RF TUNING AND INITIAL CW OPERATION OF RFQ1*

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Abstract

RFQ1, a 600 keV, 75 mA proton RFQ is the major component of a research program at Chalk River Nuclear Laboratories (CRNL) to study high-current 100% duty factor accelerator systems and develop improved accelerator technology. The mechanical assembly and rf tuning of the RFQ were completed late in 1987, giving fields that were uniform quadrant-to-quadrant and end-to-end to better than 5%. Details of the assembly and tuning will be given, and the current status of the facility, including high power pulsed and cw rf conditioning and beam experiments with the 50 keV dc injector and RFQ, will be described.

Introduction

The RFQ1 facility[1,2] is a test bed for the development of 100% duty factor Radio-Frequency Quadrupole proton accelerators suitable for a wide range of applications including fissile-fuel breeders and neutron sources. The frequency was chosen to match existing equipment and it was designed for an output energy of 600 keV as this was sufficient to demonstrate operation in principle, and RFQ1 could be used interchangeably with an existing Cockcroft-Walton dc system for testing the next stage of a proposed accelerator.

RFQ1 Design Parameters

Particle	Protons
Output Energy	50 keV (dc injector)
	600 keV (RFQ)
Output Current	240 mA (all ions from ion source)
	90 mA (protons from dc injector)
	75 mA (protons from RFQ)
Duty Factor	100%
RF Frequency	267 MHz
Peak Electric Field	1.5 * Kilpatrick (beam dynamics design)
	2.0 * Kilpatrick (thermal limit)
RFQ Length	1.5 m
RFQ Bore (r_o)	4.23 mm

RFQ1 Layout

RFQ1 consists of two subsystems, the injector and the accelerator, as shown in Fig. 1. The ion source is a 3 aperture duoPIGatron operating at a fixed voltage of 50 kV giving a beam with a normalized emittance of 0.04 π cm-mrad. The injector box contains a 60° bending magnet to separate unwanted H_2^+, H_3^+, and argon ions and deliver a 90 mA proton beam to the RFQ accelerator. The accelerator is a four-vane loop coupled RFQ operating at approximately 135 kW to deliver a 600 keV output beam at 75 mA.

RF Resonator Design

The prime goal of the rf design is to achieve the required quadrupole electric field distribution down the bore of the structure, over the range of operating conditions. Early beam dynamics calculations using a nominally flat, longitudinal field-distribution suggested that up to 7% dipole component in the electric field would not appreciably affect transmission (< 3% decrease), while up to ± 5% deviation from the theoretical, longitudinal field-distribution should produce only a few percent decrease in current. Thus a design goal of ± 5% field stability was chosen.

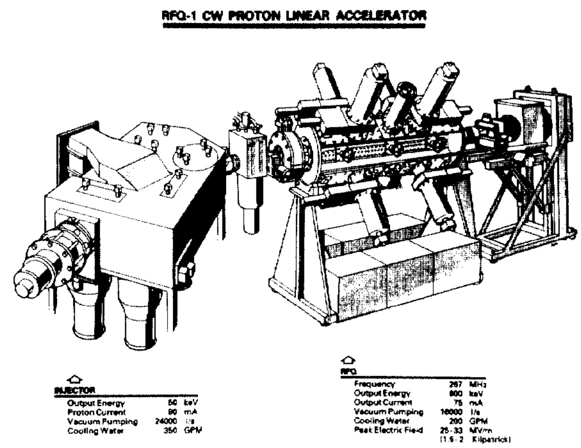

Fig. 1 Accelerator components and layout.

Field perturbation calculations were done with the code RFQ3D to establish the effect of expected vane misalignments and thermal relaxation effects (movements of ≤ 125 microns). Because of the short structure length, the required field stability was predicted to be achievable with only a pair of vane shorting straps (Vane Coupling Rings or VCR's) at each end. The increased vane-to-vane capacitance at the location of the VCR's reduces the "local" structure resonance frequency substantially and produces longitudinal field tilts. This effect can be eliminated by inserting fixed end-tuner plungers in each quadrant to decrease the "local" quadrant inductance near the VCR's and return the net "local" frequency to the nominal frequency of the rest of the structure. The size of these end tuners was determined by noting the structure frequency before the VCR's were installed, and then adjusting the end tuners to achieve the same frequency after the VCR's were in place.

The rf power is coupled into the structure via a single drive loop, with a design VSWR of 1.20, over-coupled, to compensate for beam loading (≈ 20% at 75 mA peak current). The mounting hole for the drive loop produces a large "local" increase in quadrant inductance, and thus a large "local" decrease in the drive frequency - with accompanying large azimuthal field perturbations. This must be corrected locally, as a change in the quadrant inductance elsewhere along the quadrant would produce longitudinal field variations. Thus metal must be added in the region of the loop to decrease the quadrant volume. We did this by increasing the volume of the loop itself.

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Vane Assembly

The RFQ1 vanes were constructed of mild steel with cooling channels machined into the body of the vane The three positioning mechanisms, located outside of the vacuum seal, allow the vane to be moved in and out radially and tilted sideways about a pivot axis lying in the plane of the vane-to-tank copper racetrack seal. After machining and welding the channel plates the vanes were straightened to ± 0.3 mm. An OFHC vane tip was brazed on the steel body and the tip profile was cut with a numerically controlled milling machine. The remainder of the vane was copper plated. During the tip contouring operation, pairs of reference flats for mounting an optical alignment target were machined on each tip at the three positioning-mechanism locations[3].

Optical Alignment

The vanes were centred on the copper gaskets within ± 0.4 mm. The vane base was then located on the tank to an accuracy of ± 0.05 mm. The vane tip was aligned optically using targets mounted on the vane. Figure 2 shows a view down the RFQ with the optical target positioned at mid-vane.

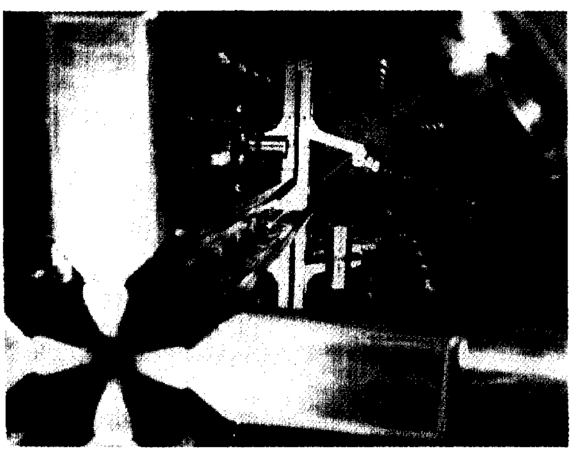

Fig. 2 Optical alignment target at mid position.

It was estimated that the vanes could be adjusted to an accuracy of ± 0.02 mm optically, but checking of the intervane gaps revealed a difference of up to 0.25 mm at 2 places among the 12 locations where the gaps were measured. At these 2 locations the vane positions were corrected using feeler gauges, with final trim adjustments of approximately 0.02 mm based on rf tuning measurements[4].

RFQ1 Tuning

The first step in tuning after mechanically aligning the vanes was done without VCR's or the drive loop installed[5]. Four fixed tuning plungers were inserted to wall depth at the structure centre, and flat copper end plates without end tuners were used. The vanes were adjusted to remove azimuthal and longitudinal asymmetries.

Next the VCR's, and temporary end plates with adjustable quadrant end plungers were installed. The end tuners were adjusted to produce acceptable longitudinal-field flatness and a set of permanent end plates with fixed tuners was machined and installed. Figure 3 shows an end view of the RFQ showing the VCR's in place. The fixed end-tuners and the output quadrupole matching magnet are shown in Fig. 4.

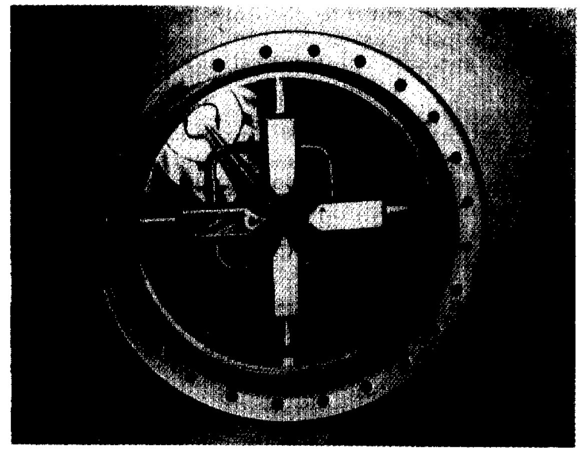

Fig. 3 End view showing vane coupling rings.

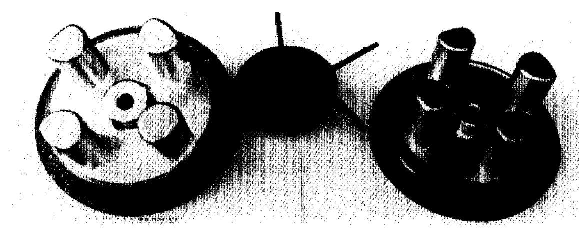

Fig. 4 Fixed end-tuners.

Finally, one central tuning-plunger was removed and the drive loop inserted. Both the shape and penetration depth were adjusted until the desired coupling and operating frequency were obtained simultaneously. This was done using a simple slide-adjustable model loop with a built-up knob of tinfoil on the loop. This shape was duplicated on the final high-power drive loop which is shown in Fig. 5.

Fig. 5 Drive loop showing built-up region.

RF Measurements

Perturbation techniques were used to measure the fields in the vane-to-vane gaps to ensure quadrupole symmetry. In this case a dielectric wedge was placed between vane tips outside the bore and drawn down the length of the vane using a fine monofilament fishing line. This indicated a longitudinal tilt in field of ± 2%.

Quadrant excitation was measured by inserting a metal perturber through vacuum pumping holes in the outer wall. Although quadrant excitation can be derived from the dielectric wedge (or "bead pull") this method is quicker and more accurate. Field variations are ± 1.5% azimuthally and ± 2.5% longitudinally.

The final bead pull results with the VCR's, end tuners, and drive loop in place are shown in Fig. 6.

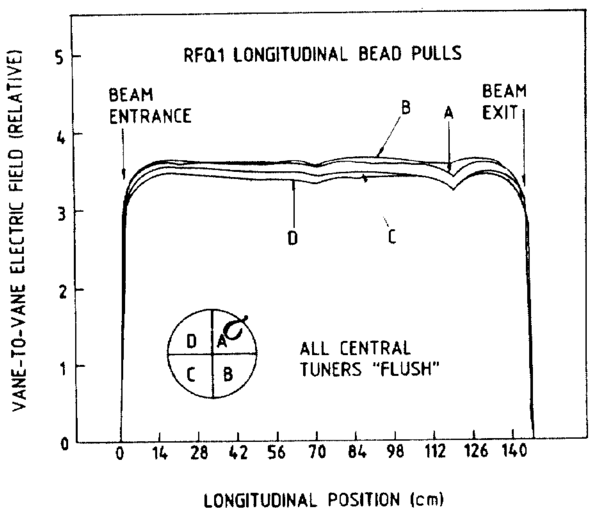

Fig. 6 RFQ1 longitudinal bead pulls.

High-Power Operation

Initial conditioning of a high-power device can be tedious because a number of systems are generally being operated for the first time. From SUPERFISH calculations and the measured unloaded Q (Q_m = 7900) design fields were estimated to require 135 kW. On the first attempt, a power level of 2 kW (100% duty factor) was reached after a few hours, with brief operation up to 5 kW. Our rf system was not designed for pulsed operation; it can be pulsed at low power, but even then filters overheat. After a brief attempt at conditioning with 10% duty factor operation, conditioning was resumed at 100% duty factor and within one day the power could be raised to the 90 kW level cw. During the commissioning, the system vacuum was used as a guide to the outgassing, and to judge how rapidly the power could be raised. With no rf the vacuum was approximately $3 * 10^{-7}$ torr and if it was allowed to exceed $1 * 10^{-5}$ or $2 * 10^{-5}$ torr, sparking usually occurred. After the first day's conditioning a level of 90 kW cw was reached.

CW conditioning of the RFQ was noticeably easier than our previous experience with the Alvarez tank of the High-Current Test Facility. One problem that plagued earlier cw conditioning runs was the shift of resonant frequency with drive power. It was so severe that following a trip due to a spark the tank would quickly shift off resonance and it was necessary to wait until the temperature had stabilized and then gradually turn up the power. With the RFQ the frequency shift is small enough (30 kHz at 100 kW) that it is not a problem and power can quickly be re-established following a trip. Another problem with the Alvarez tank that does not seem to exist here was the presence of multipactoring at low drive power that made turn-on difficult.

The following operation has been achieved to date:

Duty Factor	100%
Frequency	267.2 MHz
Total Power	100 kW (75% design)
Max. E Field on Boundary	1.3 Kilpatrick (87% design)
Max. Current on Boundary	4.0 kA/m (87% design)
Max. Surface Power Density	6.5 W/cm^2 (75% design)
Freq. Shift with Power	30 kHz/100 kW

Discussion and Conclusions

The desired field uniformity has been achieved. Cooling has proved adequate (at least at 75% of design power). The ceramic window on the drive loop cracked and during replacement the interior of the RFQ was examined for evidence of overheating. Some discoloration was seen but no damage was apparent. The racetrack seal showed no sign of overheating and caused no vacuum problems at currents up to 4 kA/m.

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