Development of a 110-mA, 75-keV Proton Injector for High-Current, CW Linacs*

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Abstract

A dc proton injector is being developed for a 6.7-MeV CW RFQ at Los Alamos. The RFQ input beam requirements are 75-keV energy, 110-mA dc proton current, and 0.20 πmm-mrad rms normalized emittance. The injector has now produced a 75-keV, 117-mA dc proton beam (130-mA total current) with the required emittance. The emittance has been measured after a 2.1-m-long two-solenoid beam transport system. The measured emittance can be explained in terms of the ion source emittance and beam transport through the focusing elements. Measured proton fractions are 90 - 92% of the beam current. The engineering of the accelerating column high-voltage design is being improved to increase the injector reliability. Injector design details and status will be presented.

Introduction

High-current (100 mA), high-energy (1 GeV) linacs are being designed for accelerator-driven transmutation technology (ADTT) applications [1]. A CW radio frequency quadrupole (RFQ) has been designed to accept a 75-keV, 110-mA proton beam from a dc injector to produce a CW 100-mA, 6.7-MeV final beam [2]. The dc proton injector and the CW RFQ are being developed for the low-energy demonstration accelerator (LEDA) project at Los Alamos [3].

This dc proton injector development began at Los Alamos with a collaborative program with Chalk River Laboratories (CRL) [4]. The microwave-driven proton source [5] developed at CRL has now been extended to meet most of the LEDA beam requirements as shown in Table 1. Beam diagnostic measurements and interpretation are described in the following sections. Other injector details may be found in a recent review [6].

Injector and Beam Diagnostics

Figure 1 shows the injector configuration which has been used in these initial 75-keV beam tests. It is a prototype to check the conceptual design before building the final LEDA low-energy beam transport (LEBT). The total LEBT length is 2.1 m from the ion source to the emittance

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Table 1.
Summary of the LEDA injector requirements and present status.

Parameter	Req.	Status
Energy (keV)	75	75
Proton current (mA)	110	117
Duty factor (%)	100	100
H_2 Gas flow (T-l/s)	0.04 - 0.1	0.04 - 0.09
Proton fraction (%)	>70	91
Reliability (%)	98	To do
Lifetime (hr)	>168	To do
Beam noise (%)	±1	±1
LEBT exit emit. (π-mm-mrad)	0.20	0.20

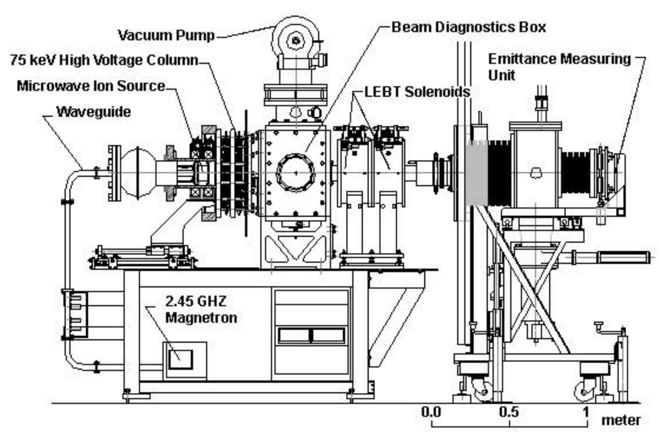

Fig. 1. Seventy-five keV proton injector showing the ion source, diagnostics/pump box, prototype LEBT, and the emittance measuring unit.

measuring unit (EMU) entrance slit. The magnetic focusing system consists of two joined solenoids. The injector is designed to operate in the dc mode at 10-kW beam power, and all of the diagnostics (excepting the EMU) are of the non-interceptive type. The diagnostics with their distance (z) from the ion source extractor are: (1) Bergoz dc beam current monitor (0.30 m), (2) four-grid energy analyzer (FGA) beam space-charge neutralization monitor (0.41 m), (3) x,y video profile CCD imaging (0.42 m), (4) ac current toroid for measuring beam current fluctuations (0.53 m), and (5) the EMU (2.1 m).

Figure 2 shows a set of measurements for the total beam current (Bergoz dc monitor) and beam fluctuations plotted versus the ion source axial magnetic field. Accuracy of the measured axial magnetic field is estimated to be 3 - 5%. Two

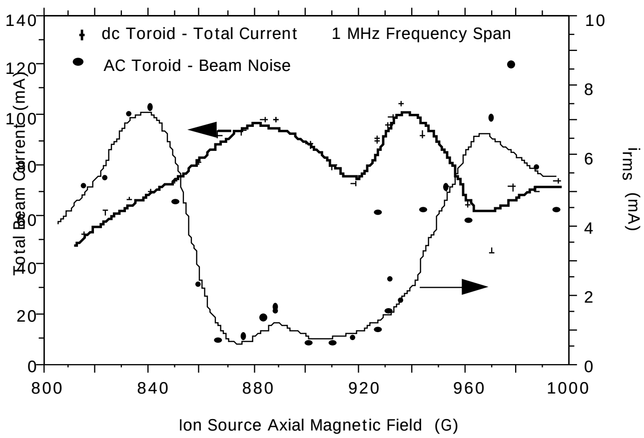

Fig. 2. 75-keV beam measurements made with the dc Bergoz and ac toroid beam monitors. Lines are drawn through the two data sets as a guide for the eye. The total beam current is read on the left vertical scale, and the rms beam noise is read on the right vertical scale.

maxima in the total current data (left scale) are seen: the first at 0.0875 T which satisfies the electron-cyclotron resonance (ECR) condition at 2.45 GHz, and the second sharper beam current resonance at 0.0935 T. This type of resonant behavior is typical [5].

The ac toroid is a Supermalloy transformer with a T_r = 1(A/V) transfer ratio with a flat bandwidth response from 1 kHz to 10 MHz. The rms beam noise (i_{rms}) data reported in Fig. 2 (right scale) is obtained from the integrated power P_t and the relation $i_{rms}(A) = (P_t{*}R)^{1/2}\ T_r$ where R = spectrum analyzer input impedance = 50Ω. The power sum is done over the beam noise frequency, f, from 12.5 kHz to 1 MHz. Measured beam noise is maximum at low frequencies, and decreases to background for f > 1 MHz. The beam is generally tuned to minimum noise at each magnetic field setting by minimizing the reflected power from the ion source by adjustment of the three-stub tuner in the 2.45 GHz waveguide. Quiescent beams are obtained over the lower field broad resonance, whereas it is somewhat more difficult to maintain a quiet beam at the higher magnetic field.

The FGA [7] has been used to measure the degree of beam space-charge neutralization f_{sc} within the LEBT. An energy distribution of the radially-flowing beam-plasma ions measured with this diagnostic is shown in Fig. 3 for a i_b = 100-mA, 75-keV hydrogen ion beam [8]. The derivative of the FGA Faraday cup current vs. the discriminating grid voltage (grid 3) is shown. The base width of this distribution

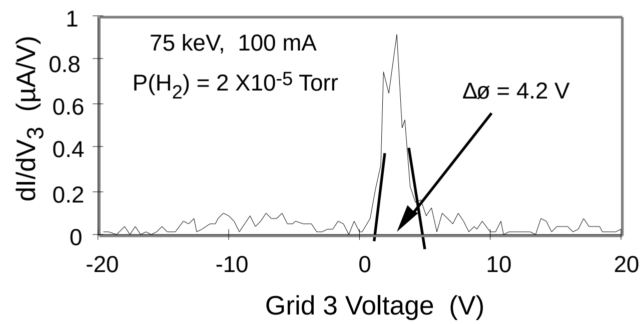

Fig. 3. Measurement of the energy distribution of positively charged particles expelled from the beam plasma.

is Δø = 4V, and this leads to $f_{sc}(\%) = (1 - \Delta\text{ø}/\Delta\text{ø}_u)*100 = 98\%$ where $\Delta\text{ø}_u$ = 240 V, the radial potential drop across an unneutralized uniform beam. The H_2 LEBT gas density = n_0 = 1.5 x 10^{12} $(cm)^{-3}$.

The measured phase-space distribution of a 130-mA, 75-keV hydrogen-ion beam is shown in Fig. 4. The proton fraction is 90%, thus the proton current is 117 mA. The focusing solenoids were both excited to 0.17 T, which gives a 7-cm diam. beam (10% contour) at the EMU. This focusing strength gives an average power loading of 0.25 kW/cm^2 at the EMU slits. The measurement is made by a two-slit technique using a dc emittance-measuring device [9]. The contaminant H_2^+ beam is focused less and is visible in Fig. 4. A Gaussian extrapolation procedure [6] is used to extract the proton rms normalized beam emittance of 0.20 (πmm-mrad) which is the design RFQ input emittance.

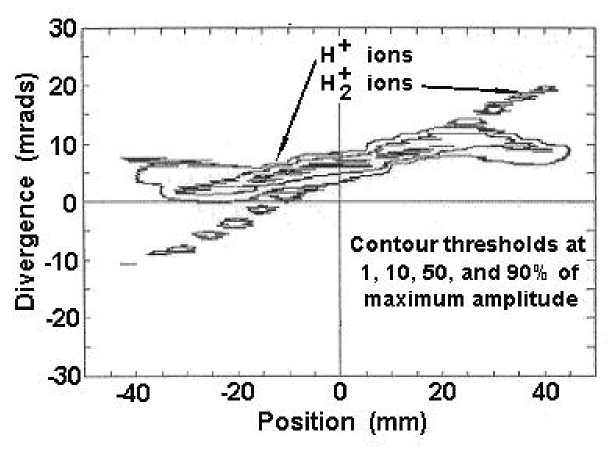

Fig. 4. Measured phase-space distribution for a 130-mA, 75-keV hydrogen-ion beam.

Discussion

The measured emittance may be partially understood by examining possible emittance growth mechanisms in the LEBT. Estimates can be made for (1) solenoid aberrations, (2) nonlinear space charge, (3) beam fluctuations, and (4) power supply regulation. The effects of (1) and (2) are estimated with the code SCHAR [10], which calculates beam trajectories through the measured solenoidal magnetic fields and takes into account the residual beam space charge. The influence of effects (3) and (4) on the measured beam emittance may be estimated by applying the mismatch factor concept to beam emittance growth in LEBTs [11].

Figure 5 shows the higher-order SCHAR code prediction for 999 macroparticles traced from the ion source extractor to the EMU superimposed on the measured 10% contour from Fig. 4. The SCHAR starting beam distribution (phase-space orientation, emittance) is deduced from drifting the measured

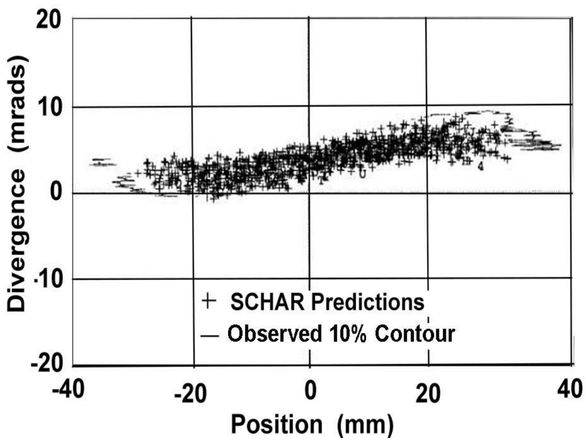

Fig. 5. Comparison of the SCHAR code prediction and the 10% measured emittance contour from Fig. 4.

beam parameters at the 10% threshold backwards through the LEBT with the first-order transport code TRACE [12]. The measured magnetic fields and a residual beam space charge corresponding to a current of 3.5 mA are included in the simulation. Onset of a third-order aberration is observed in Fig. 5 in both the measurement and prediction. The SCHAR code predicts an 18% emittance growth for the beam transport through this 2.1 m long LEBT.

Soloshenko [13] has shown that dynamic decompensation of space-charge neutralized beams will occur when $n_{+0}v_b n_0 \sigma_e/2f << \alpha n_{+0}$ where n_{+0} is the beam density, v_b is the beam velocity, $\sigma_e = 2 \times 10^{-16}$ cm^2 is the electron production cross section, and α is the beam noise amplitude. The inequality is satisfied when the electron density produced in the beam by ionization is much less than the beam current density fluctuations. This effect would be important for this injector operating at α = 1% when f > 1 MHz, but beam noise from the microwave source has typically reached background at f = 1 MHz. An effective emittance growth of <10% from beam current and voltage fluctuations is estimated using the TRACE code and the beam ellipse mismatch concept [11].

A maximum 30% emittance growth estimate from known beam-transport effects has been made. The optimum ion source only emittance is estimated to be 0.13 (πmm-mrad) by extrapolation of the published emittance vs. emission aperture radius to the 4.2 mm value used in these measurements [5]. It may thus be possible to reduce the injector emittance performance below the measured 0.20 (πmm-mrad) by optimizing the ion extraction system. Injector work has shifted to increasing extraction voltage stability in order to meet the 98% reliability requirement.

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