Determining Phase-Space Properties of the LEDA RFQ Output Beam*

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Abstract

Quadrupole scans were used to characterize the LEDA RFQ beam. Experimental data were fit to computer simulation models for the rms beam size. The codes were found to be inadequate in accurately reproducing details of the wire scanner data. When this discrepancy is resolved, we plan to fit using all the data in wire scanner profiles, not just the rms values, using a 3-D nonlinear code.

1 INTRODUCTION

During commissioning of the LEDA RFQ[1, 2], we found that the beam behaved in the high energy beam transport (HEBT) much as predicted. Thus the actual RFQ beam must have been close to that computed by the PARMTEQM code.

The HEBT included only limited diagnostics[3] but we were able to get additional information on the RFQ beam distribution using quadrupole scans[4]. An good understanding of the RFQ beam and beam behavior in the HEBT will be helpful for the upcoming beam halo experiment. The problems with the quad scan measurements were the strong space effects and the almost complete lack of knowledge of the longitudinal phase space. Also, our simulation codes, which served as the models for the data fitting, did not accurately reproduce the measured beam profiles at the wire scanner.

2 HEBT DESIGN

The HEBT[5] transports the RFQ beam to the beamstop and provides space for beam diagnostics. Here, we discuss HEBT properties relevant to beam characterization.

- *Design has Weak Focusing.* Ideally, the HEBT would have closely-space quadrupoles at the upstream end until the beam is significantly debunched, i.e., for about one meter. After this point, we could use any kind of matching scheme with no fear of spoiling the beam distribution with space-charge nonlinearities.
  Our HEBT design uses four quadrupoles, which is the minimum that provides adequate focusing for the given length. Any fewer than four quadrupoles results in the generation of long Gaussian-like tails in the beam, which would be scraped off in the HEBT.
- *Good Tune is Important.* If a tune has a small waist in the upstream part of the HEBT, the beam will also acquire Gaussian-like tails. Simulations showed that good tunes existed for our four-quadrupole beamline and were stable (slight changes in magnet settings or input beam did not lead to beam degradation).
- *Beam Size Control.* In our design, increasing the strength of the last quadrupole (Q4) increases the beam size in both x and y by about the same amount. This is because there is a crossover in x just downstream of Q4 and a (virtual) crossover just upstream of Q4 in y. If the beam turns out to not be circular, this can be adjusted by Q3, which moves the upstream crossover point.
- *Emittance Growth in HEBT.* Simulations showed that the transverse emittances grew by about 30% in the HEBT. However, this did not affect final beam size. At the downstream end of the HEBT and in the beamstop, the beam is in the zero-emittance regime (very narrow phase-space ellipses). Simulations with TRACE 3-D, which has no nonlinear effects, and a 3-D particle code that included nonlinear space-charge predicted almost identical final beam sizes.

3 OBSERVED HEBT PERFORMANCE

Near the beamstop entrance, there is a collimator with a size less than 3 times the rms beam size. Initial runs showed beam hitting the top and bottom of the the collimator, indicating the beam was too large in y. This was fixed by readjusting Q3 and slightly reducing Q4 to reduce the beam size. After these adjustments, beam losses were negligible. This indicated the HEBT was operating as predicted and the RFQ beam was about as predicted. There were no long tails generated in the HEBT that were being scraped off. Thus our somewhat risky design, having only four quadrupoles, worked as designed.

4 QUADRUPOLE SCANS

4.1 Procedure

Only the first two quadrupoles were used. For characterizing the beam in y, Q1, which focuses in y, was varied and the beam was observed at the wire scanner, which was about 2.5 m downstream. The value of the Q2 gradient was chosen so that the beam was contained in the x direction for all values of Q1. For characterizing x, Q2 was varied.

As the quadrupole strength is increased, the beam size at the wire scanner goes through a minimum. At the minimum, there is a waist at approximately the wire-scanner position. For larger quadrupole strengths, the waist moves

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upstream in the beamline.

4.2 Measurements

Quadrupole scans were done a number of times for a variety of beam currents for both the x and y directions. The minimum beam size at the wire scanner was near 2 mm, which was almost equal to the size of the steering jitter. Approximately ten quadrupole settings were used for each scan. Data were recorded and analyzed off line.

4.3 Fitting to Data

To determine the phase-space properties of the beam at the exit of the RFQ, we needed a model that could predict the beam profile at the wire scanner, given the beam at the RFQ exit. We parameterized the RFQ beam with the Courant-Snyder parameters α, β, and ϵ in the three directions. We used the simulation codes TRACE 3-D and LINAC as models for computing rms beam sizes in our fitting. The TRACE 3-D code is a sigma-matrix (second moments) code that includes only linear effects but is 3-D. The LINAC code is a particle in cell (PIC) code that has a nonlinear r-z space charge algorithm.

Figure 1 shows the rms beam size in the y direction as a function of Q1 gradient. The experimental numbers are averages from a set of quad scan runs[4]. The other curves are simulations using the TRACE 3-D, LINAC, and IMPACT codes. The IMPACT code is a 3-D PIC code with nonlinear space charge. The initial beam (at the RFQ exit) for all simulations is the beam determined by the fit to the LINAC model[4]. (This is why there is little difference between the experimental points and the LINAC simulation.) There are significant differences among the codes in the predictions of the the rms beam size. Table 1 shows emittances we

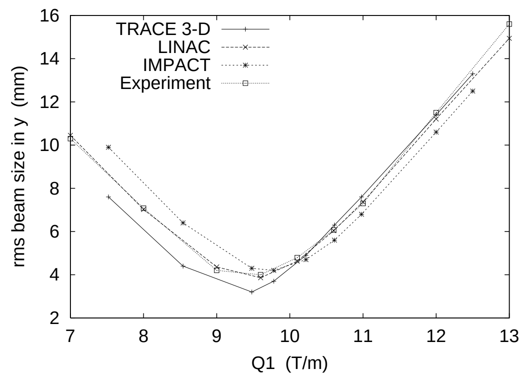

Figure 1: Rms beam size at wire scanner as function of quad strength. All simulations used the fit to the LINAC model for the input beam.

obtained when fitting to the TRACE 3-D and LINAC models.

Table 1: Rms normalized emittances (mm·mrad)

	ϵ_x	ϵ_y
Prediction (PARMTEQM)	0.245	0.244
Measured (TRACE 3-D fit)	0.400	0.401
Measured (LINAC fit)	0.253	0.314

5 QUAD SCAN SIMULATIONS

5.1 Profiles at Wire Scanner

Since only the IMPACT code has nonlinear 3-D space charge, we would expect that this code would be the most accurate and should be used to fit to the data. Both nonlinear and 3-D effects are large in the quad scans. However, we found that the IMPACT code (as well as LINAC) could not predict well the beam profile at the wire scanner. Figure 2 shows the projections onto the y axis for two points of the y quad scan, corresponding to a Q1 gradients of 7.52 and 11.0 T/m. The agreement for 11 T/m, which is to the right of the minimum of the quad scan curve, is especially poor. We see that the experimental curve (solid) has a narrower peak, with more beam in the tail than the IMPACT simulation predicts.

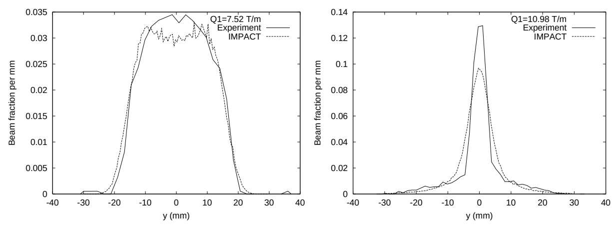

Figure 2: Profile at wire scanner for y scan with Q1=7.5 T/m (left) and Q1=11 T/m (right). Solid curve is the experimental measurement and the dashed curve is the IMPACT simulation using the LINAC-fit beam as input.

Figure 3 shows the y phase space just after Q2 for two points in the y quad scan. After Q2, space charge has little effect and the beam mostly just drifts to the end (there is little change in the maximum value of $|y'|$). The graph on the left is for a Q1 value to the left of the quad scan minimum (9.5 T/m). The graph at the right shows the situation to the right of the minimum (10.9 T/m). The distribution in the left graph is diverging, while the one on the right is converging. It is this convergence that apparently leads to the strange tails we seen in the experimental profiles at the wire scanner. Figure 4 shows similar graphs a little before

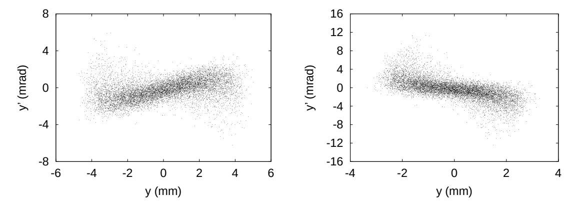

Figure 3: Phase space after Q2 in y direction for y scan with Q1=9.5 T/m (left) and Q1=11 T/m (right).

the wire scanner, 2.35 m downstream of the RFQ. We see how the tails in the y projection form for the case of the quad scan points to the right of the minimum, which correspond to larger quad gradients. While this appears to explain the narrow-peak-with-enhanced-tails seen in the wire scans, the effect is much smaller than in the experiment.

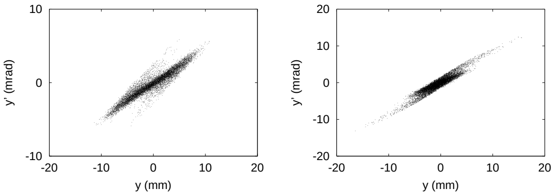

Figure 4: Same as Fig. 3 but at a point just upstream of the wire scanner.

We studied various effects looking to better reproduce the profiles seen at the wire scanner, all with negative results.

5.2 *Code Physics*

We studied the effects of mesh sizes, boundary conditions, particle number, and time step sizes with no significant change in results.

We investigated the possibility that there were errors associated with using normalized variables (p_x) in a z code, which IMPACT is. For high-eccentricity ellipses, this could be problem. However, transforming distributions to unnormalized coordinates, which are appropriate to a z code, did not noticeably change the results.

5.3 *Effects of Input Beam*

We used for input the beam generated by the RFQ simulation code PARMTEQM. We also used generated beams, which were specified by the Courant-Snyder parameters. Using the Courant-Snyder parameters of the PARMTEQM beam yielded similar results. Varying these parameters in various ways did not make the beam look any closer to the experimentally observed one.

We tried various distortions of the input beam such as enhancing the core or tail and distorting the phase space by giving each particle a kick in y' direction proportional to y^2 or y^3. These changes had little effect, even for very severe distortions. Kicks proportional to $y^{1/3}$ were more effective. These are more like space-charge effects in that the distortion is larger near the origin and smaller near the tails. In general, we found that any structure we put into the input beam tended to disappear because of the strong nonlinear space-charge forces at the HEBT front end.

5.4 *Effects of Quad Errors*

Multipole errors were investigate using a version of MARYLIE with 3-D space charge. We could generate tails that looked like the experimentally observed ones, but this took multipoles that were about 500 times as large as were measured when the quadrupoles were mapped.

Quadrupole rotation studies also yielded negative results.

5.5 *Space Charge*

We investigated various currents and variations in space charge effects along the beamline, as could be generated by neutralization or unknown effects.

5.6 *Longitudinal Motion*

We had practically no knowledge of the beam in the longitudinal direction except that practically all of the beam is very near the 6.7 MeV design energy. Since the transverse beam seems to be reasonably predicted by the RFQ simulation code, we do not expect the longitudinal phase space to be much different from the prediction. We tried various longitudinal phase-space variations and none led to profiles at the wire scanner that looked similar to the experimental ones.

6 DISCUSSION

In the upstream part of the HEBT the beam size profiles ($x_{\rm rms}$ and $y_{\rm rms}$ as functions of z) for the quad scan tune are not much different from those of the normal HEBT tune. The differences occurs quite a way downstream. But here, space charge effects are small and are unlikely to explain the differences we see in the beam profiles at the wire scanner. This is a mystery that is still unresolved.

If we succeed in simulating profiles at the wire scanners that look more like the ones seen in the measurement, then it will be reasonable to fit the data to the 3-D IMPACT simulations. In that case, we will use all the wire-scanner data, taking into account the detailed shape of the profile and not just the rms value of the beam width, as we did for the TRACE 3-D and LINAC fits. While we were able to use a personal computer to run the HPF version of IMPACT for most of the work described here, the fitting to the IMPACT model will have to be done on a supercomputer.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] H.V. Smith, Jr. and J.D. Schneider, "Status Update on the Low-Energy Demonstration Accelerator (LEDA)," this conference.

[2] L.M. Young, et al., "High Power Operations of LEDA," this conference.

[3] J.D. Gilpatrick, et al., "LEDA Beam Diagnostics Instrumentation: Measurement Comparisons and Operational Experience," submitted to the Beam Instrumentation Workshop 2000, Cambridge, MA, May 8-11, 2000.

[4] M.E. Schulze, et al., "Beam Emittance Measurements of the LEDA RFQ," this conference.

[5] W.P. Lysenko, J.D. Gilpatrick, and M.E. Schulze, "High Energy Beam Transport Beamline for LEDA," 1998 Linear Accelerator Conference.