AN 8-METER-LONG COUPLED CAVITY RFQ LINAC*

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Abstract

A model has been constructed of an 8-m-long high energy (7 MeV) Radio-Frequency Quadrupole (RFQ) to prove the concept of a resonantly coupled RFQ. The model consists of four 2-m-long RFQ segments resonantly coupled together. A small gap (3 mm) between the vane tips, at the segment joints, provides capacitive coupling. This model is of a RFQ designed for a proposed Los Alamos Accelerator Performance Demonstration Facility (APDF). The RFQ, as designed, will operate cw at 350 MHz and accelerate a 100-mA beam of protons to 7 MeV.

Introduction

The resonantly coupled RFQ concept[1,2] greatly improves the longitudinal and transverse stability of the rf fields in long RFQs. The stability is improved mostly by moving the frequency of the nearest modes farther away from the fundamental RFQ quadrupole mode. Perturbations to the ideal shape of the RFQ mix the nearby modes with the RFQ quadrupole mode. The closer in frequency the nearby modes are the more they mix with the RFQ quadrupole mode for the same size perturbation. However, that is only part of the improvement in the longitudinal stability. The section on resonant coupling discusses longitudinal stability further. A big stopband in the dipole dispersion curves at the frequency of the RFQ quadrupole mode greatly improves the transverse stability. This means that regardless of how many segments are coupled together the frequency of the nearest dipole mode can get no closer than about 5 MHz.

This model is an extension of the Continuous Wave Deuteron Demonstrator (CWDD) RFQ cold model that was originally built to determine the feasibility of building the 4-m-long CWDD RFQ[3,4]. The model was extended to 8 m by building 4 more meters of the same type structure. The model has eight 1-m-long sections bolted together to form four 2-m-long segments. Three coupling plates, shown in Fig. 1, join the four segments to resonantly couple them. The coupling plates separate the segments and prevent the magnetic field from continuing from one segment to the next, thus minimizing the magnetic coupling. Any magnetic coupling would tend to cancel capacitive coupling required by this concept. The magnetic field lines flow around the end of the vanes, through the undercuts, into the adjacent quadrants instead of continuing in the same quadrant into the next segment. Each segment is a complete RFQ with vane undercuts and dipole stabilizers on each end. The coupling plates have a hole in the center, through which the ends of the vanes extend. Vanes from adjacent segments almost touch. This small gap between vane ends provides the capacitive coupling. The dipole stabilizers are mounted on the coupling plates the same way they are mounted on the end plates of the RFQ.

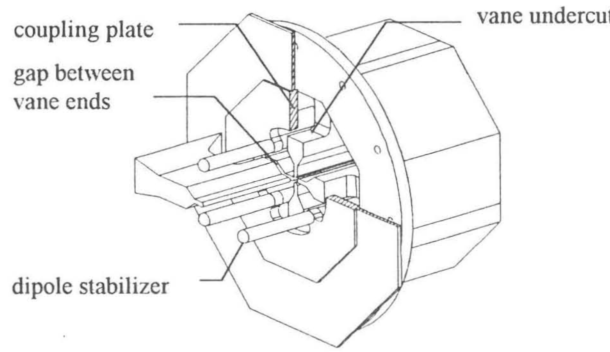

Figure 1 Cutaway drawing of the coupling plate between segments of the RFQ.

Resonant Coupling

When four identical 2-m-long RFQs are resonantly coupled together, each mode found in a 2-m-long RFQ splits into 4 modes in the coupled structure. These 4 modes can be described by the number of phase changes from segment to segment. There are 0, 1, 2, and 3 possible phase changes corresponding to the 4 modes. The capacitance between the ends of the vanes at the joints causes a splitting of the frequencies. For example, for the lowest frequency quadrupole mode the amplitude of the fields is constant down the length of the segment. For the mode with fields in each segment in phase, the frequency is unchanged by the capacitive coupling.

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For one change of phase, at the center joint the voltages of the vane ends are of opposite polarity across this joint. The additional stored energy in this mode at this point lowers the mode frequency. Two changes of phase lowers the frequency more yet. Three phase changes lowers the frequency the most.

A dispersion curve is a plot of the mode frequencies versus the phase change per segment or period. Figure 2 shows the dispersion curve for this model. The most important feature shown in this plot is the closed stopband at ϕ=0 for the RFQ operating mode, which is labeled the on the right hand side of Fig. 2. As a result of the closed stopband at ϕ=0, the dispersion curve has a nonzero slope and the mode has a nonzero group velocity. This means that the rf power flows down the RFQ easily. Hence, resonant coupling greatly improves the longitudinal stability.

The field strength in an RFQ is measured with the bead-perturbation technique.[5] In this technique a metal cylinder is suspended on a plastic tape and is drawn through the four quadrants near the RFQ's outer wall. The tape is wider than the cylinder. This allows supports to guide the edges of the tape every 2 m down the length of the RFQ. The bead perturbs the structure and changes the resonant frequency, depending on the electric and magnetic field strength. In RFQs with constant capacitance between the vane tips and constant cross sectional areas the electric field strength in the bore of the RFQ is directly proportional to the magnetic field strength. The technique actually measures the magnetic field strength because the magnetic field dominates the perturbation near the outer wall. The electric field strength near the beam axis is then inferred from the magnetic field strength.

Figure 3 shows the quadrupole mode and the admixture of the two dipole components of the field. The peaks in the field at the ends of the RFQ and at the joints located at 200, 400, and 600 cm are a result of the local field enhancement where the magnetic field flows around the end of the vanes and through the vane undercuts. The small bumps, roughly every 20 cm, are caused by local field enhancements around the tuners. Tuner adjustments achieve the correct frequency and establish the desired field profile. The wiggle in the fields at the 440-cm position is caused by the presence of the waveguide coupling iris. Previous work has shown that these variations in the magnetic field near the wall do not appear in the electric field near the beam axis.

In the resonantly coupled model the modes nearest the operating mode are at ±2.0 MHz with respect to the operating mode. Therefore, perturbations will tend to mix these modes with the operating mode equally but with opposite sign. These modes have similar characteristics. Thus, the effect of mixing one of these modes with the operating mode is canceled by the other mode. This cancellation is one way of describing the stabilization of the fields in a compensated resonantly-coupled system. However, in a RFQ with 2-m-long segments, the modes are different enough that there is only partial cancellation. The cancellation is complete only at the center of each segment.

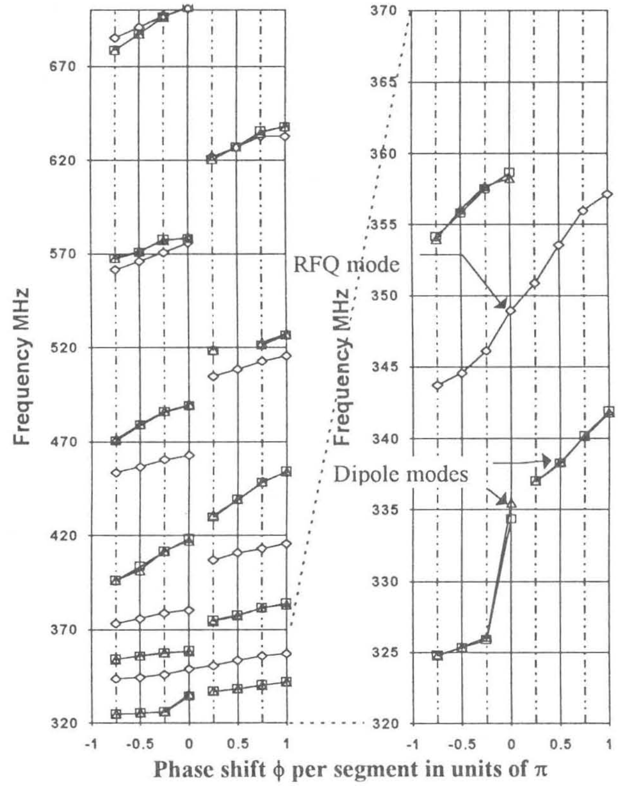

Figure 2 Dispersion curve of modes in resonant coupled RFQ. Note, chart on right has expanded scale. The diamonds indicate quadrupole modes while the squares and triangles indicate dipole modes.

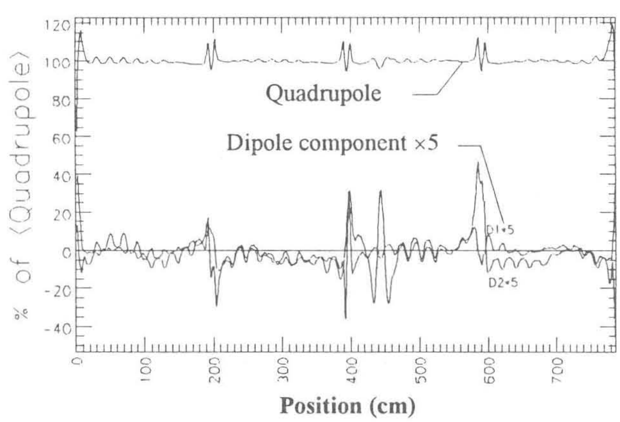

Figure 3 Bead-perturbation measurement of the 8-m-long coupled RFQ. The dipole components of the fields are shown multiplied by a factor of 5.

Sensitivity to Perturbations

The effect of perturbations was measured in the model RFQ. Figure 4 shows the percentage change in the fields from a 45-kHz perturbation. The perturbation consists of two slugs inserted into quadrants 2 and 3 at the 10-cm position. Each slug increases the frequency of the RFQ by 22.5 kHz. These perturbations mix both orientations of the dipole modes and quadrupole modes with the RFQ mode. The resulting changes in the field can be measured by taking the difference between two bead-perturbation measurements, one with the perturbations and one without the perturbations. Figure 4 shows the results for the worst-case position of the perturbation. Perturbations at other locations result in less effect on the fields.

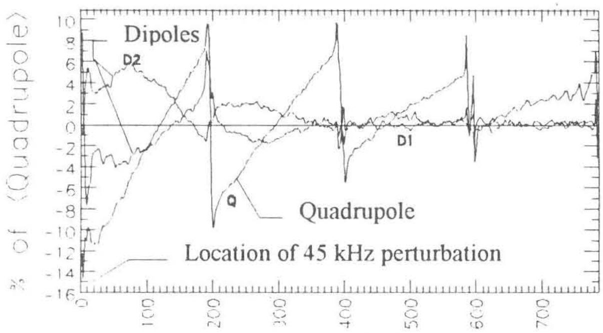

Figure 4 Difference expressed as a percentage of the average quadrupole strength between two bead-perturbation measurements showing the change in the fields caused by two 22.5 kHz perturbations, one each in quadrants 2 and 3.

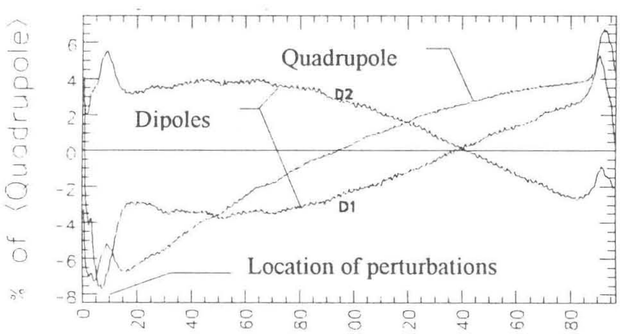

Figure 5 Difference between two bead-perturbation measurements in a 2-m long RFQ showing the change in the fields caused by two 90 kHz perturbations, one each in quadrants 2 and 3.

The perturbation affects the magnitude of the quadrupole fields the most. The dipole content is large only in the segment containing the perturbations. The quadrupole field develops a saw tooth modulation because of the perturbation, but the field amplitude is nearly unchanged in the center of each segment. A comparison of the first segment in Fig. 4 with Fig. 5 shows that this same physical perturbation in a 2-m-long RFQ causes a field tilt of about two thirds the magnitude of the tilt in the coupled RFQ. This 2-m-long RFQ is the first segment of the 8-m-long coupled RFQ uncoupled from the other three segments. For the same perturbation the quadrupole field tilts from −12% to +8% in the first segment of the resonantly coupled RFQ, while in the separated first segment the tilt is from −8% to +4%. The effect of the perturbation on the dipole modes is almost identical in the two cases. The same physical perturbation in the 2-m-long RFQ causes four times the frequency change because the longer RFQ has four times the stored energy as the 2-m-long RFQ. The displaced stored energy at the perturbation is a larger fraction of the cavity stored energy in the shorter structure.

Conclusions

The 8-m-long coupled RFQ is nearly as stable as a 2-m-long RFQ. The same physical perturbation in the 8-m-long RFQ causes errors in the amplitude of the quadrupole field only 50% greater than in a 2-m-long RFQ. Moreover, the same perturbation causes the same size dipole field errors in the 2-m-long RFQ as the 8-m-long resonantly coupled RFQ. The RFQ can be tuned in a straightforward manner with the use of the code RFQTUNE. This code uses data from the bead perturbation measurements and calculates tuner movements that reduce the field errors. About 5 or 6 iterations with this code reduces the field errors to less than 2 % in this RFQ.

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