ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME037

DEVELOPMENT OF A 72.75 MHZ RFQ FOR THE LINCE ACCELERATOR COMPLEX*

A.K. Orduz†, C. Bontoiu, I. Martel, Univ. of Huelva, Spain
A. Garbayo, AVS, Elgoibar, Gipuzkoa, Spain
A.C.C. Villari, FRIB, East Lansing, Michigan, USA
P.N. Ostroumov, ANL, 9700 S. Cass Av. Argonne, IL, USA

Abstract

Low-energy acceleration for the LINCE project [1] will be achieved using a 72.75 MHz normal conducting four vanes RFQ designed to give a 460 keV/u boost for A/Q = 7 ions in about 5 m. The vanes are modeled to accommodate windows for a clear separation of the RFQ modes and easy fitting to an octagonal resonance chamber. This article presents the main numerical results of the radio-frequency modeling and computational fluid dynamics (CFD). Particle tracking studies optimized for bunching and acceleration are shown as well.

INTRODUCTION

Development work has been carried for the highest mass-to-charge ratio considered i.e. A/Q = 7. The machine layout and performance must handle 2 ns long bunches of 40 keV/u kinetic energy. With the aim of raising the kinetic energy up to 500 keV/u a simulation was carried using the DESRFQ code [2] at 82 kV inter-vane potential on a vane tip geometry tested at ANL [3]. Thus, a 5.04 m long sinusoidal modulation was generated with the structure being split in 8 sections of 630 mm nominal length.

Complete beam dynamics simulations using ideal electric fields generated by DESRFQ and Track 3D [4] codes are reported in **BEAM DYNAMICS** proving that the target energy is reachable with 2 % energy spread and bunch duration within 1 ns. Resistive power losses obtained from an initial *RF study* in **RF ANALYSIS** are scaled and then coupled in **Heat transfer study** to a *heat transfer module* in order to obtain a temperature map at the vanes surface. Further in **CFD and structural analysis**, cooling is simulated in *fluid flow study* using water circulating through pipes drilled inside the vanes and thus a stable temperature distribution can be achieved for a given water flux. The remaining heat flux is coupled to a *solid mechanics study* which provides estimates for the displacement due to thermal expansion. Eventually, an evaluation of the RF frequency shift is obtained through a new *RF study* of the deformed structure. A complete loop of coupled numerical studies is achieved as shown in Fig. 1.

RF ANALYSIS

Eigenfrequency studies have been carried out using the Comsol software [6] for several development stages of the RFQ structure. Resonance frequencies and degeneracies for the quadrupole and dipole modes are shown in Table 1.

* Work partially supported by the Spanish Government (MINECO-CDTI) under program FEDER INTERCONNECTA
† angie.orduz@dfa.uhu.es

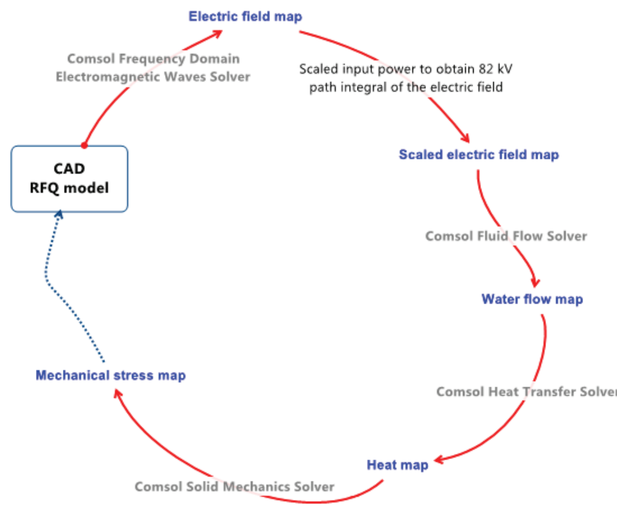

Figure 1: RFQ design work flow.

Table 1: Resonance Modes at Different Geometry Stages

Geometry Stage	Modes & Degeneracy	Frequency [MHz]
Cavity	TE_{111} (dip., 2) TE_{112} (dip., 2)	451.83 460.06
Cavity with vanes	TE_{211} (quad., 1) TE_{111} (dip., 2)	183.30 189.89
Cavity with vanes and windows	TE_{211} (quad., 1) TE_{212} (quad., 1)	70.47 75.34
Cavity with modulated vanes and windows	TE_{211} (quad., 1) TE_{212} (quad., 1)	71.77 76.98

Introducing the four vanes in the resonator enables the appearance of a quadrupole mode TE_{211} resonating around 183 MHz and one doubly degenerated dipole mode very close. The quadrupole electric field pattern in a transverse cross-section is shown in Fig. 2. The figure also shows that the magnetic field is directed longitudinally along the structure with its sign alternating from one quadrant to another.

Cutting RF windows through the vanes makes the magnetic field lines loop around the windows corners resulting in a reduction of the quadrupole mode frequency and a clear

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME037

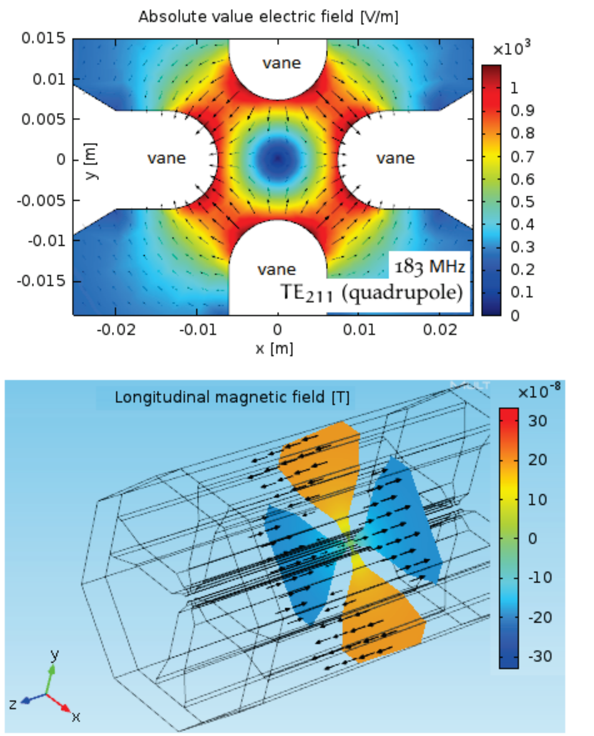

Figure 2: Quadrupole electric (top) and magnetic (bottom) field patterns for the vanes without windows.

separation from the dipole modes. This also brings the next order quadrupole mode into the range of the fundamental one. Adding the modulation raises the resonance frequency by about 1.3 MHz and using a system of fixed tuners it is possible to achieve the target frequency. Longitudinal and transverse electric fields in the input matcher region are shown in Fig 3.

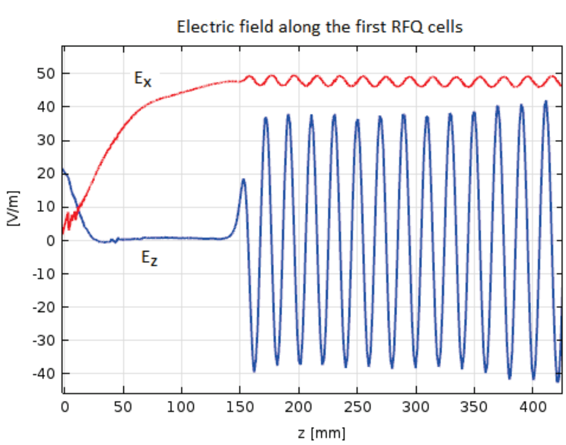

Figure 3: Longitudinal on-axis (blue) and horizontal off-axis (red) electric field for a few cells.

The quality factor of the current design is Q = 8670 and some of RF parameters for one RFQ section are listed in Table 2.

Table 2: RF Characteristics of One RFQ Section

Frequency [MHz]	Power Loss [kW]	Stored Energy [J]	Shunt Impedance [kΩ-m]
71.87	16.58	0.32	279.39

BEAM DYNAMICS

Complete beam dynamics simulations have been carried using Track 3D in order to check that the energy target is achievable, while keeping the beam transverse size within the inter-vane region. The electric RFQ quadrupole fields are generated internally by the numerical code for an inter-vane potential of 82 kV and the sinusoidal modulation obtained previously. Snapshots of the transverse and longitudinal phase space are shown in Fig. 4 for the entrance and exit of the RFQ. The input beam consists of bunches of about 2 ns length and 4 % total energy spread. This is the result of a multi-harmonic buncher [5] which induces longitudinal energy modulation.

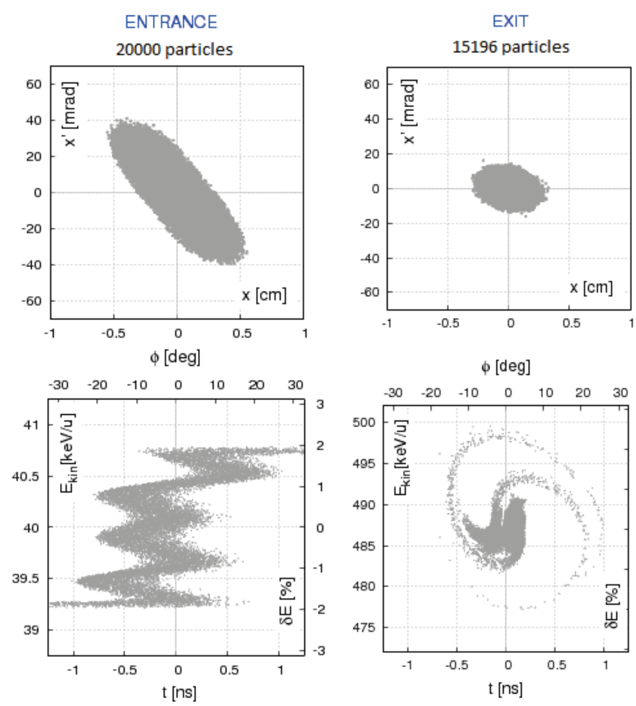

Figure 4: Beam distribution at the entrance (top) and exit (bottom) of the RFQ. The black circle represents the inter-vanes aperture. Particle transmission rate is around 76 % and we are currently working to improve it.

As shown in Fig. 5 the first part of the RFQ is used for bunching rather than acceleration. Starting with the 80th cell the aspect ratio remains constant and this enables a linear energy growth of about 6.5 keV/u.

ENGINEERING DESIGN

Results of a thermal study analysis study on the latest RFQ design is presented in the following sections.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME037

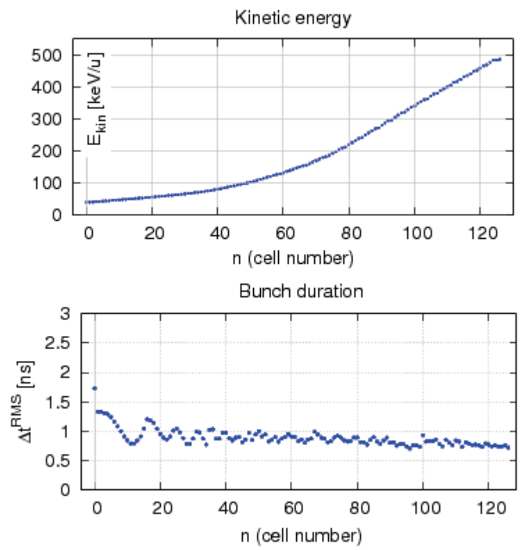

Figure 5: Kinetic energy along the whole RFQ structure.

Heat Transfer Study

Resistive power losses calculated in the **RF ANALYSIS** section are show in Fig. 6. This study is coupled with the CFD module for a non-isothermal turbulent flow in a quarter symmetry model (section) of the RFQ. Final mesh is optimized for each physics study (thermal, CFD and structural) with a total of $3.1{\times}10^5$ tetrahedral elements and minimum element size of 4 µm.The total resistive power dissipated by the RFQ working mode at mode at 71.87 MHz is 16.58 kW.

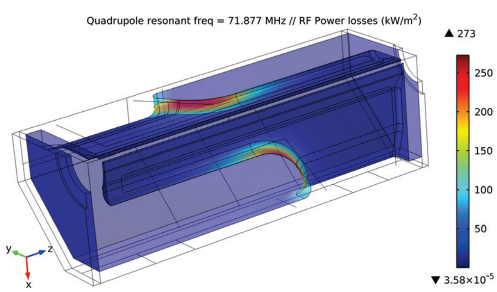

Figure 6: Heat map of the power resistive losses.

The heat is to be absorbed by the water cooling channels and the outer copper surfaces in convection to the ambient air with a heat transfer coefficient (HTC) of 10 W/m^{2}K [7]. An HTC on the cooling channels of 11.2 kW/m^{2}K was calculated by using turbulent flow $6{\times}10^4$ Reynolds number and an inlet temperature of 15 °C .

The aim was to obtain maximum deformation due to the thermal expansion $\leq$150 μm transversely and $\leq$100 μm longitudinally on the vane tip; which led to a maximum temperature of 35 °C. The design process showed that only cooling on the vanes were not acceptable and 3 more channels of 14 mm were added on the side plates for extra heat subtraction. Stationary studies of the copper structure without cooling and only convection flux with the surrounding air showed copper temperature to reach more than 1300 °C.

CFD and Structural Analysis

Fig. 7 shows the velocity field along the cooling channels of the vanes where a 0.53 bar pressure drop on the fluid is obtained. The cooling channels are to be implemented by holes drilled into solid copper parts with brazed lids and therefore maximum variation of these values occur mainly at the corners. The volume flow rate is optimized to obtain values below 5 m/s.

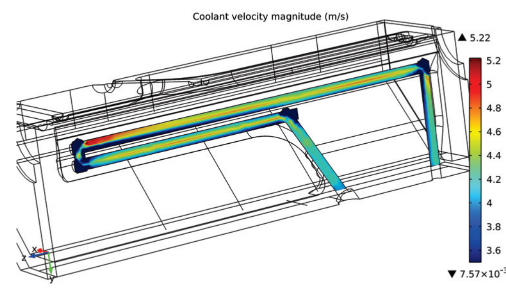

Figure 7: Flow rate along the cooling channels.

After 600 s the temperature of the copper on the cooling channels calculated by wall functions and surface roughness for drilled holes in copper of 0.61 mm reaches 20.7 °C at the window corner. The temperature increase of the coolant is 0.5 °C with a typical Reynolds number of $55{\times}10^3$. Latest calculations led to a final temperature of the copper $\leq$ 32.2 °C. Thermal expansion of the copper is implemented into a structural model to study the maximum stress and deformation along the structure. The deformation then is implemented back into a new RF study to analyze the variation of the resonant frequency. The von Mises stress on the copper has to be $\leq$7×108 N/m^2 as established by measured mechanical properties of brazing annealed OFE copper at INFN-LNL [8]. It can be observed that it causes the bottom part of the vane to expand and the top part to contract. This deformations which arise mostly on the levering part of the vanes create a frequency shift of a 0.20 % from 71.87 to 71.73 MHz.

CONCLUSIONS

Beam dynamics results are to be improved using realistic field maps obtained through RF simulations. This will include suitable input matcher and trapezoidal cells at the RFQ end, finished with an output matcher. Four adjustable moving tuners will be used to tune the resonant frequency to 71.75 MHz and fine tuning of the copper structure will be obtained by applying different inlet temperatures and velocities of the coolant. A variation of 3 °C in the inlet temperature showed a frequency shift of 50 kHz. A minimum velocity of 3 m/s and temperature inlet of 15 °C is set up for the minimum cooling requirements for continuous RFQ operation. We are still working for checking the accuracy of Beam Dynamics and RF simulations and to verify the behavior of the longitudinal emittance.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME037

REFERENCES

[1] I. Martel et al., "LINCE: A High Intensity Multi-ion Superconducting Linac for Nuclear Structure and Reactions", IPAC'14, Dresden, Germany, June 2014, THPME036, These Proceedings.

[2] A. A. Kolomiets et al., *The RFQ Design Software DESRFQ*, (ITEP/ANL Technical Note, 2005).

[3] P. Ostroumov et al., Rev. ST Accel. Beams 15, 110101 (2012).

[4] V. Aseev et al., "TRACK: The new beam dynamics code", PAC'05, Knoxville, USA, TPAT028 (2005).

[5] C. Bontoiu et al., "Design of a Multi-harmonic Buncher for the LINCE Heavy-ion Accelerator Complex", IPAC'14, Dresden, Germany, June 2014, MOPME059, These Proceedings.

[6] Comsol website: http://www.comsol.com/products/multiphysics/

[7] Engineering Toolbox website: http://www.engineeringtoolbox.com

[8] INFN-Legnaro: www.lnl.infn.it