COMPLETE RF DESIGN OF THE HINS RFQ WITH CST MWS AND HFSS*

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Abstract

Similar to many other linear accelerators, the High Intensity Neutron Source requires an RFQ for initial acceleration and formation of the bunched beam structure. The RFQ design includes two main tasks: a) the beam dynamics design resulting in a vane tip modulation table for machining and b) the resonator electromagnetic design resulting in the final dimensions of the resonator. The focus of this paper is on the second task. We report complete and detailed RF modeling on the HINS RFQ resonator using simulating codes CST Microwave Studio (MWS) and Ansoft High Frequency Structure Simulator (HFSS). All details of the resonator such as input and output radial matchers, the end cut-backs etc have been precisely determined. Finally in the first time a full size RFQ model with modulated vane tips and all tuners installed has been built, and a complete simulation of RFQ tuning has been performed. Comparison of the simulation results with experimental measurements demonstrated excellent agreement.

INTRODUCTION

Within the framework of the High Intensity Neutrino Source (HINS) program at FNAL, we plan to build and operate a portion of the Front End (up to energy of 62 MeV) as a technical feasibility proof of the proposal. A detailed description of the project and the current status is given in [1]. In the Front End test stand a four vane 325 MHz Radio Frequency Quadrupole (RFQ) will be used for bunching the beam and accelerating it from 50 keV to 2.5 MeV.

The complete beam dynamics design, resulted in a vane tip modulation table for machining, is described in [2]. The mechanical design concepts for this RFQ, tuning results, manufacturing of the RFQ in industry and the preliminary results of initial testing of RFQ at the Front End test stand are discussed in [3].

The electromagnetic design of RFQ resonators is rather complicated and requires essentially three-dimensional modeling. That, and also an additional complication with RF tuning because of some blunder made in the mechanical design of RFQ, urged us to develop a full length 3D RFQ model for simulation. Modern three-dimensional electromagnetic codes are now available and successfully used for RFQ design [4, 5, and 6]. This paper focuses exclusively on the computational technique of electromagnetic design. We report complete and detailed RF modeling on the HINS RFQ resonator using simulating codes CST Microwave Studio (MWS) and Ansoft High Frequency Structure Simulator (HFSS).

RFQ MODEL FOR ELECTROMAGNETIC SIMULATION

The basic parameters of the RFQ are given in table 1.

Table 1

Input energy	50 keV
Output energy	2.5 MeV
Frequency	325 MHz
Total length of vanes	302.428 cm
Average bore radius	3.4 mm

The RFQ design has several features that have been taken into account during electromagnetic simulations.

Instead of π-mode stabilizing loops (PISLs) usual for RFQs longer than ~3λ, where λ is the rf wavelength [7], FNAL's RFQ design uses the end-wall tuners - field stabilizers simpler than PISLs [8]. This method requires a precise knowledge of dipole mode spectrum, so simulating full length RFQ with end-wall tuners installed was needed.

Modulation of the vanes in the regular accelerating section of the RFQ is shown in Fig. 1. A variable modulation changes capacitive loading and therefore local frequency along RFQ as also reported elsewhere [4, 9, and 10]. In our RFQ the local frequency variation due to the modulation is significant, so the vane tip modulation has been included in the model.

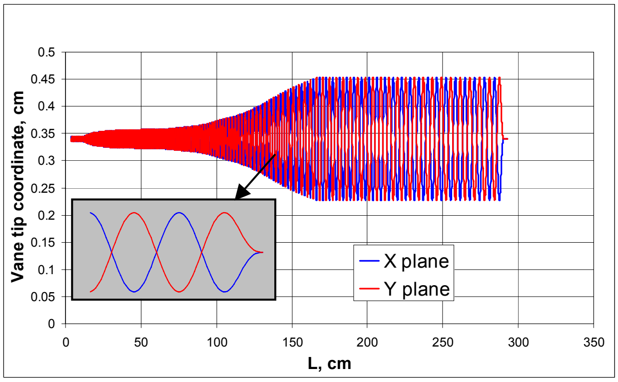

Figure 1: Vane tip modulation along RFQ. Radial matchers are excluded.

The output radial matcher is designed to form axially symmetric beam exiting the RFQ, and because of this special function it is different than the input radial matcher. Fig. 2 shows profile of the output radial matcher and imposed profile of the input matcher to compare with. The RFQ ends (cutbacks) can be tuned in simulations individually, but their combined effect on field flatness must be evaluated. Besides the end-wall tuners have

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different tuning range and sensitivity for input and output ends of the RFQ. So again, for proper RFQ end design a full length model had to be considered.

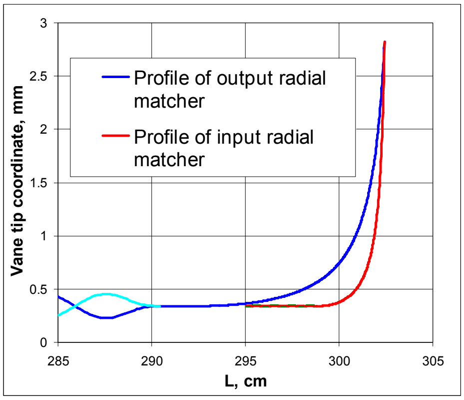


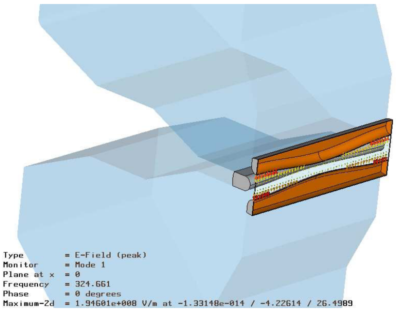
Figure 2: The Radial Matcher Profiles.

The basis of the 3D RF model prepared for simulation was a solid engineering model built in SolidWorks and stored in SAT format. The SAT file was then imported into CST Microwave Studio. CST MWS has its own well developed tools to work with solid models and to heal imported objects, so the RF model was completely prepared directly in MWS environment.

PERIODS OF RFQ

Many basic RFQ parameters can be obtained and defined with 2D approach. CST MWS and HFSS are entirely 3D codes, but RFQ "slices" with thickness of one mesh step were effectively used to define the basic RFQ parameters. Some RF features like PISLs and slug tuners can be studied with periods of RFQ [6]. The period of RFQ defined by the slug tuner spacing was simulated to evaluate slug tuning sensitivity. Also magnetic field distortion around slug tuners was investigated since the bumps created by the tuners were visible at the bead pull axis which was close to the tuners.

The specific vane tip modulation (see Fig. 1) attracted attention as a possible reason of the local frequency variation. To check whether the vane tip modulation affects local resonant frequency, one accelerating period with modulated vane tips (see Fig. 3) has been simulated. The frequency of the model was found to be 324.7 MHz, while the frequency of the same model with identical average bore radius and no modulation was 323.5 MHz. The difference of 1.2 MHz is significant for such a long RFQ and must be taken into account.



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Type          = E-Field (peak)
Monitor       = Mode 1
Plane at x    = 0
Frequency     = 324.661
Phase         = 0 degrees
Maximum-2d    = 1.94601e+008 V/m at -1.33148e-014 / -4.22614 / 26.4989
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Figure 3: A model of accelerating period #267.

RFQ END TUNING

Field flatness is always one of the most important tasks for RFQ tuning. This parameter is very sensitive (especially in long RFQs) to proper vane terminations. The RFQ ends are supposed to be tuned by appropriate geometry and dimensions of undercuts and the errors are usually hard to fix.

In the RF 3D model the end-wall tuners were set to a default value of 25.4 mm of penetration as it was during the initial RF measurements. The tuning slugs were flush with the inner wall of the RFQ cavity, so the slugs were not included in RF model for the vane end tuning. Each RFQ end can be tuned separately, so applying appropriate boundary conditions we used 1/8 of the full model, which is equivalent to full length RFQ with two input or two output ends. Actually the model can be of any length for this tuning, but we prefer to use field flatness as a tuning criterion which is more sensitive for longer cavity. If a local frequency is used as a tuning criterion, a reasonably short model should be used for higher sensitivity.

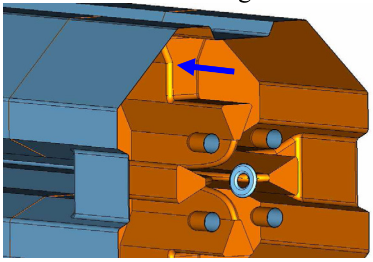

Figure 4: A model of RFQ output end. The back wall (marked by arrow) is moved for tuning.

After main dimensions of cut-backs have been found, the back wall as the most influential parameter was being moved inward (i.e. "removing" of material) for fine tuning (Fig. 4). We monitored the electric field distribution of quadrupole mode along RFQ at 4 mm and 45° off the axis (in the gap between tips). The field distribution changes with cut-back variation as it is shown in Fig. 5, and it gets flat at optimal cut-back of 65.6 mm.

COMPLETE SIMULATION

Initially the full length model was used to obtain realistic spectrum of quadrupole and dipole modes with end-wall tuners installed, since the exact mode spacing is a key for field stabilization in the RFQ. Then it was realized that the vane tip modulation cannot be ignored, and this feature has been added to the full length model.

The attempts to perform the simulation of the full model with MWS were not successful. It was decided to transfer the problem into HFSS. Using powerful MWS modeler the vane tip modulation was prepared in faceted representation of shape that is more appropriate for triangulated surface meshing in HFSS (see Fig. 6).

The model parameters were set in accordance with actual initial RFQ settings during RF measurement just after final assembly [11]. Fig. 7 shows the field distributions as simulated with and without vane modulation in comparison to the previous actual

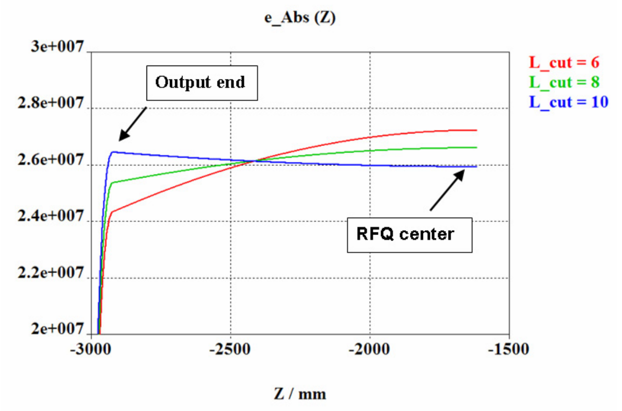

Figure 5: Field distribution with varying cut-back depths.

measurements. With the vane tip modulation included in the model, the simulation reproduces the measurements with high accuracy, including both total field distribution tilt and sinus-like shape. Therefore, the theory that the vane tip modulation is responsible for the additional field distribution distortion is supported. Without modulation, the field tilt in the simulation is due only to the detuned output matcher.

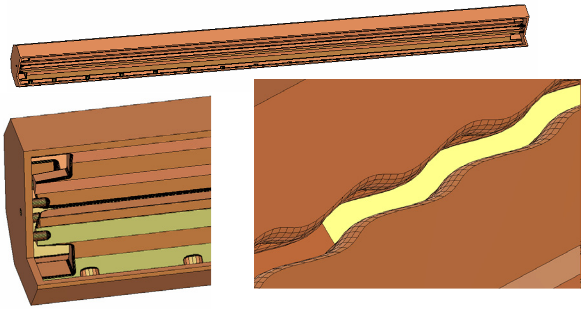

Figure 6: Full length RFQ model with vane tip modulation, radial end matchers, end-wall tuners and slug tuners.

To check final RFQ tuning in simulation, the output matcher cut-back dimensions in the solid model were set to the specified values and slug tuners were introduced. Skipping intermediate simulations of the tuning process with slug tuners, the result is summarized in Fig. 9.

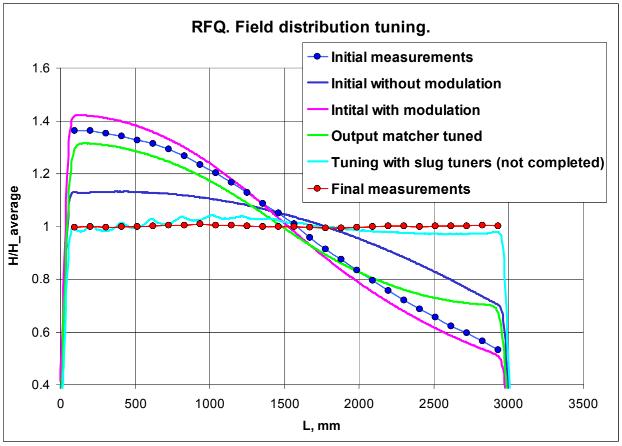

Figure 7: Evolution of field distribution. Lines – simulations, points – measurements. Due to the axial symmetry H-field distributions for only one quadrant are shown.

The slug tuners can only increase the local and overall frequency. After field flattening in the simulation, the RFQ frequency was well above required value of 325 MHz. To decrease the initial frequency of the resonator a reduction of the average bore radius by 50-70 μm was recommended after test simulations.

The results of simulations and the recommendations were taken into account during the final vane machining, RFQ assembly and tuning [4].

CONCLUSIONS

In the first time a full size RFQ model with modulated vane tips and all tuners installed has been built, and a complete simulation of RFQ tuning has been performed. Results of this complete simulation are in excellent agreement with the measurements made on the RFQ during initial assembly and tuning. All recommendation and predictions were proven correct by the final tuning results.

This work is an important step toward entirely computational RF modeling on RFQ structures.

ACKNOWLEDGEMENTS

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