REALISTIC MODELING OF 4-ROD RFQS WITH CST STUDIO

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Abstract

RFQ accelerators are usually designed and modeled with standard codes based on electrostatic field approximations. There are recent examples when this approach fails to predict the RFQ performance accurately: for 4-rod RFQs 3D effects near the vane ends can noticeably influence the beam dynamics. The same applies to any RFQ where the quadrupole symmetry is broken, e.g., 4-vane RFQ with windows. We analyzed two 201.25-MHz 4-rod RFQs – one recently commissioned at FNAL and a new design for LANL – using 3D modeling with CST Studio. In both cases the manufacturer CAD RFQ model was imported into CST. The EM analysis with MicroWave Studio (MWS) was followed by beam dynamics modeling with Particle Studio (PS). For the LANL RFQ with duty factor up to 15%, a thermal-stress analysis with ANSYS was also performed. The simulation results for FNAL RFQ helped our Fermilab colleagues fix the low output beam energy. The LANL RFQ design was modified after CST simulations indicated insufficient tuning range and incorrect output energy; the modified version satisfies the design requirements. Our PS results were confirmed by multi-particle beam-dynamics codes that used the MWS-calculated RF fields.

INTRODUCTION

Radio-frequency quadrupole (RFQ) accelerators are now common in front ends of all modern ion linacs. Usual RFQ design codes, e.g., Parmteq [1], rely on electrostatic field approximations that are justified for classical 4-vane RFQs with perfect quadrupole symmetry. Many modern RFQs contain elements that break this symmetry. RFQ vane modulations introduce symmetry perturbations to create a longitudinal accelerating field, which is the basic idea of the RFQ structure. Their effects are accounted in analytical field representation in the codes or can be calculated by solving an electrostatic problem. However, additional field effects can be introduced by asymmetric elements like vane windows in split-coax designs or stem supports in 4-rod RFQs. These 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 discuss such RF effects in two 4-rod RFQs that we have recently analyzed in details [2, 3] with CST Studio [4].

RFQ MODELS

It is important to have an accurate model of the RFQ cavity for its EM analysis. In both cases under consideration a CAD model from the manufacturer Kress GmbH was imported into CST. The model was further simplified by removing details unessential for EM calculations. The RFQ cavity walls were also removed, leaving only the resonator vacuum volume in the CST model. The outer boundaries are assumed perfect-conducting for EM simulations. The resulting model for the new LANL RFQ is shown in Fig. 1. Here the RFQ vacuum vessel, in light-blue, is 175-cm long.

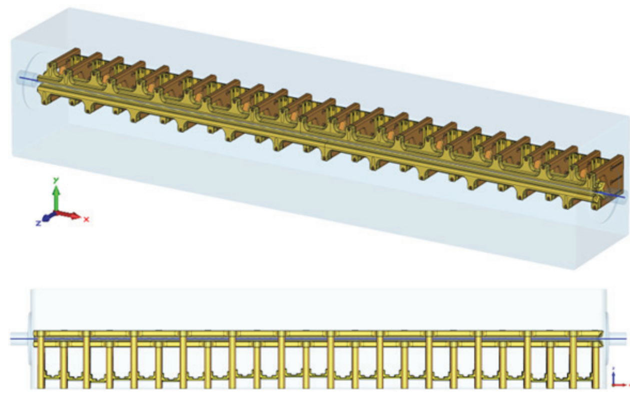

Figure 1: CST RFQ model (top) and its side view.

The tuners between the adjacent stems (bottom) are at different heights. They are adjusted in the CST model to make the inter-vane voltage flat, see Ref. [3].

ELECTROMAGNETIC ANALYSIS

We studied the RFQ models using the CST MicroWave Studio (MWS). The mode frequencies and RF fields were calculated by the AKS eigensolver that provides more accurate surface approximations. In the latest CST version of 2014 the CAD import has been improved, which may allow using its more efficient tetrahedral eigensolver. The RF fields have some interesting features. One is the longitudinal electric field in the end gaps that separate the vane ends from the RFQ box walls (end-gap bumps) as illustrated in Fig. 2 for the FNAL 4-rod RFQ, see in [5].

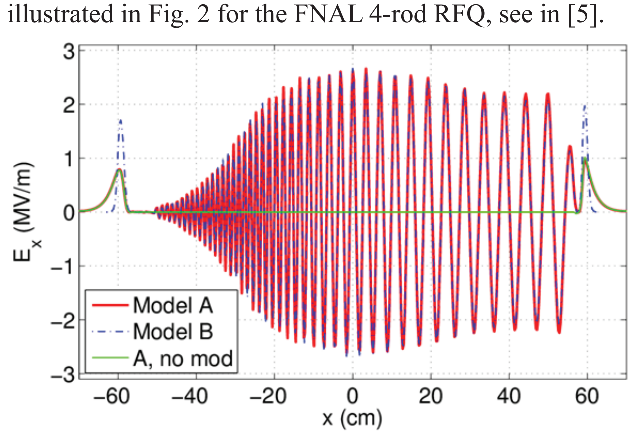

Figure 2: On-axis longitudinal field in FNAL RFQ.

Two RFQ models were studied [2]: with wide beam pipes attached to the RFQ cavity (A) and with narrow ones (B). The RFQ accelerating field – the oscillating part in the curves in Fig. 2 – is produced by the vane

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modulation; the longitudinal field, however, also has two peaks, near the entrance and exit. The RFQ cavity extends from x = -60 cm to x = 60 cm. Note that the RF fields extend into the beam pipes. The end-gap longitudinal field exists because the quadrupole symmetry is broken near the RFQ ends; it would vanish in a perfectly symmetric structure. The end-gap bumps depend on the diameter of beam pipes attached to the RFQ, cf. Fig. 2, while the accelerating fields coincide in the two models. In model B, the narrow beam pipes trap the fields in the gaps, so the peaks are higher and shorter. In model A without vane modulation (green curve) there is no accelerating field, as expected, but the end-gap bumps are the same as with modulation. The exit-end bump can change the output beam energy depending on the beam transit-time factor. This was the reason for the low output energy in the FNAL RFQ in its original configuration (B). Opening the exit beam pipe by removing an end-wall plug (change from B to A) restored the design energy [5].

One should mention that 3-D electrostatic computations of 4-vane quadrupole structure do not exhibit bumps since the static field remains quadrupole-symmetric, cf. Fig. 3. Even in 4-vane RFQs with vane cuts that distort the symmetry, e.g., the split-coaxial structure [6], the end-gap peaks are present, though in the particular case [6] they do not influence beam dynamics as drastically as here.

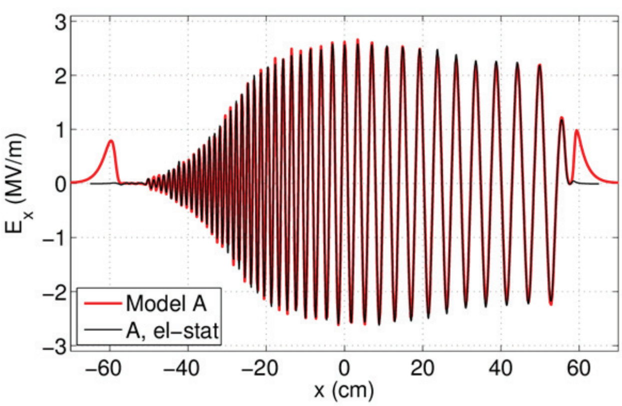

Figure 3: On-axis longitudinal field: RF vs. electrostatic.

Another feature typical for 4-rod RFQs is a small transverse horizontal (parallel to the RFQ ground plane) field component on its geometrical axis. It is illustrated in Fig. 4 that plots LANL RFQ on-axis field components: longitudinal E_l, horizontal E_h, and vertical E_v (along the stems) versus the longitudinal coordinate s. Here $s = -x$ because in the RFQ model of Fig. 1 the beam travels from right to left. This effect is due to the fact that the transverse electric fields between two upper vanes are stronger than between two lower ones. It results in the displacement of the center of the transverse quadrupole field down, to the ground plane, from the RFQ axis by 0.45 mm, to be compared to the 4-mm vane aperture. The effect is known in higher-frequency 4-rod RFQs [7]. We found no noticeable influence of this feature on beam dynamics in the two 4-rod RFQs we studied [2, 3].

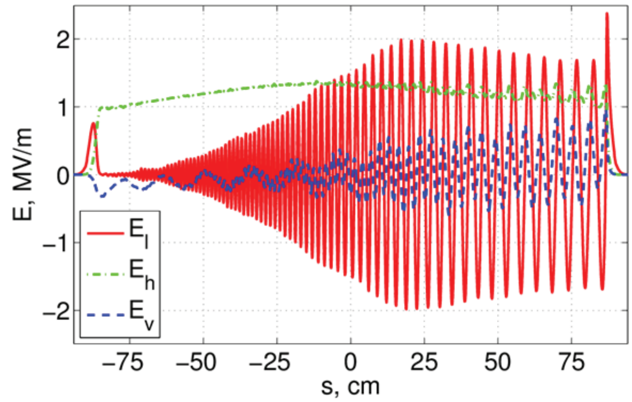

Figure 4: On-axis field components in LANL RFQ.

The end-gap bumps of the longitudinal field can also be seen in Fig. 4; their effect was taken into account in beam dynamics simulations. The initial design of the LANL RFQ was modified based on our simulation results to adjust the frequency tuning range and the final energy [3].

BEAM DYNAMICS

Multi-particle beam dynamics modeling based on the MWS calculated RF fields can be performed with either the CST Particle Studio (PS) particle-in-cell (PIC) solver or other codes. We cross-checked our PS results for the new LANL RFQ with two well-known dynamics codes, Parmela [1] and Beampath [8], and the results agree well. This comparison allowed us to find that the final transverse emittances reported in [3] were incorrect: they were calculated in the rotated coordinates of the CAD model of Fig. 1, so the horizontal and vertical emittances were mixed. The corrected results and more details on PS simulations for the LANL RFQ can be found in [9].

Initial "matched" distributions were generated using LAACG codes [1]. Matched CW beams of 10K macro-particles, one RF period long, were generated for several different currents using matched-beam Twiss parameters at the RFQ vane entrance and tracing particles back to the beam-pipe entrance. The resulting distributions were converted to CST PS format and repeatedly injected into RFQ during 10 - 100 RF periods. As an illustration, Fig. 5 shows macro-particles in the PS model of the LANL RFQ with 12-mA current at t = 405 ns (81.5T_{RF}) after the injection of 10x10K particles started. The total number of remaining macro-particles at this moment is about 97.4K, and most of them are densely packed in bunches. The particle energy is indicated by color; the energy scale is overlapped on the right. The particles propagate from right to left. More than 10 bunches are formed, due to the longitudinal space-charge push at the train ends; a few leading bunches visible in Fig. 5 are already accelerated and approaching the exit. Trailing low-energy particles are not captured in bunches. To exclude effects of space charge in the bunch-train head and tail, we analyze the average energy W, transverse normalized r.m.s. emittance ε_t, longitudinal emittance ε_l, and current transmission only for the bunches near the train center.

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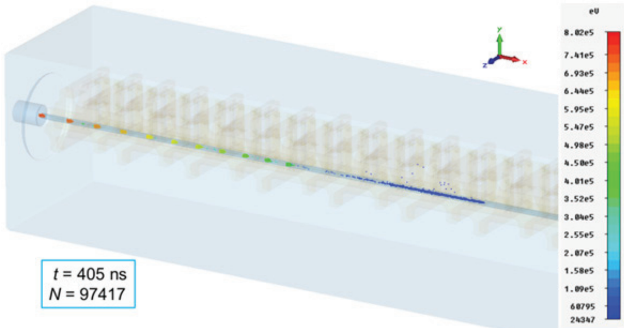

Figure 5: Particles in the LANL RFQ model for 12 mA.

Our PS results are summarized in Table 1. The initial distribution had a transverse normalized r.m.s. emittance 0.2 π mm·mrad in both transverse planes. The transverse emittance values are corrected compared to [3], cf. [9].

Table 1: Results for Different Currents in LANL RFQ

I, mA	*W*, keV	ε_t, π mm·mrad	ε_l, keV·deg	Trans-mission
0	756	0.25	128	0.99
12	756	0.26	85	0.97
35	753	0.27	87	0.88

PS simulations of RFQs can be significantly sped up if the RFQ structure is cut transversely to a narrow region around the vane aperture for particle runs. In fact, other codes [1, 8] do the same by restricting the simulation volume only to the beam aperture region. We compared results of PS runs with full and cut volumes and found no difference in the output beam parameters for the two 4-rod RFQs studied. This trick allowed us to run the initial beams up to 500 RF periods long on a PC, see in [9].

THERMAL ANALYSIS

The LANL RFQ is designed to operate at noticeable duty factors, up to 15%, so the structure thermal and stress analysis should be performed.

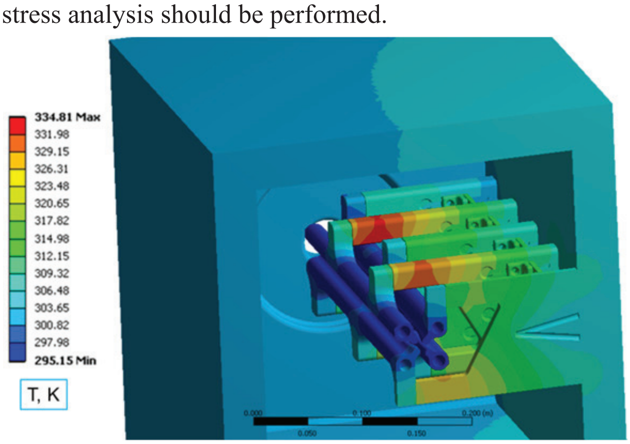

Figure 6: Temperature distribution from ANSYS [3].

The heat flux calculated in post-processing the MWS-computed RF fields was used for thermal-stress analysis with ANSYS [10]. The dissipated power is 77 kW at 100% duty for ideal copper surfaces. Cooling is provided by water running through cooling channels in stems and vanes. The temperature distribution in a structure slice near the RFQ exit is shown in Fig. 6 for the duty factor of 18% (to account for realistic surface conductivity). The temperature range is less than 40° C even in this extreme case. The maximal structure deformations were also found acceptable [3].

CONCLUSION

Detailed 3D modeling of RFQs is now possible with CST Studio. It includes importing or building a 3D CAD model followed by its EM analysis and multi-particle beam dynamics PIC simulations plus thermal analysis for high-duty RFQs. We successfully used this approach for two 4-rod RFQs with CST Studio running on a PC. Our results revealed 3D effects that were not found by standard design and analysis but significantly influence the RFQ performance. Other groups have used different tools, see Refs. [6, 11], for building RFQ models, their EM analysis, and beam dynamics studies. Independent of a particular choice of tools, this modern approach predicts the RFQ performance more reliably compared to the standard RFQ design codes.

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