RFQ DESIGN OPTIMISATION FOR PAMELA INJECTOR

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Abstract

The *PAMELA* project aims to design an FFAG accelerator for cancer therapy using protons and carbon ions. For the injection system for carbon ions, an RFQ is one option for the first stage of acceleration. An integrated RFQ design process has been developed using various software packages to take the design parameters for the RFQ, convert this automatically to a CAD model using Autodesk Inventor, and calculate the electric field map for the CAD model using CST EM STUDIO. Particles can then be tracked through this field map using Pulsar Physics' General Particle Tracer (GPT). Our software uses Visual Basic for Applications and MATLAB to automate this process and allow for optimisation of the RFQ design parameters based on particle dynamical considerations. Initial particle tracking simulations based on modifying the field map from the *Front-End Test Stand* (*FETS*) RFQ design have determined the best operating frequency for the *PAMELA* RFQ to be close to 200 MHz and the length approximately 2.3 m. The status of the injector design with an emphasis on the RFQ will be presented, together with the results of the particle tracking.

INTRODUCTION

The function of the injector system for *PAMELA* [1] is to get protons and carbon ions into the FFAG accelerator at the correct energy, with the right bunch charge and bunch structure. Current designs require protons to be injected at ~31 MeV and carbon ions to be injected at ~ 8 MeV/u.

The protons and carbon ions will be produced in separate sources, allowing faster switching between ion species in a clinical situation, improving productivity [2]. A Low Energy Beam Transport line (LEBT) will transport the particles from the sources into a pre-accelerator. Another beam transport section (MEBT) will inject the particles into *PAMELA*. A standard 30 MeV proton cyclotron can be acquired for the proton beam injection, and a radio frequency quadrupole (RFQ) and linac can be designed for the carbon injection. An advantage of this is that the facility can be realised in three stages. Firstly, proton therapy with the cyclotron and a single FFAG ring. Then the installation of a carbon injector to allow clinical and biological studies using low power carbon beams. Finally a second FFAG ring could be added to produce a carbon therapy beam. Figure 1 is a schematic of the proposed injector system including the LEBT, pre-accelerator and MEBT. The injector layout is discussed in another article in these proceedings [3].

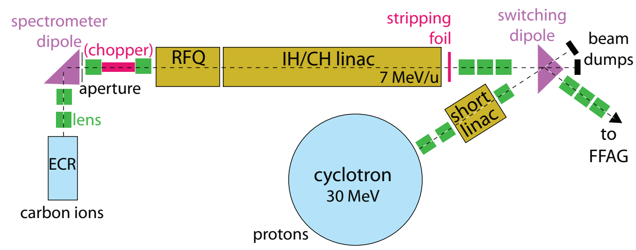

Figure 1: Schematic of proposed injector assembly, including ion sources, LEBT, pre-accelerators and MEBT. The proton source is contained within the cyclotron.

RFQ

The first stage of pre-acceleration for carbon will use an RFQ to prepare the carbon 4^+ ion beam for acceleration in the linac. The RFQ is the starting point for the injector studies, as the input and output parameters of the RFQ and linac will determine the requirements of the LEBT and MEBT, so these parameters need to be established first before the design of the LEBT and MEBT.

RFQ SIMULATIONS

Design Optimisation Software

A software solution has been developed to allow optimisation of RFQ designs for both *PAMELA* and the *Front-End Test Stand* (*FETS*) [4]. This optimisation procedure and the associated software is planned to be extended to other accelerating structures, such as the *PAMELA* linac. The software is described in detail in another article in these proceedings [5].

The design parameters for the RFQ are entered into a spreadsheet. These parameters are read into Autodesk Inventor by code written in Visual Basic and a CAD model is automatically constructed. The structural model is exported as a `.sat` file and then imported to CST EM STUDIO for electrostatic modelling. The electromagnetic conditions and simulation parameters are set by a macro in CST and then the electrostatic solver produces a field map that can be exported as a text file. From this point onwards Matlab scripts carry out the particle tracking and analysis. Particles are tracked through the CST-generated field map using GPT, which can be run from within Matlab. The particle tracks are then analysed within Matlab and the results saved as text, image and video files.

Ideally, every step of the process should be automated, which would allow an unattended optimisation process. Unfortunately, due to licensing and technical issues, the Autodesk Inventor and CST stages require some human interaction, and so batch code has been written in Matlab to enable the particle tracking and analysis to be run for any number of different field maps produced beforehand. This allows us to investigate a series of different sets of design parameters at a time, produce the field maps for each one and then automate the computations for the whole series. Comparing the results for each set of design parameters allows us to target the next series of data sets and get closer to an optimised model at each iteration of this process.

Preliminary Carbon RFQ Simulations

The initial carbon simulations were based on the design of the 3 MeV proton RFQ for *FETS*, and various scaling laws have been investigated to determine the changes required to produce a carbon RFQ.

The *FETS* RFQ field map has been generated by the RFQSIM code using the first eight terms of the field expansion for the potential between vanes [6]. Tracking particles through this field map using Pulsar Physics General Particle Tracer (GPT) shows 100% transmission and acceleration to the required energy of 3 MeV. GPT allows linear manipulations of field maps, so the field frequency and electrode potential can be scaled, as can each of the co-ordinate axes. This allows the preliminary investigation of a possible field map for a *PAMELA* RFQ. Note that the *FETS* RFQ uses four vanes, but the lower frequency of the *PAMELA* RFQ is better suited to a four-rod design, so scaling the field map cannot produce the correct field. Also, the RFQ modulation parameters will need to be altered for the best transmission and acceleration parameters for the carbon RFQ.

SIMULATION RESULTS

Design Optimisation Software

The first CAD models to be tested with CST and GPT were the 3 mm 4-vane *FETS* RFQ models, as field maps for this problem are available from other code for comparison. Once the software process is complete, the same methods can be used for the *PAMELA* RFQ.

Initial results showed poor transmission and poor acceleration, but this was improved by increasing the mesh density of the electrostatic simulation in CST. Most recent results show 94% transmission, but not all particles reach the expected energy of 3 MeV (see Figure 2 for final energy distribution and Figure 3 for trajectories).

The latest simulations (Figures 4 and 5) have concentrated on rod RFQ designs instead of vanes to see how this affects the results. These simulations have found 99% transmission and coherent acceleration to 3 MeV. This improved acceleration with rods compared to vanes matches similar findings using the RFQSIM code [6].

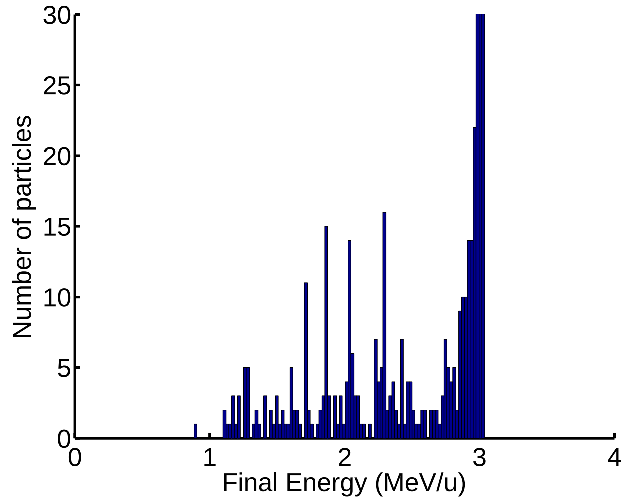

Figure 2: Histogram of output energy of the *FETS* 4-vane RFQ field simulation.

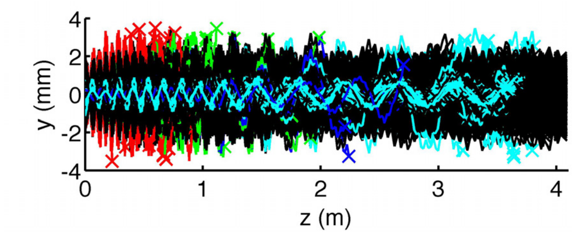

Figure 3: The trajectories of the model particles through the *FETS* 4-vane RFQ field simulation with particle tracks tagged by colour according to the end of the particle track.

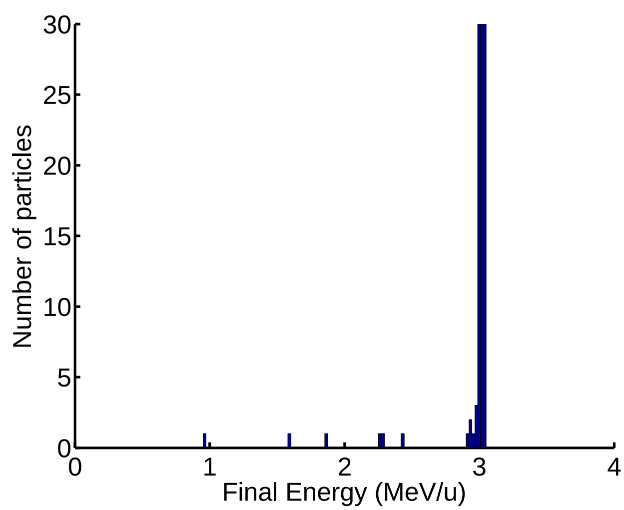

Figure 4: Histogram of output energy of the *FETS* 4-rod RFQ field simulation.

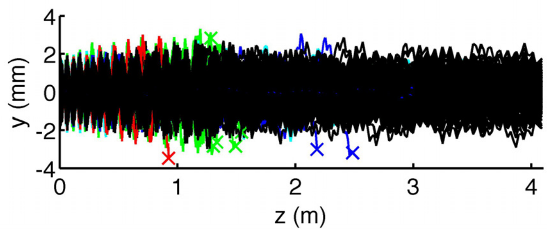

Figure 5: The trajectories of the model particles through the *FETS* 4-rod RFQ field simulation.

Preliminary Carbon RFQ Simulations

Table 1 summarises the input parameters for the carbon ion simulations. Very early particle tracking results using these values show a transmission of 75% and a mean output energy of 382 keV/u (see Figure 6). The transmission would be improved by reducing the input emittance, which is possible as the *PAMELA* RFQ will be accelerating a much lower current than the *FETS* RFQ. Particle loss analysis shows that the early losses correspond to areas of phase space that would be excluded with a lower emittance. Figure 7 shows that a large proportion of the particles that do not get transported through the RFQ are lost at around the 1 m mark, which is the point at the end of the bunching section where space charge forces are largest. Optimising the rod modulations for carbon acceleration should therefore produce higher transmission and output energy.

Table 1: Simulation parameters for carbon RFQ model.

Parameter	Value
E-field frequency	200 MHz
Initial particle energy	8 keV/u
RFQ length	2.4 m
Electrode potential	80 kV

CONCLUSION

We have developed a software solution to take a CAD model and track particles through the electromagnetic field produced by that model. Preliminary results do not exactly match with existing code, so these discrepancies need to be fully investigated and understood. When the software solution is complete it will allow the tracking of particles through a wide range of accelerating structures, and in this way the *PAMELA* carbon injection chain can be modelled from CAD through to particle tracking results, ready for the prototyping phase of the *PAMELA* project.

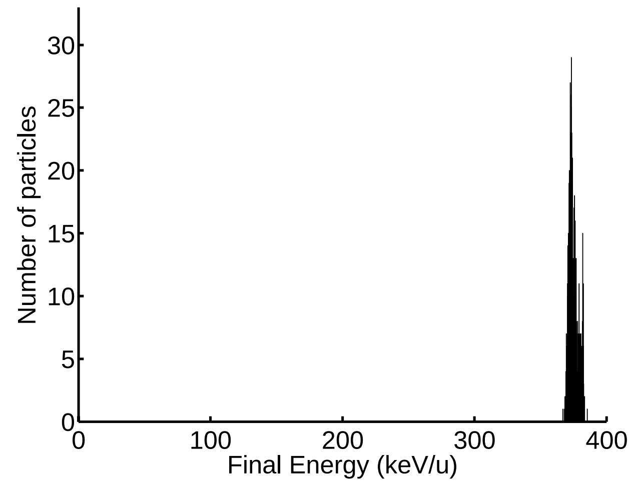

Figure 6: Histogram of output energy of carbon 4^+ ions in RFQ simulation set at 200 MHz and 2.4 m length with an input energy of 8 keV/u.

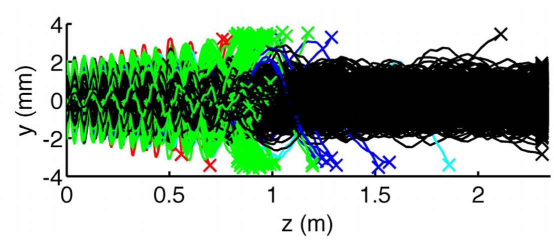

Figure 7: The trajectories of the model particles through the *PAMELA* RFQ field simulation.

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