A Radio-Frequency Quadrupole Accelerator Longitudinal Field Stabilizer*

E. R. Gray, G. Spalek, and A. H. Shapiro
MS-H817, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Abstract

The fields in a 600-MHz model of a radio-frequency quadrupole (RFQ) accelerator have been longitudinally stabilized over 86% of its length. The stabilizing elements consist of four external transverse electromagnetic (TEM) lines. Each line is coupled to the RFQ by two magnetic loops attached to voltage maxima of the TEM line. These resonant lines stabilize the RFQ fields by providing an alternate longitudinal power flow path in the RFQ. Stabilization depends on the TEM line Q and the TEM line RFQ coupling. Each stabilizer coupling-loop location in the RFQ needs to be fully azimuthally stabilized. Substantial coupling between stabilizer elements destroys stabilization.

Introduction

Radio-frequency quadrupole (RFQ) structures are operated in the mode at or near the cutoff frequency where the fields are longitudinally uniform. The field uniformity of this mode is very sensitive to mechanical tolerance errors, with the sensitivity increasing as the square of the structure length. Resonant field stabilizing devices can decrease this sensitivity (and, thus, the field non-uniformities caused by mechanical tolerance errors) by improving the longitudinal power transmission of the RFQ. This paper gives the results of tests made on one type of resonant device used to stabilize the fields in a low-power RFQ model operating at 600 MHz whose length was 3.5 wavelengths. Other stabilizing schemes have been proposed by Schempp.[1,2] Motivation for stabilizers includes hopes of improved continuous-duty RFQs.

Two-Loop Stabilizer

Figure 1 shows an exploded view of an RFQ with a two-loop external stabilizer mounted on one quadrant. Each stabilizer is a resonant transverse electromagnetic (TEM) line. The RFQ is coupled by magnetic loops to the voltage maxima of the TEM line. Figure 2 shows the stabilizer arrangement tested on a 600-MHz RFQ with the voltage pattern dotted in the upper ones. For mechanical convenience, one of the stabilizers had loops separated by one wavelength (λ) instead of $\lambda/2$. In all cases, the loops were oriented so that the TEM line was not excited if the fields in the RFQ (at the loop positions) were equal. The stabilizers were coarse-tuned by adjusting the lengths of the $\lambda/4$ stubs and fine-tuned by micrometer-adjusted loading capacitors at the voltage maxima of the TEM lines.

Testing Methods

Field sensitivity to frequency perturbations (i.e., mechanical tolerance errors) is measured by a field "tilt sensitivity." The measurement consists of putting an end plate frequency perturbation (in this case, capacitance) at one end of the RFQ to shift the structure resonant frequency. The other end is then perturbed in the opposite direction for a zero, net frequency shift. This operation produces a linear end-to-end tilt in the field. Two fields

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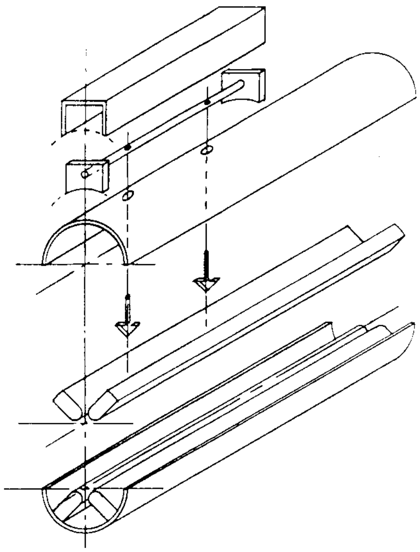

Fig. 1. Exploded view of RFQ with stabilizer.

tilted in opposite directions are measured by standard bead-perturbation methods and subtracted to produce a field end-to-end tilt sensitivity. Quadrupole and dipole field components are calculated from field measurements in each RFQ quadrant. A plot of an end-to-end tilt sensitivity curve without stabilization is then a straight line sloped down from left to right measured in percent of field change per megahertz of perturbation. A stabilizer will maintain the same field values at its coupling loops, thus putting a zero-slope section between coupling loops in the tilt sensitivity plot.

With multiple stabilizers, a zero-slope, end-to-end tilt sensitivity does not prove that each stabilizer is stabilizing locally independently of the others. (This will be demonstrated by example.) To test for independent stabilization, a frequency perturbation is introduced into the central part of the RFQ (a "side" perturbation). End perturbations are then used to return the frequency to its original value. Unperturbed fields are subtracted from the perturbed fields; the difference gives a "side-perturbation tilt sensitivity." For an unstabilized RFQ, this tilt sensitivity is V-shaped. A set of stabilizing devices must show stabilizing action (i.e., introduce zero-slope regions into the tilt sensitivity) for both end-to-end field tilts and side-perturbation field tilts.

The Stabilized RFQ

The RFQ tested was fully azimuthally stabilized by two sets of vane coupling rings at each stabilizer loop position. Stabilizers were placed in opposite quadrants for a total of four two-loop stabilizers as shown in Fig. 2. This geometry gave continuous stabilization over most of the RFQ length. The longitudinal stabilizers were tuned to the proper frequency by using the tilt sensitivity tests as a guide. When the stabilizers were tuned correctly, the tilt sensitivity plots had zero slope in the stabilizer regions.

Figures 3 and 4 show examples of the side-perturbation tilt sensitivity for the unstabilized and stabilized RFQ, respectively. The RFQ is stabilized over most of its length. The large spikes at the loop positions are an artifact of the bead pulls in the quadrants as the bead moves close to the loops. Vertical offsets of the zero-

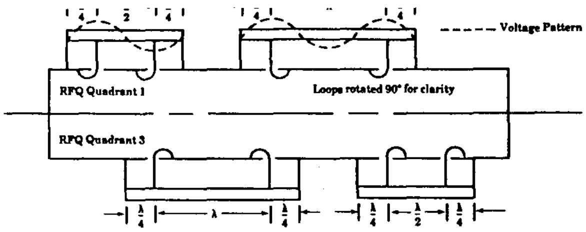

Fig. 2. Stabilizer schematic.

slope sections from the horizontal axis can be a measure of the stored energy in the stabilizers.

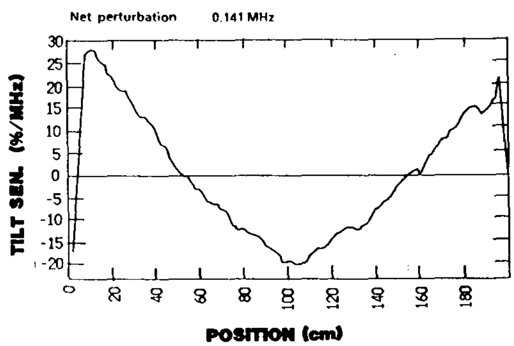

Fig. 3. Unstabilized side-perturbation tilt sensitivity.

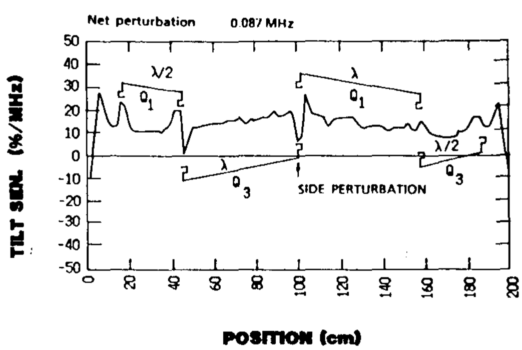

Fig. 4. Stabilized side-perturbation tilt sensitivity.

Stabilizer Q, Coupling, and Frequency

For stabilization, the stabilizers have to be tuned to the proper frequency. The dependence of the stabilizer tuning (for proper stabilization) on the coupling between the RFQ and the stabilizer was studied for a single stabilizer by measuring the difference between the RFQ frequency and the stabilizer mode frequency for different coupling-loop sizes. The strength of the coupling is a combination of loop area and the frequency spacing between the RFQ and stabilizer and determines the stored energy in the stabilizer and, therefore, the strength of the stabilizer action on the RFQ. Larger loop area requires larger frequency spacing for constant stabilizing action.

These measurements also showed that for a given stabilizer Q, no stabilization was obtained unless the RFQ-to-stabilizer coupling was increased above some critical value. Quantitative data were difficult to obtain. Qualitatively, as the stabilizer Q was decreased, its coupling to the RFQ had to be increased. The stabilizer action was weaker for lower Q.

Stabilizer Stored Energy

A longitudinal stabilizer is excited (i.e., has stored energy) when counteracting a field tilt caused by a given frequency perturbation at the RFQ ends. This stored energy can be used to calculate the stabilizer power dissipation once its Q is known.

Perturbation measurements were used to measure the stabilizer stored energy. Results showed that the smaller the RFQ-stabilizer coupling, the larger the stabilizer stored energy for a given field tilt. One such measurement made by using one stabilizer with loops spaced by $\lambda/2$ gave 0.3% of total energy in the stabilizer for 100-kHz tilt and a 2% coupling. The coupling value is the minimum mode-frequency spacing divided by the mode frequency.

Effect of Stabilizer-to-Stabilizer Coupling

The effect of stabilizer-to-stabilizer coupling was studied by placing two stabilizers in the same quadrant and separating them at their ends by a conducting plate that serves as their terminating shorts. A hole machined in the termination short coupled the stabilizers. With 0.2% coupling between the stabilizers, the end-to-end and side-perturbation tilt sensitivities showed that the stabilizers were working independently. The same two measurements are shown in Figs. 5 and 6, respectively, with the coupling increased to 0.3%. In Fig. 5, the slope change at the two stabilizers shows stabilizing action, and the positive slope indicates a slight overstabilization. However, Fig. 6 shows that one of the stabilizers does not stabilize at all. Further tuning does not succeed in getting both to work. This illustrates the fact that large stabilizer-to-stabilizer coupling destroys stabilization and points out the danger of using the end-to-end tilt sensitivity alone to test stabilizers.

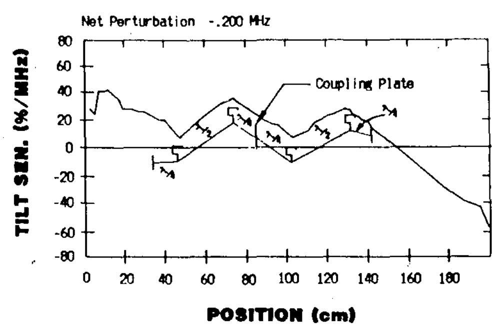

Fig. 5. End-to-end tilt of 0.3% coupling.

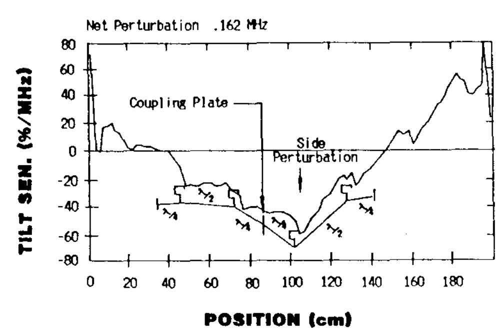

Fig. 6. Side-perturbation tilt of 0.3% coupling.

Because stabilizer-to-stabilizer coupling destroys stabilization, an RFQ cannot be stabilized by putting all longitudinal stabilizers close to each other in one RFQ quadrant. In fact, even if they are placed in opposite quadrants, as in these tests, stabilization can be destroyed by making the stabilizer loops too large (the resulting stabilizer -to- stabilizer coupling is too large).

Requirements for Azimuthal Stabilization

Vane coupling rings[3] (VCRs) are used in RFQs to move the structure dipole-mode frequencies far above the quadrupole-mode frequency by shorting the dipole modes at periodic intervals, thus producing an azimuthal field distribution that is less sensitive to mechanical tolerance errors. One set of VCRs connects one opposing vane pair at every location and moves only one of the two orthogonal dipole modes of the RFQ. For full azimuthal stabilization, two sets of VCRs in orthogonal planes are required at each location. Multiple quadrant bead pulls were made to calculate the dipole field components caused by one longitudinal stabilizer in one RFQ quadrant when one or two sets of VCRs were used at each location. The dipole field component with a full set of VCRs and no longitudinal stabilizers is less than 2%. Figure 7 shows the dipole component for one stabilizer, a full set of VCRs, and an end-to-end field tilt caused by an ~100-kHz end perturbation.

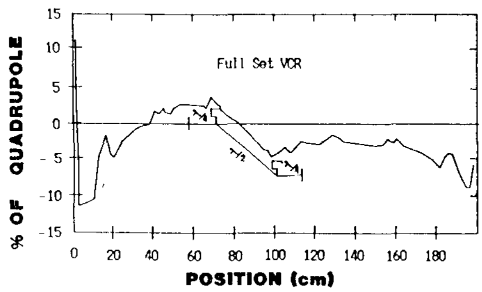

Fig. 7. Dipole mode component of RFQ (full set).

Figure 8 shows the dipole under the same conditions but with only one set of VCRs at each location. Sets of VCRs were alternated down the RFQ. The dipole component has doubled, for this case, to unacceptable levels, thus indicating that if a stabilized RFQ is to be constructed and the mechanical tolerances are expected to give large local frequency errors in the RFQ, then a full set of VCRs at the stabilizer-loop locations should be used. No attempt was made to look at the effects of shifting VCR locations relative to the stabilizer-loop positions.

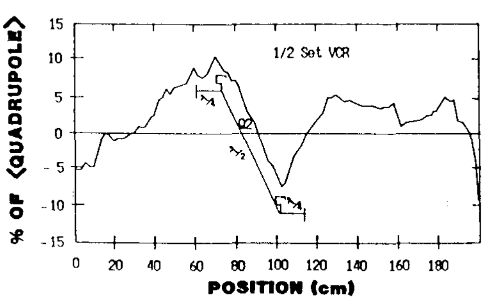

Fig. 8. Dipole mode component of RFQ (half set).

Summary

The summary of the stabilizer test results is shown below:

- Longitudinal stabilization of an RFQ using two-loop stabilizers in opposite quadrants has been demonstrated.
- Stabilizer-to-stabilizer coupling of 0.3% destroys stabilization.
- Longitudinal stabilizers, when correcting field errors, introduce large dipole field components unless the RFQ is fully azimuthally stabilized at each stabilizer-loop position.
- Stabilizer stored energy, when counteracting a field tilt, increases as the RFQ-to-stabilizer coupling is decreased.
- For a zero-slope tilt sensitivity, the frequency difference between the stabilizer and the RFQ cutoff mode will be larger for a higher Q stabilizer or for increased coupling of the stabilizer to the RFQ.

References

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