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ELECTROMAGNETIC MODELING OF 4-ROD RFQ TUNING

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Abstract

Modern codes make possible detailed electromagnetic (EM) 3D modeling of RFQ accelerators. We have recently analyzed two 201.25-MHz 4-rod RFQs – one commissioned at FNAL [1] and a new design for LANL [2] – with CST Studio using imported manufacturer CAD files. The RFQ EM analysis with MicroWave Studio (MWS) was followed by beam dynamics modeling with Particle Studio as well as other multi-particle codes. Here we apply a similar approach to study the process of RFQ tuning in 3D CST models. In particular, the results will be used to better understand tuning the voltage flatness along the new LANL 4-rod RFQ.

INTRODUCTION

Radio-frequency quadrupole (RFQ) accelerators are now standard in front ends of modern ion linacs. They are usually designed with codes that rely on electrostatic field approximations, e.g., Parmteq [3]. While this is justified for classical 4-vane RFQs having perfect quadrupole symmetry, many modern RFQs contain elements that break such a symmetry. Additional RF field effects can be introduced by asymmetric elements like vane windows in split-coax designs or stem supports in 4-rod RFQs. Such effects are more complicated and can't be easily taken into account in electrostatic calculations, even in 3D, but can influence beam dynamics in some cases. We have discussed 3D RF effects in 4-rod RFQs in [4].

LANL is moving forward with replacing one of its aging Cockcroft-Walton injectors with an RFQ-based front end for the LANSCE proton linac [5]. The LANL H^+ RFQ, operating at 201.25 MHz at a duty factor up to 15%, with 35-keV injection and 750-keV final energy, should satisfy special requirements when incorporated into the existing medium-energy beam transfer that works with multiple beam species. The 4-rod type RFQ design was developed in collaboration between IAP (Frankfurt) and LANL. The RFQ was manufactured by Kress GmbH and recently delivered to LANL. The CAD files from Kress were imported into CST Studio [6] to create an RFQ model that was used to evaluate its performance [2].

4-ROD RFQ TUNING

RFQ CST Model

The imported CAD model was simplified by removing details nonessential for EM analysis such as external supports, etc. The RFQ cavity walls were also removed, leaving only the resonator vacuum volume in the CST model. The resulting model is shown in Fig. 1. Here the RFQ vacuum vessel, in gray-blue, is 175-cm long (wall-to-wall), 34-cm wide, and 30-cm high (along the stem direction, *z*). The model includes a frequency slug tuner (cyan cylinder) and two 5-cm-long beam pipes of radius 2 cm attached to the vacuum vessel, but other ports are ignored. The RFQ vanes are supported by 24 stems that are spaced longitudinally with variable period, 75 mm in the center and 69.5 mm for three periods near each end. There are 23 tuners that electrically short two adjacent stems and can be moved along them (in *z* direction) to adjust the mode frequency and voltage profile (flatness) along the structure length. The variable stem spacing simplifies tuning the voltage flatness along the structure. Our RFQ model uses the CAD model coordinates: *x* is along the RFQ axis, and the beam is moving in *-x* direction (right to left in Fig. 1).

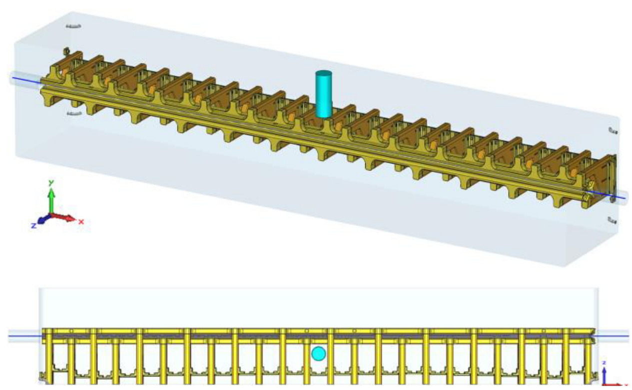

Figure 1: CST model of the LANSCE H^+ RFQ (top) and its side view (bottom).

One can see in Fig. 1 (bottom) that the tuners are at different heights: they are adjusted in the model to make the inter-vane voltage flat within ±1%. However, even with all tuners at the same height, the voltage is flat within ±5%, due to the variable stem spacing, see below.

RF Field Calculations with MWS

The fields in the RFQ model are calculated using the hexahedral AKS eigensolver; it approximates complicated surfaces well but is slow due to minimal parallelization. The efficient tetrahedral eigensolver fails to mesh the imported RFQ CAD model. The inter-vane voltages are obtained by integrating the electric field of the operating mode along short segments located in the middles of the RFQ stem periods between the vanes. The voltages calculated in different locations along one stem period show some variation (scalloping). The RFQ-model frequency is tuned to 201.226 MHz when all tuning plates are positioned at the same height, h=27.15 mm, from the ground plate. The voltage profiles calculated from the MWS eigenmode solution are plotted in Fig. 2 versus stem period number n; n = 0 is the middle of RFQ, negative n values correspond to the downstream end (left in Fig. 1). There are two profiles: V_y is calculated by integrating the field on both sides from the axis and averaging the two voltages to minimize errors – this is our usual procedure; for V_z the voltages are calculated

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between two top vanes, by integrating the field above the axis, along short blue vertical segments shown in Fig. 3. The last approach is more similar to measurements. The two profiles are very close, with only small deviations near the RFQ ends. At the same time the average voltage values are different, $V_{z,av} = 1.21V_{y,av}$. The maximum and minimum relative voltages V_y/V are +4.2% and -5.0% from the average; the total spread is 9.2%.

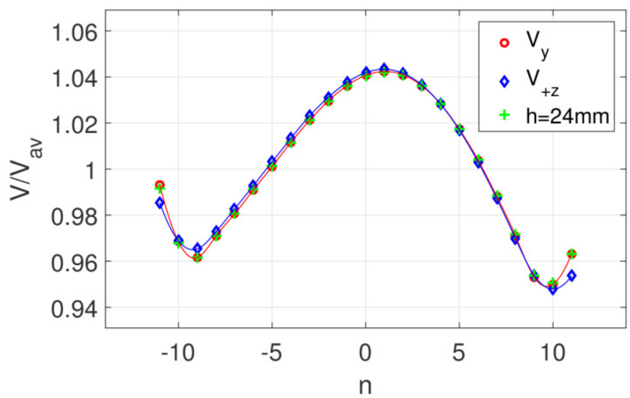

Figure 2: LANL RFQ voltage profile before tuning versus stem period number from MWS computations.

For comparison, Fig. 2 shows one more profile V_y (green crosses) for the model where all tuning plates were at h=24 mm. It practically overlaps with that for h=27.15 mm, even though the frequency with h=24 mm is lower, 198.832 MHz. The frequency sensitivity is df/dh=0.76 MHz/mm when all 23 tuners are moved together; for one tuner it is about 23 times smaller.

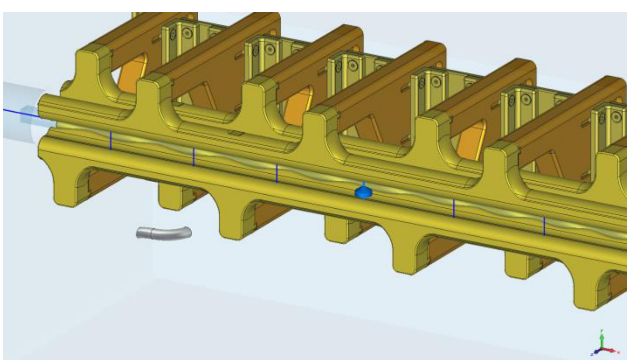

Figure 3: Details of RFQ CST model with RLC circuit between top vanes in the middle of stem period n = -8.

To flatten the profile, we move tuners up near the RFQ middle (it brings the voltages down) and down near the ends. After a few iterations, the voltage profile in the CST model is tuned, see Fig. 4. The max/min tuned voltages V_y/V are +0.63% and -0.98% from the average, with the total spread of 1.61%. To achieve this voltage profile, some tuners were displaced by as much as 12 mm from their positions before the profile tuning. The frequency in the tuned model was 201.223 MHz. After the profile is tuned, the final frequency adjustments can be done using the slug tuner shown in Fig. 1. The calculated frequency adjustment range of the tuner is about 0.4 MHz.

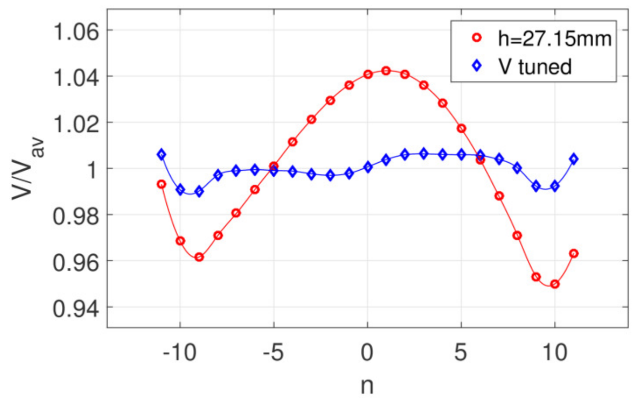

Figure 4: RFQ voltage profile in CST model before (red) and after tuning (blue) versus stem period number.

Measurements of RFQ Voltage Flatness

The procedure of frequency and voltage profile tuning in 4-rod RFQs is well developed, e.g. [7, 8]. The tuning plates are easily accessible when the RFQ box lid is open. The profile tuning starts with measuring the frequency shifts Δf_n caused by attaching a small capacitor (C_0 = 1 pF) to the middle point of each of N = 23 periods in the RFQ subsequently, n = 1, 2…N. Here $\Delta f_n = f_n - f_0$, where f_n is the measured frequency with the capacitor attached in the n^{th} connection point and f_0 is the unperturbed frequency of the RFQ operating mode, without capacitor. The main assumption is that this small added capacitor creates a small electric energy perturbation $\Delta W_n = C_0(V_n)^2/2$ by charging to the voltage V_n that exists in the RFQ operating mode in the n^{th} connection point without noticeably changing the voltages V_n, n = 1, 2…N. Within this assumption, one can relate the frequency shifts and energy perturbations using the Slater perturbation theorem: $\Delta f_n/f_0 = -\Delta W_n/W_{tot}$, where W_{tot} is the total energy in the RFQ operating mode. It provides the relation between voltages and frequency shifts. Defining the average voltage $V=\langle V_n\rangle$, where $\langle\ldots\rangle$ means averaging over N periods, the normalized voltage profile can be expressed via frequency shifts:

$$V_n/V = \sqrt{-\Delta f_n} \Big/ \left\langle \sqrt{-\Delta f_n} \right\rangle. \qquad (1)$$

As an illustration, Fig. 5 shows the voltage profile obtained using Eq. (1) from frequency measurements data for the LANL RFQ at IAP [9] for the case when all 23 tuners were at the same height, h=24 mm. The unperturbed frequency with the open lid was 198.190 MHz. In this profile, the maximum and minimum relative voltages are +4.5% and -4.7% from the average, with the total spread of 9.2%. The calculated maximum and minimum relative voltages V_y/V for h=24 mm were +4.2% and -4.9% from the average, with the total spread of 9.1%, cf. Fig. 2. These extremes are close to those in the measured profile in Fig. 5, though the calculated profile in Fig. 2 looks more symmetric while the measured one in Fig. 5 has a more pronounced tilt.

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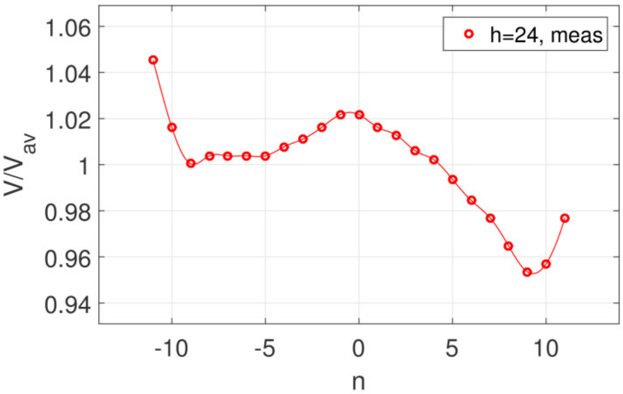

Figure 5: LANL RFQ voltage profile before tuning versus stem period number from measurements.

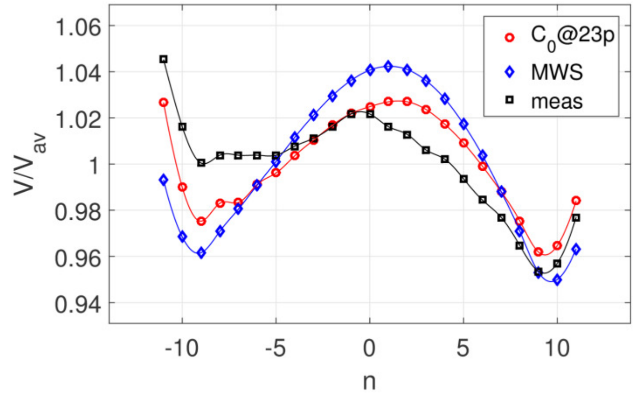

Figure 6: Profiles from MWS simulation of measurements (red), direct MWS computation (blue, same as in Fig. 2), and measurement results (black, same as Fig. 5).

CST Modeling of Flatness Measurements

The flatness measurement process can be simulated in MWS by calculating the mode frequency in a model with and without added capacitor C_0. This can be done using the hexahedral JDM eigensolver, which allows including RLC circuits. Figure 3 shows such an RLC circuit with capacitor $C_0 = 1$ pF attached to the middle of stem period $n = -8$. However, this approach is tedious since it requires at least N+1 separate MWS runs. Moreover, since the JDM solver cannot use partially filled cells, computation results may depend more on meshing details. To improve accuracy, it is useful to keep the same mesh for all runs. 23 separate MWS runs were performed with meshes ~15M points to calculate mode frequencies f_n with the capacitor $C_0 = 1$ pF added as a part of an RLC circuit in the middle of each of 23 periods. For calculating f_0 we run the same model but with capacitance set to $10^{-12}C_0$ ("effectively zero") in the central period (MWS can't accept $C_0 = 0$ in an RLC circuit). For better accuracy MWS runs with capacitance $10^{-12}C_0$ should be repeated for all 23 periods to minimize mesh effects. It was done only for a few points; calculated values of f_0 from these runs are slightly different. The resulting profile is shown in Fig. 6 (in red) for h=27.15 mm and compared with profiles from direct MWS calculation and from RFQ measurements. Though the first two profiles in Fig. 6 are for h=27.15 mm, while the profile from measurements is for h=24 mm, cf. Fig. 5, the difference should be small, as we saw in Fig. 2. The profile comparison in Fig. 6 shows that the MWS simulation of measurements gives the result somewhere between those from the direct MWS calculation and RFQ measurements. The measured profile has a larger tilt than calculated ones.

For RFQ measurements the capacitor value C_0 should be large enough to allow reliable measurements of the frequency shifts Δf_n caused by the capacitor. On the other hand, the added capacitor should provide just a small perturbation of the voltage profile. Our calculations show that though the frequency shifts are small (<1 MHz), the voltage profile with added capacitor can differ from the unperturbed one by up to 8% due to its tilt and distortion.

CONCLUSION

The RFQ tuning process was studied using 3D CST models of the new LANL 4-rod RFQ. Our simulation results are compared with results of measurements of the voltage flatness along the RFQ. We found a reasonable agreement between calculations and measurements. Some small differences can be attributed to the fact that measurements are performed on the RFQ with the open lid while computations are done for the closed RFQ box. Even without tuning, the voltage profile was rather flat due to the RFQ design with variable stem spacing.

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