PROJECT X RFQ EM DESIGN*

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Abstract

Project X is a proposed multi-MW proton facility at Fermi National Accelerator Laboratory (FNAL). The Project X front-end would consist of an H- ion source, a low-energy beam transport (LEBT), a CW 162.5 MHz radio-frequency quadrupole (RFQ) accelerator, and a medium-energy beam transport (MEBT). Lawrence Berkeley National Laboratory (LBNL) and FNAL collaboration is currently developing the designs for various components in the Project X front end. This paper reports the detailed EM design of the CW 162.5 MHz RFQ that provides bunching of the 1-10 mA H- beam with acceleration from 30 keV to 2.1 MeV

INTRODUCTION

Following the modern standards for proton linear accelerators, the Project X front end will have a radio-frequency quadrupole (RFQ) accelerator for initial acceleration and formation of the bunched beam structure. Actually the RFQ under development is intended for Project X Injector Experiment (PXIE), which will be a prototype front end of the Project X accelerator [1]. The physical 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 beam dynamics design of the RFQ is done using PARMTEQ software. Overall description of the RFQ including complicated mechanical design is given in [2]. In this paper we focus on the electromagnetic design and report detailed RF modelling on the RFQ resonator performed using simulating code CST Studio Suite. All details of the resonator such as input radial matchers, the end cut-backs, π-mode stabilizing loops (PISLs) etc have been taken into account. Since the RFQ will operate in CW regime a special attention was paid to power loss calculations. The practical PXIE RFQ design parameters are presented. Also we tried to summarize the accumulated experience of 3D electromagnetic simulations of RFQs for different projects [3-7, just a few of them] to develop a routine design procedure which would be applicable to a generic four vane RFQ cavity.

2D SIMULATIONS

Many basic RFQ parameters can be obtained and defined using 2D simulations. The SUPERFISH code is still effective tool for such 2D simulations and, as a matter of fact, the PXIE RFQ cross-section has been optimized with the use of this code. However, the cross-section geometry is a basic element in all 3D models. CST MWS is entirely 3D codes, but RFQ "slices" with thickness of one mesh step were effectively used to verify basic cross-section profile, which is shown in Fig. 1.

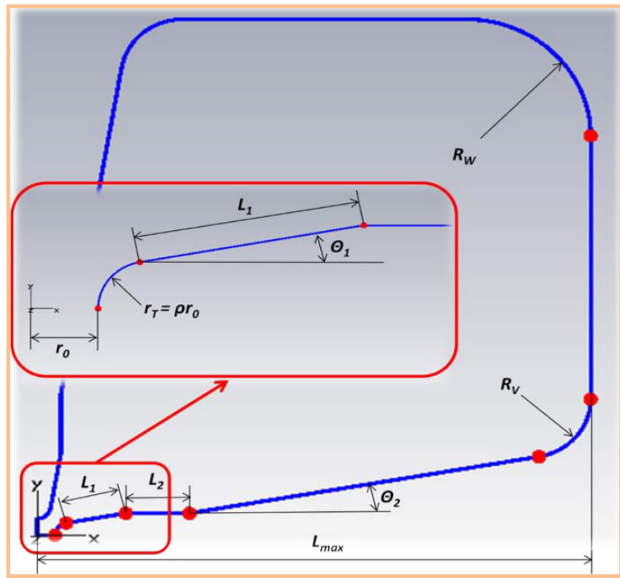

Figure 1: Cross-section geometry of PXIE RFQ.

The RFQ cross-section profile is defined with 9 independent variables as shown in Fig. 1. Their final optimized values are listed in the table below.

Table 1: Cross-section Parameters

r_0	0.5576 cm	θ_2	10 Deg.
ρ	0.75	R_V	2 cm
L_1	2 cm	R_W	4 cm
L_2	2 cm	L_{max}	17.48 cm
θ_1	10 Deg.	$r_T = \rho r_0$	0.418 cm

The final RF parameters of the RFQ cross-section as simulated with CST MWS are shown in Table 2, and they are in excellent agreement with SUPERFISH results.

Table 2: Cross-section RF Parameters

Frequency, MHz	162.492
Q factor	16813
Nominal inter-vane voltage, kV	60
Power loss per length, W/cm	133.0
Peak electric field, MV/m	13.4
Dipole mode freq., MHz	157.5
Tuning coef. ΔF/ΔL, MHz/mm	1.04
L_{max}, mm	176.59

In all subsequent 3D simulations these cross-section profile parameters were kept constant except L_{max}. We chose to restore the operating frequency at each step of

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RFQ design after detuning it by RFQ elements, and L_{max} was used as the only tuning parameter.

3D SIMULATIONS

The π-mode Stabilizers Period

Tuning and field stabilizing elements were studied with periods of the RFQ. The lengths of periods are defined by element spacing along RFQ. For proper power losses calculation the fields in the RFQ periods were always scaled to the nominal inter-vane voltage of 60 kV.

The stabilization of transverse field distribution is provided by 16 pairs of water-cooled stabilizers that separate unwanted dipole modes from the main quadrupole mode (also Vane Coupling Rings were considered, but rejected). After optimization the π-mode rods have outer diameter 10 mm and pass through 40 mm holes in the vanes.

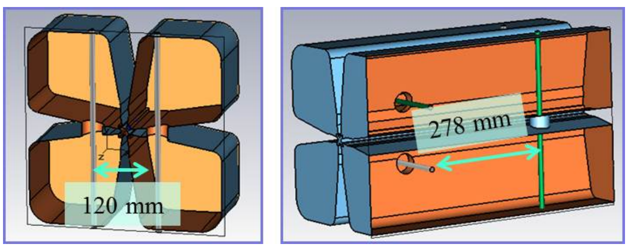

Figure 2: The π-mode stabilizers period.

In these simulations the power losses in the rods were especially interesting. The final parameters are shown in Table 3.

Table 3: PISL Period RF Parameters

Frequency, MHz	162.486
Frequency shift due PISLs, MHz	-5.56
Q factor	15333
Power loss per PISL, W	188
Dipole mode freq., MHz	179.6
Dipole mode shift., MHz	22.1
Field perturbation at x=y=5 mm, %	0.3
L_{max}, mm	171.44

The Tuner Period

For static frequency and field distribution tuning the RFQ will be equipped with 80 slug tuners. The tuners will be nominally intruded in the RFQ volume to allow frequency tuning in both directions.

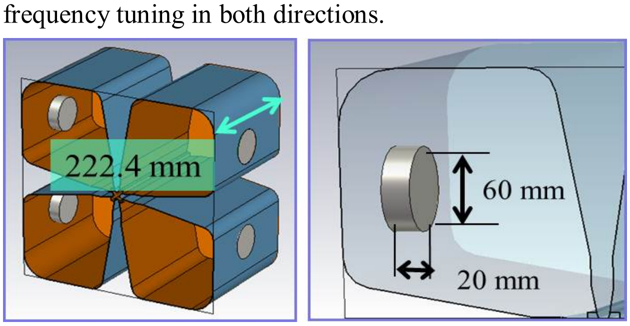

Figure 3: The slug tuner period.

The slug tuner period of RFQ was simulated to evaluate slug tuning sensitivity, field distortion and power losses. The field distortion was apparent in the slug tuner vicinity, but negligible in the inter-vane gap. Power losses per tuner are small enough to go without water cooling.

Table 4: Tuner Period RF Parameters

Frequency, MHz	162.495
Frequency shift due tuners, MHz	1.334
Q factor	16115
Power loss per tuner, W	57.7
Tuning sensitivity for 1 tuner, kHz/mm	16.7
Nominal tuner intrusion, mm	20
L_{max}, mm	177.84

One accelerating period with maximal vane tip modulation of 2.2 has been simulated to evaluate how much a vane tip modulation affects local resonant frequency. The local frequency shift due to the modulation was found to be 340 kHz which can be compensated by plug tuners with sufficient margins. So, it was decided to continue design with flat vane tips. More details on vane tip modelling are in [8].

3D FULL LENGTH MODEL

After implementation of tetrahedral mesh in CST MWS the 3D simulations of full length RFQ model are not so challenging as they used to be [3, 4, 7]. It is important to mention that accuracy of simulations has increased too. That opened new opportunities in RFQ design.

Vane Length Model with Perfect Terminations

In PXIE RFQ the π-mode rods and the tuners have different spacing. It means that a regular period of the structure, which could adequately describe combined rods and tuners effect, doesn't exist. The model of tip-to-tip vane length was used instead. The model had the complete sets of rods and tuners and magnetic boundaries at the ends, which assumes perfect terminations. With this model the tuning of RFQ main body was performed and the final tuning parameter L_{max} =172.73 mm was fixed.

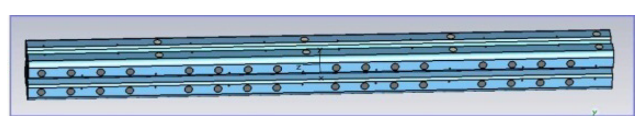

Figure 4: The model of physical vane length (4430 mm).

Shape of Cut-backs

A triangle shape of the cut-backs has been chosen following our mechanical and manufacturing preferences (see Fig. 5). We chose the dimensions of the cut-backs to minimize the heating of the vane tips due to the surface losses.

Cut-back Tuning

Field flatness is always one of the most important tasks for RFQ design and tuning. This parameter is very sensitive to the dimensions of cut-backs, and the errors are usually hard to fix.

Usually short input-output modules of RFQ with proper boundary conditions and symmetry planes can be used to tune the terminations. The results are good enough even in the absence of perfect symmetry in RFQ. However, with the advent of available powerful computers and tetrahedral meshing technique, we decided to tune the cut-backs in the full length (4447 mm between end walls) model with "everything installed".

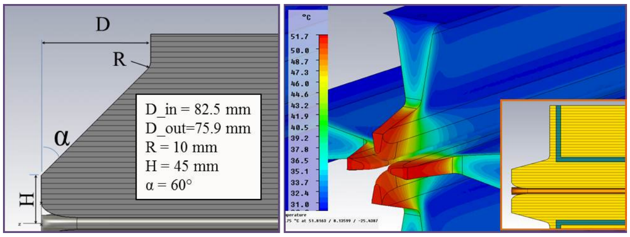

Figure 5: Cut-back shape (left). Vane tip heating (right).

For tuning the cut-back depths D were used as the most influential parameters, and electric field amplitude distribution along line in the gap between vane tips was monitored. In Fig. 6 the final steps of tuning are shown.

Tuned cut-back depths are D_{in}=82.5 mm and D_{out}=75.9 mm.

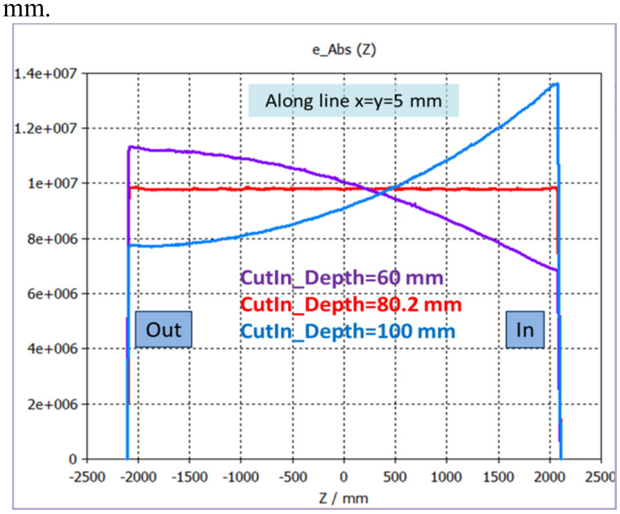

Figure 6: Input cut-back tuning (the output cut-back is tuned already).

Final Simulation with Complete RFQ Model

For final simulation the full length model has been converted into a set of solid bodies that have electrical and thermal properties of copper and represent the separate parts of the RFQ (see Fig. 7).

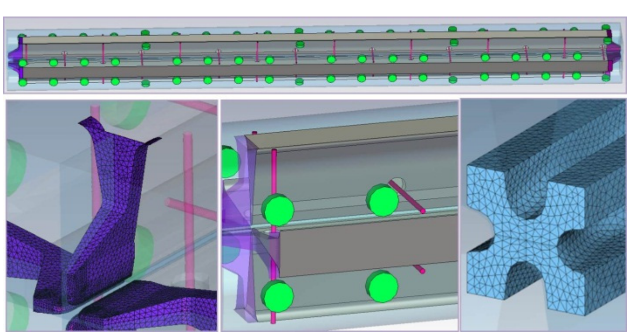
Figure 7: Complete solid model of RFQ.

It was done first of all to get a possibility to evaluate the thermal losses for the parts separately. It is useful for cooling scheme development and helps to pay an attention to most critical parts in terms of heating.

Also it adds flexibility in meshing, since each part can have its own mesh density. And finally this model is ready for further thermal-stress analyses.

The final RFQ parameters are given in Table 5. The Table 6 summarizes the power losses values for separate parts of the RFQ.

Table 5: Final RFQ Parameters

Operating frequency, MHz	162.499
Frequency of dipole mode, MHz	181.99
Q factor	14985
Q factor drop due to everything, %	-14.7
L_max, mm	172.73

Table 6: Itemized Power Losses

Part	Total, kW	%
Walls	29.84	40
Vanes, 4 units	31.33	42
Input cut-backs, 4 units	1.34	1.8
Output cut-backs, 4 units	1.57	2.1
Pi-mode rods, 32 units	5.6	7.5
Tuners, 80 units	4.85	6.5
Total	74.6	100

The simulated losses assume that the conducting surface and contacts between RFQ parts are perfect. Real total losses are expected to be higher up to 20%.

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