AZIMUTHAL STABILIZATION OF THE RADIO-FREQUENCY QUADRUPOLE WITH LOOP-COUPLED TEM LINES*

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Abstract

Azimuthal stabilization studies were performed on a RFQ-cold model, a low-power test cavity. The cold model was a 2.64-meter long aluminum structure, constructed in eight parts azimuthally, with four vane pieces and four skirt pieces, and two sections longitudinally. The structure was originally designed with vane coupling rings (VCRs) to resonate at 425 MHz. Without VCRs the structure resonates in the quadrupole zero mode at 436 MHz. Loop-coupled, lambda (2π) resonant coaxial transmission lines were installed, as shown in Fig. 1. This concept was initially proposed at Los Alamos.[1] The coupling loops are oriented such that opposite quadrant quadrupole fields induce equal but opposite currents leaving the stabilizer unexcited. Any imbalance in fields between the two quadrants (referred to as dipole components or simply dipoles) will induce a net current. Thus, the stabilizer will not couple to the quadrupole mode, but to the dipole mode.

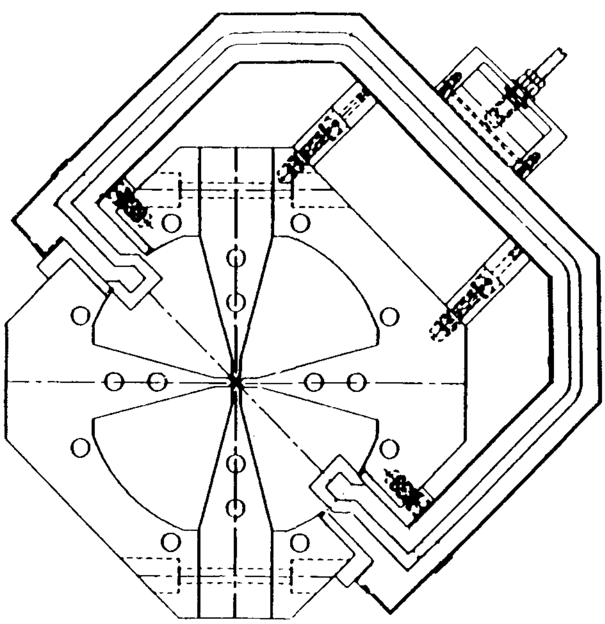

Fig. 1. Azimuthal Resonant Stabilizers.

Stabilizer Design

The stabilizers are nominally 80Ω coax, fabricated from 1-inch folded copper box for the outer conductor and 1/4-inch diameter magnet wire inner conductor.

The resonant coaxial lines are designed to be lower in frequency than the quadrupole "0" mode in the RFQ. They can be tuned higher by an inductive (slug) tuner in the H-field maximum (center) of the coax. A typical range of frequencies is 430 MHz to 440 MHz, with a Q (RFQ cavity shorted) of 900, measured at the quadrupole frequency. The frequencies of the stabilizers are determined by shorting the RFQ with approximately 40 rods inserted approximately 10/quadrant and shorting the vane tips. This moves the RFQ frequency far from the stabilizer frequency, effectively decoupling the two, and a drive and pickup loop in the stabilizer is then used to determine the resonant frequency.

In tests to date, there are eight stabilizers occupying eight longitudinal positions on the RFQ-four in each plane and alternating between orthogonal positions.

The ARSs couple to the dipole fields, and the "dipole" in the RFQ and the eight stabilizers act as a two-cavity-coupled system. Figure 2 shows the mode spectra with and without stabilizers. The ARSs have coupled to the dipole at 430 MHz, and split it into two modes, one below and one above the quadrupole. The new dipole/ARS system resonates at 425 MHz and 440 MHz, and no dipole components of the field exist at the RFQ 0-mode frequency.

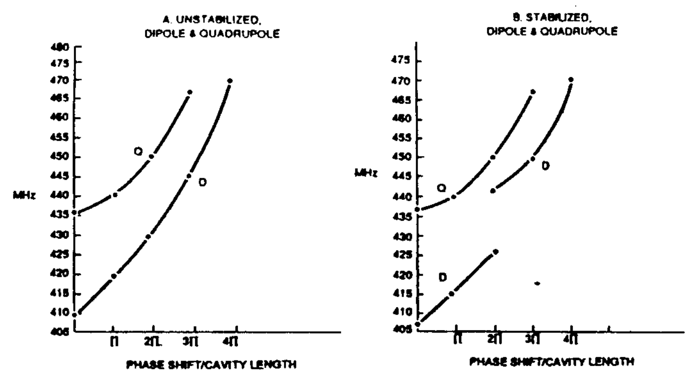

Fig. 2. Mode spectra.

Experimental Results

Relative field measurements were performed using the bead perturbation technique, with a computer analyzed beadpull test set. The cold model was tested with stabilizers in several different configurations; without vane undercuts, with vane undercuts, and with slug tuners inserted halfway for inducing field asymmetries (dipole fields).

Figures 3 and 4 show the stabilized and unstabilized quadrupole and dipole fields before vane undercuts. Quadrupole field is defined here as

$$Q = \frac{F_1 + F_2 + F_3 + F_4}{4}$$

$$DIPOLE\ 1 = \frac{F_1 - F_3}{2} \qquad DIPOLE\ 2 = \frac{F_2 - F_4}{2}$$

Dipole 2 has been reduced from 30% to 2%. (No attempt was made to reduce the high-energy end dipole at the 220 to 260 cm region, which is an artifact of the absence of undercuts.) The bumps are an artifact of the measurement, where the bead is drawn down the cavity near the wall and goes past the tuning slugs and stabilizer coupling loops. The magnetic field is compressed in the region near the slugs and loops and appears as a spike in the curve. This effect does not affect the electric fields on axis.

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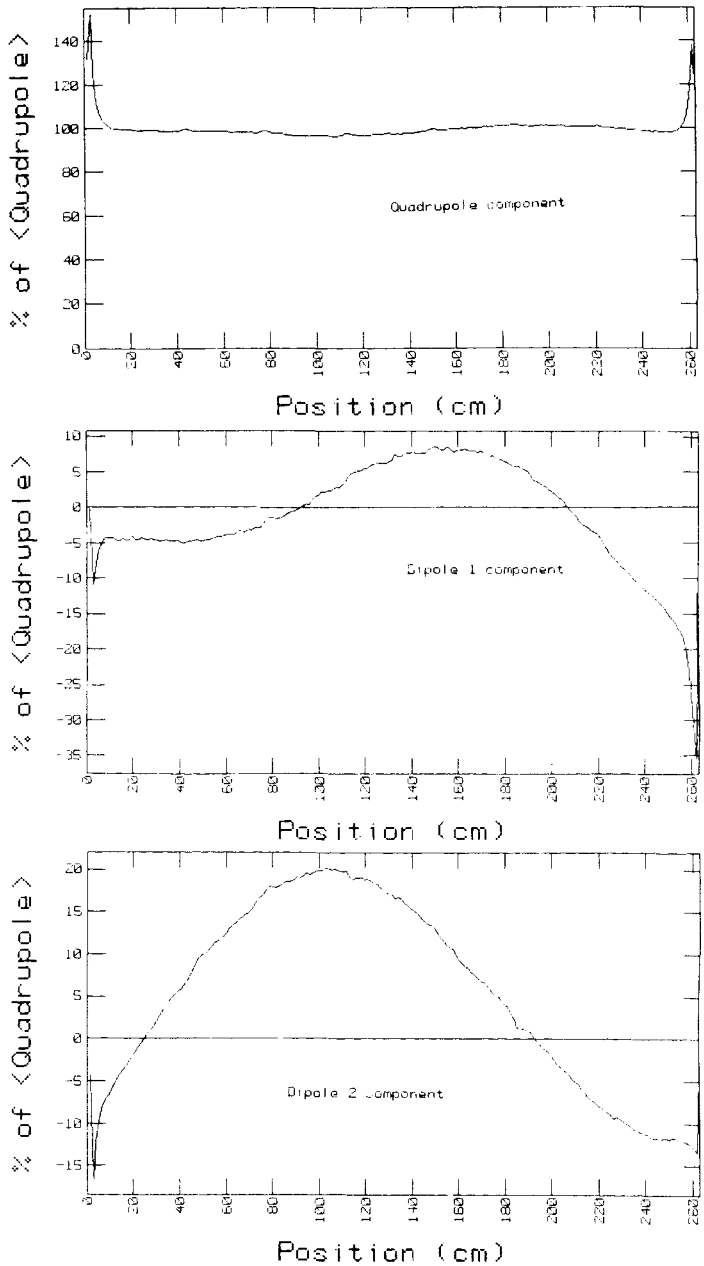

Fig. 3. Unstabilized, no undercuts.

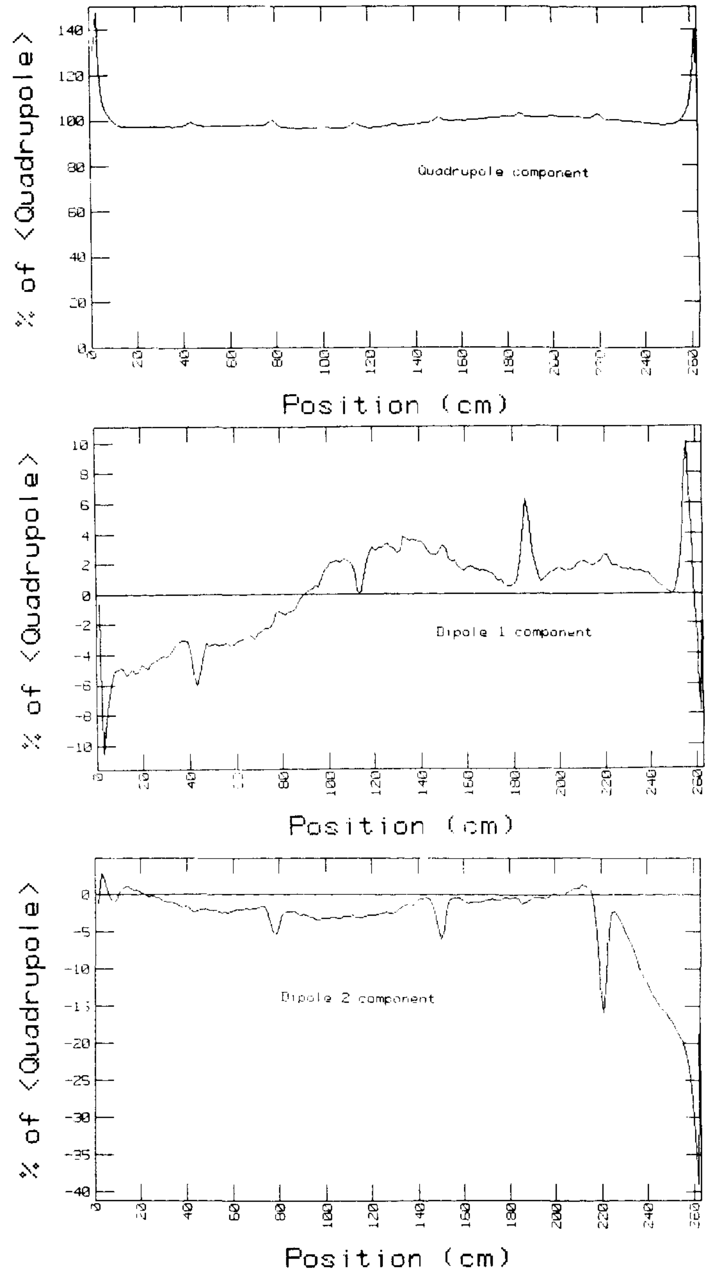

Fig. 4. Stabilized, no undercuts.

Figure 5 and 6 show the quadrupole and dipole fields after the undercuts were added. The unstabilized dipole has been reduced to approximately 10%. This is the result of two effects: first the end tuning capacitors are removed, which had tended to introduce end region asymmetries; and second the dipole mode spectrum has shifted downward, with the two nearest dipoles evenly spaced about the quadrupole zero mode, an inherently more stable configuration. This last effect is serendipitous, a function of the length of the RFQ, which is ordinarily not a free parameter to choose.

In order to perform stability measurements, all of the tuning slugs were inserted to their mid-position. This enables the introduction of a dipole field component by moving, for example, quadrant 1 slugs out producing -150 kHz local frequency shift and quadrant 3 slugs in inducing +150 kHz shift, with zero net frequency change. Figure 7 shows the unstabilized and stabilized response of the perturbations. The stabilized structure has clearly succeeded in minimizing the effect of the perturbations. It should be noted that the perturbation used here, of -150 kHz Q2 and +150 kHz Q4, is much larger and more localized than anything the RFQ would ordinarily encounter. Dipole 1 is unaffected by the perturbations in quadrants 2 and 4 (bottom plots)

Effect on Quadrupole Mode

The advantage of azimuthal resonant stabilizers vs VCRs is that they do not affect the quadrupole fields. The resonant frequency of the RFQ has been measured before and after stabilizer installation. The frequency changed from approximately 436.200 MHz to 436.00 MHz, compared to an 11-MHz frequency shift with VCRs. This simplifies the design of the RFQ considerably, since the resonant frequency of the cavity is nearly the same as that based on the SUPERFISH design using the same cross section. In addition, since the frequency of the quadrupole mode is not affected locally (or globally) by the stabilizers, the quadrupole mode is flat to within 1%. This is not the case when VCRs are used, which locally load the RFQ quadrupole mode. Since. one is forced to operate at the loaded cutoff frequency in order to obtain flat fields end to end,

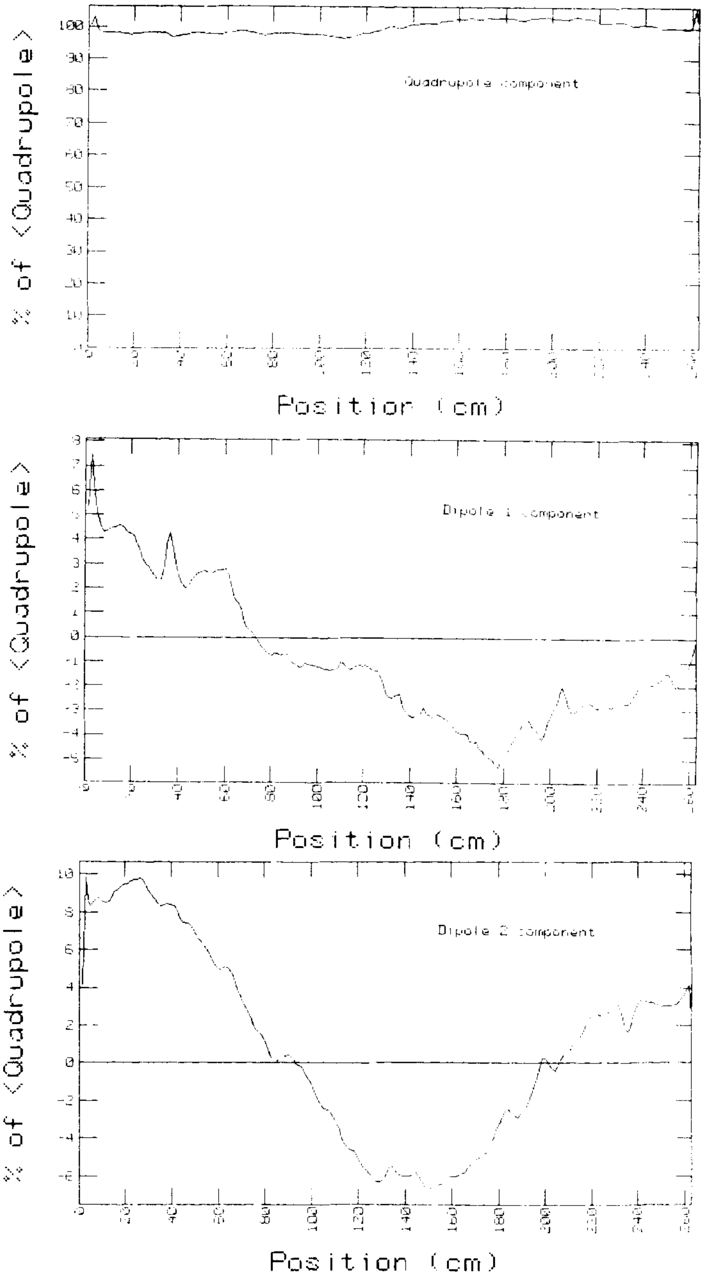

Fig. 5. Unstabilized, w/undercuts.

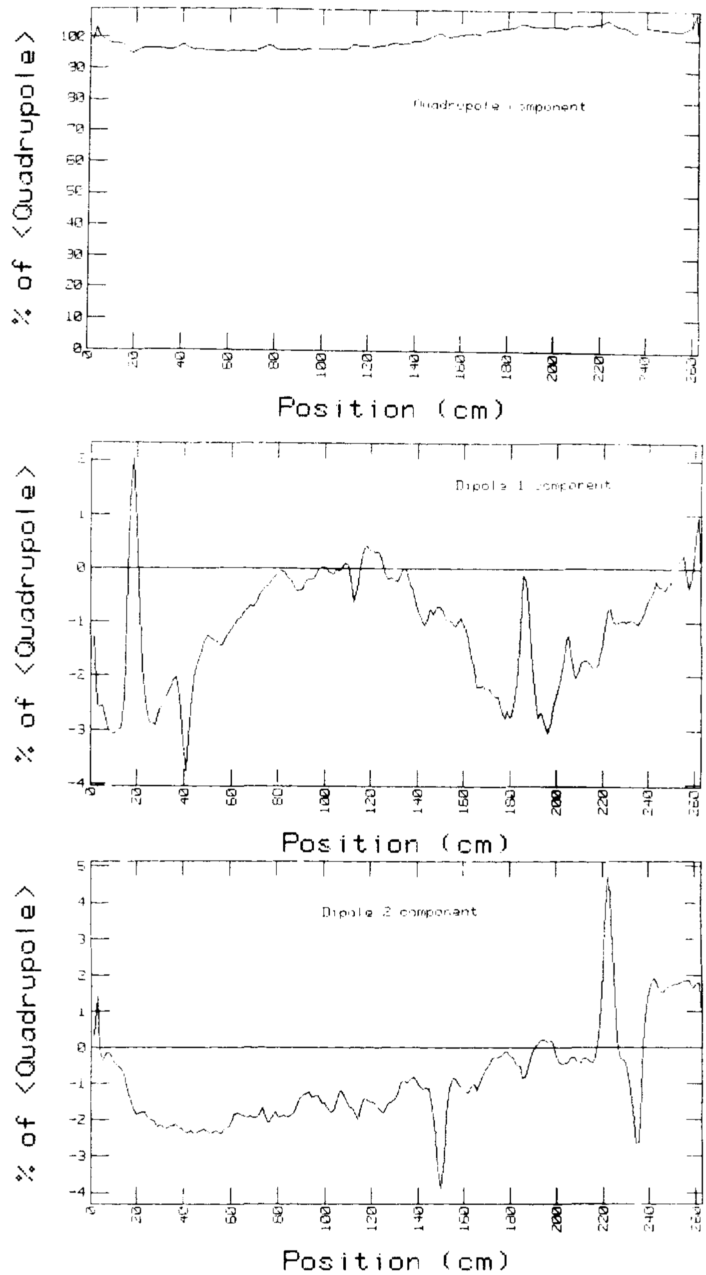

Fig. 6. Stabilized, w/undercuts.

the RFQ is operated below cutoff between VCRs, and the quadrupole O mode is evanescent and the field droops. Figure 8 shows the cold model quadrupole field plot with eight VCRs installed.

Stored Energy Measurements: Power Dissipated

The power dissipated in the stabilizers was measured making use of the principle that U/f is an adiabatic invariant in rf cavities.

$U/f = \text{constant} \qquad \therefore \lambda dU + U d\lambda = 0$

$dU/U = df/f$

The perturbation measurements, using the beadpull system, measures df/f. Two beadpulls are performed, one with, one without stabilizers, and the difference in total stored energy measured in kHz taken. This difference, divided by the original stored energy $U_{unstabilized}$ (kHz), represents the ratio of stored energy in the stabilizers relative to the RFQ. The total stored energy of the RFQ is calculated by SUPERFISH, so that the stored energy of the stabilizers can be calculated. The power dissipated can then be determined from the relation $P = \omega U/Q$, after measuring the Q of the stabilizers.

Another method that can be used is derived from the relation $Q = \omega U/P$. the total Q of the coupled system is given by

$$Q_{total} = \frac{\omega U_{total}}{P_{total}} = \frac{\omega\left(U_1 + U_2\right)}{P_1 + P_2},$$

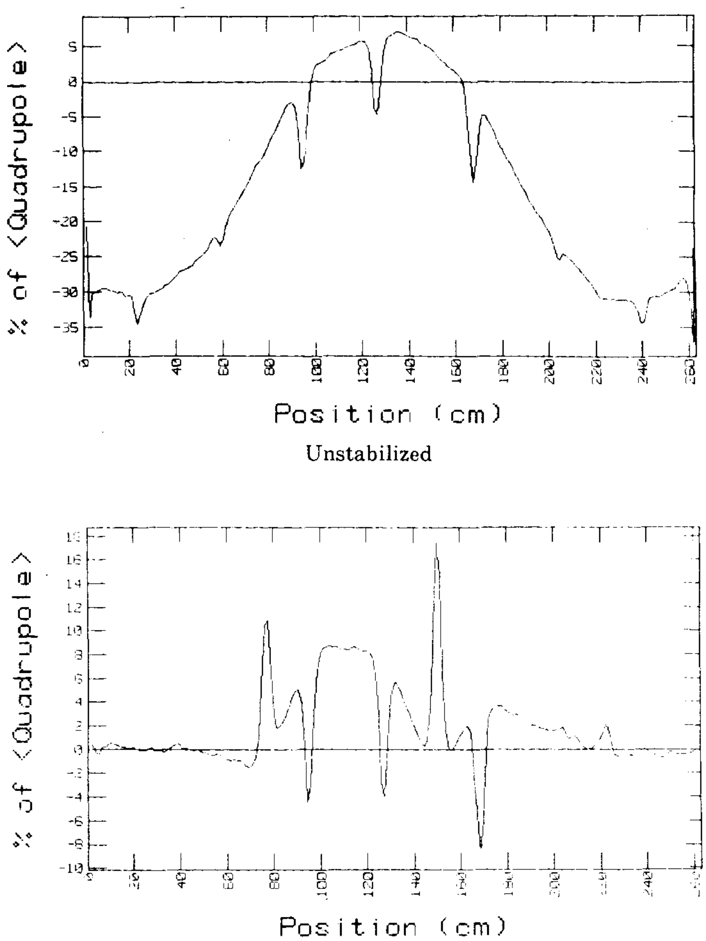

Fig. 7. Dipole perturbation measurements.

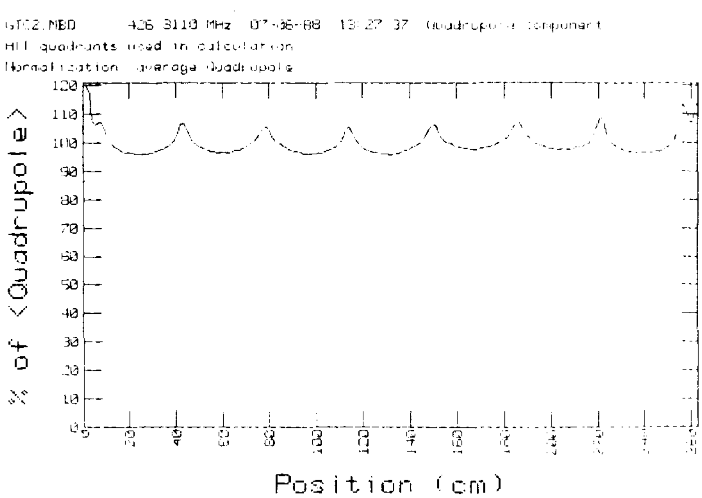

Fig. 8. Quadrupole field with VCRs.

where U_1, P_1 are the stored energy and power dissipated in the RFQ, respectively, and U_2, P_2 associated with the stabilizers. Since $P=\omega U/Q$, we can rewrite the above as

$$U_2 = U_1 \frac{\left(\frac{Q_{tot}}{Q_1} - 1\right)}{\left(1 - \frac{Q_{tot}}{Q_2}\right)}$$

Both methods are subject to relatively large errors, the first due to trying to measure differences in stored energy of a few percent, with accuracies in each measurements of approximately 1/2 percent. This leads to measurement errors of 0.7%. The second results from having to measure Q with accuracies of better than 1% for the case of the cold model.

The difference in stored energy before and after installation of stabilizers was measured by beadpulls to be 0.7%. This difference of 0.7% represents the percentage of total stored energy in the stabilizers. The SUPERFISH computed RFQ stored energy is 0.1914 J/m, times the 2.64 meters of cavity = 0.505 J, so the stored energy in the stabilizers is 0.505(.007) = 0.00354 J. The average Q of the stabilizers if 925. This was the measured Q, with the ARS installed on the RFQ and the RFQ detuned. So this represents (0.00354 J/925) (2Π 435 X 10^6 rad/sec) = 10.2 kW, distributed (unevenly) over the eight stabilizers. The difference in total stored energy between the unstabilized structure and the stabilized structure with a +150 kHz perturbation in quadrant 2 and -150 kHz in quadrant 4 was measured. Similarly, the difference for -150 kHz perturbation in quadrant 2 and +150 kHz in quadrant 4 was also examined. The stored energy in the stabilizers has decreased from 0.7% to 0.5% for the first perturbation and increased from 0.7% to 2% for the second. The first perturbation has acted to correct the original dipole inherent in the RFQ and therefore reduced the stabilizer excitation. The second perturbation has acted to increase the original dipole and shows up as an increase in the excitation of the stabilizers. The amount of dipole field levels in the stabilized structure did not change appreciably. This points out the advantage of being able to tune the original dipole to zero prior to stabilizing the structure toreduce the power dissipation in the stabilizers. These measurements were performed on the cold model with vane undercuts, when there had been approximately 10% dipoles before stabilization. The power dissipated in the ARSs is determined by the stored energy, which can be reduced by slug tuneradjustment, and by improving the Q of the stabilizers. A factor of 1-1/2 to 2 in stabilizer Q improvement should be relativelysimple.The Q method of determining stored energy resulted in 1.9% of the stored energy in the stabilizers; however, because the difference in Q_{tot} and Q_{RFQ} was small, the measurement is not accurate. The Q method should be more useful with an all copper RFQ and stabilizers, where the difference in Q_{RFQ} and Q_{TOT} is more significant and could be measured easily.

Reference

1. A. Shempp, "Field Stabilization of RFQ Structures", 1984 Linac Conference, Lufthansa-Schulungs Zentrum Seeheim, F.R.G., May 7-11, 1984 p. 338.