BEAM DYNAMIC STUDIES ON THE RADIO-FREQUENCY QUADRUPOLE FOR THE BILBAO ACCELERATOR

D. de Cos, I. Bustinduy, J.Feuchtwanger, N. Garmendia, and H. Hassanadezagan, *ESS Bilbao, Spain*
A. Letchford, ISIS (RAL), UK
S. Jolly, P. Savage and J. Pozimski, *Imperial College London*, UK
F.J. Bermejo, CSIC-UPV/EHU, Bilbao, Spain
V. Etxebarria and J. Portilla, UPV/EHU, Bilbao, Spain

Abstract

The main objective of the Bilbao Front End Test Stand (ETORFETS) is to set up a facility to demonstrate experimentally the design ideas for the future ESS LINAC that are being proposed in discussion forums by the technical scientific community. ETORFETS is focused on the first stage of the linear accelerator, namely, that of the Radio-Frequency Quadrupole (RFQ) and its pre and post beam transport systems. The RFQ bunches, focuses transverse and longitudinally, and accelerates charged particles in the low-energy range, thus becoming one of the main components of the accelerating structure. The first RFQ design and tracking simulations, performed with Alan Letchford's RFQSIM code, will be presented in this work.

INTRODUCTION

As a continuation of the ITUR ion source test stand [1], a front end test stand (FETS) for protons is being currently designed and constructed in Bilbao (Spain), comprising a Low Energy Beam Transport (LEBT), a Radio-Frequency Quadrupole (RFQ) and a High Speed Chopper [2]. The RFQ accelerator, first described in 1970 by I. M. Kapchinskiy and V. A. Tepliakov [3], is responsible for bunching, focusing (both in the longitudinal and transverse directions) and accelerating the beam to energies of up to a few MeV. The design specification of the ESS Bilbao RFQ is shown in Table 1 [4].

While many of the existing RFQ accelerators are fully brazed [5, 6, 7] or laser welded [8], the ongoing works for ISIS-FETS envisage a modular RFQ that bolts the structure together [9]. Although this design is expected to result in a cavity with an overall lower quality factor (Q) than those fully welded, ESS-Bilbao has taken steps in conjunction with colleagues from ISIS [10, 11] to develop a structure easier to maintain and to mend, and thus expected to serve a production facility for a considerable lapse of time.

RFQ DESIGN SOFTWARE AND EXPERIMENTAL PROCEDURE

The calculations presented in this work have been carried out using RFQSIM, written by Alan Letchford (ISIS) [12]. RFQSIM is a suite containing several codes that can generate a design for RFQ vane profile, as well as performing particle tracking simulations.

The vane modulation is calculated by RFQSIM as follows: first, the value of certain parameters at the end of the Gentle Buncher section must be set, which depend partly on the operation characteristics of the RFQ (such as the inter-vane voltage, maximum current to transport, etc). Once those parameters are set, RFQSIM can calculate the vane modulation all the way back to the Radial Matching Section, and forward to the end of the RFQ, following the design rules proposed by Kapchinskiy–Tepliakov. At this stage the 2–term potential function is used (see Eqn. 2 in [12]), as it provides accurate results for minimal computing overhead.

This system demands that values of certain physical parameters are provided at different parts of the RFQ, such as the phase advances at the end of each section and the energy of the particles at the output of the Gentle Buncher. Therefore, the usual procedure is to perform several calculations using different designs in which the values of certain parameters are scanned, thus searching for the best configuration.

The comparison between the different results is established in terms of the output beam characteristics (emittance growth, percentage of particles transmitted), as well as the physical characteristics of the RFQ itself, such as the total length and the maximum surface electrical field. Very long RFQs are undesired due to elevated manufacturing

Table 1: RFQ design specification.

Type	4–vane
RF Frequency	352 MHz
Species	Protons
Input Energy	75 keV
Output Energy	3 MeV
Max. current	75 mA
Peak surface field	$\leq 1.8\times$Kilpatrick limit
Pulse length	Up to 2 ms
Repetition rate	50 Hz
Duty cicle	8%

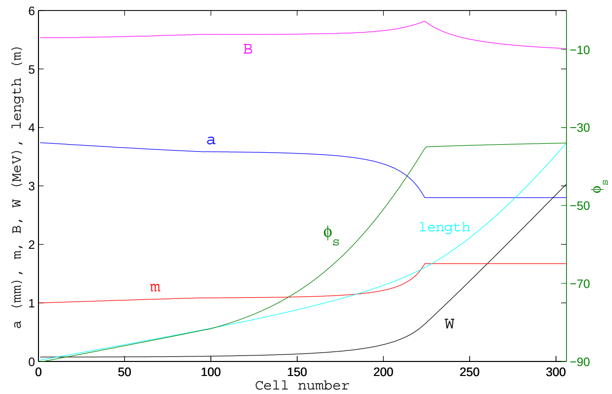

Figure 1: Evolution of RFQ parameters as a function of RFQ cell number.

costs and power consumption, while the maximum electrical field must be kept bellow a certain level (~ 33 MV/m for the ETORFETS 352 MHz RFQ) to prevent RF electric breakdown.

RESULTS

In order to find the best possible RFQ design, it is necessary to perform a number of simulations in which several parameters are scanned. Finding the optimum values for those parameters is a matter of reaching a compromise between several factors that often depend on the design parameters in opposite senses. For example, a lower radius (a) at the end of the Gentle Buncher provides both better acceleration and focusing factors, thus resulting in a shorter RFQ; but at the same time creates higher surface electric fields, which makes RF electric breakdowns more likely.

Preliminary design parameters for the ESS-Bilbao RFQ are shown in figure 1: vane radius (a), modulation factor (m), focusing factor (B), accumulated length, energy of the synchronous particle (W), and phase advance of the synchronous particle (ϕ_s) are given as a function of RFQ cell number. The RFQ consists of 306 cells, giving a total length of 3.6 m. The start of the acceleration section is clearly visible from cell 224: at this point, the modulation depth is held constant as the beam begins to experience significant acceleration.

The above design has been selected after performing a number of particle tracking simulations, in order to compare the different candidates in terms of certain parameters, such as the percentage of particles successfully transmitted and the physical state of the bunch at the output of the RFQ. Along with the RFQ vane design capabilities previously described, RFQSIM is able to: a) calculate the 8-term multipole expansion, thus generating the field map inside the RFQ (see Eqn. 4 in [12]); b) either create a custom input beam, or import a file containing the particle coordinates; and c) track the particles along the RFQ taking space charge into account, and save their coordinates at the end of each

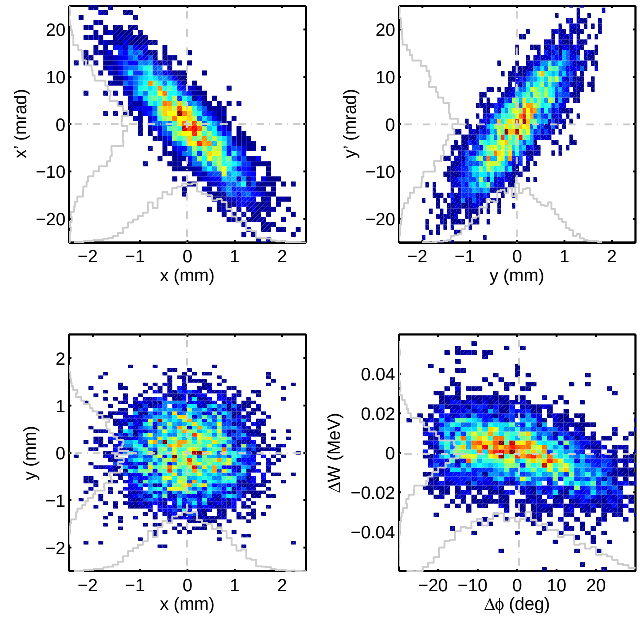

Figure 2: Beam conditions at the output of the RFQ. Top: Transverse phase-spaces. Bottom-left: Trasverse plane distribution. Bottom-right: Longitudinal phase-space.

cell. The emittance calculations are then performed on the particles transmitted to the RFQ output, 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).

A 75 mA beam of 5,000 particles with transverse 4D waterbag and 2D longitudinal distributions, and an input energy of 75 keV, was used for the particle tracking simulations. Transverse normalized *rms* emittances of $0.2\,\pi$ mm mrad were used: this is the emittance expected from the output of the LEBT. The Courant-Snyder parameters input beam were calculated with Trace2D [13], 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.

Figure 2 shows the beam conditions at the output of the RFQ: top and bottom-right plots show the transverse and longitudinal phase space distributions, with the transverse beam profile shown in the bottom-left plot. Brighter colours represent higher particle densities. Together with the color maps, the density histograms are plotted in grey lines. Only $2.5\,\%$ of the particles were lost during the transportation along the RFQ, with a further $1.4\,\%$ transmitted but incorrectly captured by the RF, giving a total transmission of $96.1\,\%$. The normalized transverse *rms* emittances grew to only $0.235\,\pi$ mm mrad, a promising result for a preliminary design, especially for such a high beam current. However, more design calculations will be performed in the near future, aiming for the best possible RFQ design achievable for the given input parameters.

CONCLUSIONS AND FUTURE WORK

We have presented the preliminary design for a 4–vane RFQ, intended to accelerate high proton currents. Although the design can be subjected to changes upon further calculations, the current status is supported by the good results achieved after beam dynamics simulations performed with RFQSIM.

Once the RFQ design is approved, the next step will consist on modeling the electromagnetic properties of the 4–vane structure, as well as analyzing its RF properties and electric field profile. Special care will be taken to study the effects of thermal stress on the vane tips.

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