COMPARISON OF BEAM SIMULATIONS WITH MEASUREMENTS FOR A 1.25-MeV, CW RFQ†

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Abstract

The Low-Energy Demonstration Accelerator (LEDA) injector is tested using the Chalk River Injector Test Stand (CRITS) radio-frequency quadrupole (RFQ) as a diagnostic instrument. Fifty-keV, dc proton beams are injected into the 1.25-MeV, CW RFQ and transported to a beamstop. Computer-simulation-code predictions of the expected beam performance are compared with the measured beam currents and beam profiles. Good agreement is obtained between the measurements and the simulations at the 75-mA design RFQ output current.

1 INTRODUCTION

To test the LEDA injector [1] under operating conditions, the ion-source extraction system is altered from a tetrode at 75 keV to a triode at 50 keV [2]. The rest of the 2.54-m-long LEDA injector is about the same as it will be when the initial tests of the LEDA RFQ [3] are made. We match the LEDA microwave-driven source H^+ beam (50 keV, 70-100 mA, >90% H^+ fraction) to the CRITS RFQ [4] using the two-solenoid, gas-neutralized low-energy beam transport (LEBT) [5] described in Ref. [6]. 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 [7]. The RFQ accelerates the beam to 1.25 MeV and a simple HEBT transports that beam to the beamstop. The RFQ transmission and spatial profiles are measured as a function of injected current and LEBT solenoid excitations [2]. The expected beam performance is calculated using the computer codes TRACE [8] and SCHAR [9] to model the LEBT [10], PARMTEQM [11] to model the CRITS RFQ, and PARMELA [12] to model the HEBT.

2 INPUT PARAMETERS

The input H^+ beam parameters are determined from measurements on the prototype LEDA injector (Fig. 3 of Ref. 1) using a procedure described in [10]. A beam with 90-mA total current, proton fraction >90% (H^+ current >81 mA), rms normalized emittance $\varepsilon_N = 0.146\ \pi$ mm mrad, and $\alpha = -0.546$ and $\beta = 8.254$ mm/mrad at 10% threshold is measured at the emittance-measuring unit (EMU).

Using TRACE [8] to drift the beam back along that 2.1-m long LEBT, from the EMU to the ion source, gives a predicted 6.98-mm-diam H^+ beam size, close to that of the 6.8-mm-diam ion source emitter, for an unneutralized current $I_{eff} = 1.825$ mA, $\alpha = 0.411$, $\beta = 0.215$ mm/mrad, and $\varepsilon_N = 0.146\ \pi$ mm mrad (Table 1). Using these TRACE parameters as SCHAR* [9] input, and scaling them using $\alpha_{new} = \alpha_{old}[\varepsilon_{old}/\varepsilon_{new}]$ and $\beta_{new} = \beta_{old}[\varepsilon_{old}/\varepsilon_{new}]$, gives the measured ε_N to within 0.1% after two iterations. The resulting SCHAR-predicted input beam (Table 1) has $\varepsilon_N = 0.134\ \pi$ mm mrad. When SCHAR transports the beam parameters in Table 1 through the 2.1-m LEBT, the approximate phase-space shape at the 10% contour (Fig. 1) and beam profile at the video diagnostic (Fig. 2) result. Although the beam-profile data in Fig. 2 were obtained three days earlier than the phase-space data in Fig. 1, the source parameters were nearly identical for both data sets.

Table 1. TRACE and SCHAR input H^+ beam parameters.

TRACE (I_{eff} = 1.825 mA)	SCHAR (I_{eff} = 1.825 mA)
E = 50 keV	$v_o = 3.095 \times 10^6$ m/s
$\alpha = 0.411$	$r_{12} = -0.4131$
$\beta = 0.215$ mm/mrad	$x_{max} = 4.271 \times 10^{-3}$ m
$\varepsilon_N = 0.146\ \pi$ mm mrad	$v_{x\ max} = 6.117 \times 10^4$ m/s

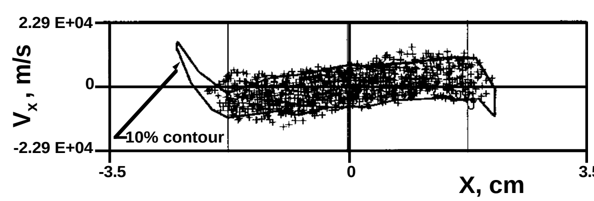

Fig. 1. The SCHAR-calculated phase space (crosses) at the EMU for the LEDA prototype LEBT. The solid line is the 10% phase-space contour measured with the EMU.

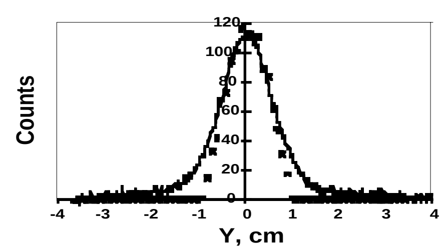

Fig 2. Hydrogen beam profile 42.9 cm from the source measured with a video camera (line) and predicted by SCHAR (squares).

3 LEDA LEBT SCHAR SIMULATIONS

The LEBT (Fig. 3) is simulated with the non-linear space-charge computer code SCHAR. These simulations use a 4-volume distribution and the line mode with 999

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

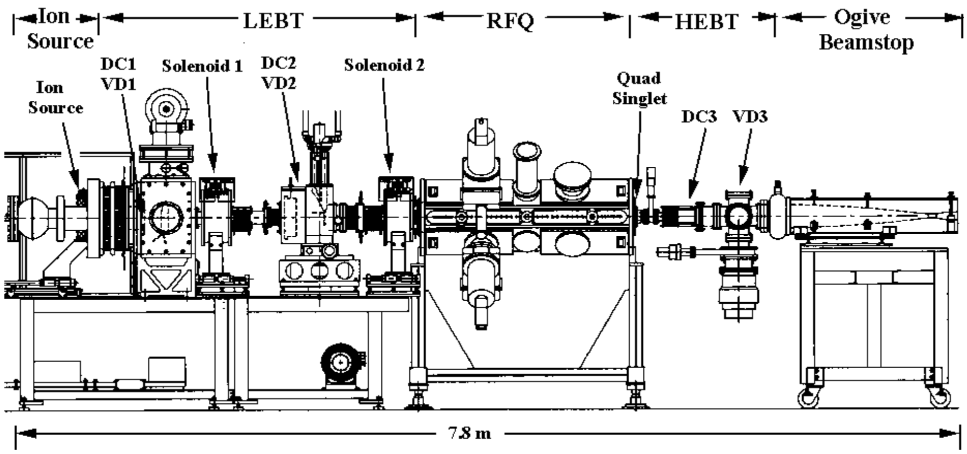

Fig. 3. The CRITS RFQ experiment beamline. The LEDA injector, ion source plus LEBT, is at the left. The CRITS RFQ is in the center, and the LEDA prototype ogive beamstop is at the right. The locations of the two LEBT solenoids (Solenoid #1 and Solenoid #2), RFQ exit quadrupole singlet, three Bergoz dc current transformers (DC1, DC2, and DC3), and three videocamera diagnostics (VD1, VD2, and VD3) are indicated.

lines. The LEBT dimensions are extractor to solenoid 1, 89.8 cm; solenoid 1 to solenoid 2, 138.4 cm; and solenoid 2 to RFQ match point, 25.6 cm. A beam neutralization of 98.0% (I_{eff} = 1.825 mA) is used. SCHAR predicts no proton beam loss in the LEBT. Using SCHAR input files, PARMTEQM predicts that the best match to the RFQ (Fig. 4) is obtained for $B_{sol\ 1}$ = 2100 G and $B_{sol\ 2}$ = 3675 G, giving ε_N = 0.169 π mm mrad at the RFQ match point. The actual $B_{sol\ 1}$ setting for the measurements, 1940-2010 G, is close to the SCHAR prediction whereas the actual $B_{sol\ 2}$ setting, ~4000 G, is 10% higher than the SCHAR prediction. The $B_{sol\ 2}$ setting is underestimated because of the absence in the SCHAR model of the un-neutralized section of beam transport just in front of the RFQ. Most of the SCHAR-calculated emittance growth (26.2%) is due to spherical aberrations in solenoid #1 (6.0%) and solenoid #2 (15.1%). The non-linear, space-charge-induced emittance growth is low (3.4%).

To obtain the 75-mA design RFQ output current requires operating the proton source at ~1200 W microwave power, 50% higher than used to obtain the SCHAR input parameters given in Table 1 (~800 W). The result is a larger-diameter beam at VD1 (Fig. 5) than in the case of the prototype LEBT measurements. At the ~1200 W power level the measured beam profile at VD2 (152.6 cm from the source) is also larger than SCHAR predicts.

4 CRITS RFQ PARMTEQM SIMULATIONS

The SCHAR output file is used to generate a 5,000 particle input beam for the PARMTEQM computer code to calculate the RFQ transmission and output ε_N. The proton fraction can be as high as 95% [13], but plasma effects caused by beam interactions with the beam-pipe walls [2] reduce the observed DC2 current by ~5%. These effects offset each other, so we use the measured DC2 current for the PARMTEQM input current. The result (Case 2, Table 2) is transmission = 75.1% and output ε_N = 0.207 π mm mrad (Fig. 6) for 97.5 mA input beam current and known RFQ intervane voltage (70.4, 72.6, 74.4, and 68.5 kV for Cases 1-4, respectively [14]). The predicted CRITS RFQ output current for other measured input beam currents [2] and RFQ vane voltages are given in Table 2. The SCHAR input parameters in Table 1 for a 90-mA beam (measured just in front of the EMU) are used for all of the simulations summarized in Table 2. Although RFQ output currents of up to 100 mA were measured [2], we limit our analysis to just those cases that have a complete set of beam currents and profiles.

5 HEBT PARMELA SIMULATIONS

The PARMELA [12] model of the HEBT uses the CRITS RFQ PARMTEQM output files for input. PARMELA,

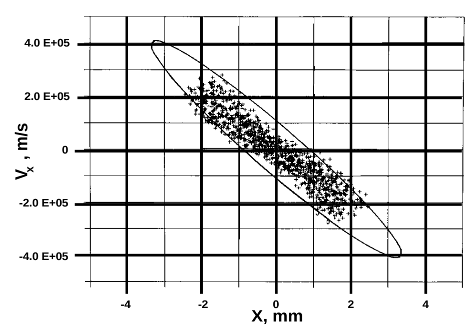

Fig. 4. SCHAR-calculated phase space (crosses) at the RFQ match point and the RFQ acceptance (curve) at 90-mA and 0.20-π mm mrad.

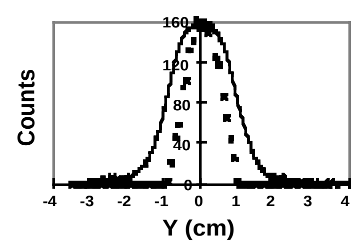

Fig. 5. Measured Hydrogen beam profile at VD1 (42.9 cm from the source) for case #2 in Table 2 compared with the SCHAR prediction calculated using the parameters in Table 1. Note the increase in the measured beam size over that in Fig. 2 as discussed in the text.

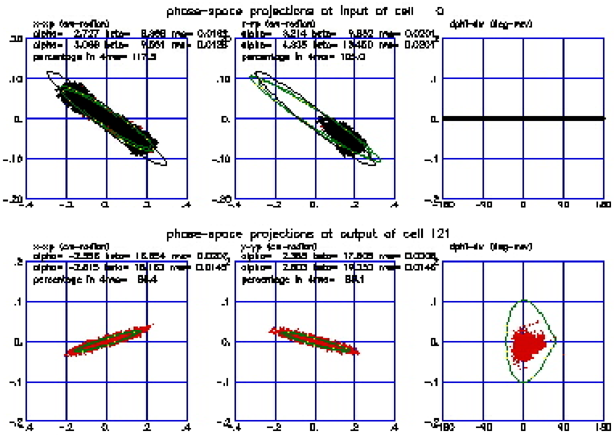

Fig. 6. PARMTEQM-calculated RFQ input (top) and output (bottom) phase space for Case 2 (Table 2).

set up to transport H^+ ions, predicts the beam transmission from the RFQ to the dc toroid (DC3 in Fig. 3), 57.5 cm downstream from the RFQ vanes, and also the x and y beam profiles at video diagnostic #3 (VD3 in Fig. 3), 87.7 cm downstream from the RFQ, for the known fields in the quadrupole singlet, located 7.8 cm downstream from the RFQ vanes. Table 2 lists the PARMELA predictions (note that the predicted beam loss between the RFQ and DC3 is small) along with the measured DC3 currents. Figure 7 shows the predicted x and y beam profiles at VD3 for Case #2.

Table 2. Results of the LEBT, RFQ, and HEBT simulations with SCHAR, PARMTEQM, and PARMELA, respectively. The measured LEBT beam currents at DC1 and DC2, the assumed PARMTEQM RFQ input current, the PARMTEQM-predicted RFQ output current, and the PARMELA-calculated and the measured HEBT current at DC3 are given in columns 2-7, respectively.

Case No.	Meas. LEBT current (DC1) mA	Meas. LEBT current (DC2) mA	PARM-TEQM RFQ in current mA	PARM-TEQM RFQ out current mA	PAR-MELA HEBT current mA	Meas. HEBT current (DC3) mA
1	123	94	94.4	70.33	69.95	74
2	124	98	97.5	73.18	73.16	76
3	123	96	96.0	75.11	74.96	75
4	138	102	102.1	71.98	71.61	90

6 DISCUSSION

There is good overall agreement between the measured beam currents and those predicted by the simulations for the 3 cases that have measured HEBT currents near the 75-mA CRITS RFQ design output current. These 3 cases are for the RFQ exit quadrupole singlet defocussing in x (Case 1), focusing in x (Case 2), and off (Case 3). The best agreement between the predicted current and the measured current is Case 3, but the best agreement between the predicted profiles and measured profiles is Case 2. The simulation of the 90-mA exit beam from the RFQ gives much lower beam transmission (DC2/DC3 = 70%) than the measured value (88%). It is likely that the beam input parameters in Table 1 are not as accurate a representation of the ~140 mA output beams (DC1) as they are for the ~120 mA beams. The measured and code-calculated RFQ transmissions are larger than those in [4] because of the steering and focussing flexibility of the LEDA LEBT (Fig. 3), features missing in the no-steering-magnet, single-solenoid LEBT employed in [4].

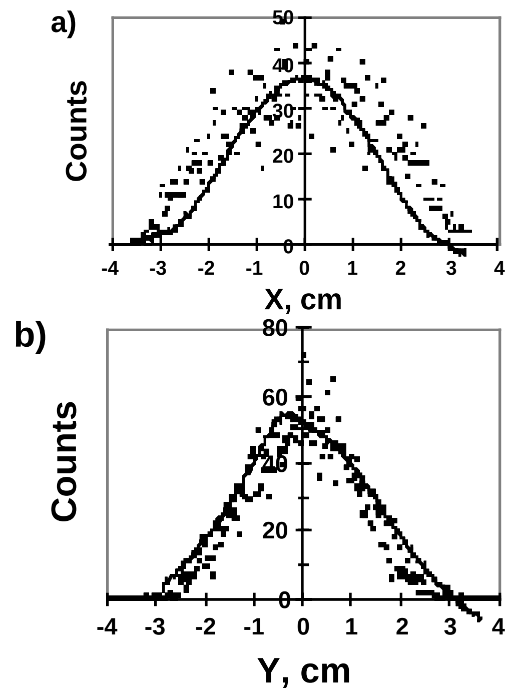

Fig. 7. PARMELA-predicted x (a) and y (b) beam profiles (squares) and the measured x and y beam profiles (lines) at VD3 for Case #2.

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