# DESIGN OPTIMISATION AND PARTICLE TRACKING SIMULATIONS FOR *PAMELA* INJECTOR RFQ

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## *Abstract*

The *PAMELA* project aims to design an ns-FFAG accelerator for cancer therapy using protons and carbon ions [1]. For the injection system for carbon ions, an RFQ is one option for the first stage of acceleration. Our integrated RFQ design process [2] has been further developed using *Comsol Multiphysics* for electric field modelling. The design parameters for the RFQ are automatically converted to a CAD model using *Autodesk Inventor*, and the electric field map for this model is simulated in *Comsol*. Particles are then 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. Possible designs for the *PAMELA* RFQ, including super-conducting and normal-conducting solutions, are presented and discussed, together with results of the field map simulations and particle tracking for these designs.


## INTRODUCTION

The function of the injector system for *PAMELA* is to get protons and carbon ions into the FFAG accelerator at the right energy, with the correct bunch charge and bunch structure. Current designs require protons to be injected at ~30 MeV and carbon ions to be injected at ~8 MeV/u.

The protons and carbon ions are produced in separate sources, allowing faster switching between ion species in a clinical situation, improving productivity [3]. A Low Energy Beam Transport line (LEBT) transports the particles from the sources into a pre-accelerator. Another beam transport section (MEBT) injects 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 are being 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 can 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 [4].

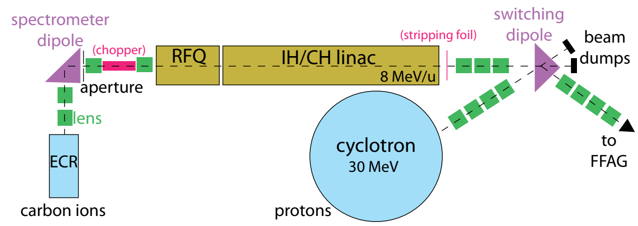


Figure 1: Schematic of proposed injector assembly, including ion sources, LEBT, pre-accelerators and MEBT. The proton source is contained within the cyclotron.

## *RFQ*

The first stage of pre-acceleration for carbon uses an RFQ to prepare the carbon ion beam for acceleration in the linac. The RFQ bunches the beam and accelerates the particles to match the acceptance of the linac. There are various options for injection into the ns-FFAG that affect the design of the RFQ, and two main choices to be made.

Firstly, the ion source produces both carbon $4^+$ and carbon $6^+$ ions. The proportion of carbon $6^+$ ions is significantly lower, however, and so the beam current output from the injector is significantly lower using this ion species. To achieve the target average beam current in the accelerator of $3 \times 10^8$ particles per second with a repetition rate of 1 kHz using single-turn injection, an injection current of $6 \times 10^{11}$ particles per second is required [4]. For carbon $6^+$ ions, this is operating close to the limit of available current. If the output current requirements became higher than this present value, the only viable option for carbon $6^+$ ions would be multi-turn injection.

Secondly, the RFQ design could be normal-conducting or super-conducting. The required repetition rate and injection scheme limit this also. A normal-conducting cavity at 200 Mhz with a $q$-value ~1000 would have a filling time of the order of 5 $\mu$s. Half-filling the *PAMELA* ring at 1 kHz in a single turn will require a ~500 ns pulse, so the dissipated power would be ten times higher than the useful beam. With the high current of carbon $4^+$ ions available, this would not be an issue. However, for carbon $6^+$ ions, the reduced current means that these losses would be too high. With a super-conducting RFQ, the increased $q$-value means the dissipated power would drop from 50 kW to 0.5 W and the carbon $6^+$ acceleration becomes attainable.

## RFQ SIMULATIONS

### Design Optimisation Software

Our RFQ design software has been further developed to allow optimisation of RFQ designs for both *PAMELA* and the *Front-End Test Stand* (*FETS*) [5]. The software is described in more detail in another article in these proceedings [6].

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. From this point onwards *Matlab* scripts carry out the electrostatic modelling, particle tracking and analysis. The structural model is opened in *Comsol Multiphysics*, the electromagnetic conditions and simulation parameters are set by the *Matlab* code and then the electrostatic solver produces a field map that can be exported as a text file. Particles are tracked through this field map using *Pulsar Physics' General Particle Tracer (GPT)*, which is also run from within *Matlab*. The particle tracks are then analysed within *Matlab* and the results saved as text, image and video files.

*Comsol* allows live-linking to the CAD model, rather than using a static SAT file. This means that changes to the CAD model automatically update the *Comsol* model. As the CAD model is live-linked to the spreadsheet containing the RFQ modulation parameters, updating this spreadsheet therefore updates the *Comsol* model automatically. This allows optimisation code to adjust the modulation parameters and iterate, without needing to run *Autodesk Inventor* for CAD modelling. As *Comsol* also exposes an interface to *Matlab*, which is already handling the particle tracking simulation code, 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.

### Carbon RFQ Simulations

The simulations are based on the design of the 3 MeV proton RFQ for *FETS*, with various scaling laws applied to produce a starting point for a carbon RFQ.

The *FETS* RFQ field map is generated by the *RFQSIM* code using the first eight terms of the field expansion for the potential between vanes [7]. Tracking particles through this field map using *GPT* shows 100% transmission and acceleration to the required energy of 3 MeV. By scaling the geometric dimensions of the RFQ but using the same modulation profile along the length of the vanes, a carbon RFQ is simulated. The final stage of RFQ design for *PAMELA* is to optimise the modulation parameters based on the particle tracking results to get the best possible acceleration for carbon ions.

## SIMULATION RESULTS

### Design Optimisation Software

The first CAD models to be tested were the 3 mm 4-vane *FETS* RFQ models, because field maps for this problem are available from other code for comparison. Previous results [2] showed 94% transmission, but not all particles reaching the expected energy of 3 MeV. After solving various problems with the field map construction code, the final results show a good agreement with expected results [6]. The output distributions are plotted in Figures 2 and 3.

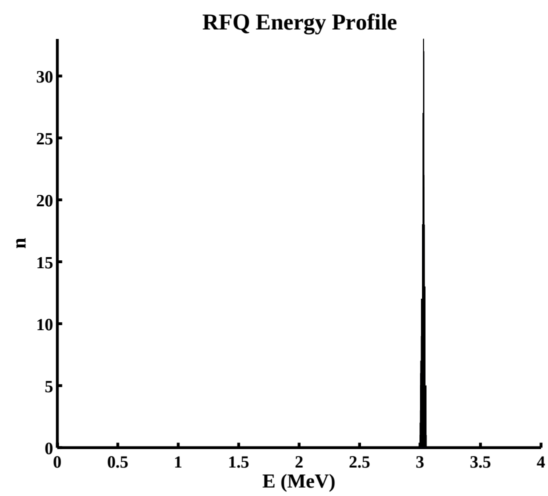


Figure 2: Histogram of output energy of the *FETS* RFQ field simulation.

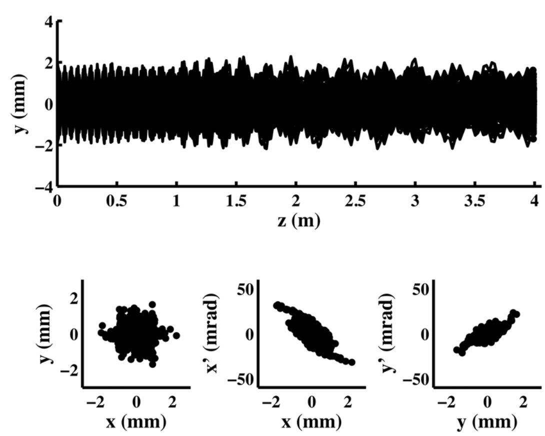


Figure 3: The trajectories of the model particles through the *FETS* RFQ field simulation and the output distributions in real space and phase space.

### Carbon RFQ Simulations

Table 1 summarises the input parameters for the carbon ion simulations. The results for carbon $4^+$ and carbon

$6^+$ are qualitatively similar, so Figures 4 and 5 plot the output distributions for the carbon $4^+$ simulations only. The results of the simulations are described in Table 2 and compared with the *FETS* simulation results.

The transmission of particles is above 95% in both carbon simulations. However, the large energy spread indicates that the particles are not coherently accelerated. Some particles are falling out of the RF bucket and not experiencing the full accelerating force. To reduce this effect and produce an effective RFQ design for carbon, the existing design based on the *FETS* proton RFQ should be optimised for the acceleration of carbon ions using the *Matlab*-driven iterative code described above.

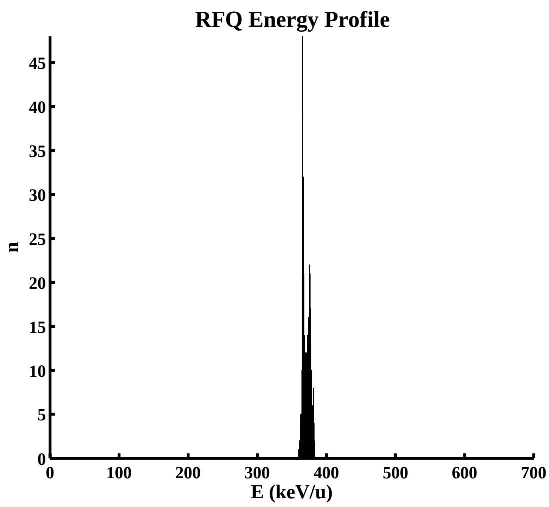


Figure 4: Histogram of output energy of the carbon $4^+$ RFQ field simulation.

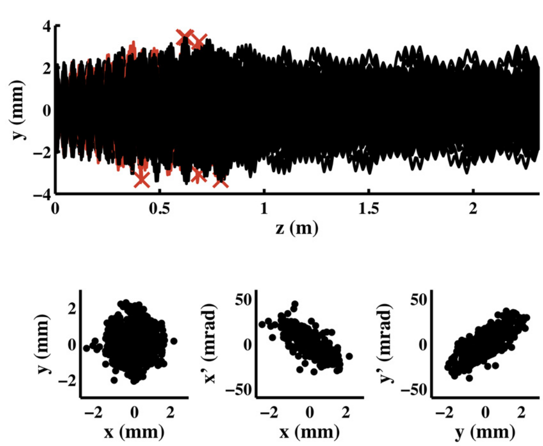


Figure 5: The trajectories of the model particles through the carbon $4^+$ RFQ field simulation and the output distributions in real space and phase space.

Table 1: Simulation parameters for carbon RFQ models.

| **Parameter** | **$4^+$ Value** | **$6^+$ Value** |
|---|---|---|
| $E$-field frequency (MHz) | 200 | 280 |
| Initial particle energy (keV/u) | 8 | 12 |
| RFQ length (m) | 2.3 | 2.1 |
| Electrode potential (kV) | 75 | 85 |

Table 2: Results for proton and carbon RFQ simulations.

| | ***FETS*** | **$4^+$** | **$6^+$** |
|---|---|---|---|
| Transmission (%) | 100 | 98.9 | 95.6 |
| Mean energy (keV/u) | 3026 | 445 | 729 |
| RMS energy (keV/u) | 9.9 | 62.8 | 105.6 |

## CONCLUSION

An integrated RFQ design software solution has been created, controlled by *Matlab* code and using *Comsol Multiphysics* and *GPT* to optimise RFQ modulation parameters based on particle tracking considerations. This solution has been tested with the *FETS* RFQ design and found to agree with the results of prior simulations using alternative code [6]. Two carbon RFQ designs have been created, for two alternative injector scenarios for the *PAMELA* FFAG. Simulations for both designs show transmission higher than 95%, but large spreads in energy. To reduce this energy spread and increase the efficiency of the RFQ, the modulation parameters should be optimised further based on the particle tracking results as well as the electromagnetic field map.

## REFERENCES

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