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COUPLED RADIO-FREQUENCY QUADRUPOLES AS COMPENSATED STRUCTURES*

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Abstract

The usefulness of radio-frequency quadrupoles (RFQs) for accelerating and bunching high-current beams in a compact, lightweight structure is well known. Until now, however, RFQs have been used only for low-energy acceleration because the structure operates in the 0 mode, and problems of mode coupling and field uniformity multiply as the length of the RFQ increases. In general, significant improvements against perturbations in the 0 or π mode can be obtained by providing the structure with another passband that couples to the first to produce a non-zero slope of the dispersion curves. Such a modified structure is called a compensated structure. The three-dimensional MAFIA codes were used to study the feasibility of designing compensated RFQs by dividing long RFQs into sections coupled together by short gaps between the end regions. We found that such a structure does have improved mode spacing and longitudinal stability. Results from this study will be presented.

Introduction

This paper discusses an investigation of a scheme proposed by one of us (LY) to extend the usefulness of radio frequency quadrupoles (RFQs). RFQs use strong electrostatic focussing in a narrow channel, thus allowing high-current beams. They also combine the functions of acceleration and bunching, which means these functions can be accomplished in a compact, lightweight structure. Unfortunately, the amount of acceleration given to a particle depends upon the length of the RFQ used. Problems of mode coupling and field uniformity multiply as the length of the structure increases, so until now RFQs have been used only for low-energy acceleration. Since RFQs are operated in the zero mode, we hypothesized that coupling together short, e.g. one-meter long, sections of RFQs to make a longer compensated[1] structure could improve mode separation and longitudinal stability. We have tested this hypothesis by simulating such coupled RFQs using the MAFIA 3-D electromagnetic analysis codes.[2]

Modeling the Structure

A simulation was done of a coupled RFQ consisting of four approximately one-meter sections separated by variable (0.168 cm–0.26 cm) gaps between the overhangs and by variable-thickness (0.168 cm–0.26 cm) plates with 20.4-cm^2 holes cut in the center. Figure 1 shows a three-dimensional plot of the MAFIA model of this structure,

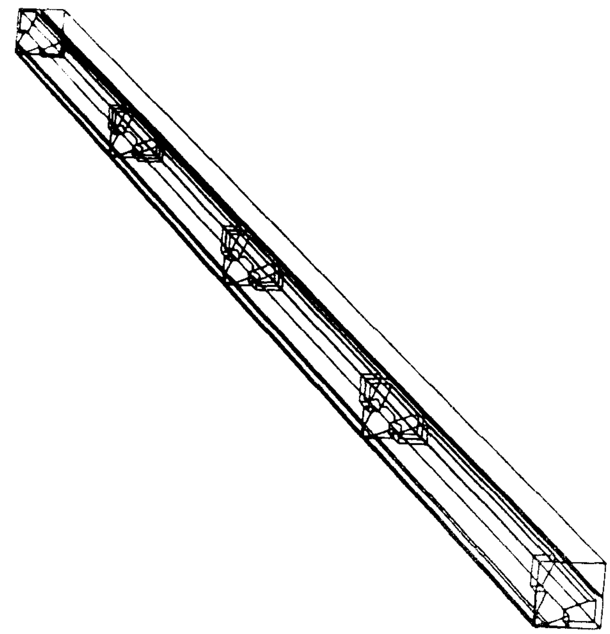

Fig. 1. A four-section coupled RFQ as modeled by MAFIA.

and Fig. 2 shows a cross section of the overhang-coupling-gap region of the MAFIA model.

Because of symmetry only one-quarter of the structure needs to be generated. The boundary conditions were chosen so that only the quadrupole modes and the gap modes, i.e., TM-like modes with fields concentrated in the gaps between the RFQs, were studied.

The MAFIA region has the dimensions 7.92 cm × 7.92 cm × 399.2 cm. The MAFIA model was designed to have some of the characteristics of the Beam Experiment Aboard a Rocket (BEAR) RFQ.[4] In particular, the cross-sectional area of the MAFIA overhang and the capacitance/length and cutoff frequency of the MAFIA model were approximately that of the BEAR RFQ. Except for these criteria, the exact shape of the MAFIA cross section was not a concern; the concern was to keep the number of mesh points used as small as possible for reasons of economy. More details of the MAFIA mesh and of the comparison of the MAFIA model with the BEAR RFQ are found in Ref. 3.

An RFQ is essentially a waveguide operated at cutoff, terminated by an end region whose fields must be matched to those of the waveguide.[5–8] This matching is done by undercutting the vanes.[6] The metal that is removed is called

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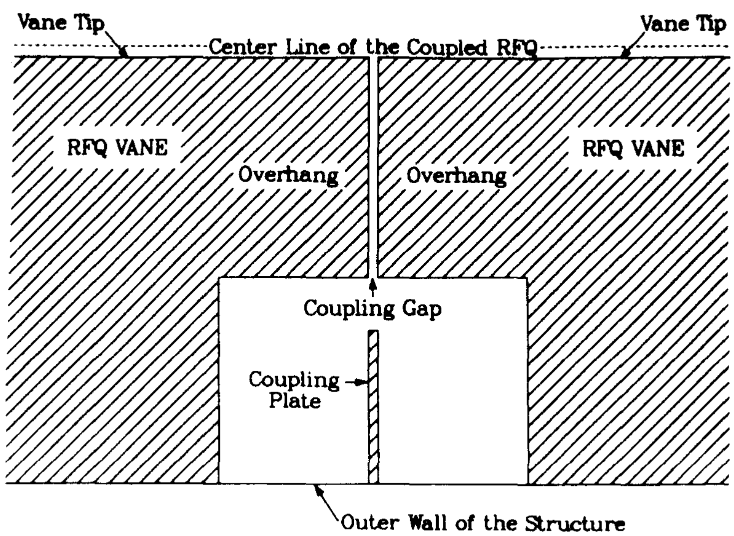

Fig. 2. A cross section of the overhang-coupling-gap region of the RFQ, taken through the center of one of the vanes.

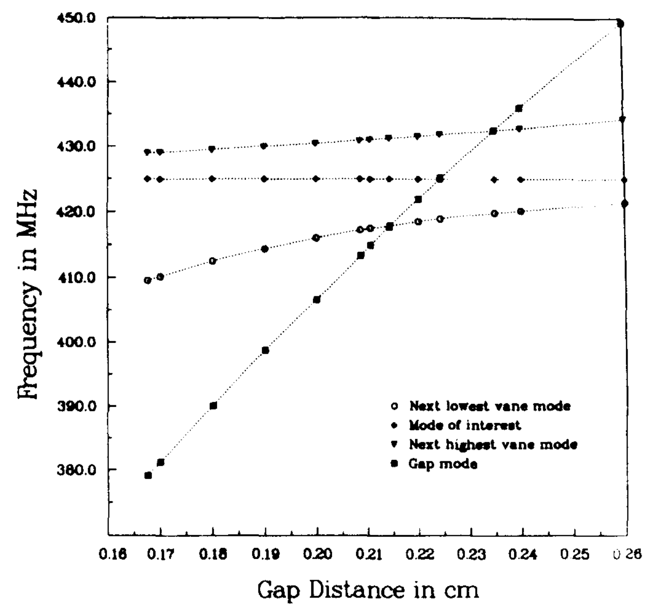

Fig. 3. Plot of frequency vs gap distance for the quadrupole RFQ mode, the nearest quadrupole modes, and the gap mode.

the undercut; the part of the vane remaining (in the region where the metal has been removed) is called the overhang. Again, see Fig. 2.

The overhangs at both the ends of the RFQs and at the gaps were adjusted to make the electric field between the vanes approximately constant along the length of the RFQ. The following overhangs were used in the MAFIA model:

Overhangs at ends of the structure	2.65 cm
Overhangs at the coupling gaps	2.83 cm

THE EFFECT OF GAP DISTANCE ON MODE SEPARATION AND ON LONGITUDINAL STABILITY

We know from the theory of compensated structures[1] that varying the gap distance will affect the mode spacing in the coupled RFQ system. Figure 3 illustrates this point. We can see that a 0.22 cm gap results in a near-optimum separation between the quadrupole modes. At this gap there is a difference of 6.5 MHz between the RFQ quadrupole mode, ω_0, and the next lowest quadrupole mode, ω_-, and 6.6 MHz between ω_0 and the next highest quadrupole mode, ω_+. By contrast, there is only a 1.9 MHz separation between ω_0 and the next highest mode in a 399.2-cm uncoupled RFQ.

A coupling gap of 0.22 cm should also be near optimum for the longitudinal stability of the structure, because the difference $(\omega_-^2 - \omega_0^2) \approx -(\omega_+^2 - \omega_0^2)$. Again, we know from the theory of compensated structures that when this condition is true the improvement against perturbations is by far greater than that due to the improved mode spacing alone[1].

In order to test this expectation, we added a 4.12 cm^3 perturbation to the end of both the coupled and uncoupled structures. Fig. 4 compares the electric field between the vanes as a function of distance along the RFQ for the two structures. The perturbation was chosen larger than what would be expected in practice in order to test the relative stability of the rf fields for the two systems. Notice that the field droops significantly more for the uncoupled RFQ and that the field of the coupled RFQ is essentially constant from cell-to-cell.

Unfortunately, as we can see from Fig. 3, for the cross-sectional geometry chosen the frequency of the gap mode is 421.8 MHz for the 0.22-cm gap, which is only 3.1 MHz different from the 424.9-MHz frequency of the mode of interest. Thus the frequency of the gap modes would be a factor in the design a real coupled RFQ.

THE EFFECT OF THE SIZE OF THE COUPLING HOLE ON TUNING AND ON LONGITUDINAL STABILITY

We also tested the possibility of tuning the individual sections of the coupled RFQ at the gaps by changing the shape of the coupling hole rather than by changing the length of the overhang.[3] We were able to show that tuning the coupling holes has the same effect on the longitudinal stability as tuning the gap overhang lengths. The equivalence of the two methods of tuning is important if coupled

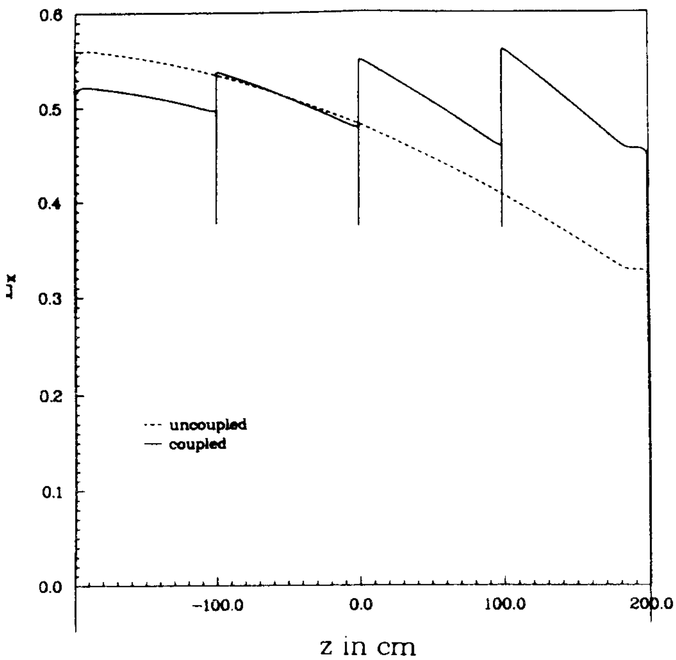

Fig. 4. Comparison of the fields between the vanes for the perturbed coupled and uncoupled RFQs.

RFQs are to be built, since it is much easier to vary the size of the coupling hole than to vary the length of overhangs.

EFFECT OF THE COUPLING PLATES ON POWER LOSS

The effect of the presence of the plates on the power loss in the structure was a concern, but the MAFIA calculations indicated that coupling the RFQs decreased the quality factor of the structure by only 0.4%.

CONCLUSIONS

As we have seen above, coupling together four approximately one-meter sections of RFQs, assuming one tuned the gap distance and either the size of the coupling holes or the length of the gap overhangs, did improve the mode separation between the quadrupole modes. Coupling the RFQs also improved the longitudinal rf stability.

The presence of the TM-like gap modes was discovered to be a problem, and the effect of the cross-sectional geometry on the frequency of these modes would need to be studied before a real coupled RFQ could be built. It should also be noted that the dipole modes were not looked at in this study, but it is expected that their mode separation would be also be improved by coupling the RFQs.

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