BEAM DYNAMICS SIMULATIONS ON THE ESS BILBAO RFQ

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Abstract

The ESS Bilbao RFQ is aimed to accelerate a 75 mA proton beam from 75 keV to 3 MeV, while keeping the beam both transversely and longitudinally focused, and presenting a minimum emittance growth. We report on the current status of the project, mainly focusing on the Beam Dynamics aspects of the design. Several particle simulations were carried out with RFQSIM and GPT codes, in order to confirm the vane design validity.

RFQ DESIGN OVERVIEW

The main characteristics of the ESS Bilbao RFQ are presented in Table 1. The 4–vane RFQ follows a multi-specimen LEBT [1], which has particles injected from either H^+ or H^- ion sources at 75 keV, and a maximum projected current of 75 mA. The RFQ bunches and accelerates the particles up to 3 MeV.

The electromagnetic studies of the RFQ are being performed using Comsol Multiphysics. A 2D design of the cavity is created to match the operating frequency. A 3D model is then extruded, with both RFQ ends (radial matcher, covers) being parametrically designed in order to achieve operation at the selected frequency, and ensure adequate field flatness along the longitudinal axis. Other factors, such as tuners and coupler positions, are considered at this stage. The final corrections to the model geometry are then performed to get the final electromagnetic design of the cavity, aiming for a 352.2 MHz resonance. Any small deviations from this frequency will be corrected by a Low Level RF (LLRF) control system.

Table 1: RFQ Design Specification

Type	4–vane
RF Frequency	352.2 MHz
Vane-to-vane voltage	85 kV
Material	Copper
Species	H^+/H^-
Input Energy	75 keV
Output Energy	3 MeV
Max. current	75 mA
Pulse length	Up to 2 ms
Repetition rate	50 Hz
Duty cycle	8%

In parallel, thermo-mechanical simulations are performed, in which the heat production in the copper is simulated. This allows to analyze thermal stresses and expansions that might change the RFQ geometry (and thus the electromagnetic behavior). These heat charges and displacements will be used as an input for the design of an adequate cooling system.

The power input will be provided by two couplers connected in a T-configuration to a klystron. The couplers will be ended in a loop that enters the cavity, thus being inductively coupled to the cavity resonating mode. Different coupler prototypes and a test-bench are planned to be designed and implemented.

In order to validate the design and test the mechanical feasibility, a cold model of the RFQ will be designed and built in aluminium. The transverse dimensions of the cold model will be equal to those of the full RFQ, but its length will only be 1 m (about four times shorter than the full one). This model will allow us to study several aspects of the electromagnetic behavior of the RFQ cavity, such as tuning by LLRF, dipolar mode suppression, and field flatness.

The RFQ fabrication system will be carefully studied in order to successfully join the RFQ parts with no movement or distortion, aiming to achieve a Q factor as high as possible. The joints must be vacuum-tight and act as a barrier for the RF power. The secondary goal is to be able to easily dismantle the RFQ, should the cavity need to be re-polished after an RF breakdown. In order to cover the main alternatives, four RFQ joint test assemblies will be manufactured, in which the parts will be joined: a) by electron beam welding, b) by laser beam welding, c) by vacuum brazing, and d) mechanically. The method used to assemble the final RFQ parts will be selected based on the quality of the resulting joints provided by these four test models.

VANE DESIGN

Designing the vane modulation demands using a computer program, since the physics behind the electric fields in the RFQ is described by complex expressions that cannot be easily handled. The ESS Bilbao RFQ modulation presented in this work has been created with RFQSIM [2]. This program is also capable of performing particle tracking simulations, which will also be presented in this work.

The procedure used for the optimal vane modulation design, which was better covered in a previous work [3], ba-

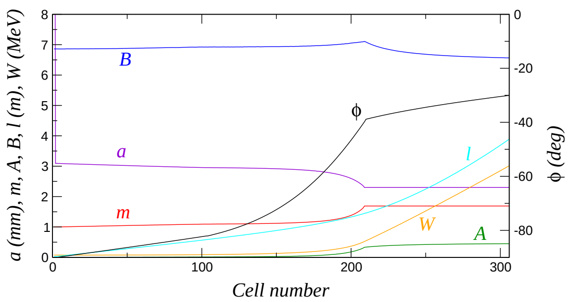


Figure 1: Evolution of several RFQ parameters as a function of the cell number.

sically consists of scanning values for several design parameters, such as the synchronous phases and energies at certain points of the RFQ. By performing a number of simulations, the initial values are refined one by one, until the best possible results are achieved, i.e., until both increasing and decreasing a parameter's value gives worse results. The flatness of the design (this is, a slight change in any parameter value provides similar results) must also be taken into account, thus finding a robust solution.

The selected vane modulation design is depicted in figure 1, in which the evolution of some parameters along the RFQ is plotted. The left axis displays the aperture (a), modulation factor (m), accumulated length (l), acceleration efficiency (A), focusing efficiency (B), and synchronous energy (W). The right axis displays the synchronous phase (ϕ_s). The start of the acceleration section is clearly visible from cell 209: at this point, the modulation depth is held constant as the beam begins to experience significant acceleration.

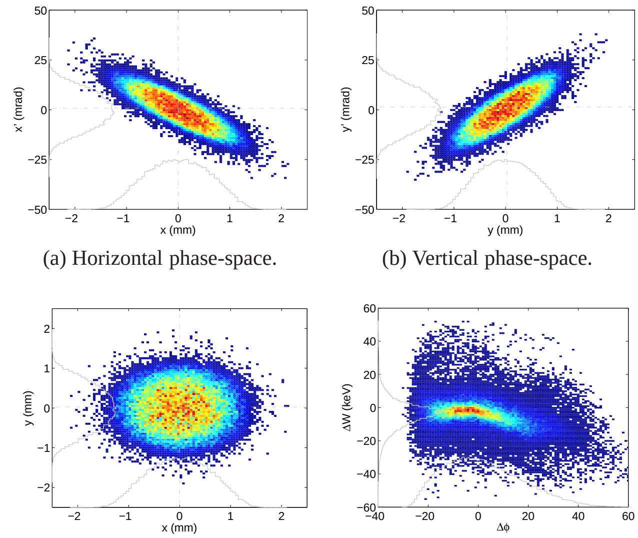
The total length of the proposed design is 3.89 m, with a maximum estimated *Bravery Factor*[1] of 1.79. It also presents very good particle tracking results, as explained in the following section.

BEAM DYNAMICS SIMULATIONS

RFQSIM

A 75 mA beam of 5000 particles with transverse 4D waterbag and 2D longitudinal distributions, and an input energy of 75 keV, was used for the main particle tracking simulations. Transverse normalized *rms* input emittances of $0.2\,\pi$ mm mrad were used: this is the emittance expected from the output of the LEBT [1]. The Courant-Snyder parameters of the input beam were calculated with Trace2D [4], which finds the periodic match for the first cell after the Radial Matching Section and tracks the beam backwards to the input of the RFQ.

The simulations resulted in a successful transmission of 96.3 % of the particles, with an emittance growth of 7.46 %. The transmission percentage is calculated by discarding both the particles that impacted with the RFQ vanes and those that were not captured by a bunch (i.e., transmitted particles with an energy significantly lower than that of the synchronous particle)[2]. The emittance growth ($\Delta\varepsilon$) is calculated as the mean of the relative increases in ε_x and ε_y, both referred to input normalized rms emittance of $0.20\,\pi$ mm mrad.



(a) Horizontal phase-space. (b) Vertical phase-space.

(c) Transverse plane distribution. (d) Longitudinal phase-space.

Figure 2: Particle density plots at the output of the RFQ.

Figure 2 presents particle density plots at the output of the RFQ, in the transverse and longitudinal phase-spaces. The successfully transmitted particles remain within a 2 mm radius from the RFQ axis, with 90 % of them found within a 1 mm radius, and 55 % of them found within a 0.5 mm radius. The maximum particle inclinations are below ± 40 mrad. The energy dispersion is quite low, with 92 % of the transmitted particles presenting energies less than 20 keV apart from that of the synchronous particle (calculated to be 3.015 MeV). The synchronous phase at the output of the RFQ is clearly seen in fig. 2d, as slower particles abruptly disappear at $-30°$ (greater phase shifts involve entering the unstable region of the longitudinal phase-space).

GPT

In order to verify the results provided by RFQSIM, we have performed particle tracking simulations with GPT [5]. Although GPT does not currently have a built-in RFQ routine, it allows to import a custom electromagnetic field map, which is time–modulated during the simulation[3]. Using this feature, one can perform simulations with similar quality to those obtained with RFQ-oriented codes.

The full RFQ field map was created based of the analytical expressions for the electrical field produced by the

[1] Ratio between the maximum electrical field at the vane surface and the Kilpatrick limit (~ 18.4 MV/m for $f = 352.2$ MHz).

[2] The energy threshold is placed at $\Delta E < 0.1$ MeV.

[3] Custom element `map3D_EB` must previously be compiled and added to the GPT binary.

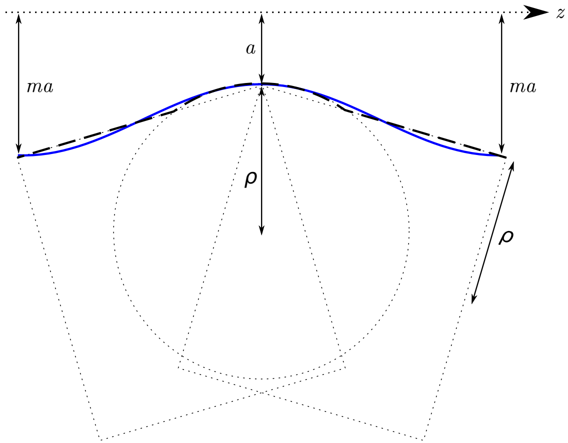


Figure 3: Representation of the vane profile approximated by spheres and inclined cylinders. The spheres are created with radius ρ and centered at $a + \rho$, and the inclination of the cylinders is calculated so that their upper edges join consecutive minima and maxima vane apertures.

8–term multipolar expansion. The field map was calculated using a uniform mesh, with 0.5 mm of spacing in the three directions.

In order to compare the particle tracking results provided by both codes, we selected the same input beam particle coordinates as the ones used for the RFQSIM simulations. The space charge forces were calculated by SCtree3D function, which implements into GPT the algorithm used by RFQSIM.

The main drawback of using an external field map to simulate an RFQ in GPT is the fact that the physical boundaries (in this case, the surface of the vanes) are not specified. Therefore, there is no automatic way of removing the particles that impact with the vanes. To overcome this problem, we have developed a Matlab routine that approximates the vane tip boundaries using GPT built-in statements, which are then included in the simulation input file. Figure 3 shows a longitudinal portion of the vane tip profile (blue) approximated by spheres and inclined cylinders (dashed black).[4] This disposition approximates the area surrounding the vane tips both in the longitudinal and transverse directions, since the spheres and cylinders are created with radii ρ, i.e. the pole tip transverse radius of curvature.

Comparison Between Codes

We have performed particle tracking simulations for different input currents, using the procedures explained above, with RFQSIM and GPT. The results are evaluated in terms of particle transmission and emittance growth, as presented in figure 4. Both figures of merit present very good values, with transmissions in the 96–100 % range and emittance growths bellow 10 % for any input current. The agreement between both codes is remarkable, although GPT presents slightly higher emittance growths.

[4] Both being geometric shapes for which GPT built-in functions exist (`scattersphere` and `scatterpipe`, respectively).

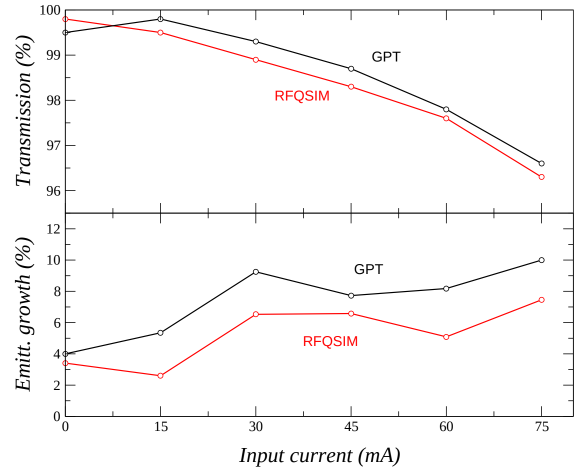


Figure 4: Successful particle transmission (top) and emittance growth (bottom) as a function of the input current, calculated by RFQSIM and GPT.

CONCLUSIONS AND FUTURE WORK

We have presented a vane design for the ESS Bilbao RFQ. The beam dynamics simulations, carried out with GPT and RFQSIM, confirm the validity of the design, with both codes presenting very good results for the figures of merit considered.

We are currently working with Brahim Mustapha (ANL) on an implementation of the RFQ design in Track [6]. Additionally, we will perform a finite element analysis of the vane design, which should provide a very accurate field map to be used in further beam dynamics simulations.

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