COMPARISON OF BEAM SIMULATIONS WITH MEASUREMENTS FOR THE LEDA LEBT H^+ BEAM†

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Abstract

The Low-Energy Demonstration Accelerator (LEDA) injector is designed to provide 75-keV, 110-mA, proton beams for the LEDA RFQ. After testing the LEDA injector using a 1.25-MeV, CW RFQ, we shortened the low-energy beam transport (LEBT) to 2.69 m, replaced the first LEBT solenoid with one that has a shorter length but the same focusing power, and installed and operated the LEDA injector in the beam tunnel. In this paper we use the TRACE, SCHAR, and PARMELA computer codes to model the proton beam for the as-installed LEBT and we compare the results of these simulations with the LEBT beam measurements. We use the computer code PARMTEQM to transport the SCHAR- and PARMELA-generated beams through the RFQ so that we can compare the predicted RFQ performance with the measured RFQ performance. For a 100-mA, 0.239-π-mm-mrad input beam, PARMTEQM predicts the LEDA RFQ transmission will be 92.2%.

1 INTRODUCTION

The LEDA injector [1] was tested under operating conditions by altering the ion-source extraction system from a tetrode at 75 keV to a triode at 50 keV [2] and injecting the hydrogen beam into a 1.25-MeV, CW RFQ [3]. The LEDA microwave-driven source beam (50 keV, 70-100 mA, ≅ 90% H^+ fraction) was matched to that RFQ using the two-solenoid, gas-neutralized low-energy beam transport (LEBT) [4] described in Ref. [2]. Two steering-magnet pairs provided the desired beam centroid position and angle at the RFQ match point. Beam neutralization of 95-99% occurred in the LEBT residual hydrogen gas [5]. The RFQ accelerated the beam to 1.25 MeV and a simple HEBT transported that beam to a beamstop. The RFQ transmission and spatial profiles were measured as a function of injected current and LEBT solenoid excitations [2]. The expected beam performance was calculated using the computer codes TRACE [6] and SCHAR [7] to model the LEBT [8], PARMTEQM [9] to model the RFQ, and PARMELA [10] to model the HEBT. Excellent agreement between the simulations and the measurements was obtained (see Table 2 of [11]).

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The LEDA injector is now installed in the beam tunnel [12] and connected to the LEDA RFQ [13]. Low-current, pulsed-beam commissioning of this 6.7-MeV RFQ has commenced [14, 15]. Changes in the LEBT since the work reported in [11] include reconfiguration of the ion-source extraction system to a tetrode at 75 keV and replacement of the first LEBT solenoid with one that has a shorter length but the same focusing power.

Ultimately we will compare the beam measurements with simulations of the LEDA LEBT, RFQ, and HEBT. In this paper we report the first step toward obtaining these end-to-end simulations — comparison of the as-installed LEDA LEBT measurements with simulations. We also report predictions for the RFQ transmission using the simulated beam as input. Our procedure is as follows. The hydrogen beam is first characterized using the Emittance-Measuring Unit (EMU), Fig. 1. We use these results and the TRACE code to get the input parameters for the SCHAR code. We iterate on the input parameters until SCHAR reproduces the measured phase space. Then the LEBT beam line, from the extractor to the RFQ match point (Fig. 1), is simulated and the resulting SCHAR-generated beam is transported through the RFQ using PARMTEQM to predict the RFQ performance. A preliminary study of the LEDA LEBT is reported in [8].

2 INPUT PARAMETERS

The input H^+ beam parameters are determined from phase-space measurements of the LEDA injector beam

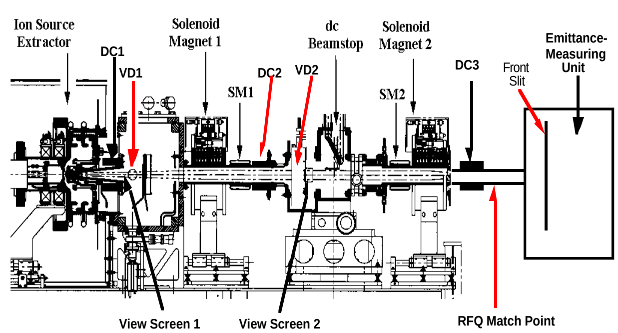

Fig. 1. The LEDA injector with the EMU. The positions of the RFQ match point, and the beam-line components, are indicated and discussed in the text.

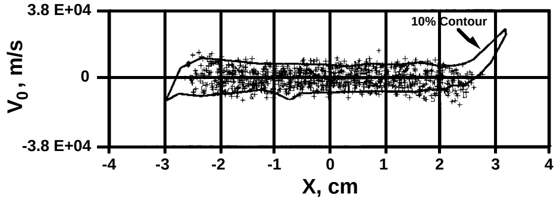

Fig. 2. The SCHAR-calculated phase space (crosses) at the EMU for the 100-mA H^+ beam in the LEDA LEBT (Fig. 1). The solid line is the 10% phase-space contour measured with the EMU.

using the EMU (Fig. 1). Beams with 50-, 80-, and 111-mA total current are characterized using the EMU. Assuming the proton fraction is ≅ 90%, the resulting H^+ currents are 45-, 72-, and 100 mA, respectively. Using TRACE [6], with the rms normalized emittance ε_N and Twiss parameters α and β at 10% threshold as input, the beam is drifted back along the LEBT, 3.28 m from the front slit of the EMU to the ion source, as a function of the un-neutralized current. The un-neutralized current that gives the predicted H^+ beam size closest to that of the 8.6-mm-diam ion source emitter is noted, and the resulting α and β, as well as ε_N, are used as input to the first round of the SCHAR simulations.

3 LEDA LEBT SCHAR SIMULATIONS

The LEBT, in both the EMU and the RFQ configuration, 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. The LEBT dimensions are extractor to solenoid 1, 87.7 cm; solenoid 1 to solenoid 2, 140.4 cm; solenoid 2 to EMU, 100.1 cm; and solenoid 2 to RFQ match point, 40.7 cm (Fig. 1). Beam neutralizations of 95-99% are used [5], depending upon the results of the TRACE-backs. In all cases SCHAR predicts no proton beam loss in the LEBT.

SCHAR Input Parameter Determination

Using the TRACE parameters as SCHAR* [7] 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 at the EMU to within 0.1%, usually within two iterations. The resulting SCHAR-predicted input beams (Table 1) have ε_N lower than that measured at the EMU because of predicted emittance growth in the LEBT transport (primarily arising from aberrations in the LEBT solenoid lenses). When SCHAR transports the beam parameters in Table 1 3.28 m through the LEBT, the approximate phase-space shapes at the 10% contour and beam profiles at the video

Table 1. SCHAR input H^+ beam parameters for the three input beams. For these cases, $v_o = 3.790 \times 10^6$ m/s.

I_{H^+} (mA)	r_{12}	X_{max} (mm)	$V_{x\,max}$ (x 10^4 m/s)	I_{eff} (mA)	ε_N (π mm mrad)
45	0.8027	2.394	13.13	0.5	0.1032
72	-0.2288	5.124	6.137	2.0	0.1714
100	-0.2701	5.171	7.049	5.5	0.1955

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

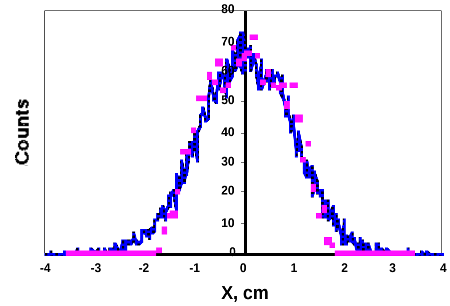

Fig. 3. Profile for the 100-mA H^+ beam 152.6 cm from the source measured with a video camera (line) and predicted by SCHAR (squares).

diagnostics are reproduced. The agreement between the SCHAR-predicted phase space at the EMU and the measured phase space is shown in Fig. 2 for the 100-mA H^+ input beam. The agreement between the SCHAR prediction and the videocamera data 42.2 cm from the source (VD1 in Fig. 1) is typically good at moderate microwave power levels (Fig. 2 of Ref. 11) and poor at high microwave power levels (Fig. 5 of Ref. 11). The agreement between the SCHAR prediction and the videocamera data 152.6 cm from the source (VD2 in Fig. 1) is usually good (example for the 100-mA H^+ beam is shown in Fig. 3). The centroid and amplitude of the videocamera data in Fig. 3 have been normalized to display the match to the SCHAR-predicted profile.

SCHAR Simulations of the LEDA LEBT

Using the input data from Table 1, SCHAR is used to predict the best match to the RFQ for the 2.69-m-long LEBT. The sample in Fig. 4 is for the 100-mA input beam with $B_{sol\,1}$ = 3052 G and $B_{sol\,2}$ = 3650 G, giving ε_N = 0.238 π mm mrad at the RFQ match point. Our previous experience [11] is that the actual $B_{sol\,1}$ setting is close to the SCHAR prediction whereas the actual $B_{sol\,2}$ setting 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 is due to spherical aberrations in solenoid #1 and solenoid #2 (Table 2). SCHAR predicts that the non-linear, space-charge-induced emittance growth in the LEBT is low compared to the

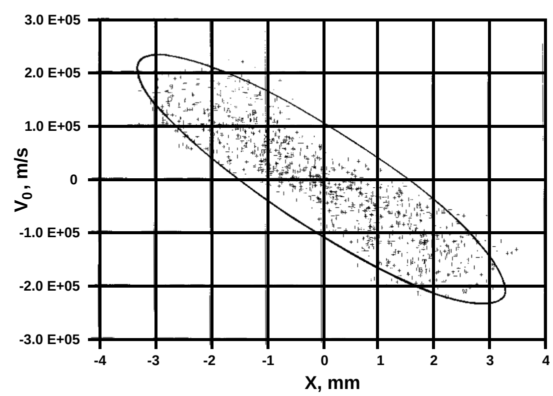

Fig. 4. SCHAR-calculated phase space (crosses) at the RFQ match point for the 100-mA input beam. The curve is the RFQ acceptance for 110 mA and 0.02 π cm mrad.

overall emittance growth — 2.1% vs. 57.2% for the 45-mA beam, 1.4% vs. 13.7% for the 72-mA beam, and 3.7% vs. 21.7% for the 100-mA beam.

4 LEDA RFQ PARMTEQM SIMULATIONS

The SCHAR output files are used to generate 5,000 particle input beams for the PARMTEQM computer code to calculate the RFQ transmission and output ε_N. The proton fraction can be as high as 95% [16], but typical values are ~90%. We use the measured DC2 [DC2 is a dc parametric current transformer] current (Fig. 1), multiplied by 0.9, for the PARMTEQM input current. The result for the 100 mA beam (111 mA at DC2) is transmission = 92.2% and output ε_N = 0.232 π mm mrad (Fig. 5, Table 2) at the design RFQ intervane voltage. The predicted LEDA RFQ transmissions and output beam emittances for the other input beam currents are given in Table 2.

5 DISCUSSION

There is good overall agreement between the simulation for 100 mA reported here and that for 110 mA reported in Ref. [8]. This is striking because the input parameters for the simulations in [8] were obtained for a prototype LEBT in which the two solenoid magnets were placed next to each other, with no separation (see Fig. 3 of Ref. 1). The large emittance growth in solenoid #1 for the 45-mA beam (Table 2) arises from the large divergence of the 45- mA beam from the ion source extraction system. This extraction system is designed for 110-mA H^+ beams — at 50 mA there is a large perveance mismatch, with a cross-over in the extraction gap. This accounts for the large divergence, and small beam size, for the 45-mA case (Table 1).

In the initial LEDA accelerator commissioning stage, we are injecting pulsed low-current (10-20 mA), low-duty-factor (~1%) beams into the RFQ to allow us to gain understanding of the system operation without damaging components. To produce these low-current pulsed beams,

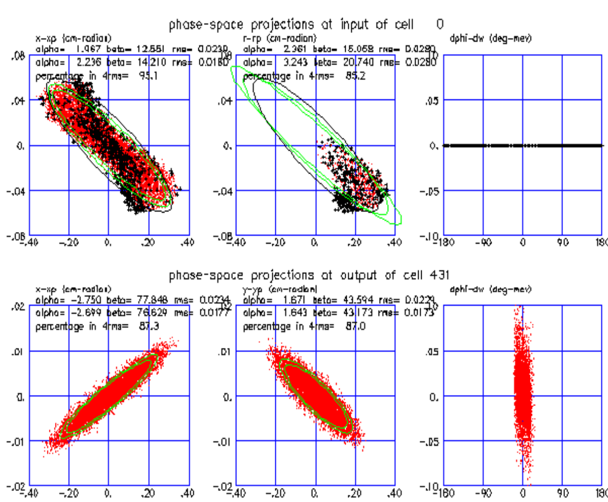

Fig. 5. PARMTEQM-calculated RFQ input (top) and output (bottom) phase space for the 100-mA beam.

Table 2. Results of the LEDA LEBT and RFQ simulations with SCHAR and PARMTEQM, respectively.

I_{H^+} mA	ε growth in Sol#1, %	ε growth in Sol#2, %	SCHAR RFQ ε_{in}, π mm mrad	PARM-TEQM RFQ ε_{in}, π mm mrad	PARM-TEQM RFQ ε_{out}, π mm mrad	RFQ trans-mission %
45	31.1	17.5	0.162	0.164	0.173	96.6
72	0.5	11.6	0.195	0.195	0.206	96.5
100	5.2	11.6	0.238	0.239	0.232	92.2

we have installed a 5.0-mm-diam aperture in place of the 8.6-mm-diam aperture used for the measurements and simulations reported in this paper. Also, a variable beam iris has been installed just in front of solenoid #1. In our initial tests, 40 mA of hydrogen ions are extracted from the source, and the iris used to aperture out 50-75% of the beam current. We simulated the low-current beams from the 5-mm-diam emission-aperture based extraction system with PARMELA [10]. Using the PARMELA LEBT results as input to PARMTEQM, we find good agreement between the PARMTEQM RFQ simulations and the initial RFQ measurements [14]. After we have demonstrated good operation of the RFQ with the 5-mm-diam extraction system at its full current (~50 mA), we will install the 8.6-mm-diam extraction system to test the LEDA RFQ up to its full design current of 100 mA.

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