DETERMINING PHASE-SPACE PROPERTIES OF THE LEDA RFQ OUTPUT BEAM

AUTHOR(S):
Walter P. Lysenko  LANSCE-1
J. Douglas Gilpatrick  LANSCE-1
Lawrence J. Rybarcyky  LANSCE-1
J. David Schneider  APT-TPO
H. Vernon Smith, Jr.  APT-TPO
Lloyd M. Young  SNS-PO
Martin E. Schulze  General Atomics

SUBMITTED TO:
LINAC 2000 Conference
Monterey, California
August 21-25, 2000
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Determining Phase-Space Properties of the LEDA RFQ Output Beam*

W.P. Lysenko, J.D. Gilpatrick, L.J. Rybarcyk, J.D. Schneider, H.V. Smith, Jr., and L.M. Young, LANL, Los Alamos, NM 87545, USA
M.E. Schulze, General Atomics, Los Alamos, NM 87544, USA

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 value.

1 INTRODUCTION

During commissioning of the LEDA RFQ, 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 predicted by the PARMTEQM code.

The HEBT included only limited diagnostics[5] 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, which is the next stage in the LEDA program. 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 transports the RFQ beam to the beamstop and provides space for beam diagnostics[1]. 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.

- **Importance of Good Tune.** Simulations showed that it is important to have a good tune to prevent beam degradation. If a tune has a small waist in the upstream part of the HEBT, the beam will acquire the Gaussian-like tails. The simulations showed that good tunes did exist for our four-quadrupole beamline and that they were stable (slight changes in magnet settings or input beam do 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 the x and y directions by about the same amount. This comes about because there is a crossover in one direction just downstream of Q4 and a (virtual) crossover just upstream of Q4 in the other direction. 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, which included nonlinear space-charge effects predicted almost identical final beam sizes.

3 MEASURED 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 the y direction. This was fixed by readjusting Q3 and slightly reducing Q4 to reduce the beam size going into the beamstop. 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

In these measurements, only the first two quadrupoles were used. For characterizing the beam in the y direction, Q1, which focuses in the y direction was varied and the beam was observed with 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 used. For characterizing the x direction, Q2 was

---

*Work supported by US Department of Energy*
As the quadrupole strength is increased, the beam spot size at the wire scanner decreases and then increases. At the minimum, there is a waist at approximately the wire-scanner position. As the quadrupole strength is increased, the waist moves 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 approximately 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 position, given the beam at the RFQ exit. We parameterized the RFQ beam with the Courant-Snyder parameters $\alpha$, $\beta$, and $\epsilon$ in the three directions. Because of space charge, simple models are inappropriate. We used the simulation codes TRACE 3-D and LINAC as models. We used 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 $r\times z$ 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. 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. (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.

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 case for 11 T/m, which is to the right of the minimum of the quad scan curve, is especially bad. We see that the experimental curve (solid) has a narrower peak, with more beam in the tail than the IMPACT simulation predicts.

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 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 ex-
plain the narrow-peak-with-enhanced-tails seen in the wire scans, the effect is much smaller than in the experiment.

We considered various effects that could better reproduce the profiles seen at the wire scanner.

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 \(p_z\) in a z code, which \textsc{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 \textsc{parmteqm}. We also used generated beams, which were specified by the Courant-Snyder parameters. Using the Courant-Snyder parameters of the \textsc{parmteqm} beam yielded similar results. Vary 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 the very large space charge effects at the upstream end of the \textsc{hebt} tended to wash out any structure we put into the input beam.

5.4 Effects of Quad Errors

Multipole errors were investigate using a version of \textsc{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 effects 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 well 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 that looked similar to the experimental ones.

6 DISCUSSION

In the upstream part of the \textsc{hebt} the beam profile (\(x_{\text{rms}}\) and \(y_{\text{rms}}\) as a function of \(z\)) for the quad scan tune is not much different from the normal \textsc{hebt} tune. The difference occurs downstream, close to the wire scanner. But here, space charge effects are very small and are unlikely to explain the difference we see in the beam profiles at the wire scanner. So this is the 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 \textsc{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 \textsc{trace} 3-D and \textsc{linac} fits. While we were able to use a personal computer to run the \textsc{hpf} version of \textsc{impact} for most of the work described here, the fitting to the \textsc{impact} model will have to be done on a supercomputer.

7 ACKNOWLEDGEMENTS

We thank Robert Ryne and Ji Qiang for providing the \textsc{impact} code and for help associated with its use.

8 REFERENCES