THE TAO ACCELERATOR SIMULATION PROGRAM *

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Abstract

A new accelerator design and analysis simulation program based on the Bmad relativistic charged particle dynamics library has been developed at Cornell University. Called Tao (Tool for Accelerator Optics), it implements the essential ingredients needed to solve many simulation problems. This includes the ability to design lattices subject to constraints, simulate errors and changes in machine parameters, and simulate machine commissioning including simulating data measurement and correction. Tao is designed to be easily customizable so that extending it to solve new and different problems is relatively straight forward. The capability to simultaneously model multiple accelerator lattices, both LINACs and storage rings, along with the ability to inject from one lattice to another allows for the design and commissioning of large multi stage accelerators.

INTRODUCTION

Since the mid 1990's, a software library for relativistic charged particle simulations has been in development at Cornell. Called Bmad[1], this software toolkit has proven to be very versatile and is the engine powering the majority of the programs used for simulating Cornell's Electron/positron Storage Ring CESR. Bmad's usefulness not only comes from its demonstrated ability to accurately model CESR, but from other factors such as its ability to simulate machine errors and control room knobs.

The disadvantage of Bmad, common to all toolkits, is that by itself it is not a program — It cannot be run straight "out–of–the–box". To partially remedy this, an accelerator design and analysis program, based upon Bmad, has been developed called Tao[2] (Tool for Accelerator Optics). Tao is written in Fortran90 in an object–oriented fashion. Tao implements the essential ingredients needed to solve many simulation problems including:

- Designing lattices subject to various constraints.
- Lattice corrections including orbit, Twiss, and coupling corrections
- Simulation of errors and changes in machine parameters.

These types of problems have common elements: There is the data and machine parameters (beta functions, etc.) that needs to be plotted, there are model variables that need to be varied, and, in the first two categories above, there needs to be an automatic way to adjust the model variables to match the data or constraints to the model.

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Since the matching of the machine model to the data (here "data" may mean either data or constraints) may involve multiple data sets under different machine conditions, Tao employs the concept of a "universe". A universe is defined to be a set of data taken under a particular set of conditions and a corresponding machine model. The matching of model to data is done via non–linear optimization which involves minimizing a merit function. Standard optimizers available in Tao include Levenburg–Marquardt[3] and the Differential Evolution method of Storn and Price[4].

The concept of a universe is actually more general than this since different universes can correspond to different machines in a network. Different universes can be coupled together thus, for example, it is a simple matter to simulate a damping ring attached to a LINAC.

Lattice input for Tao can be either Extended Standard Input Format[5] (XSIF) or Bmad standard format. Bmad standard format is similar to the MAD standard lattice format but includes such elements as combination quadrupole/solenoids, LINAC accelerating cavities, and Taylor maps. The Bmad standard format also includes "multipass" elements where the beam goes through an element multiple times (this is useful, for example, in an Energy Recovery LINAC). Additionally, "I–Beam" (girder) support elements, and "control room knob" elements (where an element can be set up to control the attributes of other elements) are available.

In order to show how Tao can be used, the following sections discuss some of the applications.

INTERNATIONAL LINEAR COLLIDER

The International Linear Collider[6] (ILC) is a 33 km long 500 GeV center of mass electron/positron collider currently in the design phase. The current plan calls for each beam to pass through a 14 km long LINAC containing over 10,000 superconducting cavities and over 350 superconducting quadrupoles. There is also a damping ring for each beam along with a 4 km long Beam Delivery System plus several other beam lines. In all, the beams are transported through about half a dozen different stages before they reach the Interaction Point. Tao can model each stage after the injector through the damping rings to the interaction point. Figure 1 illustrates this. Here, each damping ring quadrupole was misaligned by 1 micron RMS. The resulting damping ring closed orbit is shown in Fig. 1A. This closed orbit is used to track through the main LINAC as shown in Fig. 1B and the resulting orbit through the Beam Delivery System to the Interaction Point is shown

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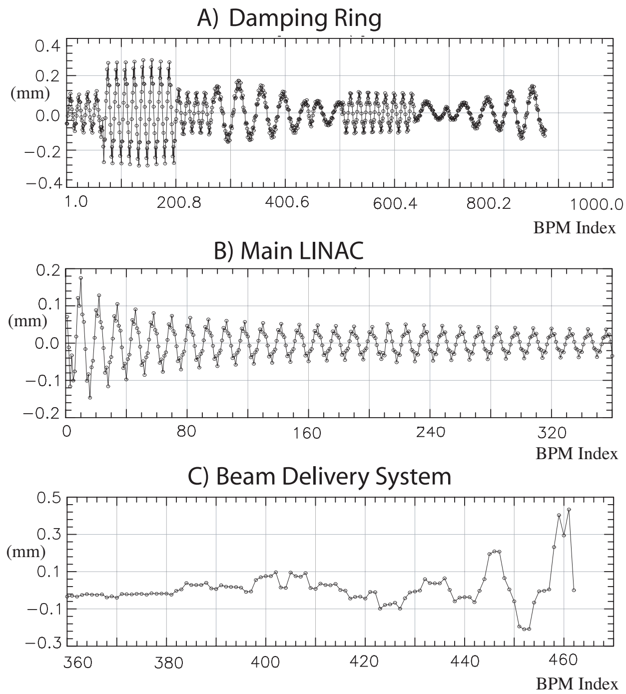

Figure 1: A 1 micron RMS misalignment was placed on the damping ring quadrupoles in the ILC and the orbit error was tracked to the interaction point.

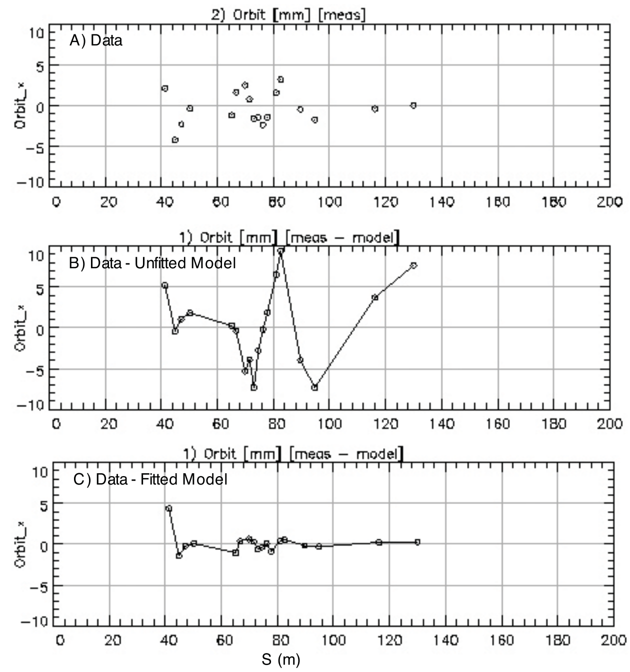

Figure 2: Difference orbit data due to the change in one steering. A) Data. B) Data - unfitted Model. C) Data - fitted Model.

in Fig. 1C.

A serious concern for the ILC is emittance preservation in the main LINAC. The principle sources of emittance dilution include dispersive kicks in the quadrupoles, pitched cavities, wakefields, and transverse coupling. Critical to removing these sources is to align the machine to micron precision. Since survey alone cannot achieve this precision, beam-based alignment algorithms must be developed to effectively remove any sources of emittance dilution. Tao has been used in the testing of these alignment algorithms as discussed by Smith and Sagan[7].

JEFFERSON LAB FEL

The Jefferson Lab FEL is a kilowatt-class high average-power, sub-picosecond recirculating free-electron laser, covering the mid-infrared spectral region[8].

The application of Tao to the Jefferson Lab FEL was in response to the need of modeling the Beam Break–Up (BBU) instability[9] which can limit the maximum current in a machine. Central to the analysis of BBU is the accurate modeling of the machine optics. The FEL optics is obtained by using steerings to kick the beam and measuring the resulting orbit. Twenty kickers are involved: 10 horizontal and 10 vertical. For each kicker, a difference orbit is measured between the kicker on and kicker off states. The optics is calculated by finding the lattice model quadrupole and kicker settings such that the orbit, as calculated from the model, best fits the data.

The variables in the fitting process are the 54 quadrupoles and the 20 steering magnets. The quadrupole variables are varied in parallel across all the universes. That is, the quadrupole strength of a given quadrupole must be the same for all 20 universes. In contrast, a given steering variable is specific to the universe where it was used to kick the beam.

Results are shown in Figure 2 which shows difference orbit data of one specific universe. Figure 2A shows the data. Figure 2B shows the data minus the associated model with the model quadrupole and steering strengths set according to the measured current through them. The fit between data and model is poor. Figure 2C shows the data minus the associated model where the model quadrupole and steering strengths in all universes have been varied to fit the measured data. The fit in general is excellent except for the first point. Examination of the other universes shows that this particular BPM gives data that, in general, is not consistent with the fit indicating a bad BPM or perhaps an error in the placement of the BPM in the model.

Once the data has been fit and the optics determined, the BBU calculation can be performed. In this case, since the standard Tao program does not do this calculation, a customized version of Tao had to be created to interface Tao to some existing BBU code[10]. Since Tao is designed to be extensible, the changes to Tao needed to interface to the BBU code proved to be fairly trivial.

CORNELL ERL

The Cornell ERL is a 5 GeV, 100 mA Energy Recovery LINAC[12] currently in the prototype phase. Tao has been

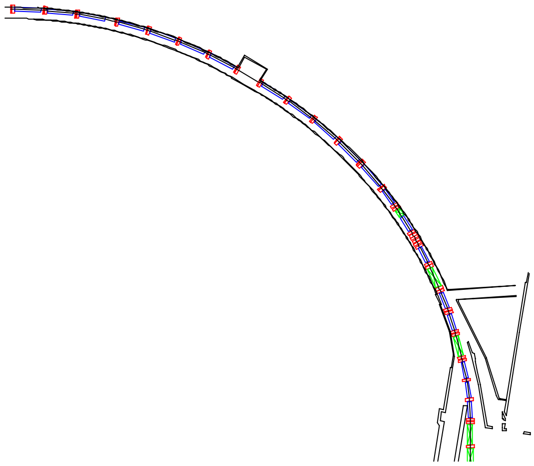

Figure 3: Design for an ERL in the CESR tunnel. Only part of the recirculation arc is shown.

used for the design of the ERL LINAC and recirculating arc.

One study using Tao focused on understanding the implications imposed by using the existing CESR tunnel to house the recirculating arc. A preliminary design is shown in Fig. 3 which shows part of the ERL recirculating arc inside the CESR tunnel. The variables in the design were drift lengths and quadrupole strengths. These variables were varied to satisfy several design constraints. First and foremost, the machine was constrained to stay within the physical tunnel. Additional constraints included constraining the dispersion to be zero at the wigglers, and the beta function values at the wigglers were constrained to be half the wiggler length. The resulting beta and dispersion functions are shown in Fig. 4.

Like the FEL simulation, a customized version of Tao had to be created. In this case, Tao needed to be able to read in the tunnel wall outline file and to be able to compute the distance from the machine to the inner and outer walls. Again, since Tao is designed to be extensible, the interfacing to the customized code proved to be fairly trivial.

CONCLUSION

The Tao program implements the essential ingredients needed to solve various design and simulation problems including lattice design, error simulation, and orbit and optics correction. Were this all, Tao would be similar to other design programs. However, Tao is different since it is written in an object–oriented style, and has been designed from the bottom up to be easily customizable. Thus extending Tao to solve different problems is relatively straight forward.

The disadvantage of Tao is that, to take full advantage of its customization abilities, there is a significant learning curve. Nevertheless, once mastered, Tao can be used to vastly cut down on the time needed to solve new simulation problems.

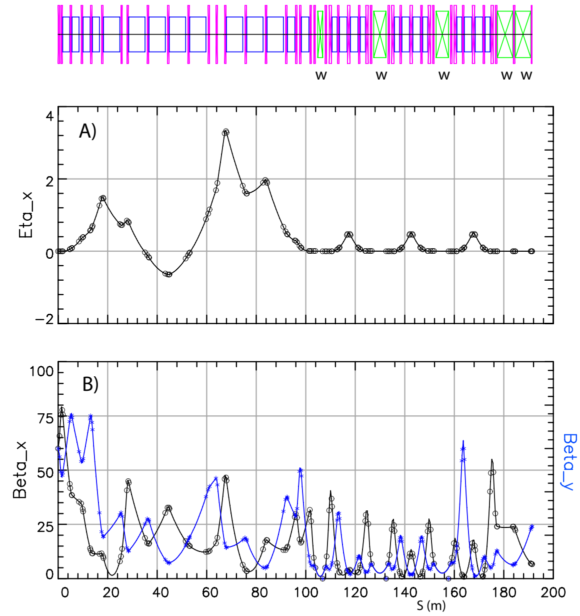

Figure 4: A) Dispersion and B) Beta function for a preliminary ERL in CESR design. The wigglers are marked with a “W”.

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