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ESS RFQ ELECTROMAGNETIC SIMULATIONS USING CST STUDIO SUITE

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Abstract

The Radio Frequency Quadrupole (RFQ) of the European Spallation Source (ESS), operates at 352.21 MHz with an RF pulse length of 3.2 ms and repetition rate of 14 Hz. The RFQ focuses, bunches and accelerates the 62.5 mA proton beam from 75 keV up to 3.6 MeV. In an effort to study and compare the results from 3D electromagnetic codes, different models of the RFQ were simulated with CST Studio suite ®. This paper presents the selection of optimal parameters for simulation of the RFQ cavity voltage and comparison of the results with the RFQ design code Toutatis.

INTRODUCTION

The ESS RFQ was designed and manufactured by CEA-IRFU in France and installed at ESS site in 2019 [1]. Following a period of system installation and testing, RF power conditioning was successfully completed in summer 2021 and first proton beam injected in the RFQ in October of the same year. The cavity has a total length of 4.55 m divided in 5 segments (each $\sim 0.9m$ long) operating at the resonance frequency of 352.21 MHz. The vane type RFQ, achieves a voltage of 80 kV at the entrance and 120 kV at the high energy end. The RF power is delivered to the RFQ using two coaxial antenna couplers placed symmetrically 45 deg from the vertical axis equipped with ceramic windows that couple in total 1.1 MW of RF power during operation. In order to compensate for manufacturing errors that influence the resonant frequency of the cavity, 60 slug tuners are used and adjusted in fixed position during initial bead pull tuning of the cavity. Frequency detuning due to cavity thermal expansion (caused by RF power losses) is mitigated using water cooling circuits [2]. Main parameters of the ESS RFQ are presented in Table 1 whereas the 3D RFQ model with main interfaces is presented in Fig. 1.

3D electromagnetic (EM) simulation software possesses a prominent role in design and characterisation methodologies of a wide spectrum of accelerating cavities. Using designed and as-built models consists the most efficient way to investigate the impact of manufacturing and tuning errors on beam parameters incorporating simultaneously all EM effects [3-8]. Motivation for this study is the use of this approach in the frame of an integrated design methodology for RFQ design serving future ESS update projects. Towards that goal, benchmark of the cavity field results using different RFQ models, meshing techniques and electromagnetic solvers is considered essential.

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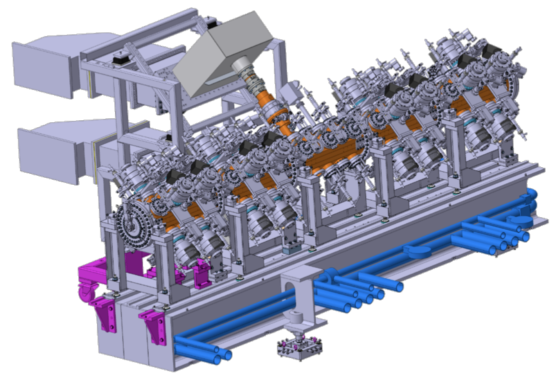

Figure 1: ESS Radio Frequency Quadrupole.

Table 1: ESS RFQ Main parameters

Requirement	Value
Operating Frequency	352.21 MHz
Vane-to-vane voltage	80-120 kV
Total Length	4.55 m
Input Energy	75 keV
Output Energy	3.6 MeV
RF Pulse Length	3.2 ms
Repetition Rate	14 Hz
Nominal RF power with beam	933 kW

ELECTROMAGNETIC SIMULATIONS

Simulations presented in the next sections have been performed with CST Studio suite®, a 3D EM analysis software package for designing, analyzing and optimizing electromagnetic components and systems [9]. For this analysis the in-built eigenmode solver was used. RFQ 3D models and geometries have been processed with CATIA® V6 CAD software to increase result accuracy, reduce computation time and respectively allocate memory footprint.

The goal of the simulations was the selection of the optimal parameters in an effort to reduce the error on resonant frequency calculation and increase resolution of the electric field distribution on the beam acceleration axis. Starting from the equation for obtaining the eigenvalues ω and eigenvectors $\overrightarrow{E}$:

$$\nabla \times \mu^{-1} \nabla \times \overrightarrow{E} = -j\omega^2 \left(\epsilon + \frac{\sigma}{j\omega} \right) \overrightarrow{E} \quad (1)$$

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CST Eigenmode solver uses the Finite Integration Technique (FIT) [10] where the closed integrals of Maxwell equations are approached by sums of electric and magnetic potentials in each element of the discretized simulation space. Results were compared with Toutatis, a CEA developed software for particle tracking through RFQs. Toutatis solves the Poisson's equation using the Finite Differences method applying the Gauss-Seidel numerical method in combination with multigrid techniques for simulation acceleration [11]. Initial benchmarking of the results was performed using the derivative of the well-known 2-term analytical solution for beam axis potential at between RFQ electrodes:

$$U(r,\theta,z,t) = \frac{V_0}{2}\left[X\left[\frac{r}{a}\right]^2 cos2\theta + AI_0(kr)cos(kz)\right] \quad (2)$$

the dimensionless constants A (accelerator efficiency), X (focusing efficiency) are defined:

$$X = \frac{I_0(ka)+I_0(kma)}{m^2 I_0(ka)+I_0(kma)}, A = \frac{m^2-1}{m^2 I_0(ka)+I_0(kma)} \quad (3)$$

where m is the electrode modulation factor, α is the bore radius (aperture), I_0 the modified Bessel function and k the wave number.

Different design models were used in a feedback process between CATIA® and CST® with mesh perameter scans in order to define the optimal simulation settings for improved field quality. Using the CST VBA macro tool, single RFQ cell models were extracted from the full cavity model for initial simulations. Subsequently, a full transverse quadrant of the RFQ 3D model with the tuners at their nominal positions was simulated using a tetrahedral mesh. Key factor to address the need for finer mesh around the vanes, reduce the computational time and improve field quality results, is proper selection of parameters that define the mesh generator's behavior towards curved model geometry. Towards that goal, dynamic adaptive mesh refinement was used that improves mesh distribution from run to run converging to a selected frequency criterion with curved element settings like vector's angle of adjacent tetrahedrons and curved surfaces approach with third order polynomials.

The meshing parameters were scanned for the following three cases:

(i) uniform mesh without curved elements settings

(ii) uniform mesh with curved elements

(iii) a multi-meshed model with detailed mesh around the vanes and coarser towards the outer part of the cavity.

Multi-meshed geometry derived using again the CST VBA macro tool for plane splicing the model defining regions with different mesh parameters.

Figure 2 presents the meshed RFQ geometry with a detailed view of a finer mesh around the electrode area. In order to use the eigenmode solver, the supplementary vacuum model of the cavity was used with the background material set to perfect conductor (PEC). In order to impose the quadrupolar symmetry to the model and extract the fundamental quadrupolar mode, boundary conditions of perfect electric conductor ($E_t = 0$) to z (beam propagation) axis and perfect magnetic conductor ($H_t = 0$) to transverse planes were selected.

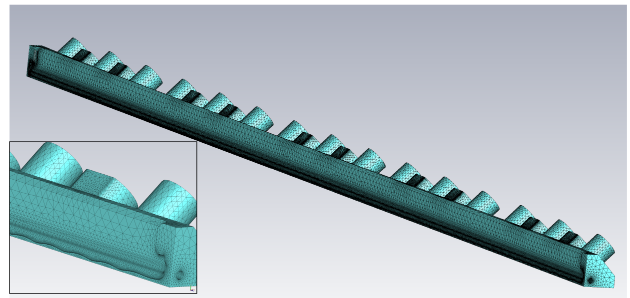

Figure 2: ESS Radio Frequency Quadrupole Simulated model.

Figure 3 presents the electric and magnetic field for the fundamental quadrupolar mode for 90^o phase difference and Fig. 4 the simulated frequency error compared to expected theoretical for the different simulation scenarios. Mesh parameter k (number of mesh cells per max box edge) corresponds to the cases with uniform mesh with and without curved element settings, whereas the mesh parameter c (max cell width) defines the mesh cell dimensions in multi-meshed scenario. Smaller values of mesh parameter c correspond to finer mesh around the area of interest. Although the relative error in all cases is considered small, the scenarios (ii) and (iii) present much improved field quality at the expense of a larger number of mesh elements and computational time.

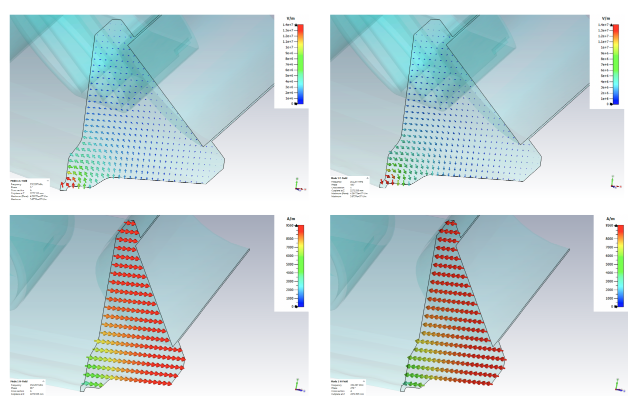

Figure 3: Electric and magnetic field for fundamental quadrupolar mode.

Figure 5 presents the calculated electric field on axis for normalised CST (scenario iii: multi-meshed model) results, Toutatis and 2-term analytical solution indicating a good agreement between the 3D EM codes. Figure 6 presents the envelopes of the peaks of the field using the Hilbert trans-

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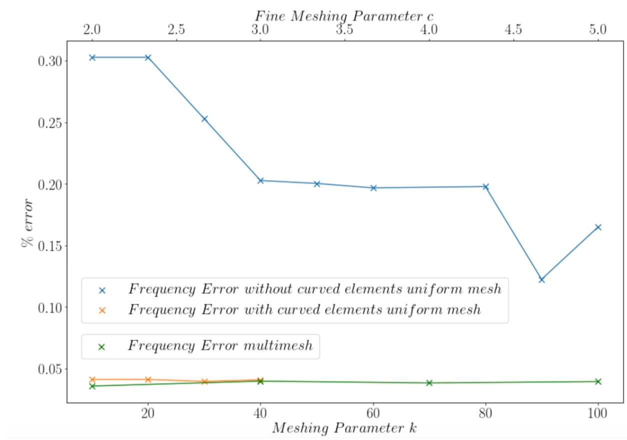

Figure 4: Frequency error for different values of scanned parameters.

formation across the total length of the cavity. Analytical solution presents a difference of 9% compared to CST due to the electrode geometry approximations used in the 2-term analytical equation extraction.

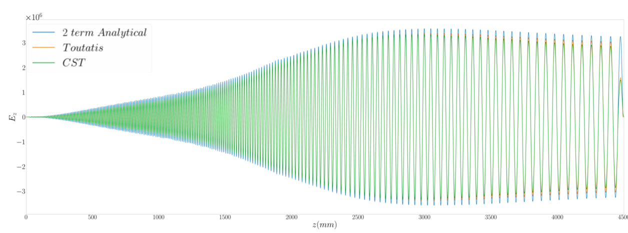

Figure 5: Accelerating field on axis, comparison between CST®, Toutatis and 2-term analytical solution.

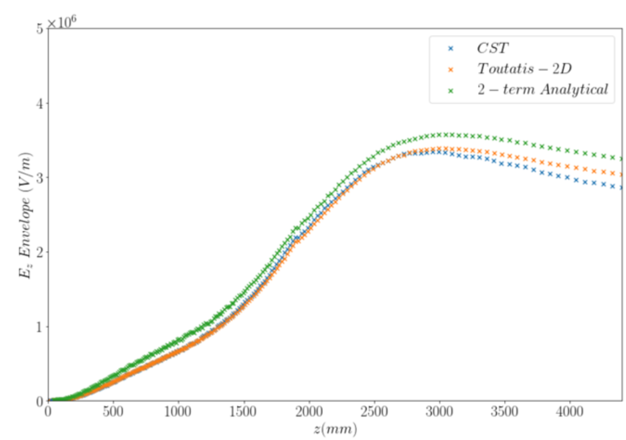

Figure 6: Field waveform envelope comparison between Toutatis and CST®.

Figure 7 provides an analysis of the calculated error between CST optimal multi-mesh simulation result and Toutatis, along with the corresponding mean absolute (2.5%) and rms percentage error (3.3%) along the RFQ z axis. We can observe that 2 cells in the first 500 cm of the RFQ present higher error an outcome of possible geometry flaw . The

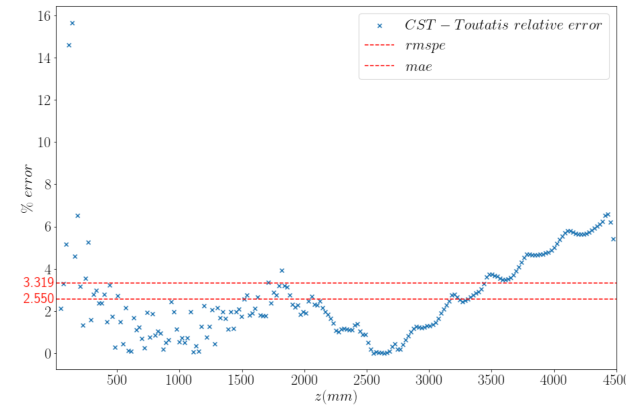

Figure 7: Electric field error on z-axis between Toutatis and CST®.

error increases towards the end cells of the RFQ due to RFQ cell dimension increase while keeping fixed the number of tetrahedrons (to discretize the region). Models with different mesh sizes, providing additionally finer mesh to the cavity high energy end, will be further investigated.

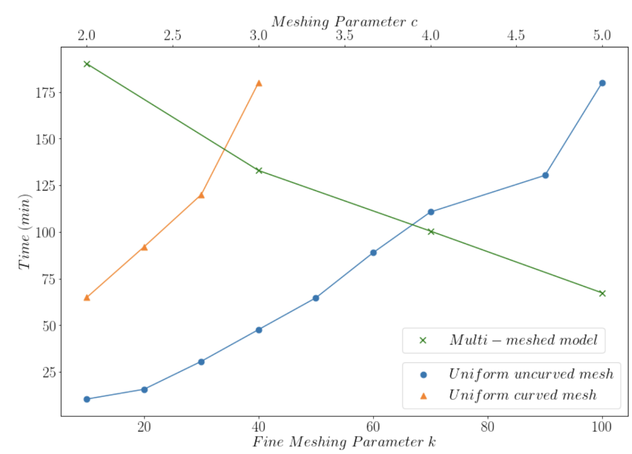

Figure 8: Simulation times as a function of model mesh parameters.

Figure 8 presents the simulation time results for the scan of the mesh parameters k and c performed with a 32 GB RAM and 500 GB SSD hard disk computer. As expected, the use of curved element settings or multi-meshed model greatly increases the computational time even with lower number of tetrahedrons, playing an essential role on the selection of the optimal simulation parameters.

CONCLUSION

Simulations with CST® permitted to investigate the impact of different models, meshing strategies and simulation parameters to obtain the optimal electric field distribution and results. Comparison between CST® and Toutatis indicated a good agreement in terms of resonant frequency and electric field amplitudes as a first step of an integrated RFQ design methodology.

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