BEAM PARAMETER MEASUREMENTS ON THE CW RFQ1-1250 ACCELERATOR*

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Abstract

Measurements are reported on the output beam transmission, emittance and beam energy of the RFQ1-1250 proton accelerator. The RFQ1 accelerator, which comprises a 50 keV dc injector and a cw radiofrequency quadrupole accelerator (RFQ), is a test bed for a wide range of high-power RFQ experiments. Recently, a new set of vanes for the RFQ increased the output energy of the beam to 1.25 MeV. The measurements are compared to the operating characteristics of the earlier 600 keV RFQ1-600 version.

Introduction

The Chalk River RFQ1 proton accelerator comprises a 50 keV dc injector and a 100% duty factor 267 MHz RFQ. Commissioned in mid-1988, the facility first operated with a 75 mA 600 keV RFQ (RFQ1-600). By the end of 1990, design targets had been achieved on RFQ1-600 [1] and the RFQ was upgraded with a new set of vanes to increase output energy to 1.25 MeV (RFQ1-1250) [2].

RFQ1 is a test bed for cw RFQ accelerator and component development. To facilitate rf field balance experiments, and to allow for vane upgrades, the RFQ was built with adjustable/replaceable vanes. Design peak inter-vane fields on RFQ1-600 were 1.5 times the Kilpatrick limit [3], a limit now thought to be conservative. The vanes for RFQ1-1250 were designed for peak fields of 1.8 Kilpatrick. The increased field and an improved vane-tip profile recipe allowed the output energy to be doubled (to 1.25 MeV) using the same length structure while keeping the same high design transmission.

Initially, measured beam transmission on RFQ1-1250 was low and accelerated current was limited to less than ≈ 35 mA. Problems with alignment and beam steering on the original RFQ1 injector are suspected to be the major causes. A recent experiment on RFQ1-1250 demonstrated the viability of direct injection (without molecular species separation) from a high proton fraction ECR ion source [4]. Accelerated currents up to 55 mA (75% of design) were achieved. Results of RFQ output-beam-parameter measurements performed during this experiment are reported.

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Description

The increased peak field levels in the new vane design result from a reduction in the mean bore radius from 4 to 3.3 mm. Therefore, RFQ1-1250 reaches the design peak fields of 1.8 Kilpatrick (28.8 MV/m) at approximately the same rf cavity power (135 kW) and intervane voltage (78 kV) as RFQ1-600 [5].

The injector for the direct-injection experiment consisted of a 50 keV, 2.45 GHz ECR ion source with a single-aperture triode extraction system, and a linear low-energy beam transport (LEBT) system. The LEBT was a "point-to-point" focusing system with a solenoid at the RFQ entrance. The high 70-90% proton fraction of the ECR ion source made this "direct" injection scheme possible; H_2^+ and H_3^+ constituents in the beam to the RFQ were typically < 10 mA.

The single-aperture ECR ion source emittance was expected to be less than one-quarter the 0.05 π cm mrad (rms normalized) RFQ acceptance. However, due to a constraint on the LEBT design [4], an "over-convergent" RFQ input beam was necessary. The LEBT was designed to just fit a minimum divergence/emittance ("matched") ion source beam of 15 mrad rms divergence into the RFQ acceptance space. Matched beams were produced at "low" (≈ 30 mA) and "intermediate" (≈ 60 mA) injection currents and could be optimized to the RFQ acceptance space without significant proton beam loss. Injection current could be varied over a limited range by operating the ion source "under-" or "over-" matched (at the expense of increased divergence and degraded LEBT-to-RFQ match).

RFQ Transmission

Excepting the higher energy output, RFQ1-1250 was designed for the same input and output beam parameters as RFQ1-600. The PARMTEQ code predicted ≈ 85% transmission (75 mA output current) for a 90 mA 0.05 π cm mrad (rms normalized) emittance input beam. At injection currents less than 50 mA, transmissions in excess of 90% are predicted. Similar results were calculated for the optimized input beams from the direct injection LEBT. (A companion paper presents transmission parameters calculated with PARMTEQ and with a finite-element method code, RFQTRAK [6].)

Injected and accelerated currents were measured using non-intercepting current monitors in the injector and at the exit of the LEBT. Injected proton current was calculated assuming previously measured ion source proton fractions.

Transmission through the RFQ was nearly constant for under-matched ion source currents and decreased when the ion source was operated over-matched. Maximum transmissions of 80% and 75%, corresponding to accelerated currents of 24 mA and 45 mA, were achieved at low and intermediate injection currents, respectively. Prior to modifying the ion source for a matched current of 90 mA, the 60 mA configuration was operated over-matched and the RFQ intervane voltage was increased to 10% above design to accelerate 55 mA. After the modification, losses in the LEBT were excessive, and to date injection at design current has not resulted in increased accelerated current.

Figure 1 shows the measured RFQ transmission as a function of intervane voltage for the optimized low and intermediate injection currents. The measured transmissions are ≈ 15% lower than the PARMTEQ predictions and ≈ 5% lower than the measurements on RFQ1-600 at similar injected current levels.

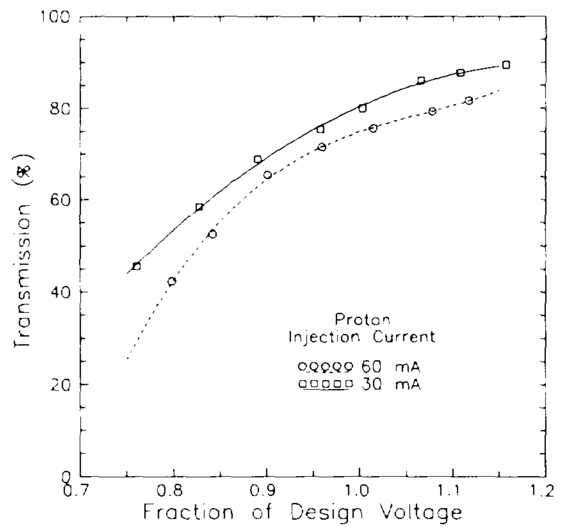

Fig. 1 RFQ1-1250 transmission versus vane voltage.

Emittance Measurements

The emittance measurement unit (EMU) for RFQ1 is a double slit device. The RFQ output beam is intercepted by a moveable water-cooled beam-stop fitted with a 50 mm long by 0.12 mm wide copper slit assembly. A second moveable slit (of the same dimensions), backed by a Faraday cup, allows the divergence of the beam transmitted through the first slit to be measured. Cooling on the first slit assembly was adequate for RFQ1-600, but the doubled beam energy and lower divergence from RFQ1-1250 presented difficulties. Initially, over-heating resulted in melting and closing up of the slit. The slit cooling was improved and the EMU was moved back to reduce peak power intensity. However, mechanical distortions of the slit persisted and many absolute measurements are in doubt. Nevertheless, qualitative trends have been established and some reasonable results have been obtained. To date, measurements have only been made in the horizontal plane.

Figure 2 shows the results of an emittance scan for a ≈ 60 mA injection current at 100% design field. Throughout the experiments, results for matched ion source beams were within ≈ ±10% of 0.05 π mm mrad. As predicted by PARMTEQ, the RFQ output emittance is increased (although by twice the code prediction) over the ion source emittance, due to the less-than-ideal LEBT-to-RFQ match. When the current and input beam emittance were increased by operating the ion source over-matched, the RFQ acted as an emittance filter and the output emittance remained constant. At low currents, the output emittance increased when the source emittance increased, in general agreement with PARMTEQ predictions. The measured RFQ1-1250 emittance is marginally larger than the 0.04 π cm mrad measured on RFQ1-600, but the difference is within the estimated errors on the measurement.

Varying the RFQ field had a more pronounced effect on output emittance. Lowering the field reduces the longitudinal acceptance, resulting in a growth of lower-energy beam components, leading to a decrease in transmission and an increased emittance. The design synchronous phase angle, ϕ_s, at the output end of RFQ1-1250 is -36.6° (and cos[ϕ_s] = 0.8). Therefore, at 80% of the design RFQ field, particles are not able to maintain synchronism and severe deterioration of the output beam was expected. Such deterioration did occur. Operation at 80% of design field increased the energy spread (see Fig. 4) and resulted in a > 50% increase in emittance; output current at this field was reduced by the same amount

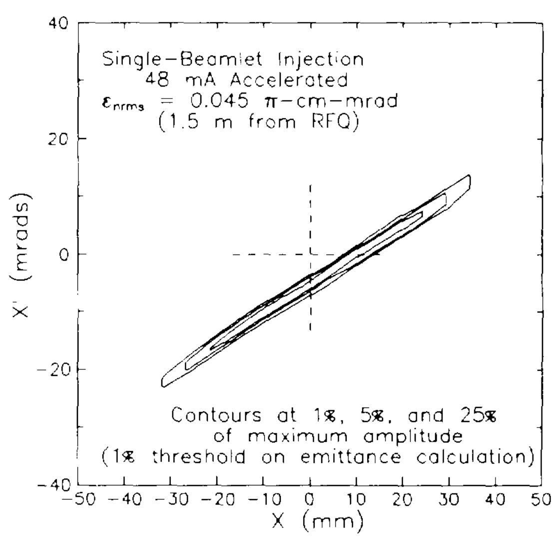

Fig. 2 RFQ1-1250 output emittance for single beamlet injection.

(see Fig. 1). As the RFQ field was increased to 10-15% above the design level, both emittance and output beam current were observed to increase in about equal proportion.

Beam Energy

The energy spectrum for RFQ1-1250 was measured in the low-injection current range using an on-axis 45° bend, magnetic-energy analysis system with an energy resolution of ≈ 0.2%. Figure 3 shows the energy spectrum from the RFQ at 100% of design field at accelerated currents of 10 and 32 mA. The higher current spectrum is characterized by a single broad peak at 1.25 MeV with full-width at half maximum (FWHM) of ≈ 65 keV. At the lower current, the spectrum broke into several narrow energy peaks, each having a FWHM of ≈ 20 keV and spaced at ≈ 20 keV intervals. These results are in qualitative agreement with PARMTEQ.

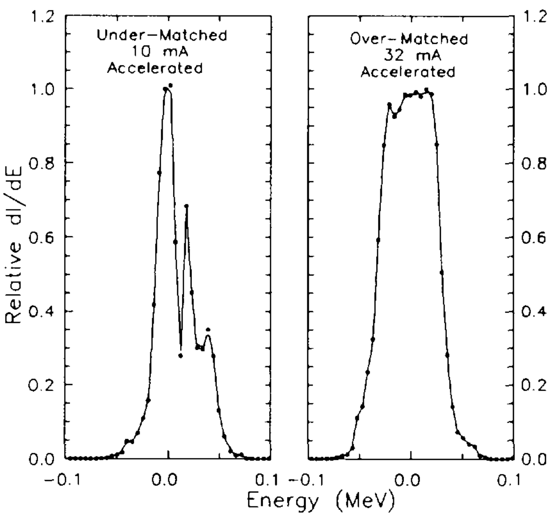

Fig. 3 RFQ1-1250 energy spectrum (1.25 MeV centroid) at 100% design field.

Figure 4 shows the effect on the energy spectrum at the higher current when the RFQ field is reduced to ≈ 80% of design. The main peak FWHM is reduced by ≈ 1/4 and cuts off above 1.25 MeV. The base is broadened on the low-energy side and lower energy peaks are apparent. These peaks are present in the design field spectrum, but are over three orders of magnitude smaller. Operation at ≈ 75% of design field resulted in a totally degraded spectrum, with a cut-off of ≈ 1.2 MeV.

Energy peaks from unaccelerated H^+, H_2^+ and H_3^+ beam constituents were observable in all of the measured energy spectra. While reduced in intensity by about four orders of magnitude, they served as useful calibration markers. Energy measurements on RFQ1-600 were made at higher currents and showed characteristics similar to RFQ1-1250.

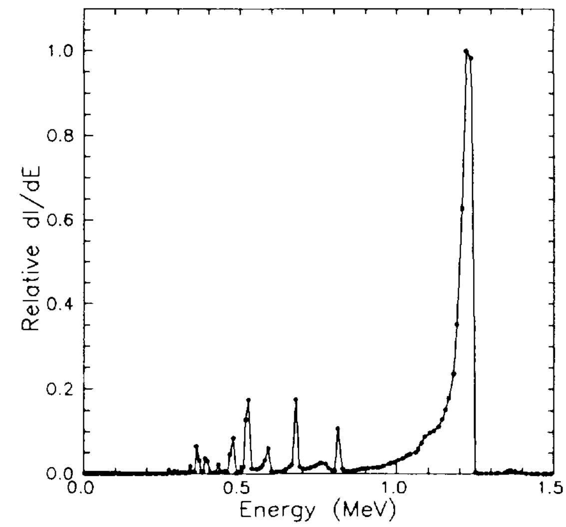

Fig. 4 RFQ1-1250 energy spectrum at 80% of design field.

Concluding Remarks

RFQ1-1250 has accelerated up to 75% of the design current using a direct injection scheme. As was the case on RFQ1-600, transmission is lower than code predictions, but this may be due to the less-than-ideal LEBT-to-RFQ matches achieved to date. Emittance and energy spectrum measurements are in general agreement with code and RFQ1-600 results.

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