03: MARK,LABEL= "MARK V100 3"
!
! BEAMLINE
!
SAMPLE : LINE= ( DRIF0001,K0000111,DRIF0001,&
                Q010111T,DRIF0001,DBMARK03 )
!
! COMMANDS
!
USE      , SAMPLE , INS
!
ENDPPROC
!
STOP

```

Note that each database pointer element ("POINTER") also contains a default value ("DEFA") for the element associated with it and a value called "FRAC". The default value is the magnet strength or accelerator energy contribution taken from the SLC design lattice for the associated device. A flag in the computation request message from SCP to COMFORT specifies whether the default values or the database values are

to be used to resolve pointer references.

For magnets, the *FRAC* values allow the modelers to define arbitrary *judge* factors which can be used to model empirically determined errors in the strengths of the associated devices. For klystrons, the *FRAC* value tells what fraction of a klystron's energy contribution is to be attributed to a given accelerator section; this is needed since each of SLC's klystrons feeds four accelerator sections, and also because SLC utilizes "wraparound" magnets which may be strapped around an accelerator section at an arbitrary position.

Two non-standard commands in each skeleton deck are the *DATABASE* command and the *ENDPPROC* command. The *DATABASE* command tells COMFORT's preprocessor routine to resolve the pointer references, using values from the database, if this has been requested, or the default values. The *ENDPPROC* command causes COMFORT's preprocessor routine to return control of program execution to "standard" COMFORT for the actual optics computations.

The modular nature of this file-driven protocol makes adding a new area of the SLAC complex to the "modeled" world extremely easy. A design lattice for the new area is delivered to us and is translated into a skeleton input deck; if the appropriate database entries exist, pointers are created and added to the skeleton deck. The model definition files are then modified to include the new area and a display group is established in the database for it. Once the operator requests SCP to read the modified model definition files the new area is available for selection and modeling.

Model Output Files

The online model optics computation facility was designed to permit computation of the optics of any part of the machine given the extant settings of all beamline devices, to be able to easily compare these optics with design optics, and to have this model available to all control stations. In addition, an operator or machine physicist at any control station should be able to perform lattice simulation and testing for any part of SLC without interfering with other modeling work which may be going on at other control stations. In order to implement these goals, we have defined three varieties of COMFORT output files which essentially contain three different models of each SECTION of the machine.

Whenever an optics computation is performed by COMFORT on behalf of a given control station, the output files generated have a special code appended to their filenames which

identify the files as belonging to that control station. This type of file is known as a *scratch* file. Obviously, the number of scratch files can potentially grow quite large as there are many available control stations and each one can have a scratch file for every defined model SECTION. In order to conserve disk space a scratch file purging protocol is in effect which keeps the actual number of these files small.

The second type of COMFORT output file available to the control system is known as the *design* file. There is one unique design file for each model SECTION which contains the SLC design optics for that SECTION. Graphic displays of the design optics can be called up at any time. Of course, the operator can create a scratch file containing the design optics by requesting that COMFORT use the design magnet strengths contained in the skeleton decks when computing optics; however, in order to retain the capability of comparing any scratch optics to the design optics, we have created a separate design file.

The third type of COMFORT output file is called the *database* file. This file contains the extant optics of the currently selected beam and beamline. There is one database file per model SECTION. When an operator decides that his scratch optics should become the database optics he invokes a procedure that strips the control station identification code from the scratch files and then reads these files, depositing Twiss values contained therein into the database for the appropriate devices. The contents of the database optics files can be displayed graphically at any control station at any time.

Even with file purging protocols in effect as mentioned above, there still are quite a few COMFORT output files saved on disk at any given moment (as of this writing, there are approximately 50 model SECTIONS defined). In order to conserve space, all files are created by COMFORT in binary format; a facility is provided for generating printed output of the optics of any section which converts the binary files to ASCII, prints them, and then deletes the ASCII version.

As mentioned above, a complete graphics presentation facility is provided which can display the contents of any of these files on request. Included in this facility are zooming and scaling options and the ability to request either an iconic representation of beamline elements or their database identification numbers directly on the display beneath the plotted Twiss functions. Figure 4 shows a typical β function display with the beamline elements depicted iconically at the bottom; Figure 5 shows a zoomed-in view of a portion of this same display.

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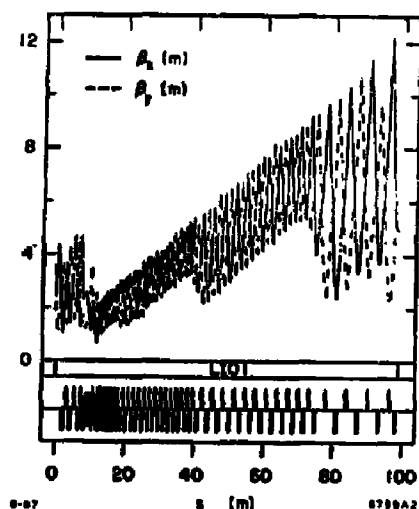


Fig. 4. Typical Twiss parameter display showing beamline elements in iconic form at the bottom.

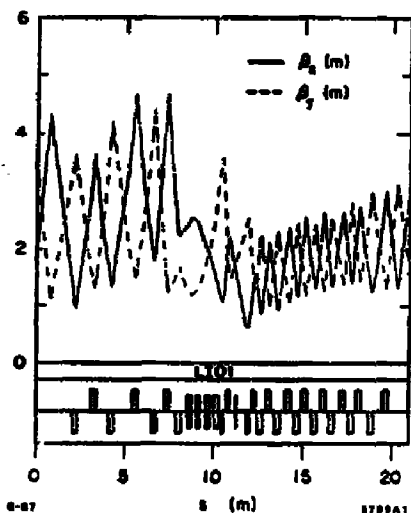


Fig. 5. "Zoomed-in" view of Twiss parameter display depicted in Figure 4.