APPLICATION AND CALIBRATION ASPECTS OF A NEW HIGH-PERFORMANCE BEAM-DYNAMICS SIMULATOR FOR THE LANSCE LINAC *

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Abstract

The Los Alamos Neutron Science Center utilizes a linear accelerator (linac) consisting of two 750-keV injectors, a 100-MeV drift tube linac and an 800-MeV coupled cavity linac to provide both H^- and H^+ beams to several user facilities. We are presently developing a graphics processing unit (GPU)-based high-performance multiparticle beam-dynamics simulator to aid in tune-up and operation of the linac. Our primary goal is to create an on-line tool that will act as a virtual beam diagnostic and in pseudo real-time provide accelerator operators and physicists with insight into the evolution of the beam throughout the linac. This paper will discuss potential applications of this tool and aspects of the various calibrations that are a prerequisite to using the model.

INTRODUCTION

High power linacs, such as the Los Alamos Neutron Science Center (LANSCE) 800-MeV accelerator, use a combination of well defined physics-model based tune-up procedures and empirical optimization to establish low-loss operation under high-power beam conditions. Although the low beam power tune-up is typically performed with an array of beam diagnostics, the subsequent adjustments under high beam power conditions are performed with little or no direct beam information and focus mainly on reducing beam spill as measured with radiation monitors located along the linac and beam lines. A better situation would be one where tuning activities are guided by more detailed information about the beam properties along the linac. Although one possible option would be to install numerous beam diagnostic devices all along the accelerator, this is rather impractical due to cost considerations and the interceptive nature of many of the desired devices. Another possible option is to utilize a beam dynamics model along with a *realistic* beam distribution to predict the beam characteristics along the linac. The beam dynamics model would need to contain enough physics to predict with reasonable accuracy the properties of the beam along the linac, but also be fast enough to provide near real-time feedback, as an actual beam diagnostics device would. At LANSCE we are pursuing the latter approach as a means to provide additional information and insight into the evolution of the beam along the linac. Besides serving as a virtual beam diagnostic during tune-up and operation, this model can also serve other functions as will be discussed.

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THE SIMULATOR

The new high-performance, multi-particle, beam-dynamics simulator is based upon the widely used ion linac design and simulation code PARMILA [1], but rewritten in C++ and NVIDIA's CUDA C [2] to enable a modern code architecture that can utilize the power of the Graphics Processing Unit (GPU) technology for tremendous performance improvements [3]. PARMILA was chosen as it incorporates essential physics required to simulate a realistic beam distribution in various ion linac structures and beam line components, algorithms that have been tested and benchmarked and approximations that enable faster execution without sacrificing significant accuracy.

The physics model for the linac is based upon design and as-built information regarding the linac geometry and accelerating fields and is stored in an SQL database. When the simulator is used in an "on-line" mode, a *data server* reads in real-time the linac parameters from the EPICS control system and pipes the data into the SQL database, where they are converted into physics model quantities. Alternatively, in the "off-line" mode, the user may chose to modify the stored values of linac parameters, which are subsequently converted to physics model quantities. In either case, the simulator reads the database at the beginning of the simulation. This SQL database also contains the conversions and calibration constants that relate the data system set points to the corresponding physics model quantities. Specific procedures are performed to establish the correct value for each of the calibration constant required by the model.

APPLICATIONS

Although originally developed to serve as an online model for tune-up and operation of the linac, it has become clear that the high-performance, multi-particle, beam-dynamics simulator can also be used in other valuable ways. Many of the following activities could be performed with a standard off-line, "slow", beam dynamics code. However, the benefit for many of these applications is that the simulator response is rapid, i.e. pseudo real-time, and the connection to the accelerator control system conveys the sense of operating a real machine, not just a model, which facilitates these activities.

Virtual Beam Diagnostic

The main goal of the simulator development is to provide operations personnel with pseudo real-time information about the beam evolution along the linac to

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aid in the tune-up and subsequent empirical fine-tuning of machine parameters. In this case the simulator is configured to run in an online mode, continuously updating the model with the latest operational set points and then looping through the beam dynamics simulation before updating the graphical output of various quantities along the linac. An example of the simulator running H^- beam through the LANSCE drift tube linac (DTL) is shown in Figure 1. As various DTL parameters are adjusted via EPICS controls the simulator continually updates the display in pseudo real-time with beam information, such as profiles, emittances, losses and phase-space distributions.

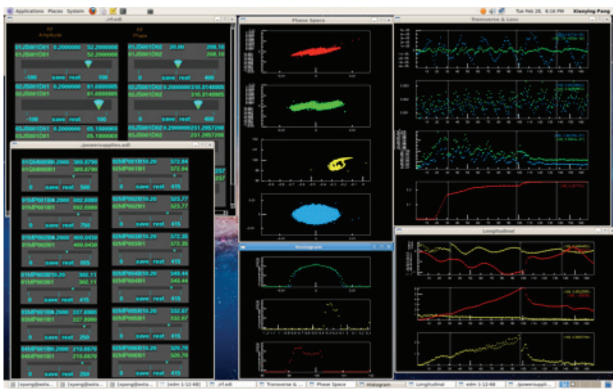

Figure 1: EPICS control sliders (left) and simulation output that includes profile, phase space, centroid, size, emittance and loss plots.

Training

In an off-line mode the simulator can be used to help train operators and physicists regarding the nuances of operating a high-power linac. Along this vein it can be used to develop better insight and understanding into the effect that various accelerator parameter changes have upon the beam along the linac.

Troubleshooting

Troubleshooting linac performance often occurs during the start-up phase when measurements do not meet expectation. The simulator can be invaluable here to help diagnosis and debug particular problems with the linac.

During the most recent start-up of the LANSCE linac, we observed characteristically different phase scans in the last tank of our DTL. About the same time we observed unexpected changes in the cavity field phase in the first DTL tank. Using the simulator we were able to reproduce similar phase scan results when a significant phase shift was introduced into the first tank. This led us to find and fix a problem with the signal path from the RF reference line to DTL tank 1 LLRF controls.

Test Bed

Another valuable use for the simulator is as a development and test facility for various feedback and control schemes. These are schemes that would normally require access to the linac control parameters via the EPICS control system. Recently, this was done using the simulator and was aimed at testing a model-independent optimization approach for establishing control set points in the linac. [4]

Optimization

Since the simulator is meant to provide detailed information about the beam along the linac, it can also be used to find a more optimal way to operate the accelerator. Over many years of high power beam operation at LANSCE, the operations staff has found lower beam loss solutions that require operating the machine away from design values. This can also be explored with the simulator. Evolutionary optimization approaches such as the multi-objective genetic algorithm (MOGA) and multi-objective particle swarm optimization (MOPSO) are being investigated as a way to help find stable, low beam-loss solutions that better define and quantify the beam conditions along the linac [5].

CALIBRATIONS

Before using the simulator to provide meaningful information about the beam evolution along the linac it must be calibrated. That is, the transformations associated with the control system set points to physics model parameters must be established. These calibrations include focusing magnet strengths, RF field phase and amplitude for the bunching and accelerating structures, and space-charge compensation in the low-energy beam transports. Some of the calibrations are done offline and some are beam-based.

The magnet calibrations relate power supply current to field. These are done offline and based upon fitting excitation curve data of field vs. current.

Depending upon the type of cavity, the RF bunchers and accelerating tanks utilize both offline and beam based approaches. The single-gap buncher cavities that are used in the 750-keV beam transports utilize an offline calibration. An EM-field calculation of the cavity was performed using SUPERFISH [6] to extract the theoretical E_0TL, Q_u and P_{cav}. In addition, measurements were made of the cavity Q along with each buncher cavity amplifiers output power vs. amplitude set point. These results were combined to produce the effective gap voltage vs. amplitude set point. The phase set point is calibrated with a beam-based measurement known as a phase scan and is described below.

The accelerating sections of the linac require beam-based measurements to establish the RF calibrations. For each section driven by one RF amplifier there is a separate phase offset and amplitude scale factor that must be determined to properly tie the control setting to the physics model. For the DTL these are calibrated using a standard phase scan method. The phase scan measures the beam current above an energy threshold as a function of the phase setting of the tank being scanned. The size and location of the current distribution is related to the

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amplitude and phase of the accelerating field in the tank. Figure 2 shows two measured phase scans of DTL tank 1 along with the fits produced by the simulator. The phase scans represent the cases with the first of two LEBT bunchers off and on, respectively. Tank 1 amplitude scale factor and the two buncher cavity phase offsets were extracted from the fits to these data.

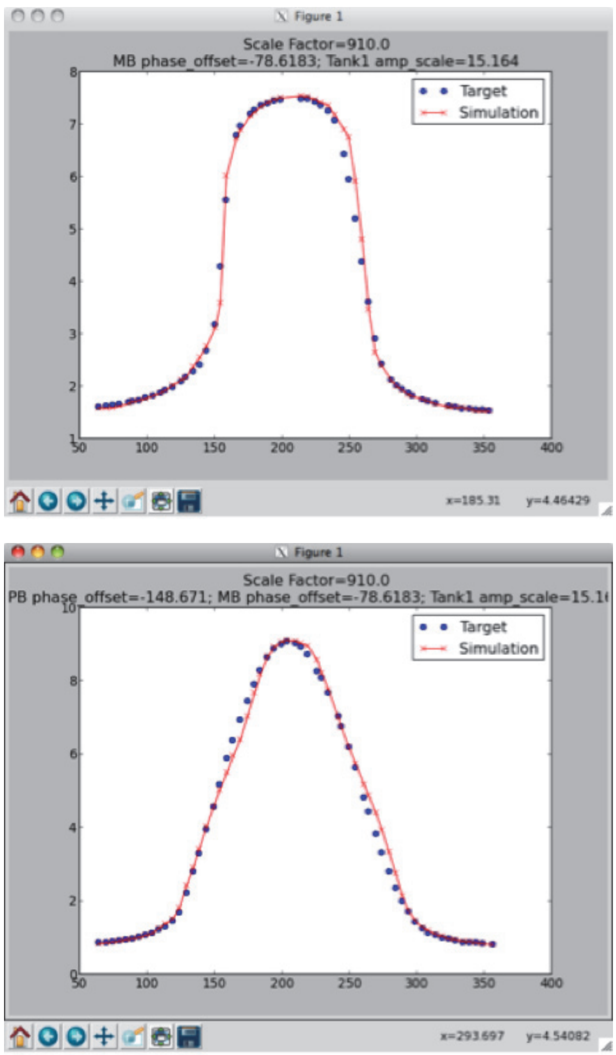

Figure 2: Measured (blue dots) and simulated (red line) phase scan data for Tank 1 of the DTL. Upper (lower) panel is for the case when the first of two LEBT buncher cavities is off (on).

The coupled cavity linac (CCL) is just now being incorporated into the simulator and therefore has not yet been include in LANSCE linac model. However, the calibration of the phase offset and amplitude scale factor for each CCL accelerating module will be performed by fitting measured phase scans similar to what has been done elsewhere [7].

An additional factor that we have chosen to include in the model is the space-charge compensation of the beam, which is the result of interactions with residual gas in the nominally evacuated beam line. Measurements in the low-energy beam transports (LEBT) where space-charge forces are significant showed different degrees of compensation present [8]. This space charge compensation factor is derived from a comparison of measured beam emittances and model predictions.

SUMMARY

A high-performance, multi-particle beam dynamics simulator is being developed for the LANSCE linac and will serve as a virtual beam diagnostic by providing staff with additional information about the beam along the linac during tune-up and operation of the facility. In addition it can also function as a tool for training linac operations personnel, troubleshooting issues associated with beam operations, as a test-bed for new control schemes and for optimization of the linac operation. The simulator requires the calibration of various constants that relate linac control system parameters to various physics model values. These are done using a combination of offline and beam-based procedures. The beam-based approach extracts calibration constants from fits to various tune-up measurements.

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