# SIMULATIONS OF THE LEDA LEBT $H^+$ BEAM†

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*Abstract*

The computer codes TRACE and SCHAR model the Low-Energy Demonstration Accelerator (LEDA) Low-Energy Beam Transport (LEBT) for 75-keV, 110-mA, dc $H^+$ beams. Solenoid-lens location studies verify that the proposed LEBT design gives a near-optimum match to the LEDA RFQ. The desired RFQ transmission (≥ 90%) and output emittance (≤ 0.22 π mm mrad, transverse) are obtained when PARMTEQM transports the file for the SCHAR-generated optimum beam through the RFQ.

## 1 INTRODUCTION

The LEDA microwave-driven source $H^+$ beam (75 keV, 130 mA, 85% $H^+$ fraction) is matched to the LEDA RFQ [1] using the two-solenoid, gas-neutralized LEBT [2] described in Ref. [3]. Two steering-magnet pairs provide the desired beam position and angle at the RFQ match point. Beam neutralization of 95-99% occurs in the LEBT residual hydrogen gas [4]. We model the emittance growth in the LEDA LEBT design (Fig. 1) using TRACE [5] and SCHAR [6]. The RFQ output beam is calculated by transporting the SCHAR-generated beam through the RFQ with PARMTEQM [7].

## 2 INPUT PARAMETERS

The LEBT input $H^+$ beam parameters are determined from measurements on the prototype LEDA injector, shown in Fig. 1 of Ref. [8]. TRACE drifts the beam (Fig. 4 of Ref. [8]) back along that 2.1-m long LEBT, from the emittance-measuring unit (EMU) to the 8.6-mm-diam ion source emitter. At the EMU this beam has total current = 130 mA, proton fraction = 87.7% ($H^+$ current = 114 mA), rms normalized emittance $\varepsilon_N$ = 0.207 π mm mrad, and $\alpha$ = -2.087 and $\beta$ = 16.908 mm/mrad at 10% threshold.

TRACE gives an $H^+$ beam size at the ion source emitter $\leq R_{emit}$ (= 4.3 mm) for unneutralized currents ($I_{eff}$) between 0.6 and 4.0 mA. The beam is converging for 0.6 mA; for 4.0 mA, it is diverging. The diverging beam is used because it is the "worst case." Unlike TRACE, SCHAR is a "6rms" code, so a value of $I_{eff}$ that gives a beam size of 4.3 mm/$(1.5)^{1/2}$ = 3.51 mm is chosen for the SCHAR calculations. The TRACE calculation for $I_{eff}$ = 3.5 mA, with $\alpha$ = -0.620, $\beta$ = 0.19 mm/mrad, and $\varepsilon_N$ = 0.207 π mm mrad, matches this value closely (3.52 mm).

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* $v_o = [2E/m_pc^2]^{1/2}c$, $r_{12} = -\alpha/[1+\alpha^2]^{1/2}$, $x_{max} = [\beta\varepsilon(6rms)]^{1/2}$, $v_{x\,max} = [\gamma\varepsilon(6rms)]^{1/2}v_o$

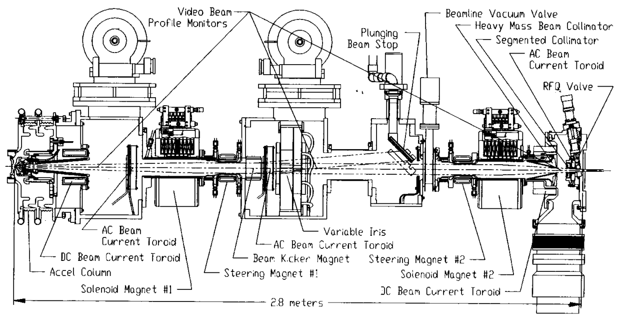


Fig. 1. The LEDA baseline LEBT design.

Using those TRACE parameters, SCHAR* predicts $\varepsilon_N$ = 0.243 π mm mrad at the EMU, about 17% higher than the measured value. The input parameters are scaled using $\alpha_{new} = \alpha_{old}[\varepsilon_{old}/\varepsilon_{new}]$ and $\beta_{new} = \beta_{old}[\varepsilon_{old}/\varepsilon_{new}]$, keeping the phase-space ellipse orientation and $x_{max}$ the same but adjusting the phase-space area up or down depending on $[\varepsilon_{old}/\varepsilon_{new}]$. SCHAR gives the measured $\varepsilon_N$ to within 0.01% after two iterations. The resulting SCHAR-predicted input beam (Table 1) has $\varepsilon_N$ = 0.175 π mm mrad. Using SCHAR to transport the beam parameters in Table 1 through the 2.1-m LEBT also gives the approximate measured phase-space shape at 10% contour (Fig. 5 of Ref. 8). The LEDA LEBT TRACE and SCHAR simulations described below use the input $H^+$ beam parameters given in Table 1.

## 3 LEDA LEBT TRACE SIMULATIONS

The $H^+$ beam matching parameters for the RFQ are $\alpha$ = 1.909 and $\beta$ = 0.1175 mm/mrad for an RFQ input $H^+$ beam current = 110 mA and $\varepsilon_N$ = 0.20 π mm mrad. The TRACE-calculated tuning curves for the baseline LEBT design are shown in Fig. 2. These tuning curves are generated by fixing the magnetic field of solenoid #1 ($B_{sol\#1}$) and varying the magnetic field of solenoid #2 ($B_{sol\#2}$). The matched $\alpha$ and $\beta$ values result for $B_{sol\#1}$ = 2700 G and $B_{sol\#2}$ = 3667 G. The 21.59-cm-long, 10-cm-i.d. solenoid lenses provide dc fields ≤5000 G, so the LEBT design shown in Fig. 1 has the tuning capability to match the $H^+$ beam from the source into the RFQ.

Table 1. TRACE and SCHAR parameters that reproduce the previously-measured phase-space distribution [8].

| TRACE ($I_{eff}$ = 4.0 mA) | SCHAR ($I_{eff}$ = 3.5 mA) |
|---|---|
| E = 75 keV | $v_o$ = 3.79 x $10^6$ m/s |
| $\alpha$ = -0.873 | $r_{12}$ = 0.585 |
| $\beta$ = 0.26 mm/mrad | $x_{max}$ = 4.32 x $10^{-3}$ m |
| $\varepsilon_N$ = 0.207 π mm mrad | $v_{x\,max}$ = 9.14 x $10^4$ m/s |

 

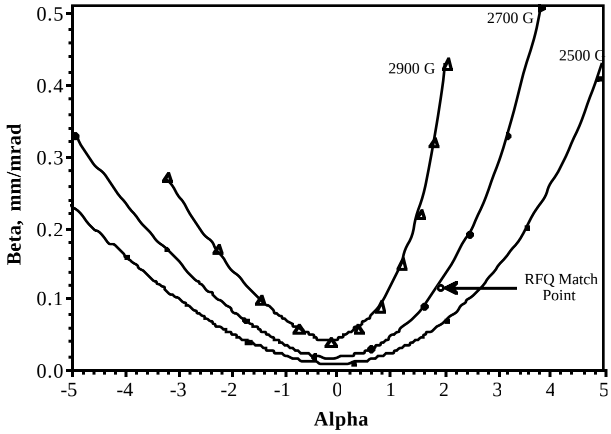


Fig. 2. The TRACE-calculated tuning curves for the baseline LEBT design. The RFQ match point is indicated.

## 4 LEDA LEBT SCHAR SIMULATIONS

The LEBT (Fig. 1) is simulated with the non-linear space-charge computer code SCHAR. These simulations use a 4-volume distribution and the line mode with 999 lines. Case No. 1 in Table 2 has the LEBT dimensions used for the SCHAR model of the baseline design. The distance between the center lines of the two solenoids is 151.72 cm for all simulations in this paper. The beam neutralization is assumed to be 2.7% ($I_{eff}$ = 3.5 mA), about mid-way in the 1-5% range measured [4] on the prototype LEDA injector.

The TRACE-derived solenoid settings, $B_{sol\#1}$ = 2700 G and $B_{sol\#2}$ = 3667 G, are used as starting values. SCHAR predicts that the best match to the RFQ (Fig. 3) is obtained for $B_{sol\#1}$ = 2500 G and $B_{sol\#2}$ = 3500 G. The predicted $\varepsilon_N$ at the RFQ match point is 0.228 $\pi$ mm mrad. SCHAR predicts that most of the 30% emittance growth is due to spherical aberrations in solenoid #1

Table 2. Results of the LEBT and RFQ simulations with SCHAR and PARMTEQM, respectively. The LEBT dimensions are in columns 2 and 3, the SCHAR-calculated $\varepsilon_N$ at the RFQ match point in column 4, the input $\varepsilon_N$ for the PARMTEQM RFQ simulations in column 5, and the PARMTEQM-calculated RFQ transmission and output $\varepsilon_N$ in columns 6 and 7.

| Case No. | Extractor to Sol#1, cm | Sol#2 to RFQ Match Point, cm | SCHAR RFQ $\varepsilon_{in}$, $\pi$ mm mrad | PARMTEQM RFQ $\varepsilon_{in}$, $\pi$ mm mrad | PARMTEQM RFQ $\varepsilon_{out}$, $\pi$ mm mrad | RFQ transmission % |
|---|---|---|---|---|---|---|
| 1 | 87.58 | 40.70 | 0.228 | 0.226 | 0.214 | 93.0 |
| 2 | 57.58 | 40.70 | 0.220 | 0.218 | 0.206 | 92.7 |
| 3 | 87.58 | 25.70 | 0.204 | 0.202 | 0.200 | 93.4 |
| 4 | 57.58 | 25.70 | 0.189 | 0.188 | 0.196 | 92.7 |
| 5 | 87.58 | 45.70 | 0.246 | 0.244 | 0.225 | 91.9 |
| 6 | 87.58 | 50.70 | 0.383 | 0.382 | 0.251 | 79.2 |
| 7 | 87.58 | 55.70 | 0.456 | 0.467 | 0.274 | 77.2 |

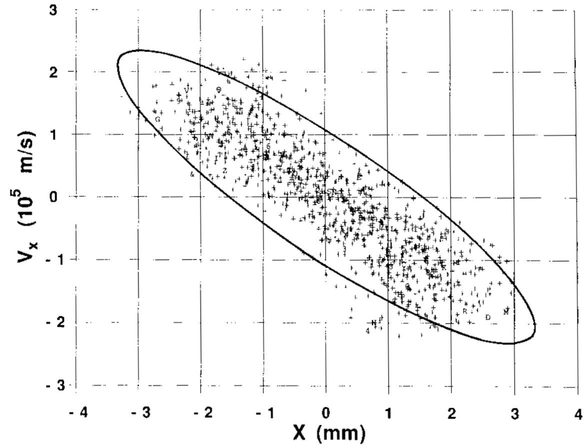


Fig. 3. SCHAR-calculated phase space (crosses) at the RFQ match point for the baseline LEBT design (Case No. 1). The curve is the RFQ acceptance ellipse for a 110-mA, 0.20-$\pi$ mm mrad beam.

(12%) and solenoid #2 (14%). The non-linear, space-charge-induced emittance growth is low (4%). The SCHAR output file is used to generate a 5,000 particle input beam for the PARMTEQM computer code to estimate the RFQ transmission and output $\varepsilon_N$. The result is transmission = 93.0% and output $\varepsilon_N$ = 0.214 $\pi$ mm mrad (Fig. 4). This is the baseline case against which the rest of the SCHAR modeling is compared.

Next the distance between the source and solenoid #1 center line and/or the distance between solenoid #2 center line and the RFQ match point (z) are varied. The SCHAR beams are then rematched and used as input for the PARMTEQM code to predict the RFQ transmission and $\varepsilon_N$. The results of these simulations are given in Table 2 and are discussed below. When the source-Solenoid #1 distance is reduced by 30 cm (Case 2), the SCHAR-predicted RFQ input $\varepsilon_N$ drops by only 3.5%, the PARMTEQM-predicted RFQ output $\varepsilon_N$ drops by only 3.7%, and the RFQ transmission is almost unchanged. When both the source-Solenoid #1 and Solenoid #2-RFQ

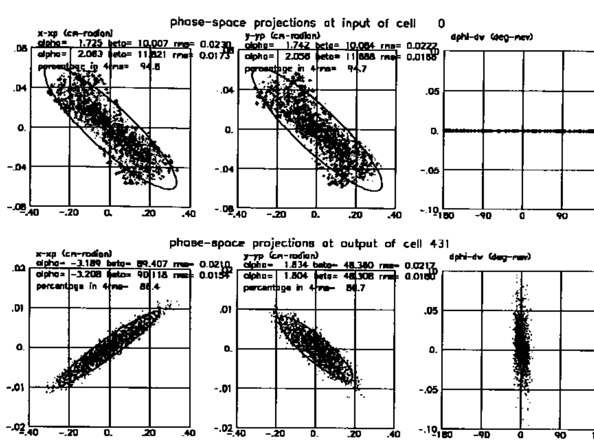


Fig. 4. PARMTEQM-calculated RFQ input (top) and output (bottom) phase space for the baseline LEBT design.

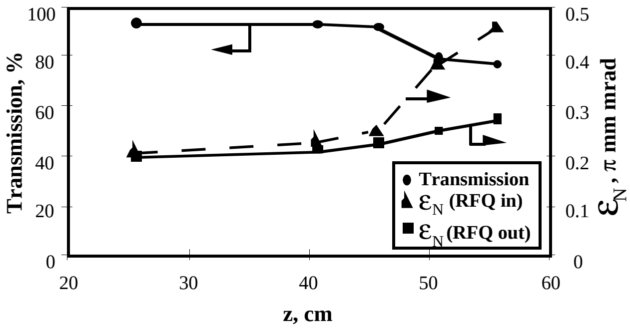


Fig. 5. PARMTEQM-calculated RFQ transmission (circles) and output $\varepsilon_N$ (squares), and SCHAR-calculated RFQ input emittance (triangles) as a function of the distance between Solenoid #2 and the RFQ match point.

distances are shortened by 30 cm and 15 cm, respectively (Case 4), the SCHAR-predicted RFQ input $\varepsilon_N$ drops by 17% and the PARMTEQM-predicted RFQ output $\varepsilon_N$ drops by 8.4%, but the RFQ transmission is almost the same. The codes predict that reducing the source-Solenoid 1 distance by as much as 30 cm gives no significant gain.

When the Solenoid 2 center line-RFQ distance (z) is shortened by 15 cm (Case 3), compared with Case 1 the SCHAR-predicted RFQ input $\varepsilon_N$ drops by 11% and the PARMTEQM-predicted RFQ output $\varepsilon_N$ drops by 6.5%, but the predicted RFQ transmission is higher by 0.4%. This small difference in output RFQ $\varepsilon_N$ would not significantly effect the rest of the LEDA accelerator.

Increasing z would allow adding more beam diagnostics and/or beamline components in front of the RFQ. In Cases 5-7 (Table 2) z increases from 40.7 to 55.7 cm in 5-cm steps. For the baseline case (z = 40.7 cm), the beam size in solenoid #2 is small enough that spherical aberrations are low (Fig. 3). When z increases to 45.7 cm (Case 5), the LEDA RFQ transmission lowers slightly (from 93.0% to 91.9%) and the RFQ output $\varepsilon_N$ rises slightly (from 0.214 to 0.225 $\pi$ mm mrad). Increasing z to 50.7 and 55.7 cm increases the beam size in solenoid #2 enough that spherical aberrations dominate $\varepsilon_N$ at the RFQ match point (Fig. 5), causing unacceptable RFQ transmission (Cases 6 and 7). Increasing z from 40.7 cm to 45.7 cm is acceptable, if there is a good reason to do so.

## 5 TRACE STEERING SIMULATIONS

The LEDA injector will provide a range of beam centroid motion at the RFQ match point. Error studies show that if the input phase space distributions are centered on the RFQ axis to within ±0.2 mm in position and ±10 mrad in angle, the transmission degrades by <1%. The solenoid lenses will be aligned to meet these tolerances, but there will be inevitable misalignments between the ion source, column and RFQ that can produce centroid errors in excess of these tolerances. The LEBT steering system will permit rapid, on-line correction of these errors.

Independent control of X and Y motions is desirable

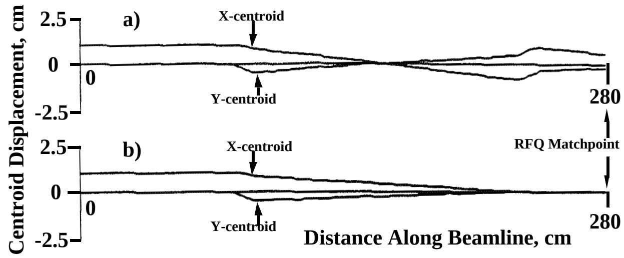


Fig. 6. a) Beam centroid motion for an initial 1 cm offset. b) Beam centroid motion after steering.

to match the symmetry of the RFQ. We place two steering pairs in the LEBT between the solenoid lenses (Fig. 1) and provide a computer algorithm to decouple the desired steering motion in the X and Y planes from the rotation effects produced by the solenoid lenses [9]. It is desirable to align the optical elements in the beam line so that changes in the focusing strength of the solenoids do not result in the introduction of steering errors. This makes the matching and steering control independent and greatly facilitates tuning this beam line.

We use TRACE to model the effects of misalignment errors in this beam line and to determine the required steering corrections. The two steering pairs can correct a 1 cm horizontal offset in the alignment of the ion source to the LEBT as shown in Fig. 6.

## 6 SUMMARY

For the LEDA RFQ operating at 110 mA, high beam transmission is more important than low beam emittance within the range of RFQ output emittances reported here. Because the PARMTEQM-predicted RFQ transmission is about as high (or higher) for the baseline LEBT design as for any of the other geometries studied, we conclude that the LEDA baseline LEBT design is near optimum. Also, TRACE predicts that the steering proposed for the LEDA LEBT will allow correct spatial and angular positioning of the $H^+$ beam for injection into the RFQ.

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