DC PROTON BEAM MEASUREMENTS IN A SINGLE-SOLENOID LOW-ENERGY BEAM TRANSPORT SYSTEM*

Ralph R. Stevens, Jr., Patrick Schafstall, J. David Schneider, Joseph Sherman, and Thomas Zaugg
Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA
and
Terence Taylor
Chalk River Laboratories, AECL Research, Chalk River
Ontario, Canada KOJ 1J0

Introduction

High current, CW proton accelerators are being considered for a number of applications including disposition of nuclear wastes, reduction of fissionable nuclear material inventories, safe production of critical nuclear materials, and energy production. All these applications require the development of high current, reliable, hydrogen ion injectors. In 1986, a program using CW RFQ technology was undertaken at CRL in collaboration with LANL [1] and was continued there until 1993. During this time, an accelerator was built which produced 600 keV, 75 mA and 1250 keV, 55 mA CW proton beams. The present program at Los Alamos using this accelerator is aimed at continuing the CRL work to demonstrate long-term reliability. In the present work, we are seeking to determine the optimal match to and the current limit of the 1250-keV RFQ [2]. This paper discusses the characterization of the 50 keV beams at the exit of the single-solenoid LEBT [3] and presents both the experimental measurements and the beam simulations done to model this system.

50 keV Injector Description

A schematic injector layout is shown in Fig. 1 with a beam envelope calculation superimposed below. This figure shows the relative locations of the microwave ion source [4], the Bergoz current monitor, the beam diagnostic box, the focusing solenoid, and the emittance measuring unit (EMU) [5] used to characterize the proton beams.

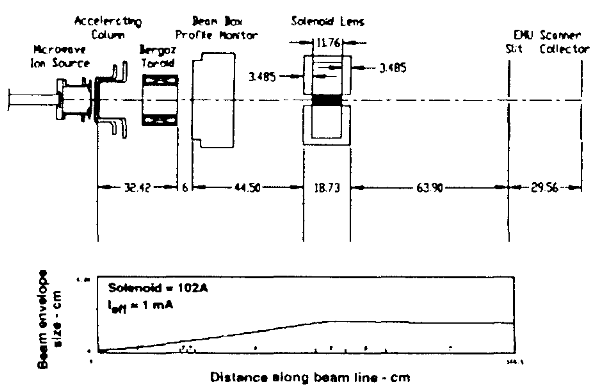

Fig. 1. Schematic layout of the single-solenoid LEBT system for beam transport to the EMU.

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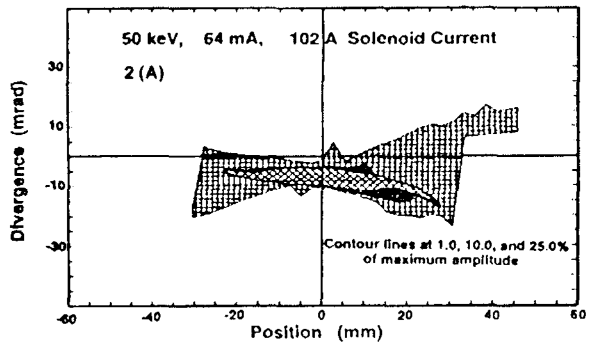
The microwave ion source has several desirable features. It has already demonstrated stable operation for many hours [6] and has relatively low emittance. Proton discharge efficiencies (390 mA/cm^2 kW) and gas efficiencies (0.31) measured at Los Alamos are better than other candidate ion sources [7]. Even higher microwave ion source efficiencies have been measured at CRL [4]. Improved efficiencies result in minimum injector vacuum pumping and cooling requirements, leading to higher reliability and longer ion-source lifetime. Typically, 75-mA dc hydrogen ion beams are generated with 600-700 W of 2.45 GHz discharge power P_d. Less than 100 W of isolated power (power at the 50-kV high voltage deck) is required to operate the gas flow system. The details of the injector system have been described previously [3,4,8].

The solenoid lens was mapped at Los Alamos for excitations up to 260 A. The excitation curve is essentially linear, indicating no saturation. Multipole field measurements, however, revealed a 170 G-cm dipole component which will significantly steer the proton beam.

The species ratios in the extracted beam were determined by inserting a 50-mm aperture dipole magnet just after the EMU main slit and ramping the current driving this magnet. The species ratios H^+: $H_2{}^+$: $H_3{}^+$ equal 75%:17%:8% were observed with P_d = 550 W and gas flow Q = 2 sccm. The LEBT solenoid was turned off during these measurements in order to ensure a more homogeneous hydrogen ion beam at the EMU. The ion source current and beam fraction measurements are comparable to those reported by CRL [4,9].

The EMU is a conventional two slit system capable of measuring CW beams with power densities up to 1 kW/cm^2. A typical emittance scan is shown in Fig. 2 (A) for a 50-keV, 64-mA beam with the LEBT solenoid at 102 A excitation. The intense central part (10% and 25% threshold contours) of this phase space distribution is primarily protons while the unfocused components at the 1% threshold are primarily the $H_2{}^+$ and $H_3{}^+$ molecular ion species. A plot of total emittance with beam fraction F as a function of ln $(1-F)^{-1}$ is shown in Fig. 2(B). For a Gaussian distribution [10], a linear plot would indicate a beam characterized by an effective ion temperature kT. The observed data contain two separate linear regions with a break at F ~ 0.86. The curve for F < 0.86 is characteristic of the proton distribution while the data for F > 0.86 includes the $H_2{}^+$ and $H_3{}^+$ species. The lower portion of this plot gives a Gaussian-extrapolated rms normalized emittance, $\varepsilon_{rms,n}$ = 0.25 (πmm-mrad) for the proton beam. The Gaussian extrapolation procedure has been used to analyze all the emittance data presented here on the 10% and 25% thresholds. The phase space distributions expected for



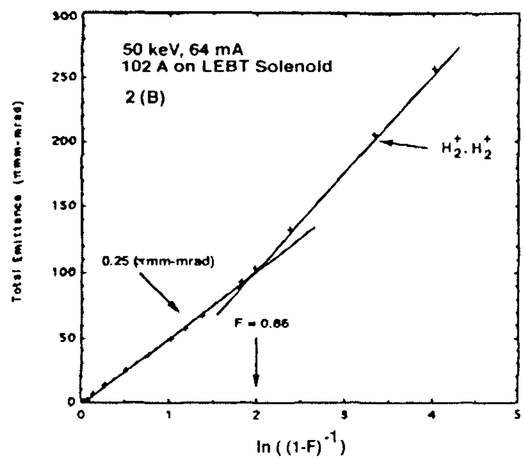


Fig. 2. (A) A typical emittance scan measurement. (B) Total emittance at beam fraction F vs. ln $(1\text{-F})^{-1}$ for the emittance measurement in (A).

the H_2^+ and H_3^+ components were calculated from the TRACE [11] beam envelope code and agree with the observed data as the solenoid excitation is varied.

Measurement Results

The emittance measurements were used to infer the input beam at the ion source by transporting the observed phase-space distributions backwards through the LEBT to the source using the beam-envelope code TRACE. The effective beam current was varied over a range from zero to several mA in order to obtain a fit to the known 2.5-mm emission aperture radius. The best fit obtained gave an effective current I_{eff} = 1 mA, yielding Courant-Snyder parameters α=0.513 and β=0.16 mm/mrad for an emittance of 0.20 (πmm-mrad). Ion source beam envelope size for I_{eff} = 2 mA varied from 3.5 to 7.5 mm and is clearly an inferior fit. These tracebacks were made using the 10% threshold emittance results as a function of the LEBT solenoid lens current from 70A to 120A.

Emittance measurements were taken for P_d=600 W for a range of solenoid excitations. The Gaussian extrapolations at the 10% and 25% thresholds are clustered around ~0.20 (πmm-mrad) while the emittances obtained for the 1% threshold level are 50% greater. This behavior is expected because the 1% threshold data include the H_2^+ and H_3^+ contributions to the total phase space area. Ion source-only emittance measurements (no LEBT system) from CRL gave ~0.12 (πmm-mrad) [4,9], implying that a 70% emittance increase occurs when the beam is transported through the LEBT.

Average beam position at the EMU location was measured for five EMU data sets with different LEBT solenoid excitations. Transforming these EMU measurements to the RFQ match point shows that 0.5 - 3.2 mm steering errors may be expected at this location. This steering effect is quite reproducible and consistent with the observed solenoid dipole-field component.

Calculations were done to estimate the space-charge compensation of these beams [12]. The voltage drop within a 50-keV, 90-mA proton beam with a 1.0 cm beam radius and a background gas density of 6.6 x 10^{11} cm^{-3} is $\Delta\phi_n$ = 5 V. For a totally unneutralized beam, $\Delta\phi = I_b R/\beta$ = 218 V where R = 30 ohms and β is the relativistic velocity factor. Most of the positive-ion-beam space charge is compensated by the accumulation of electrons generated by ionization of the background gas. Taking $I_{eff} = I_b (\Delta\phi_n/\Delta\phi)$, we obtain 1.4 mA, in good agreement with the I_{eff} derived from TRACE.

Discussion

The emittance measurements described above were used to infer the Courant-Synder (CS) beam parameters at the exit of the 50 keV accelerating column by doing tracebacks from the emittance scanner to the extractor and varying the effective current to obtain the known beam size at the exit of the column. Using the above tracebacks at the optimum effective current of 1 mA, we predicted the RFQ match point beam parameters. The results of these simulations are shown in Fig. 3 where the CS beta parameter (beam size) is plotted against the alpha parameter (beam divergence) to give the alpha-beta tuning diagram for this LEBT. We see that as the solenoid excitation is increased from 205 A to 230 A , the operating point in alpha-beta space moves down the tuning curve from a highly converging beam (205 A) to a diverging beam (230 A).

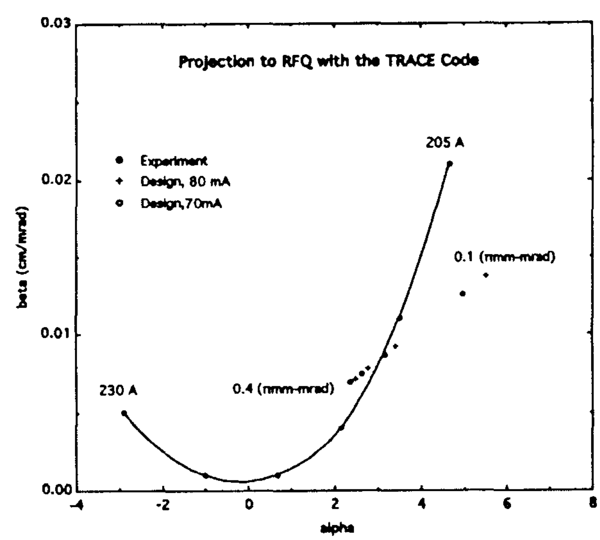


Fig. 3. Alpha-beta tuning diagram for a single-solenoid LEBT.

Simulations with the RFQ code PARMULT [13] were used to predict the RFQ matched beam parameters for a range of assumed emittances from 0.1 to 0.4 (πmm-mrad) and for two input beam currents (70 and 80 mA). These results are also plotted on this same alpha-beta tuning curve. We see that the predicted CS match parameters overlap with the predicted LEBT tuning curve for a solenoid excitation of 213 A and for an input RFQ beam of 75 mA with an emittance between 0.1 to 0.2 (πmm-mrad).

For an input beam emittance of 0.12 (πmm-mrad), a solenoid excitation of 213 A, and an effective current of 1 mA, the macroparticle code SCHAR [14] predicts an overall emittance growth of 38% of which 32% is due to solenoid lens aberrations and 6% is due to residual space charge effects. Figure 4(A) shows the input beam phase space to the LEBT. Figure 4(B) shows the final phase space distribution focused to 1.4 mm-diameter at the RFQ match point. Figure 4(B) also shows the onset of third-order focusing and space charge aberrations and the effect of the solenoid dipole field as the beam is approximately 1mm from the RFQ axis. SCHAR simulations also show that emittance preservation in this LEBT is crucially dependent on obtaining low divergence in the extracted beam.

The SCHAR simulation includes the measured dipole

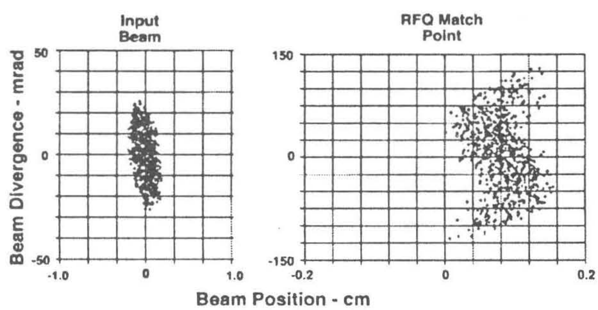


Fig. 4. Calculated phase space distributions in the single-solenoid LEBT.

component of the solenoidal field which results in the 1 mm displacement at the RFQ match point. RFQ simulations using PARMULT [13] predict that a 1 mm displacement will reduce the RFQ beam transmission from 89% to 80%. Beam centroid errors of this magnitude have been both observed and predicted. Thus, steering before the RFQ will be necessary to obtain optimum transmission.

Conclusions

The primary goal of this work has been to characterize the LEBT to obtain optimum RFQ performance. Further studies are needed to address the problems of solenoid steering errors, LEBT emittance growth, and LEBT beam mismatch to the RFQ.

Acknowledgments

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