PRACTICAL ASPECTS OF TUNING A RINGED RFQ*

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Summary

A radio-frequency quadrupole (RFQ) constructed at Los Alamos for high-current H^- operation at 425 MHz and 2.0-MeV output energy has been retrofitted with vane coupling rings (VCRs) introduced at Berkeley. The initial set of seven complete VCR pairs produced excessive operating frequency change, and an arrangement of alternating horizontal and vertical coupling rings eventually was adopted.

Because of the periodicity and length of the system, end effects were pronounced. A new type of end tuner was used to adjust the field strength at the ends of the structure that should be of general utility for high-power RFQs.

Tuning data for various ring and tuning configurations are given. Operating data are given in a companion paper.[1]

Introduction

Construction and operation of an RFQ linac operating at 425 MHz to accelerate H^- ions to 2.0 MeV has been reported previously.[2] Operating deficiencies of the original design were attributed to its extreme sensitivity to alignment and machining errors. This sensitivity was demonstrated to follow the relationship

$$\frac{\delta V}{V} = -\frac{1}{6}\left(\frac{L}{\lambda}\right)^2 \frac{\delta C}{C} \quad ,$$

where V is the quadrupole vane voltage, L the length of the accelerator structure, λ the rf wavelength, and C the intervane capacitance. Thus, if one made the additional correlation that $\delta C/C \sim (-)1/2\ \delta g/g$ where g is the intervane separation, it followed that vane positioning errors as small as 0.005 mm could produce voltage variations of 10% or more. Actual machining tolerances and positioning errors exceeded this value by a considerable margin.

The dominant effect of this stringent vane positioning requirement for an electrically long RFQ is not upon the longitudinal voltage distribution, which can be adjusted by a relatively modest amount of vane shimming or end tuning, but through the large dipole components of the field that can be introduced by minimal vane position errors. A solution to the dipole problem had been proposed by the Berkeley group[3] and has since been implemented.[4] The Los Alamos 2.0-MeV H^- RFQ has been retrofitted with a version of the VCRs proposed by Berkeley with satisfactory results.

Vane Coupling Rings

VCRs are simply devices used to short together opposing vanes of an RFQ. Customarily they are installed with periodic spacing. The shorting rings suppress unwanted dipole modes by shifting the dipole passband higher in frequency toward the mode for which the ring spacing is one-half the guide wavelength. The VCRs increase the effective quadrant coupling, producing a large separation of nearby interfering dipole modes from the desired operating mode.

VCRs pass through apertures in the adjacent vanes of the RFQ, producing a periodic capacitive loading of the structure. This loading can be both a weakness and a strength of the concept. Unless the structure is originally designed with rings, they will produce a lowering of the operating mode frequency that must be compensated by other methods. But, rings also offer a convenient means of deliberately introducing capacitive loading to produce the desired longitudinal field distribution.

Installation of the rings does nothing to improve longitudinal field stability in the RFQ. Viewed as a waveguide operating at cutoff frequency, one may say the group velocity in the RFQ remains zero and no longitudinal power flow occurs. Viewed physically, one might simply note that the Poynting vector in all quadrants is radial and no longitudinal power flow occurs. Rings do not change this. However, the rings do allow considerable freedom in correcting the longitudinal field distribution by other means, with little constraint imposed by the possibility of dipole admixtures.

RFQ Tuning Procedures

Azimuthal Tuning

Our initial plan was to install a periodic system of seven VCR pairs. The rings were located under the RFQ drive slots to allow post installation access, producing a ring system with the rings located at the $\lambda/2$ points of the structure. Capacitance calculations based on a test of the ring design in a spark test chamber gave an expected capacitance of 2.3 pF per ring and a frequency shift of approximately 18 MHz in the operating point of the RFQ. Figure 1 shows the longitudinal field distribution, measured by magnetic perturbations near the quadrant walls, with the seven VCR pairs installed. The operating frequency was 401.7 MHz rather than the calculated value of 405.5 MHz. The discrepancy between calculation and performance probably is due to neglect of the ring inductance in the test setup, which would tend to decrease the observed frequency shift and lead to a smaller apparent capacitance. The longitudinal field pattern shown is characteristic of a cavity operating slightly above the cutoff frequency. The magnitude of the local voltage excursions produced by the capacitive loading of the ring

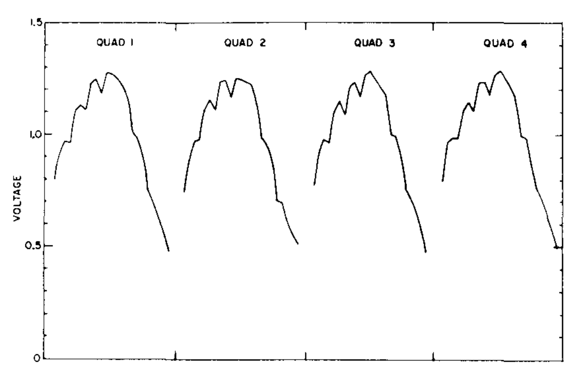

Fig. 1. A magnetic perturbation measurement of RFQ2 with seven VCR pairs located at the λ/2 points of the structure.

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pairs is affected by the difference between the operating frequency and the cutoff frequency and in this case was quite small. Dipole components of the field are negligible (<1%).

We investigated the possibility of using four sets of VCRs located at (2n - 1)λ/2 points. (The structure is 4λ in length). The results are shown in fig. 2. Again, the dipole component of the field was negligible. However, the local voltage excursions produced by the rings became pronounced. Operating frequency increased to 409.6 MHz.

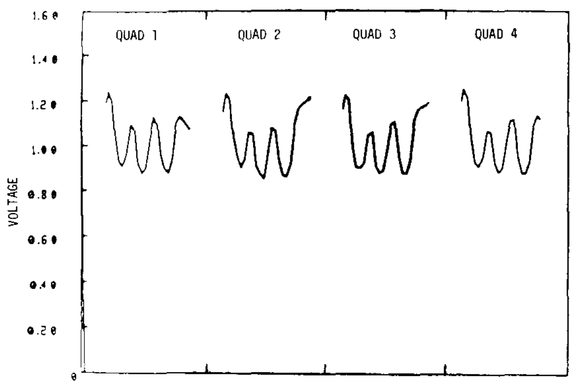

Fig. 2. Magnetic perturbation measurements of the RFQ with four VCR pairs.

To reduce the local voltage excursions that are due to the rings and also to raise the operating frequency to a point more acceptable to our klystron rf system, a ring system was installed in which horizontal and vertical vane pairs were alternately shorted together. One of the initial perturbation measurements for this arrangement is shown in fig. 3. Here vane extenders have been added to the output end of the RFQ with a consequent raising of the field at the input end. Operating frequency is 412.9 MHz. Investigation revealed that this ring configuration suppressed dipole field components (<4% maximum), provided vane misalignments were held to less than 0.05 mm. This tolerance is rather easy to obtain mechanically, and this basic configuration was chosen for final tuning.

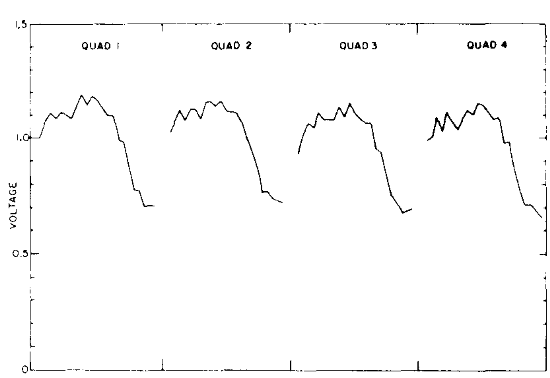

Fig. 3. Quadrant voltage distributions with seven alternating horizontal and vertical VCRs located at the λ/2 points. Vane extenders located at the output end of the vanes have been used to raise the field at the input end for this preliminary measurement.

Longitudinal Tuning

Methods of establishing appropriate longitudinal field distributions in RFQs have most often made use of capacitive end tuners and vane extenders both to adjust individual quadrant fields and to establish an effective open circuit termination of the cavity.[3,5-7] For electrically short RFQs, these methods have been quite satisfactory because the nonlinear terms in the longitudinal field distribution are small for reasonable operating points near the cutoff frequency.[8]

The Los Alamos H^- RFQ is electrically long ($L/\lambdabar \approx 25$). Attempts to obtain sufficient capacitive loading of the ends with standard end-tuner configurations usually have led to convex longitudinal field distributions because the capacitance required to force the operating frequency toward cutoff is large and the vane to end-tuner gap required becomes so small that the probability of sparking becomes a problem.

The longitudinal tuning problem was addressed by three methods. (1) A modest amount of vane shimming was done (<7%), decreasing the effective r_0 at the ends of the structure. (2) At selected locations the capacitance introduced by the rings was varied by changing the minor diameter of the ring. (3) A type of end tuner, originally considered at Los Alamos[4] but discarded in favor of the "conventional" design, was resurrected and used.

The longitudinal field distribution after vane shimming and ring adjustment is shown in fig. 4. The final field distribution after adjustment of the end tuners is shown in fig. 5. The final field distribution has a deliberate ramp of about 12% toward the high-energy end of the accelerator. Local field excursions, because of ring loading, average about 4% with a maximum of 9% at one location. Final operating frequency was 413.3 MHz.

The end tuners used are shown in fig. 6. The copper tuning stubs are approximately 15 mm in diameter and extend into the quadrants approximately 50 mm at the high-energy end of the accelerator and 30 mm at the low-energy end. The height of the end cap platform from which the tuners protrude has been adjusted to provide a constant 3.75-mm vane end to end cap distance for all vanes. Stub spacing from the RFQ vanes is approximately 5 mm, which is more than adequate to suppress sparking at the approximately 0.7 times Kilpatrick field gradient present. The penetration of the tuning stubs into each quadrant can be adjusted slightly to minimize any residual dipole present at the ends of the structure.

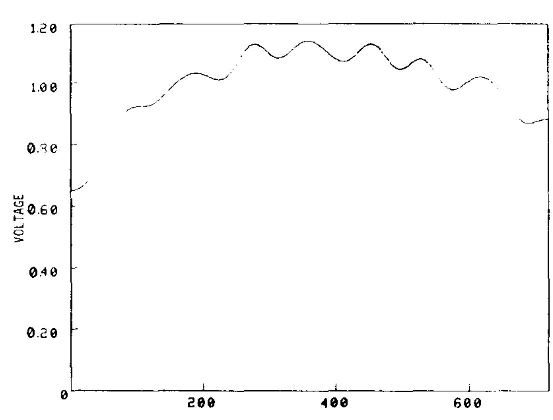

Fig. 4. Longitudinal variation of the quadrupole field after vane shimming and ring adjustment. Data for this measurement were taken with an on-axis dielectric bead pull.

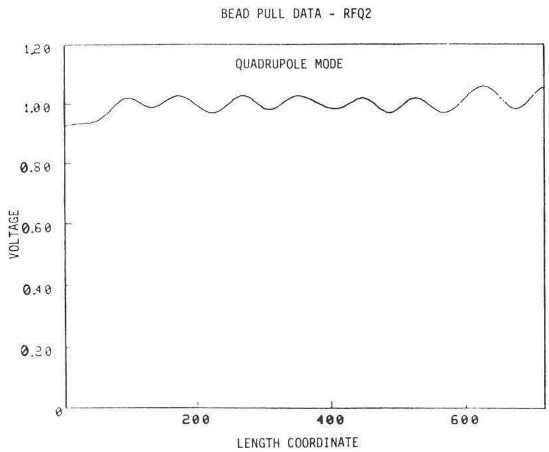

Fig. 5. Longitudinal variation of the quadrupole field shown in fig. 5 after adjusting end tuners.

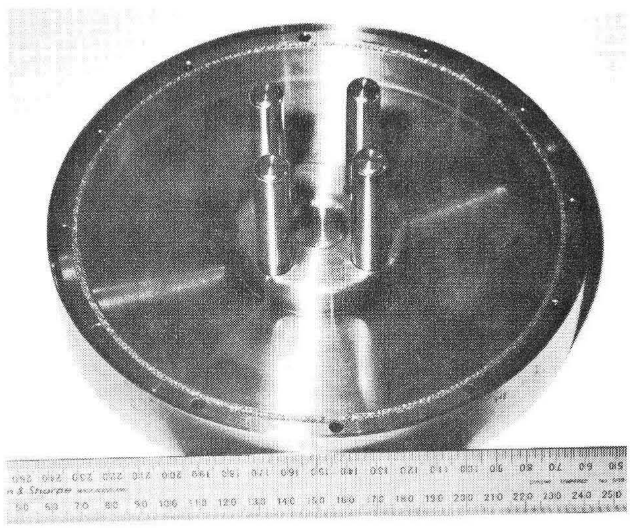

Fig. 6. End tuners used in RFQ2. The tuning stubs insert into the quadrants rather than face the vane ends.

This type of end tuner provides both a capacitive loading of the ends and also a reduction in the inductance. As the tuner stub is moved radially outward, the effect of the inductance reduction begins to dominate, and the same type of tuner can be used to correct concave longitudinal vane voltage distributions by proper choice of radius. For high-power applications, this tuner offers obvious cooling advantages over conventional vane extenders used for the same purpose.

Conclusions

A comparison of the total quadrupole field for the RFQ with the total dipole field is shown in fig. 7. These measured fields were used as input for a PARMTEQ calculation[9] of expected RFQ performance. In table I, expected results for an "ideal" flat field RFQ with no dipole present are compared with the results to be expected from the present field distribution, with and without dipole terms. The calculation indicates that performance should be affected very little by the existing departures from the ideal case. Actual measured performance characteristics are reported elsewhere.[1]

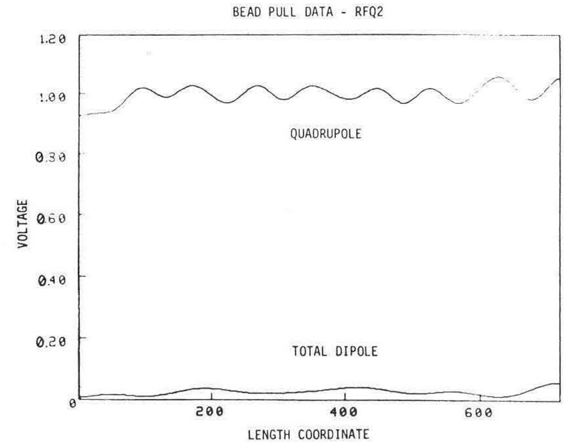

Fig. 7. Quadrupole and dipole components of the RFQ field from the final tuning measurements.

TABLE I

PARMTEQ OUTPUT THROUGH RFQ2

	Normalized Emittance π•cm•mrad				Trans-mission
	x-x', rms	x-x', 90%	y-y', rms	y-y', 90%	%
Design	0.020	0.086	0.022	0.097	92
Quadrupole (Measurements)	0.020	0.082	0.022	0.096	88
Quadrupole and r_0	0.018	0.080	0.023	0.106	90
Quadrupole, r_0, and dipole	0.020	0.095	0.021	0.092	89

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