LOW POWER RF TUNING OF THE RFQ1 ACCELERATOR*

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Abstract

The RFQ1 radiofrequency quadrupole accelerator is being built to produce 75 mA of 600 keV protons at 100% duty factor, and will be a test bed for a wide range of high-power RFQ experiments. Low-power rf tuning of the structure has verified the rf design features and operation up to 1.5 Kilpatrick has demonstrated the applicability of the design to high-power cw accelerators. This report documents the design philosophy and the measured performance characteristics of the various systems, including drive loop, tuning plungers, end tuners and vane shorting rings.

Introduction

The RFQ1 radiofrequency quadrupole accelerator system was designed to produce a 600 keV, 75 mA proton beam at 100% duty factor. The accelerating structure (Fig. 1) is a 1.5 m long, 4-vane RFQ with several very demanding operating requirements[1]. The rf design of a stabilized, tunable, high-current RFQ system was achieved while satisfying compatible with extreme pumping and cooling requirements[2]. Several design innovations were introduced, including distributed pumping, compensated straps, dual dynamic balanced tuners and a compensated drive loop. The code RFQ3D[3] was used to predict the rf tuning characteristics. Low-power measurements have verified the rf design features of the device, and high-power operation at up to 1.55 x Kilpatrick has demonstrated the practicality of the design features at high voltages and high average power.

RF Resonator Design Philosophy

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 suggested a design goal of ± 5% field stability would be adequate. Field perturbation calculations were done with the code RFQ3D to establish the effects of expected vane misalignments and thermal relaxation effects (movements of $\leq$ 125 microns). The required field stability was predicted to be achieved with only a pair of vane shorting straps (VCR's) at each end.

The increased vane-to-vane capacitance at the VCR reduces the "local" structure frequency substantially and produces longitudinal field tilts[2]. These were reduced by inserting fixed quadrant end tuner plungers (Fig. 2) 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 quadrant end tuners was determined by noting the structure frequency before the straps were installed, and then adjusting the quadrant end tuners to achieve the same frequency after the straps were installed. In this way, the insertion of the straps has no effect on the nominal structure frequency or longitudinal field distribution.

The structure dimensions were determined using SUPERFISH (modified for long RFQ's - no end effects) with a "corrected" quadrant radius. Because of the large number of distributed vacuum pumping holes, the "effective" quadrant radius was slightly larger than the physical radius, lowering the cutoff frequency slightly.

Calculations of the thermal expansion of the structure predicted a cold-to-hot frequency shift of up to 400 kHz. As the system is envisaged to eventually drive a drift-tube linac, a frequency tuning system was required. Modeling of opposite pairs (Fig. 2) of central tuning plungers using the RFQ3D code demonstrated that the frequency shifts could be achieved with acceptable longitudinal field variations[2]. A third tuning plunger, opposite the drive loop, was installed to correct for small errors in the drive loop tuning. All four holes into the centre of the structure (three tuners, one drive port) were made the same diameter to maintain symmetry for tuning procedures.

The rf power is coupled into the structure via a single drive loop, which should not perturb the structure fields and should be over-coupled (VSWR ≈ 1.08) to compensate for beam loading (≈ 20% at 75 mA peak current). The mounting hole for the drive loop produces a large "local" decrease in the drive quadrant 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. Metal was added in the region of the loop to decrease the drive quadrant volume. The solution chosen was to actually increase the volume of the loop itself, while still maintaining the desired field coupling (Fig. 3).

RF Field Measurement Techniques

The tuning procedures for RFQ1 require only relative measurements of field strength at different locations. The usual perturbation technique was used to measure accurate relative field strength by introducing a small volume of perturbing material (metallic or dielectric) into the cavity and measuring the change in resonant frequency.

In an RFQ, the requirement of a pure quadrupole field means that, if the vane-to-vane gaps are identical, the vane-to-vane electric fields must be identical. In this case, a dielectric wedge placed between vane tips outside the bore and drawn down the length of each quadrant produces a frequency shift proportional to the square of the individual quadrant electric field.

The fields near the outer quadrant wall of an RFQ are almost purely magnetic, and thus a metal perturber produces a frequency shift proportional to the square of the local magnetic wall field. With RFQ1, the distributed vacuum pumping holes (Fig. 1) provide a convenient way of inserting a metal perturber of fixed diameter and penetration into the outer wall of each quadrant at a variety of longitudinal positions. These "poke tests" provided very easy and accurate measurements of the azimuthal field symmetry and a reasonable indication of the longitudinal distribution as well.

RFQ1 Structure RF Tuning Sequence

(A): Initial Verification of the Operating Frequency

The purpose of these tuning checks was to confirm, before copper plating, that the necessary resonant frequency 268MHz could be achieved by vane positioning

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and machining of the quadrant end tuning plungers. To facilitate the low-power tuning, end flanges with screw-adjustable tuning rods and movable slug tuners for the centre ports were fabricated from aluminum.

(B): Exact Vane Adjustment for Azimuthal Field Symmetry Before VCR Installation

After copper plating, the next step was to position the vanes, without straps, such that the field had optimal azimuthal symmetry at all longitudinal positions.

This was done because, although the vane-coupling-rings (VCR's) reduce azimuthal field imbalances by tending to keep opposite vanes at the same potential, rf currents must flow in the VCR's to accomplish this field stabilization. To minimize these currents (which contribute to strap heating) and to minimize field imbalances, the quadrant fields should be balanced as well as possible prior to VCR installation.

This was done as follows: The relative outer wall magnetic field was measured at six points along each quadrant by inserting a magnetic probe a fixed distance into the vacuum pumping holes and measuring the transmitted power. The magnetic field distributions so obtained, together with theoretical perturbation calculations done with the RFQ3D computer program, were used to estimate the vane trim movements required to balance the fields. During this process, the RFQ also had no quadrant end tuners (flat copper plates were used in place of the shaped end flanges). During this step the quadrupole mode frequency ($f = 272.5$ MHz) was well above cutoff ($f_{co} \approx 267$ MHz), causing the field to droop at either end of the tank (i.e., "convex" longitudinal field distribution).

The measured mode spectrum was that expected from a simple, unstrapped short 4-vane RFQ, with the two n=0 dipole modes close together (267.9 and 268.3 MHz) and well below the n=0 quadrupole mode. The azimuthal field flatness was adjusted to be ≈ ± 3%.

(C): Compensating the VCR-Induced Frequency Decrease and Longitudinal Field Tilt

Following the vane alignment, the next step was to ensure that the frequency shift and longitudinal field tilts introduced by the VCR's were adequately compensated by the quadrant end plungers - i.e., the quadrupole frequency had returned to the "SUPERFISH" frequency and the fields were sufficiently flat.

Adding the straps, but retaining the flat copper end plates (as in STEP (B)), the quadrupole mode frequency dropped to $f = 263.45$ MHz, well below cutoff. The frequency shift due to the straps (-9.0 MHz) compares reasonably well with the calculated value of -10.8 MHz.

The quadrant end tuning plungers (Fig. 4) were installed and after some adjustment and shaping of the end tuners, a field distribution with acceptable flatness was achieved (Table 1) at a frequency of 267.1 MHz. Insertion of the quadrant end tuning plungers had thus raised the frequency 3.7 MHz. The measured mode spectrum is shown in Table 2.

Table 1

Relative Quadrant Wall Field Values for Configuration with Straps and End Tuners but No High Power Drive Loop

f = 267.14 MHz

Quadrant Label	Axial Position, Z(cm) -49.7	-34.4	-19.2	19.2	34.4	49.7
A	1.00	1.00	1.00	1.00	1.01	1.03
B	1.00	1.00	1.00	1.01	1.02	1.04
C	Drive Probe	0.98	0.97	0.99	1.01	1.03
D	0.98	0.98	0.97	0.98	1.00	1.02

Table 2

Mode Spectrum: With Straps and Quadrant End Tuner Plungers, Without High Power Drive Loop

Frequency (MHz)	Mode Type	Longitudinal Mode Number
267.1	quadrupole	n=0
278.3	dipole	n=0
279.2	dipole	n=0
282.6	quadrupole	n=1
322.0	dipole	n=1
323.0	dipole	n=1

(D): Determination of Longitudinal Field Tilt and Tuning Range Produced by the Central Tuning Plungers

The central tuning plungers will eventually be used to compensate for frequency shifts caused by rf or beam heating of the structure. Identical movement of opposing plungers should have no effect on the azimuthal symmetry, but will affect the longitudinal field distribution. The tuning range of the plungers was estimated[2] using RFQ3D. Simultaneous movement of two opposite 96 mm diameter plungers into the quadrant was expected to produce 56 kHz/mm frequency increase.

The tests on RFQ1 were done by moving all four tuning plungers, simultaneously, to show maximum longitudinal field tilts. Bead pulls (Fig. 5) were done to demonstrate the change in longitudinal distribution caused by ± 5.1 mm of plunger movement around the zero or "flush" position. As expected, the frequency shift was dependent on the direction of movement, since the magnetic fields decrease rapidly as a function of depth into the hole.

(E): Adjustment of the Shape and Coupling of the RF Drive Loop

The final tuning step was to remove only one of the central fixed tuning plungers and to insert a drive loop (Fig. 3) until the desired coupling and operating frequency were simultaneously obtained. In practice this is not difficult, as the coupling depends primarily on the inner open area of the loop, while the frequency shift is largely a function of the volume of the "knob" that penetrates into the cavity.

A built-up aluminum foil mock-up of the loop was used to get the initial rough loop dimensions. A water-cooled solid copper version was then built, slightly oversized, and final frequency adjustment obtained by small machining cuts. When the frequency had returned to exactly that of STEP (C), the azimuthal distribution was measured to confirm the expected return to azimuthal symmetry. Small rotations of the loop about the rf line axis produced changes in coupling while leaving the frequency (and thus azimuthal symmetry) effectively unchanged. The final resonant frequency and coupling constant, for 0° loop angle, were

$$f_{res} = 267.18 \text{ MHz}, \qquad \rho_v = 0.2, \text{ overcoupled.}$$

References

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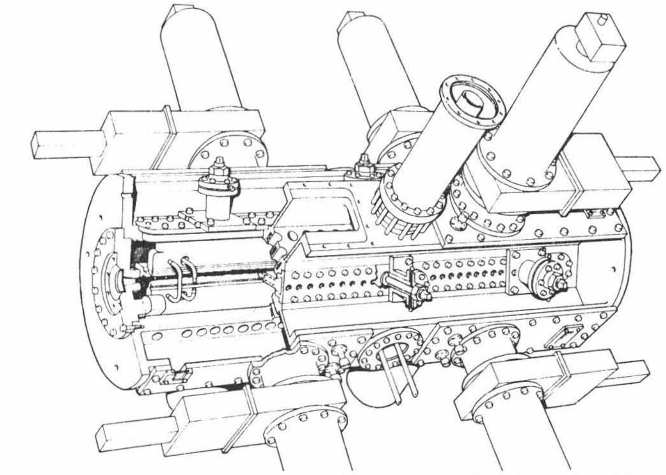

Fig. 1 Cutaway drawing of the RFQ, showing the fixed quadrant end tuners, the VCR's and the distributed pumping holes.

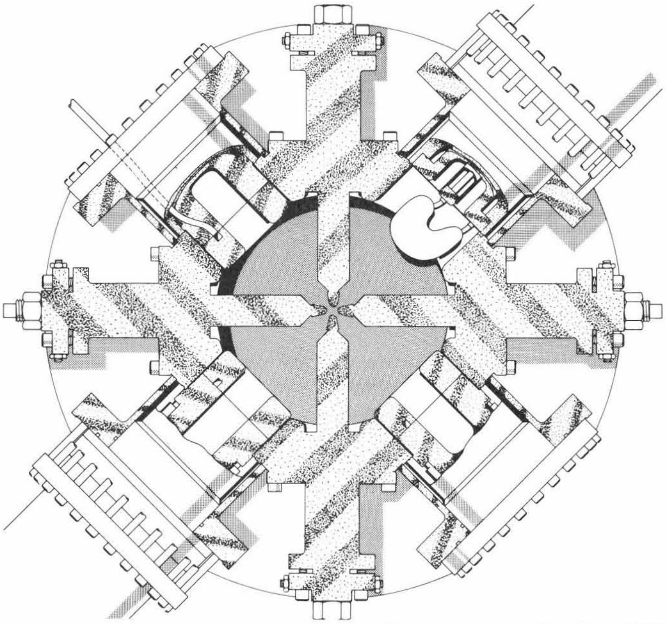

Fig. 2 A cross-section at the centre of the RFQ structure showing the rf drive loop and the three central tuning plungers.

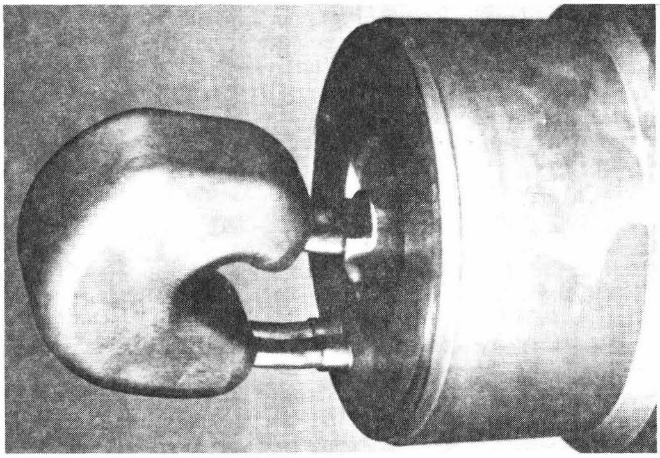

Fig. 3 The rf drive loop for RFQ1. The large block on the loop provides local quadrant frequency compensation.

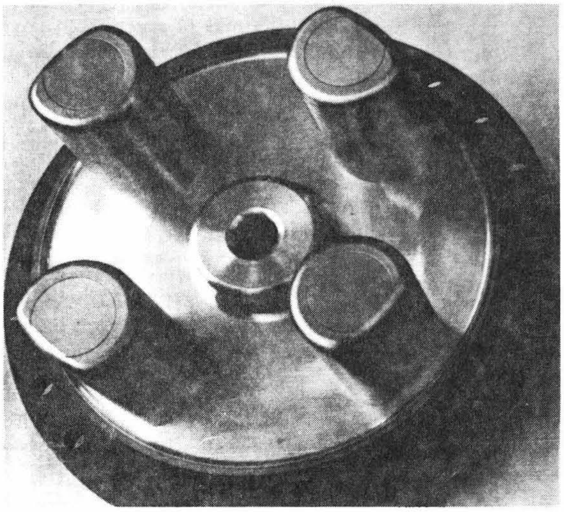

Fig. 4 An RFQ end flange with fixed quadrant end tuning posts.

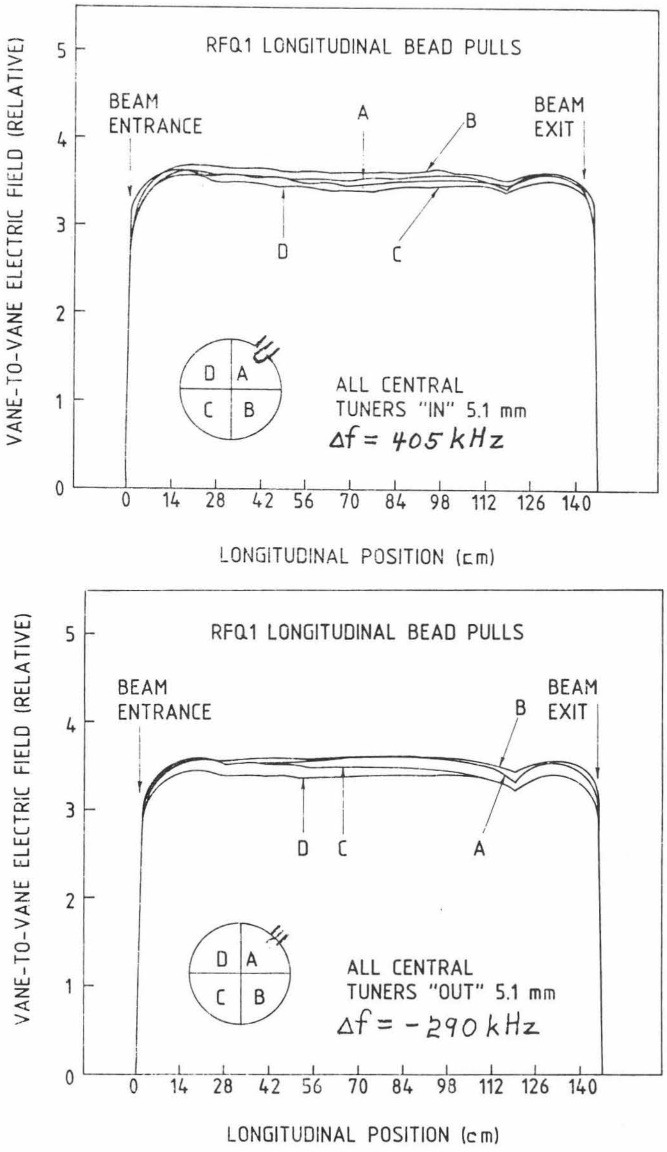

Fig. 5 Bead-pull measurements of the longitudinal distribution of vane-to-vane electric field in each quadrant, for central tuning plunger extremes.