Segmented Resonantly Coupled Radio-Frequency Quadrupole (RFQ)*

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Abstract

In this experiment a 4-m-long radio-frequency quadruple (RFQ) resonating at 348 MHz was split into two 2-m-long RFQs. The two RFQs were then rejoined with resonant coupling[1] to form a segmented 4-m-long RFQ. This coupling improved both the longitudinal and transverse stability of the 4-m-long RFQ. The frequencies of all the modes near the RFQ mode and the sensitivity of the RFQ mode to perturbations were measured. This paper presents the results of these measurements and the compares them with measurements of the original 4-m-long RFQ. Both the original RFQ and the resonant-coupled RFQ use four rods (dipole stabilizers) on the end plates to adjust the frequencies of the dipole modes. Slug tuners distributed along its outer walls tune the RFQ. Modifications to the program RFQTUNE[2] allow its use for tuning the segmented RFQs. This paper also describes the tuning procedure.

INTRODUCTION

The Continuous Wave Deuteron Demonstrator (CWDD) RFQ cold model was originally built to determine the feasibility of building the 4-m-long CWDD RFQ.[3] The model has four 1-m-long sections that are bolted together to form one continuous structure. The modifications for resonant coupling consisted of (1) machining undercuts on the end of the vanes at the center joint and (2) joining the resulting two 2-m-long segments with a coupling plate (see Figure 1) that separates the two segments. Each segment is a complete RFQ with vane undercuts and dipole stabilizers on each end.

Although each segment can be tuned to the correct frequency and field distribution before they are joined, in this experiment the two segments were joined before tuning. The coupling plate has a large center hole through which the vane ends, above the undercut, partially extend. When the two segments are joined, the vane tips almost touch. The distance between the vane tips is adjusted to provide the correct amount of capacitance between the two segments. The coupling plate has dipole stabilizers on both sides.

Figure 1 shows the details of the resonant-coupling joint in the 8-m-long RFQ designed for the Accelerator for the Production of Tritium (APT) project. The coupling plate has stabilizer rods mounted on both sides of it that are identical to the stabilizer rods at the ends of the RFQ. These rods adjust the frequency of the dipole modes to minimize the mixing of dipole modes with the operating frequency. The APT RFQ requires cooling channels for cw operation. Some of the cooling channels are shown in Figure 1.

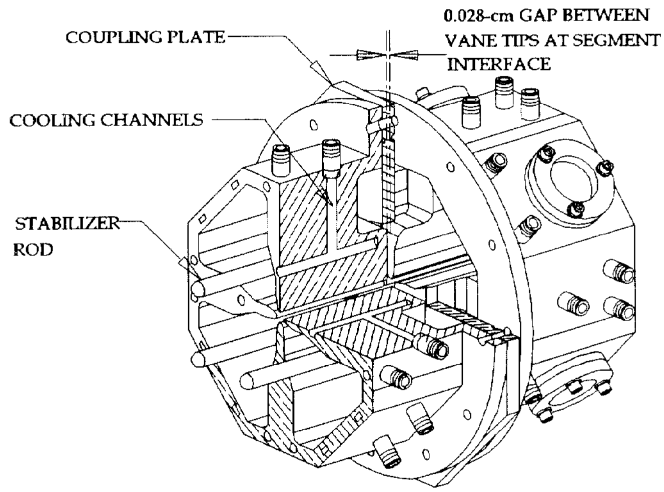

Figure 1 Details of the joint between segments

RESONANT COUPLING

Resonant coupling in a segmented RFQ provides longitudinal field stabilization. In this RFQ design resonant coupling also provides a stop band in the dipole mode dispersion curve around the operating frequency of the RFQ. This stop band improves the transverse stability of the RFQ by eliminating the dipole modes close to the frequency of the operating mode.

Figure 2 shows the modes in the 4-m-long CWDD RFQ cold model without segments. The modes labeled "1-3 dipole" are dipole modes with fields that are predominantly in the quadrants labeled 1 and 3; the modes labeled "2-4 dipole" have fields in the quadrants labeled 2 and 4. The quadrants are labeled clockwise from 1 to 4 with the lower left quadrant labeled 1, when viewed from the low energy end of the RFQ. Figure 2 also shows where the estimated frequencies of the additional modes that are found in an 8-m-long RFQ would lie if its dispersion curves were superimposed on those of the 4-m-long CWDD RFQ cold model. Figure 3 shows the dispersion curves of this same RFQ after it was modified with resonant coupling. This Figure also shows the estimated frequencies of additional modes labeled "8-m RFQ," that occur in the 8-m-long RFQ with resonant coupling. There are twice as many modes in a given frequency range in the 8-m-long RFQ as in the 4-m-

*Work supported by the U. S. Department of Energy, Office of Defense.

long RFQ. The mode numbers shown at the bottom of Figure 2 are for the 4-m-long RFQ. The two orientations of the dipole modes are degenerate in a perfectly symmetric RFQ and the dipole dispersion curves lie on top of each other in both figures.

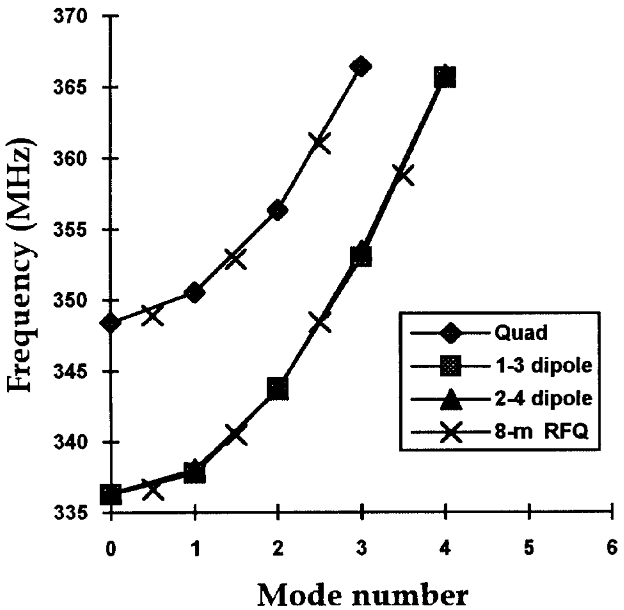

Figure 2 **Modes found in CWDD RFQ cold model.**

The operating mode is the quadrupole mode near 348 MHz in these figures. In Figure 2 the operating mode is the quadrupole mode number 0. In Figure 3 the operating mode is the quadrupole mode with 0 phase shift per segment. Note that the mode nearest the operating mode in both cases is a quadrupole mode. In the CWDD cold model the nearest mode is the quadrupole mode number 1 which is 2.1 MHz higher than the operating mode. Doubling this RFQ in length would make the nearest quadrupole mode only 0.5 MHz higher than the operating mode. This slight difference would probably make the 8-m-long RFQ difficult if not impossible to tune. The dipole mode could be moved away from the quadrupole mode in an 8-m-long RFQ but not by more than 2 MHz.

In the resonantly coupled CWDD RFQ cold model the modes nearest the operating mode are at ±4.45 MHz. In the APT RFQ the nearest modes are at ±2.2 MHz. Therefore, perturbations will tend to mix these modes equally but with opposite sign with the operating mode. These modes will 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. In places where the modes actually add, the amplitude of the modes is small.

In a resonantly coupled RFQ of this type the nearest dipole is about 8 MHz from the operating mode. This separation of the dipole modes from the operating mode is a factor-of-two improvement over the CWDD RFQ. This separation of modes is also better than the mode separation in the 2.2 m long Super conducting Super Collider (SSC) RFQ[4] which has dipole modes at ±6.4 MHz from the operating mode.

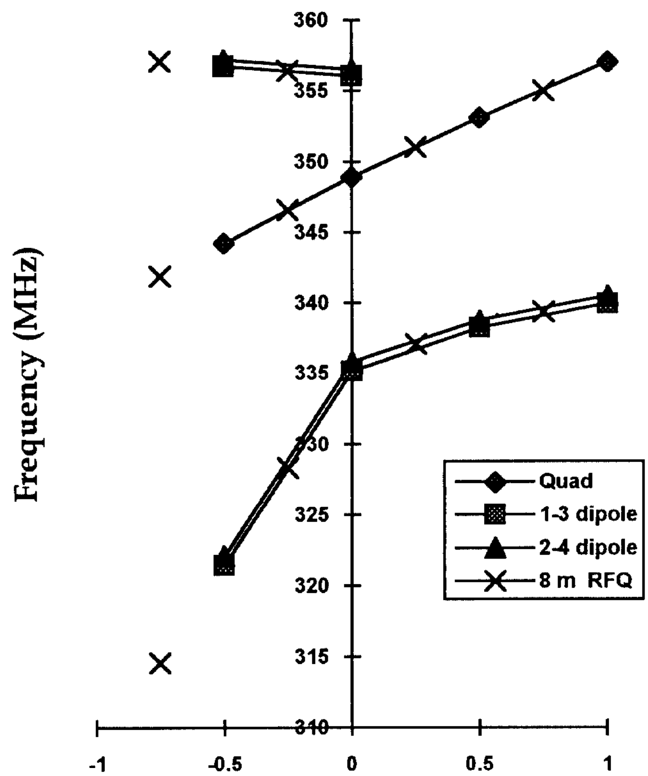

Figure 3 **Dispersion curves of the modes found the in resonantly coupled CWDD RFQ cold model.**

SENSITIVITY TO PERTURBATIONS

The effect of perturbations was measured in the CWDD RFQ cold model before (Figure 4) and after the RFQ was modified with resonant coupling (Figure 5). Figure 4 shows the percentage change in the fields from a 25-kHz perturbation. Figure 5 shows the percentage change in the fields from a 100-kHz perturbation that consisted of two 50-kHz perturbations.

Note that the vertical scale in Figure 4 is ±3%, while in Figure 5 it is ±6%. The perturbation in the resonantly coupled RFQ cavity is four times greater than that in the continuous RFQ's cavity. These perturbations distort the quadrupole fields differently. However, the maximum change in the coupled RFQ cavity is only twice as great for a four times greater perturbation. In addition, this comparison also shows that the average field in the two halves of the resonantly coupled RFQ is almost unchanged, whereas the average field in the first two meters in the CWDD RFQ is about 2% less than in the second two meters.

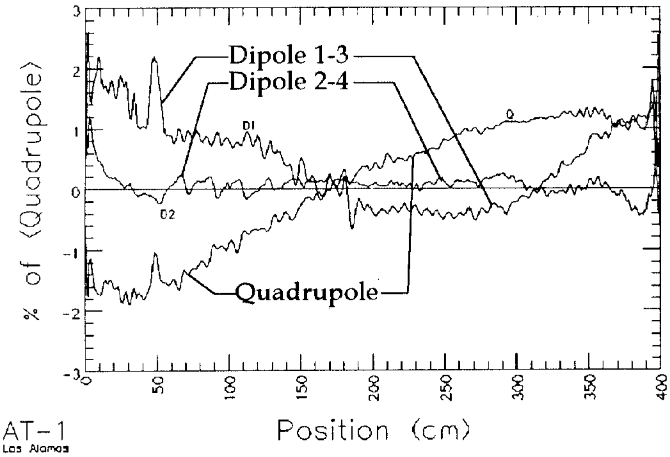

Figure 4 Percent change in fields in CWDD RFQ (25-kHz perturbation).

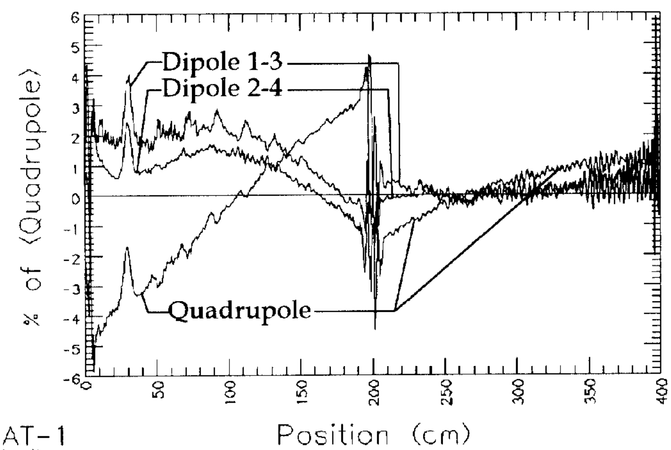

Figure 5 Percent change in fields in resonant coupled RFQ (100 kHz perturbation).

In the resonantly coupled CWDD RFQ, the effect of the perturbations on the dipole fields appears to be localized to the segment containing the perturbation. As shown by the perturbation measurements, which were performed about every 50 cm throughout the first segment, this localization of the perturbation effects held true for all measured locations.

TUNING

The field strength in an RFQ is measured with the bead-perturbation technique.[5] In this technique a metal bead is suspended on a nylon line and is drawn through the four quadrants near the RFQ's outer wall. 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 section 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 desired magnetic field profile as well as the bead-perturbation data is input to the program RFQTUNE. The measured frequency of all the nearby modes must also be input to RFQTUNE so that it can calculate the shape of each mode and the effect of a perturbation at each slug tuner. Then, RFQTUNE calculates the position of each tuner to adjust the fields in the RFQ to the desired profile. The program has tuned the following RFQs: CWDD, the Ground Test Accelerator,[6] SSC, and the 4-m-long resonantly coupled CWDD cold model. The CWDD RFQ and the 4-m-long CWDD cold model each have 80 tuners.

Final rf tuning includes the following:

1. Machine the undercuts on the vane ends to achieve the desired shape of the fields at the end of the vanes.
2. Machine the end of the vanes at the segment joints to adjust the resonant coupling. This process adjusts the frequency of the nearby dipole modes to equalize the spacing of the dipole modes.
3. Machine the dipole stabilizers to the proper lengths to establish the optimum frequencies of the dipole modes.
4. Machine the slug tuner lengths to achieve the required frequency, the required quadrupole field profile, and the minimum dipole field.

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