DESIGN STUDY FOR FRONT-END SYSTEM AT RARE ISOTOPE SCIENCE PROJECT

[1,2]Eun-San Kim*, [1]JungBae Bahng, [1]Ji-Gwang Hwang, [1]Si-Won Jang, [2]Byung-Chul Kim
[2]Bong-Hyuk Choi, [2]Hye-Jin Kim, [2]Sun-Kee Kim, [2]Dong-O Jeon
[1]Kyungpook National Univ., Deagu, Korea, [2]IBS, Daejeon, Korea

Abstract

Heavy ion beams of 400 kW and 70 kW are generated at the RISP by in-flight and ISOL methods, respectively. Front-end system for the in-flight at the RISP consists of two 28 GHz superconducting ECR-IS with 10 keV/u, a LEBT with two 90 degree bends and two bunchers with 40.625 MHz, a RFQ with 81.25 MHz and 300 keV/u, and a MEBT with two re-bunchers. The front-end system design studies have been performed to optimize the beam and accelerator parameters to meet the required design goals. For this, we performed front-end simulations with two-charge state beams and present the design performance and results of the beam dynamics.

INTRODUCTION

RISP (Rare Isotope Science Project) is designed to accelerate the ions from proton to uranium for 400 kW in-flight system. The accelerator can be segmented into front-end accelerator and superconducting linear accelerator. The front-end includes two ECR ion sources, low energy beam transport (LEBT), radio frequency quadrupole (RFQ) and medium energy beam transport (MEBT). ECR ion source generates various charge states of ions from proton to uranium. LEBT delivers these ion beams to the RFQ efficiently. Bunching at the LEBT is considered by two bunchers. RFQ accelerates the uranium beam up to 300 keV/u. The MEBT matches the beam from the RFQ to the superconducting linac. Fig. 1 shows the layout for the front-end system. We show the design results in the front-end system.

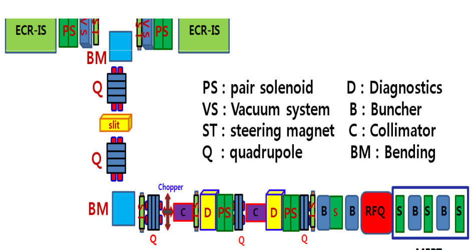

Figure 1: Layout of the front-end system for the drive linac.

ECR ION SOURCE

The goal of the design of the ECR-IS is to produce various ions with 10 keV/u of the kinetic energy and normalized rms emittance of 0.1 πmm-mrad. Two ECR ion sources are considered for the RISP, as shown in Fig. 1. Superconducting magnets and RF source of 28 GHz are used and the main design parameters from the two R&D groups of KAERI and KBSI are summarized in Table 1[1]. The design of the superconducting magnets is the most important part of the ECR ion source design. The feature of KAERI model is to use five solenoids for adjusting ECR zone efficiently. On the other hand, the step winding technique for sextupole coils is the KBSI's idea to build the ECR ion source compactly.

For the superconducting magnets, 4 K cryogenic system has to be prepared. The ECR ion source needs more than 10 W cooling powers at 4 K during the operation because X-rays from the plasma chamber could be an extra heat load to the cryostat. Reducing the X-rays, therefore, is also a key design factor for the ECR ion source. A tantalum is used as a radiation shielding material. Dual frequency operation improves the overall performance so that considering an extra 18 GHz RF source can be a good choice to achieve high charge states and high current ions. Additionally, a high temperature (2000 ^oC) oven for solid isotopes and a high voltage platform of 70 kV for heavy ions are necessary.

* eskim1@knu.ac.kr

Table 1: Main parameters of the ECR-IS.

	KAERI	KBSI
Frequency(GHz)	28	28
RF power (kW)	10	10
Chamber diameter(mm)	150	150
Chamber material	Al	Al
Mirror length(mm)	500	500
External voltage(kV)	30	30
SC wire	NbTi	NbTi (OK35,38)
Number of solenoid	5	3
Sextupole winding type	Saddle	Race track
$B_{inj}(T)$	4.2	3.6
$B_{ext}(T)$	2.2	2.1
$B_r(T)$	3	2.2
$B_{min}(T)$	0.3-0.8	0.4-0.8

LEBT

The LEBT consists of two 90 degree bends and quadrupoles for achromatic optics, solenoids for beam matching with ECR-IS and RFQ, two bunchers, steering magnets, collimation systems and diagnostics. Fig. 2 shows designed optics and beam envelopes for the LEBT beam line that is optimized by TRANSPORT code. The dc beam from the ECR-IS is bunched before injection into the RFQ. To get a short bunch length with high bunching efficiency, two bunchers with the 40.625 MHz are applied. To perform the beam simulations, IMPACT-Z code is utilized for 6-dimension tracking that includes the effect of space-charge force[2,3,4,5]. A normalized rms emittance of 0.1 π mm-mrad and intrinsic energy spread of 0.05% are considered. 20,000 macro-particles are initially generated in 4-dimensional water-bag transverse distributions with uniform longitudinal distributions in phase spaces and are tracked in the simulations.

Fig. 3 shows the (top) initial horizontal, vertical and longitudinal beam distributions for two-charge state beam of $^{238}U^{33+}$(blue) and $^{238}U^{34+}$(red) with 400 eμA in the LEBT. Fig. 3 also shows the beam distributions (middle) before and (bottom) after first buncher in the LEBT. Fig. 4 shows the beam distributions (top) before and (bottom) after second buncher in the LEBT. Two-charge state beam due to first buncher with 40.625 MHz is bunched as well as longitudinally separated from each other due to velocity difference. Second buncher in 40.625 MHz is used to provide each of two-charge state beams with the same velocity at the entrance of RFQ. A distance between first buncher and second buncher is given by 1.18 m, which corresponds to the two-charge state beam of $^{238}U^{33+}$ and $^{238}U^{34+}$. Fig. 5 shows the longitudinal beam distribution at the entrance of RFQ.

The cores of the two-charge state beams well overlap and tail particles increases the beam emittance. The simulation shows that the designed LEBT under the effect of space-charge force provides good beam matching and bunching for the two-charge state beam. Adequate transverse and longitudinal emittances are also obtained by the entrance of RFQ. It is shown that the space-charge effect for the uranium beam of the 400 eμA is small in the LEBT.

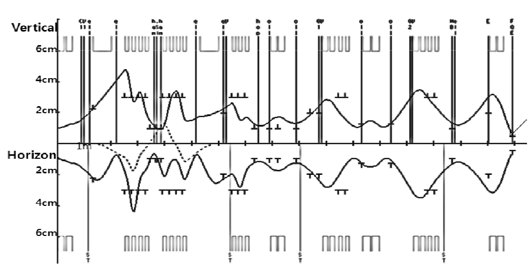

Figure 2: Designed optics and envelopes for LEBT.

RFQ

The RFQ is designed to accelerate the beam of 12 pμA two-charge state ($^{238}U^{33+}$ and $^{238}U^{34+}$) beams from 10 keV/u to 300 keV/u. PARMTEQ is used to get the RFQ design parameters[6]. Table 2 shows the main input parameters of RFQ. Charge state of 33.5 for the simulations of U beam in PARMTEQ is used for multi-charge state beam of the uranium.

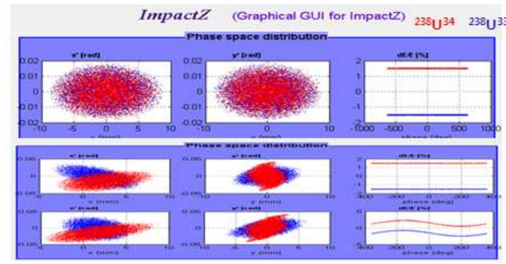

Figure 3: (top) Initial beam distributions, beam distributions (middle) before and (bottom) after first buncher in the LEBT .

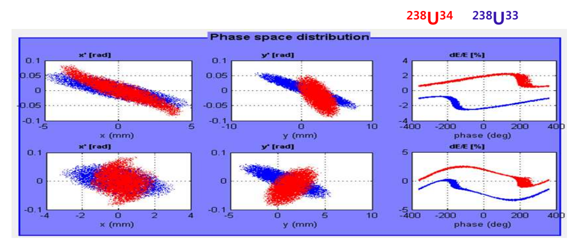

Figure 4: Beam distributions (top) before and (bottom) after the second buncher in the LEBT.

Fig. 6 shows the behavior of the physical quantities of the RFQ as a function of length. The vane voltage is fixed to be 70 kV. The focusing strength(B) is adopted as a constant of 5.08 along the RFQ. The accelerating efficiency is fixed to be 0.55 in order to reduce length of the RFQ. The synchronous phase becomes to -30 degrees at the end of gentle buncher from -90 degrees at the entrance of the RFQ. The modulation factor increases from 1 to about 2 and the average radius is 5.32 mm. The total length of RFQ is 3977.87 mm and number of cell is 220. The maximum peak surface electric field E that occurs at cell 218 is 17.7659 MV/m and the value E corresponds to 1.69E_k, where E_k is the Kilpatrcik criterion. 10,000 particles are

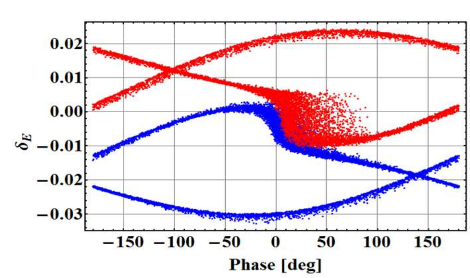

Figure 5: Longitudinal beam distribution at the entrance of RFQ.

generated by the beam current of 12 pμA.

Table 2: Main parameters of the RFQ.

Reference particle	$^{238}U^{33+}$ and $^{238}U^{34+}$
RF frequency	81.25 MHz
Input charge state	33.5
Input energy	10 keV/u
Output energy	300 keV/u
Beam current	12 pμA
Input normalized emittance	0.1 π mm-mrad rms
Vane voltage	70 kV
Total length	4 m

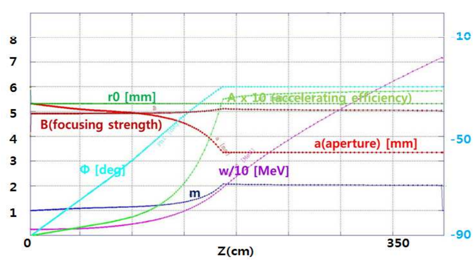

Figure 6: Evolution of synchrotron phase, modulation factor, focusing strength, aperture, kinetic energy and acceleration efficiency along RFQ.

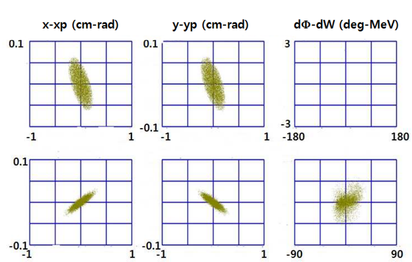

Figure 7: Beam distributions at the entrance (top) and exit (bottom) of the RFQ.

Fig. 7 shows the (top) input and (bottom) output particle distributions in the transverse and longitudinal phase spaces. We used 4D water bag model for input transverse particles and 2D uniform model for longitudinal particles. Their Twiss parameters are $\alpha_{x,y}$ = 0.7445 and $\beta_{x,y}$ = 4.7536 cm/radian. Fig. 8 shows the particle distributions in the transverse (horizontal, vertical) envelopes, phase deviation and kinetic energy deviation as a function of cell number. Transmission rate in the RFQ shows 90.8%. The normalized rms transverse emittance of output beam are ϵ_x = 0.12 π mm-mrad and ϵ_y = 0.12 π mm-mrad, respectively. Then the longitudinal emittance is 6.6 MeV-deg.

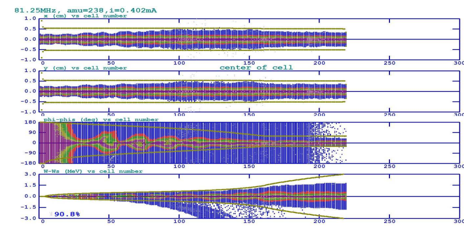

Figure 8: Beam envelopes, phase deviation and kinetic energy deviation along RFQ.

Each single charge state of +33 and +34 with 12 pμA was also tracked by the same RFQ design.

TRACK code is also used for the simulations of the two-charge state beam. Field informations from PARI and PARMTEQM are used. In the TRACK code, the aperture radius is fixed to be 5.32 mm. Twiss parameters and emittance of input beam are the same as the PARMTEQ program. 10000 particles are used and beam current is 12 pμA. Fig. 9 shows the results of TRACK code for the two-charge state beam ($^{238}U^{33+}$ in blue and $^{238}U^{34+}$ in green). The beam transmission rate is 93% and the normalized rms transverse emittance of output beam are ϵ_x =0.103 π mm-mrad and ϵ_y =0.103 π mm-mrad in horizontal and vertical direction, respectively, and longitudinal emittance is 1.3 keV/u ns.

When the two-charge state beam from the LEBT is tracked by TRACK code in the RFQ, the beam transmission rate is 80% and normalized rms transverse emittances of output beam are ϵ_x = 0.14 π mm-mrad and ϵ_y = 0.14 π mm-mrad in the horizontal and vertical directions, respectively, and longitudinal emittance is 1.08 keV/u ns.

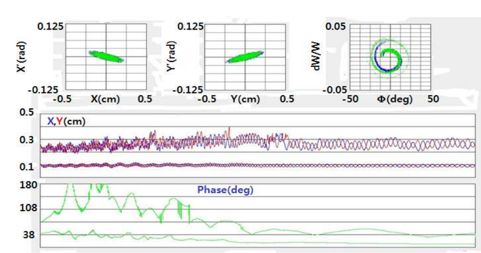

Figure 9: Beam distributions at the exit of RFQ by TRACK code.

MEBT

The Medium Energy Beam Transport (MEBT) system, which is installed between the RFQ linac and superconducting linac, requires to match the optical parameter in transverse plane and also remove the unaccelerated ion beams from the RFQ linac. The optics design of the MEBT system is performed by using TRACE3D code and particle tracking is performed by using IMPACT-Z code. The optics function is matched to the betatron function at the entrance of the superconducting linac. MEBT is studied to find the better way to compensate the growth of transverse emittance due to the effect of the space-charge. The MEBT system also provides the enough space for beam diagnostic devices such as beam profile monitor, beam position monitor and wire scanner. The transverse beam size can be controlled by the knobs which are installed in the up-stream of beam diagnostic devices to measure the beam information in MEBT system.

Five room temperature quadrupole magnets are used to minimize the transverse emittance growth of two-charge state beams and provide the transverse focusing to achieve the small beam size and focusing gradient at the entrance of the superconducting linac. Two rebunchers are also used to provide flexible longitudinal matching from the exit of the RFQ to the entrance of the superconducting linac. TRACE3D code to design the MEBT is used. To estimate the space charge effect in MEBT system, we performed the calculation by using IMPACT-Z code. The results on the beam distributions and beam envelopes are shown by Fig. 10. The quadrupole magnets have a field of less than 0.5 T at the pole-tip. The room temperature rebuncher has 81.25 MHz and β_{opt} = 0.025 λ/4. The total length of the MEBT is about 3.7 meters.

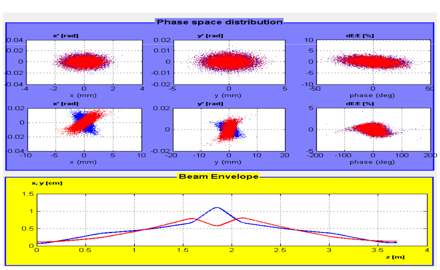

Figure 10: (top) Initial and (middle) final phase space beam distributions, and (bottom) beam envelopes in the MEBT by IMPACT code.

FRONT-END SIMULATIONS

Fig. 11 shows the beam distributions in transverse and longitudinal phase planes at the (top) entrance of MEBT and at the (bottom) exit of MEBT when the front-end beam simulations from the LEBT to MEBT are performed. When the two-charge state beam from the LEBT is tracked to the MEBT, the beam transmission rate is 79% and normalized rms transverse emittances of output beam are ϵ_x = 0.2 π mm-mrad and ϵ_y = 0.14 π mm-mrad in the horizontal and vertical directions, respectively, and longitudinal emittance is 9.3 MeV-degree.

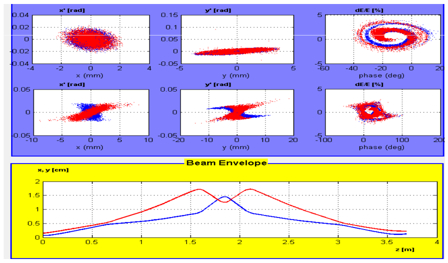

Figure 11: Phase space beam distributions at the (top) entrance and at the (bottom) exit of the MEBT by the front-end simulations.

SUMMARY

First front-end beam simulations at RISP are performed to optimize the front-end system. The results show that the performance results exist within scope of the requirements by RISP.

The beam from the ECR-IS will be used for the front-end simulations and performance on multi-harmonic buncher in the LEBT will be examined as the future works. In addition to front-end system for the driver linac, front-end system that includes charge breeder, LEBT, RFQ and MEBT for the re-accelerator will be also studied.

REFERENCES

[1] B. Oh et al., RISP Heavy-ion workshop, May, Daejeon, Korea (2012).

[2] J. Qiang et al., J. Comput. Phys. 163 p. 434 (2000).

[3] X. Wu et al., PAC'07, Albuquerque, June 2007, TUPAS053, p. 1769.

[4] R.W. Garnett et al., PAC'05, Knoxville, June 2005, p. 4218.

[5] T.P. Wangler et al., PAC'07, Albuquerque, June 2007, TH-PAS051, p. 3606.

[6] Q. Zhao et al., PAC'07, Albuquerque, June 2007, TUPAS054, p. 1772.