AN RF POWER MANIFOLD FOR THE RADIO FREQUENCY QUADRUPOLE LINEAR ACCELERATOR*

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Introduction

An important consideration in the design of a practical radio-frequency quadrupole (RFQ) accelerator is the electromagnetic properties of the rf power coupling circuit. Coupling rf power through an iris or coupling loop into one quadrant disturbs the symmetry of the azimuthal field distribution and the uniformity of the longitudinal field distribution, both of which are crucial for good performance of an RFQ accelerator.

Stabilizing the field distribution against perturbations with some form of resonant coupling was found to be impractical because of limitations inherent in the RFQ structure. Instead, a means was developed for coupling to the RFQ by using a resonant power manifold without perturbing the RFQ fields. This paper discusses the properties of rf power manifolds for the RFQ in the context of a coupled-circuit model.

A Circuit Model for the RFQ

The success of the coupled-circuit model of Nagle, Knapp, and Knapp[1] has led us to consider a similar concept for studying the RFQ. The coupled-circuit model has been an effective means for understanding some of the rf properties of the side-coupled, the post-coupled drift tube, and the disk-and-washer linear accelerator structures. However, these structures can all be approximated to some degree by one-dimensional chains of coupled discrete oscillators.

This approximation is not well suited for describing the RFQ because, except for the small modulations of the vanes necessary to produce an accelerating component of electric field, it is a waveguide transmission line of constant cross section. Two-port network analysis using the chain matrix notation,[2] on the other hand, provides an ideal framework for describing continuous transmission lines. This theory also accommodates discrete circuits easily, permitting them to be combined with distributed circuits in the same model.

Let us examine, briefly, a two-port model for the RFQ. The general form for a uniform transmission line of length ℓ is:

$$M = \begin{bmatrix} \cosh \gamma\ell & Z \sinh \gamma\ell \\ Z^{-1} \sinh \gamma\ell & \cosh \gamma\ell \end{bmatrix} ,$$

where γ is the propagation factor for the transmission line and Z is its characteristic impedance. For waveguide, both γ and Z are functions of the excitation frequency and the cutoff frequency. The characteristic impedance is also a function of the normalization chosen. Note that this matrix represents only one waveguide mode. A different set of parameters, γ and Z, are required for each waveguide mode being considered.

The matrix M relates the voltage and current at the output port to the voltage and current at the input port (Fig. 1). That is:

$$\begin{bmatrix} V' \\ I' \end{bmatrix} = M \begin{bmatrix} V \\ I \end{bmatrix} .$$

The variables need not actually be current and voltage. In fact, a more useful normalization uses variables related to the square root of stored energy analogous to the variables used in the original coupled-circuit model.[3]

The RFQ operating mode is an electric mode, heavily loaded, capacitively, by transverse vanes, topologically equivalent to and derived from the TE_{210} mode of a right circular cylinder. This mode is chosen because it has the necessary quadrupole component of electric field with a uniform distribution from end to end.

Existence of the TE_{210} mode requires open-circuit boundary conditions. This is achieved, in practice, by terminating each end of the RFQ with a shorting plane spaced a small distance from the end of the vanes. The effective shunt inductance of this termination is resonated with the capacitive end tuners (Fig. 2) to achieve a high impedance termination at the frequency of the TE_{210} mode.

A suitable model for this configuration is illustrated in Fig. 3. In the stored energy normalization, the shunt conductance of the parallel LC combination becomes

$$Y_o = 1 - \omega_o^2/\omega^2 .$$

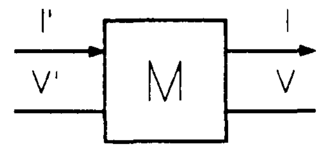

Fig. 1. Representation of a general two-port network.

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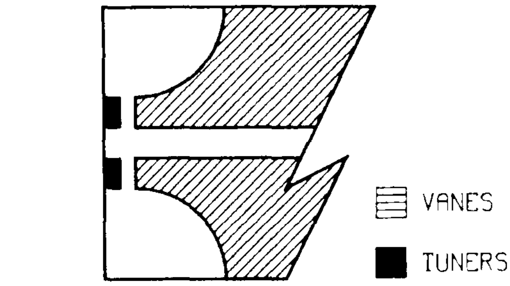

Fig. 2. The RFQ end cap and end tuners.

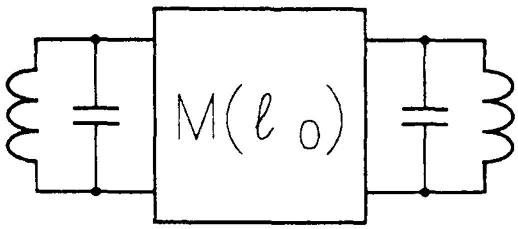

Fig. 3. Two-port model for RFQ.

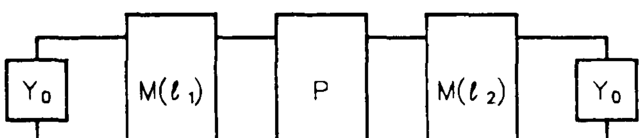

Fig. 4. Two-port model with added perturbation.

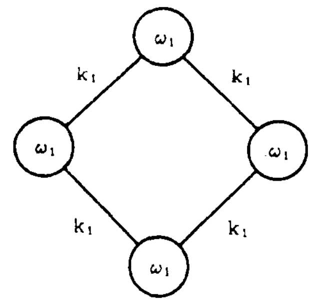

Fig. 5. Four-resonator model for RFQ.

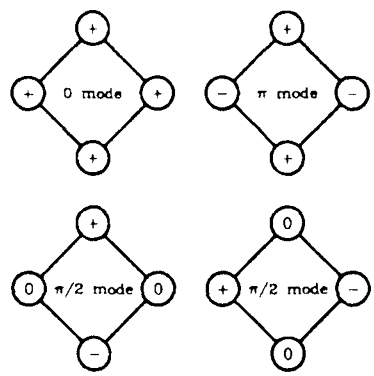

Fig. 6. Field patterns for the four-resonator model.

The effects of perturbations on the field distribution can be studied by breaking M into sections of length less than ℓ_0 and inserting appropriate two-port representations of the perturbing elements (Fig. 4).

The above model describes only the longitudinal field distribution of the RFQ. Because the symmetry of the vane-tip potentials is important to the quality of the beam in the transverse plane, we would like the ability to model the azimuthal distribution of fields as well. The four-fold symmetry of the RFQ cross section suggests that we could describe an arbitrary distribution of vane-tip potentials by considering the fields to result from an admixture of TE_{21}, TE_{11}, and TE_{01} waveguide modes.

Although such a model might be feasible, it is unnecessarily complex for our present purposes. Instead, we propose to ignore coupling between the azimuthal and longitudinal field distributions and to develop a separate model for the azimuthal direction.

With increasingly heavy loading, i.e., a smaller aperture, the frequencies of the TE_{110} and TE_{210} modes asymptotically approach each other. This suggests that if we ignore the higher modes, TE_{11n} and TE_{21n} for $n > 0$, we can approximate the RFQ by a ring of coupled oscillators as illustrated in Fig. 5. This amounts to ignoring the longitudinal extent of the RFQ.

A ring of four oscillators is characterized by four modes of oscillation (Fig. 6). The ring will have a π mode, corresponding to the TE_{210} mode; two degenerate $\pi/2$ modes, corresponding to the two TE_{110} modes; and a zero mode. We are tempted, by simple extension, to identify the zero mode with the TE_{010} mode. However, there is a problem: experimentally there is no fourth mode in the mode spectrum near the other three modes. Furthermore, the effect of the vanes on the TE_{010} mode suggests that it would be far removed in frequency from the TE_{110} and TE_{210} modes.

This apparent problem has an interesting resolution. For an appropriate form of resonator, the zero mode frequency can be zero Hertz. Figure 7 depicts two forms, equivalent through a series-to-parallel transformation, that the unit oscillator might take to have a zero mode of zero frequency. That is, the network will pass direct current. Four of these oscillators are joined together (Fig. 8) to form a circuit model for the azimuthal direction of the RFQ.

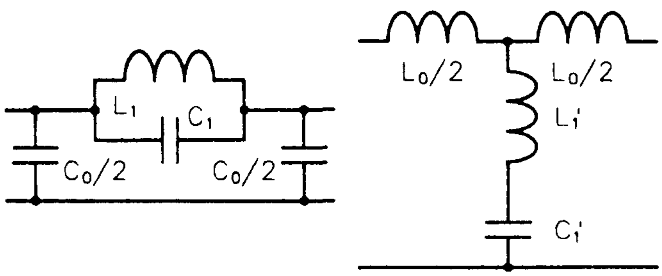

Fig. 7. Equivalent unit cells for RFQ coupled-circuit model.

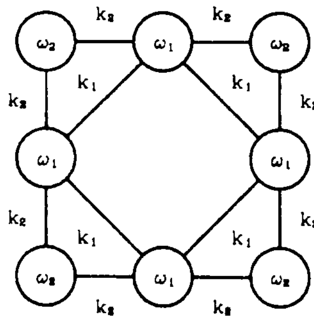

Fig. 9. Resonant coupling of four-resonator model.

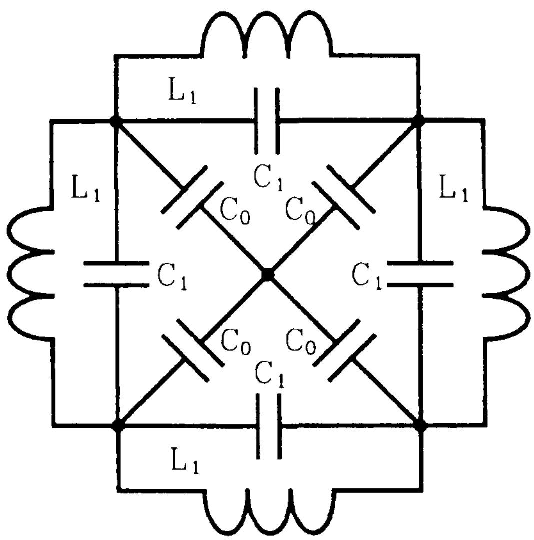

Fig. 8. Equivalent circuit for RFQ.

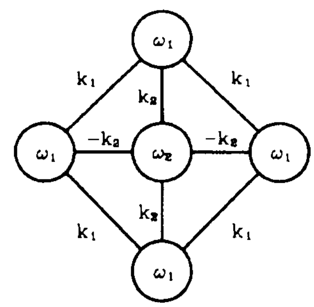

Fig. 10. Four-resonator model with nonresonantly coupled manifold.

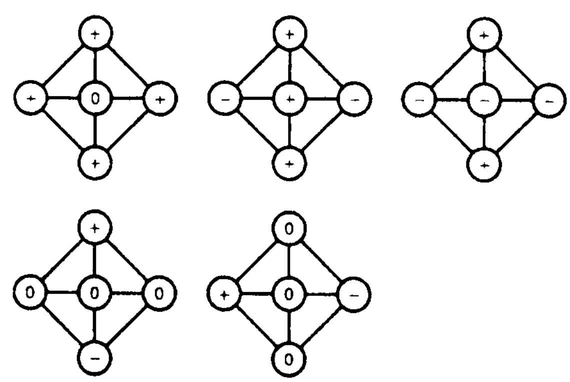

Fig. 11. Field patterns for four-resonator model with manifold.

Resonant Coupling Techniques

At first, resonant coupling methods were considered as a means of stabilizing the azimuthal and longitudinal field distributions against perturbations. Figure 9 shows a scheme for stabilizing the azimuthal field distribution with coupling cells using the same principle as the side-coupled structure. This version suffers from a fatal defect: the $\pi/2$ mode is doubly-degenerate because of the circular symmetry. With only a slight tuning error most of the stored energy could end up in the coupling cells.

Although azimuthal resonant coupling has been rejected for now, it could probably be saved if the degeneracy were eliminated by removing one of the coupling cells.

Attempts to find internal modes suitable for longitudinal resonant coupling in the manner of the post-coupled drift tube or disk-and-washer structures have failed.

These problems led to the investigation of an external means for stabilizing the RFQ fields using an arrangement related to the manifold of Voelker.[4]

A Nonresonantly Coupled Manifold for the RFQ

The manifold concept that subsequently evolved is not suitable, directly, for stabilizing the field distribution. However, it does

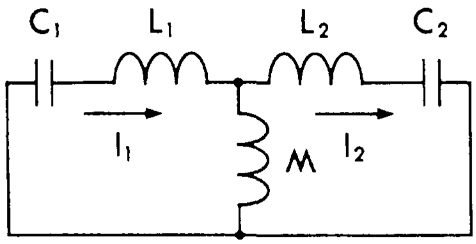

Fig. 12. Two-resonator, coupled-circuit model of RFQ with manifold.

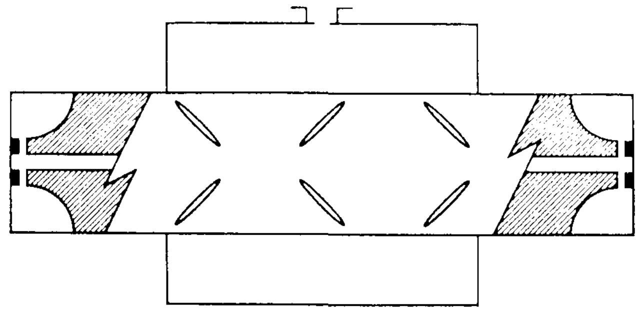

Fig. 13. Cross section of RFQ with nonresonantly coupled manifold.

provide symmetric drive points that do not, in principle, disturb the RFQ field distribution.

Figure 10 illustrates the simplicity of the nonresonantly coupled manifold. The central oscillator represents the manifold. With five oscillators there are five modes of oscillation (Fig. 11). Only two of the modes shown can be excited by driving the manifold. These two modes can be thought of as radial zero and π modes involving only the RFQ TE_{210} mode and the manifold.

By symmetry, we see that the coupling k_2, at worst, perturbs the azimuthal distribution in a way that cannot mix in the $\pi/2$ modes and introduce sextupole field components.

The situation is even better than it seems. To see this we first simplify the discussion by reducing our model to two coupled oscillators, one representing the RFQ TE_{210} mode and one representing the manifold. Figure 12 is a schematic of a discrete-circuit model of two coupled oscillators. If L_1C_1 equals L_2C_2, then I_1 equals I_2 for zero mode and I_1 equals $-I_2$ for the π mode. Furthermore, the frequency of the zero mode is $(L_1C_1)^{-1/2}$, independent of M.

How does this relate to the RFQ and manifold case? Suppose that an otherwise unperturbed RFQ is magnetically coupled to the manifold through a slot. If the frequency of the TE_{210} mode equals the manifold frequency before the coupling slot is cut, the zero mode of the combination will be at the frequency of the TE_{210} mode. The consequences of this are that the longitudinal field distribution of the RFQ is still flat because it is being excited at its cutoff frequency. In addition the current intercepted by the slot is equal and opposite on opposite sides of the wall. There is no excitation of the slot and, therefore, no perturbation of the RFQ by the slot.

This fact is not easy to illustráte using the coupled-circuit theory in the stored-energy normalization because the definition of the frequencies of the oscillators includes the effects of the coupling slots and because the wall currents are related to the stored energy in a geometry-dependent way.

A Physical Realization of the Manifold

The requirements of symmetry dictate that the manifold should couple equally to each quadrant of the RFQ. This is achieved by placing the RFQ inside the manifold that operates in a TEM coaxial resonator mode with the RFQ shell as its center conductor (Fig. 13). The length of the manifold must be a multiple of a half-wavelength at the operating frequency or tuned to the electrical equivalent by capacitive tuners at the electric field maxima. Coupling between the manifold and the RFQ takes place through slots cut in the RFQ walls at the current maxima of the manifold. Advantage is taken of the multiple maxima to increase the effective coupling.

The fields to be coupled are orthogonal to one another. The manifold magnetic field is azimuthal and the RFQ magnetic field is longitudinal. To couple them, the coupling slots must make an angle with respect to both fields to intercept wall currents on both sides. The sign of the slot angle must be alternated to compensate for the alternating signs of the RFQ fields azimuthally and the manifold fields longitudinally.

The relative stored energies of the RFQ and manifold can be controlled by adjusting the slot angle to intercept more current on one side and less on the other. The tuning considerations discussed above insure that the intercepted fractions of the wall currents are equal.

Coupling to the manifold is achieved by a loop or iris at a magnetic field maxima. If center drive is desired, the manifold should be an even number of half-wavelengths long.

Experimental Data on a Cold Model

A cold model of the RFQ with constant vanes was combined with a nonresonantly coupled manifold as described above. The model is pictured in Fig. 14. The RFQ structure operates at 313 MHz, nominally. The manifold is one-wavelength long and coupled to the RFQ through twelve 45° slots about 90 mm long by 10 mm wide.

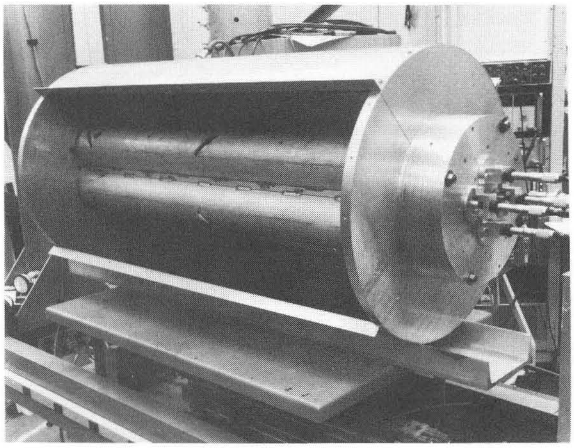

Fig. 14. The RFQ cold model with nonresonantly coupled manifold.

The frequency of the zero mode was 313.268 MHz and the frequency of the π mode was 310.618 MHz. The net coupling constant from the twelve slots was determined to be 0.0085 by measuring the change in RFQ stored energy resulting from a perturbation of the manifold frequency. According to the coupled-circuit analysis of the two oscillator model, the coupling constant is given by

$$k = \frac{\Delta f_{man}/f_{man}}{(\Delta U_{RFQ}/U_{RFQ})^{1/2}} \quad ,$$

if the oscillators have the same frequency.

The accuracy of the coupling-constant determination was insufficient to permit calculating the individual frequencies of the two oscillators from the frequencies of the zero and π modes. Figure 15 is a graph of $(\Delta U_{RFQ}/U_{RFQ})^{1/2}$ versus manifold detuning.

The change in RFQ stored energy was measured by comparing the frequency perturbation of a needle pulled along the RFQ axis for various perturbations of the manifold to the case with no manifold detuning. The fraction of stored energy in the RFQ was similarly measured by comparing beadpulls with and without the manifold. In the zero mode 71% of the stored energy was in the RFQ and in the π mode 30% was in the RFQ. The fact that the ratio of RFQ to manifold stored energy for the π mode is the reciprocal of the same ratio for the zero mode is predicted by the coupled-circuit model.

Variations on a Manifold

It is possible to construct a resonantly coupled manifold by interposing a resonator between the RFQ and the manifold resonator

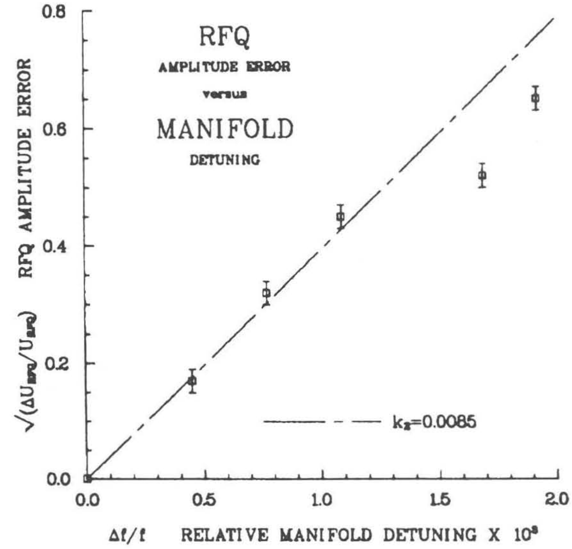

Fig. 15. The RFQ amplitude error versus manifold detuning.

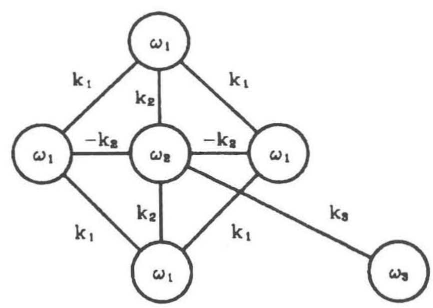

Fig. 16. Four-resonator model with resonantly coupled manifold.

(Fig. 16). The intermediate oscillator is most conveniently a TEM-mode resonator coaxial with the RFQ and manifold. Coupling between the manifold and coupling resonator is through azimuthal slots in the magnetic field region of the intermediate wall.

In principle, this "triaxial" manifold should lock the average RFQ amplitude to the outer resonator amplitude in the $\pi/2$ mode. However, it does not serve to stabilize the internal field distribution of the RFQ. In addition, there are two serious drawbacks to this scheme: fabrication and tuning are more complicated than for the relatively simple nonresonantly coupled manifold; and the RFQ slots are excited and could affect the longitudinal field distribution. The cold model was adapted to the triaxial configuration, but test results were inconclusive because of a design error in the intermediate cavity.

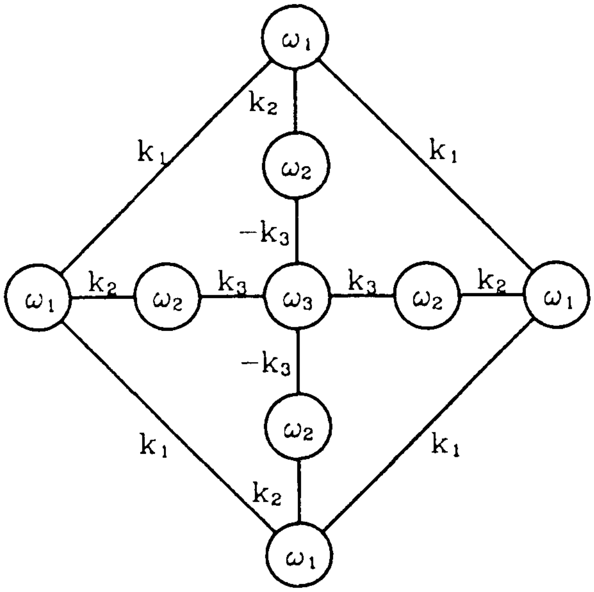

Fig. 17. Four-resonator model with individual coupling resonators.

If each of the coupling slots could be replaced by individual resonators (Fig. 17), perhaps stabilization of the RFQ internal fields could be achieved. An attempt to model this concept was made using resonant coupling loops. Insufficient coupling was obtained with these loops for proper mode separation.

Conclusions and Opinions

A simple manifold has been developed that permits coupling rf power to the RFQ without seriously perturbing the field distribution. Resonantly coupled manifolds could provide better performance at the expense of increased complexity. It is not known if the improved performance would really be useful with a practical RFQ structure.

An extension of the coupled-circuit model to include distributed circuits has proved useful in obtaining a qualitative understanding of the RFQ structure. Further understanding could be developed through computer simulations based on this model.

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References

1. D. E. Nagle, E. A. Knapp, and B. C. Knapp, "Coupled Resonator Model for Standing Wave Accelerator Tanks," Rev. Sci. Instrum. 38, No. 11, p. 1583, 1967.
2. L. Brillouin, Wave Propagation in Periodic Structures, 2nd ed., Dover Publ., 1953.
3. B. C. Knapp, E. A. Knapp, G. J. Lucas, and J. M. Potter, "Resonantly Coupled Accelerating Structures for High-Current Proton Linacs," IEEE Trans. Nucl. Sci. NS-12, No. 3, p. 159, 1965.
4. F. Voelker, "Theory of the RF Manifold and Measurements on a Model Manifold System," Univ. of Calif., LRL, UCLR-17508, 1967.