PROGRESS OF THE RAON HEAVY ION ACCELERATOR PROJECT IN KOREA*

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Abstract

The Rare Isotope Science Project (RISP) of Institute for Basic Science (IBS) has been initiated for constructing a heavy ion linear accelerator complex in Daejeon, Korea. The goal of the accelerator complex, named RAON meaning joyful and happy in Korean, is to produce variety of stable and rare isotope (RI) beams for researches in basic science and various other applications. Powered by a 400-kW superconducting linac, the facility is intended to establish the In-flight Fragment (IF) and Isotope Separation On-Line (ISOL) facilities to become the most effective producer of rare isotope (RI) beams worldwide. The prototype construction of major accelerator components is almost complete and testing is ongoing. Progress on the development of components, especially those important for the accelerator system, that will be integrated for demonstrating the successful operation of the front-end of RAON are presented.

INTRODUCTION

In Korea, two large accelerator facilities, presently operating for public users, currently exist. A new heavy ion accelerator, RAON, is now under construction. With the completion of RAON, the accelerator facilities in Korea will be able to probe matter from the macroscopic- to femtoscopic- scale, enabling not only the study of properties of matter at this scale but also to create (synthesize) new states of matter.

Accelerators are often said to be microscopes with high resolution. Their resolving power depends strongly on beam species and energies, with each accelerated beam particle quantum mechanically associated with a corresponding de Broglie wave; beams of higher mass and energy correspond to waves of shorter wavelength, essentially providing higher resolution. Therefore, accelerated heavy ions (HI) which have shorter wavelengths than any other beam species, such as electrons and protons, can interact with matter more energetically and on a smaller scale; they can deposit large amounts of energy to bulk materials on the nano to femto scale. The energy transfer to the matter by energetic HI irradiation is in the order of keV in atomic scale (1eV~10^4K, temperature elevation due to HI irradiation is converted to macroscopic temperature by lattice-phonon coupling in the matter). HIs can produce tracks well-localized along both directions, e.g. transversely on the order of nm, and longitudinally on the order of mm via the irradiation of a target by a ~100 MeV/u carbon beam. Another important and interesting feature of HI irradiation is on the soft-landing of HIs on the lattice of solid materials after imparting a large amount of energy along the ion track. This allows one to use radioactive HI beams as a probe of the electromagnetic properties of materials. There are many nuclear methods, such as nuclear magnetic resonance (NMR), Mössbaur, emission channeling (EC), perturbed angular correlation (PAC) etc., that utilize the radioactive characteristics of HI beams, incorporated into the materials of interest, for various applications. Therefore, in this way, HI beams can be used to create new states of matter, as well as probe matters in an excited state (and/or modified into completely different forms) or just in an as-fabricated state.

HIs can interact with nuclei in nuclear scale, via collisions; this is simply nuclear reactions between heavy ions, through which new nuclides can be produced, i.e. through target and projectile fragmentation. In the case of target fragmentation the products remain almost stationary inside the target material, which requires further processing (diffusion, effusion, ionization and re-acceleration) for further use as an accelerated HI beam. In the projectile fragmentation case however, the fragmented projectiles fly away with most of their initial energy, and therefore can be separated in-flight. Using heavy ion collisions, the evolution of the Universe after the Big Bang (BB) can be also simulated on a time scale inversely proportional to the energy scale of the accelerator. For example, the LHC has a time scale corresponding to around 10^{-10} sec, while RAON can simulate 3min after the BB. Therefore the origin of elements and chemical evolution will be simulated using RAON.

Fully utilizing the diversity of HI beams, in addition to the new availability of radioactive isotope beams, RAON is intended to become one of the world-leading heavy-ion facilities. RAON could provide new research opportunities in rare isotope science, which is recently attracting many interdisciplinary scientists, manifesting itself in the form of a second renaissance in heavy ion science.

Here, we initially overview the Rare Isotope Science Project, and then present the status of the main developments of the accelerator facility.

PROJECT OVERVIEW

A big vision was drawn for promoting basic science research in Korea, within the scope of the International Science Business Belt (ISBB), by the Korean Government in 2009. Thereafter a new world-class research organization, the Institute for Basic Science (IBS) was established in the ISBB to provide a creative research environment for basic science in Korea. The Rare Isotope Science Project (RISP) was launched at the end of 2011

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for the construction of the RAON heavy ion accelerator complex as a key research facility of IBS.

Facility Concept of RAON

The use of rare isotopes existing for a very short time(radioactivity with short lifetime) is nowadays increasingly used in various advanced research fields, e.g. for basic researches in nuclear physics investigating origin of matter, synthesis of new atomic elements, and exotic nuclear structure of rare isotopes, as well as for applied researches in medical-bio-life, materials and nuclear sciences.

The degree of usability of various rare isotopes relies largely on the development of particle accelerator facilities for the effective production and on-line separation of rare isotopes. Two methods have been adopted separately in existing facilities world-wide, that depend on the facility's configuration; Isotope Separator On Line (ISOL) and In-Flight (IF), which are complementary to each other in character [1, 2].

The IF method uses an electromagnetic (EM) separator to separate and guide rare isotope beams (RIBs) to experimental halls for further studies. Projectile fragmentation of high-energy heavy-ions, together with other reactions (e.g. transfer reactions and fission in-flight) with incident energies from a few MeV/u to a few GeV/u have also been used. Only a select few ion species need to be accelerated; fragmentations of the incident beam produce wide variety of elements in a similar energy range. Therefore, the facility configuration is relatively simple, requiring a heavy-ion accelerator and an EM separator. The technical issues for this type of facility are involved with the development of heavy-ion sources and high-power targets, allowing for an incident beam with as high an intensity as possible.

The ISOL method, often called the reacceleration method, uses the ISOL technique to produce radioactive nuclei, then ionizes and accelerates the desired nuclei to energies high enough for further studies. The ISOL technique has been mainly developed at CERN/ISOLDE in order to separate out radioisotopes of interest from the target fragments produced, by bombarding a heavy nuclear target (like UCx target) with a high-energy proton beam (target fragmentation). This type of facility requires some additional complicated systems, including an ISOL-system and an accelerator for radioactive ions. High efficiencies are required at each stage of production; ionization, separation, and transportation. These developments are inter-related and thus many developments are still necessary. Especially, one has to extract the rare isotope of interest from the bulk of the production target. The rate-determining steps are the diffusion and effusion of the rare isotope in the target materials, the rate of which depends on the combination of target material and element to be extracted, and is often slow compared to the lifetime of the nuclide of interest. Therefore most of the effort has been put into the development of targets and ion sources.

For the production of radioactive nuclei, ISOL has a much greater advantage (about 10^4 times) than the in-flight method due to the target thicknesses and primary beam intensities available for production. For the in-flight method, only an electromagnetic separator is necessary. More factors are involved for the ISOL method however, including the efficiencies for extraction from the target materials and ionization. In the case of the in-flight method the necessary separation time (<1 s) is much shorter than lifetimes of any beta-decaying nuclei (>1 ms). Concerning the quality of produced RIB, the ISOL facility provides better quality; the energy spread and emittance of the beam is essentially same as those of stable heavy-ion beams. Beam contamination due to other nuclides in ISOL-type facilities is small in many cases, compared to the IF method in which the beam delivered is usually a mixture of different nuclides. The energy spread and emittance is also wider in the IF method.

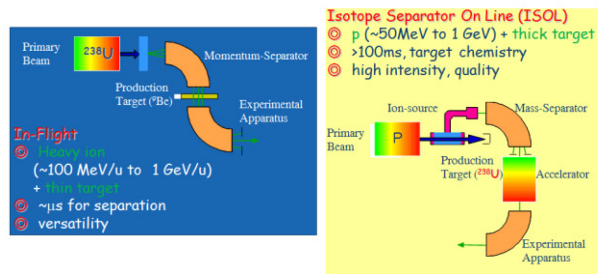

Figure 1: Comparison if the two RIB production methods.

As summarized in Fig. 1, there are both advantages and disadvantages associated with the two types of facilities. Most of studies involving RI beams have been conducted at one of these two types of facilities. However in any of the facilities, present and near future, studies that require more neutron-rich nuclei present a great challenge. What if the ISOL-type facility connects to the IF-type facility? An ISOL system, probably with actinide target, is used to produce high-intensity beam of neutron-rich isotopes of the easiest-to-extract elements (i.e. fast diffusion and effusion in the target materials) then this RIB is accelerated to an energy high enough for projectile fragmentation to occur. The in-flight technique for fast separation can then be applied to obtain beams of very neutron rich nuclei. This method is expected to yield neutron rich beams with a greater intensity than that achieved by any existing facilities. This is the one of the most important aspects of the concept of RAON, as shown in Fig. 2.

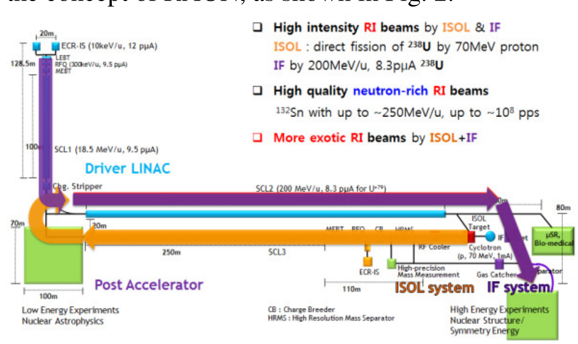

Figure 2: Schematic view of RAON. The operation modes, namely flow of driving beams for RI production, are shown.

The accelerator complex, to be constructed at Sin-Dong in Daejeon, consists of three accelerator systems; a heavy ion superconducting linear accelerator driving the IF isotope separation system, a proton cyclotron as the driver for the ISOL system, and a post-accelerator for the ISOL system. The ISOL and the IF system can be operated separately and independently, as indicated by arrows in Fig. 2. In addition, the rare isotopes produced via ISOL can be injected into the driver linac, accelerating the RI beam to even higher energies, or they can be used in the IF system to produce even more exotic rare isotopes. RAON has the unique feature of having both ISOL and IF system for the production of isotope beams. Such high intensity rare isotope beams provide opportunities for a wide range of basic science researches and applications.

The characteristics of RAON, in terms of production of neutron-rich isotope beams and of their neutron richness (ratio of mass number to atomic number; A/Z), are compared with the performance in other facilities that are present and under construction in Fig. 3.

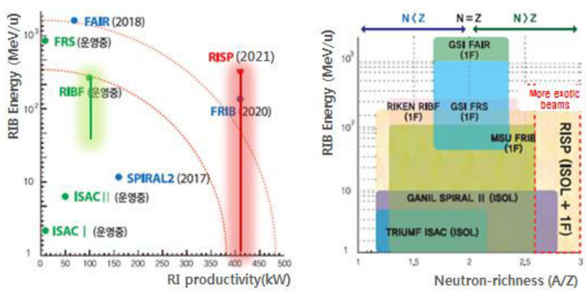

Figure 3: Characteristics of RISP. RISP will provide RIBs with energies ranging from tens of keV to intermediate energies of around 200MeV/nucleon with a high intensity and neutron richness. (*FAIR and FRS in GSI, Germany; ISAC I and II in TRIUMF, Canada; RIBF in RIKEN, Japan; SPIRAL2 in GANIL, France; FRIB in MSU, USA.)*

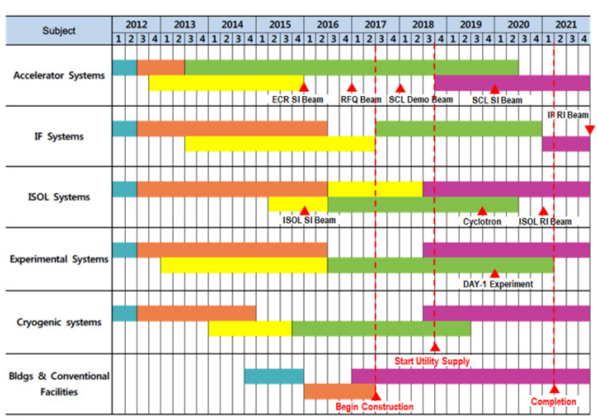

Figure 4: Time plan of the project. Some important milestones are also given.

Time Plan and Construction Site

The period of RISP is from Nov. 2011 to Dec. 2021. The time schedule for the completion of the project by the end of 2021 is shown in Fig. 4, where some important milestones can be identified for both the subsystems of accelerator and experimental devices, and for conventional facilities. We successfully extracted stable beams from ion sources using the Driver LINAC and ISOL at the end of 2015, at the ion source test benches, and acceleration of beams at the off-site test facility is expected in 2017. For the conventional facilities, the site will be available for constructing buildings accommodating accelerator complex at the beginning of 2017, and the utilities at the end of 2018. Installation and commissioning of the accelerator and experimental system will commence accordingly.

The construction site for the facility was confirmed in the middle of 2014 as Sindong, located about 10-km from the center of Daejeon. The site development work is currently under progress.

CONSTRUCTION STATUS OF RAON

The RAON design has been finalized to provide various high-intensity stable ion beams and rare isotope beams from protons to uranium [3], shown schematically in Fig. 2. RAON will be a unique facility that combines both IF and ISOL facilities.

The driver accelerator for the IF facility is a 400-kW superconducting linear accelerator that can accelerate heavy ion beams with mass to charge ratios (A/q) less than 7, with accelerated energies ranging from 200 MeV/u, in case of the uranium beam, to 600 MeV for protons. To generate highly charged heavy ion beams, a 28-GHz superconducting electron cyclotron resonance ion source (ECRIS) will be employed. Multi-charged ions, e.g. $^{238}U^{34+}$ extracted with the energies of 10 keV/u from the ECRIS, will be injected into an 81.25-MHz Radio Frequency Quadrupole (RFQ) linac and accelerated to 500 keV/u. The ion beams will be further accelerated up to 18.5 MeV/u by a superconducting (SC) linear accelerator, either SCL1 or SCL3. The charge states of U ions with A/q ~ 7 after being accelerated by SCL1 (SCL3), will be boosted to higher charge states (A/q ~ 3) by a liquid lithium charge state stripper, and then the charge-bred ions will be reinjected to a high-energy superconducting linear accelerator, SCL2 for further acceleration to 200 MeV/u.

The driver for the ISOL facility is a 70-MeV H^- cyclotron that will deliver 70-kW beam power to the ISOL target. The RIBs generated by the ISOL system will be re-accelerated by the RFQ and SCL3 linacs mentioned above, and can be delivered to the low-energy experimental hall, or injected through a charge stripper section to SCL2 (the high-energy part of driver linac for the IF system) for acceleration to higher beam energies.

The prototype construction of major accelerator components (SC cavities, slow-tuners, RF couplers, RF power suppliers, cryomodules etc.) has been almost finished and their test is ongoing. The progress on the development of some components, especially those important for an accelerator system to be integrated for demonstrating the successful operation of the RAON, will be focused on in the following. The demonstration system includes only the front-end of RAON, from an ion source to the exit of

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the first stage of superconducting linear accelerators. The demonstration system consists of a 28-GHz ECRIS, an 81.25-MHz RFQ, and the first one or two cryomodules of SCL3, and will be installed at an off-site test facility currently under construction.

28-GHz ECRIS The ECRIS was developed for the effective production of highly charged ions of U, with A/q ~7 [4]. Figure 5 shows the recently fabricated and tested source. It is operating with a microwave frequency of 28 GHz and a maximum power of 10kW. The configuration of the axial magnetic field strength (B_{min} structure) is achieved by four low-temperature superconducting solenoids, while the radial configuration is generated by a hexapole consisting of six saddle-type superconducting magnets. The fabricated superconducting magnets were installed inside the cryostat schematically shown in Fig. 5 and tested at a temperature of 4K. Though, before assembling together, all magnets were able to operate at the designed current value without quenching. Quenches were observed in the heaxpole however, seemingly due to the stress by the magnetic force caused by solenoids operating after being assembled. Optimization of the magnet training was attempted and best result was achieved by a simultaneous increase of the currents through both the solenoid and hexapole magnets. More than 80% of the design currents can be routinely introduced to all magnets, and the magnetic field configuration can be controlled in the following ranges; B_{inj}< 2.9 T, B_{min}> 0.6 T, B_{ext}<1.6 T, B_r<2T, B_{ECR}= 1T. Where the magnetic field strength at the injection side, at the minimum, at the exit side, and at ECR resonance frequency of 28-GHz, respectively (the design values are B_{inj}= 3.5T, B_{min}= 0.4~0.8 T, B_{ext}=2T.) The first beam was extracted; an O^{5+} beam of about 100μA with a charge state distribution having a maximum at 5+ when the ECRIS operated with a magnetic field configuration of 70% of the design value and a microwave power input of 1kW. Further performance test and optimization of the ECRIS recently re-installed at an off-site test facility is in progress.

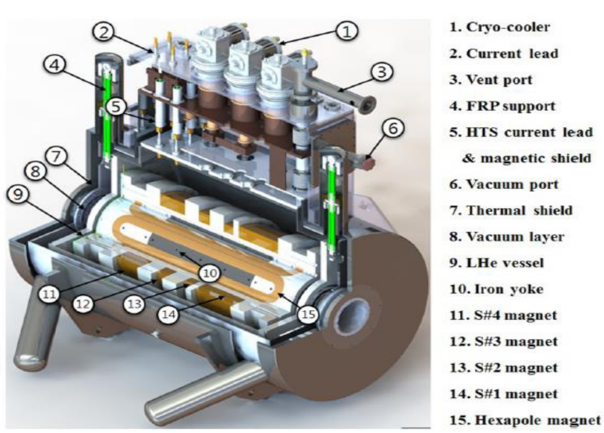

Figure 5: Schematic view of the 28-GHz superconducting ECRIS. Only SC magnets and the cryostat is shown. The cylindrical plasma chamber, not shown here, is made of aluminium, 147 mm in diameter and 500 mm in mirror length (V_{plasma}~85L) [2].

RFQ Linac The RFQ linac will accelerate the heavy ion beams extracted from the ECRIS with energy of 10keV/u to 500 keV/u. The RFQ can accelerate two charge states of uranium beams (U^{33+} and U^{34+}, δA/q~ 0.2) simultaneously. For such simultaneous transport and acceleration, the longitudinal beam shaping by a multi-harmonic buncher and a velocity equalizer is necessary before injecting the beam into the RFQ linac [5]. For the RFQ, an octagonal four-vane-type resonator operating at 81.25 MHz was adopted. Design parameters can be found in Ref. [3]. The RFQ is segmented into 9 sections with a full length of 4.94 m and is currently under fabrication. A prototype of the RFQ, consisting of a single end-section, was fabricated and successfully tested. The test of continuous-wave RF power input was performed. After several hours of RF conditioning, the RF power was increased to about 14kW, which corresponds to the RF power needed for accelerating heavy ions of A/q~6.7 to 500 keV/u.

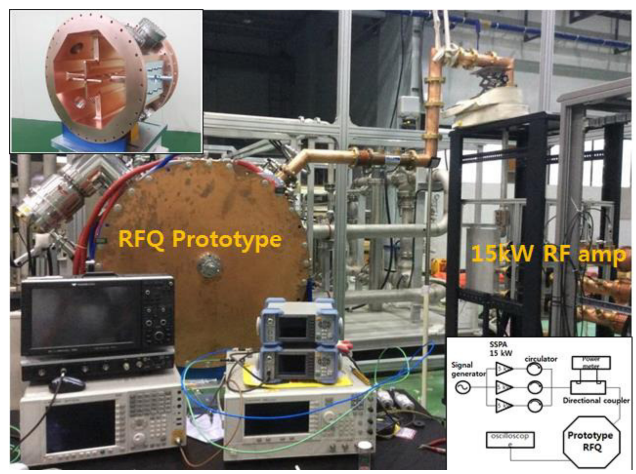

Figure 6: Photo of the prototype RFQ connected to the 15kW RF power amplifier. Insets display a segment of the RFQ fabricated as prototype (upper-left) and the block diagram of the RF power circuit starting from a signal generator (lower-right).

Superconducting Linac The superconducting linacs for RAON have been designed to accelerate high intensity ion beams with relatively large apertures of cavities (40 mm and 50 mm). The optimized geometric betas (β_g) of superconducting cavities are 0.047, 0.12, 0.30 and 0.51, and were accordingly adopted as the optimum cavity structures of quarter-wave resonator (QWR), half-wave resonator (HWR), single-spoke resonators (SSR1, SSR2). The first prototypes of all different types of bare cavities were fabricated by a domestic vendor, and their RF and mechanical properties are undergoing testing. Especially, the prototypes of QWR and HWR fabricated by a domestic vendor were tested by using the test facility at TRIUMF. The RF and mechanical properties measured in the cryogenic environments of 4K and 2K turned out to be acceptable. The Q factors of the QWR cavity measured after different post-treatments are compared in Fig. 7. The baking at 135°C for 2 hours improved significantly the value of Q-factor at higher acceleration electric fields (E_{acc}).

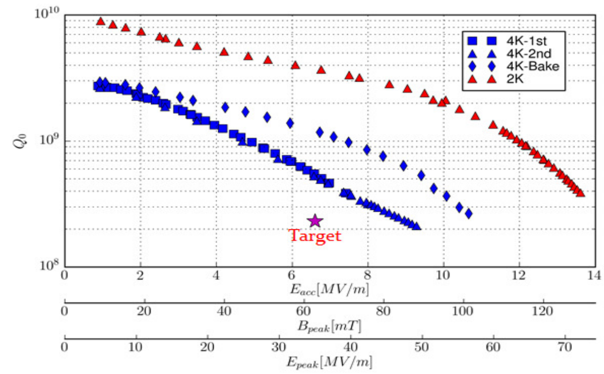

Figure 7: Measured Q factor of the QWR bare cavity measured before and after baking. After baking, the measurements were performed at 4K and 2K. The target value of Q factor at the operating condition is also given.

The X-ray emission was observed at an electric field higher than 8.5 MV/m and the emission threshold was greatly improved after BCP of 135µm. The liquid He jackets, slow tuners, RF couplers, and cryomodules for the QWR and HWR have been developed, and will be assembled together in the cryomodules and tested in the off-site test facility later this year.

Off-site test facility A superconducting RF test facility is under construction, off-site from RAON, for the integrated test of the accelerator components in cryogenic environments and the quality control of SC cavities in mass-production. The integrated tests include vertical tests of SC cavities and horizontal tests of cryomodules where all sub-components such as cavities, tuners, and RF couplers are assembled altogether. For the quality improvement of SC cavities, various equipment is necessary for the surface treatments of cavities, which will be installed in the test facility as shown Fig. 8. At the corner of the facility, (upper-right corner E in Fig. 8), a demonstration system is being installed. Figure 9 shows schematically the layout of the demonstration system.

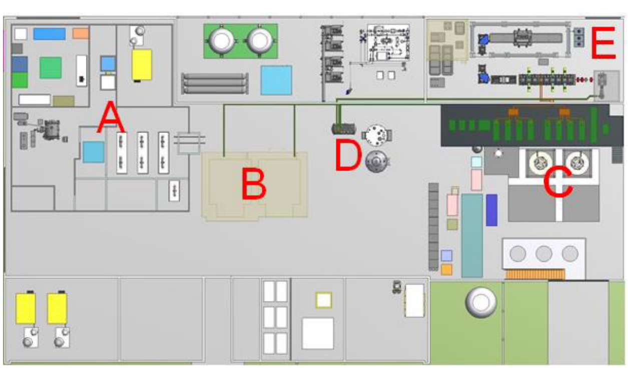

Figure 8: Layout of the SRF test facility. The area indicted by A, B, C and D are the main utilities of the facility: (A) Clean room for surface processing SC cavities; (B) Horizontal test area for cryomodules; (C) Vertical test area for cavities; (D) Cold box, liquid reservoir, distribution box (main components of 330W He cryoplant); (E) Area for installing the demonstration system.

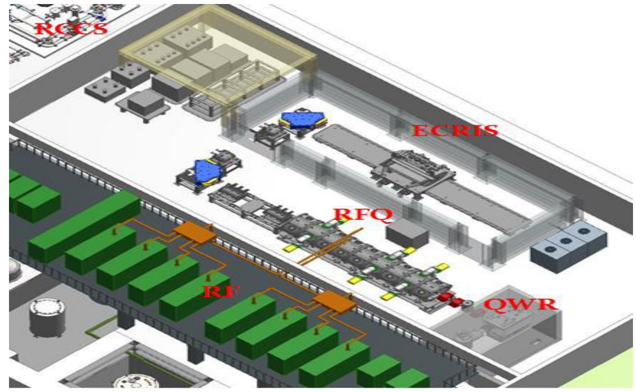

Figure 9: Layout of the demonstration system. The main components of the system was named; ECRIS, RFQ, and a single cavity cryomodule of QWR. The resonance control cooling system (RCCS) for the RFQ is shown partly in the upper-left side of the area.

CONCLUSION

The RISP, launched for the construction of the RAON heavy ion accelerator complex, has reached the half way stage of the project period. Various R&D issues have been addressed from scratch through our persistent efforts. More collective efforts for the successful completion of the construction, as well as continuous encouraging support from related academic communities, are highly required.

ACKNOWLEDGEMENT

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