SPACE-CHARGE NEUTRALIZATION MEASUREMENT OF A 75-keV, 130-mA HYDROGEN-ION BEAM

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Abstract

A 75-keV, 130-mA dc mode proton injector is being developed at Los Alamos. The two-solenoid focusing system used in this injector relies on effective beam space-charge (s.c.) neutralization by beam ionization of the residual gas. The degree of s.c. neutralization is determined by measurement of the energy distribution of slow ions created in the beam region. A non-interceptive gridded-energy analyzer is used for the slow ion-energy measurement. Application and development of this diagnostic to a positive hydrogen-ion beam is presented. One feature of the ion-energy distribution measurement is a double-humped distribution. The higher energy component contains less than 20% of the total ion current. Measurements are reported which help validate the axisymmetric model used here to derive the degree of beam s.c. neutralization, f. Fairly weak dependencies of f on beam current and background gas densities are found, and f is typically found to vary between f = 95 - 99% depending on the presence of the "high-energy" tail on the slow ion distribution. This degree of beam s.c. neutralization assures good transport of the hydrogen positive ion beam to the next accelerator.

1 INTRODUCTION

Low-energy (50 - 75 keV) beam transport (LEBT) of high-current (50 - 130 mA) positive-ion beams in background gas pressures of order 10^{-5} Torr are predicted to have their s.c. largely neutralized by electrons accumulated in a beam plasma [1]. The degree of s.c. neutralization f is an important parameter in beam transport calculations. One technique [2,3] developed for the experimental investigation of f for positive ion beams is the measurement of the slow ion energy distribution. In a one-dimensional axisymmetric model of the beam-plasma interaction, where plasma ions are born cold (25 meV), measurement of the ion-energy distribution can be interpreted in terms of the residual beam space potential, $\Delta\phi$. This method has the advantage of not intercepting the primary ion beam.

A four-grid energy analyzer (FGA) has now been applied to the measurement of dc positive hydrogen-ion beams in a magnetic solenoid focusing channel. This diagnostic has previously been used for determinations of f in low energy (35 keV) H^- ion beam in a solenoidal LEBT [4], and high-energy (870 keV) proton transport [5] in a quadrupole focusing channel. Design considerations for the FGA used in these measurements are given in ref. [6].

2 EXPERIMENTAL METHOD

The FGA diagnostic is mounted in the injector prototype for the low-energy demonstration accelerator (LEDA) project at Los Alamos [7]. Hydrogen-ion beams at 75-keV energy and 50-130 mA beam currents are used in these measurements. A microwave proton source originally developed at Chalk River Laboratories [8] has been extended to meet LEDA requirements. A line drawing of the injector is shown in ref. [9]. The hydrogen-ion beams are produced with 600 - 800 W of microwave power, which typically yield a 85 - 90% proton beam fraction. The H_2^+ ion comprises the remaining beam fraction. The FGA is located at an axial distance z = 44 cm from the ion source extraction electrode. For all measurements discussed here the LEBT solenoids are off. The magnetic field at the FGA location is 10 gauss. The FGA is heated to 300°C to maintain reproducible energy distribution measurements [3,6].

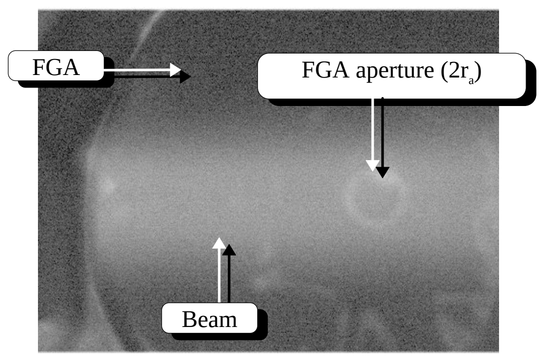

Fig. 1. An image of the hydrogen-ion beam passing the FGA.

The FGA is mounted opposite a video diagnostic port, and a video image of the beam propagating by the FGA is shown in Fig. 1. The light is generated by a 100-mA, 75-keV beam interacting with the background gas at a pressure of 1.9×10^{-5} Torr. The FGA aperture diameter ($2r_a$) is 8 mm. The residual gas in the low-energy beam transport (LEBT) is H_2.

Before beam measurements were made, the FGA was calibrated in an auxiliary test stand by a low energy electron beam obtained from a tungsten wire heated to thermal electron emission temperature. The tungsten filament heating current is pulsed off, and the wire biased from voltages ranging from 2 to 40 V. The emitted electrons current are recorded in the FGA's Faraday cup (I_{FGA}). Figure 2 shows I_{FGA} plotted vs. grid 3 voltage (dotted line) for a 2 eV electron beam. Voltage biases on grid 2, grid 4 and the Faraday cup are set in order to transmit the electrons with energy greater than the absolute value of grid 3 voltage (V_3). The equation $I_{FGA}(V_3) = \int_{|eV_3|}^{\infty} f(E)dE$ relates the energy distribution *f(E)* to I_{FGA} and V_3 by *f(E)* = $dI_{FGA}/d(eV_3)$. The *f(E)* from the electron gun measurement is shown as the solid curve in Fig. 2. The distribution peak occurs at $V_3 = -2$ V with an estimated error of ± 0.1 V, and with a full-width half-maximum energy spread of 0.67 eV. These data show the absolute energy calibration is sufficient (< 1 eV), and the energy resolution (<1 eV) is similarly acceptable for the expected range of ion energies (0 - 10 eV) to be measured from the beam plasma [1]. The analyzer temperature is maintained at 325 °C during these calibration measurements.

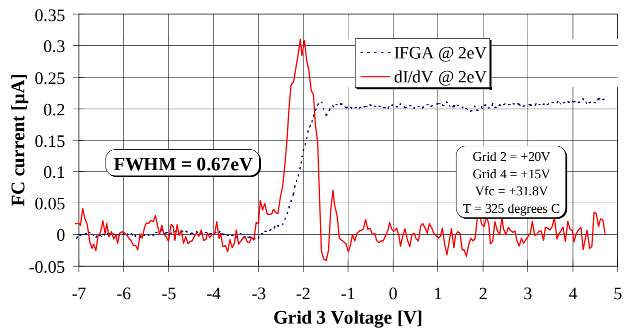

Fig. 2. Electron gun calibration of the FGA.

The data acquisition program was made using Labview v4, with around 250 points on grid 3 voltages, each point averaged at least 700 times. Data acquisition takes 10 to 30 s, so data described here is an average over possible fast beam fluctuations.

3 BEAM PLASMA MEASUREMENTS

A measured ion spectrum from a 120 mA beam at 75 keV energy is shown in Fig. 3. The LEBT pressure during this measurement is 1.9×10^{-5} Torr or a background H_2 gas density of 1.4×10^{12} (cm)$^{-3}$. The main section of the figure shows I_{FGA} measured as a function of V_3 (dashed line). Its saturation value of 0.14 μA is found for $V_3 < +1$ V, and then it decreases to 0 in the $V_3 = 1$ to 12 V range. The derivative of this curve is the ion distribution function $f_i(E)$ (solid curve). A deviation from the higher FGA current characteristic decrease is noted at $V_3 = 3 - 4$ V where the $I_{FGA} = 0.02$ μA. This current and its derivative are shown as an insert to Fig. 3. This accounts for about 10% of the saturated I_{FGA} at this pressure, but this component may increase to order 20% at higher LEBT pressures.

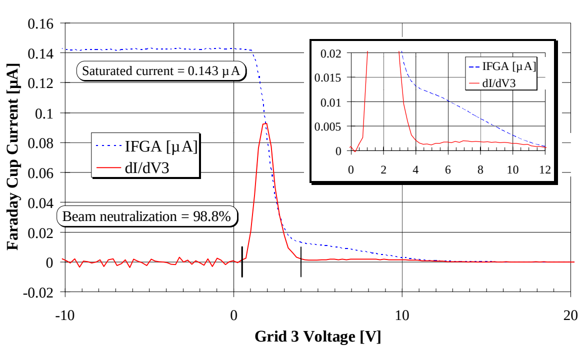

Figure 3. The FGA Faraday cup current and its derivative with respect to grid 3 voltage are plotted vs. V_3.

The width of the ion energy distribution ($\Delta\phi$) is taken to be the width of $f_i(E)$ at the distribution base. The degree of beam space-charge neutralization is given by $f = 1 - \Delta\phi/\Delta\phi_u$ where $\Delta\phi_u$ is the potential drop across a uniform unneutralized beam $\Delta\phi_u = i_b R/\beta$ where i_b is the beam current (A), $R = 30\ \Omega$, and β is the beam velocity. The unneutralized beam potential is about 285 V at $i_b = 0.12$ A for 75 keV beam. The increased width of the ion distribution $\Delta\phi$ then decreases f.

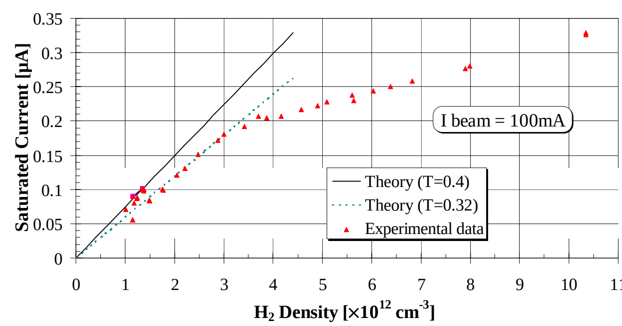

Fig. 4. Comparison of the measured and calculated FGA saturated currents.

The saturated FGA current $(I_{FGA})_s$ may be related to the FGA solid angle, beam current, neutral gas density (n_g), and positive ion production cross section (σ_i) by applying the 1-D continuity equation [6]. The equation is $(I_{FGA})_s = (r_a)^2\, T\, i_b\, (\Sigma n_g \sigma_i)/2d$ where r_a is the FGA entrance aperture radius of 0.4 cm, T is the FGA grid material transparency (40%), $\sigma_i = 2.9\times10^{-16}$ cm^2, and d the distance of the FGA entrance aperture from the beam centerline (10.5 cm). Figure 4 shows the measured and calculated $(I_{FGA})_s$ vs. the LEBT gas density. Here an auxiliary gas feed was attached to the LEBT box, and hydrogen gas was introduced to study the effect of larger LEBT pressures on f. The solid line shows the prediction while the discrete points show the measurement. Two calculations are shown for T = 0.4 and T = 0.32. There is good agreement considering the possible systematic measurement errors.

Figure 5(a) shows f vs. n_g, taking $\Delta\phi$ from the low ion energy distribution (cf. Fig. 3). Little variation in f is observed with increasing n_g. If $\Delta\phi$ were taken from the full ion distribution width, f is again independent of n_g, but it's value reduced to 95%. Figure 5(b) shows f vs. total beam current for 75 keV beam energy with $n_g = 1.2\times10^{12}$ cm^{-3}. It increases slowly from 96 to 99% with increasing beam current.

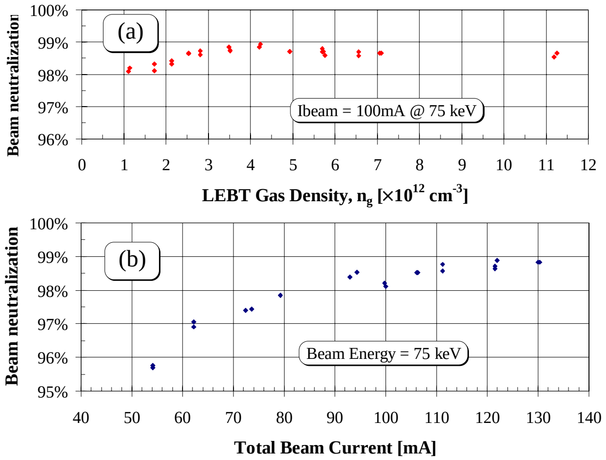

Figure 5. Plot of f vs. (a) the H_2 gas density in beam transport, and (b) total beam current.

4 DISCUSSION

Using a gridded-energy analyzer technique we have found residual beam potentials in the 0 -4 V range, or 0 - 10 V range for 75 keV hydrogen-ion beams with up to 130 mA current. The two potential ranges depend on whether a lower-intensity (< 20% of the FGA saturated current) but higher energy distribution is included in the analysis (Fig. 3). This leads to f ranging from 99 to 95%. The range of measured residual beam potentials (3 - 10 V) for an equilibrium beam agrees with that calculated by Soloshenko [1]. TRACE beam envelope calculations [10, 11] for the proposed LEDA LEBT for LEDA RFQ matching show that this range of beam s.c. neutralization may be successfully matched. Further, higher-order beam transport calculations show that this range of beam space-charge neutralization may be transported to the RFQ without large beam emittance growth [11].

We do not have a clear physical understanding of the measured two-energy ion distribution. It is unlikely an instrumental effect. However, since the higher energy portion of the distribution becomes more dominant at the higher gas pressures, we propose that the detected higher-energy ions come from a process other than lower energy ions being accelerated out of the beam channel by the residual beam s.c. potential. At higher gas densities the beam plasma would become more dense, and this may lead to excited H_2 molecules which decay to charged particles with ≈10 eV [12]. This interpretation is supported by the observation that the measured electron temperature increases from 1 to 3 eV as the LEBT gas density increases.

Earlier high-energy (870 keV) proton beam neutralization measurements [5] invoked halo H_2^+ and H_3^+ beam contributions to the measured ion energy distribution to explain multiple low energy distributions. However, the present distribution occurs at higher energy than the main distribution, and it seems unlikely the 10 - 15 % H_2^+ beam component can account for the ion distribution at V_3 > 4 V observed here.

Another possibility is the beam is rapidly oscillating between two s. c. neutralization states by collective oscillations in the ion-beam plasma [1]. This experiment would record the time-average of such a collective oscillation. This could possibly lead to emittance growth, but cannot be very large, as the rms beam emittance at the end of the beam transport has been determined to be 0.20 π mm-mrad [9].

5 ACKNOWLEDGMENTS

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