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Lattice Design and Beam Dynamics Simulation for the Simultaneous Operation of Stable Ion Beam and Rare Isotope Beam in the RAON Accelerator

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The Rare Isotope Accelerator of Newness (RAON) accelerator is under construction to generate and accelerate the stable ion beams and the rare isotope beams for various kinds of experiment programs. Especially, the post accelerator section was designed to be able to separately accelerate and transport the stable ion beams created by the superconducting electron cyclotron resonance ion source (ECR-IS) and the rare isotope beams created by the Isotope Separation On-Line (ISOL) system. However, recently, the research of the simultaneous operation of the stable ion beams and the rare isotope beams has been conducted to more efficiently satisfy the a wide range of beam requirements of the experimental halls. For the operation, we has modified the lattice of the post low energy beam transport (LEBT) section for the injection of the rare isotope beam and the next lattice after the low energy superconducting linac (SCL3) section for the extraction of the accelerated beam in the post accelerator section of the RAON accelerator. In this paper, the new lattice designs of the injection and extraction parts will be presented and we will describe the results of the beam dynamics simulations for the simultaneous operation of the two kinds of beams.

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I. INTRODUCTION

The Rare Isotope Science Project (RISP) of the Institute of Basic Science (IBS) is developing the RAON (Rare Isotope Accelerator of Newness) accelerator for a wide range of science programs [1]. The RAON accelerator will generate the stable ion beams from the proton to the uranium and the rare isotope beams, and accelerate those beams with the superconducting linac. So as to produce the rare isotope beams, the RAON accelerator takes two systems; In-flight fragmentation (IF) system and Isotope Separation On-line (ISOL) system. At first, in order to generate the rare isotope beams in the IF system, the driver linac is taken, which is composed of the superconducting electron cyclotron resonance ion source (ECR-IS), the main low energy beam transport (LEBT) section [2], the radio-frequency quadrupole (RFQ) accelerator, the medium energy beam transport (MEBT) section, the low energy superconducting linac (SCL1), the charge stripper section (CSS) and the high energy superconducting linac (SCL2). For a uranium beam case, the beam energy becomes 200 MeV/u and beam power does 400 kW at the end of the SCL2. The accelerated beam will collide with the IF target and then, from the collision, the rare isotope beams are created. Secondly, the ISOL system uses a cyclotron to deliver 70 kW power of the proton beam to the ISOL target. The rare isotope beams are generated from the collision of the proton beam on the target and then re-accelerated by the post accelerator which consists of the the post LEBT [3], the post RFQ, the post MEBT, and the low energy superconducting linac SCL3. Also, another ECR-IS is installed in the post accelerator to produce stable ion beams. The accelerated beam by the SCL3 will be used in the low energy experimental hall or accelerated again by the SCL2 after passing through the post accelerator to driver linac transport (P2DT) section [4]. Figure 1 shows the schematic layout of the RAON accelerator.

In recent years, the simultaneous operation of the stable ion beam and the rare isotope beam has been researched in ATLAS [5]. In the RAON accelerator, this simultaneous operation has also been considered in the post accelerator section for more efficient operations of various kinds of beams. In order to put it into practice, the lattice of the post LEBT is necessary to make modifications for injecting the rare isotope beam into the bunch train of the stable ion beam. Also, the extraction system is required at the end of the SCL3 for extracting the rare isotope beam from the bunch train. Both

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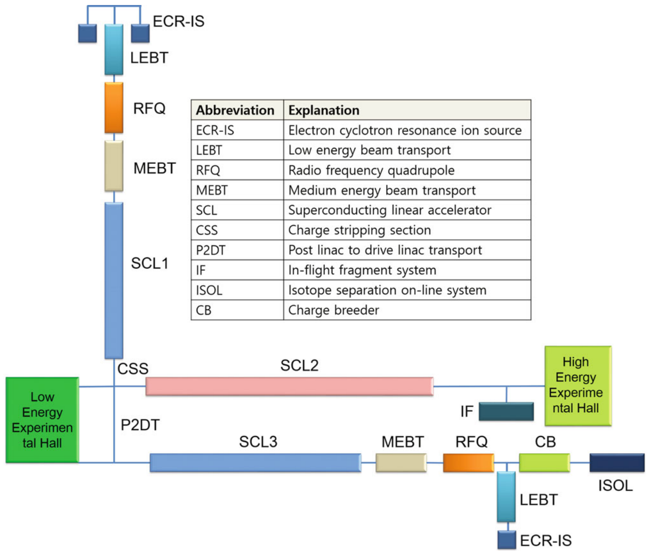

Fig. 1. (Color online) Schematic view of the RAON accelerator.

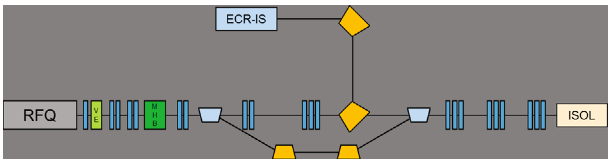

Fig. 2. (Color online) Schematic view of the injection part at the post LEBT.

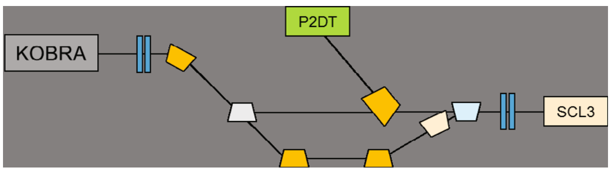

Fig. 3. (Color online) Schematic view of the extraction part after the SCL3.

lattices of the injection and extraction parts should be designed for satisfying the achromatic condition in order to remove the effect of the dispersion. Figure 2 shows the schematic layout of the injection part at the post LEBT and the layout of the extraction part after the SCL3 is shown in Fig. 3.

To satisfy the achromatic condition at the injection and extraction parts and at the same time to make the beam size small, the twiss parameters should be calculated. For this beam optics calculation, the ELEGANT code [6] is used. Next, the results of the ELEGANT code are applied to the TRACK code [7] for the particle tracking simulation. The simulation of the stable ion beam and the rare isotope beam is also carried out from the post RFQ to the SCL3 with the TRACK code.

Table 1. Characteristics of the tin beam at the entrance of the beam line to the NSF.

Characteristic	Value	Unit
Beam	$^{132}Sn^{32+}$	-
Energy	10.0	[keV/u]
Velocity in unit of c	0.00463	-
$\epsilon_{x,y,rms}$	0.1	[mm·mrad]
$\beta_{x,y}$	0.2	[mm/mrad]
$\alpha_{x,y}$	0.1	-
Rms. beam size	2.0	[mm]
Number of macro-particles	10,000	-
Beam distribution	4D water-bag	-

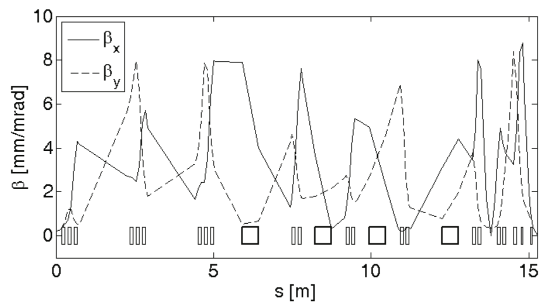

Fig. 4. Beta function at the injection part.

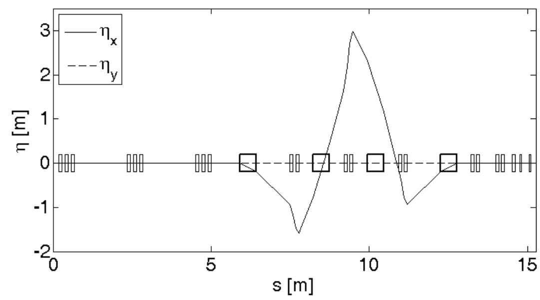

Fig. 5. Dispersion function at the injection part.

II. INJECTION PART

1. Lattice design

In following simulations, the tin beam is used as a reference beam of the ISOL system and the beam information is listed in Table 1. The tin beam, $^{132}Sn^{32+}$, has an initial beam energy 10 keV/u after passing the ISOL system and the transverse root-mean-square (rms) emittance is 0.1 mm·mrad. The initial beta function and alpha function are 0.2 mm/mrad and 0.1, respectively.

Four bending magnets which have 45 bending angles are installed to inject the rare isotope beam from the ISOL system to the post LEBT and the last one is used as a kicker magnet. Figure 4 shows the beta function along the injection part of the post LEBT. The maximum

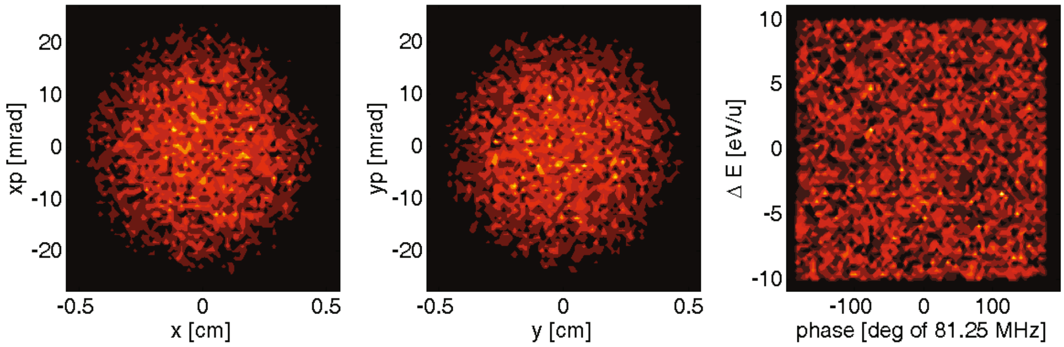

Fig. 6. (Color online) Transverse and longitudinal beam distribution at the entrance of the injection part.

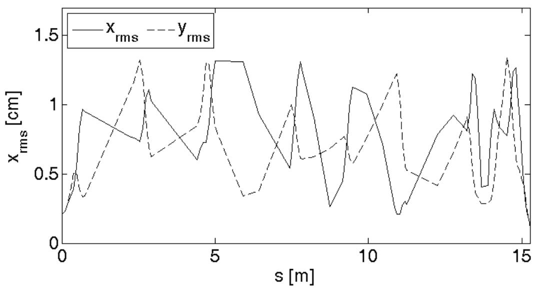

Fig. 7. Transverse rms beam size along the injection part.

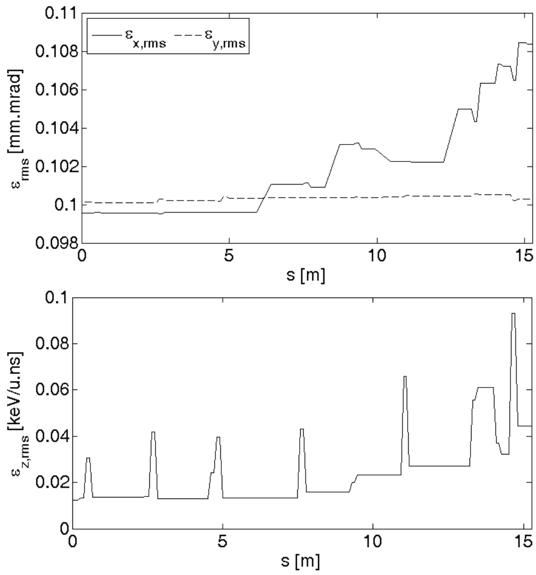

Fig. 8. Transverse and longitudinal rms beam emittance along the injection part.

beta function keeps smaller than 10 mm/mrad to make the beam size small. The matching condition, 0.0567 mm/mrad beta function and 0.324 alpha function, at the post RFQ entrance is also satisfied. Additionally, the dispersion function is shown in Fig. 5. The horizontal dispersion disappears after the beam passes the last bending magnet, which means that the lattice matches the achromatic condition.

2. Beam dynamics simulation

Figure 6 shows the transverse and longitudinal beam distribution at the entrance of the injection part. As listed in Table 1, 4D water-bag model is used with 10,000 macro-particles. With this beam distribution, the particles are tracked through the injection part. Figure 7 shows the transverse rms beam size along the injection part. The maximum beam size is less than 1.5 cm which is much less than the beam pipe radius 6.0 cm.

The transverse and longitudinal rms emittance along the injection part is shown in Fig. 8. Because of the electro-static quadrupoles, the beam energy changes slightly, which has an effect on the transverse and longitudinal rms beam emittance. The horizontal rms emittance increases about 8.1% because of the energy change and the non-zero dispersion at the dispersive section. Figure 9 shows the transverse and longitudinal beam distribution at the entrance of the post RFQ and the growth of the horizontal and longitudinal rms emittance can be identified.

III. ACCELERATION PART

1. Beam dynamics simulation

The stable ion beams and the rare isotope beams are injected in to the post RFQ in series with different time structure. They are accelerated by the post RFQ and the SCL3 before the extraction of the rare isotope beam. For these two beams, the beam information at the injection point and the charge-to-mass ratio are different and these differences affect the beam when the beam passes through the quadrupoles and cavities. For that reason, the transportation and acceleration of two beams from the post RFQ to the SCL3 should be examined. In the

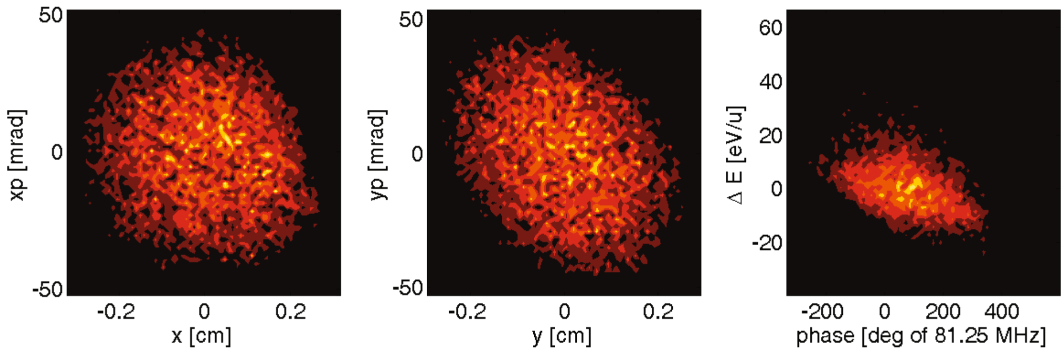

Fig. 9. (Color online) Transverse and longitudinal beam distribution at the end of the injection part.

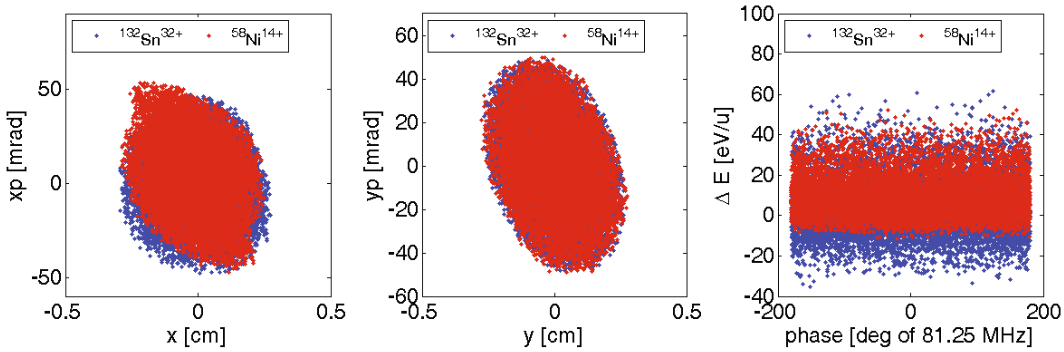

Fig. 10. (Color online) Transverse and longitudinal beam distributions of $^{132}Sn^{32+}$ beam and $^{58}Ni^{14+}$ beam at the entrance of the post RFQ.

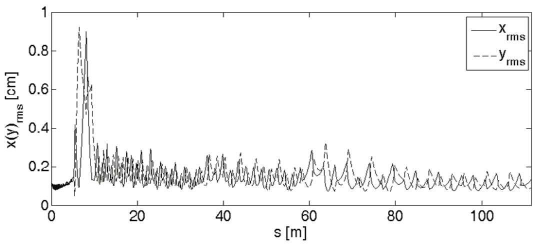

Fig. 11. Transverse rms beam size from the post RFQ to the SCL3.

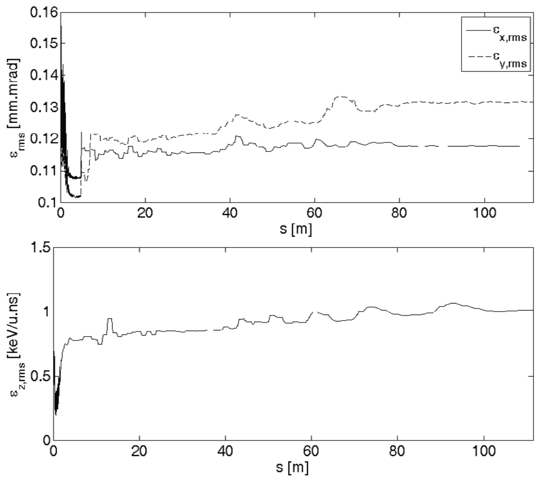

Fig. 12. Transverse and longitudinal rms beam emittance from the post RFQ to the SCL3.

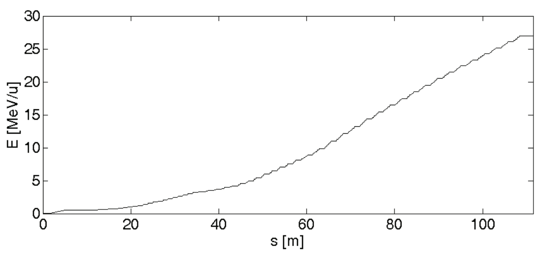

Fig. 13. Beam energy from the post RFQ to the SCL3.

simulations, the nickel beam, $^{58}Ni^{14+}$, is used as a stable ion beam and the transverse emittance of the nickel beam is 0.1 mm·mrad after the ECR-IS. Also, the nickel beam is tracked from the ECR-IS to the injection point of the post LEBT individually and then this beam passes through the post accelerator with the tin beam as a reference beam coming from the ISOL system. The difference of the charge-to-mass ratio of two beams is about 0.43%. The beam distribution of the tin and nickel beams at the entrance of the post RFQ is shown in Fig. 10.

Figure 11 shows the transverse rms beam size from the RFQ to the extraction point through the SCL3. For two beams, the rms beam size at the SCL3 is less than 0.4 cm, which is much smaller than the beam pipe size 2.0 cm. The transverse and longitudinal rms emittances are shown in Fig. 12. The vertical rms emittance becomes larger than the horizontal one because of the effect of the unsymmetrical vertical field of the quarter-wave res-

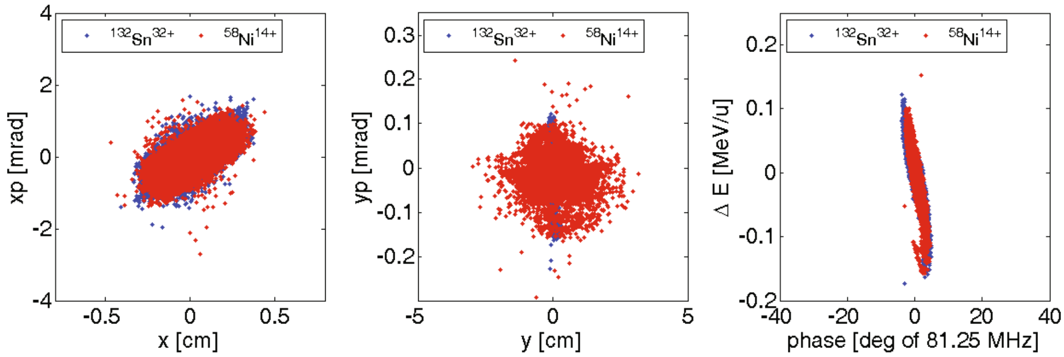

Fig. 14. (Color online) Transverse and longitudinal beam distributions of ^{132}Sn^{32+} beam and ^{58}Ni^{14+} beam at the end of the SCL3.

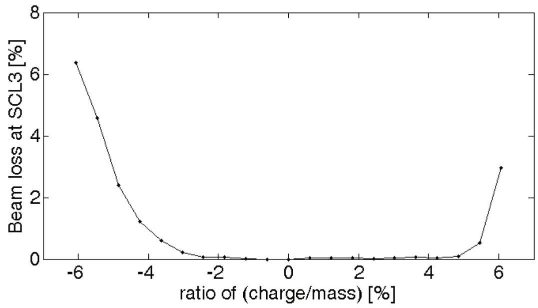

Fig. 15. Beam loss at the SCL3 depending on the charge-to-mass ratio.

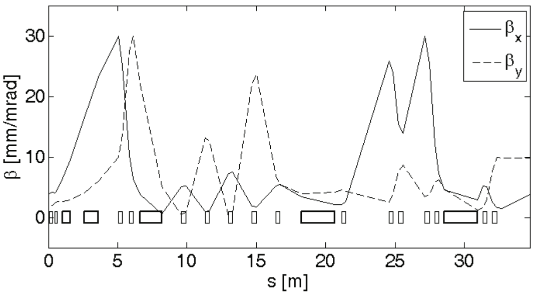

Fig. 16. Beta function at the extraction part.

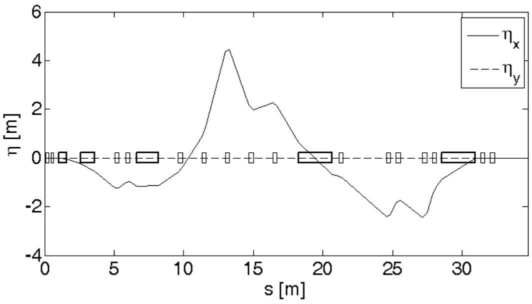

Fig. 17. Dispersion function at the extraction part.

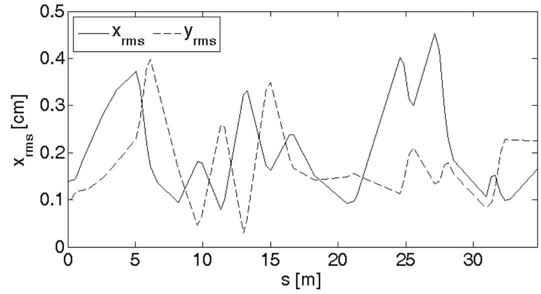

Fig. 18. Transverse rms beam size along the extraction part.

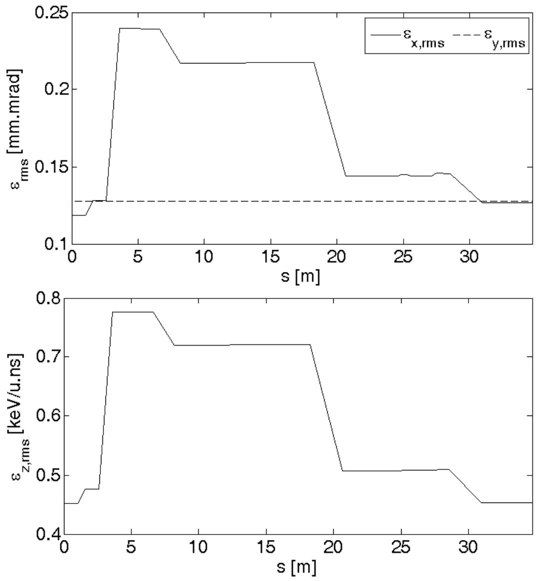

Fig. 19. Transverse and longitudinal rms beam emittance along the extraction part.

onator (QWR) cavity at the SCL3. Also, after the beams pass through the post RFQ, the longitudinal rms emittance increases to the relatively large value because of the adiabatic bunching process in the post RFQ.

Figure 13 shows the average beam energy of two beams from the post RFQ to the SCL3. The beam energy becomes about 27.0 MeV/u at the end of the SCL3. The transverse and longitudinal beam distributions of two beams at the end of the SCL3 are shown in Fig. 14. Becuase of the difference of the charge-to-mass ratio and unsymmetrical vertical field of the QWR cavity, the vertical beam distributions of two beams are different but the horizontal and longitudinal ones are similar.

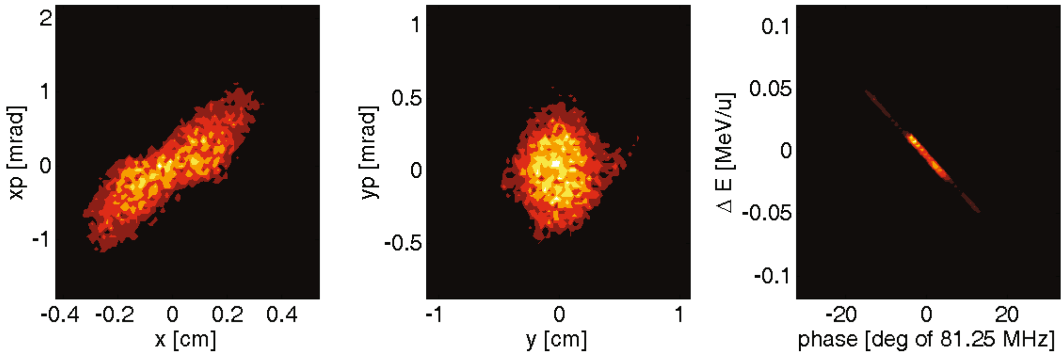

Fig. 20. (Color online) Transverse and longitudinal beam distribution at the end of the extraction part.

2. Acceptance of the charge-to-mass ratio

Because the beam loss at the superconducting linac is considered as a significant issue, we perform a simulation to check the transmission of the stable ion and rare isotope beams through the SCL3 when the difference of the charge-to-mass ratio of two beams becomes larger. Figure 15 shows the beam loss at the SCL3 as the charge-to-mass ratio changes. The lattice of the SCL3 is set to the $^{132}Sn^{32+}$ beam and the charge-to-mass ratio changes based on this beam. Within $\pm 3\%$ of the charge-to-mass ratio, the beam loss is less than 0.2% which is acceptable in the SCL3.

IV. EXTRACTION PART

1. Lattice design

In order to extract the rare isotope beam, a kick magnet which has 10 degree kick angle is installed after the SCL3. In addition, the one bending magnet with 20 degree bending angle is equipped at 1.0 m from the kicker magnet to avoid the overlap of the quadrupoles in two separated lines as shown in Fig. 3. The beta function along the extraction part is shown in Fig. 16. Maximum beta function keeps smaller than 30 mm/mrad, with the beam size small along the extraction part. Figure 17 shows the dispersion function along the extraction part. For getting rid of the effect of the dispersion to the beam, the achromatic condition is satisfied at the deflecting section.

2. Beam dynamics simulation

With the distribution of the $^{132}Sn^{32+}$ beam as shown in Fig. 14, the particle tracking simulation is carried out at the extraction part with the beam distribution of the previous simulation. Figure 18 shows the transverse rms beam size along the extraction part. The rms beam size keeps less than 0.5 cm which is much smaller than the beam pipe radius 4.0 cm. The transverse and longitudinal rms emittance growth is shown in Fig. 19. The growth of the horizontal and vertical rms emittance is about 6.4% and 0.2%, respectively, and the longitudinal rms emittance growth is about 0.1% along the extraction part. Figure 20 shows the transverse and longitudinal beam distribution at the end of the extraction part and this extracted rare isotope beam will be used in the low energy experimental halls.

V. CONCLUSION

We presented the results of the lattice design and beam dynamics simulation for the simultaneous operation of the stable ion beam and rare isotope beam in the RAON accelerator. The lattice of the post LEBT was modified for injecting the rare isotope beam, $^{132}Sn^{32+}$, from the ISOL system with the achromatic condition in the bending section. The particle tracking simulation was also carried out from the post RFQ to the SCL3 with the $^{132}Sn^{32+}$ beam and the stable ion, $^{58}Ni^{14+}$, beam. There was no beam loss during the transportation and acceleration of two beams at the SCL3. The difference of the charge-to-mass ratio of two beams was available within 3% with the beam loss less than 0.2%. After the SCL3, the rare isotope beam was extracted from the SCL3 with the kicker magnet. The extracted beam was transported to the low energy experimental hall and this extraction part was also designed achromatically. The researches for the simultaneous operation of various kinds of the stable ion beams and rare isotope beams will be continued and the results will be applied to the RAON accelerator.

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