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Title: DIRECT-CURRENT PROTON-BEAM MEASUREMENTS AT LOS ALAMOS

Author(s): J. Sherman
R. R. Stevens
J. D. Schneider
T. Zaugg

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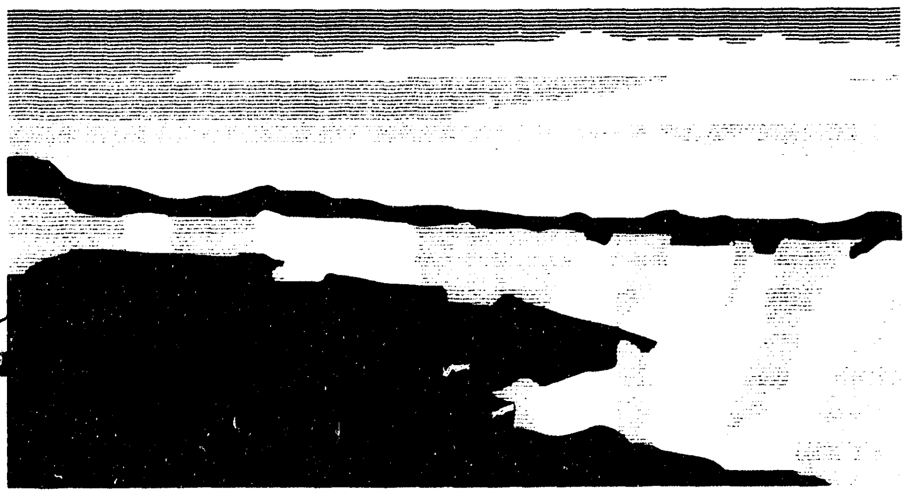

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Direct-Current Proton-Beam Measurements at Los Alamos*

Joseph Sherman, Ralph R. Stevens, J. David Schneider, and Thomas Zaugg
AOT-10, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Abstract. Recently, a CW proton accelerator complex was moved from Chalk River Laboratories (CRL) to Los Alamos National Laboratory. This includes a 50-keV dc proton injector with a single-solenoid low-energy beam transport system (LEBT) and a CW 1.25-MeV, 267-MHz radiofrequency quadrupole (RFQ). The move was completed after CRL had achieved 55-mA CW operation at 1.25 MeV using 250-kW klystrode tubes to power the RFQ. These accelerator components are prototypes for the front end of a CW linac required for an accelerator-driven transmutation linac, and they provide early confirmation of some CW accelerator components. The injector (ion source and LEBT) and emittance measuring unit are installed and operational at Los Alamos. The dc microwave ion source has been operated routinely at 50-keV, 75-mA hydrogen-ion current. This ion source has demonstrated very good discharge and H_2 gas efficiencies, and sufficient reliability to complete CW RFQ measurements at CRL. Proton fraction of 75% has been measured with 550-W discharge power. This high proton fraction removes the need for an analyzing magnet. Proton LEBT emittance measurements completed at Los Alamos suggest that improved transmission through the RFQ may be achieved by increasing the solenoid focusing current. Status of the final CW RFQ operation at CRL and the installation of the RFQ at Los Alamos will be given.

INTRODUCTION

Accelerator-Driven Transmutation Technologies (ADTT) address many current societal concerns - energy production, disposition of nuclear wastes, reduction of fissionable material inventories, and safe production of critical nuclear materials. Part of the ADTT requires the development of very powerful and reliable proton beams. In 1986 a program using CW RFQ technology was undertaken at CRL in collaboration with Los Alamos [1], and continued through April 1993, when CRL terminated this development program. While at CRL the RFQ produced 600-keV, 75-mA and 1250-keV, 55-mA CW proton beams. Subsequently the equipment has been moved to Los Alamos.

One of the present program goals is to establish the experimental 1250-keV RFQ current limit which will depend on the LEBT performance [2]. Beam measurements on the 50-keV single-solenoid [3] LEBT system completed at Los Alamos are discussed here. The LEBT function is to preserve beam quality and match the low-energy beam into the RFQ.

50 keV INJECTOR DESCRIPTION

The major injector components are a proton microwave ion source [4], a single-lens LEBT system with online diagnostics, and a dc emittance measuring unit (EMU) [5]. The EMU is inserted in the normal RFQ position (offline mode) to characterize the injected proton beam.

The microwave ion source has several desirable features. It has already demonstrated good reliability [6], and sufficiently low emittance to meet ADTT linac requirements [4]. Proton discharge efficiencies (390 mA/cm^{2}kW) and gas efficiencies (0.31) measured at Los Alamos are quite attractive compared to other candidate ion sources [7]. Higher 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 ion source longevity. 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 isolation power (power at the 50-kV high voltage deck) is required to run the gas flow

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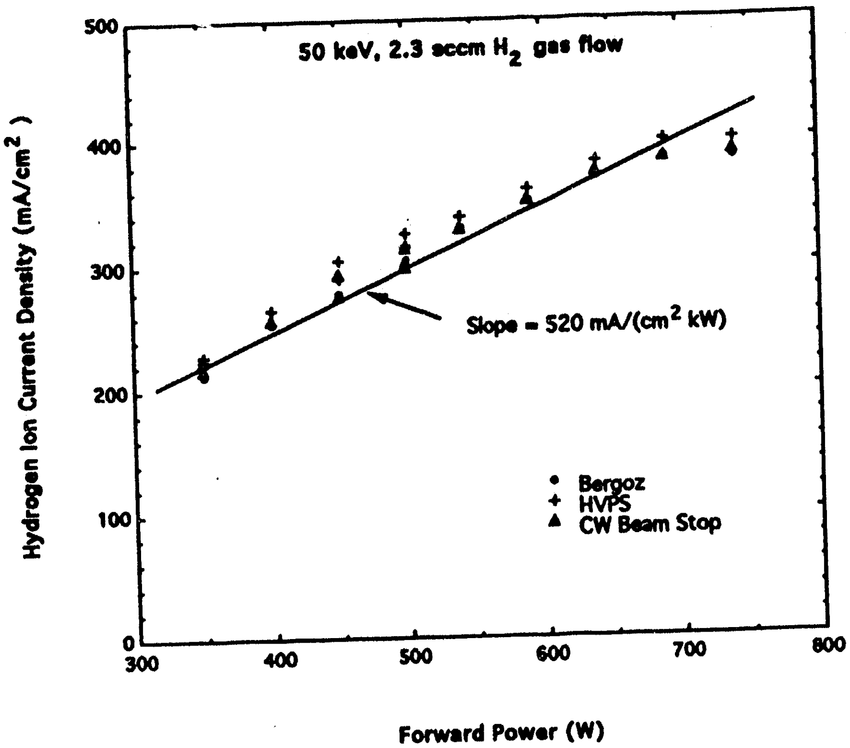

Fig. 1. Forward power vs. the hydrogen ion current density. A hydrogen ion beam production efficiency of 520 mA/(cm^{2}kW) is derived from this plot which corresponds to 390 mA/(cm^{2}kW) proton efficiency.

system. All other power supplies are located at ground voltage, eliminating the need for high power isolation transformers.

The dependence of the extracted current density, j, on P_d is shown in Fig. 1 for 50-kV extraction potential. The beam current is $I_b = j(\pi R_e^2)$ where R_e = 2.5 mm = emission aperture radius. At f = 2.45 GHz the solenoidal field required to establish an electron cyclotron resonance condition is B_s = 875 G. Optimal operation for this microwave ion source is at 5 - 10% greater magnetic field. The scaling of this source to an ADTT linac (140-mA hydrogen ion current at 75-keV beam energy) is discussed in an accompanying paper [8].

Beam current monitoring is accomplished with three diagnostics: the high voltage power supply (HVPS) drain current, a Bergoz dc current monitor [9], and a CW beam stop capable of handling the full beam power. Secondary electron emission is suppressed at the beam stop by the application of a 160-G transverse magnetic field. Error among these diagnostics is ≤ 5% (cf. Fig. 1).

A 50-mm aperture dipole magnet has been installed after the EMU main slit to measure proton fraction. Typical data are shown in Fig. 2 where the beam currents at the Faraday cup are plotted as a function of the magnetic field ramp time. The species ratio $H^+:H_2^+:H_3^+$ equals 75:17:8% with P_d = 550 W and gas flow Q = 2 sccm. The LEBT solenoid was turned off during these measurements to ensure a homogeneous hydrogen ion beam at the EMU. The ion source current and beam fraction measurements are comparable with those reported by CRL [4,10].

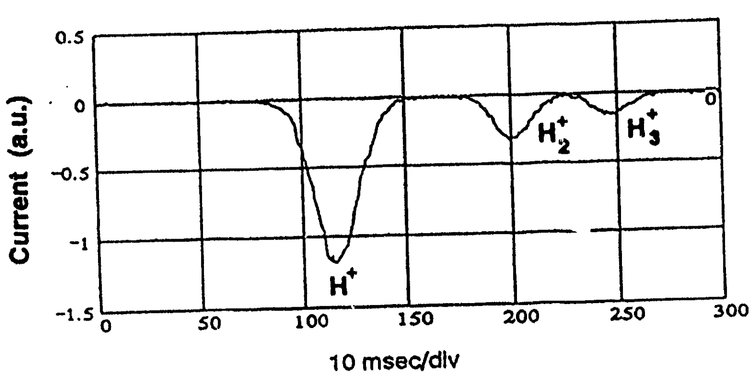

Fig. 2. Measurement of the hydrogen ion species at the LEBT exit.

Beam extraction is accomplished with a triode accelerator system, composed of a 5-mm diam emitter, a 4.5-mm diam extractor/ suppressor electrode, and a 5-mm

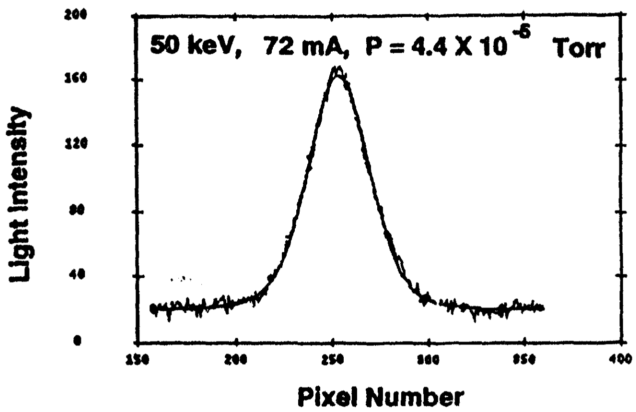

Fig. 3. Beam profile extracted from the Cohu data.

diam ground electrode. The extractor electrode is over-biased by 2 kV to suppress electrons backstreaming from the LEBT. The gap between the emission and extraction electrodes is $g_1 = 6.9$ mm, and the gap between the extraction and ground electrodes is $g_2 = 2.9$ mm.

Beam profile monitoring located in the beam diagnostics station is accomplished with a two dimensional Cohu imaging system [11]. It is located 35 cm from the ion source. Fig. 3 shows the profile of a 50-keV, 72-mA hydrogen ion beam in H_2 gas at $P = 4.4 \times 10^{-5}$ Torr. The FWHM of this distribution is 1.10 cm.

A 50-keV emittance measurement sample is shown in Fig. 4(A). The LEBT solenoid is excited to 102 A. The intense central part of the phase space contains the proton component ($\geq$10% threshold contour) while the unfocused components at 1% contour are primarily the H_2^+ and H_3^+ species. A plot of total emittance at beam fraction F vs. F (in the form $\ln(1-F)^{-1}$) is shown in Fig.

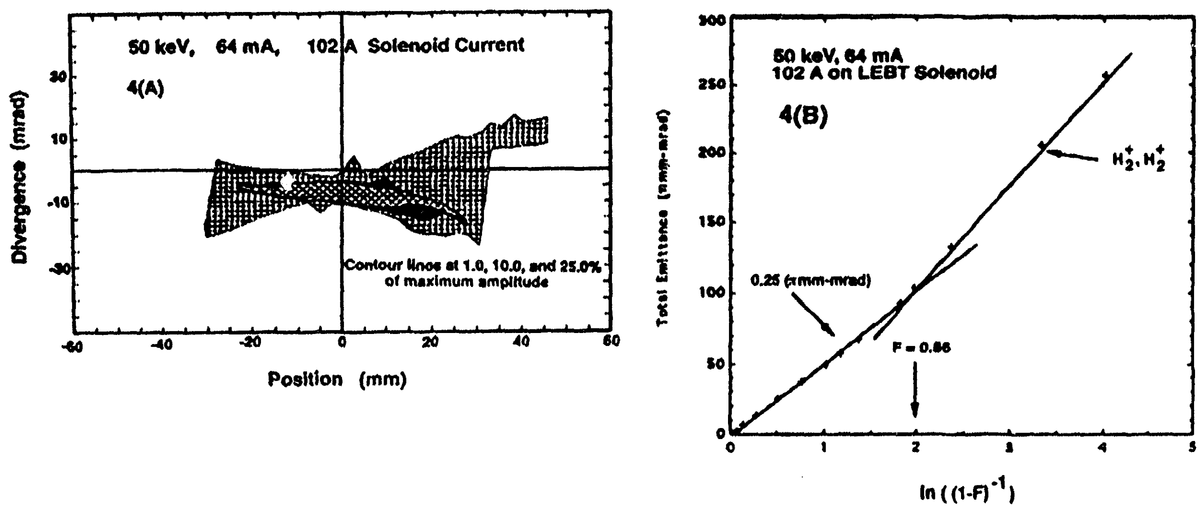

Fig. 4. (A) A sample emittance measurement. (B) Total emittance at beam fraction F vs. $\ln(1-F)^{-1}$ for the emittance measurement in (A).

4(B). For a Gaussian beam distribution [12] a linear plot would indicate a beam distribution characterized by an ion temperature kT. The data contain two separate linear relations with a break at $F \approx 0.86$. The curve for $F < 0.86$ is characteristic of the proton distribution while the distribution for $F > 0.86$ includes the H_2^+ and H_3^+ species. The lower curve yields the Gaussian-extrapolated rms normalized emittance= $\varepsilon_{rms,n} = 0.25$ (πmm-mrad) for the proton beam. All proton beam emittance data presented here have been analyzed by using the Gaussian extrapolation procedure on 10% and 25% threshold emittance data. The phase-space distributions expected for the $H_2^+$and H_3^+ components were calculated from the TRACE code and agree with the observed

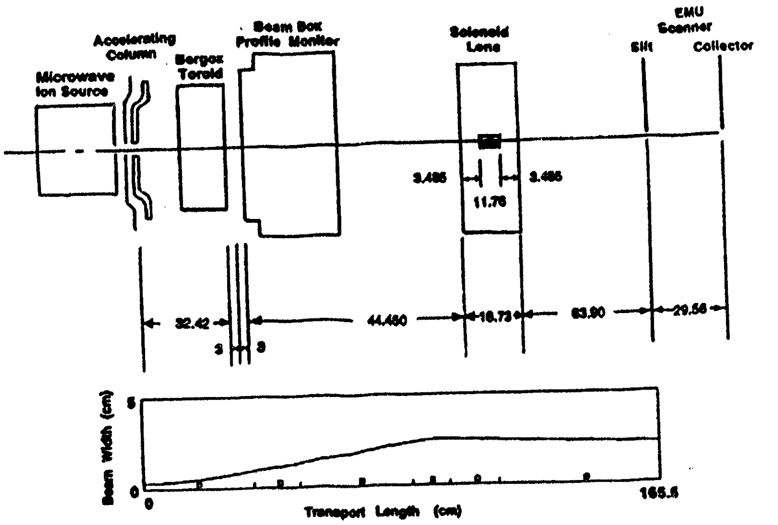

Fig. 5. Schematic layout of the single-solenoid LEBT system for beam transport to the EMU. The TRACE 50 keV beam envelope calculation for 102 A solenoid excitation with $I_{eff} = 1$ mA is shown below.

data for the 1% threshold contour. The break in the emittance vs. $\ln(1-F)^{-1}$ plot is very similar to a single-species beam with aberrations [13].

The LEBT solenoid field has been mapped at Los Alamos to 260-A excitation current. Measured multipole fields have revealed a 170 G-cm dipole component which significantly steers a 50-keV proton beam.

MEASUREMENT RESULTS

Figure 5 shows a schematic layout of the single solenoid LEBT system with TRACE calculations [14] superimposed below. The distance along the beam is in the z direction, and the distances transverse to z are the x and y directions. This figure shows the relative locations of the microwave ion source, Bergoz current monitor, diagnostics box, focusing solenoid, and the EMU. In principle, the Courant-Snyder beam parameters at the ion source can be determined by transporting the emittance measurement results backward through the LEBT using the TRACE code. The only unknown in this procedure is the effective current, I_{eff}. I_{eff} in the TRACE code was varied to give the best fit to the known ion source emission aperture size. The best fit obtained over a series of solenoid settings gave a 3-mm beam envelope size at $I_{eff} = 1$ mA, yielding the Courant-Snyder parameters $\alpha = 0.513$ and $\beta = 0.16$ (mm/mrad) for $\varepsilon_{rms,n} = 0.20$ (πmm-mrad). These projected calculations were made as a function of the LEBT solenoid current using the 10% threshold emittance results. Below 70-A LEBT solenoid current not all of the proton current is scanned by the EMU, and for this reason these data are not included in the TRACE projections for determining I_{eff}. Ion source beam size predictions for $I_{eff} = 2$ mA varied from 3.5 to 7.5 mm depending on the solenoid current, and are clearly inferior to the $I_{eff} = 1$ mA results.

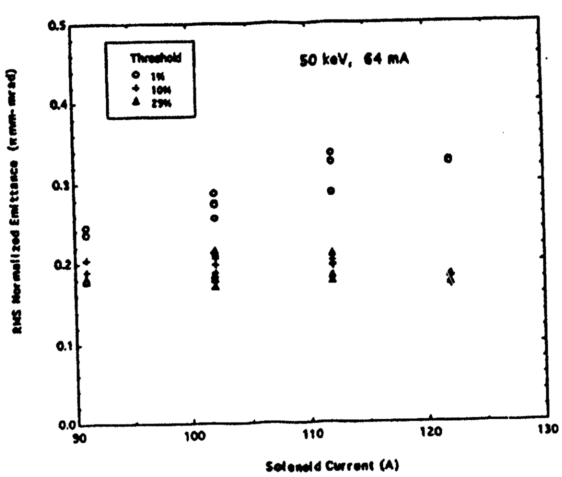

Fig. 6. Measured LEBT emittances as a function of solenoid coil current. The measured emittances at 10 and 25% beam thresholds have been used in a Gaussian beam model to derive the proton beam rms normalized emittances.

Calculations [15] for the voltage drop within a 50-keV, 90-mA proton beam show that for our beam radius (1.0 cm) and gas density (6.6 X 10^{11} $(\text{cm})^{-3}$) we should have a residual beam space potential = $\Delta\phi_n = 5$ V. For a totally unneutralized beam, $\Delta\phi = I_b R/\beta = 218$ V where $R = 30\ \Omega$ and β is the relativistic velocity factor. Most of the positive-ion-beam space charge is neutralized by the accumulation of electrons generated by ionization of the background gas by the hydrogen ion beam. Taking I_{eff} =

$I_b(\Delta\phi_n/\Delta\phi)$ = 1.4 mA, which is in good agreement with I_{eff} derived from the TRACE calculations.

Extracted $\varepsilon_{rms,n}$ for P_d = 600 W are plotted vs. the LEBT solenoid current in Fig. 6. The Gaussian projections at 10 and 25% beam thresholds are clustered at ≈ 0.20 (πmm-mrad) while projections using the 1% threshold emittances are 50% greater. This is expected because the 1% threshold data includes H_2^+ and H_3^+ contributions to the phase-space area. Ion-source-only emittance measurements (no LEBT transport) from CRL give ≈ 0.12 (πmm-mrad) [ref. 4,10], thus indicating a 70% emittance increase observed at Los Alamos is brought about by beam transport through the LEBT.

Average beam position at the EMU location was measured for five EMU data sets on different days with different LEBT solenoid excitations. Translation of these EMU measurements to the RFQ location shows that 0.5 - 3.2 mm steering may be expected at the RFQ matchpoint. The steering effect is quite reproducible, and is consistent with the observed solenoid dipole field.

DISCUSSION

Predictions have been made with the TRACE code for RFQ matching by using the derived Courant-Snyder parameters. Figure 7 shows the (α,β) tuning plot [2] for the single-solenoid LEBT; as solenoid current is increased from 205 A to 230 A the α–β tune moves from right to left down the solid curve. The design matched beam [16] parameters for RFQ input beam currents of 80 and 70 mA with the rms normalized input emittances varying from 0.1 to 0.4 (πmm-mrad) are shown as crosses and open circles in this figure. The best match would occur at ≈ 213 A LEBT solenoid current, 13 A higher than CRL was able to obtain in their last RFQ measurements because of power supply limitations.

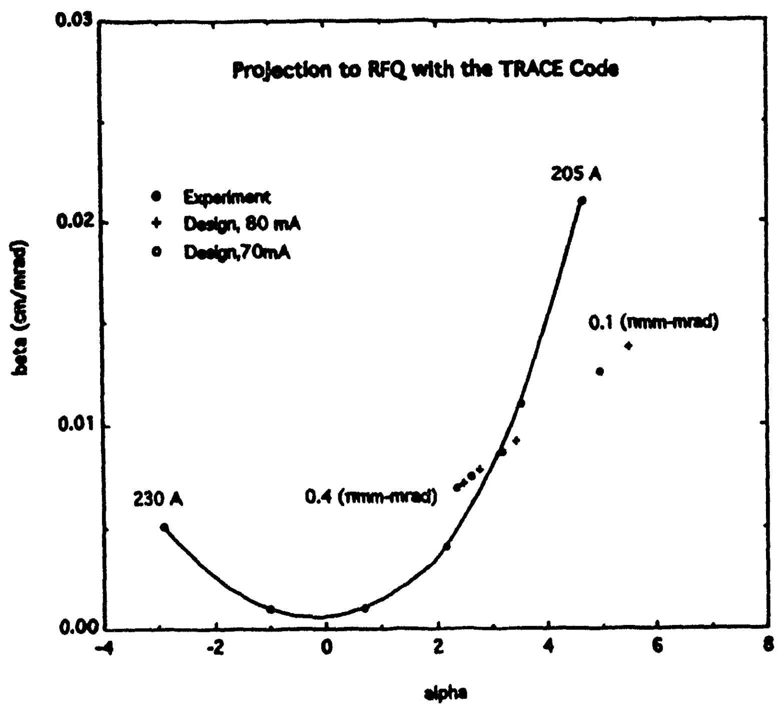

Fig. 7. Single-solenoid LEBT (α,β) tuning plot derived from EMU beam measurements.

A higher-order beam transport LEBT model using the SCHAR code [17] predicts an emittance growth of 40% using the projected Courant-Snyder parameters and taking the $\varepsilon_{rms,n}$ = 0.12 (πmm-mrad) for the initial emittance. Figure 8(A) shows the SCHAR beam phase space (transverse velocity = v_x vs. x position) representation at the ion source. Figure 8(B) shows the phase space at the solenoid entrance where the beam has expanded to 36 mm diameter. Figure 8(C) shows the beam phase space focused to approximately 1mm at the RFQ matchpoint. Figure 8(C) also shows (1) the effect of the solenoid dipole field as the beam is displaced to x ≈ -1mm and (2), the onset of focusing and space-charge aberrations. These calculations were performed with I_{eff} = 1 mA and initial ion source beam radius equal to 2.5 mm. Taking an initial beam radius equal to 1.3 mm, a LEBT emittance growth of 3.5X has been calculated. A smaller beam at the ion source with constant emittance results in a larger beam at the solenoid position because of increased ion source divergence. Emittance preservation in this LEBT is thus crucially dependent on the ion source operation.

The SCHAR calculation takes into account the solenoid dipole field, and an approximate 1 mm displacement is noted at the RFQ matchpoint. RFQ simulations [16] predict that a 1 mm displacement will reduce the beam transmission through the RFQ from 89 to 80%. Beam steering of this magnitude has now been both observed and calculated, and control of the beam centroid parameters going into the RFQ will be an important parameter in determining its transmission.

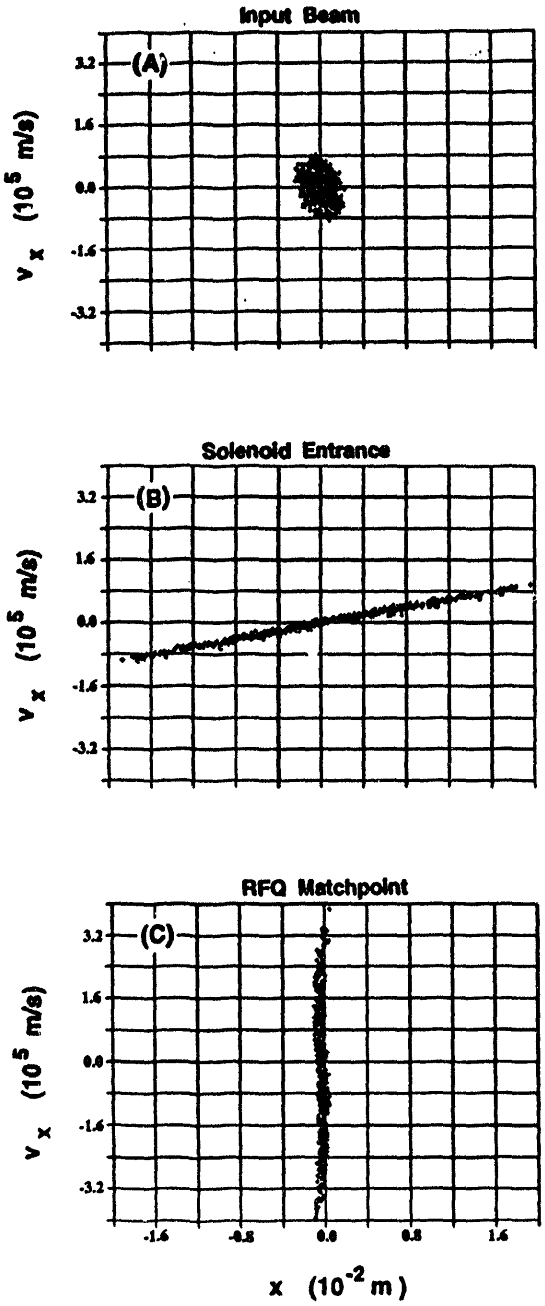

Fig. 8. SCHAR predictions for the beam phase space at (A) the ion source, (B) entrance to the solenoid focusing magnet, and (C) the RFQ matchpoint. All three plots have the same scale on both coordinate axes.

A primary goal of this work is to study possible LEBT problems in achieving the RFQ design current. Three potential problems with the direct injection scheme have become apparent: mismatch of the 50 keV beam into the RFQ, solenoid steering problems, and emittance growth in the LEBT. In future RFQ studies, influence of these effects will need to be considered.

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