INTEGRATED DESIGN METHOD AND BEAM DYNAMICS SIMULATIONS FOR THE FETS RADIOFREQUENCY QUADRUPOLE

S. Jolly, M. Easton, Imperial College, London, UK
J. Pozimski, STFC/RAL, Chilton, Didcot, Oxon, UK/Imperial College, London, UK
A. Letchford, STFC/RAL, Chilton, Didcot, Oxon, UK

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. A novel design method, integrating the CAD and electromagnetic design of the RFQ with beam dynamics simulations, is being used to optimise the design of the RFQ. Basic RFQ parameters are produced with the RFQSIM code. A full CAD model of the RFQ vane tips is produced in Autodesk Inventor, based upon these parameters. This model is then imported into a field mapping code to produce a simulation of the electrostatic field around the vane tips. This field map is then used to model the beam dynamics within the RFQ using General Particle Tracer (GPT). Previous studies have been carried out using field mapping in CST EM Studio. A more advanced technique using Comsol Multiphysics and Matlab, that more tightly integrates the CAD modelling, field mapping and beam dynamics simulations, is described. Results using this new method are presented and compared to the previous optimisation process using field maps from CST.

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 and the current status is given in [1]. To accelerate the beam to 3 MeV, a 4-vane RadioFrequency Quadrupole (RFQ) channel, consisting of 4 resonantly coupled sections operating at 324 MHz, has been selected for FETS.

In order to fully optimise the design of the FETS RFQ, an integrated design method has been developed. Vane modulation parameters for the RFQ are generated using the RFQSIM code [2]: 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. These parameters are then imported into Autodesk Inventor and, through a custom Visual Basic script, a 3D CAD model of each vane is generated. This CAD model is exported to an electrostatic modelling package and a full 3D field map is generated of the electrostatic field surrounding the RFQ vane tip modulations. This field map is then imported into GPT to carry out beam dynamics simulations. Matlab is used to generate the necessary field map data files for GPT import and to analyse the results: custom Matlab functions have been written to allow GPT to be called from Matlab and to load and analyse the resultant GDF data files. The eventual aim is to be able to fully automate the CAD import, field mapping and beam dynamics simulation process using Matlab. For details of the CAD modelling process and field mapping in GPT, see [3]; further details of the electrostatic modelling and application to the PAMELA project are given in [4].

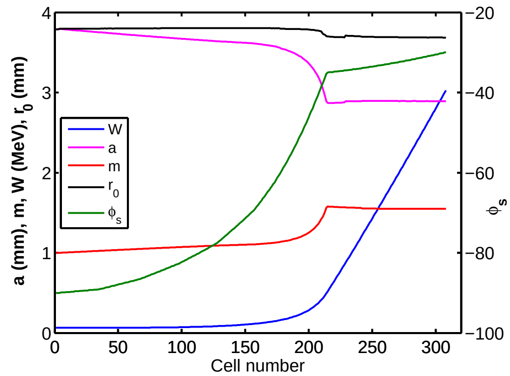


Figure 1: Design parameters for the FETS RFQ.

Since the results presented in [3], progress has been achieved in 3 main areas:

1. Integration of RFQSIM field mapping into Matlab.
2. Refinement of CST electrostatic modelling.
3. New electrostatic modelling using Comsol.

RFQ FIELD MAPPING

3 codes are used to generate field maps for the RFQ beam dynamics simulations: CST, Comsol – both using the CAD-based approach previously described – and RFQSIM. RFQSIM is used as the control to benchmark the two CAD-based methods, since the RFQSIM field map represents an idealised model of the electric potential close to the beam axis.

RFQSIM

In order to generate a field map from the RFQ solution provided by RFQSIM, the first 8 terms of the RFQ potential function are used (see Eqn. 4 in [2]). RFQSIM generates coefficients for each of these 8 terms, giving 8 coefficients for every cell of the RFQ. It is then possible to model the field in a region slightly larger than the vane tip-to-tip distance at an arbitrary position within each cell.

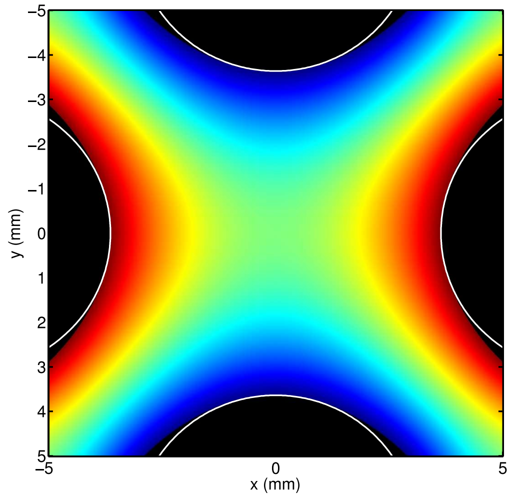
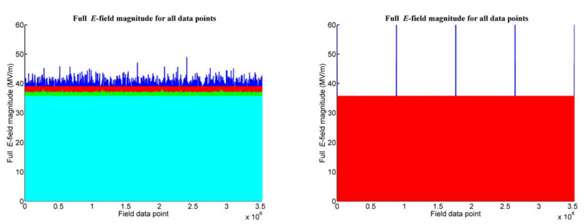


Figure 2: RFQSIM electric potential for the 2nd RFQ cell; real vane tip profiles are shown in white.



(a) Sparse/Dense Meshes (b) Open/Tangential Boundaries

Figure 3: Electric field magnitudes for sparse tetrahedral (blue), sparse hexahedral (red), dense tetrahedral (green) and dense hexahedral (cyan) CST meshes of an RFQ vane with no modulations.

To allow greater control over the granularity of the field maps produced, and to integrate the field map generation into any future iterative optimisation process, the field mapping part of RFQSIM has been rewritten in Matlab. This allows more sophisticated visualisation of the RFQ field at any arbitrary point within the RFQ. The resultant electric potential, generated from the RFQSIM field coefficients, is shown in Fig. 2. The vane tip profiles from the CAD model are overlaid in white: note that the vane profiles produced by RFQSIM – shown in black – are virtually identical close to the vane tip, but that small discrepancies appear with increasing vane tip radius. It is to be expected therefore that small differences will appear in the field maps produced by RFQSIM and by the CAD-based methods, even for fully optimised meshing. It is hoped that the CAD-based methods will eventually supersede the field maps produced by RFQSIM.

CST

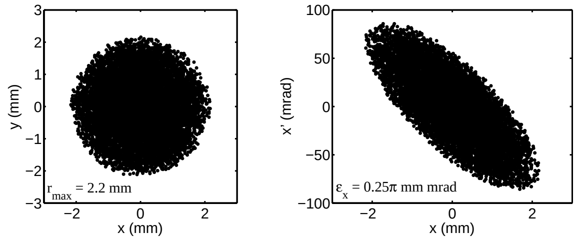
The meshing of the RFQ vane tip CAD model in CST and field map output follows the method outlined in [3]. Attention has focussed on refining the quality of the meshing and improving the resultant field map. Various options were investigated and compared for meshing the vane tips and solving for the electrostatic field: an unmodulated vane model was used, since any E_z-field from such a model would be the result of the limitations of the meshing and therefore easier to measure. For such a vane model, a hexahedral mesh gives smoother field maps that are closer to ideal solutions, but produces technical difficulties in the calculation for complicated structures. A tetrahedral mesh gives a noisier field map, but is more robust in dealing with the RFQ vane geometries (see Fig. 3a). Tangential boundary conditions at the ends of the RFQ sections, rather than open boundary conditions, were chosen to remove the unphysical large spikes in the horizontal field between each section (see Fig. 3b).

Comsol

Comsol provides similar functionality to CST, but with a number of distinct advantages. Comsol allows live-linking to the CAD model, rather than using a static SAT file, allowing the Comsol model to update automatically whenever the CAD model is adjusted. As the CAD model is live-linked to a spreadsheet containing the RFQ modulation parameters, updating this spreadsheet automatically updates the Comsol model. This allows the optimisation code to use the output of the electrostatic field map from Comsol to iteratively adjust the modulation parameters. As Comsol also features a Matlab interface, this creates a programmatic connection from the modulation parameters through to the particle tracking results, allowing the optimisation loop to be based on the particle tracking results rather than the electric field. Comsol also provides a multiphysics environment, potentially allowing the integration of the electrostatic modelling and beam dynamics simulations with the mechanical design [5] and thermal modelling [6] of the FETS RFQ that is already underway. Comsol features an interactive meshing system, which can create a dense swept tetrahedral mesh along the vane tips and close to the beam axis, with a sparser mesh in the surrounding area, producing a higher mesh density where needed. The meshing of the area surrounding the RFQ vanes reduces the impact of the open boundary conditions so that the field discontinuities between model sections no longer have a significant effect on the particle dynamics. In addition, Comsol can output field map data at arbitrary points within the model, rather than the fixed point spacing required by CST.

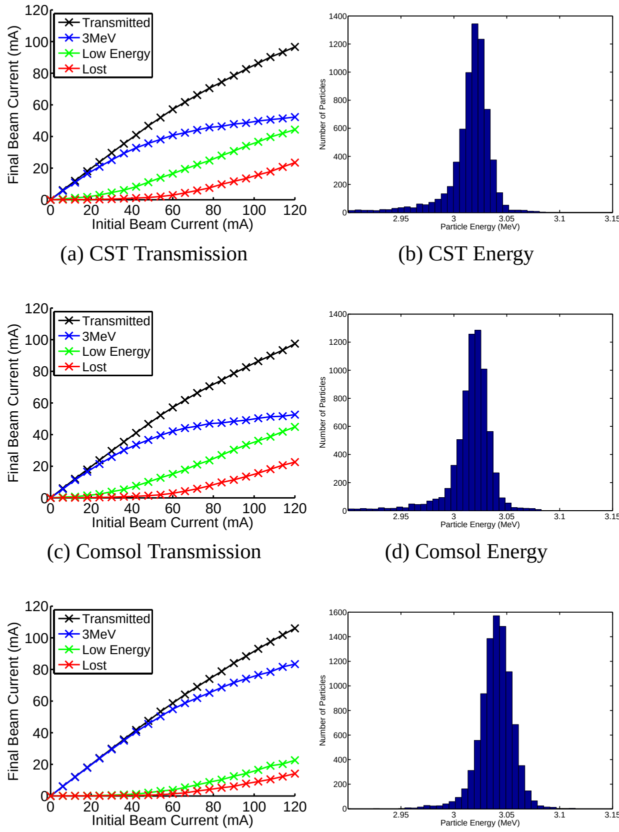
BEAM DYNAMICS SIMULATIONS

As before, beam dynamics simulations were carried out using GPT. A custom space charge routine has been implemented, based on the Barnes-Hut algorithm: this multi-threaded code provides significant speed enhancement over the built-in GPT space charge functions for multi-core systems and also allows the simulation of bunched beams without a corresponding increase in the number of simulated particles. An input



(a) $x - y$ (b) $x - x'$

Figure 4: Input beam profile and horizontal emittance.



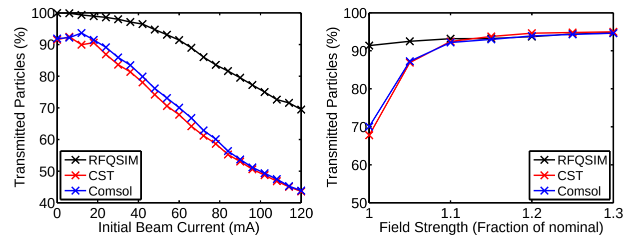
(a) CST Transmission (b) CST Energy

(c) Comsol Transmission (d) Comsol Energy

(e) RFQSIM Transmission (f) RFQSIM Energy

Figure 5: Beam transmission and final energy for the 3 field maps: transmitted current (black), particles accelerated to 3 MeV (blue), low energy particles (green) and lost particles (red) are shown as a function of input beam current.

beam distribution representing the optimal output beam from the FETS LEBT was used: a waterbag distribution with $x_{max} = y_{max} = 2.2$ mm, $x'_{max} = y'_{max} = 90$ mrad and $\epsilon_{x,rms} = \epsilon_{y,rms} = 0.25\,\pi$ mm mrad (see Fig. 4). The input current was varied between $0 - 120$ mA and the beam tracked through each of the 3 RFQ field maps to measure beam transmission and energy spread. Two results are clear from these simulations (see Fig. 5): 1) Comsol and CST produce very similar results; 2) RFQSIM gives significantly better beam transmission at the desired energy of 3 MeV, particularly for high current. While all 3



(a) Beam Current (b) Field Strength

Figure 6: Transmission of particles accelerated to 3 MeV as a function of input beam current and field strength.

methods give similar transmission overall, for any currents approaching the design specification of 60 mA both Comsol and CST are unable to correctly capture and accelerate the beam, resulting in a significant fraction of "low energy" particles, below 2.9 MeV, that are still transmitted by the RFQ (see Fig. 6a). Both CST and Comsol produce a mean final beam energy of 3.02 MeV compared to 3.04 MeV from RFQSIM, but with a similar energy spread. Given that the transverse losses are broadly similar for all 3 methods, this would indicate problems with the longitudinal fields: naively one could assume that transverse losses result from inadequate transverse focussing, while low energy transmission results from poor RF capture and therefore incorrect longitudinal fields. However, it is possible to counteract this effect by increasing the field strength. Fig. 6b shows the effect of increasing the field strength by up to 30%: note that a significant improvement in transmission is seen for only a 10% increase. In reality, such an increase would be undesirable, since it would require a 20% increase in RF power. It remains to be seen whether this effect is a result of the more realistic field map produced through the CAD modelling approach or through inadequate meshing during the field solving stage.

CONCLUSIONS

Progress on the integrated design method for the FETS RFQ has been made on a number of fronts. However, a number of issues remain, in particular the poor transmission of the two CAD-based methods at higher currents with the nominal field strength. Future simulation work will focus on Comsol, since it has the potential to fully integrate all aspects of the RFQ design within a single simulation framework.

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