TUNING AND STABILIZATION OF RFQ'S*

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Abstract

Recent advances in tuning and stabilization of Radio Frequency Quadrupoles (RFQ) will be presented. New designs of RFQs as long as four times the free-space wavelength and requiring field flatness of a few percent and less than a few percent dipole component can now be built and tuned. The tuning is performed by measuring the RFQ fields with a beadpull in each quadrant and using a computer program (RFQPERT) to analyze the beadpull data. The program calculates a set of perturbations to an ideal RFQ that would mix in nearby modes to give the measured fields. Slug tuners are then used to cancel the calculated perturbation in the real RFQ to get the desired pure RFQ mode. The pros and cons of several methods that have been used to stabilize the field in RFQs will also be discussed.

Introduction

A large number of Radio Frequency Quadrupole (RFQ) accelerators have been studied but there are relatively few operating RFQs in the world[1,2]. The two major types of RFQs are the 4-vane and the 4-rod; names that signify the construction technique used in each case. The 4-vane RFQs are generally higher frequency (80 - 425 MHz) and used for light ions; the 4-rod RFQs are generally lower frequency (6 - 220 MHz) and used for heavy ions. The 4-rod RFQs are, in general, short compared to the wavelength of their operating frequency and, therefore, are fairly easy to tune. Opposite rods are supported by common supports that eliminate problems with dipole modes in the 4-rod RFQ. The only long RFQs (i.e., RFQs that are greater in length than two wavelengths) currently in existence, are the 4-vane type.

The sensitivity to tuning errors has been expressed as proportional to $(L/\lambda)^2$, where L is the length of the RFQ and λ is the free-space wavelength[3]. This expression only applies to the longitudinal stability of the TE210 mode (the RFQ mode) and not to tuning sensitivity (with respect to dipole components mixing with the RFQ mode), which depends only on the difference between the frequency of the nearby dipole modes and the frequency of the RFQ mode. Because short RFQs are comparatively easy to tune and easy to stabilize, long RFQs that are all 4-vane RFQs will be emphasized in this paper. The stabilization techniques discussed in this paper will refer mostly to stabilizing the RFQ mode from the effects of the dipole modes. A technique of stabilizing RFQs longitudinally is discussed in a contributed paper to this conference titled Coupled Radio-Frequency Quadrupoles as Compensated Structures. [4]

The Ideal RFQ

The ideal RFQ is defined in this paper as a 4-vane RFQ with the end region tuned to the cutoff frequency of the RFQ in such a way that the frequency of the TE210 mode (the quadrupole mode) is equal to the cutoff frequency of the RFQ. The computer program SUPERFISH calculates the frequency of the TE210 mode for a cross section of the RFQ, and this calculation is shown in Fig. 1. The frequency of the TE21n mode is then given by

$$freq\{TE21n\} = \frac{c}{2\pi} \times \sqrt{\left[\frac{2\pi}{c} \times freq\{TE210\}\right]^2 + \left(\frac{n \times \pi}{L}\right)^2}\ , \tag{1}$$

where n is the number of nodes in the mode and L is the length of the RFQ.

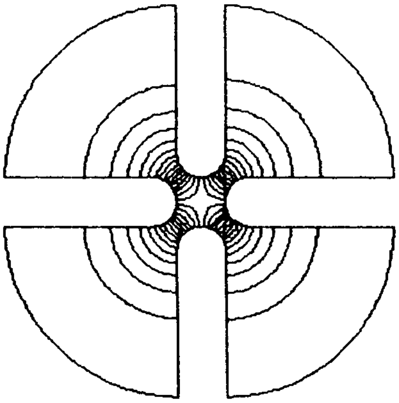

Fig. 1. The TE210, or Quadrupole Mode in a Simple RFQ as calculated by SUPERFISH.

This expression assumes that the end regions are also tuned correctly for the TE21n modes, which, for a long RFQ, is a very good approximation because the TE211 mode, for example, is very close to the frequency of the TE210 mode. For a RFQ that is 4 wavelengths long the TE211 mode is only 0.78% higher than the TE210 mode. If the ends of the RFQ were also tuned correctly for the TE11n modes (the dipole modes), the same form of the expression could be used for the TE11n modes. A SUPERFISH calculation of one orientation of the dipole mode is shown in Fig. 2. In the ideal RFQ the ends of the RFQ are also tuned correctly for the TE110 mode. The frequencies of the TE21n and the TE11n modes are shown in Fig. 3 for an ideal RFQ that has a length of 4.25 wavelengths. Figure 4 shows the longitudinal variation of the amplitude of the TE21n and TE11n modes from $n = 0$ to $n = 3$. The amplitude of the fields of the TE21n and TE11n in the ideal RFQ will have the form

$$\cos\left(\frac{n \times z \times \pi}{L}\right)\ , \tag{2}$$

where z is the position along the RFQ. A plot of the first 4 modes given by Eq. 2 is shown in Fig. 4. In a real RFQ that is tuned well, the amplitude of the TE21n modes are described very well by Eq. 2. However, the TE11n modes can be significantly different.

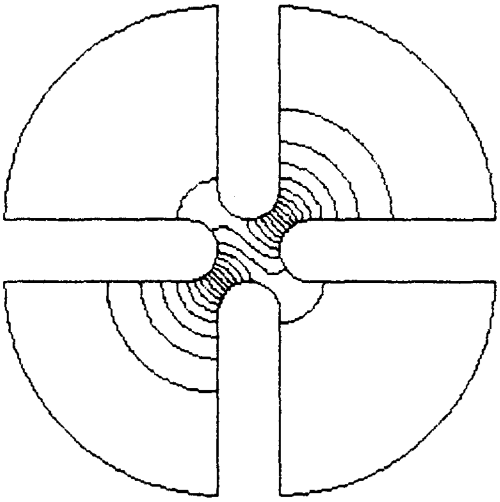

Fig. 2. One orientation of the TE110, or Dipole Mode in a Simple RFQ as calculated by SUPERFISH.

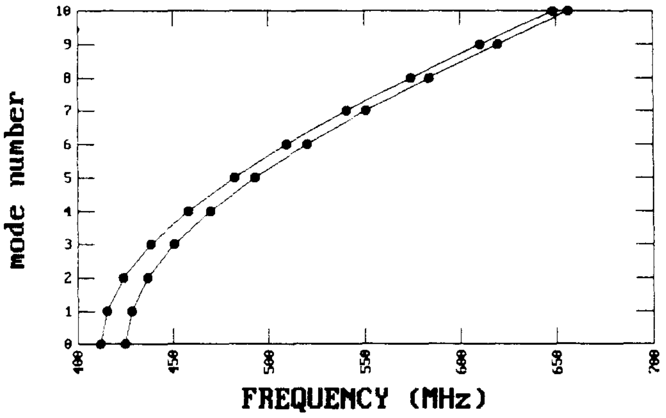

Fig. 3. The Frequencies of the TE21n and TE11n modes in an ideal RFQ with open boundary conditions for n=0 to 10. This ideal RFQ is 3m long and operates at 425 MHz.

Real RFQ

In a real RFQ the ends can be tuned so that the frequencies of the TE21n modes are given quite accurately by Eq. 1, but normally the ends of the RFQ are not tuned correctly for the TE11n modes. Therefore, Eq. 1 will not be accurate and the longitudinal variation of the amplitude will not be as shown in Fig. 4. For example, if the ends of the RFQ are tuned high for the TE11n modes, then the longitudinal variation of the amplitude of the TE11n modes will look more like that shown in Fig. 5. Because the ends are tuned high, the frequency of the first mode will be above cutoff and will approach the frequency of the TE111 mode in a RFQ with the ends shorted. Tuning the ends lower than the cutoff frequency is also possible, and then the fields may look like those shown in Fig. 6, where the modes are identified by the number of nodes.

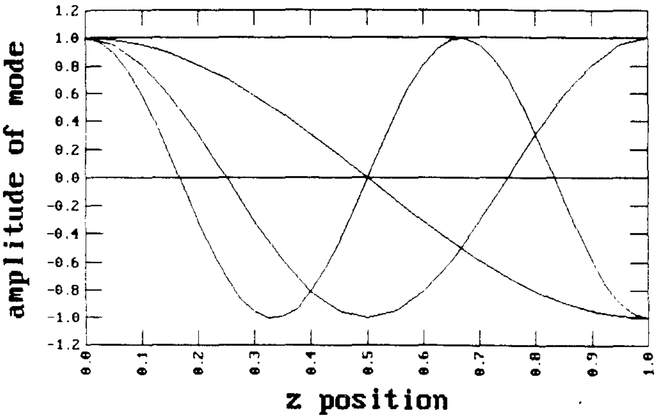

Fig. 4. The Amplitude of the First 4 Modes in an Ideal RFQ as a function of position with open boundary conditions on the ends.

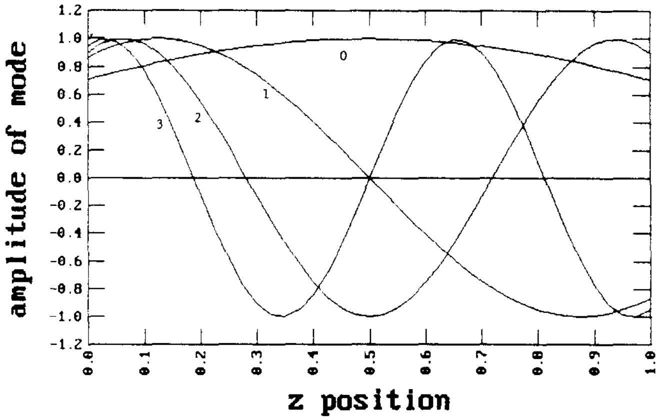

Fig. 5. The Amplitude of the First 4 Modes in an Ideal RFQ with ends that do not have open boundary conditions. In this case, the ends are tuned high in frequency.

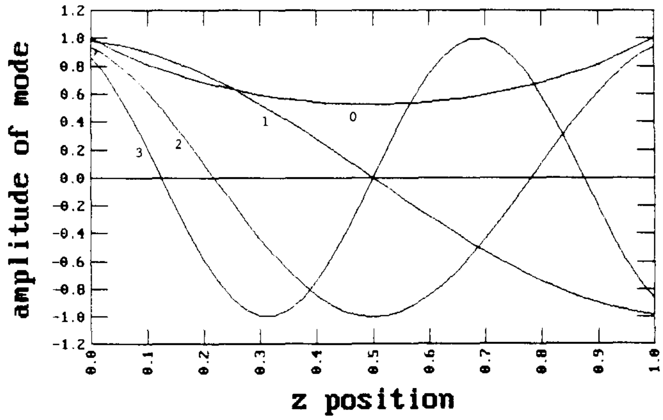

Fig. 6. The Amplitude of the First 4 Modes in an Ideal RFQ with ends that are tuned low in frequency.

In a waveguide, the wavelength λg is given by

$$\frac{1}{\lambda_g} = \frac{1}{c} \times \sqrt{\text{frequency}^2 - (\text{cutoff frequency})^2} \qquad (3)$$

If the frequencies of the modes are given by Eq. 1 the form of Eq. 2 can be changed to

$$cos\left(\frac{2 \times z \times \pi}{\lambda_g(n)}\right) \tag{4}$$

where $\lambda_g(n)$ is the waveguide wavelength of the n'th mode. In a real RFQ the frequencies of the modes may not be given exactly by Eq. 1 and therefore L will not equal $n \times \lambda_g(n)/2$. Equation 4 must therefore be modified to accurately represent the actual modes in the RFQ. In an ideal RFQ where end regions are not tuned to the frequency of the cutoff frequency, the modes are given by:

$$cos\left[\frac{(z - \text{offset}) \times 2 \times \pi}{\lambda_g(n)}\right] \text{for frequencies} > \text{cutoff frequency}$$

or

$$cosh\left[\frac{(z - \text{offset}) \times 2 \times \pi}{i \times \lambda_g(n)}\right] \text{for frequencies} < \text{cutoff frequency} \tag{5}$$

where i is square root of -1 and offset is the factor that makes the expression symmetric or antisymmetric about the middle of the RFQ. If n is even, the expression is symmetric; if n is odd, the expression is antisymmetric. $Offset$ is given by $L/2 - \lambda_g(n) \times n/4$.

With the expression for the modes in an ideal RFQ with untuned ends, representing the actual measured field distribution in a RFQ as a combination of the ideal modes is now possible using Eq. 5. If $f(z,l)$ is the field in quadrant l (l is 1, 2, 3, or 4 representing the 4 quadrants) at position z, then

$$f(z,\ell) = \sum_{n=0}^{N}[A(n) \times Q(z,l,n) + B(n) \times D1(z,l,n) + C(n) \times D2(z,l,n)] \tag{6}$$

where
$Q(z,l,n)$ is $Qn(n) \times (-1)^{(l-1)} \times$ Eq. 5; $D1(z,l,n)$ is 0 for $l = 2$ or 4 and is $\pm D1n(n) \times$Eq. 5 for 1 = 1 or 3; and $D2(z,l,n)$ is 0 for l = 1 or 3 and is $\pm D2n(n) \times$ Eq. (5) for l = 2 or 4. $Qn(n)$, $D1n(n)$, and $D2n(n)$ are normalization factors that equalize the stored energy of of each mode. $Qn(0)$ is chosen to be equal to 1, and then the rest of the normalization factors are determined. $A(n)$, $B(n)$, and $C(n)$ are the coefficients that represent how much of each mode is mixed with the desired mode. N is the number of modes used to approximate the actual Field distribution. N is typically less than ten. A perfectly tuned RFQ will have $A(0) = 1$ and all other coefficients zero. However, if there is a small perturbation that raises the frequency by $P(k)$ in this perfectly tuned RFQ at position $Z(k)$, in quadrant $L(k)$ then the other coefficients will be given by

$$A(n) = \sum_k \frac{P(k) \times Q[Z(k), L(k), n)]}{[FQ(0) - FQ(n)]} \quad , \tag{7}$$

$$B(n) = \sum_k \frac{P(k) \times D1[Z(k), L(k), n)]}{[FQ(0) - FD1(n)]} \quad \text{, and} \tag{8}$$

$$C(n) = \sum_k \frac{P(k) \times D2[S(k), L(k), n)]}{[FQ(0) - FD2(n)]} \quad , \tag{9}$$

where $FQ(n)$, $FD1(n)$, and $FD2(n)$ are the frequencies of the corresponding quadrupole or dipole mode.

These relationships suggest a method of tuning RFQs, because if the perturbations are assumed to be at the locations of the tuners and the value of the perturbations are known, then the tuners can be moved to remove the perturbations. The perturbations can be found by applying a least square fit of Eq. 6 to the beadpull data. The program RFQPERT implements this method for tuning RFQs. Ideally, this method should be able to tune a RFQ in one step, but in practice it has taken at least two or three iterations to tune a long RFQ, such as the Continuous Wave Deutron Demonstrator (CWDD) cold model or the Ground Test Accelerator (GTA) RFQ. With enough tuners the RFQ can be tuned so that the fields are flat to within 1% and with less then 1% dipole component. The reproducibility and accuracy of the beadpull data limits the tuning to this level.

The ends of the RFQ need to be undercut an appropriate amount so that the frequency of the TE210 mode equals the cutoff frequency of the RFQ. If there are tuners near the ends, the undercuts do not have to be exactly right, because the end tuners can be used to trim the end tuning. Capacitive end tuners that have been used in the past on RFQs (especially without undercuts) are inefficient, because they increase the stored energy in the RFQ unnecessarily.

Stabilization Of RFQs

Several methods of stabilizing RFQs have been used to reduce the susceptibility to dipole mode mixing with the desired quadrupole mode. Vane coupling rings (VCRs) have been used with good results in a number of RFQs. VCRs raise the dipole modes well above the frequency of the quadrupole mode and practically eliminate the dipole problem even in poorly aligned RFQs. VCRs do not affect the longitudinal stability. However, the disadvantage of VCRs is that they lower the frequency of the quadrupole mode substantially and cause scalloping of the fields on axis. Both the lowering of the frequency and the scalloping of the fields are caused by the extra intervane capacitance at the location of the VCRs. Because VCRs lower the frequency so much, a RFQ must be designed to use VCRs, and if it is designed to use the VCRs, they must be used or the frequency of the RFQ will be wrong. Another problem with VCRs is the difficulty of installing VCRs that could be actively cooled in high-duty-factor RFQs.

In very short RFQs, it is possible to use resonant circuits at the end of the RFQ that couple to the dipole modes and split the lowest dipole mode into two modes equally spaced above and below the quadrupole mode, thus stabilizing the RFQ from the effects of the dipole mode mixing. In short RFQs, the frequency of the dipole mode can be very close to the frequency of the quadrupole mode, because the ends of the RFQ are tuned for the quadrupole mode and not for the dipole modes. In general, the ends of the RFQ will raise the frequency of the dipole modes with respect to the quadrupole modes. The cutoff frequency of the TE11 modes is usually about 3% lower than the cutoff frequency of the TE21 mode. However, in a short RFQ the TE110 dipole mode can be nearly degenerate with the TE210 quadrupole mode, because the ends of the RFQ raise the frequency of the TE11 modes. In a long RFQ the ends will not have as much effect on the frequency of the dipole modes, but the frequency of the TE111 or TE112 modes may come very close to the TE210 quadrupole mode. If the ends of the RFQ are tuned independently for the dipole modes with devices that do not affect the TE210 quadrupole modes, the frequency of the TE11n modes can be shifted so that none of the TE11n modes are near the frequency of the TE210 quadrupole mode. The Beam Experiment Aboard a Rocket (BEAR) RFQ used this method successfully to lower the frequency of the TE110 mode[5]. The GTA RFQ is using this method to lower the frequency of the TE112 mode, which was slightly above the frequency of the quadrupole mode to well below the quadrupole mode. The TE113 mode is still well above the quadrupole mode. In the CWDD cold model, similar results were obtained. These end tuners are compatible with the program RFQPERT.

The end tuners can be made in several forms. The BEAR RFQ used four simple L-shaped rods attached to the end plate of the RFQ on the center line, midway between the vanes. The end tuners were tuned by a hollow cylindrical tuner on the outer wall of the quadrant. The gap between the tuner and the L-shaped rod formed the capacitance of the LC circuit which could be tuned by adjusting this gap. Some of the magnetic field of the TE11 modes must pass through this (LC) circuit, and, therefore, the frequency of the TE11 modes can be changed by this end tuner. Because the L- shaped rods are on the center line between the vanes, the magnetic field of the TE21 modes do not pass though the loop of the end tuners and therefore are unaffected by them.

Azimuthal stabilizers, which are resonant coaxial lines that are loop coupled to opposite quadrants, were tried on the GTA cold model and on the CWDD cold model. (They were planned to be used on the GTA RFQ and on the CWDD RFQ). They worked by splitting the dipole mode nearest the TE210 quadrupole mode. On these RFQs the TE112 mode was nearest the TE210 mode. The splitting of the TE112 mode was very unpredictable, and the split modes could not be simply described by equations similar to Eq. 5. Thus, the program RFQPERT could not be used to tune the RFQ once the azimuthal stabilizers were mounted which changed the field distribution enough to require further tuning. The effectiveness of the azimuthal stabilizers was attributed to splitting the dipole mode nearest to the quadrupole mode into two modes that had similar characteristics – one with frequency above the quadrupole and one below the quadrupole. Perturbations would tend to mix these modes equally with opposite polarity, thus canceling their effect. Another problem encountered with the azimuthal stabilizers was that mode splitting occurred, but the two modes did not always have the same characteristics and, therefore, the cancellation was ineffective. The end tuners worked better and have now been adopted on both the GTA RFQ and the CWDD RFQ.

RFQ Construction

RFQs must be fabricated with precision, because the gap between the vanes is small with respect to the overall dimensions of the cavity, and small changes in the gap cause large changes in the frequency. An RFQ can be thought of as a waveguide with open boundary conditions on the end. The desired mode operates at the cutoff frequency of the waveguide. If the gaps between the four vanes vary or are unequal, the fields of the quadrupole mode will not be flat, and the dipole modes will mix with the quadrupole mode. One method of tuning RFQs has been to move the vanes to equalize the gaps, which sometimes involved bending the vanes with positioners holding the vanes in the RFQ. After the vanes were aligned mechanically, improving the field distribution was only possible by trail and error; furthermore, this procedure left the RFQ with built-in stresses that would slowly release with time, which could change the field distribution. In addition, this tuning procedure was usually very time consuming.

A better method of constructing RFQs has been to machine the vanes so that they are straight, align them mechanically without bending the vanes, and assemble them in as stress-free condition as possible. Those designs that use C seals for the rf joint will necessarily have some stress associated with the compression of the C seals. The structure can then be tuned with slug tuners on the outer wall as described above. Moving vanes for tuning the RFQ in the precise way that slug tuners can be moved for tuning is impossible. Some of the RFQs that have been built with this philosophy include the BEAR RFQ, the CWDD RFQ, the GTA RFQ, and the CERN RFQ, called RFQ2[6].

When designing an RFQ, maintaining a constant capacitance per unit length along the length of the RFQ is important. New designs do not have a constant r_0, the average distance from the vane tip to the center line, along the RFQ. This average distance is.increased when the modulation of the vane tips would otherwise decrease the aperture of the RFQ. Decreasing the aperture of the RFQ would decrease the current carrying capacity. If the RFQ cross section is not changed, a change in r_0 would result in a change in the capacitance and a change in the local cutoff frequency of the waveguide, which would cause a severe tilt in the fields. To keep a constant capacitance per unit length when r_0 is not kept constant, Los Alamos changes the radius of curvature (ρ) of the vane tip. As r_0 is increased, ρ is increased in such a way that the cutoff frequency remains constant as calculated by SUPERFISH. Keeping the cutoff frequency constant by maintaining a constant capacitance per unit length has an important advantage: measuring the magnetic field with a beadpull near the outer wall gives an accurate measure of the voltage across the gap. If the cutoff frequency was kept constant by changing the outer wall and allowing the capacitance to vary, the beadpull data would need to be corrected to measure the gap voltage, or a beadpull in the gap would need to be performed.

Summary

New methods of building and tuning RFQs have resulted in RFQs that have high quality fields and that are easy to tune.

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