SIMULATION STUDIES OF THE LAMPF PROTON LINAC

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I. INTRODUCTION

The LAMPF accelerator consists of two 0.75-MeV injectors, one for H^+ and the other for H^-, a separate low-energy beam transport (LEBT) line for each beam species, a 0.75 to 100-MeV drift-tube linac (DTL) operating at 201.25 MHz, a 100-MeV transition region (TR), and a 100 to 800-MeV side-coupled linac (SCL) operating at 805 MHz. Each LEBT line consists of a series of quadrupoles to transport and transversely match the beam. Each LEBT also contains a prebuncher and an electrostatic deflector, but share a common main buncher. The deflector is used to gate beam into the linac. The DTL consists of four rf tanks (modules 1-4), each driven by a separate rf amplifier, and uses singlet FODO transverse focusing. The focusing period is doubled in the last two tanks by placing a quadrupole only in every other drift-tube. Doublet FDO transverse focusing is used in the SCL. The SCL tanks are bridge-coupled together into rf modules with a single klystron powering each module. Modules 5-12 consist of four coupled-cavity tanks bridge-coupled together with 32-36 cells/tank. Modules 13-48 consist of two bridge-coupled tanks with 49-61 cells/tank. The TR consists of separate transport lines for the H^+ and H^- beams. The path lengths for the two beams differ, by introducing bends, so the arrival of both beams is properly phased relative to the rf field. Peak H^+ beam currents typically range from 12 to 18 mA for varying duty factor, which give an average beam current of 1 mA. The number of particles per bunch is of the order 10^8.

The work presented here is an extension of our previous work [1]. We have attempted to do a more complete simulation by including modeling of the LEBT. No measurements of the longitudinal structure of the beam, except phase-scans, are performed at LAMPF. Transverse measurements include slit and collector emittance measurements, and wire scans to determine beam size and centroids. Comparison of simulations to beam loss data suggest that the primary causes of beam spill are incomplete longitudinal capture and the lack of longitudinal matching. Measurements to support these claims are not presently made at LAMPF. However, agreement between measurement and simulation for the transverse beam properties and transmissions serve to benchmark the simulations.

*Work supported by Los Alamos National Laboratory Directed Research and Development, under the auspices of the United States Department of Energy.

II. SIMULATION TECHNIQUES

The LEBT, DTL, and TR were modeled using the PARMILA code and the operational set points obtained from the operations group. All simulations began with an initial distribution of either 10,000 or 100,000 macroparticles. The transverse beam was generated as a Gaussian distribution in 4-D transverse space and was truncated at 3σ. A uniform longitudinal distribution was generated with zero energy spread. Simulations were done separately for H^+ and H^-, and were started with a dc beam at the center of the prebuncher in each LEBT. The beam was initially propagated to the center of the endwall quadrupole of the first tank of the DTL. A comparison was then made between the simulation results and transverse emittance measurements just downstream of the prebuncher and just upstream of the first DTL tank. The prebuncher and main buncher voltages used in the simulations were estimated for the actual cavities from Q and input power measurements, and SUPERFISH calculations. The prebuncher and main buncher voltages were 2.8 kV and 8.2 kV, respectively. Because the level of space-charge neutralization in the LEBT is unknown and no measurements of longitudinal beam parameters are made, there is some uncertainty in the conditions in the LEBT. We examined the effect of space-charge in the LEBT, however, the best agreement between simulations and measurements was achieved when a fully neutralized beam was assumed. An iterative procedure to determine the initial transverse-beam Twiss parameters (α,β) at the prebuncher center gave the best agreement with measured emittances. In general, during emittance measurements, most of the beam is stopped in the deflector beam dump. We believe this results in a copious source of electrons. Therefore, it is not unreasonable to assume that the beam may be nearly fully neutralized in the region of the deflector during these measurements.

At LAMPF, the operators generally reduce the DTL tank rf amplitudes below the design values to reduce beam spill in the SCL above 100 MeV. The 1993 relative rf amplitudes, as determined from power measurements, were estimated to be 0.93, 0.94, 0.90, and 0.98 of the design amplitudes for modules 1-4, respectively. These settings were used in the simulations when comparing to measurements taken under nominal operating conditions.

The output distributions from the PARMILA DTL simulations were used as input for the coupled-cavity code, CCLDYN. The design values for rf amplitudes and quadrupole gradients were used in the SCL simulations. It was assumed that the effects of misalignments of tanks and magnets in the SCL are small and therefore these data were not used in the simulations.

III. COMPARISON WITH MEASUREMENTS

A. H^+ Beam Simulation

Table 1 shows the results of both measurements and simulations for the H^+ beam at 100 MeV. The measured rms normalized (true rms with no factor of 4) emittance values were obtained by the slit and collector method. These measurements were made at the entrance to the DTL (0.75 MeV) and in the TR (100 MeV). Normally, emittance measurements are not recorded at 800 MeV. The simulated emittance values agree with the measurements to within 46% and 11% for ε_x and ε_y, respectively. The simulated transmission through the DTL agrees with measurements to within 3%.

Table 1 - H^+ 100 MeV Measurement and Simulation Results. The initial transverse rms normalized emittance at 0.75 MeV of 0.0063 π-cm-mrad was used in simulations.

	Measured	Simulated
$\varepsilon_x(\pi - cm - mrad, rms, norm)$	0.026	0.038
$\varepsilon_y(\pi - cm - mrad, rms, norm)$	0.020	0.018
$\varepsilon_{x-out} / \varepsilon_{x-in}$	4.2	9.7
$\varepsilon_{y-out} / \varepsilon_{y-in}$	5.3	4.7
DTL Transmission	67%	70%

B. H^- Beam Simulation

The two LEBT lines (H^+ and H^-) converge into one single line with the two beams bent by a common dipole magnet. There is an aperture restriction in the H^- beam line just before the convergence point. Downstream of the dipole magnet, there are four quadrupoles which are adjusted to match the H^+ beam into the DTL. The tuning of the H^- beam is a compromise between maximizing transmission through the aperture restriction and its match to the DTL. This is accomplished by varying the settings of quadrupoles which are upstream of the dipole magnet. Simulations suggest that some of the observed emittance growth of the H^- beam is due to the transverse mismatch at injection to the DTL. Table 2 shows the results of both measurements and simulations for the H^- beam at 100 MeV. The measured emittance growths are larger than that determined from the simulations using the nominal operating parameters. However, in the simulations, a 3% variation in the gradients of the quadrupoles just upstream of the DTL produces good agreement with the measured emittance growth. Unfortunately, this sensitivity was not seen in a later experimental test on the machine.

A few percent variation in some of the 140 quadrupole magnets of the DTL from the nominal operating gradients was required, in the simulations, to produce an output beam with Twiss parameters matching the measured beam. These variations in the quadrupole gradients are well within the known accuracy of their measured values.

Table 2 - H^- 100 MeV Measurement and Simulation Results. The initial transverse rms normalized emittance at 0.75 MeV of 0.019 π-cm-mrad was used in simulations.

	Measured	Simulated
$\varepsilon_x(\pi - cm - mrad, rms, norm)$	0.059	0.038
$\varepsilon_y(\pi - cm - mrad, rms, norm)$	0.042	0.034
$\varepsilon_{x-out} / \varepsilon_{x-in}$	3.2	1.8
$\varepsilon_{y-out} / \varepsilon_{y-in}$	2.2	1.5

C. Beam Loss at LAMPF

Simulations and operational data both show that the majority of beam loss after the DTL occurs at three locations along the linac: 1) In the transition region (TR), where the beam is transported from the DTL to the SCL at 100 MeV, 2) In module 5, at injection to the SCL at 100 MeV, and 3) near module 13 (212 MeV), where the SCL transverse focusing becomes weaker by a factor of two. The simulations give 1.2% losses in the SCL for the H^+ beam. Experimental results based on activation measurements predict 0.1% losses for H^+. Better agreement is achieved in the simulations for the H^- beam, where the simulations predict 0.2-1.0% losses depending on the assumed initial conditions. Experimental data predict approximately 1% losses for H^-. We believe that magnetic stripping of the H^- beam can be ignored, but a contribution to beam loss from residual gas stripping cannot yet be ruled out.

Before the beam from the ion source is injected into the DTL, it must be bunched and matched transversely. The present two-buncher system in the low-energy beam transport line is not capable of 100% bunching of the beam. The fraction of the beam which lies outside of the longitudinal acceptance of the DTL will not be captured or accelerated. This has been verified in the simulations. Figure 1 shows the DTL output distributions at 100 MeV from the H^+ simulations; the longitudinal phase space plot is in the lower-right corner. It should be noted that the particles which populate the tail of the longitudinal output distribution originated from the outer edges of the longitudinal acceptance at injection. Due to the factor of four decrease in the longitudinal acceptance at injection to the SCL (transition from 201.25 MHz to 805 MHz), some of these particles will be outside of the longitudinal acceptance of the SCL and will be lost there.

Simulation studies were used to determine the effect

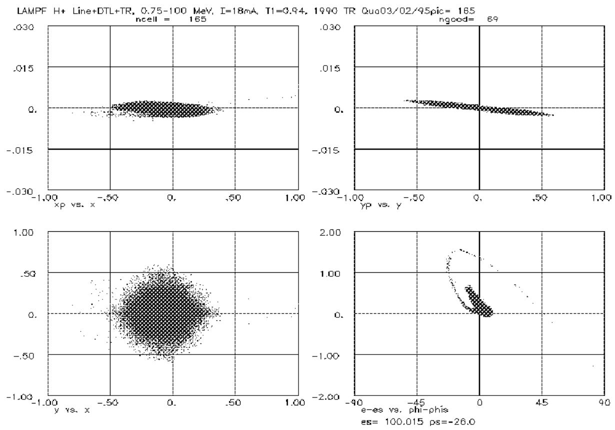

Figure 1: DTL output phase space and xy distributions at 100 MeV. The lower right plot is the longitudinal phase space. Note the long tail in the distribution.

of the DTL-module amplitudes on the DTL output longitudinal emittance at 100 MeV. It was found that there is a broad minimum in longitudinal emittance near 96% of design amplitude for module 1. This module was operated near 0.94 times the design-amplitude value during the 1993 run cycle. The result from the simulation is rather dramatic. A 6% reduction in module-1 amplitude reduces the transmission by 30% and reduces the longitudinal emittance by 60%. The transverse output emittance is not affected.

Figure 2 shows the energy spectrum of only particles lost in the SCL from H^+ simulations. It can be seen that these particles have energies of approximately 100 MeV. Figure 3 shows the energy spectrum of particles lost in both the TR and the SCL from simulations. This distribution has a low-energy tail with particle energies extending down to approximately 15 MeV. The particles in the low-energy tail are lost in the first two dipoles of the TR and therefore cause structure activation in the TR only. The particles in Fig. 3, with energies near 100 Mev, are not captured longitudinally in the SCL and are lost at the SCL entrance provided, they oringinated at the outer edge of the transverse distribution. Otherwise, these particles drift in the SCL until they are sufficiently deflected to the beam pipe or structure wall near module 13.

IV. A POSSIBLE UPGRADE PATH

We have done H^+ simulations where the first tank of the DTL was replaced with a 5.39-MeV RFQ and a bunch-rotator cavity was placed in the TR for longitudinal matching into the SCL. Fig 4 shows the DTL output distributions at 100 MeV from simulations with the RFQ. The longitudinal phase space plot is shown in the lower right corner and should be compared to Fig. 1. The longitudinal tail of the distribution is much reduced.

Because the beam is bunched adiabatically over many synchrotron-oscillation periods in the RFQ, the bunching process is more complete. In the simulations, the DTL modules were at full design amplitude and the simulated DTL transmission was found to be 100%. The simulated losses in the SCL were found to be 1.4% without longitudinal matching into the SCL at 100 MeV. However, simulations including the effect of a single multi-gap bunch-rotator cavity in the TR reduced the SCL losses to 0.005%, compared to 1.2% for simulations of the existing machine. These simulations demonstrate the importance of good longitudinal capture and matching.

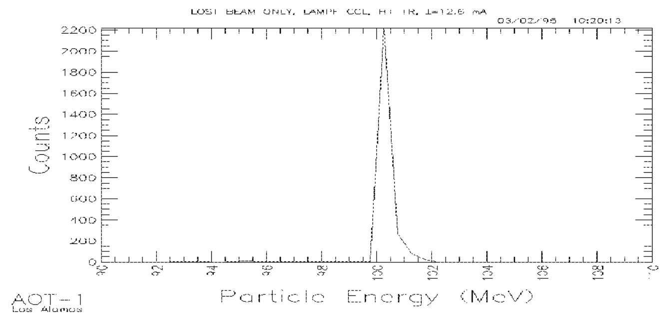

Figure 2: Energy spectrum of particles lost only in the SCL as determined from H^+ simulations.

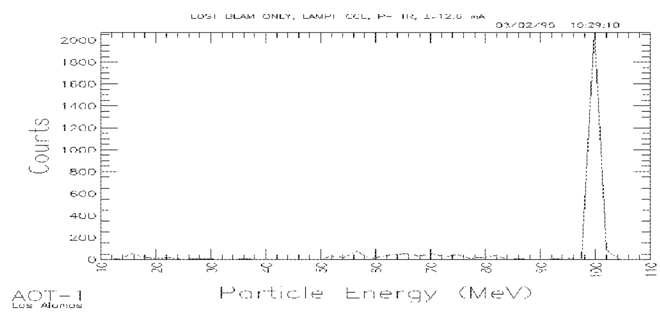

Figure 3: Energy spectrum of particles lost in the TR and the SCL as determined from H^+ simulations.

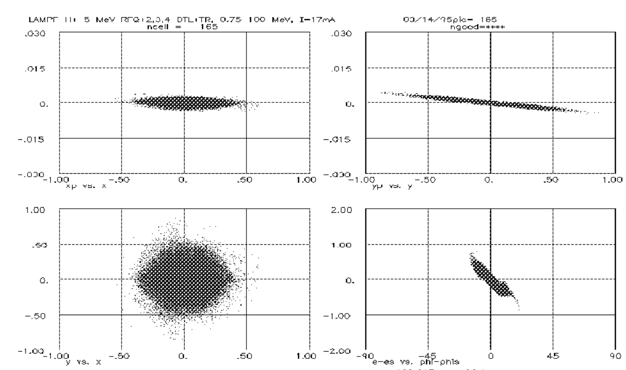

Figure 4: DTL output phase space and xy distributions at 100 MeV for the 5.39-MeV RFQ. Note the lack of a long tail in the longitudinal distribution compared to Fig. 1.

IV. REFERENCES

[1] R. W. Garnett, R. S. Mills, and T. P. Wangler, "Beam Dynamics Simulation of the LAMPF Linear Accelerator," Proceedings of the 1990 Linac Conference, Sept. 9-14, 1990, Albuquerque, NM.