NOVEL INTEGRATED DESIGN METHOD AND BEAM DYNAMICS SIMULATIONS FOR THE FETS RFQ COLD MODEL

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Abstract

A 4m-long, 324MHz four-vane RFQ, consisting of four coupled sections, is currently being designed for the Front End Test Stand (FETS) at RAL in the UK. Previous beam dynamics simulations, based on field maps produced with a field approximation code, provide a baseline for the new design. A novel design method is presented that combines the CAD and electromagnetic modelling of both the RFQ tank and the vane modulations with more sophisticated beam dynamics simulations using the General Particle Tracer code (GPT). This approach allows the full integration of the optimisation of the RFQ, based on beam dynamics simulations using a 3D EM-field map of the CAD model, with the design and manufacture of the RFQ vane modulations and RFQ tank. The design process within the Autodesk Inventor CAD software is outlined and details of the EM modelling of the RFQ in CST MicroWave Studio are given. Results of beam dynamics simulations in GPT are presented and compared to previous results with field approximation codes. Finally, possible methods of manufacture based on this design process are discussed.

INTRODUCTION

As part of the ongoing development of future high power proton accelerators (HPPA's) and to contribute to the UK design effort on the neutrino factory, the Front End Test Stand (FETS) is being constructed at the Rutherford Appleton Laboratory (RAL) in the UK. The aim of FETS is to demonstrate the production of a 60 mA, 2 ms, 50 pps chopped beam: a detailed description of the project is given in [1]; for the current status, see [2, 3].

To accelerate the beam up to the desired 3 MeV energy, a 4-vane RadioFrequency Quadrupole (RFQ) channel, consisting of 4 resonantly coupled RFQ sections operating at 324 MHz, has been selected for FETS. Previous measurements on a half-size 4-vane RFQ cold model demonstrated the close agreement between electromagnetic field simulations of a CAD model and the RFQ cold model itself, for both resonant frequency and field uniformity [5]. However, this model is limited in that only covers the bulk RF characteristics of the RFQ, not the vane modulations. In order to extend this synergy between CAD modelling, RF simulation and CNC machining of the RFQ, based on the CAD model, and to also include beam dynamics simulations within the optimisation process, a novel design method has been developed that provides full integration of all stages of the RFQ design process.

RFQ INTEGRATED DESIGN METHOD

Previously, RFQ development for FETS has followed a well-trodden path: a field approximation code (RFQSIM), originally written as part of the development of the ISIS RFQ [6], produces a set of optimised parameters for every cell of the RFQ. These paramaters, describing the depth of modulation (r_0, a and m), cell length (L) and vane tip radius (ρ), are shown in Fig. 1. Traditionally, the next step would be to check the optimised field produced by the code using beam dynamics simulations and then manufacture the RFQ based on these optimal parameters.
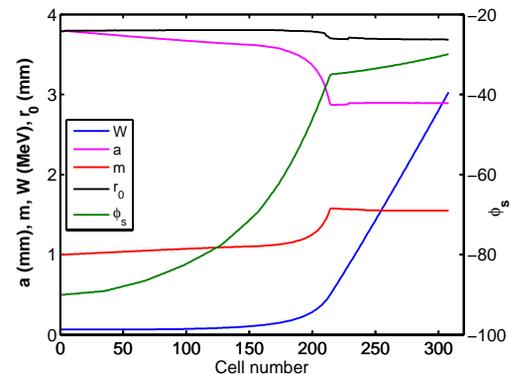
Figure 1: Design parameters for the FETS RFQ.

However, it was felt that in order to fully categorise the fringe fields surrounding the vanes and to correctly model the fields of the vane as it would be manufactured, as well as adjusting the model based on the manufacturing limitations of the vanes, a new design process was necessary. This design method was based around the experience gained with the cold model design (see [5] and Refs therein) – using the same CAD model for both E-field modelling and to create a CAM model for CNC manufacture – but with the added step of integrating beam dynamics simulations, based on the same CST field map, into the design process and to use the results of those simulations to influence the design of the RFQ.

This integrated design method has the advantage of simulating the electrostatic field produced by the real vane profile, rather than an idealised model from a field approximation code. This vane profile is in turn influenced by the limitations of the techniques used in manufacturing the RFQ. It is then possible, for example, to simulate the effect of using different tooling options in the manufacture of the RFQ on the transmitted beam parameters, or to modify the

the profile of the vane tips to improve cooling access and directly observe the effects on the beam dynamics. The design process is therefore subdivided into 4 distinct stages:

1. Generation of RFQ parameters using RFQSIM field approximation code.
2. CAD modelling of RFQ vane tip modulations in Autodesk Inventor using RFQ parameters.
3. Electrostatic simulations of the field region around the vane tips in CST EM Studio.
4. Beam dynamics simulations in General Particle Tracer (GPT) using the CST field map.

This technique is not unique to 4-vane RFQ's: indeed, identical simulations have been developed for a parallel 4-rod design, since the majority of the process is identical [4].

RFQ CAD MODELLING

CAD modelling of the RFQ vanes is carried out using Autodesk Inventor, the same package used for the design of the cold model [5]. This method takes advantage of the Visual Basic integration between Inventor and Microsoft Office. Parameters from RFQSIM are input into a spreadsheet in Excel: this file is then linked to the Inventor model, allowing the model to reshape dynamically based upon the values in the spreadsheet.

RFQ vane tip models in Autodesk Inventor are assembled from 2 sketches, representing the transverse and longitudinal profiles of the vane. The only variable governing the size of the transverse profile is ρ which is read dynamically from the spreadsheet and is used for both the matching section and the vane tips. The height of the vane tip is adjusted by hand to match the dimensions of the rest of the vane. The sketch describing the longitudinal profile of the vane tip is shown in Fig. 2. As with the real RFQ, this curve is constrained at 3 points, corresponding to the distances a_n, r_{0n} and ma_{n+1} from the beam axis. The longitudinal positions of each of these points are defined by the length of the cell, L. As with the transverse profile, each of these values is read from the spreadsheet. In a real RFQ, these points define the reference points of a sinusoid. Since it is not possible to draw sinusoidal curves in Inventor, cubic splines are used instead. By constraining the spline curve at the 3 reference points within a cell a very good approximation to a real sinusoid is achieved, with a maximum difference of 2%.

The 3D model of the vane tip is then constructed using the "sweep" function in Inventor: the 2D transverse profile is traced out along the longitudinal modulation profile to produce the complete vane. An extrusion is then used to remove the modulation from the back surface of the vane tip and ensure that this surface is a constant distance from the beam axis. Multiple vane tip models are then assembled into a complete vane model assembly, a section of which is shown in Fig. 3.

The complete CAD model is assembled in 6 sections: 1 for the matching section and 5 for the main part of the vane
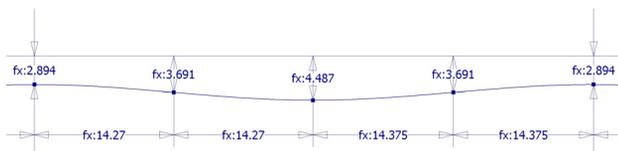
Figure 2: Autodesk Inventor RFQ vane modulation sketch (2 cells): upper horizontal line represents the beam axis.
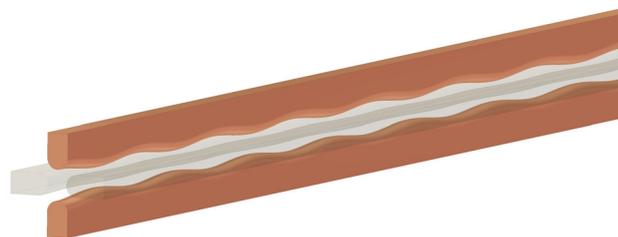
Figure 3: CAD model of the vane modulations of the FETS RFQ starting at $z = 2.037$ m; x-vanes are semi-transparent.

tip. This subdivision of the vane tip models is necessary to keep the number of cells in a single sketch below 100, since this proved to be the limiting factor for Inventor to render the spline correctly.

CST FIELD MODELLING

The completed CAD model is imported to CST as a platform independent SAT-file. A custom macro is used to set the correct model geometry, the vane voltage and the meshing parameters for each run. A fixed voltage of ± 42.5 kV is applied to opposing pairs of vanes to give the vane-to-vane voltage of 85 kV required for the real FETS RFQ. Considerable effort has been made to optimise the CST meshing paramaters: a tetrahedral mesh is used to map the surface of the vane tips. To provide the maximum mesh density, the minimum number of mesh steps is always set to 1,000: the automatic tetrahedral mesh generator then sets the mesh density and number of mesh points. For more accurate field simulations, each of the 6 sections of the CAD model is
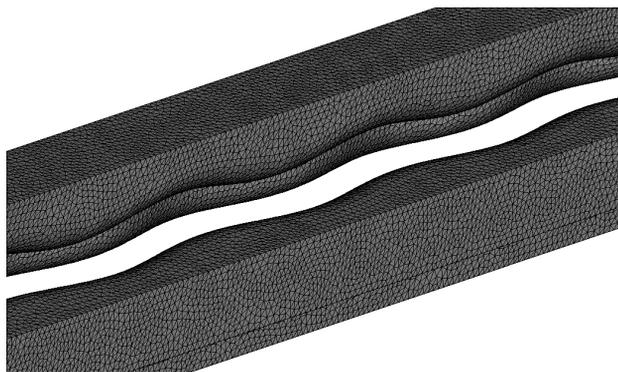
Figure 4: Meshed CST model of the FETS RFQ vane tips at $z = 2.1$ m.

solved separately and the resultant field maps recombined in GPT. Maximum values for geometry accuracy (10^{-6}) and curvature refinement ratio (0.05) are used to provide maximum model accuracy. A fully meshed CST model of the vane tip modulations is shown in Fig. 4. This model is then solved in CST to provide an electrostatic field map of the field surrounding the vane electrodes. The field map from this model can be exported as a text file for use in beam dynamics simulations.

BEAM DYNAMICS SIMULATIONS

Beam dynamics simulations were the primary method used to benchmark the success of the integrated design process in order to compare the field from the CST model to the optimised fields from RFQSIM. Since RFQSIM calculates only the first 8 terms of an infinite series describing the potential between RFQ electrodes [6], there will clearly be differences to that produced by CST. While the accuracy of the model shape produced by Inventor is potentially better than that from RFQSIM, the accuracy of the resultant field produced by CST is limited by the mesh density of the CST model, which is in turn limited by the computing power available.

Beam dynamics simulations have been carried out using GPT. The CST E-field map was imported using the "map3d_EB" function: this takes a static E- and B-field map and sinusoidally modulates the magnitude of the field in time, producing a time-varying field map. Since the on-axis B-field in an RFQ is zero, all the B-field components are set to zero on import to GPT. The same input beam distribution used for previous RFQ beam dynamics simulations [7], representing the optimal output beam from the FETS LEBT, was used: a waterbag distribution with $x_{max} = y_{max} = 2.5$ mm, $x'_{max} = y'_{max} = 60$ mrad and $\epsilon_{x,rms} = \epsilon_{y,rms} = 0.2\,\pi$ mm mrad. The beam was then tracked through the RFQ field map and the beam transmission, final energy distribution and horizontal and vertical rms emittances measured at the RFQ exit plane.

The first stage of the beam dynamics simulations was to benchmark the quality of the CST field mapping. Particles were tracked through the RFQ field map in GPT for different CST field mesh densities. A point spacing of 0.5 mm in all 3 dimensions was required for the field map output from CST: no change in beam dynamics was observed for a finer grained field map. This is a similar field map point density to the RFQ field map produced by RFQSIM that was used for previous FETS beam dynamics simulations [7]. The results of these simulations is shown in Fig. 5. A clear threshold is apparent above a mesh density of 1,100 points: below this level, the beam transmission is extremely poor (Fig. 5a) and a large emittance and energy distribution are present as a result of the beam being incorrectly captured and focussed (Figs. 5b and 5c). Above this threshold, full beam transmission occurs, the x and y rms emittances stabilise at $0.2\,\pi$ mm mrad and the desired energy of 3.03 MeV is reached. In addition, a gaussian peak in the transmitted

(a) Transmission   (b) Emittances

(c) Energy   (d) Energy Distribution
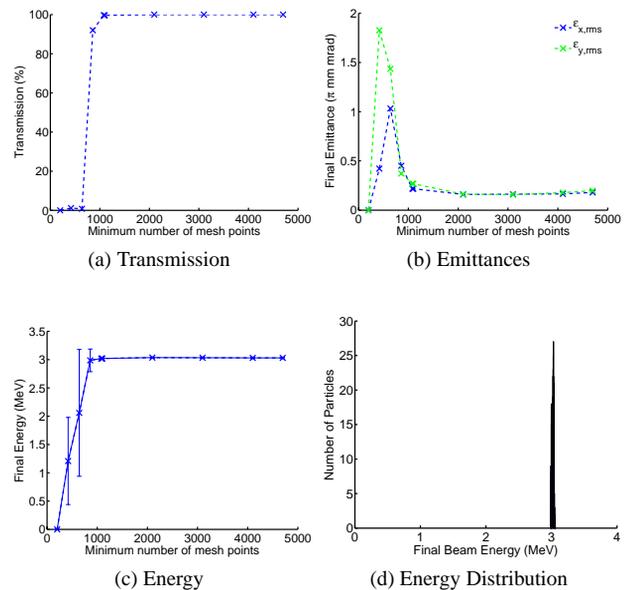
Figure 5: Final beam parameters for GPT simulation with variable CST mesh density; energy distribution is for 1,100 point mesh.

energy is observed, with a width of 28 keV (Fig. 5d): this matches closely the distribution seen with earlier simulations using the RFQSIM field map. However, differences in the beam dynamics do appear up to a mesh density of 4,700 points: further investigations are required to establish whether these variations are the results of numerical noise. Further results from both rod and vane models produced using this method, as well as comparisons to the field maps produced by RFQSIM, are given in [4].

CONCLUSIONS

While testing is still at the benchmarking stage, results from this integrated design method have been extremely promising. A CAD model has been produced in Autodesk Inventor that models the RFQ vane tip modulations. This model can be imported into CST to produce an E-field map: beam dynamics simulations can then be carried out in GPT using this field map. A minimum CST mesh density and maximum field map spacing has been set based on these simulations, providing a benchmark for further simulations in order to optimise the design of the RFQ.

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