LIAM - A Linear Induction Accelerator Model*

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Abstract

We have developed a flexible Linear Induction Accelerator Model (LIAM) to predict both beam centroid position and the beam envelope. LIAM requires on-axis magnetic profiles and is designed to easily handle overlapping fields from multiple elements. Currently, LIAM includes solenoids, dipole steering magnets, and accelerating gaps. Other magnetic elements can be easily incorporated into LIAM due to its object-oriented design. LIAM is written in the C programming language and computes fast enough on current workstations to be used in the control room as a tuning and diagnostic aid. Combined with a non-linear least squares package, LIAM has been used to estimate beam energy at various locations within the ETA-II accelerator.

Introduction

Linear induction accelerators, such as ETA-II, are complex instruments. To obtain the best performance from such complex machines requires good, working models. Such a model must be capable of dealing with the as-built configuration of the accelerator so that actual accelerator performance can be predicted. With such a model coupled to a parameter estimation routine, and with proper beam position data taken as a function of varying magnetic element field strengths, the beam can be used as a diagnostic tool to estimate those alignment and field parameters that can not be directly measured. Once this phase of experimentation and model validation is complete, the model, now closely matched to the actual accelerator, can be used to estimate beam parameters over the entire length of the accelerator given sparse beam position data. Such prediction/estimation capabilities can greatly aid in the tuning process. In addition, these capabilities can be use to diagnose component failures and misalignments.

The LIAM Model

Motivation for LIAM

Concerned by problems in matching beam position data from early runs on ETA-II to traditional matrix-per-element transport models [1], we began a theoretical investigation of transport models. We compared the results obtained by solving the equations of motion for a one MeV electron passing through a typical, isolated ETA-II solenoid with the results obtained using the traditional matrix-per-element approximation. Poor agreement between the two models was observed. This is due to the use of a rectangular B_z profile in the derivation of the matrix elements whereas the typical B_z profile of an ETA-II solenoid is nearly gaussian.

However, when we modified the matrix method to divide the transport region into a number of subregions, or "mini-matrices", each described by a standard solenoid matrix calculated from the solenoid's B_z field strength at the center of the subregion, we obtained better results. As the length of the subregion was decreased, the results of the matrix method rapidly approached the results obtained from solving the equations of motion until, with the subregion length of four centimeters, excellent agreement obtained.

Armed with this information, we decided to construct LIAM. LIAM was designed to be a flexible linear induction accelerator modelling code that would calculate the beam centroid position either by solving the equations of motion or by mini-matrix transport. Both beam position calculation schemes are available at the same time, and both work from the same database of electromagnetic elements. This design has proven to be very valuable. First, the method of solving the equations of motion of the beam centroid is limited only by the accuracy of the input fields. Accordingly, as better field models became available, they could be easily incorporated. Solving the equations of motion directly also eliminated the immediate need to do the sophisticated analysis required to calculate the elements of the transport matrices. Second, when the formulas for the mini-matrix transport elements were derived, they could be easily checked by direct comparision of the results from the two techniques. This capability of LIAM has proven useful on numerous occasions. Third, whenever a change was made to the code implementing one of the centroid tracking techniques, those changes could be immediately checked by comparing the results of the two techniques. And, finally, the mini-matrix approach provides roughly a factor of seven increased performance which is very useful when LIAM is used with a nonlinear parameter estimator where the centroid must be tracked under various conditions hundreds to thousands of times.

Capabilities of LIAM

LIAM was designed in an attempt to provide the physicist with a highly interactive tool for linear accelerator modeling. It was also designed to provide a flexible interface to the programmer and be very modular in construction by employing simple object-oriented programming techniques. It was written in the C programming language to be as portable as possible. Currently, it is being used interactively in both a standalone configuration and primarily under Common Lisp in the MAESTRO [2] environment.

Modelling As-Built Accelerator Characteristics

LIAM uses field profile parameterizations to closely match the modelled electric and magnetic fields to the actual fields within the accelerator. Nonlinear least squares parameter estimation is used to obtain the field parameterizations by fitting to either the directly measured field profile (in the case of magnetic elements), or to the theoretically calculated E_z of accelerator gaps.

For solenoids, the on-axis B_z field profile is parameterized by H, k_2, and k_4 in the equation

$$B_z(z) = H\left(pe^{\left(-k_2 z^2\right)} + (1-p)\, e^{\left(-k_4 z^4\right)}\right).$$

Dipole steering magnets ($B_x(z)$ and $B_y(z)$) are similarily parameterized. The on-axis E_z field of an acceleration gap is parametered by

$$E_z(z) = He^{\left(-k_2 z^2\right)}$$

This simplified form was found to match the theoretically calculated field profile quite well.

LIAM has been programmed to calculate the remaining off-axis field components (e.g. B_x and B_y for a solenoid) by Taylor expansions obtained from

$$\nabla \cdot \vec{B} = \nabla \cdot \vec{E} = \nabla \times \vec{B} = \nabla \times \vec{E} = \vec{0}.$$

Using this scheme, LIAM can sum the fields $\vec{B}(x,y,z)$ and $\vec{E}(x,y,z)$ across all (contributing) accelerator elements to calculate the fields anywhere within the accelerator.

Because real accelerators are not perfect, LIAM include the formulas for handling elements that are misaligned. LIAM currently handles all three translational and all three rotational degrees of freedom for each element.

Finally, because of the large beam current and low energy used in ETA-II, the effects of images induced on the accelerator's vacuum pipe are not neglegible. Accordingly, LIAM includes code to calculate the (equivalent) fields produced by the images on the vacuum pipe, including the effects occuring at the breaks in the pipe where the accelerator gaps are located.

Beam Centroid Calculation

LIAM utilizes the LSODE [3] differential equation integration package to solve the equations of motion of the beam centroid as it moves through the electromagnetic fields of the accelerator. The LSODE package provides control over both the absolute and relative error of the solution along with automatic variable step size adjustment. LIAM treats the state variables $\left(x(z), y(z), \frac{dx}{dz}(z), \frac{dy}{dz}(z), \gamma(z)\right)$ as a system of ODEs for LSODE to solve.

LIAM utilizes in-house calculated transport matrix elements (including the first order energy correction terms) when employing the mini-matrix solution. LIAM's matrix transport can handle axial solenoidal magnetic fields overlapped by transverse dipole fields and an accelerating electric field. The matrix elements are calculated from $B_x(0,0,z_{center})$, $B_y(0,0,z_{center})$, $B_z(0,0,z_{center})$ and $E_z(0,0,z_{center})$ where the field values have been calculated using all the misalignments. (Implied here is the fact that we have found that generality of handling misalignments can be subsumed by the generality of handling overlapping fields.)

Beam Envelope Calculation

LIAM has been extended to provide for the calculation of an approximate beam radius simultaneous with the calculation of beam centroid when employing the differential equation solution technique. The extension consists of merely adding $R(z)$ and $\frac{dR}{dz}(z)$ to the vector of state variables for which LSODE solves along with the Lee-Cooper [4] envelope equation for the RMS beam radius. When calculating the beam envelope, the coupling between beam radius and beam energy is automatically included.

Usage of LIAM

LIAM is the modelling code beneath the MAESTRO system that supports daily operations in the ETA-II control room. In this role, LIAM has been used to study the effect of various solenoidal magnet field strengths upon the beam envelope prior to, or during, the use of beam emittance diagnostics. It has also been used to conduct various other theoretical studies particularily concerning various tuning strategies prior to using those strategies on ETA-II.

Another less visible, but no less valuable, use of LIAM has been as a simulator of ETA-II performance to test software changes, new software, and possible new techniques and algorithms. In this role, LIAM and some ancillary software is used to simulate the raw waveform data produced by the beam position monitors. In this way, a nearly end to end test of the MAESTRO software can be conducted.

LIAM as a Tuning and Diagnostic Aid

Before LIAM can be effectively used to tune or diagnose ETA-II, it must first be validated against the per-

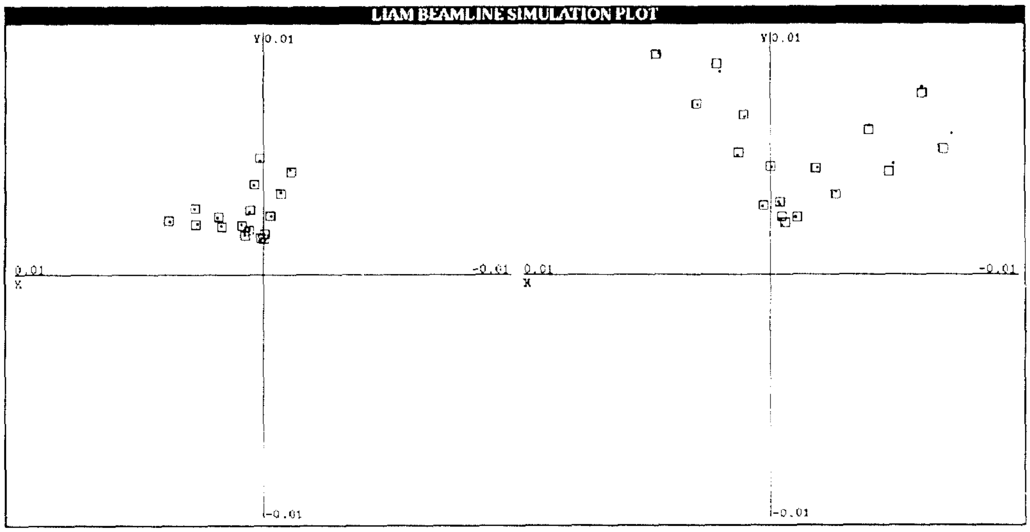

Figure 1: LIAM Fit to an ETA-II Focus-and-Steering-Sweep, note: Axes span ±0.01 meters

formance of ETA-II. During the past run period we began this process. Beam position data was collected as "focus-and-steering-sweeps" where horizontal and vertical dipole steering magnets were used to deflect the beam (to form a cross or half cross) at various values of the superimposed solenoidal field strength (see figure 1). A nonlinear parameter estimation package that closely interfaces with LIAM was used to estimate the beam launch parameters $\left(x(z_{launch}), \frac{dx}{dz}(z_{launch}), y(z_{launch}), \frac{dy}{dz}(z_{launch}), \gamma(z_{launch})\right)$ and, when necessary, various magnetic element parameters and misalignments. Initial results overestimated the beam energy by up to 80%. After much investigation, we believe we have isolated the problem to the beam position monitors and the associated signal processing of their signals. A LIAM model fit to a focus-and-steering-sweep is shown in figure 1. The measured beam position is shown as a small point, the LIAM model predicition is shown as an open square. Figure 1 depicts the focus-and-steering-halfcross deflections at two beam position monitors, the leftmost at 22 centimeters beyond the center of the dipole magnets, and the rightmost at 68 centimeters.

Another important tuning task for the ETA-II accelerator is matching the beam envelope into the Free Electron Laser (FEL) wiggler assembly. Once the LIAM model has been validated against ETA-II, and the experimental beam radius diagnostics work [5], it will be possible to include $\left(R(z_{launch}), \frac{dR}{dz}(z_{launch})\right)$ in the beam parameters estimation process. With this added information, the nonlinear parameter estimation can then be used to find appropriate field strengths to match the beam into a wiggler.

Conclusions

LIAM is a powerful modelling tool that has proved it worth in the control room of ETA-II. So far LIAM has been most valuable as a simulation tool for developing tuning techniques and algorithms that have been sucessfully used to tune ETA-II, and for developing and debugging new MAESTRO software. We plan to solve the problems we have experienced with the beam position monitors prior to the upcoming ETA-II run period. With the problems behind us, and with the introduction of the new beam radius diagnostics, LIAM should become an even more valuable addition to the ETA-II control room.

References

[1] K.L. Brown, B.K. Kear, S.K. Howry, *TRANSPORT/360, A Computer Program for Designing Charged particle Beam Transport Systems*, SLAC-91, Stanford Linear Accelerator Center, Stanford University, CA 94305, USA (1969).

[2] D.L. Lager, et. al., *MAESTRO - A Model And Expert System Tuning Resource for Operators*, Nuclear Instruments and Methods in Physics Research, North-Holland Materials Science and Engineering, Amsterdam, The Netherlands, (1990).

[3] A.C. Hindmarsh, *LSODE and LSODI, Two New Initial Value Ordinary Differential Equations Solvers*, ACM SIGNUM Newsletter, **15**, No. 4 (1980), pp. 10-11.

[4] E.P. Lee, R. Cooper, *General Envelope Equations for Cylindrically Symmetric Charged-Particle Beams*, Particle Accelerators, **7**, No. 83, (1976).

[5] W.E. Nexsen, private communication, (1991).

*Work performed jointly under the auspices of the US DOE by LLNL under W-7505-ENG-48 and for the DOD under SDIO/SDC MIPR No. W31-RPD-0-D4074.