BEAM DYNAMICS SIMULATIONS IN PROJECT X RFQ WITH CST STUDIO SUITE*

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Abstract

The room temperature CW RFQ design for the Project X at Fermilab operates at 162.5 MHz with acceleration of H^- beam from 30 keV to 2.1 MeV. A long complicated high-bandwidth bunch selective chopper downstream RFQ and SC accelerating cavities right after MEBT requires high quality and well defined beam after RFQ to avoid excessive particle losses. The new advanced computing capabilities made it possible to simulate beam and even dark current in the realistic 3D electromagnetic fields in RFQ. The full 3D field distribution was used for beam dynamics simulations using both PIC solver of CST Particle Studio and the beam dynamics code TRACK.

INTRODUCTION

The main parameters of the Project X RFQ are listed in Table 1.

Table 1: RFQ Design Specification

Operating frequency, MHz	162.5
Vane-to-vane voltage, kV	60
Total length, m	4
Input energy, keV	30
Output energy, MeV	2.1
Particles	H^-
Maximum beam current, mA	10
Duty cycle, %	100

CW operation, a long complicated high-bandwidth bunch selective chopper downstream RFQ and SC accelerating cavities right after MEBT requires accurate beam dynamics study to avoid excessive particle losses and emittance growth.

Currently there is a growing interest in combining or integrating RFQ beam dynamics design, electromagnetic design, and beam tracking using "realistic" field maps into a single process [1-4]. This approach is supposed to result in more accurate RFQ beam output parameters since electromagnetic model takes into account real physical features of the RFQ. Besides it seems to be the most adequate way to study impact of manufacturing and tuning errors on the RFQ's output.

The main motivation for this integration is a basic fact that the vane tip modulation in the RFQ design codes and the machining tables, i.e. real vane tip shape, are different. In principle it is not topologically possible to manufacture vanes which conform exactly to the Hyberbolic-and-Bessel dependence [5]. To avoid physical discontinuity at cell boundaries some averaging is used to make the vane tip smooth. For easy RF tuning the local frequency change due to the modulation may be compensated by making the modulation valley shallow [6].

Finally, the field distribution in RFQ is not absolutely uniform due to imperfect manufacturing and tuning, influence of stabilizers, tuners, end terminations etc.

In this study the basic RFQ design has been done with PARMTEQ. For beam dynamics simulations using TRACK [7] and CST PS (PIC solver) the field maps prepared with CST EM (electrostatic solver) and CST MWS (eigenmode solver) were used.

SOLID MODELS OF RFQ VANES

Following the idea of integrated RFQ design it is imperative to use real vane tip shape in electromagnetic simulations. Actually programs PARI and VANES deal with real shape of vane tips, while PARMTEQ is a design and beam transport simulation code that uses idealized RFQ geometry. Program PARI adjusts the cell geometry to produce the accelerating and focusing forces assumed by the two-term potential function. When making these adjustments, PARI modifies the modulation to give the required accelerating field and the code modifies the mid-cell radial aperture r_0 to give the required transverse focusing. VANES reads a file written by PARI and creates files of machine tool data. The physical vertical vane tip geometry of Project X RFQ is shown in Fig.1.

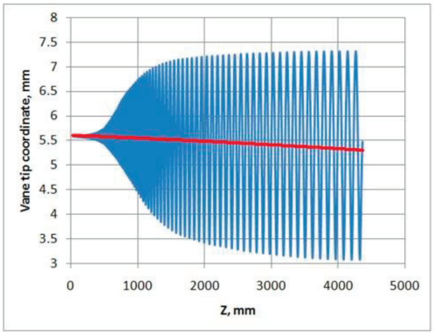

Figure 1: Project X RFQ vertical vane tip profile.

The tables of vane tip coordinates from VANES output file are imported into CST MWS, and the points are interpolated with splines. Then the vane tip profile is swept along the modulation curve and the vane tip solid model is created (see Fig.2)

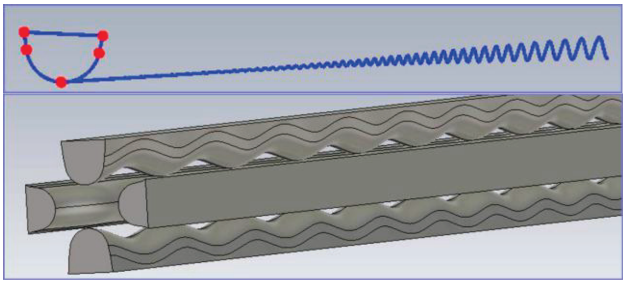

Figure 2: Upper – sweeping vane tip profile along modulation curve. Bottom – complete vane tip solid models.

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* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

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These vane tip solid models were used to build complete models for both CST EM and CST MWS

The geometries of input matcher and output end termination are also included in VANES tables. The solid models for them were prepared separately since a different technique is used.

ELECTROSTATIC MODEL

The electrostatic model consists of four solid models of vane tips with end terminations attached and two disks that imitate end walls. The potentials of ±30 kV were applied to the vanes, the disks were grounded (see Fig.3).

The main advantage of the electrostatic model is a field distribution defined by the electrode geometry only. So, the field distribution can be considered as an ideal one after perfect manufacturing. During beam dynamics simulation harmonic time dependence with exact operating frequency was assigned to this static field.

The low frequency tetrahedral mesh, which is available for the CST EM solver, is apparently not very advanced. To achieve reasonable field map smoothness the mesh of up to 10 M tetrahedrons is needed, and mesh generation is very time consuming. The solver itself is very fast though.

The hexahedral mesh of ≈500M cells with maximal cell size of 0.4 mm and minimal size of 0.02 mm has provided better field map. This map was used in subsequent beam dynamics simulations.

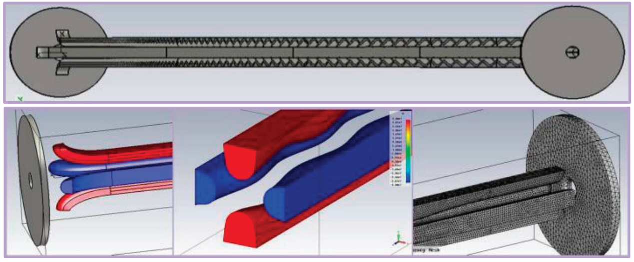

Figure 3: Upper – general view of RFQ electrostatic model. Bottom – the input matcher, the electrodes and the meshed output end.

ELECTRODYNAMIC MODEL

At first the same RFQ model described in [8] was used for CST MWS (see Fig.4). But later the pi-mode rods and the tuners have been removed from the model to make the filed map closer to analytical and electrostatic solution to compare with.

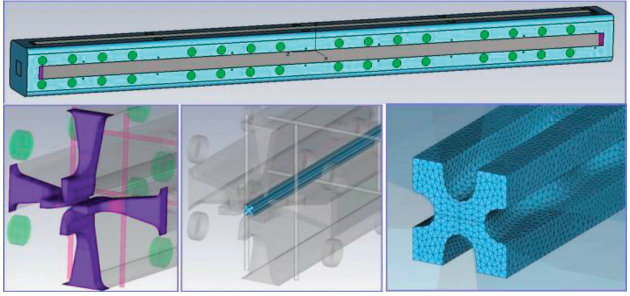

Figure 4: The MWS RFQ model.

After removing of PISLs and tuners, and adding the vane tip modulations the RFQ model has been re-tuned to restore operating frequency and field flatness. The final field distributions are shown in Fig.5.

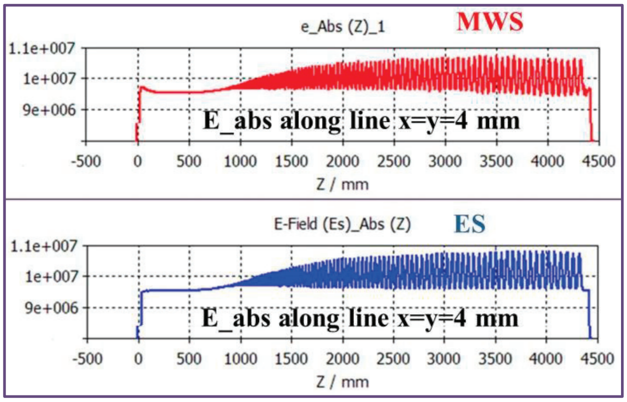

Figure 5: Field distributions in the tuned MWS model and in the electrostatic model.

The tetrahedral meshing of the model is flexible because it consists of separate solids and each solid can have its own mesh density. But since the finite elements and curved elements are of order 2 in MWS, a mesh with much smaller total number of tetrahedrons (≈1M, computer limited) can be generated compare to low frequency mesh in electrostatic problem. Nevertheless, the RF field distribution was smoother than the electrostatic one, though just opposite was expected.

BEAM DYNAMICS SIMULATIONS USING TRACK CODE

The 3D field distributions were exported from CST projects in plain text format using a grid defined by TRACK requirement. The field grid had 25x25x4001 points uniformly distributed over 11 mm x 11 mm x 4380 mm rectangular box. That corresponds about 7 points per shortest cell in z direction. Then the extracted files for E and H fields have been reformatted and combined by special code in one binary file that is used in TRACK (a dummy H field file for the electrostatic problem was filled with zeros).

Table 2: Input Beam Parameters

	α	β, cm/rad	ε, norm rms, cm·mrad
x	1.331	7.414	0.0115
y	1.336	7.455	0.0113

Table 3: Output Beam Parameters

	α	β	4 ε n_rms	Axis
MWS	0.02	0.025 cm/mrad	0.054 cm·mrad	x
	-0.55	0.012 cm/mrad	0.054 cm·mrad	y
	0.2	18.4 °·(% of ΔW/W)	3.25 keV·ns	z
EM	0.028	0.023 cm/mrad	0.054 cm·mrad	x
	-0.1	0.012 cm/mrad	0.054 cm·mrad	y
	0.21	19.0 °·(% of ΔW/W)	3.25 keV·ns	z

The input beam parameters used in TRACK simulations were not exactly the same that were used in PARMTEQ simulations. Only emittance exactly corresponded to the measured beam from the ion source [9]. The Twiss parameters have been transferred to the

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supposed physical entrance of RFQ and adjusted for better matching. They are shown in Table 2. But the most significant difference between TRACK and PARMTEQ simulations was transverse particle distribution. In TRACK simulations a water-bag model was used, in PARMTEQ the model used was Gaussian approximation of measured beam profile.

The TRACK simulations show that RMS parameters of output beam practically the same for both field maps, though the shapes of halo slightly differ (Table 3). But TRACK and PARMTEQ simulations produce not-negligible difference of the longitudinal tails behaviour (see Fig. 6).

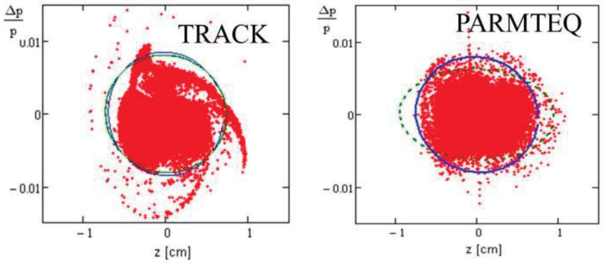

Figure 6: Longitudinal beam output.

The tails will result in particle losses in further acceleration in Project X linac. We launched additional studies to understand this difference and possible ways for reduction of the loss.

BEAM DYNAMICS WITH CST PIC SOLVER

Beam dynamics simulation in RFQ using CST Particle Studio is very interesting direction. It combines the whole simulating process in one program and gives an opportunity to look at beam dynamics in RFQ in non-traditional way.

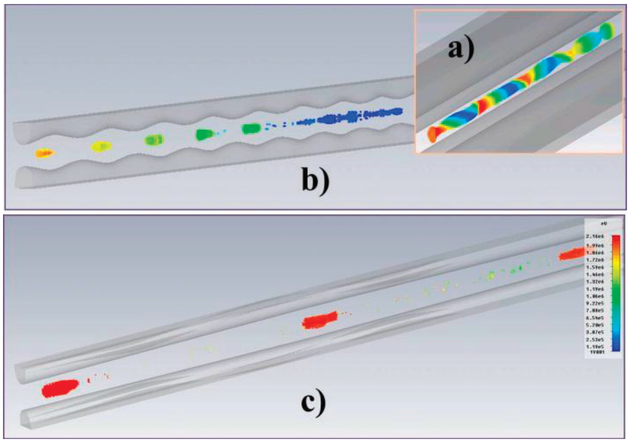

Figure 7: CST particle-in-cell simulation.

The simulation starts with 30 keV uniform DC beam pulse 60 mm (4-5 RF periods) long entering the electrostatic model of RFQ. The DC current in this simulations was 1 mA and the number of macroparticles was 600,000. Figure 1a shows the beam just after input matcher and the beginning of bunching process.

In the buncher section some particles are not captured in acceleration, their energy remains ≈ 30 keV, but they will travel further and exit the RFQ (Fig.1b). This low energy tail will be probably lost in the first focusing elements of MEBT.

At the end of acceleration section some high energy tail can be seen in Fig.1c. The total number of lost particles is remarkably low – only 0.4 %. It is very close to PARMTEQ transmission of 99.8% for 5 mA input DC beam.

At the moment the PIC solver can produce interesting qualitative pictures and movies, but it is not an effective tool for RF design yet because of a number of very serious technical difficulties.

ACKNOWLEDGMENT

The author would like to thank Brahim Mustapha (ANL) for his invaluable help with beam dynamics simulations using TRACK.

CONCLUSION

Eventual integrating the electromagnetic and beam dynamics simulations seems to be a promising way for RFQ design progress.

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