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BENCHMARKING HPSIM WITH THE LANSCE LINAC*

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Abstract

High-Performance Simulator (HPSim), the GPU-powered multi-particle simulation code developed for LANSCE, can provide critical 6-D beam distributions in near real-time to LANSCE operation crew and user facilities. We will present the benchmarking results for HPSim to the LANSCE linac.

INTRODUCTION

The linac at the Los Alamos Neutron Science Center (LANSCE) [1] serves five user facilities, simultaneously delivering 100-MeV H^+ beam to the Isotope Production Facility (IPF) and 800-MeV H^- beam other four user facilities, including the proton Radiography (pRad), Ultra-Cold neutron (UCN), Weapon Neutron Research (WNR), and the Lujan Center. Prior to the Lujan Center, the beam is accumulated in the Proton Storage Ring (PSR), which produces a high-intensity, short-pulse for the target. Though diagnostics like the loss monitors and beam position & phase monitors (BPPMs) are common tools for optimization, beam distributions created by fast multi-particle simulations can provide valuable beam distribution information. HPSim [2, 3], based on the PARMILA [4] code, was developed at LANSCE with a goal to create a digital twin of the linac that can provide minute-by-minute 6-D beam distributions with energy (E), phase (ϕ), and positions and angle (x, x', y, y') coordinates.

Such distributions are beneficial for both the users and the high-intensity operations. For example, though the IPF beam energy is measured via the BPPMs, the beam energy spread remains unknown, creating a compounding uncertainty as the beam propagates through stacked isotope production targets. Beam distributions provided by the HPSim could help narrow the uncertainties in isotope production. For pRad, the imaging resolution also depends on the energy spread of the beam. Moreover, the beam current delivered to the Lujan Center would be reduced if the energy spread increases for the beam-loss-limited operation of PSR. Figure 1 shows a beam distribution from HPSim after a physics tune. The distribution shares similarity with a measurement of high energy spread observed at the wire-scanner at a high-dispersion point after the linac. For the operation, a digital twin of the accelerator can speed up the problem-solving process and help the development of machine-learning algorithms.

In this proceeding, we will present our efforts in aligning HPSim with the machine status via benchmarking HPSim with the measurements in both operation and the startup period.

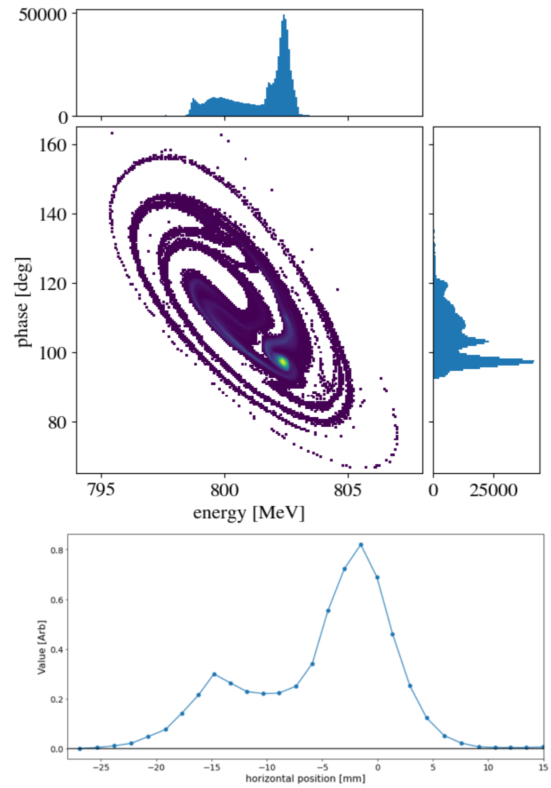

Figure 1: (top) A beam distribution in the energy and phase space at the linac from HPSim after a physics tune in the simulation. (bottom) A measurement of the horizontal wire-scanner at a high-dispersion point after the linac during a startup period. A large energy spread, demonstrated in the double peaks, is similar to the energy distribution above.

METHODS

The linac can be separated into three major parts: (1) the Low Energy Beam Transport (LEBT) region, (2) the Drift Tube Linac (DTL) that accelerates both H^+ and H^- from 750 keV to 100 MeV and, (3) the Side-Coupled Cavity Linac (CCL) that accelerates H^- from 100 MeV to 800 MeV. We will discuss our methods and results for each section below.

Several code improvements were also made to the public repository in [2] including Python 2-to-3 conversion, CUDA 4-to-11, and the modularization of the package. Beam information at mid-points become accessible without stopping the simulation, and the integration with Python pandas DataFrame is implemented. Tutorials in Jupyter notebooks, including the procedures below, are also created. The updated HPSim will be pushed to a new repository pending internal approval.

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Low Energy Beam Transport

The 750-keV H^+ and H^- beams go through separate pre-bunchers and then are merged into one beamline. Both H^+ and H^- beams go through the same main buncher before they enter the DTL. Several emittance stations are present along the LEBT. For our effort, we took the first emittance measurements immediately downstream of the each pre-buncher. With the measured Twiss parameters, we traced back to the beginning of the pre-bunchers. Every simulation starts from these two points with longitudinal distribution assumed to be continuous current and particle energy is set at the nominal 750 keV unless specified otherwise. The tune-up of the pre-bunchers and the main buncher will be discussed in the next section together with the DTL. For the H^+ beamline, the quads are further adjusted at ~10% level with Gaussian Process from Xopt [5] to achieve a good match into the DTL. Since we primarily focus on the longitudinal distribution and such changes are considered relatively small in operation, we believe this would not significantly influence our results.

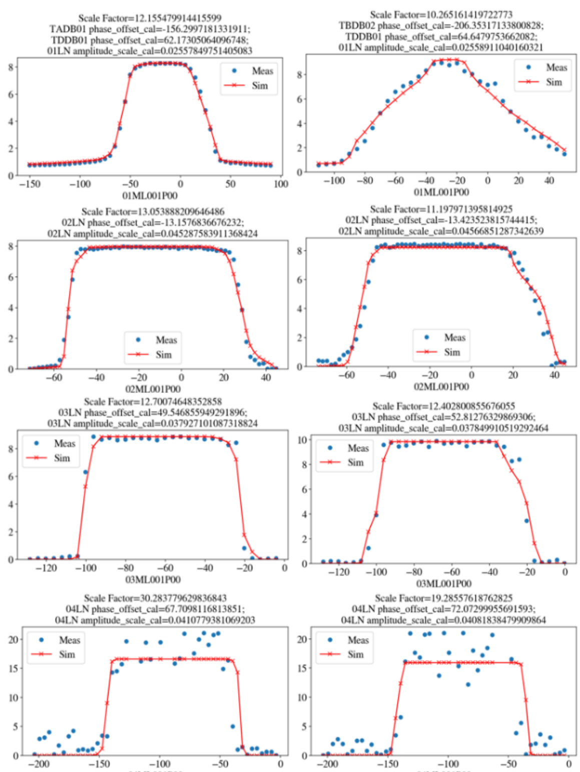

Figure 2: Matching of HPSim simulations with measurements for the phase scans in the DTL. From top to bottom, it corresponds to the four modules in the DTL. The left (right) column is for the H^+(H^-) beam.

Drift Tube Linac

Six RF cavities, including the main buncher, the respective pre-buncher, and 4 modules in the DTL, are benchmarked at this stage. The main diagnostics are the three absorber/collector pairs. The absorber stops all particles below a well-calibrated energy threshold from reaching the collector where the current from particles above the threshold is measured. This diagnostics tool is especially sensitive to the longitudinal size and therefore the energy spread. Six phase scans are conducted with different absorber/collector pairs, one scan for each cavity. In the actual tuning, the measured full width half maximum and the distance to the left edge are matched to the empirically established values. For HPSim, we set the EPICS setpoints in HPSim identical to the values in the machine. We then optimize the calibration constants to fit the HPSim phase scan simulations to the actual measurements. Figure 2 shows the best-fit results for modules 1-4 in the DTL. In general, the HPSim results are more consistent for H^+ than for H^-, while atypical noise in the module 4 scans could be clearly observed.

Side-Coupled Cavity Linac

The main tuning method for the CCL is measuring the change of time of flight (TOF) in terms of phases in the BPPMs. During the startup period, phase scans are conducted for each of the 5 to 48 modules in the CCL. A single particle model fits the measured phase scan and determines current fractional amplitude and relative phase to the design value. The amplitude and phase setpoints are adjusted accordingly after consideration of measurement and model uncertainties. For HPSim, we applied the final fractional amplitude relative to design and the relative phase for each module. Immediately after such applications, the loss in the CCL for HPSim is around 30%, while <1% loss is observed for the actual machine. Optimization were conducted to move module phase setpoints within 10 degrees and fractional amplitudes within 2% to minimize the beam loss in simulation. After optimization, around 8% of the particles are still lost in the CCL for HPSim.

RESULTS

After the tune-up of HPSim with the procedures above, the changes of readback channels, including the measured amplitudes and phases of RF cavities and various magnets are applied. HPSim simulated these archived changes prior to the tune-up in 1 min (10 mins) interval for H^+(H^-). For H^-, two sets of archived data are used for the RF modules in the DTL and CCL: one is the default command-readback channels while the other one is from independent field measurements. Simulated results are compared with the operational data for phase drifts for the BPPMs, energy drifts, loss locations and changes in the CCL.

The changes of phases measured via BPPMs along the CCL for H^- are compared with the HPSim results over a two-day period. Figure 3 shows the results of four selected BPPMs. The black dots are the actual data, while the blue and orange dots correspond to the default command-readback channel and the independent field measurements, respectively. Simulated data confirm that the independent measurements are better representations of the RF module status. In operation, energy drifts are observed via measured TOF of two pairs of BPPMs at the end of the linac. This measure suffers from large uncertainties, while simulated results do not appear to follow this measurement.

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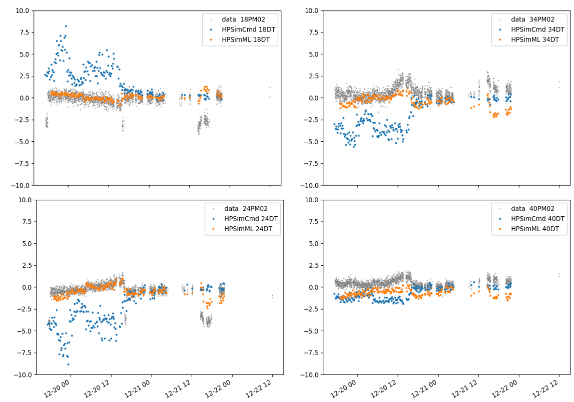

Figure 3: Phase changes at four selected BPPMs in the CLL between data (black dots), HPSim with default command-readback channels (blue) and HPSim with independent field measurements (orange). See text for more discussion.

Similarly, the trends in BPPM phase changes, a reflection of energy drift, for H^+ downstream from the DTL are consistent between data. While well-controlled energy distribution is vital for the H^+ beam delivered to IPF for activation, Fig. 4 shows the changes in energy distributions predicted by HPSim over a period of 24 days. Almost 0.5 MeV drift out of the 100 MeV proton beam is observed in the simulation, and the standard deviation of the energy spread ranges from 0.25 to 0.18 MeV.

The locations of the losses observed from HPSim at the beginning of the CCL follows the data. However, the increase of losses in the second half of the CCL was not reproduced in HPSim, as losses from intra-beam stripping and residual gas currently are not considered in the model. These two effects could contribute to higher losses.

FUTURE WORK

A new graphical user interface with HPSim will be created for the H^+ beamline for the beamline physicists to observe the changes between the linac and HPSim. In a controlled experiment, the beam energy will be shifted within 1 MeV via changing RF phases in the DTL. The beam with shifted energy will be delivered to a stacked target at IPF. The prediction from HPSim will be used as input to determine the impact of energy distributions to their activation. For the CCL, HPSim simulations will be directly compared with the measured phase scans to avoid using values from a single-particle model as an intermediate step. After the CCL, the beamline for the high energy beam transport will be developed. The energy spread and the distributions of off-momentum particles will be compared with inputs from user facilities and the phosphor near the high-dispersion point after the linac. The phosphor is the tool to monitor off-momentum particles, also commonly generated in HPSim. Moreover, a third buncher will be added to the HPSim model to simulate the beam pattern for the WNR. HPSim will also serve as the testbed for new control algorithms and training dataset for machine-learning applications.

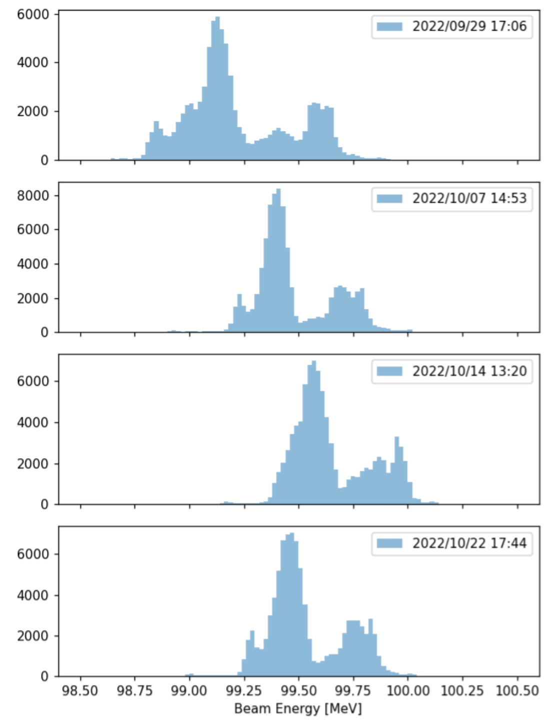

Figure 4: Simulated energy distributions for the H^+ beam over a period of 24 days. See text for more detail.

CONCLUSION

HPSim was benchmarked with the linac at LANSCE for both H^+ and H^- beam in an effort to create a digital twin for the accelerator. Consistency of phase drifts is observed at multiple BPPM locations. While more work is needed to improve the fidelity, HPSim will help improve the operation via providing a near-omniscient view in near real time and serving as a surrogate model for machine learning applications.

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