ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPWI033



# ADVANTAGES TO AN ONLINE MULTI-PARTICLE BEAM DYNAMICS MODEL FOR HIGH-POWER PROTON LINACS*

L.J. Rybarcyk#, X. Pang and S.A. Baily, LANL, Los Alamos, NM 87545, USA


*Abstract*

High-power proton linacs like the 800-MeV LANSCE accelerator typically use a physics-based approach and online single-particle and envelope beam dynamics models to establish nominal set points for operation. However, these models are not good enough to enable immediate transition to high-power operation. Instead, some amount of empirical adjustment is necessary to achieve stable, low beam-loss operation. At Los Alamos, we have been developing a new online model, which employs multi-particle beam dynamics, as a tool for providing more information and insight to the operations staff, especially during this transition to high-power operations. This presentation will discuss some of the advantages and benefits of using this type of tool in the tune-up and operation of a high-power proton linac.


## INTRODUCTION

Examples of high-power proton linear accelerators (linacs) range from the relatively compact yet powerful LEDA CW RFQ that once demonstrated 670 kW of beam at 6.7 MeV [1] to a more extensive system like the SNS pulsed linac that has recently provided over 1.2 MW of beam at 940 MeV [2]. At present, the 800-MeV linac at the Los Alamos Neutron Science Center (LANSCE) operates at 120 Hz and provides proton and $H^-$ beam macro-pulses, with a combined power of over 100 kW, to several target stations in support of basic and applied research. However, one thing that these and other high power linacs have in common is the need to minimize beam losses and the resultant deleterious effects on the structure and to the operation.

A physics-based tune-up approach is generally used to establish operational set points of beam-line devices in order to simultaneously produce beams with the desired characteristics and low loss. This approach utilizes online single-particle and beam-envelope models, e.g. [3-5], that enable the accelerator operations staff to set beam centroids and rms widths to their desired trajectories and matched sizes, respectively. However, at many high-power facilities, the model-based tuning is not the final solution. In addition, some amount of empirical loss-based tuning is required to achieve loss-levels necessary for sustained high-power operation [6].

It is this shortcoming with the existing approach that has motivated us to pursue a new online multi-particle beam dynamics model for our linac. A multi-particle model brings a higher level of realism and accuracy to the process and should begin to enable operations staff to reach a more complete tune-up solution as well as monitor on-going performance. Previously, multi-particle simulations were confined to offline analysis due to computational limitations. This new model [7], however, combines well-established beam dynamics algorithms and high-performance GPU technology in a workstation-class computer with access to the accelerator set points via the control system to provide rapid results of the actual linac operation to personnel 24/7. This new model can be operated in continuous mode, where the results are constantly being updated as machine variables are modified, or as a script-based tool to analyze measurement results or carry out beam simulations studies. In this paper we will explore some of the advantages of this new approach.

## MODEL ADVANTAGES

A multi-particle beam dynamics model has several advantages over existing online single-particle and envelope models currently used on proton linacs. Some of these are features that machine designers have benefited from for years. First, the multi-particle model is not limited to simple beam representations but can utilize more realistic beam distributions. Secondly, important emittance growth mechanisms are included in the model. Thirdly, beam losses can now be included in evaluating machine settings. Fourthly, virtual measurements provide feedback on the effect of set-point adjustments and tuning. These benefits are discussed below.

### *Realistic Beam Distributions*

The use of multi-particle distributions in modeling is especially advantageous in high-power proton linacs where transverse and longitudinal tails can contribute to beam losses. For example, at LANSCE each beam species is accelerated up to 750 keV using Cockcroft-Walton (C - W) technology. Following each C-W is a low-energy beam transport (LEBT) that contains a number of elements including quadrupole magnets and a single-gap 201.25-MHz buncher cavity. Just upstream of the 201.25-MHz drift-tube linac (DTL) the two beam species ($H^+$, $H^-$) are merged into a common LEBT that contains four matching quads and another identical buncher cavity. Since each C-W produces DC beam within a macropulse, the two RF cavities are used to prebunch these beams and increase the longitudinal capture in the DTL. This prebunching results in significant tails on the beam distributions. Shown in Fig. 1. are the simulated $H^+$ beam phase space distributions at the end of the LEBT. The input beam to the simulation is a combination of a transverse 4-D hypersphere, generated with Twiss

* Work supported by the United States Department of Energy, National Nuclear Security Agency, under contract DE-AC52-06NA25396.
#lrybarcyk@lanl.gov

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPWI033

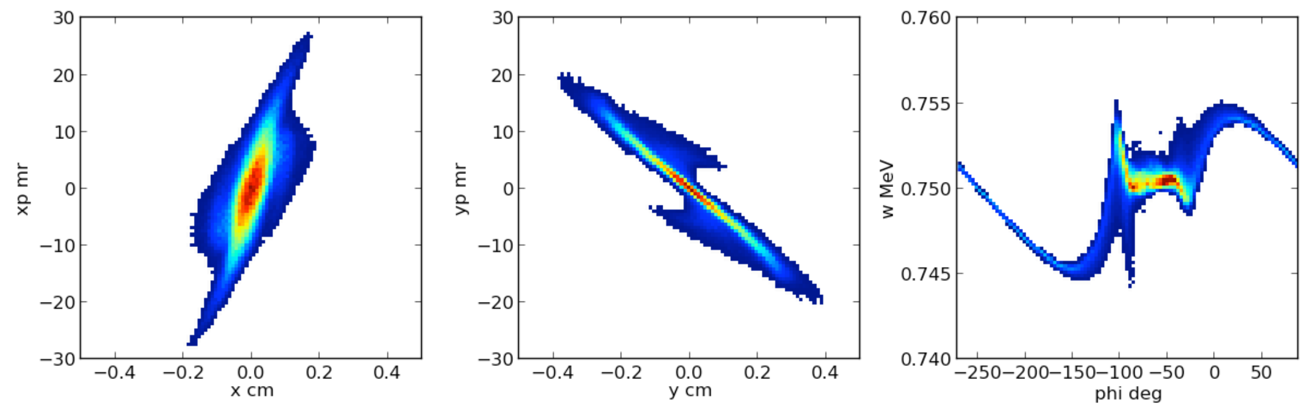

Figure 1: Simulated H$^+$ beam transverse and longitudinal phase-space distributions at the end of the LANSCE LEBT. Color indicates intensity where red is high and blue is low.

parameters taken from emittance measurements, and a longitudinal distribution that is monoenergetic and uniform in phase. The beam-line elements, i.e. quads and bunchers, are at representative operating values. It is clear from the phase-space distributions shown that an envelope code cannot capture the detailed features present in this type of beam.

### *Emittance Growth*

Enabling emittance growth in the beam is vital to more accurately model it's evolution in a real linac. This multi-particle simulation model contains features e.g. space charge, transverse-longitudinal coupling via the RF fields, etc., that contribute to emittance growth.

Space charge is an important nonlinear effect that can produce emittance growth. This online model employs the particle-in-cell (PIC) method where the collective space-charge force is estimated numerically and applied to each macro-particle in the bunch. This is in contrast to envelope models, e.g. TRACE3D [8], where only the linear part of the force is considered with an rms equivalent beam and therefore cannot contribute to emittance growth.

RF fields used in accelerating and bunching the beam can also lead to tail formation and emittance growth. Although a model like TRACE3D does include transverse emittance growth in an RF gap, this is in an rms sense and does not represent the tails that can appear. An example of distortions caused by these and other emittance growth mechanisms that can appear on a realistic beam are shown in Fig. 2. This simulation result is a continuation of the H$^+$ beam, shown in Fig. 1, but to the end of the 100-MeV DTL. More pronounced transverse and longitudinal tails have appeared on the output beam.

### *Beam Losses*

Beam losses are one of the main concerns in operating a high-power linac [9]. By employing an online multi-particle model operations staff can begin to evaluate the effects of various machine parameter choices on the simulated beam quality and loss. An example of this is in predicting the effect of operating set point changes on beam losses following standard tune up. In this hypothetical case the energy of the beam into the LANSCE CCL was adjusted through a standard tweak, a phase set point adjustment on DTL tank 3. The CCL input beam and fractional beam loss along the CCL before and after the adjustment are shown in Fig. 3. This small adjustment resulted in slight changes to the longitudinal distribution and a reduction in the simulated total beam loss from 2.81% to 0.40%.

Presently in the model, beam losses occur when a

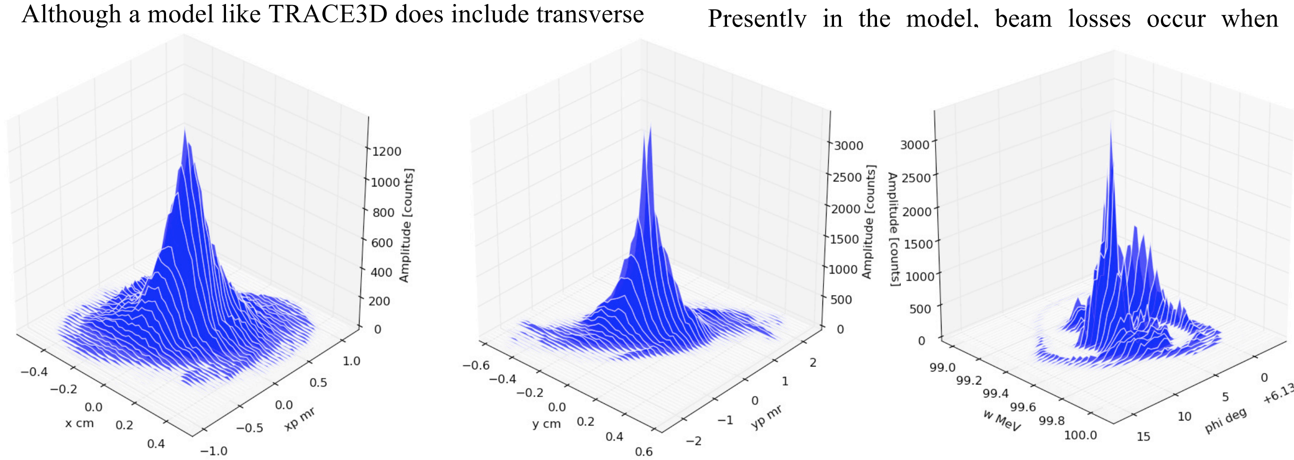

Figure 2: Simulated H$^+$ beam transverse and longitudinal phase-space distributions at the end of the LANSCE DTL.

6th International Particle Accelerator Conference IPAC2015, Richmond, VA, USA JACoW Publishing
ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPWI033



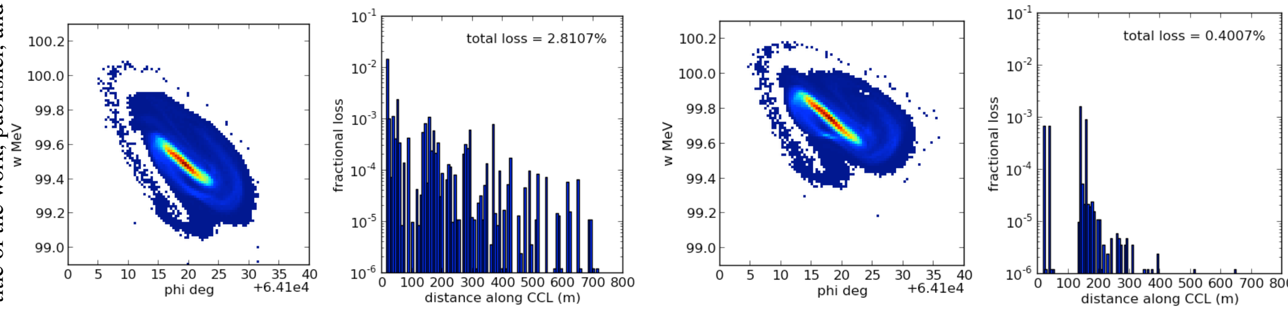


Figure 3: Simulated H⁻ beam distribution at the entrance to the CCL and corresponding beam loss along the CCL. Higher losses after hypothetical tuneup (left pair) and subsequent lower losses following small phase adjustment of DTL tank 3 to increase beam energy into CCL (right pair).

particle strikes an aperture due to motion associated with either space-charge or the external forces produced by the accelerator. However, other mechanisms, e.g. loss of H⁻ ions due to residual gas, intra-beam and Lorentz field stripping, could be incorporated into the model to provide these beam-dependent stripping rates as well.

### *Virtual Beam Measurements*

Once the model has been calibrated [10] against a working linac, it can be used to provide beam information where no diagnostics are present. This *virtual* beam measurement can provide new insight into the evolution of the beam in the accelerator. As in the example in Fig. 3, one can evaluate the change in the input beam properties that resulted in a reduction in losses. This is a vast improvement over tuning solely to reduce beam spill without understanding the impact of those changes on the overall beam quality. The virtual measurements can be used to quantify various beam characteristics while tuning so that a more optimal solution can be found and a deeper understanding of the results gained.

## PERFORMANCE AND LIMITATIONS

The performance of this model is quite good. On a single NVIDIA K20 GPU in a desktop workstation, an initial beam distribution of 64K particles is accelerated from 750 keV to 800 MeV (~5100 RF gaps, 400 quads and 6000 space charge kicks in a total length of ~800 m) in under 6 sec, which is fast enough to be useful in a control room environment.

However, any model of this sort does have limitations. In this case, the fidelity of the model, i.e. underlying physics approximations, actual vs. model representations of systems, set point uncertainties, etc., and the actual vs. model representation of the beam, including the number of macro-particles included in the simulation, ultimately limit the accuracy and precision of the predictions for a real machine. Nonetheless, this model has numerous advantages over other approaches. Finally, as GPU technology advances and performance improves and more accurate representations of the beam and the machine are incorporated into the model, the full advantage of this approach can be realized.

## ACKNOWLEDGMENT

The authors would like to thank AOT division for their continued support of this activity.

## REFERENCES

[1] L.J. Rybarcyk et al., “LEDA Beam Operations Milestone and Observed Beam Transmission Characteristics,” Linac 2000, Monterey, CA, USA, Aug 2000, TUD15, p. 584, (2000), http://www.JACoW.org.

[2] J. Galambos, “SNS Performance and the Next Generation of High Power Accelerators,” PAC2013, Pasadena, CA, USA, Oct 2013, FRYAA1, p. 1443 (2013), http://www.JACoW.org.

[3] R. Cole, “TRACE User Information Manual,” LANL Internal Document, (1985).

[4] K.R. Crandall, “The Delta-T Tuneup Procedure for the LAMPF 805 MHz Linac,” LANL Report LA-6374-MS, June 1976.

[5] C.K. Allen et al., “A Novel Online Simulator for Applications Requiring a Model Reference,” ICALEPCS2003, Gyeongju, Korea, Oct 2003, p. 315, (2003), http://www.JACoW.org.

[6] J. Galambos et al., “Summary of the Commissioning, Operations and Performance Working Group of the HB-2010 Workshop,” HB2010, Morschach, Switzerland, Sept 2010, FROP04, p. 703, (2010), http://www.JACoW.org.

[7] X. Pang, “Advances in Proton Linac Online Modeling,” WEXC2, IPAC’15.

[8] K.R. Crandall et al., “TRACE 3-D Documentation,” 2nd Ed., Dec 1990, Los Alamos National Laboratory report LA-11054-MS.

[9] M.A. Plum, “Beam Loss Mechanisms in High Intensity Linacs,” HB2012, Beijing, China, Aug. 2012, MOI1C03, p. 36, (2012), http://www.JACoW.org.

[10] L.J. Rybarcyk et al., “Application and Calibration Aspects of a New High-Performance Beam-Dynamics Simulator for the LANSCE Linac,” NA-PAC’13, Pasedena, CA, Sept. 2013, TUPSM19, p. 676, (2013), http://www.JACoW.org.