HIGH-CURRENT RFQ DESIGN STUDY ON RAON

Jungbae Bahng, Eun-San Kim#, Kyungpook National University, Daegu 702-701, Korea
Bonghyuk Choi, IBS-RISP, Daejeon 305-811, Korea

Abstract

The Rare isotope Accelerator Of Newness (RAON) heavy ion accelerator has been designed for the Rare Isotope Science Project (RISP). RAON will produce 400 kW continuous wave (CW) heavy-ion beams, from proton beams to uranium beams, to support research in various scientific fields. The RAON system consists of an electron cyclotron resonance (ECR) ion source, low-energy beam transport systems (LEBTs), CW radio frequency quadrupole (RFQ) accelerators, a medium-energy beam transport (MEBT) system, and a superconducting linear accelerator (LINAC). We present the design study of the RFQ accelerator for deuteron beams with energies of 30 keV/u to 1.5 MeV/u and currents meeting the requirement of at least 15 mA at the target. We optimized the normal conducting CW RFQ accelerator, which has a high transmission and low longitudinal emittance. In this paper, we will present the design results of RFQ beam dynamics studies and their 2D and 3D EM analyses.

INTRODUCTION

The Rare isotope Accelerator Of Newness (RAON) heavy ion accelerator has been designed as a facility for the Rare Isotope Science Project (RISP). RAON will produce 400 kW continuous wave (CW) rare-isotope beams, from proton beams to uranium beams, using both the In-Flight Fragment (IF) and Isotope Separation On-Line (ISOL) systems, as shown in Fig. 1. For RISP to accomplish its objective, a high-intensity light-ion beam injector is required. An injector for a relatively light heavy-ion beam consists of a short low-energy beam transport (LEBT) system with two solenoids, radio frequency quadrupole (RFQ) accelerators, and a medium-energy beam transport (MEBT) system. The generated and accelerated ion beam from the high-intensity injector is then transferred to the main MEBT and accelerated by the main linear accelerator (LINAC). For use in the high-intensity injector system of RISP, we studied RFQ accelerators that are designed to accelerate high-intensity deuteron beams from 30 keV/u to 1.5 MeV/u. RFQ accelerators [1] are among the main components that can provide high-intensity beams by strong focusing, adiabatic bunching, and efficient acceleration. Since the main LINAC base frequency was chosen to be 81.25 MHz, we considered RFQ frequencies that are harmonics of this base frequency. To meet the requirement of at least a 15 mA current and achieve an economical structure, the RFQ frequency was chosen to be twice the base frequency, and the beam intensity was chosen to be 40 mA. In this paper, we focus on the beam dynamics and EM structure design of the RFQ.

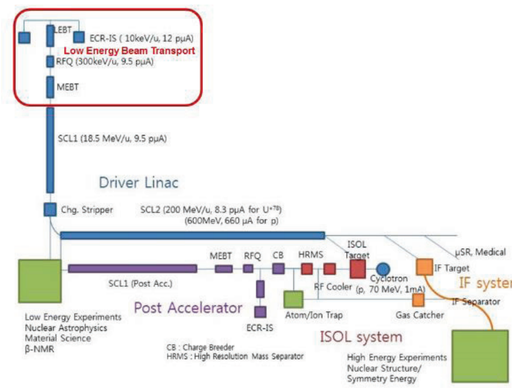

Figure 1: The layout of the RISP.

BEAM DYNAMICS DESIGN

The main RFQ design parameters are shown in Table 1.

Table 1: RAON RFQ Design Parameters

Particle (q/A)	D+ (1/2)
Frequency	162.5 MHz
I/O beam energy	30 keV/u → 1.5 MeV/u
Beam current	40 mA
Vane voltage	65~100 kV
Length	496 cm
Transmission rate	96.44 %
Tr. emittance	0.25 n.r. π mm-mrad
Max Surface Field	20.64MV/m (1.52 kilp.)

The goals of RISP high-intensity RFQ beam dynamics studies are to minimize the RFQ length, beam loss, and emittance growth. The basic objective regarding RFQs is to design beams with acceptable longitudinal bunching at the entrance of the LINAC. PARMTEQM [2] code, which was developed at Los Alamos National Laboratory, is used to generate RFQ parameters. In this study, we considered an RFQ operated at 162.5 MHz and a deuteron beam accelerated to 40 mA. We assumed that the RFQ had a low longitudinal emittance, thus avoiding transverse emittance growth, as well as a high transmission rate and short length. To optimize the RFQ design, we adopted a ramped vane voltage, slowly increased the modulation factor in the radial matching section, simultaneously

eskim1@knu.ac.kr

increased the phase in the acceleration section, and adjusted the focusing strength across the entire region, as shown in Fig. 2.

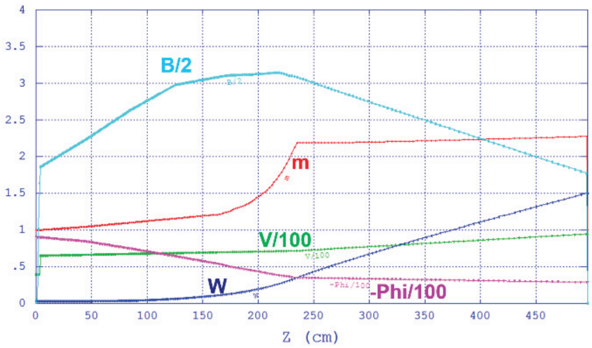

Figure 2: Design parameters of the RFQ.

Here, B is the focusing strength, m is the modulation factor, v is the vane voltage (kV), and Φ is the phase (degrees). As shown in Fig. 2, the vane voltage linearly increases from 65 kV to 100 kV, the modulation factor smoothly increases in the radial matching and shaper sections, and the focusing factor and synchronous phase are optimized in the entire cavity. The synchronous phase becomes -35° at the end of the gentle buncher section and -28° at the end of the acceleration section in order to avoid the space charge effect. Since the RFQ design parameters were optimized, it was possible to obtain advantages such as length reduction; high transmission rate, as shown in Fig. 3; and reasonable emittance, as shown in Table 2. Transmission rates of 96.44% and 98.07% and emittance growths of 15% and 6.8% were obtained for currents of 40 mA and 20 mA, respectively.

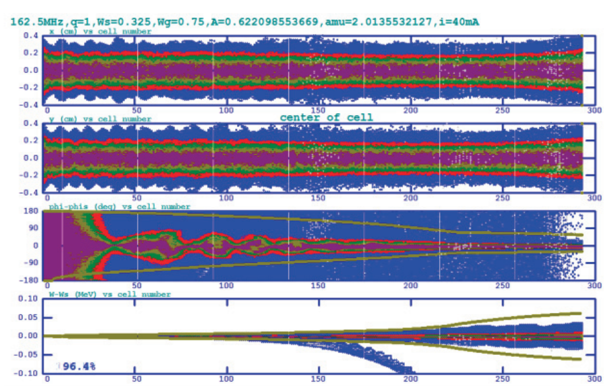

Figure 3: Result of the RFQ physical design.

Table 2: RAON RFQ Design Parameters

Emittance (n.r)	Input	Output	Unit
Horizontal	0.25	0.2886	π mm-mrad
Vertical	0.25	0.2672	π mm-mrad
Longitudinal	CW	0.3098	π mm-mrad

The ratio $\varepsilon_Z/\varepsilon_T$ is related to the space charge effect, emittance growth, halo formation, and acceleration efficiency. If $\varepsilon_Z/\varepsilon_T$ is small, for example, 0.5, a large space charge effect, large emittance growth, and halo formation are caused. In contrast, if $\varepsilon_Z/\varepsilon_T$ is large, for instance, 2.0, large bunch length, low acceleration, and beam loss result [3]. We designed the RFQ to have $\varepsilon_Z/\varepsilon_T = 1.07$ to optimize the acceleration efficiency and avoid emittance growth due to the space charge effect.

TWO-DIMENSIONAL CAVITY DESIGN

The main objective in RFQ cavity design is to minimize the power dissipation. Low power dissipation results in easy cooling. A high quality factor (Q factor) indicates slow energy loss relative to the stored energy and low power dissipation. We designed the vane structure to have a high Q factor at the resonant frequency.

The 2D cavity was designed by the SUPERFISH [4] code, and the structure parameters were optimized at the design frequency of 161 MHz. It was decided to design the frequency to be lower than the resonant frequency due to manufacturing errors. Figure 4 shows the cross-section of one quadrant of the RFQ cavity. The red line indicates the vacuum space of the vane's low-energy section, and the blue line indicates the high-energy section.

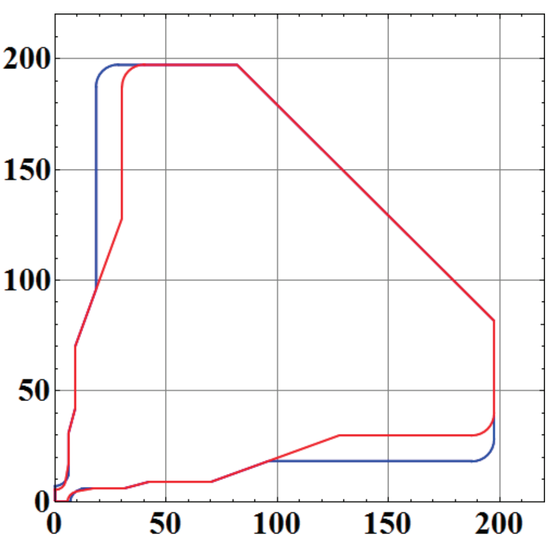

Figure 4: Design of vane base for the RFQ.

The quadrant structure of the RFQ cavity was designed with the geometrical parameters listed in Table 3.

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Table 3: Geometrical Parameters of the RFQ Cavity

Parameters	Values	Unit
Breakout angle	10	degree
Blank Half Width	0.6	cm
Blank Depth	3.1	cm
Shoulder Half Width	0.9	cm
Base Half Width	3.0	cm
Height	20.0	cm

We obtained a well-matched design resonant frequency, Q-factor of 15126, and power consumption of 31 kW from SUPERFISH. The total power consumption is related to the 2D result from SUPERFISH through the relation [5]

$$P_{total} = P_{SF} \bullet \alpha_{3D} \bullet \alpha_v + P_{beam} \quad \text{(Eq. 1)}$$

where α_{3D} = 1.3 is a factor that accounts for the 3D losses, P_{beam} is the beam power, and $\alpha_v = 1.1^2$ accounts for intra-vane voltages of up to 10%. We obtained a 3D power consumption of 200 kW in the RFQ cavity. The adjacent dipole mode frequency was found to be 156.5 MHz, as shown in Fig. 5. Since the difference between the quadrupole and dipole modes is large, a stabilizer rod was not considered.

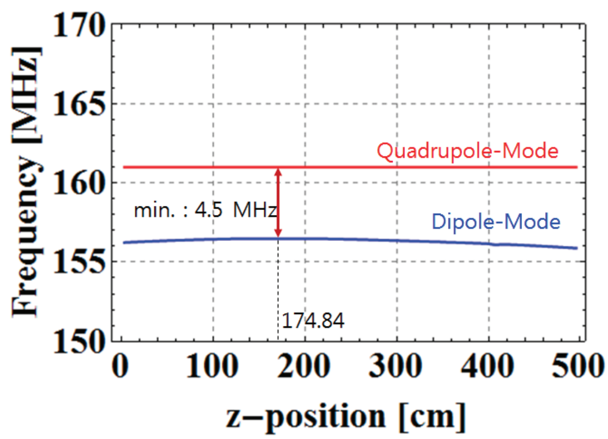

Figure 5: The adjacent mode frequency.

The tuners were adjusted in order to tune the resonant frequency of the RFQ cavity. The tuner radius was chosen to be 30 mm based on the standard CF-flange size. The tuning sensitivity was 200 kHz/mm in both the low- and high-energy sections.

THREE-DIMENSIONAL CAVITY DESIGN

In general, a longitudinal magnetic field is induced in an RFQ cavity and should be parallel to both the entrance and exit plates. The vane cutback is designed to solve the boundary value problem [6]. The detailed geometrical parameters of the cutback in this study are listed in Table 4. The cutback was designed at the resonant frequency of 161.1 MHz, which is close to the design frequency. We optimized the cutback for fixed values of *h1, h2, b*, and radius.

Table 4: Geometrical Parameters of the Cutback

Parameters	Values	Unit
Slope angle, θ	40	degree
Gap btw. end and vane, g	0.20	cm
Depth, d	8.80	cm
Height-1, h1	19.73	cm
Height-2, h2	7.02	cm
Radius, r	0.557	cm

To investigate the 3D EM field properties of the RFQ cavity in more detail, a 3D model of the cavity was prepared, and 3D EM simulation was conducted with CST [7] code. Quadruple and dipole mode frequencies of 161.5 MHz and 156.6 MHz, respectively, were obtained.

CONCLUSION

A high-intensiy RFQ accelerator for RAON was designed to optimize the transmission rate and minimize the RFQ length, beam loss, and emittance growth. The RFQ operation frequency was chosen to be 162.5 MHz to minimize the RFQ size, while the beam intensity was increased to 40 mA to achieve the required 15 mA at the target. We considered an RFQ with $\varepsilon_Z/\varepsilon_T$ = 1.08 to avoid emittance growth. An RFQ beam dynamics study was performed with the PARMTEQM code. With the optimization, a high transmission rate of 96.5% and emittance growth of 15% were achieved. Two-dimensional EM analysis of the RFQ was conducted with the SUPERFISH code. A total power consumption of 200 kW and Q factor of 15126 were obtained for the RFQ quadrupole mode. The adjacent dipole mode obtained 156.5 MHz, which is far from the 4.5 MHz of the quadrupole mode. To investigate the 3D EM properties, cutback design was performed to achieve a resonant frequency close to the design frequency. Finally, a 161.5 MHz resonant frequency was obtained from both 3D EM and RF analysis. Based on these results, we plan to perform more detailed 3D EM studies as well as investigations of the tuning in the radial matching section end region and of the mechanical design.

REFERENCES

[1] J. W. Staples, “RFQs- An Introduction,” LBL-29472.
[2] K. R. Crandall, T. P. Wangler, L. M. Young, J. H. Billen, G. H. Neuschaefer and D. L. Schrage, “RFQ Design Codes,” LA-UR-96-1836.
[3] N. Solyak, A. Vostrikov, “Longitudinal Emittance reqs,” 2011.
[4] J. H. Billen and L. M. Yong, “Poisson Superfish”, LA-UR-96-1834.
[5] A. Pisent et al., Proc. EPAC2008, Genoa, Italy, THPP078, http://jacow.org/.
[6] R. Gaur, P. Shrivastava, Journal of Electromagnetic Analysis and Applications, Vol 2, 519-528, (2010).
[7] CST Studio Suite, “CST Microwave Studio,” 2012, http://www.cst.com/.