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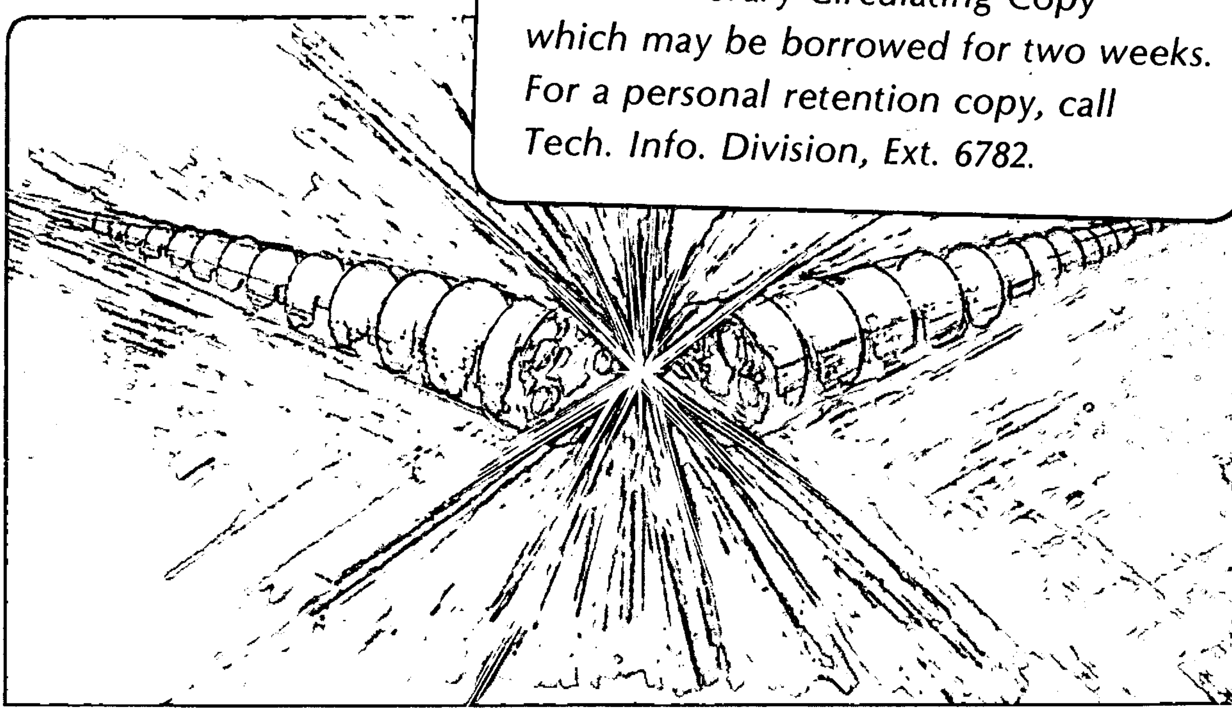

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VANE COUPLING RINGS SIMPLIFY TUNING OF THE LBL RFQ ACCELERATOR*

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Summary

A new heavy ion RFQ accelerator has been commissioned as part of a Bevalac injector upgrade project.(1) This RFQ is the first four vane type to incorporate vane coupling rings (VCR's) as part of the structure(2), (see Figure 1). This paper reports on the simplified tune up procedure made possible by the use of VCR's including field flattening, end tuning, and frequency adjustment. Also included is a discussion of high power performance including conditioning.

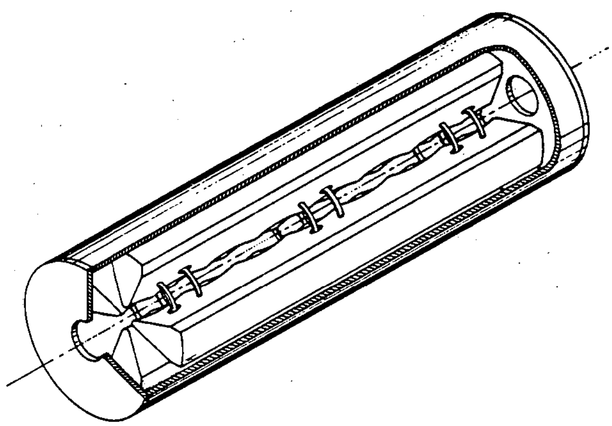

Figure 1: A four vane RFQ with VCR's.

Introduction

The tuning process, to achieve field and frequency tolerance, for four vane RFQ's has often been a difficult process. The many interacting adjustments that are necessary because of the extreme sensitivity of the structure to mechanical misalignments, make it difficult to control axial and azimuthal fields. Even though the RFQ beam performance is relatively independent of field variations, this sensitivity raises questions concerning the long term operational stability of the accelerator.

The VCR's used in the LBL RFQ represent a significant improvement in the tune-up process. By assuring azimuthal symmetry with strong coupling between quadrants it is no longer necessary to accomplish this by moving the vanes. Furthermore, axial field flattening can be done by simply moving the end walls. All bead pulling tests to measure the axial field are done in one quadrant only.

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From start to finish the entire tune-up procedure took one month including end wall and fixed tuner machining and manufacturing the bead pulling apparatus. With our present understanding, one week should be sufficient for tune-up of a similar structure.

The general parameters of the RFQ accelerator are given in Table I.

Table I
RFQ Parameter Summary

Design ion	$^{28}Si^{+4}$
Input energy	8.4 keV/amu
Output energy	200 keV/amu
Frequency	200 MHz
Total length	225 cm
Average bore radius (r_o)	0.254 cm
Exit matcher	
length	64 cm
r_o (max)	0.312 cm
Maximum surface field	27 MV/m (1.85 Kilpatrick)
Vane-Vane Voltage	51 kV
Peak RF power	150 kW
Duty factor	0.002
Stored energy	0.6 J

Mechanical Alignment

As described in reference 3, the four vanes were positioned mechanically with a tolerance of less than ± 0.002 inches. Tests show the vanes can be removed and replaced with a reproduceability of better than 0.0005 inches. The vanes were not moved at any time during the field alignment. The VCR's were easily installed in about one hour. The center VCR's required a special long handled, right angle screw driver.

Test Set-Up

The testing apparatus was similar to that used in other RFQ alignments, and is shown in Figure 2. For bead perturbation tests a phase-locked loop fed the RFQ at the resonant frequency through a voltage controlled oscillator (VCO) with a linear frequency versus voltage function. The voltage was used to plot $(\text{field})^2 \propto$ frequency. Perturbations were made using a 3/4 inch diameter by 1 inch long hollow polystyrene bead pulled longitudinally in the notch between and touching two vanes to measure electric field, and a 5/8 inch square by 3/4 inch long brass bar pulled longitudinally along the RFQ wall beside the pick-up loop holes to measure magnetic field. Six H-field probes in each quadrant wall gave additional field information.

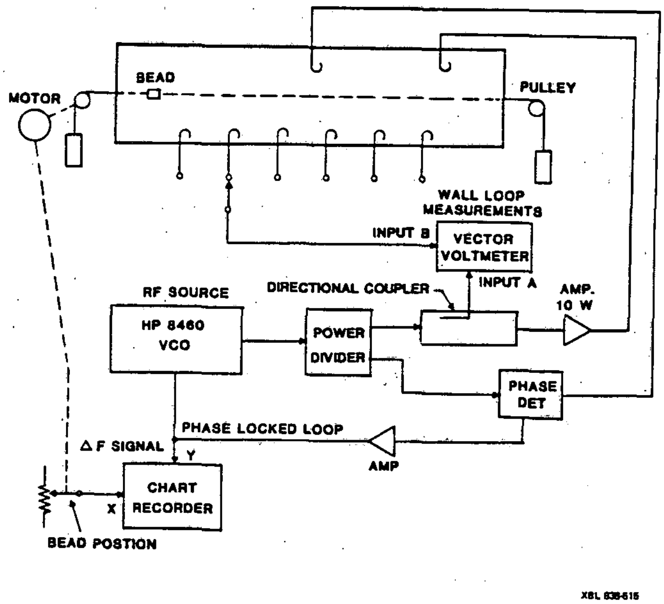

Figure 2: Field alignment test apparatus.

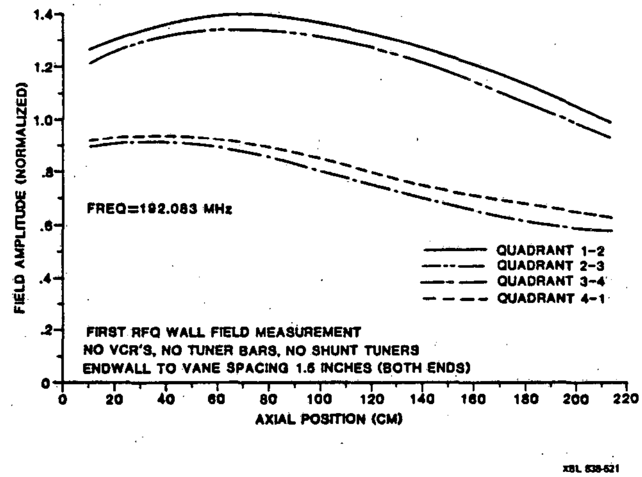

Figure 3: Initial RFQ field alignment.

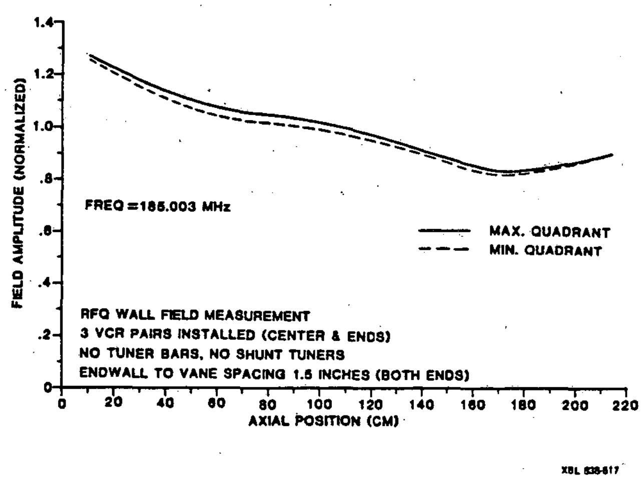

Figure 4: RFQ field alignment with VCR's installed.

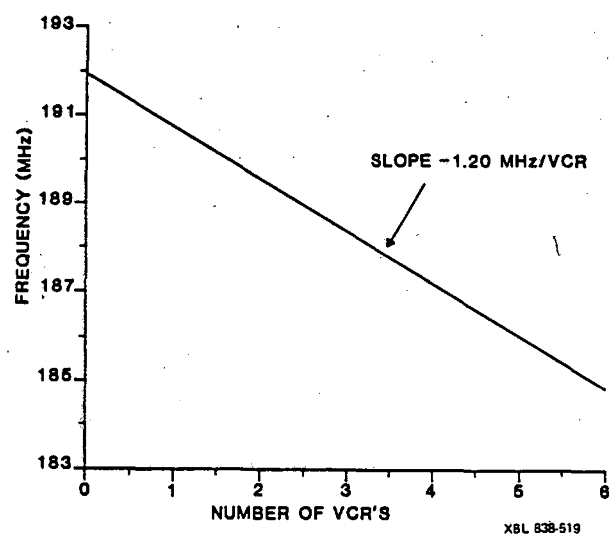

Figure 5: RFQ quadrupole mode frequency shift versus number of VCR's.

Tune-Up Strategy

It was apparent from earlier tests on a model [4] that with the VCR's installed and the fields in the four quadrants of the RFQ tracking each other, the axial field behaved essentially like a single cylindrical waveguide excited at a cut-off mode. That is, local frequency perturbations cause axial field tilts. It was assumed that the variations caused by small local perturbations along the walls such as vacuum ports, drive loop, and tuning loop would cause small axial field variations. The larger local frequency perturbations caused by VCR's and end geometry could be compensated by additional VCR's (five equally spaced pair positions were available) and by moving the end walls to adjust the end frequency.

Initial Tests

Figure 3 shows initial axial field variations in the four quadrants of ±40% with azimuthal quadrant differences of ±30%. Figure 4 shows the same measurements with three pairs of VCR's installed. A large average tilt of ±20% with high ends still exists, but azimuthal quadrant differences are reduced to ±2.5%. The frequency was lowered 7 MHz by the addition of the VCR's, in excellent agreement with calculation[2]. Figure 5 shows the effect on frequency when adding VCR's.

End Tuning

After installing three pairs of VCR's, it was necessary to tune the ends to remove the average axial tilts and the high ends. A local frequency lower than cut-off raises the local field. A local frequency higher than cut-off lowers the local field.

To determine the proper end wall position, crude moveable end walls with circumferential spring fingers were built. Figure 6 shows the end tuning curve where the effect of the inductance, formed by the area of the vane end cut-back angle and the end wall, dominates until the end wall gets very close to the vane end, where the capacitance dominates.

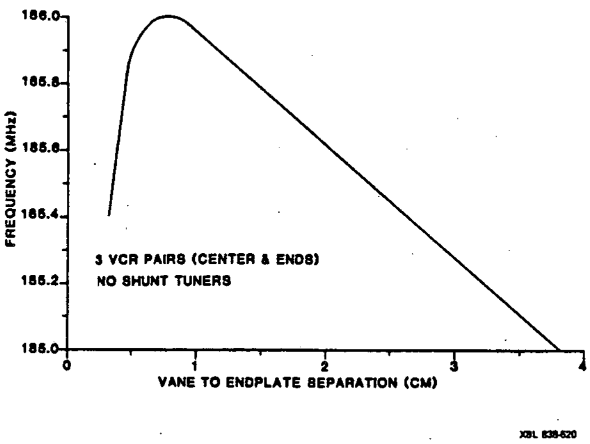

Figure 6: RFQ end tuning curve.

The spacing between the end of the vanes and the end wall was decreased on each end from 1-1/2 inches to 3/8 inch. This lowered the higher end fields but did not eliminate the average axial tilt.

Bar Tuners

The bar tuners were then mounted on the base of the vanes. They extend the full length of the vanes to uniformly raise the cut-off frequency slightly above the desired operating frequency. The incremental frequency change caused by the tuning bars was 15.9 MHz. Final coarse tuning will be done by decreasing the area of these tuners at a later time.

The LBL RFQ has an exit matching section extending over the final 64 cm of the vanes.[5] Over this length the radius parameter r_0 increases slowly to a final value which corresponds to an increase in cut-off frequency of 5.6 MHz. The bar tuners were tapered over this length to theoretically compensate for this local frequency change.

Final End Tuning

To compensate for the average axial tilt the entrance end frequency was raised and the exit end lowered. To reach the desired frequency on both ends small pieces of metal (shunt tuners) were attached to the vane ends to decrease the cut-back angle area allowing the end wall to be further from the vane end. The shunt tuners were attached so contact with the cylinder wall was avoided, as shown in Figure 7. The final end wall to vane end spacings were entrance 5/8 inch, and exit 7/8 inch. Figure 8 shows the final bead perturbation curves. The H-field perturbation along the wall shows the vacuum port and the decreasing flux density caused by the exit matching section.

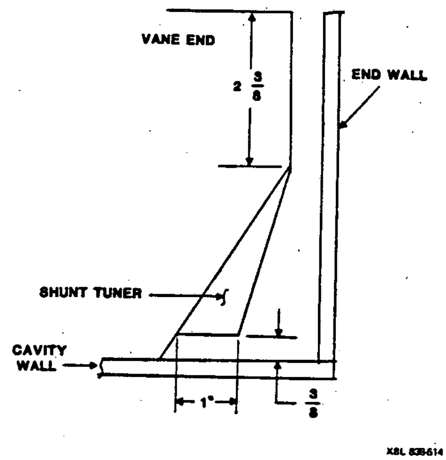

Figure 7: FRQ shunt tuner geometry.

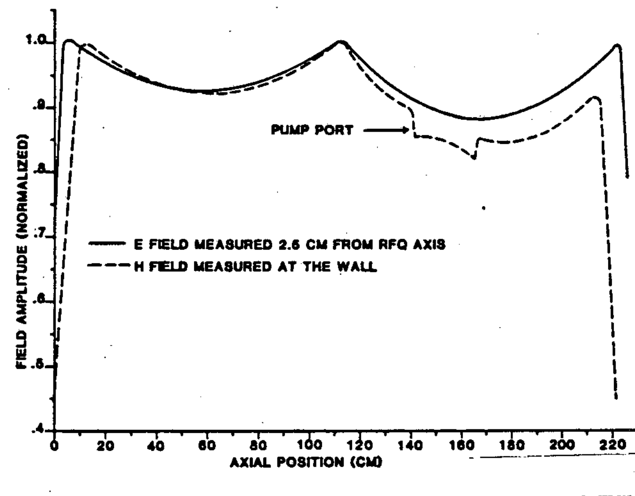

Figure 8: RFQ final axial E and H fields.

Drive Loop and Tuner Loop

The drive and tuner loop are located at the center of the RFQ near the center VCR pair position but in diametrically opposite quadrants. The drive loop can be rotated to give drive impedances from essentially zero to 125 ohms. At 45° rotation the impedance is 80 ohms. The tuner consists of a shorted copper loop 2-5/8 inches in diameter which can be rotated by a motor to keep the RFQ tuned to the proper frequency. The tuning range is ±90 kHz. This tuning range changes the azimuthal and axial field alignment by less than ±1%.

Quality Factor

The initial Q-value was 8700. Adding three VCR pairs lowered the value to 7500-8000 depending on end wall spacing. The final Q-value after low power tests was 4800. Almost all of this decrease can be attributed to the joint losses and increased surface area of the tuning bars. After initial high power operation, the Q-value increased to approximately 6000.

Dipole Modes

Initially, the lowest frequency dipole modes were at 189.4 MHz and 189.9 MHz when the quadrupole fundamental mode was 192.1 MHz. After final tune-up, with 3 VCR pairs installed, the lowest frequency dipole modes were at 239.9 MHz and 240.4 MHz and the quadrupole mode frequency was at 202.4 MHz. The three VCR pairs have eliminated the dipole modes from the operating frequency area.

Full Power Tests

The conditioning of the RFQ with high power went smoothly. The maximum gradient was reached in about 24 hours. The normal problems of surface conditioning and outgassing occurred, but no serious roadblocks were encountered. A lock-level at 1/3 full field persisted, but did not interfere with normal operation. Subsequent examination of the RFQ interior showed evidence of sparking and surface conditioning at the vane tips. No evidence of sparking could be seen at the VCR's. At this time the field amplitude and the frequency tuning control systems were made operational.

After full gradient was reached, an N^{+2} beam was accelerated and found to have the designed characteristics. [6]

During full warm-up the RFQ frequency without automatic frequency tuning changes by 70 KHz. This indicates the extreme sensitivity of the structure to dimensional changes. This must be taken into account in the loop tuner design.

The Q-value during repeated heat cycling gradually increased to 5950. This was attributed to the better seating of the RF contacts between surfaces.

A check of the axial and azimuthal field variations at high power, using the wall probes, showed no significant difference from low power measurements.

Conclusion

The tune-up of the LBL RFQ with VCR's has confirmed our model test results. The azimuthal field balance ensured by the strong coupling and the elimination of nearby dipole modes makes the field behavior very predictable. Axial field adjustment is reduced to end wall movement. An additional advantage is the ability to automatically tune the frequency during operation with one simple tuner in one quadrant. Full gradient tests confirmed proper operation of the VCR's with designed beam acceleration.

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