Vol. 47 (2016) *ACTA PHYSICA POLONICA B* No 3

STUDIES FOR A 72.75 MHz FOUR VANES CW-RFQ FOR ECOS-LINCE PROJECT*

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(Received January 18, 2016)

The ECOS is considering the construction of a new facility for accelerating high intensity stable beams with energies at and above the Coulomb barrier, the LINCE light and heavy ion accelerator. This facility could be based on a normal conducting CW-RFQ and a superconducting linac, working at 72.75 MHz. This paper presents a design study for the RFQ system which is able to achieve 500 keV$/u$ output for $A/Q = 7$ ions in only 5 m length.

DOI:10.5506/APhysPolB.47.619

1. Introduction

The RFQ is one of the most important devices of the low-energy section of ECOS-LINCE [1]. A complete beam dynamics study was carried out with the codes DESRFQ [2] and TRACK [3], considering the highest mass-to-charge ratio to be $A/Q = 7$, and a maximum beam intensity of 1 mA. The initial acceleration of heavy ions delivered from an ECR (electron cyclotron resonance) ion source [4] which is similar to the system of INFN-Legnaro National Laboratories [5]. At the RFQ entrance, the beam is already bunched into 2 ns long pulses of 40 keV$/u$ kinetic energy. At the exit, the beam should achieve 500 keV$/u$, maximum energy spread of 2%, and bunch length of 1 ns. This is the result of a multi-harmonic buncher [6] which induces longitudinal energy modulation. Optimum injection into the SC-linac imposes maximum normalized transverse and longitudinal emittances of 0.125 cm mrad and 25 ns keV$/u$, respectively [7]. The principal design characteristics are shown in Table I.

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[*] Presented at the XXXIV Mazurian Lakes Conference on Physics, Piaski, Poland, September 6–13, 2015.

TABLE I

RFQ principal characteristics.

Characteristic	Value	Units
Frequency	72.75	MHz
Input kinetic energy	40	A keV
Output kinetic energy	500	A keV
Design mass-to-charge ratio	1–7	
Maximum vane voltage	82	keV
Maximum field strength	1.5	Kilpatric
Length	5	m
Average radius	6	mm

A combined electromagnetic, radiofrequency and thermo-mechanical design study has been carried out using COMSOL Multiphysics [8]. A particular RF-window system over the resonator vanes has been designed and optimized, in a similar manner to that realized in the ATLAS RFQ structure [9]. This has the advantage of greatly reducing the cavity volume for a given resonance frequency. The software allows varying the geometrical parameters to maximize the quality factor and accelerating fields, while reducing the resistive power losses.

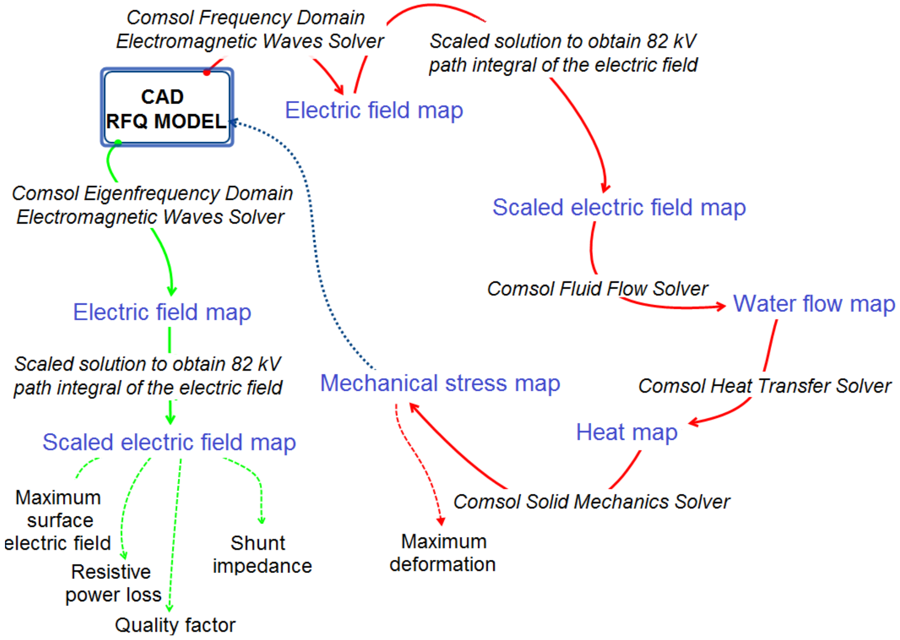


Fig. 1. RFQ design loop.

We used the Heat Transfer module coupled to the Mechanical Stress module to obtain the corresponding temperature map at the vanes [7] and the mechanical deformation, which may affect beam dynamics. To control the heating effects, we have studied a cooling system based on water circulating through pipes drilled inside the vanes [10]. The displacements and stress are obtained by coupling the heat-flux and solid-mechanics modules. Eventually, an evaluation of the RF frequency shift is obtained through a new RF study of the deformed structure. A simplified diagram of the design loop followed for performing the coupled numerical studies is shown in Fig. 1. In the final design, we achieved a total RFQ length of 5.04 m. It is proposed to construct the RFQ by coupling 10 sections of about 500 mm length each.

2. Optimization of the RFQ geometry

An optimization process of the quality factor, resistive power loss and resonant mode frequency TM_{21} has been carried out, following a loop of simulations in two stages. The first stage was dedicated to the optimization of the vane height and thickness using only the transverse shape of the vane without windows (2D), and the second one to the optimization of the RF window parameters (3D).

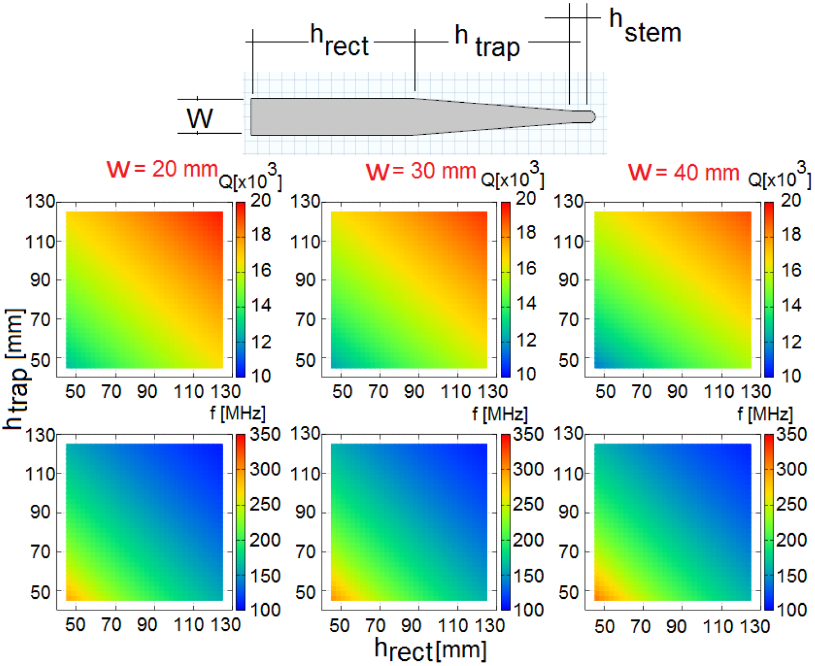
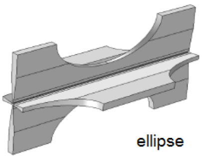
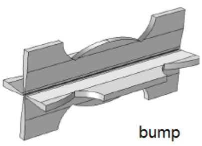
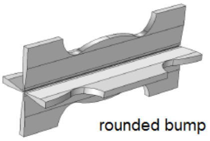


Fig. 2. Geometrical parameters of the vane. Bottom: Evaluation of the quality factor Q and resonance frequency as a function of vane geometry.

In Fig. 2 (top), we show the main parameters of the vane shape, which was divided in a rectangle, a trapezoid and a stem shape. As an example of the first stage optimization process, we plot in Fig. 2 (bottom) a scan of the parameters h_{rect} (height of the rectangular shape) and h_{trap} (height of the trapezoidal shape), for three values of the vane thickness W (rectangle width). In these calculations, the values for the tip radius $r_1 = 4.8$ mm, stem height $h_{\text{stem}} = 14$ mm and the inter-vane distance between electrodes $R_0 = 6$ mm keep constant. The selected values were $W = 40$ mm, $h_{\text{rect}} = 130$ mm and $h_{\text{trap}} = 130$ mm as there is the maximum quality factor.

In the second stage, we have studied different shapes of the RF windows varying (a_1) and (b_1) in order to obtain the maximum quality factor at the design frequency, and some results are shown in Fig. 3 (left). The best result is obtained by using elliptical window, with quality factor $Q \sim 10^4$ and shunt-impedance $r_s \sim 400$ kΩ-m. The process followed for the optimization of ellipse parameters is illustrated in Fig. 3 (right). The two plots in the upper part depict the variation of the value of the quality factor and resonant frequency, respectively, as a function of the major (b_1) and minor (a_1) semi-axis. The cavity Q value increases drastically by increasing a_1 and reducing b_1 but, at the same time, increasing the resonant frequency. For example, for $b_1 = 375$ mm, $a_1 = 200$ mm, it is obtained $Q \sim 10200$.

Geometry	Q	r_s [kΩ-m]	f_{RF} [MHz]
 ellipse	10221	390.426	70.98
 bump	9386	321.557	69.61
 rounded bump	9532	325.309	70.05

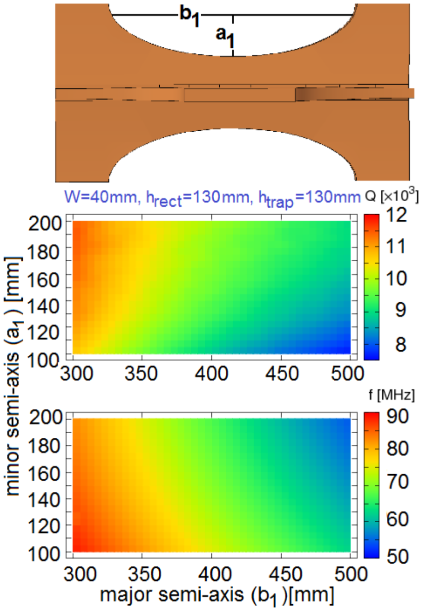


Fig. 3. Left: Three different shapes of the RF window considered in this study. Right: Evaluation of the quality factor Q and resonance frequency f as a function of semi-axes length a_1 and b_1 of the elliptical shapes.

3. RF analysis

The complete RFQ structure of 5 m length was simulated using the RF Module of COMSOL Multiphysics, and the main resonance modes are shown in Table II. Cutting RF windows through the vanes makes the magnetic field lines loop around window corners resulting in a reduction of the quadrupole mode frequency and a clear separation from the dipole modes. This also brings the next order quadrupole mode into the range of the fundamental one.

TABLE II

Resonance modes and degeneracies.

Geometry stage	Modes and Degeneracy	Frequency [MHz]
Cavity	TE_{111}	451.83
	TE_{112}	460.06
Cavity with vanes	TE_{211}	183.30
	TE_{111}	189.89
Cavity with vanes and windows	TE_{211}	70.47
	TE_{212}	75.34
Cavity with modulated vanes and windows	TE_{211}	71.77
	TE_{212}	76.98

Adding the modulation raises the resonance frequency by about 1.3 MHz, but with the aid of a dedicated RF-tuner system, it is possible to achieve the target frequency. A detailed study of the tuner geometry was also done by varying penetration depth, diameter and its position on the wall with respect to the beam entrance. The results of this study are shown in Fig. 4.

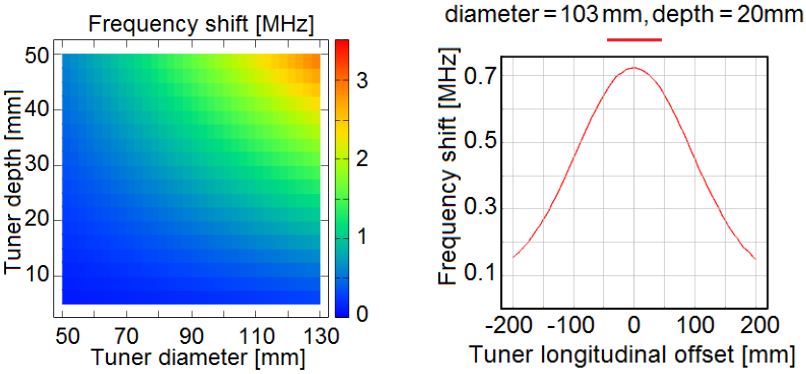


Fig. 4. Frequency shift of the whole RFQ as a function of tuner diameter and depth (left), and position offset (right).

The bandwidth of the tuner increases with diameter and penetration depth, and the maximum effect occurs when the tuner is on the center of the cavity wall, equidistant from both ends. A list of RF parameters for whole RFQ is given in Table III.

TABLE III

RF characteristics of the RFQ.

Frequency [MHz]	Power loss [kW]	Stored energy [J]	Shunt impedance [kΩ-m]	Quality factor
71.62	92.354	2.0478	390.43	9977

4. RFQ prototype

In order to test the quality and reliability of the calculations, a simple aluminium model of one RFQ section was built in collaboration with local Spanish companies. The system was assembled and tested in the RF Laboratory at the University of Huelva, as shown in Fig. 5 (left). The RF measurements were performed using an Agilent N90000A CKA spectrum analyzer. The cavity without vanes resonates at 485 MHz (dashed/red line), which is in agreement with COMSOL simulations (solid/blue line) with a difference of 5 MHz, the results are shown in Fig. 5 (above). Introducing the four vanes in the resonator leads to the appearance of a quadrupole mode TE_{211} and the system resonates at 157 MHz as shown in Fig. 5 (bottom) — it corresponds to the fundamental mode and it is very close to a doubly degenerated dipole mode.

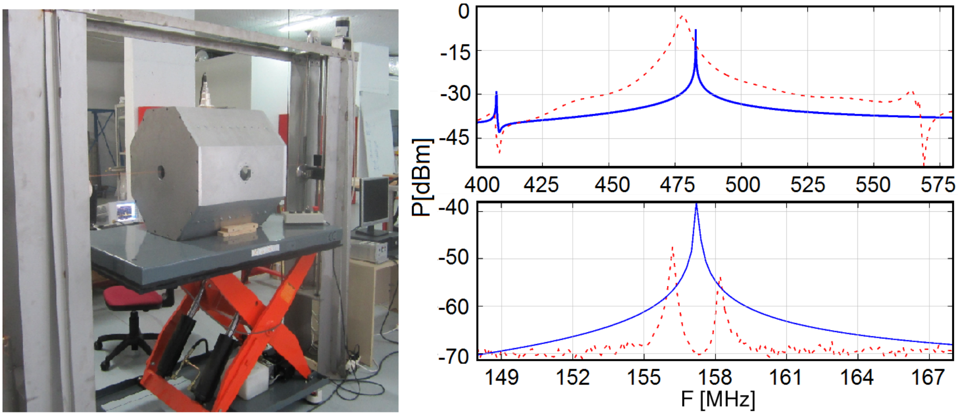


Fig. 5. Left: Aluminium RFQ section prototype. Right: Experimental and simulated RFQ frequency mode without vanes (above) and with vanes (bottom).

The differences between the spectrum and simulation are due to the construction characteristics of the structure like tolerance, precision, the size of the pick up antenna and the coupler. The prototype has 2 mm of precision, this variation can produce a maximum change of 20 MHz in the resonance frequency. The tuners system can solve a frequency shift of 2 MHz, therefore, we need to improve the measurement with the coupler in order to reduce the 5 MHz difference in the first test.

5. Conclusions

Beam dynamics simulations [7] have been carried out using TRACK and DESRFQ codes. The design has been obtained using realistic field maps and simulated in RF module, heat transfer, fluid flow and mechanical deformations of COMSOL. Future developments will include suitable input matcher and trapezoidal cells to shorten the length and improve the performance of the cavity.

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