RFQ BEAM DYNAMICS MODEL DEVELOPMENT†

A. M. M. Todd and M. F. Reusch
Grumman Space Systems Division, 4 Independence Way, Princeton, NJ 08540, U. S. A.

Abstract

A generalized electric multipole coefficient fitting code, VFIT, that has been developed to match arbitrary RFQ vane profiles to high accuracy is described. These coefficients of a generalized potential are then passed to a modified version of PARMTEQ which performs the RFQ beam dynamics in the presence of arbitrary vane errors. For a particular high brightness mass 2 RFQ design, the results of both symmetric and asymmetric vane displacement errors are presented. The resultant performance degradation due to the induced dipole mode is found to be small at conventional tolerance levels (1 mil) and above. The effect of machining the vanes according to a two-term potential or constant transverse radius prescription is also examined. Only an n=1, m=4 octopole, and to a lesser extent an n=0, m=6 dodecapole term, are found to lead to serious transmission performance degradation at high values of the cell modulation factor combined with small values of $\beta\lambda/2r_o$ and ρ/r_o. For the mass 2, $\rho = 3/4\ r_o$, RFQ considered, the transmission drops an additional 13% with the constant transverse radius cut. Further, the additional losses are in the high energy accelerating section of the device.

1. Introduction

High brightness accelerator design requires improved attention to details of the beam dynamics design of the components. To that end, we have developed improved RFQ beam dynamics models that address these issues.

A code, VFIT, that calculates the various multipole components corresponding to arbitrary vane geometry has been developed. We have also modified our standard version of PARMTEQ to accommodate axially varying arbitrary input multipole components.

These codes are then applied to the beam dynamics study of a high brightness, 352 MHz mass 2 RFQ design. This 430 cell RFQ accelerates the ion beam from 200 KeV to 2 MeV in a distance of 4.6 wavelengths. The peak modulation factor is 1.6, $r_o \sim 0.328$ cm, a constant transverse radius $\rho = 3/4\ r_o$ vane design is used and the peak surface electric field is 1.8 Kilpatrick.

Initial results indicate that attention needs to be paid to high order multipole terms since there are conditions under which significant performance degradation can result from their inclusion. However, minor design modifications can generally recover close to the basic two term potential performance.

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2. RFQ Vane and Beam Dynamics Models

A generalized electric multipole coefficient fitting code, VFIT, has been developed to match arbitrary RFQ vane profiles to high accuracy. However, unlike the image charge model of Crandall[1] and the finite element solution technique of Diserens[2], the potential coefficients are determined by a relatively simple least-squares fitting technique to a given vane geometry, which is tolerant of the large problem condition number. This is accomplished by using a single value decomposition (SVD) numerical scheme applied with regularization techniques[3] to stabilize the solution.

The potential is expanded as,

$$U(r,\theta,z) = V \{ \sum_{m=0}^{\infty} A_{om}\, r^m \cos(m\theta) + \sum_{m=0}^{\infty} B_{om}\, r^m \sin(m\theta)$$
$$+ \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} A_{nm}\, I_m(nkr) \cos(m\theta) \cos(nkz)$$
$$+ \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} A'_{nm}\, I_m(nkr) \cos(m\theta) \sin(nkz)$$
$$+ \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} B'_{nm}\, I_m(nkr) \sin(m\theta) \cos(nkz)$$
$$+ \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} B_{nm}\, I_m(nkr) \sin(m\theta) \sin(nkz) \} / 2 \qquad (1).$$

VFIT calculates the coefficients A_{nm}, A'_{nm}, B_{nm}, B'_{nm} of Eq.[1], which can be used to represent both dipole and other non-quadrupole terms of arbitrary azimuthal and longitudinal symmetry. Specific features of the VFIT calculation include the automatic generation of geometry for Crandall's vane types, the ability to study asymmetric vane geometries, and a multi-cell fitting algorithm for longitudinal variation. An important aspect is that we have demonstrated the ability to accurately resolve moment coefficient variation for vane displacements of less than ± 1 mil (0.001 inch), which is the order of the engineering vane tolerance level for high brightness RFQs. Figure 1 shows a comparison between VFIT and Ref. [1] results for the accelerating efficiency, A_{10}, of a type 1 vane at three different values of $l = \beta\lambda / 2 r_o$, as a function of the vane modulation factor, m. Good agreement is evident for these disparate solution procedures.

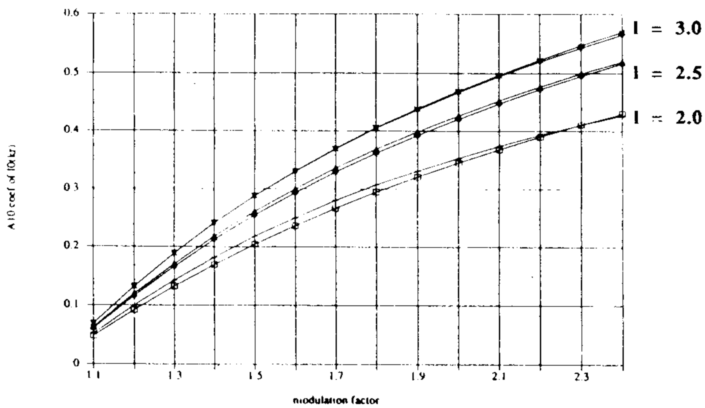

Figure 1. Comparison of the Accelerating Efficiency, A_{10}, Calculated by Crandall[1] and VFIT

3. Beam Dynamics Results

We have used VFIT to pass the various potential multipole coefficients to a modified version of PARMTEQ in order to perform RFQ beam dynamics in the presence of arbitrary vane errors. The results for a high brightness mass 2 RFQ design of both symmetric and asymmetric vane displacement errors show no significant performance degradation within a ± 1 mil engineering tolerance for vane machining and alignment.

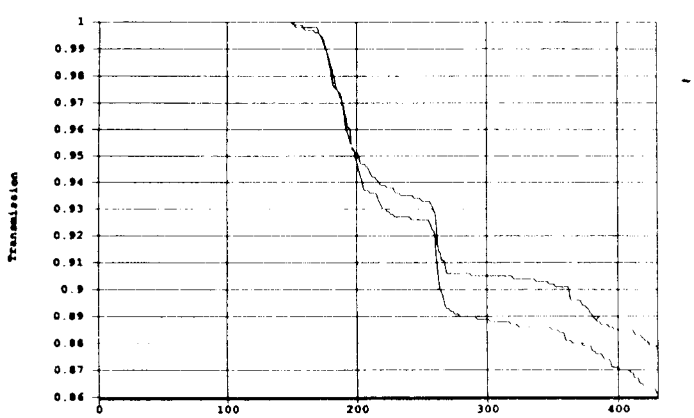

Figure 2. Transmission Profile for the Baseline Case and a 5 mil Off-Set "Y" Vane

Figure 2 shows the resultant axial transmission profile for the baseline case and one in which one "Y" vane is off-set by -5 mils along the entire length of the RFQ. This extreme case, as compared to the engineering tolerance level, introduces a dipole electric field component which leads to insignificant longitudinal (not shown) and transverse emittance growth, figure 3, and to the illustrated minor transmission loss (~ 1.5 %) with respect to the design point value. There is however an offset of the output beam axis due to the presence of the dipole field component which is shown in figure 4. The magnitude of this offset would however be readily correctable and is not significant.

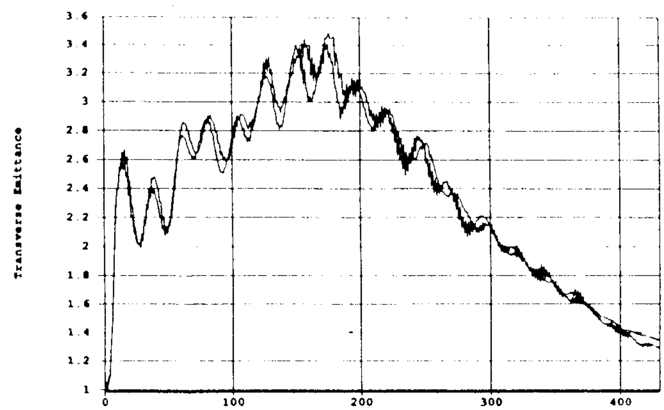

Figure 3. Axial Transverse Emittance Growth for the Baseline Case and a 5 mil Off-Set "Y" Vane

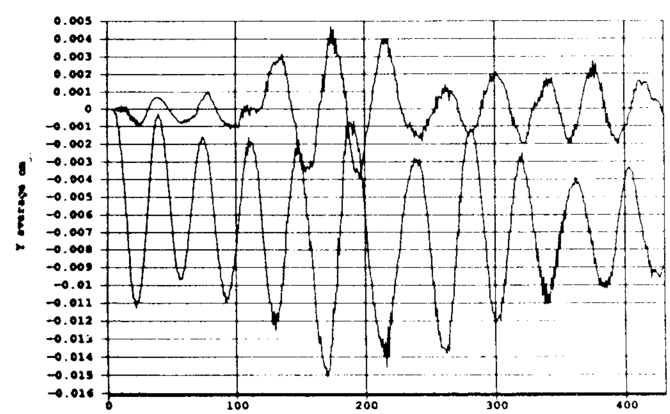

Figure 4. Axial Beam Axis Variation for the Baseline Case and a 5 mil Off-Set "Y" Vane

Next, we considered the effect of the specific vane tip geometry on output performance. For this study we compared the beam dynamics performance of a constant transverse radius ($\rho = 3/4\ r_0 \rightarrow$ Type III Vane) RFQ vane geometry with an equivalent two term potential cut. A comparison of the various multipole coefficients at a modulation factor, m=1.5, for two values of $I = \beta\lambda/2r_0$ is illustrated in Table 1. The VFIT values yield an rms voltage error of less than 0.003. When we apply these coefficients to our mass 2 RFQ design, as shown in figure 5, we find that this can lead to significant degradation in transmission performance (~13% reduction). By considering the effect of various coefficients we have identified the n=1, m=4 octopole term as the culprit. The n=0, m=6 dodecapole mode can also plays a significant role in the resultant beam dynamics performance. Table 2, illustrates the impact on transmission of these various multipole components.

These results agrees with those of Chidley[4], who found similar behavior at high modulation (m ~ 2) in a mass 1 RFQ design. Increasing ρ with respect to r_0 leads to improved transmission because the octopole coefficient decreases rapidly as $\rho \rightarrow r_0$. The correlation of the transmission loss with the rise of the octopole coefficient along the RFQ length can be seen by comparing figures 5 and 6. Figure 6 shows that our mass 2 RFQ has a rapid rise of the octopole term in the accelerating section due to the rapidly increasing modulation factor, although l ~ 5.7 for m=1.6 at the 2 MeV exit energy. Regrettably, the additional loss consists of high energy particles in the RFQ accelerating section.

Table 1a. Multipole Coefficient Comparison

m = 1.5, l = 2.0				
n	m	Two Term	VFIT ρ=3/4	Crandall ρ=3/4
0	2	1.000	1.003	0.992
0	6	0.000	0.036	0.037
1	0	0.395	0.295	0.324
3	0	0.000	0.001	0.002
1	4	0.000	0.134	0.099
2	2	0.000	0.033	0.023
2	6	0.000	0.002	0.005
3	4	0.000	0.001	0.002

Table 1b. Multipole Coefficient Comparison

m = 1.5, l = 4.0				
n	m	Two Term	VFIT ρ=3/4	Crandall ρ=3/4
0	2	1.000	0.983	0.983
0	6	0.000	0.037	0.033
1	0	0.392	0.361	0.363
3	0	0.000	0.002	0.001
1	4	0.000	0.066	0.060
2	2	0.000	0.017	0.016
2	6	0.000	-0.001	-0.001
3	4	0.000	-0.001	0.002

Table 2. Transmission Dependence on Multipole Coefficients

Transmission(%)	n=1, m=4	n=0, m=6	Other Terms
87 (Two Term)	No	No	No
76 (Eight Term)	Yes	Yes	Yes
84	No	No	Yes

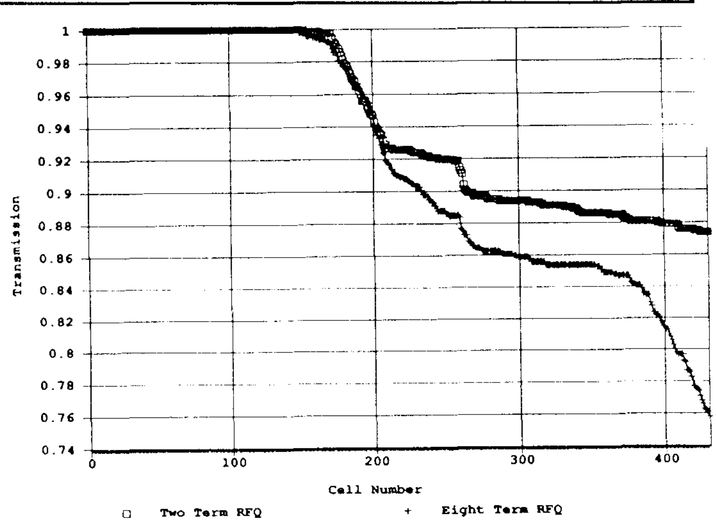

Figure 5. Axial Transmission Variation of Two Term and Eight Term (Type III) RFQ Vane Geometries.

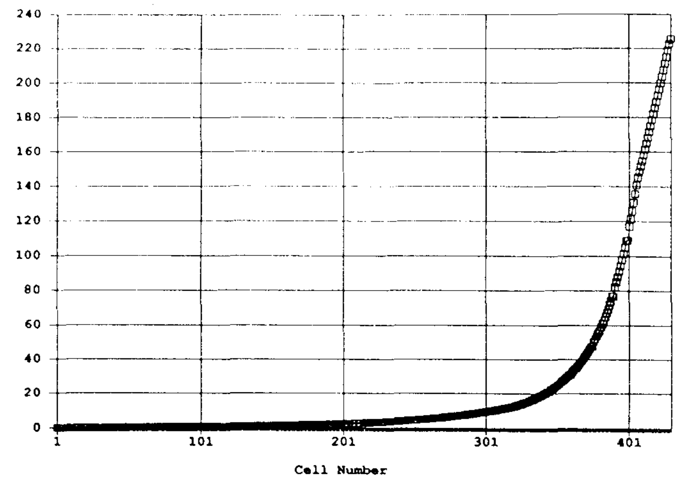

Figure 6. Axial Variation of the n=1, m=4 Octopole Term

4. Conclusions

Recent model development for high brightness RFQ beam dynamics analysis has been described. Specific applications that illustrate the utility of these models have been presented. We conclude from the dipole results that the principal driver for high accuracy vane machining appears to be the RF cavity characteristics (frequency sensitivity) rather than the beam dynamics performance. However, the high order multipole beam dynamics performance should be checked since particularly the n=1, m=4 octopole and the n=0, m=6 dodecapole mode can lead to beam dynamics performance degradation when the modulation factor is high ($m \geq 1.5$) while either ρ/r_0 is small ($\rho/r_0 \leq 0.75$) or $\beta\lambda/2r_0$ is small ($l \leq 4$). Relatively minor vane design modifications should circumvent this problem and recover close to the two term potential beam dynamics performance. Further studies are required to confirm and understand this behavior and to more clearly map out the regions of parameters space that lead to performance degradation problems.

5. References

1 K. R. Crandall, "Effects of Vane-Tip Geometry on the Electric Fields in Radio-Frequency Quadrupole Linacs", *Los Alamos Report* LA-9695-MS, April 1983.

2 N. J. Diserens, "Investigation of the Effects of Space Charge and Image Charge Forces on Beam Loss in an RF Quadrupole", *Proceedings of the 1984 Linear Accelerator Conference*, Santa Fe, New Mexico, page 91.

3 A. N. Tikanov, *Dokl. Akad. Nauk SSSR* **151** (1963) 501.

4 B. Chidley and G. McMichael, *Priv. comm.*