STATUS OF THE RAON HEAVY ION ACCELERATOR PROJECT

Dong-O Jeon# and Hyung Jin Kim representing the RAON
Institute for Basic Science, Daejeon, Republic of Korea

Abstract

Construction of the RAON heavy ion accelerator facility is under way in Korea to build the In-flight Fragment (IF) and Isotope Separation On-Line (ISOL) facilities to support cutting-edge researches in various science fields. At present prototyping of major components are proceeding including 28 GHz ECR ion source, RFQ, superconducting cavities, magnets and cryomodules. Superconducting magnets of 28 GHz ECR ion source are fabricated and tested. First article of prototype superconducting cavities are delivered that were fabricated through domestic vendors. Prototype HTS quadrupole is under development. Progress report of the RAON accelerator systems is presented.

INTRODUCTION

The RAON facility will be a unique facility that has the 400 kW In-flight Fragmentation (IF) facility and the 70 kW Isotope Separator On-Line (ISOL) facility providing wider range of rare isotope beams for users.

The driver accelerator for the IF facility is a superconducting linac that can accelerate up to 200 MeV/u in case of uranium beam and up to 600 MeV for proton beam delivering more than 400 kW of beam power to the IF target and various other targets. The driver for the ISOL facility is an H^- 70-MeV 1 mA cyclotron that delivers 70 kW beam power to the ISOL target. The cyclotron has dual extraction ports with thin carbon foils for charge exchange extraction of H^- beam.

The rare isotope beams generated by the ISOL system is re-accelerated by a chain of post accelerators: RFQ, MEBT and superconducting linac SCL3 up to 18.5 MeV/u. The RI beams can be delivered to the low energy experimental hall or can be injected through P2DT to the SCL2 to accelerate to higher beam energy. The schematic layout of the RISP facility is shown in Fig. 1.

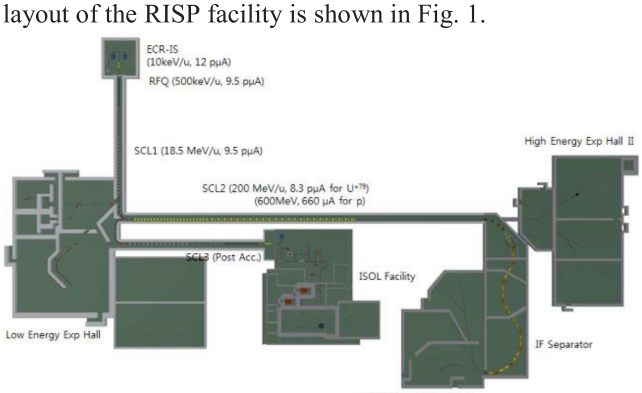

Figure 1: Plot of the RAON facility layout.

To meet the diverse needs, the RISP design is optimized to provide various high intensity stable ion beams and radioactive isotope (RI) beams from proton to uranium for domestic and international users.

Construction of the RAON heavy ion accelerator facility has begun December 2011. The assessment of the conceptual design has followed and design changes were introduced [1]. Detailed design of the accelerator systems has progressed, and prototyping of critical components and systems have been materialized. In this paper, the status of the RAON accelerator systems is presented along with prototyping progress.

THE DRIVER LINAC

The RAON has two linear accelerators; one is the driver linac and the other is the linac as post-accelerator. The driver linac delivers beams to In-flight Fragment (IF) facility and is designed to accelerate high intensity stable ion beams from uranium to proton. Driver linac consists of 28 GHz ECR ion sources, LEBT, RFQ accelerating beam to 0.5 MeV/u, MEBT, low energy superconducting linac (SCL1) accelerating uranium beam to 18 MeV/u, Charge Stripper Section (CSS) for charge state increase and collimation, and high energy superconducting linac (SCL2) accelerating uranium (proton) beam to 200 MeV/u (600 MeV). The driver linac is designed to deliver 400 kW beam power with uncontrolled beam loss less than 1 W/m to IF target and other targets. Figure 2 shows the diagram of the RAON driver linac.

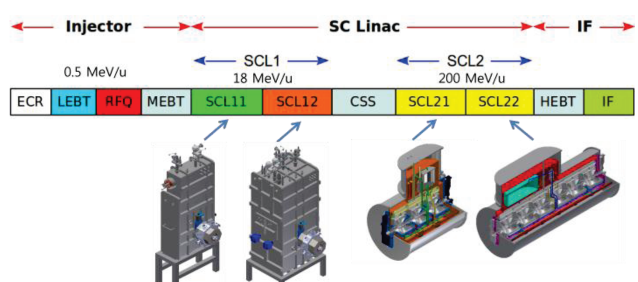

Figure 2: Diagram of driver linear accelerator of the RAON. Driver linac consists of four types of cryomodules and transverse focusing is provided by normal conducting quadrupole doublets as shown in the figure. For diagnostics, there are beam boxes located between quadrupole doublets.

Injector

The injector consists of 28 GHz superconducting ECR ion source (ECR IS), Low Energy Beam Transport (LEBT), Radio Frequency Quadrupole (RFQ) and Medium Energy Beam Transport (MEBT). For ECR IS, superconducting magnets and dual high power RF sources

#jeond@ibs.re.kr

ISBN 978-3-95450-142-7

of 28 GHz and 18 GHz are used to improve its performance. Figure 3 shows the configuration of superconducting magnets for the ECR IS that generates high magnetic field for confinement and minimizes mechanical stress.

The saddle type sextupole is more difficult to wind than the racetrack type one. For the saddle type sextupole, one can wind ~20% more SC wires for the same space, thus can lower operating current. Sextupole and solenoid prototypes were tested individually with success. Now the assembly of superconducting magnets has been fabricated and installed in the ECR IS cryostat.

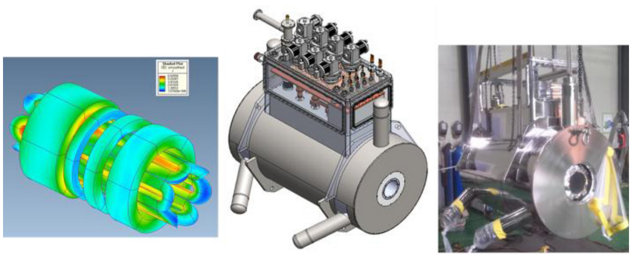

Figure 3: Plot of 28 GHz ECR ion source and its superconducting magnet assembly.

The LEBT (Low Energy Beam Transport) is to transport ion beams from the ECR ion source to the RFQ. Especially simultaneous transport of $^{238}U^{+33}$ and $^{238}U^{+34}$ is an important aspect of the design. The LEBT consists of two bending dipoles that form an achromat and electrostatic quadrupoles, solenoids, and chopper etc. This achromatic bending section functions as charge selector. The beam distributions at the LEBT entrance are shown in the upper plots and those at the exit in the lower plots of Fig. 4. The blue dots represent $^{238}U^{+33}$ beam and red ones $^{238}U^{+34}$ beam.

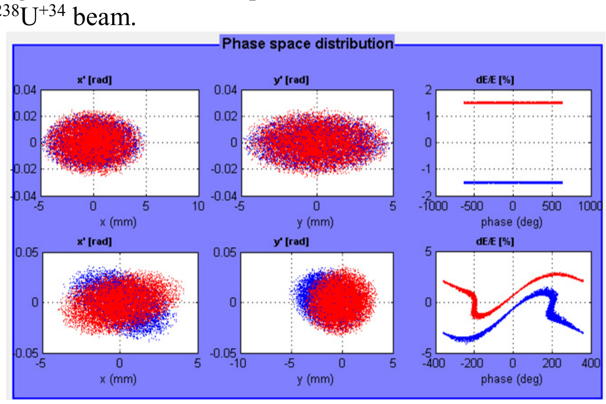

Figure 4: Plots of beam distribution at the LEBT entrance (upper plots), those at the LEBT exit (lower plots).

The RFQ is designed to accelerate proton to uranium beams from 10 keV/u to 500 keV/u. One feature is that this RFQ can accelerate two-charge states of uranium beams ($^{238}U^{33+}$ and $^{238}U^{34+}$ of 12pμA) beams simultaneously. Design of the RFQ was completed and Table 1 lists parameters of this RFQ. PARMTEQ code is used to obtain the RFQ design parameters. Prototyping of RFQ was tried and initial fabrication procedures have manifested a few issues. Recently these issues have been resolved and the prototype RFQ will be delivered in September 2014, followed by the test of the prototype RFQ. Figure 5 shows the some results of the RFQ design and RFQ prototype fabrication.

Table 1: RFQ Design Parameters

Parameter	Value
Frequency	81.25 MHz
Reference Particle	H^{+1} to $^{238}U^{+33\&+34}$
Input energy	10 keV/u
Output energy	0.500 MeV/u
Input emittance (rms,normalized)	0.12 mm-mrad
Output emittance	0.125 mm-mrad
	~ 26 keV/u-deg.
Transmission	~ 98 %
Peak surface field	1.70 Kilpatrick
Structure power (for $^{238}U^{+33}$)	92.4 kW
Total Length	4.94 m

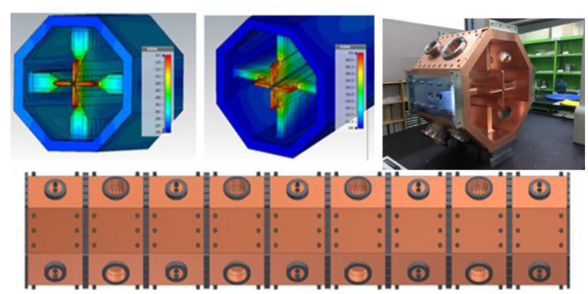

Figure 5: Plot of RFQ design and photograph of the RFQ prototype.

Superconducting Linac (SCL)

The RAON has two superconducting linacs; driver SCL (SCL1 and SCL2) for stable ion beams and SCL3 as a part of post accelerator of rare isotope beams. All the superconducting cavities are individually phased. Relatively large cavity apertures (40 and 50 mm) are adopted to reduce uncontrolled beam loss on the superconducting cavities because beam loss is a serious issue for superconducting accelerators. The input energy to the driver SCL is 0.5 MeV/u. Cavity geometric betas are optimized and an optimum set of β = [0.047, 0.12, 0.30, 0.51] is obtained. Its results of energy gain per cavity for uranium beam are shown in Fig. 6. With the cavity geometric betas determined, cavity geometries are optimized with respect to R/Q, QR_s, E_{peak}/E_{acc}, B_{peak}/E_{acc} etc. for improved performance and Table 2 lists the optimized parameters of the four types superconducting cavities. Normal conducting quadrupole doublets are employed for transverse focusing and none of the cryomodules contain superconducting solenoids.

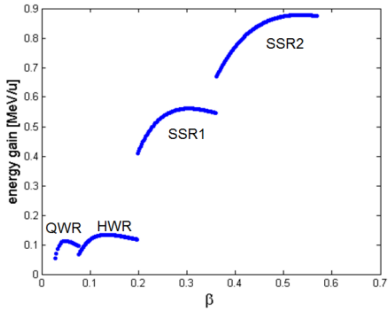

Figure 6: Plots of the optimized geometric betas of the superconducting cavities employed by the RAON.

Table 2: Cavity Parameters

Parameters	Unit	QWR	HWR	SSR1	SSR2
β_g	-	0.047	0.12	0.30	0.53
Resonant frequency	MHz	81.25	162.5	325	325
No of cavities	-	22	123	84	136
Aperture dia.	mm	40	40	50	50
QR_s	Ohm	17.5	41.2	86.1	104.7
R/Q	Ohm	472.3	264.8	237.0	298.0
V_{acc}	MV	1.02	1.07	2.04	3.53
E_{peak}	MV/m	30	30	30	30
B_{peak}	mT	54.1	40.8	52.2	62.3
Operating temp	K	2	2	2	2
P_0	W	2.7	2.0	4.8	8.4
Beam current (U)	pmA	9.5	9.5	8	8

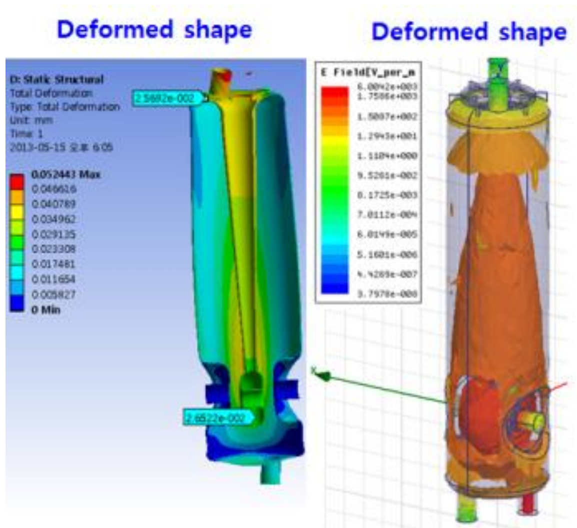

Figure 7: Plot of the QWR stiffening analysis with gussets and disk. This reduces pressure sensitivity to 0.6 Hz/mbar.

Mechanical characteristics of the superconducting cavities is analyzed using the CST and ANSYS codes to study and to ensure that the cavity design meets the requirement of Lorentz force detuning, detuning due to helium pressure fluctuation (df/dP), microphonics detuning etc. EM design has been conducted to reduce B_{peak} and E_{peak} which in turn reduces the Lorentz force detuning. Stiffening the cavity endwalls and shell reduces the Lorentz force detuning and detuning due to helium pressure fluctuation. Endwalls of spoke resonators are reinforced with two types of ribs: donut ribs and daisy ribs. The design of the helium jacket is to be studied in light of the df/dP characteristics. Figure 7 shows the stiffening structure with gussets and disk reduces the pressure sensitivity of the QWR cavity to 0.6 Hz/mbar. The design of the helium jacket is studied in light of the df/dP characteristics. Analysis has been conducted of mechanical vibration modes and its characteristic frequencies. Analysis shows that lowest frequency of the QWR is 80 Hz for bare cavity and it is expected that stiffening and helium jacket would shift this frequency upward.

It is important to avoid multipacting barriers as much as possible and the design should be optimized by using the CST electron tracking code. Multipacting analysis will be conducted for the combined structure of the cavity and power coupler. Analysis shows that some multipacting bands can be found at low cavity field, which is not critical. More details of SCL design and cavity prototyping can be found in [2,3].

Thermal analysis is done for the superconducting cavities and special attention will be paid to high magnetic field region, around the coupler port, and beam tubes etc. The thermal analysis of SSR2 cavity for instance shows that the beam tube temperature rises to 2.1K when the operating temperature is 4K.

Following the detailed engineering analysis of the four types of superconducting cavities, contracts for prototyping superconducting cavities were awarded to two domestic companies in 2013 and the first article of superconducting QWR cavity was delivered in May 2014 achieving an important project milestone. Figure 8 shows the photographs of the prototype QWR and HWR cavities. These cavities are to be tested using the SRF test facility of the TRIUMF. The project is also pursuing to do prototyping through international vendors with sufficient experience in superconducting cavity prototyping and production. The call for tender will go out soon.

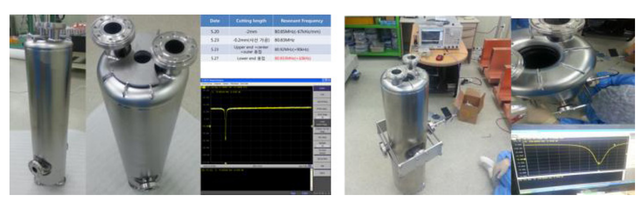

Figure 8: Photographs of the prototype QWR (the left plot) and the HWR cavities fabricated through domestic vendors.

Cryomodule Development

It is known that the position of each component in a cryomodule changes by no less than a millimeter during the cool-down and it is not trivial to predict and compensate accurately enough the alignment of superconducting solenoids or cavities in a cryomodule. Accurate alignment of focusing elements such as superconducting (SC) solenoids is very crucial for maintaining the beam quality of high intensity beams. For high intensity operations, the foreseen uncertainty greater

ISBN 978-3-95450-142-7

than ±0.5 millimeter displacement of superconducting solenoids can induce emittance growth, leading to beam loss and activation of accelerator components and potential quench of superconductors inside cryomodules.

Beam loss at superconducting solenoids can lead to an issue such as quench. Having a high field superconducting solenoid can magnetize surrounding elements in the cryomodule and may require demagnetization and complicated turn-on procedure. The SCL employing long cryomodules that contain multiple cavities and solenoids can impose significant restriction on the beam diagnostics access. This leads to difficulties in the accelerator tuning.

These are crucial design considerations in designing the SCL, for the intensity heavy ion beams has increased steadily with the progress of ECR ion sources. It was decided to employ a SCL lattice with normal conducting quadrupole doublets for the RAON SCL as shown in Fig. 9. The SPIRAL2 project also adopted quadrupole doublet focusing lattice for high intensity ion beam acceleration (for instance, 1 mA of heavy ion beams and 5 mA deuteron beam) [4].

Figure 9 shows the design of the QWR, HWR and SSR1 cryomodules of the RAON. Detailed engineering design is under way and prototyping of cryomodules is in progress. Prototype cryomodules are scheduled to be delivered by April 2015. Thermal load of each type of cryomodules is analyzed and reflected on the cryogenic system design. With 40% engineering margin, an 18-kW cryogenic system is needed.

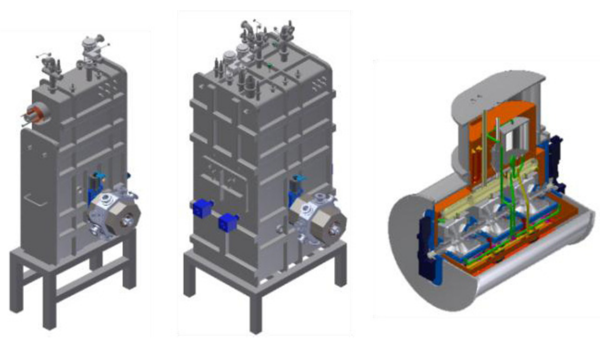

Figure 9: Plots of the QWR (the left plot) and the HWR (the middle plot) and the SSR1 cryomodules (the right plot) with normal conducting quadrupole doublets.

Beam Physics

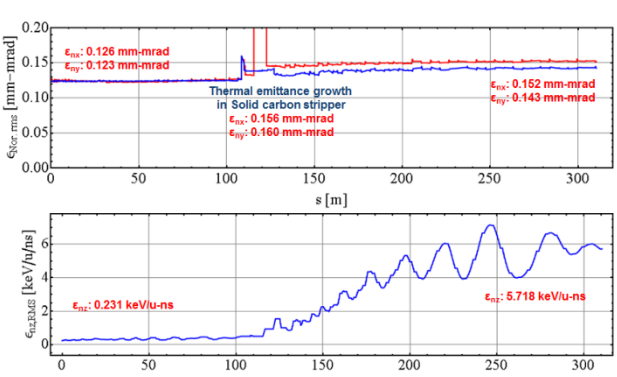

Figure 10: Plots of the start-to-end beam dynamics simulations for uranium beam. The upper plot shows the transverse emittance growth along the driver linac and the lower plot the longitudinal emittance growth.

Start-to-end beam dynamics simulations are done for various ion beams such as uranium, proton, carbon, and calcium beams etc. Effects of machine imperfections are studied and the results show that the uncontrolled beam loss requirement less than 1 W/m is met. Fig. 10 shows, for instance, the plots of transverse and longitudinal beam rms emittances for uranium beam along the SCL1, Charge Stripper Section and the SCL2. The spike in x beam emittance at ~120 m is due to uranium beams going through the charge stripper section producing multiple charge states and through 90° bend.

IF SYSTEM

The IF (In-flight Fragment) system consists of target, separator and beam dump. The in-flight isotope beam separator system can be largely divided into pre and main separators. Fig. 11 shows the schematic layout of the IF separator, which has been designed to be a two-stage RI beam separator. The momentum acceptance of the separator has been designed to be ±3 %, while the angular acceptances will be ±40 mrad horizontally and ±50 mrad vertically. The magnetic rigidity is designed to be around 10 Tm. Basic parameters of the in-flight separator are listed in Table VII. Design of IF target, beam dump and separator is progressing. Thermal and mechanical analysis of target and beam dump is done. Development of the IF target is under way [5]. Baseline design of separator is fixed now. Prototyping is going on for the High Tc Superconducting magnets. Beam delivery system from the SCL2 to the target is designed, consisting of second order achromats.

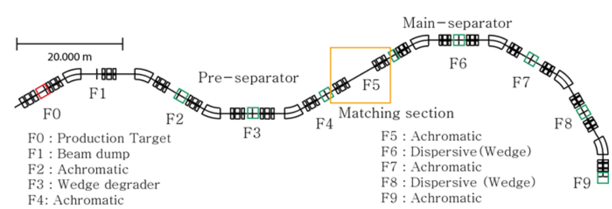

Figure 11: Schematic plot of the target and separator.

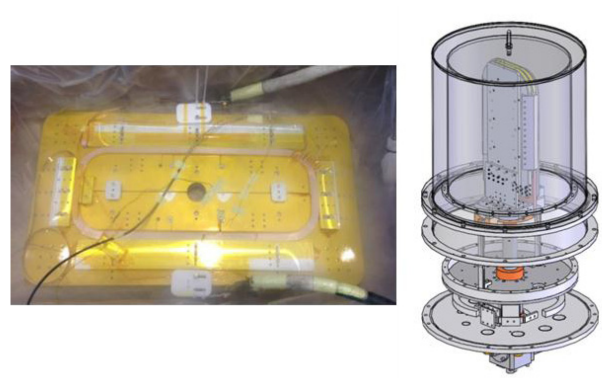

Figure 12: Photograph of High Tc Superconducting quadrupole coil and test bench setup.

In the pre-separator which consists of four superconducting dipoles and seven superconducting quadrupole triplets, the primary beam and fragments are separated by momentum dispersion, and a beam dump is used to remove the separated primary beam and unwanted fragments in the localized area. About 25% of 400 kW beam power is dissipated by the target and the rest is dumped to the beam dump. Due to high power dissipation, the target adopts rotating multi-layer carbon disks with radiation cooling. Development of carbon disk is under way and 0.1-mm thick carbon slice is fabricated and recently tested with high power electron beam. Measurements show a good agreement with thermal and mechanical analysis.

This pre-separator area has high-level of radiation, and radiation heating on the magnetic elements is high. HTS (High Tc Superconducting) magnets are used for efficient heat removal. Prototyping of HTS magnets is going on and Fig. 12 shows the photograph of HTS coil prototype being tested in LN2 and test bench setup inside a dewar equipped with a cryocooler.

A remote handling system based on servo-motor controlled crane is being considered. The design of beam dump is quite challenging because the system needs to separate different kinds of rare isotope beam from the primary beam in different beam energies. A rotating water drum, which can be moved perpendicular to beam axis, is being considered.

The main separator from F5 focus to the F9 focus consists of four dipoles with a bending angle of 30 degrees and eight superconducting quadrupole triplets with warm aperture of 26 cm. The F6 and F8 are momentum-dispersive, while the F7 is achromatic and the F9 is doubly achromatic. The main separator is aimed to identify RI-beam species, because several unwanted isotopes are mixed in the produced RI beams. Position-sensitive detectors, timing detectors and ΔE detectors are placed at the focuses of the main separator to identify isotopes and deliver tagged RI beam to experimental area placed downstream of the in-flight separator. Additionally, it is also possible to placing second and third energy degrader at the F6 and the F8 on the main separator. The main separator allows to be operated in both high dispersion and large acceptance modes. Momentum resolution is about 2700 at F6 in the large acceptance mode while it is about 3700 at F7 in the high resolution mode. Figure 13 shows the optics of the separator for two different modes.

CONCLUSION

The design of the RAON accelerator system is well progressing, optimized for the acceleration of high intensity heavy ion beams. Prototyping is progressing including SC magnets and cavities, IF target and RF systems [6].

ACKNOWLEDGEMENT

This work was supported by the Rare Isotope Science Project of the Institute for Basic Science funded by the Ministry of Science, ICT and Future Planning (MSIP) and the National Research Foundation (NRF) of Korea under Contract 2013M7A1A1075764.

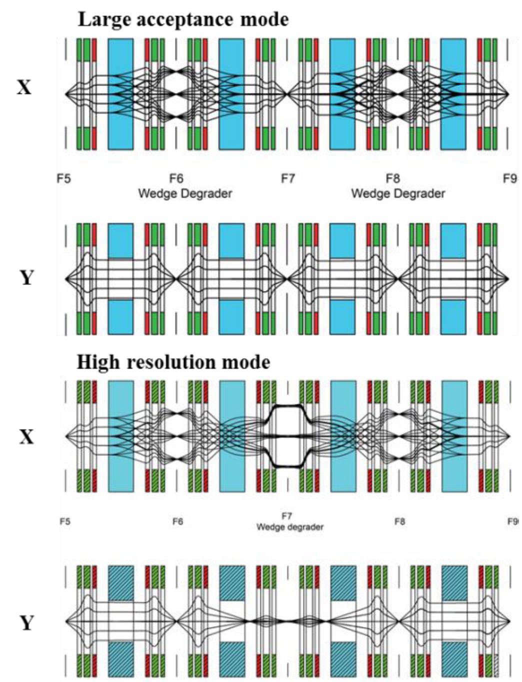

Figure 13: The first order optics of main separator in two different modes: horizontal (denoted by X) and vertical (denoted by Y).

REFERENCES

[1] Baseline Design Summary, The Rare Isotope Science Project, Institute for Basic Science, Korea (http://www.risp.re.kr/orginfo/info_blds.do).

[2] H.C. Jung, M.O. Hyun, H.J. Kim, D.O. Jeon, *Prototyping of TEM-like mode resonators in the RAON*, Proc. of IPAC 2013, p. 2384, Shanghai, China (2013).

[3] Hye-Jin Kim et al., *Optics design and correction of high order aberration of the charge stripper beam line of RAON*, Proc. of IPAC 2013, p. 3906, Shanghai, China (2013).

[4] R. Ferdinand et al., *Status and Challenges of the SPIRAL2 Facility*, Proc. of LINAC Conference 2010, p. 16, Tsukuba, Japan (2010).

[5] J.S. Song et al, *Development of target system for rare isotope beam with high power heavy ion beams*, Proc. of Cyclone Conference 2013, Vancouver, Canada (2013).

[6] J. Han et al, *Design of the RF system for the accelerator complex of Rare Isotope Science Project*, Proc. of Cyclone Conference 2013, Vancouver, Canada (2013).