Artificial Intelligence Techniques for Tuning Linear Induction Accelerators*

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Abstract

We have developed an expert system that acts as an intelligent assistant for tuning particle beam accelerators called MAESTRO — Model and Expert System Tuning Resource for Operators. MAESTRO maintains a knowledge base of the accelerator containing not only the interconnections of the beamline components, but also their physical attributes such as measured magnet tilts, offsets, and field profiles. MAESTRO incorporates particle trajectory and beam envelope models which are coupled to the knowledge base permitting large numbers of real-time orbit and envelope calculations in the control-room environment. To date we have used this capability in three ways: 1) to implement a tuning algorithm for minimizing transverse beam motion, 2) to produce a beam waist with arbitrary radius at the entrance to a brightness diagnostic, and 3) to measure beam energy along the accelerator by fitting orbits to focusing and steering sweeps.

I. Introduction

Particle-beam accelerators are members of a class of large, complex systems where a combination of automatic and manual techniques are required to control the system. This is especially true in a research environment where goals for understanding the physics of the machine coexist with goals for producing beams with desired characteristics. In order to satisfy these requirements we have applied Artificial Intelligence techniques to develop a Model and Expert System Tuning Resource for Operators (MAESTRO). It has been applied to tuning the Advanced Test Accelerator [1] and Experimental Test Accelerator (ETA) [2] at Lawrence Livermore National Laboratory.

MAESTRO is a metaphor for a musical conductor orchestrating the activities of control, diagnostics, physics models, and post-run analysis to control and understand the behavior of the machine. MAESTRO acts as an intelligent assistant to an operator tuning a particle-beam accelerator and contains within its framework the capability for representing the heuristic rules-of-thumb followed by human operators, rigorous physics models for computing the trajectory and envelope of the beam from knowledge of the beamline components, and a variety of displays and interfaces for automatically and manually controlling the machine.

II. The Knowledge Base

The MAESTRO architecture consists of two distinct layers, a real-time control system and a quasi-real-time layer containing the expert system, models, and operator interfaces. The real-time control (and diagnostics) system deals with events on the order of 1 second or less where a deterministic response time is a critical issue as in responding to hardware interrupts. For control it operates at level of power supplies and currents, translating requests into hardware commands for the physical supplies. The quasi-real-time layer deals with events on the scale of 1 to 30 seconds and is primarily concerned with making decisions about which supplies to control, performing computations with the model based on current supply values, and acquiring data to interpret and present to the operator. The critical issue is flexibility and capability of the software.

The interface between the two layers is the Knowledge Base (KB). It is an object-oriented database for representing the components of the beamline, their relationships, and their interconnections. The KB utilizes the concept of access-oriented programming to permit the physicist to operate at the level of fields in magnets by automatically performing, when a field value is accessed, the translations from field-in-magnet to current-in-supply to supply-powering-the-magnet to control-system-register-address-and-value. All the information needed to make the translations is in the KB, such as the measured $B_{x,y,z}(z)$ field profiles for each of the magnets. The consistentcy of the KB is automatically maintained to reflect, for example, the replacement of a power supply by one with different calibration coefficients or the insertion of a new component within the beamline.

Within the KB the machine components are represented in a class/subclass hierarchy, so the class of compensated-solenoids (assemblies with a solenoid and two steerers) is a subclass of solenoids which is a subclass of magnets. There are also classes and subclasses not only based on the component type but also the machine sections. This hierarchical structure permits dealing with the components at different levels of "granularity" making it easy to construct spread sheets, for instance, of "all the solenoids in the accelerator section".

Since some of the beamline components have data associated with them, e.g. oscilloscope traces from beam position monitors (beambugs), the KB also contains new and historical data acquired from the machine. We have developed a variety of browsers for examining not only the structure and contents of the KB but also the historical data contained within it.

III. Tuning Methods

The MAESTRO environment supports three distinct approaches to tuning particle-beam accelerators. In the first approach, "cloning the operator," the procedures and reasoning followed by the operator are encoded as faithfully as possible. A second approach, model-based tuning, exploits a near-real-time numerical simulator coupled with real-time data acquired from the machine. The third approach is to tune the machine

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manually, but provide the operator with more powerful tools and displays. The goal is to achieve a blend of these approaches that minimizes the tuning time and maximizes the time available for performing physics experiments. Each of these approaches is discussed below.

A. Cloning the Operator

This approach reflects two kinds of reasoning followed by the operator. In the first the operator employs a "global strategy" concerned with the overall tuning of the machine subject to constraints like "don't put the beam into the wall". The global strategy is made up of many lower-level "local strategies" concerned with the tuning of a subsection of the machine. Local strategies usually deal with a single diagnostics device (e.g. a beambug) and the components immediately upstream from it capable of correcting an error in beam position. The expert system decides which components to use based on their nearness, type, and expected effect on the beam. These strategies and how they are implemented are discussed in more detail in [1] and [3].

B. Model-Based Tuning

This approach is based on an on-line numerical model for computing the beam radius and centroid trajectory [4] given the current magnet settings and measured magnet field profiles, tilts, offsets, etc., stored in the KB. This approach hinges on bringing the models and the machine into agreement, "commissioning" [5] and has succeeded to the point where this method will be used to estimate the beam energy by fitting the computed beam behavior to the measured while sweeping focus and steering magnets over a range of values[4,3]. Ultimately the models will be used to compute an optimum set of parameters and to download those parameters onto the machine.

C. Manual Tuning

For the manual tuning approach MAESTRO presents a variety of interfaces to the operator (and physicist) to ease both the control and interpretation tasks. The interfaces are constructed from information in the KB and automatically reflect, for example, insertion or deletion of components from the beamline. An icon-based Machine Interrogation and Control Interface (MICI) presents a scaled drawing of the beamline with icons for the components. The operator uses a mouse and cursor to select components and change settings, control data acquisition, or browse historical data. Spread-sheets are particularly useful for setting and displaying magnet fields and currents. Color bargraph overlays are provided for "at a glance" monitoring of B(z) fields, discrepancies between target and measured values, and on/off status. Spread-sheets also provide a mechanism for archiving tunes and creating new tunes by cutting and pasting values from past tunes into the spread-sheet controlling the machine.

A graphical interface is provided for displaying raw and processed shot data. The operator can interact with a plot window using the mouse and control the attributes of the plot, including such things as producing a plot by grabbing points from several others.

As part of the manual interface the operator can enter commands to run various tuning algorithms. One such algorithm minimizes the transverse beam motion by sweeping the current in a steering coil over a range of values and displaying the corkscrew amplitude as a function of current. The operator then sets the current to the value producing the minimum corkscrew and repeats the procedure, sequentially optimizing all the magnets in the beamline. The algorithm is discussed in more detail in companion papers [6,2].

Commands are also available for running the models to gain insight into the machine behavior. For example, for a whole-beam brightness measurement it was desired to bring a beam with a specific radius to a waist at the face of a pepper-pot[7]. Experimentally it appeared there were certain radii where it was impossible to achieve a waist. The beam envelope model was run for a variety of settings of the two focusing solenoids upstream from the pepper pot, and the beam radius and its z derivative (r-dot) plotted for each setting, Figure 1. Since a waist occurs at r-dot=0, the figure shows that it is impossible to produce a waist for beam radii between 1 and 1.5 cm. Further simulations with the model and experiments with the machine produced changes in the transport section tune that reduced the effect of the phenomenon.

IV. Future Plans

The immediate plans for MAESTRO are to decrease the time to execute the algorithm for minimizing transverse beam motion and automate the process. Our goal is to reduce the time by a factor of 10 to 20. This will make it possible to attempt optimization of the $B_z(z)$ field profile -- during the last run period the profile was essentially fixed. Modified versions of the algorithm will be used for maximizing wiggler gain and minimizing beam radius oscillations [2].

The centroid trajectory model will be used for estimation of the beam energy at various locations down the beamline by curve fitting to focus and steering sweeps with energy as a free parameter. The beam envelope model will be used for matching the beam into an FEL wiggler as described above for matching into the pepper-pot.

V. Discussion

AI techniques have proven especially useful for tuning particle-beam accelerators, not because of any explicit "intelligence" within the system but because of the flexibility and capabilities of the environment. The unification within a single software environment of control, diagnostics, and modeling made possible the development of entirely new tuning methods and diagnostics displays. MAESTRO provided the flexibility to trade-off between the three tuning approaches as experience with the machine dictated. Having models within the environment made it relatively easy to perform pre-run simulations and gain insight into the expected effect of, for example, magnet tilts and offsets. During a run the models were used to make on-line comparisons of computed and measured behavior. And finally the models and history displays were useful for post-run analysis of the data.

The environment proved so flexible that many of the tuning algorithms and uses of the models discussed here either did not exist or were substantially refined during the run period, by literally modifying the software as the machine was coming up each day.

VI. References

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Figure 1. Beam R vs R-dot -- Some Radii Are Unachievable for R-dot =0