HIGH-CURRENT DIRECT INJECTION TO A CW RFQ USING AN ECR PROTON SOURCE*

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Abstract

The results of a direct injection experiment on the cw RFQ1-1250 proton accelerator are reported. The experiment was made possible by a high-current low-emittance electron cyclotron resonance ion source, with a 70 to 90% proton fraction and a gas efficiency of up to 60%. A beam transport system, consisting only of drift spaces and a solenoid lens, matched the beam to the radiofrequency quadrupole. A relatively high pressure in the low energy beam transport system ensured a high degree of neutralization to counteract space charge forces.

Introduction

The RFQ1 proton accelerator at Chalk River comprises a 50 keV dc injector and a 100% duty factor 267 MHz radiofrequency quadrupole (RFQ) linac. Previous operation was with a 600 keV RFQ (RFQ1-600) [1]. PARMTEQ calculations for RFQ1-600 predicted 85% transmission for a 90 mA input proton beam with a normalized rms emittance of 0.05 π cm mrad. Recently, new vanes were designed and installed in the RFQ to increase output beam energy to 1.25 MeV (RFQ1-1250) [2]. The calculated transmission characteristics for the two RFQ versions are similar.

The original RFQ1 injector [3] was designed for a multi-aperture duoPIGatron ion source. The proton fraction (the ratio of proton current to total-ion current) was 30-40% and a 60° dipole magnet was included in the low-energy beam transport (LEBT) system to separate the unwanted H_2^+ and H_3^+ from the protons. RFQ1-600 accelerated the 75 mA design current; but with a $\approx$ 125 mA proton current (350 mA total current) from the ion source, well in excess of the 100 mA design current. The inability of the injector/LEBT to generate and transport the proton current within the design acceptance, and losses on an injector aperture were contributing factors.

A high-current low-emittance electron cyclotron resonance (ECR) ion source with a 70-90% proton fraction has been developed at Chalk River [4]. Initial tests with this ion source on RFQ1-600 [5] proved that the design beam current could be accelerated with comparable proton current, but with less than half of the total current required with the duoPIGatron source. However, losses at the injector aperture were still high. Loss of neutralization and astigmatic distortions in the dipole magnet, and emittance growth throughout the LEBT are suspected causes of the excessive losses.

The high proton fraction of the ECR ion source removed the requirement for the dipole magnet for species separation, and introduced the possibility of direct injection into the RFQ. (Experiments on RFQ1-600 showed that the RFQ could handle beam spill exceeding 30 mA without adverse effect.) An experiment was performed on RFQ1-1250 to examine direct injection. Other features of the experiment were ion beam extraction from a single aperture to reduce the initial emittance, and the introduction of a short LEBT (one-third the length of the original LEBT) with "point-to-point" focusing to minimize emittance-growth.

Ion Source and LEBT Description

The ion source and injector arrangement for the direct injection experiment is shown in Fig. 1.

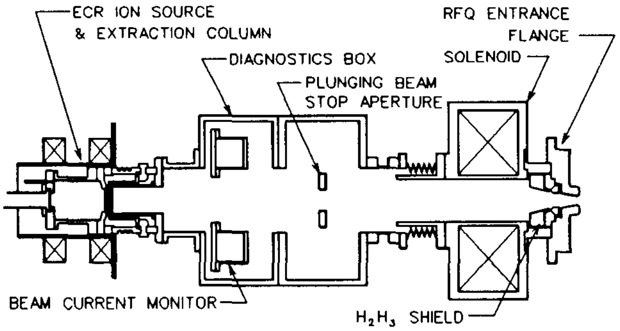

Fig. 1 Direct injection ECR ion source and LEBT.

The ion source is the production version of the 2.45 GHz ECR ion source previously mentioned [6]. The 50 kV extraction system is a single-aperture triode arrangement with a high-voltage acceleration (or accel) gap and a low-voltage deceleration (or decel) gap. The decel electrode prevents electrons generated by the ion beam from entering the accel gap. The ion source was capable of producing current densities at the extraction meniscus as high as 500 mA/cm^2 with a proton fraction of up to 90%. Experiments on a test stand showed that the beam emittance from the source was minimized when the source was operated to give a minimum-divergence beam [7]. In addition, the minimum-emittance and minimum-divergence was shown to be uniform over a range of aspect ratios (aperture radius to gap distance) up to 0.5.

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With a 2.5 mm aperture radius and 5 mm gap, proton currents in excess of the 90 mA design were expected, with a rms normalized emittance of $< 0.012\ \pi$ cm mrad and an rms divergence of 15 mrad.

Existing RFQ entrance beam-line components were used in the LEBT. These included: a diagnostics box, plunging beam stop (PBS) and focusing lens. The PBS was required to allow for ion source tune-up prior to injection. A power density limit of $\approx$ 1 kW/cm^2 placed a constraint on the minimum drift between the PBS and the source extraction column. When the PBS was raised, an aperture at the base limited the beam size. A cooled, shielding aperture behind the solenoid intercepted some of the H_2^+ and H_3^+ ions. Typically, the ion source operated at a hydrogen gas flow of $\leq$ 3 sccm (4.5 μg/s). A 2000 L/s cryopump at the PBS kept LEBT pressure $\leq$ 50 μtorr.

Circular apertures in the LEBT were electrically isolated with grounded shunt resistors to monitor intercepted currents. A similarly equipped "four-jaw" aperture at the RFQ entrance monitored beam size and misalignment. Non-intercepting beam-current monitors in the diagnostics box and at the RFQ exit measured the injected (ion source) and the accelerated beam current. A pair of optical beam-profile sensors (Reticon cameras) [8] on the diagnostics box, located $\approx$ 35 cm from the extraction column exit, monitored the vertical and horizontal beam profiles and alignments. (These cameras provided the principal means of determining the minimum beam width and, hence, the minimum divergence.)

Beam Transport and RFQ Matching

Figure 2 shows the TRANSOPTR [9] prediction for the LEBT beam match to the RFQ, assuming a waist at the extraction column and a 0.5 m drift to the PBS (overall LEBT length $\approx$ 1 m). The calculated orientation of the LEBT output emittance ellipse was optimized to fit within the RFQ acceptance, by varying the RFQ solenoid induction. Because of the extended drift, the beam is "stretched" into the RFQ acceptance space. Even this compromise results in a peak power density of $\approx$ 1.5 kW/cm^2 at the PBS at design current.

For a given extraction column, the injected beam current can be varied over a limited range by operating the ion source at currents over or under the matched current (that which gives a minimum divergence/emittance). This results in increased ion source divergence and a further elongation of the LEBT output ellipse, thus worsening the match to the RFQ. The apertures at the PBS and at the RFQ entrance were sized to intercept the beam when the ion source divergence exceeded $\approx$ 60 mrad (or 25 mrad rms). Although, H_2^+ and H_3^+ ions are not as sharply focused by the solenoid, an estimated 70 and 50%, respectively, will enter the RFQ (corresponding to $\approx$ 10 mA, at most).

Full space-charge neutralization of the beam was assumed in the calculations. Incomplete neutralization, depending on where it occurs in the LEBT, can result in further worsening of the match into the RFQ.

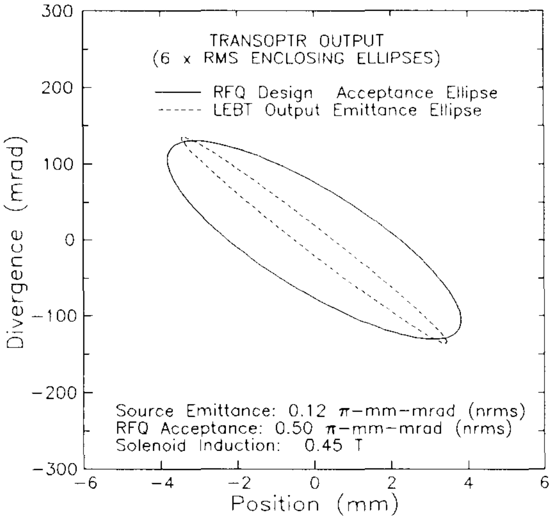

Fig. 2 LEBT beam match to RFQ.

Experimental Results

Experiments started at low injection currents, using a 2.5 mm radius aperture and a 10 mm extraction gap to produce a low-current minimum divergence beam [7]. The gap was decreased to 7 mm for intermediate currents and then to 5 mm to provide the design injection current. Figure 3 shows how the injected and accelerated currents with the 7 mm gap varied as a function of total current. The injected proton current was calculated by assuming proton fractions previously measured on the ion source [6]. (In Fig. 3 the proton fraction peaked at $\approx$ 82% for the highest currents.) The ion source operated stably over the range 50 mA to 90 mA, although the "matched" (minimum divergence) beam current was $\approx$ 73 mA (corresponding to $\approx$ 60 mA protons). The accelerated beam current varied between 20 mA and 50 mA, but dipped at the minimum divergence beam current. The dip could be eliminated by lowering the extraction column decel voltage to the minimum value at which the ion source would operate stably. Decreasing the decel resulted in a beam profile (on the Reticon cameras) with a less intense core. However, the overall width of the beam did not appear to increase. With this decel adjustment, RFQ transmission was $\approx$ 75% for proton input currents $\leq$ 60 mA (minimum divergence beam) and decreased for higher injected currents. Up to 55 mA was accelerated by increasing the ion source current above match and the RFQ field above the design value [2]. The solenoid induction required for an optimum LEBT-to-RFQ match varied little over the beam-current range in Fig. 3 and was in good agreement with the calculations. With the decel electrode at its normal (high) setting, only a slight dip was noted with the 10 mm extraction gap (low-current injection) and 25 mA was accelerated with a transmission of $\approx$ 80%.

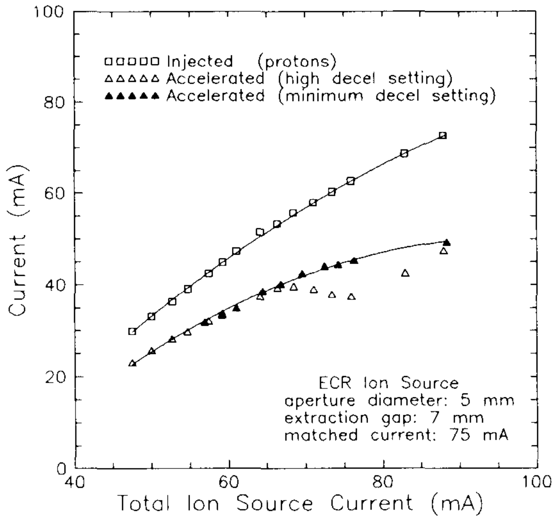

Fig. 3 Injected and accelerated beam currents for the 7 mm extraction gap.

The Reticon cameras showed that the beam profiles obtained near matched currents for the 10 and 7 mm extraction gaps were approximately Gaussian. These beams could be transported to the RFQ without significant loss. However, the beam extracted from the 7 mm gap was ≈ 30% wider at the camera location and had a more intense core. The cameras also indicated that the beams were non-circular. The shape changed with current, but matched beams were typically ≈ 10% wider in the horizontal than in the vertical plane [8].

With a 5 mm extraction gap, the matched beam profile width increased a further ≈ 20% (an increase of 50% over the width measured for the 10 mm gap [8]), and losses > 5% were indicated on the PBS aperture. The matched ion source current was ≈ 90 mA, lower than the 120 mA expected from the demonstration source results [7]. Maximum transmission through the RFQ was ≈ 70% and the maximum accelerated current was ≈ 50 mA, indicating a poorer LEBT-to-RFQ match. Neither increasing the LEBT pressure (to accelerate space-charge neutralization) nor changing the ion source gas flow had a significant effect on the beam.

The aperture radius was increased from 2.5 to 3.5 mm to see if extraction at a lower-current density at the same aspect ratio would improve performance. However, losses on the PBS and beam-profile widths were further increased and beam steering became more of a problem. Losses on the four-jaw aperture at the RFQ entrance were unequal and too high to allow injection at the design current level. The cameras indicated that the beam was steered ≥ 2 mm off-axis for small changes in ion source operating parameters such as gas flow and solenoid current. (With the 2.5 mm radius aperture, matched beams were within ≈ 0.5 mm of the axis and steering only became a problem when the ion source was operated well off-match.)

Concluding Remarks

Direct high-current injection to a cw 1.25 MeV RFQ (RFQ1-1250) from a single-aperture ECR proton source was demonstrated. A 55 mA proton beam (75% of the RFQ1-1250 design current) was accelerated. At low and intermediate injection currents, beam losses in the LEBT were small, and could be attributed to H_2^+ and H_3^+ constituents of the beam. Performance was limited by beam current losses in the LEBT and an apparent degradation of the LEBT-to-RFQ match as ion source proton current was increased to the 90 mA design level.

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