

Accelerator Modeling System for the Future*

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ABSTRACT

Many computer programs and a variety of models exist for the design of accelerator lattices and the correction of errors. Many physicists contributed to this work by developing codes to suit a variety of machines. At present, we are integrating some of these codes into a unified framework to design and control any type of machine. We will refer to this system of interactive accelerator design, control, and analysis codes as the All-In-One Modeling system (AIM). This paper will explore the utilities of AIM for future accelerator modeling and control. As an example, we will describe a procedure to produce both a linear and a nonlinear model for SPEAR.

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INTRODUCTION

For almost three decades at SLAC, we used model-based computer programs to design and control accelerators. Our use of models started when we designed the two-mile linac. Later, we developed computer programs to change lattice

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configurations and to correct orbit errors in the storage rings SPEAR and PEP-I. Finally, during the last ten years, we used computer programs to find a working model and to correct the linear beam optics in the linear collider SLC. As the complexity of the projects increased, we discovered the need for new accelerator modeling and beam simulation codes. Now that SLAC is constructing the *B* Factory (PEP-II) and preparing a proposal for the Next Linear Collider (NLC), it is natural to ask this question: what kind of modeling codes will we need for these "next generation" machines?

The operation of the next generation of accelerators will rely on model driven controls and feedback systems (1). In addition, we will need modeling techniques to find and correct both linear and nonlinear optics errors during the commissioning of new accelerators, and during the operation of these accelerators. This is also true when we extend the operation of an existing accelerator to a new regime. As an example, we realized the need for an accurate nonlinear model during a 'low-alpha' experiment at SPEAR (2). For this experiment, we planned to reduce the momentum compaction factor (α) by changing the linear optics of the ring. To change the ring optics, we used a linear modeling code to compute the quadrupole magnet strengths for lattice configurations having different values of α . This process required an accurate linear model of the ring to find the strength of the quadrupole magnets and to avoid beam loss. During the lattice configuration change, we also needed to preserve the dynamic aperture. Since the lattice modification required nonlinear optics correction, we also needed an accurate nonlinear model to calculate the strengths of the sextupole and octupole magnets.

One step toward solving this problem was to develop AIM (All-In-One Modeling system). The AIM system is a 'platform' on which we integrate a collection of existing modeling codes for beam control and lattice diagnostics. At the same time, we began to develop nonlinear modeling codes to integrate into AIM. In this paper, we will describe the basic structure of AIM, and the method to integrate existing codes into AIM. We will also describe new codes under development, and plans for the future. The next section describes the use of modeling codes to obtain a linear and a nonlinear model for SPEAR.

ACCELERATOR MODELS

One way to describe the linear optics of the ring is to use the transport matrix (3), starting from a reference point, for a single revolution around the ring. If we let x and x' represent the values of the horizontal position and angle, at the reference point, 0, the coordinate values after one turn are given by

$$\begin{aligned} x_0 &= R_{11}x_0 + R_{12}x'_0 \\ x'_0 &= R_{21}x_0 + R_{22}x'_0. \end{aligned} \quad (1)$$

This linear ‘R-Matrix’ model depends upon the strength and location of the quadrupole magnets and of course the orbit deviation through the sextupole magnets in the ring.

An equivalent way to describe the linear model of the ring is with the one-turn Lie operator (4) $e^{:f_2:}$ where

$$f_2 = k_1x^2 + k_2xp_x + k_3p_x^2 \quad (2)$$

where the coefficients (k_1, k_2, k_3) are constants whose values depend on the quadrupole magnet strengths. In this representation,

$$p_x = \alpha x + \beta x' \quad (3)$$

where β and α are the values of the beta and alpha functions at the reference point. The linear model of the ring for propagation through one revolution is given by the one-turn map:

$$\begin{aligned} x_1 &= e^{:f_2:} x \Big|_{x=x_0, p_x=p_{x0}} \\ p_{x1} &= e^{:f_2:} p_x \Big|_{x=x_0, p_x=p_{x0}} \end{aligned} \quad (4)$$

One of the useful features of this formalism is that we can readily extend the map to include high order effects. For example, by transferring all of the nonlinear effects at the end of the turn (4), the third order map is given by

$$e^{:f_2:} e^{:f_3:} \quad (5)$$

where

$$f_3 = \lambda_1 x^3 + \lambda_2 x^2 p_x + \lambda_3 x p_x^2 + \lambda_4 p_x^3. \quad (6)$$

Note that the values of the coefficients ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) depend on the strengths of both the quadrupole and sextupole magnets in the ring. The effects due to the nonlinearities are described by the following terms:

$$\begin{aligned} x_2 &= e^{i f_3} x \Big|_{x=x_1, p_x=p_{x1}} \\ p_{x_2} &= e^{i f_3} p_x \Big|_{x=x_1, p_x=p_{x1}}. \end{aligned} \quad (7)$$

This modeling procedure can be applied to both the vertical and longitudinal planes by introducing additional coefficients. Higher order nonlinear fields can be included by adding more terms to the map:

$$e^{i f_2} e^{i f_3} e^{i f_4} \dots \quad (8)$$

THE MODELING SYSTEM (AIM)

Today, numerous modeling codes are available for storage ring lattice design. We have selected two of these modeling codes, COMFORT (5) and MAD (6), to integrate into a single subsystem which we call the Modeling part of AIM. In addition, there are application codes available for beam control and lattice diagnostics such as RESOLVE (7) and CALIF (8). We have collected some of these into a different subsystem of AIM. We will refer to these programs as the Calibration, Diagnostic, and Control subsystems (see Fig. 1).

We integrated the programs contained in each subsystem by simple 'connector' codes (as depicted by the lines shown in the diagram above). To integrate a new program into AIM, we first convert the program into an 'object' by the use of two 'connector' codes: (1) FILin to write the input data file for the code, and (2) FILout to read the output data file from the code. After a new program has been encapsulated by the converter code, it is incorporated into AIM.

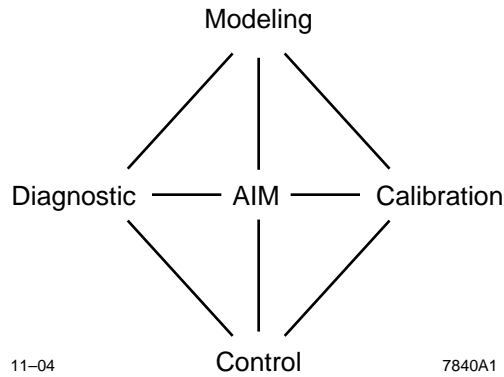


FIGURE 1. AIM, a system of four types of codes for the commission and operation of storage rings being developed at SLAC.

We used a similar method to connect AIM to the database of SPEAR. In this case, we simply used a set of two 'adapter' codes: (1) DBGet for getting information from the Database, and (2) DBPut for putting information into the Database. Using this simple procedure, we can connect AIM to the database of any existing or future accelerator.

MODELING CODES

Most accelerator model programs can be classified into two types: (1) Matrix, and (2) Map. For example, MAD primarily uses matrices to model the accelerator, while DESPOT (9) uses maps. Linear modeling programs can easily compute the values of the ring parameters such as the beta functions, tunes, chromaticities, damping times, beam sizes, etc. for a given ring lattice and magnet strengths. In addition, we need the model program to compute nonlinear effects such as resonance width and tunes shifts. It is therefore important to have consistent linear and non-linear models.

CONTROL CODES

To operate any storage ring, it is necessary to change the values of the ring parameters such as tunes, betafunctions, and emittance. Ring parameter changes are accomplished by computing the strengths of the quadrupole magnets with modeling codes. In general, this procedure involves two steps: (1) specify the ring

parameters to be changed, and (2) compute the required change in quadrupole or sextupole magnet strengths. We will call this process 'configuration change'. Since the calculation of a configuration change is inherently a nonlinear process, we have developed a code, TIPTOE, to make a series of linear configuration changes which we call mini-steps.

For instance, the use of TIPTOE with the modeling code COMFORT makes it possible to change the momentum compaction (α) without changing the tunes in SPEAR. Here is how each mini-step works:

- (1) Enter the new value for a set of ring parameters (desired α and betatron tunes in this example).
- (2) Calculate the partial derivatives of α and the tunes with respect to the quadrupole strengths from the model.
- (3) Calculate the desired change in α and tunes (old minus new).
- (4) From these partial derivatives, estimate the change in the quadrupole magnet strengths to change α while keeping the tunes constant.
- (5) Compute the predicted value α and tunes from the model for the new quadrupole strength.
- (6) Compute the difference between the predicted and desired value of α and tunes.
- (7) If the differences are not acceptable, reduce the desired change in α by 1/2 (define a sub-goal) and return to step (4).
- (8) If the difference is acceptable, 'download' the magnet strengths to the database of the storage ring.

In the future, we can also include the non-linear one-turn map in the model. Since we can calculate parameters such as resonance widths and tune-shifts with amplitude from the one-turn map, we can control these parameters using the TIPTOE procedure and the measured one-turn map of the ring. (See Fig. 2).

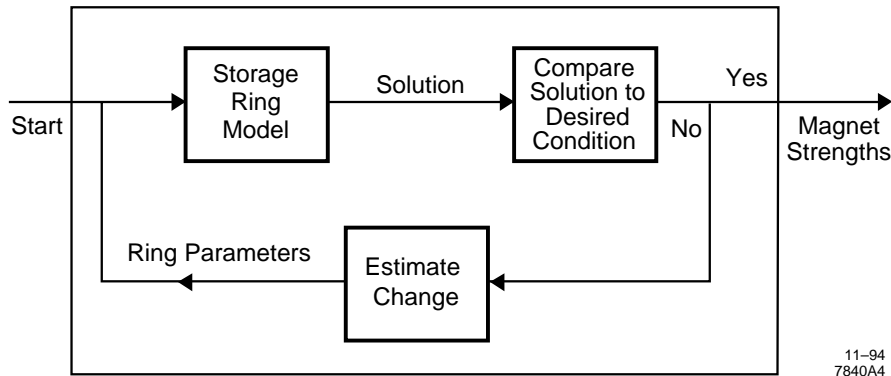


Figure 2. A block diagram of the model-based expert system TIPTOE used to calculate magnet strengths.

MODEL CALIBRATION PROGRAMS

The function of model calibration programs is to adjust the magnet strengths in the model to the actual magnet strengths as 'seen' by the beam. For example, we have used the code, CALIF (8), to update the quadrupole magnet strengths in the model of SPEAR. Here is how we use CALIF to find the calibration of the quadrupole strengths automatically:

- (1) Measure the response matrix (the change in closed orbit at each position monitor caused by a unit kick from a corrector).
- (2) Calculate the difference between measured and predicted response matrix from the model.
- (3) Solve for the 'beam-based' calibration in the magnet strengths by minimizing this difference.
- (4) Update the model with the 'beam-based' calibration.

This procedure also enables us to calibrate the corrector strengths and beam position monitor scale sensitivities. Work is underway to develop a similar procedure to determine the beam position in sextupoles and sextupole strengths.

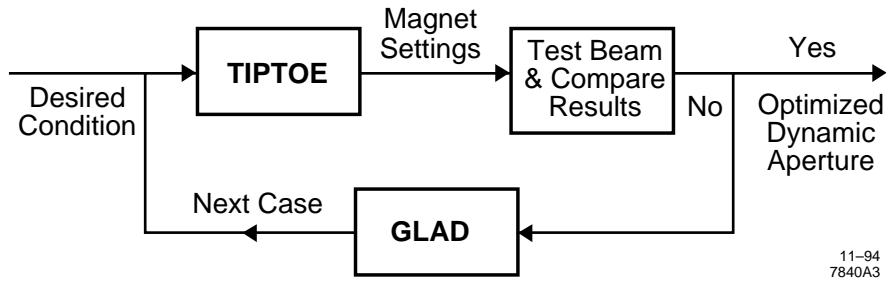


Figure 3. A schematic diagram of AIM that shows the relationship between TIPTOE and GLAD.

DIAGNOSTIC CODES

Like model calibration programs, we use error diagnostic codes to find the causes of errors in the measured orbit. One of the existing codes is RESOLVE (10) which can perform the following steps:

- (1) Measure the orbit change introduced by a corrector kick.
- (2) Predict the orbit change using the model.
- (3) Compare the measurement with the model prediction.
- (4) Identify the 'good' (10) regions where the measured orbits agree with predicted orbits.
- (5) Predict causes of errors that help to connect the 'good' regions.

We have used this method to predict misalignment and quadrupole field errors in the SLC (10) and in SPEAR. In the future, new codes (GLAD (11)) will find nonlinear errors such as those affecting dynamic aperture (See Fig. 3).

CURRENT STATUS

At present, we have incorporated a set of existing codes (COMFORT, MAD, CALIF, TIPTOE, and RESOLVE) into the AIM system. In addition, we are using AIM to develop an algorithm to optimize the dynamic aperture in SPEAR for the low-alpha experiment. Since the success of our experiment depends on the control of nonlinearities in the ring, we are planning to study the nonlinearities explicitly.

One part of this study is to measure the one-turn map. The one-turn map will then be used to correct nonlinear field errors from unknown sources.

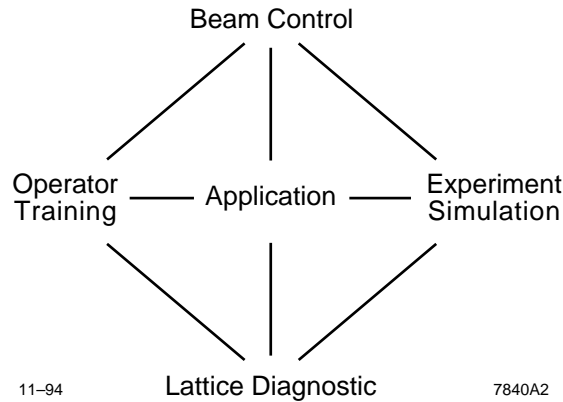


Figure 4. Four possible applications of the AIM system: on-line beam control, lattice diagnostics, off-line operator training, and machine physics experiment simulation.

CONCLUSIONS

We have developed a modeling system to commission and operate particle accelerators (see Fig. 4). The AIM system can include as many modeling codes as are available, and simulate experimental procedures. Indeed, AIM could become a 'knowledge' system for accelerators. This 'knowledge' system could then be used to control beam parameters and diagnose errors in the lattice. It could also be used to train accelerator operators and to simulate accelerator physics experiments.

REFERENCES

1. Marc Ross, SLAC-PUB-6134. ***
2. P. Tran, et al., in *Proc. IEEE 1993 PAC*, Washington, D.C., 1993, p. 173.
3. K. L. Brown, et al., SLAC-91, Rev. 2, UC-28.
4. See for instance, J. Irwin, *NIM A***298**, 460 (1990).
5. M. D. Woodley et al., SLAC-Pub-3086.
6. F. C. Iselin and J. Niederer, CERN/LEP-TH 88-38 (1988).
7. Y. Zambre (Stanford Research Institute, Menlo Park, Calif.).

8. W. J. Corbett, et al., SLAC-PUB-6111 (1993), and J. Safranek and M. Lee, in *Proc. of Orbit Correction and Analysis Workshop*, Brookhaven Nat'l. Laboratory, 1994.
9. E. Forest (LBL, Berkeley, Calif.). ***
10. M. Lee et al., in *Proc. Europhysics Conf. on Control Systems for Experimental Physics* (Villars, Switzerland, 1987); SLAC-PUB-4411.
11. M. J. Lee, in *Proc. 1991 Int. Conf. on Accelerators and Large Experimental Physics Control Systems*, Tsukuba, Japan, 1991.
12. M. J. Lee, Y. Zambre, and W. Corbett, in *Proc. Int. Conf. Cum Workshop on Current Trends in Data Acquisition and Control of Accelerators*, Calcutta, India, 1991.