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Title
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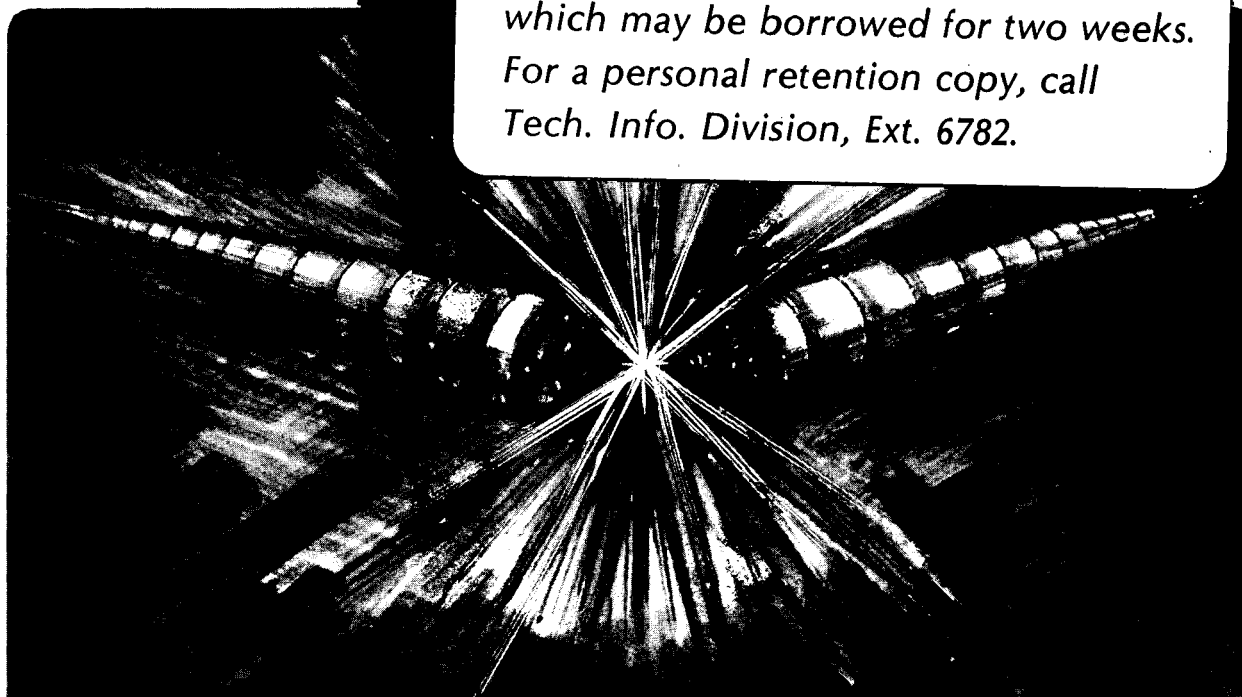IMPROVED FIELD STABILITY IN RFQ STRUCTURES
WITH VANE COUPLING RINGS

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IMPROVED FIELD STABILITY IN RFQ STRUCTURES WITH VANE COUPLING RINGS*

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Summary

The small apertures common in many RFQ linac designs lead to tuning difficulties, primarily because asymmetries in the quadrant fields can arise as a result of small non-uniformities in the vane to vane capacitances. Sensitivity to such capacitance or other tuning variation in the quadrants is greatly reduced by the introduction of pairs of vane coupling rings that provide periodic electrical connections between diametrically opposite vanes. Results of measurements on a cold model RFQ structure with and without vane coupling rings are presented. The number of rings required for field stabilization and the effect of rings on mode frequencies are discussed.

Introduction

Most RFQ designs currently being studied or fabricated are based on the four vane structure similar to that used for the proof-of-principle model at Los Alamos[1]. From the point of view of tuning to establish the quadrupole fields between the vanes, this structure has several disadvantages. Because the operating mode, a heavily loaded TE_{210} mode of a cylindrical cavity, is a cut-off mode, the field amplitude along the length is sensitive to variations of the structure parameters, particularly inter-vane capacitance. Also, coupling between the quadrants, for the small vane spacings required in practical RFQ designs, is weak. This results in a small separation between the TE_{210} quadrupole and TE_{11n} dipole modes, and makes the quadrant field amplitude sensitive to azimuthal variations in structure parameters, with inter-vane capacitance again the most critical parameter.

In the course of design studies and cold model testing for the LBL heavy ion RFQ for the Bevatron injector upgrade project[2] it became apparent that vane placement and adjustment with a precision in the range of .005 mm together with a complicated adjustment of eight interacting capacitive end tuners would be necessary to achieve acceptable field flatness and balance.

A desire to reduce this vane alignment requirement and simplify end tuning to something more readily achievable led to the development of the vane coupling ring (VCR) concept [3][4]. The rings are similar to the straps of a strapped vane magnetron and play a similar role by separating the operating mode from nearby interfering modes.

The low impedance connections (rings) between diametrically opposite vanes provide a strong coupling between the quadrants and tend to equalize the quadrant field amplitudes locally. Because the connections are between vanes that are nominally at

equal potentials in the TE_{210} mode, the field distribution and resonant frequency are not otherwise greatly affected.

For the dipole modes however, the rings introduce a short circuit between vanes that normally have opposite polarities. Resonant frequencies and axial field distributions are then both significantly changed.

In this paper we report on an investigation of field stabilization with vane coupling rings using a precision scale model of the Bevatron injector RFQ[2].

RFQ Cold Model

This model, designed to resonate at 372 MHz has wedge-shaped aluminum vanes with a tip radius of 1.02 mm and a base width of 50.4 mm mounted inside a copper plated aluminum cylinder with an inner radius of 84.9 mm and a length of 1.2 m.

The vane tips are not modulated. Four mounting bolts equally spaced along the length, attach each vane to the cylinder and allow radial adjustment of the vane position. Two screws located aziumthally on either side of the mounting bolts allow lateral adjustment of the vane position. R.F. contact between the vane and cylinder is made through r.f. finger stock clamped to the vane base. Before final r.f. tuning the vanes were centered and positioned with vane adjusting screws so the vane tip gaps between adjacent vanes were all .965 mm ± .038 mm as measured with pin gauges at eight positions along the length.

To adjust the termination impedance, eight capacitive tuners that screw in through the end plates vary the capacitance of each vane to the end plates. In addition the area available in the end space for the magnetic flux return around the vanes could be varied by installation of various shapes of vane termination pieces (shunt tuners) in cut-outs in both ends of each vane.

Provision was also made for the installation of up to seven pairs of vane coupling rings. The rings are installed as two semicircular pieces attached to two diametrically opposite vanes with set screws and passing through clearance holes in the orthogonal vanes. Ring and clearance hole dimensions were chosen to insure that the peak fields around the rings would be much less than the fields near the vane tips and so the local perturbation of the field near the axis would be small.[4] The rings have a major and minor diameters of 38.1 mm and 6.35 mm respectively. Axial separation of a ring pair is 25.4 mm and the clearance hole diameter is 19.05 mm.

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Field Stability Measurements

Most field measurements reported here were made using a small loop probe to determine the relative H field amplitude at the cavity wall. Probe holes in

the cavity wall allowed measurements to be made in each quadrant at eight equally spaced locations along the RFQ length.

After mechanical alignment of the vanes and subsequent tuning adjustments, without coupling rings, the field amplitudes in each quadrant were flat to within ,± 6% and azimuthally balanced to within ± 3.4%. Axial flatness or quadrant balance is defined here as the rms deviation of the field amplitude from the average amplitude, expressed as a percentage of the average.

Introduction of a small tuning perturbation in a quadrant demonstrates the tuning sensitivity of the field balance. For example, a small dielectric wand inserted in the vane gap of one quadrant midway along the RFQ produced a 0.08% resonant frequency shift for the quadrupole mode and a 26% change in the quadrant field balance. To appreciate the sensitivity of the field balance of dimensional changes one should note that this frequency shift corresponds to a radial displacement of a vane by approximately 0.01 mm.

Figure 1 illustrates the effect of similar quadrant perturbations on the fields for three arrangements of vane coupling rings in the RFQ. Note that the VCRs tend to clamp the quadrant fields locally so the balance is affected only in the region between the two VCR pairs containing the tuning perturbation or, in the case of one VCR pair at the center, in the half of the RFQ containing the perturbation.
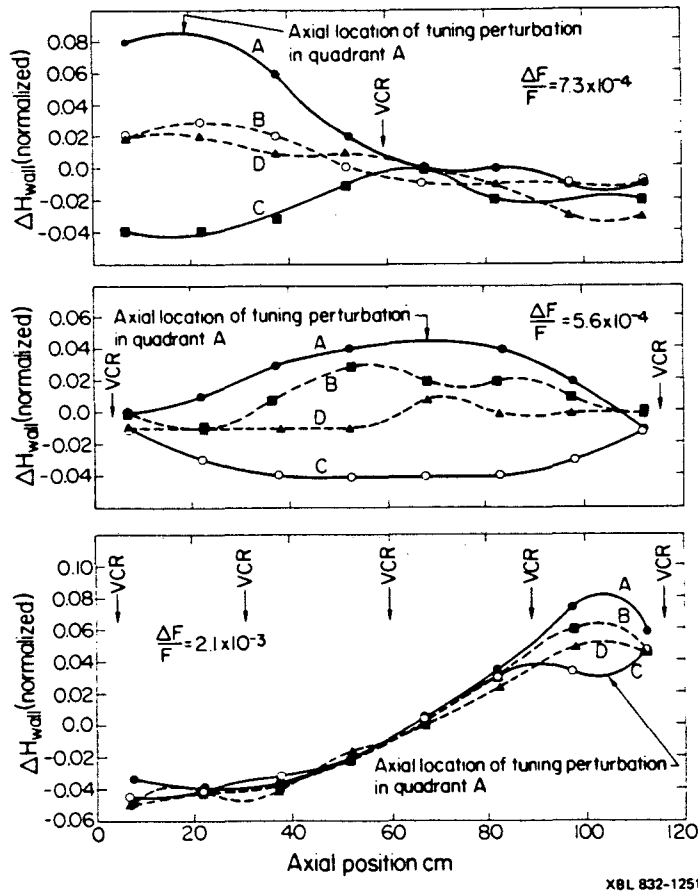

Fig. 1: Fractional change in quadrant field amplitudes (ΔH) when a tuning perturbation is introduced in a RFQ structure with one, two or five pairs of vane coupling rings.

Sensitivity of the quadrant field balance to a tuning perturbation is proportional to the distance between the perturbation and the nearest VCR. Perturbations at VCR locations have little effect on the quadrant balance.

For purposes of comparison of the various RFQ configurations we define a quadrant tuning sensitivity S(z) at axial position z by,

$$S(z) \equiv \frac{\frac{1}{2}\sqrt{\frac{\Sigma(\Delta H_i(z) - \overline{\Delta H(z)})^2}{\overline{H(z)}}} \times 100\%}{\Delta F}$$

where ΔF is the resonant frequency change caused by the tuning perburbation, $\Delta H_i(z)$ is the difference between the perturbed and unperturbed field amplitude in quadrant i and $\overline{H(z)}$ is the mean unperturbed quadrant field. The maximum values of S(z) for the RFQ configurations studied are given in Table I.

Table I
Maximum Quadrant Tuning Sensitivity S(z) For the RFQ With and Without VCRs

Number of VCR Pairs	Location	$\hat{S}(z)$ %/MHz
0		91
1	Center	17.0
2	both ends	16.9
3	both ends and center	8.6
5	Both ends and equally spaced	2.6

The one and two VCR cases have essentially equal $\hat{S}(z)$ values because the perturbation to VCR distance was approximately the same in both cases. As the number of installed VCRs increases the maximum distance between the perturbation and VCR decreases and the $\hat{S}(z)$ value decreases proportionately.

Although the tuning perturbation has a small effect on the quadrant field balance when 5 VCRs are installed, one can see in Figure 1 that the rather large ΔF required to produce a measurable change in the quadrant balance did produce a significant axial tilt in all quadrants. This is so because the operation remains in a cut-off mode. Since the quadrant fields are tightly coupled, it is possible to adjust axial field tilts or bowing by simple end tuner adjustments, provided the RFQ is not too long. Fig. 2 illustrates the tilt adjustment capability by showing the result of a plus and minus 1 MHZ adjustment of the capacitive end tuners at both ends
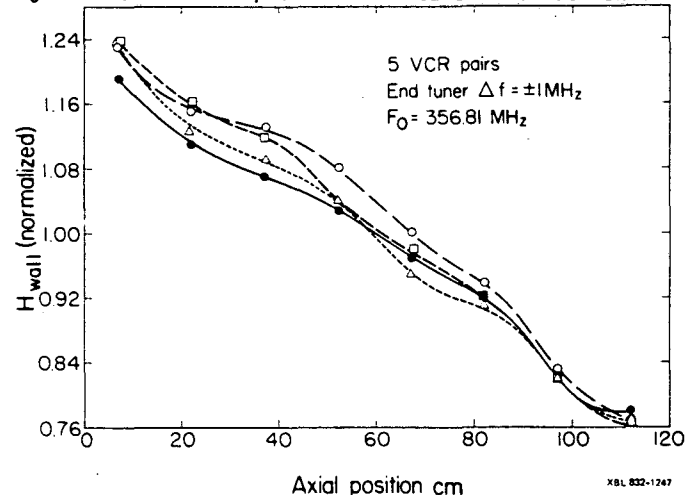

Fig. 2: End tuner effect on the axial field tilt in the RFQ with 5 VCR pairs

of the RFQ. For equal and opposite tuning of the two end tuners the linear tilt is directly proportional to the magnitude of the resonant frequency shift caused by one end tuner.

Tuning Effects on Quadrupole and Dipole Modes

The coaxial capacitors formed by a VCR passing through clearance holes in the two vanes not connected by it increase the inter-vane capacitance slightly and lead therefore to a decrease in the quadrupole resonant frequency as shown in figure 3. From the slope df/dn of this essentially linear plot and a calculated value for df/dc the effective shunt capacitance of one VCR was found to be 0.4 pf per quadrant.
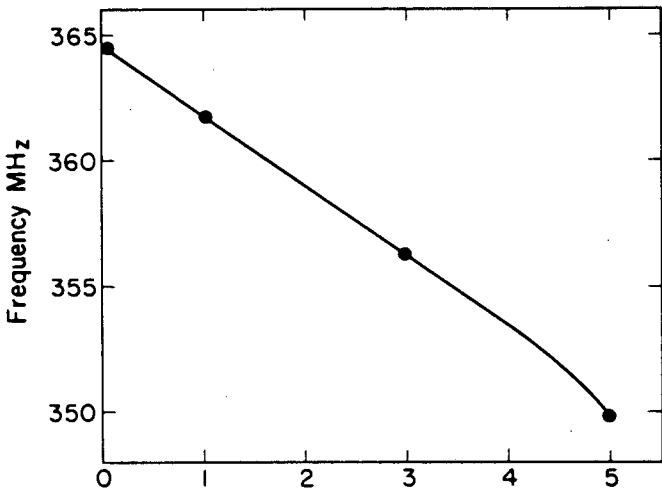
Number of vane coupling ring pairs

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Fig. 3: Resonant frequency of the fundamental quadrupole mode as a function of the number of pairs of vane coupling rings installed in the RFQ.

The effect of coupling rings on the dipole mode is more pronounced, as shown in Table II where the lowest dipole resonant frequency is listed for various numbers of VCRs in the structure.

Table II
Lowest Dipole Resonant Frequency For Various Numbers Of Vane Coupling Rings

Number of VCR Pairs	Location	Lowest Dipole Resonance, MHz
0		358.7
1	center	380.0
2	both ends	375.0
3	center and both ends	424.9
5	both ends and equally spaced	521.6

Placing one VCR pair at the center of the RFQ or a pair at each end has approximately the same effect in terms of the resonant frequency shift. In both cases the TE_{110} mode is eliminated by the boundary conditions, so the lowest dipole mode is a TE_{111} with either an open circuit or a short circuit termination. Keeping VCRs at the ends to define a short circuit termination for the dipole modes and symmetrically increasing the number of VCRs in the structure has a progressively larger effect on the dipole resonant frequency as the resonant length, i.e. the distance between successive sets of rings, decreases.

Conclusion

It is evident from the results presented in Table I that vane coupling rings in a four vane RFQ significantly decrease the field amplitude sensitivity to quadrant tuning errors. In fact by placing coupling ring pairs only at each end of the vanes (a spacing of approximately 1.5) and without dealing with the mechanically more complex problem of installing rings in the interior, a factor 5 improvement in quadrant field stability was realized. With three VCR pairs there is roughly an order of magnitude improvement in the quadrant stability. Moreover the possiblity of interference from dipole modes is minimized because they are far removed from the operating frequency.

As a consequence of the improved stability it becomes practical to excite the RFQ with a single loop drive in one quadrant and to provide fine tuning with a rotatable loop in another quadrant. This is the arrangement adopted for the RFQ of the Bevatron injector.

The problem of axial field tilting is not reduced by the coupling rings. Most RFQs now being designed or built are relatively short i.e. less than two free space wavelengths long, so the axial shape of the field can be compensated with proper tuning of the terminations. If in the future long structures are desired it is probable that some form of axial stabilization will have to be devised.

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