

REVIEW ARTICLE

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Status of the RAON project in Korea



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Abstract

A new rare-isotope beam (RIB) accelerator complex, RAON, is under construction in South Korea. RAON employs two RIB production methods, namely, isotope separation online (ISOL) and in-flight fragmentation (IF). According to the original design, ISOL and IF can run independently, and RAON ultimately combines them to provide more neutron-rich ion beams for the experiments. In 2021, due to the delay in developing high-energy superconducting cavities and modules, it was decided to proceed with the RAON construction project in two steps. In the first phase, the injector system, the low-energy accelerator system, ISOL, the IF separator, and all experimental devices will be completed by the end of 2022. The high-energy accelerator system will be developed, manufactured, installed, and commissioned in the second phase. In this article, the status of the superconducting accelerators, RIB production systems, and experimental equipment for RAON is reviewed.

Keywords: RAON, Superconducting linac, ISOL, In-flight fragmentation, Rare-isotope beams, Nuclear structure, Nuclear astrophysics, Equation of state

1 Overview

The primary goal of nuclear physics is to understand the origin of elements, the detailed structure and shape of exotic nuclei, and the strong interaction in dense nuclear matter. The answers to these questions are closely related to the evolution of the Universe and the states of various astrophysical objects such as neutron stars, supernovae, and gravitational waves. A heavy-ion accelerator is an essential tool for investigating these subjects, and in particular, the RIB accelerator can provide crucial data to solve many fundamental problems. However, technical challenges have been prevalent in developing RIB accelerators and experimental devices, as nuclear physicists require rarer isotope beams with unprecedented intensities to test novel ideas.

The Institute of Basic Science (IBS) in Korea decided to contribute to such a worldwide endeavor by launching the Rare Isotope Science Project (RISP) in 2011. RISP aims not only to provide an additional RIB facility to the worldwide nuclear physics community but also

to push forward the technological advancement of RIB production and acceleration. The task of RISP is to construct a novel RIB accelerator complex, called RAON, in Korea [1–3]. RAON is the acronym for Rare isotope Accelerator complex for ON-line experiments; nonetheless, it also means “joyful” in the Korean language. RAON comprises a high-energy and high-power (200 MeV/ u and 400 kW, respectively) RIB accelerator, and it is one of the most advanced accelerator systems of its type. RAON is expected to provide high-quality RIBs via both ISOL and IF production methods for nuclear physics and applications. ISOL uses direct-fission processes initiated by intense proton beams, and IF uses projectile fragments of heavy nuclear beams.

Figure 1 shows the layout of the original design for the RAON facility. The color of the boxes in Fig. 1 distinguishes the nature of the components: the items in green and brown boxes are the accelerator systems and the RIB production systems, respectively. The components in the purple boxes represent the seven experimental systems.

In the original design of RAON, an independent operation of the ISOL and IF systems were possible; however, due to budget shortage, one of the low-energy superconducting linac systems, SCL1, and the two connected ECR ion sources were canceled. With this modification,

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Fig. 1 Layout of the overall RAON facility. The items written in green and brown are the accelerator systems and RIB production systems, respectively. The items in purple are the experimental setups. One of the low-energy superconducting linac SCL1 and the associated ECRs were canceled because of the budget shortage, and the SCL3 and another set of ECRs play their role instead. The small panel in the upper-right corner shows the recent bird's-eye-view image of the RAON area

another low-energy superconducting linac SCL3 and the associated set of ECRs assumed the role of the canceled SCL1 and ECRs. Consequently, the implementation of the important feature for the simultaneous operation of ISOL and IF is a future task. A recent bird's-eye-view

image of the RAON area is shown on the small panel in the upper-right corner of Fig. 1.

Figure 2 shows the schematic of the acceleration scheme, the RIB production systems, and the beam extraction positions for the seven experimental

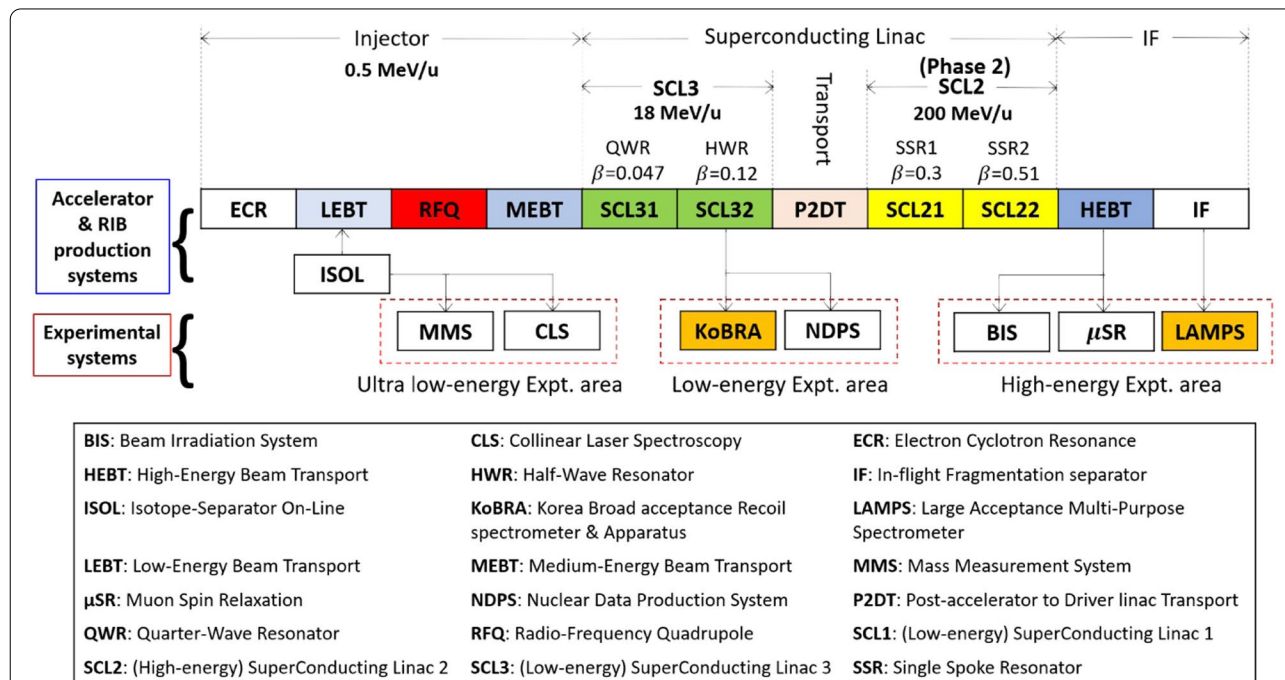


Fig. 2 Schematic of RAON for the accelerator components, RIB production system, and beam extraction positions for seven experimental setups. The bottom table shows the full names of acronyms used in this article

systems. In the absence of SCL1, the stable ion beams from the ECR ion sources or RIBs from the ISOL system are transported and accelerated by the injector system and the SCL3. Possible RIB generation and acceleration methods can be summarized as follows:

- KoBRA: Stable ion beams from the SCL3 bombard the production target of KoBRA. Direct or multi-nucleon transfer reactions mostly produce light radioactive ions up to a few tens of MeV per nucleon. Because this method uses stable ion beams, it will be attempted in the early phase of RAON operation.
- ISOL: RIBs are produced by impinging high-intensity proton beams from a cyclotron on the target ion source (TIS). In this method the SCL3 plays the role of a post-accelerator, increasing the energy of RIBs to a few tens of MeV per nucleon.
- IF: This method can be applied after the SCL2 system is completed. A wide spectrum of beam species is available based on different combinations of beam production techniques and accelerator systems. For example, one possibility is to use the stable ion beams from the ECR ion source that are accelerated by SCL3 and, consecutively, the SCL2 and bombard the IF target. The projectile fragmentation provides various RIBs to the experiments at the highest energies, for example, up to approximately 250 MeV/*u* for the ^{132}Sn beam. Ultimately, RAON bombards RIBs from the ISOL system on the IF target to generate more neutron-rich ion beams. The simulations have shown that the combination of ISOL and IF can produce new RIB species close to the neutron dripline or increase the yields of certain isotopes by several orders [4].

In 2021, the Korean government and IBS decided to proceed with RISP in two phases because of the delay in developing the high-energy superconducting linac system SCL2. As indicated in Fig. 2, the SCL2 employs the Single-Spoke-Resonator-type (SSR) cavities for the first time in ion-beam acceleration. Because it requires more time than that anticipated to develop cavities and cryomodules, the R&D, construction, and commissioning of SCL2 belong to the second phase. Therefore, the first phase to be completed by the end of 2022 includes the installation and beam commissioning of the injector system, SCL3, and the ISOL system with a cyclotron. The first phase also includes the installation and commissioning of all experimental devices as well as the IF separator.

2 Status of the accelerator system

2.1 Injector system

A schematic of the injector system for RAON is displayed in the top panel of Fig. 3. It consists of two ECR ion sources, LEBT, RFQ, and MEBT before SCL3. The two ECR ion sources are the 14.5-GHz source made of a permanent magnet and the 28-GHz source made of a superconducting magnet. The beams from the LEBT are accelerated by the RFQ from 10 keV/*u* to 500 keV/*u* at the frequency of 81.25 MHz, matching the characteristics of the QWR of the SCL3.

The commissioning of the injector system started in October 2020 by using $^{40}\text{Ar}^{8+}$ and $^{40}\text{Ar}^{9+}$ beams from the 14.5-GHz ECR ion source. The pulse length of the beam was 100 μs and the repetition rate was 1 Hz. The peak currents of the commissioning beams were 47 and 30 $e\mu\text{A}$ at the LEBT for $^{40}\text{Ar}^{8+}$ and $^{40}\text{Ar}^{9+}$, respectively. From the beam currents measured by the monitoring detectors at LEBT and MEBT, the transmission rate of the RFQ was estimated to be larger than 92%, agreeing with the simulation results. The beam energy was measured by the time-of-flight information by the two beam-position monitors (BPMs) in the MEBT. Currently, the 28-GHz superconducting ECR ion source is under a high-voltage test.

2.2 Superconducting linac

Figure 4 shows the detailed compositions of the superconducting linac systems. The SCL3 system consists of 22 QWR and 32 HWR modules. The HWR modules have two different types: 13 type A modules with two cavities in each module and 19 type B modules with four cavities in each module. Furthermore, the SCL2 system that is under development consists of 23 SSR1 modules and the same number of SSR2 modules. The SSR1 and SSR2 modules are designed to have three and six cavities, respectively, in each module. Presently, the performance test of the prototype SSR1 and SSR2 cavities and modules is in progress.

RISP has set up the superconducting radio frequency (SRF) test facility for testing the performance of the superconducting cavities and cryomodules. The onsite SRF test facility is presently equipped with three vertical test pits (each pit for testing three cavities simultaneously) and three horizontal test bunkers. Two additional vertical test pits with two cavities per pit will be available in the future.

The QWR and HWR cavities and modules for SCL3 were tested and assembled with the warm sections in a clean booth in the tunnel. In Fig. 5, the left panel shows the assembly of the SCL3 cryomodules and

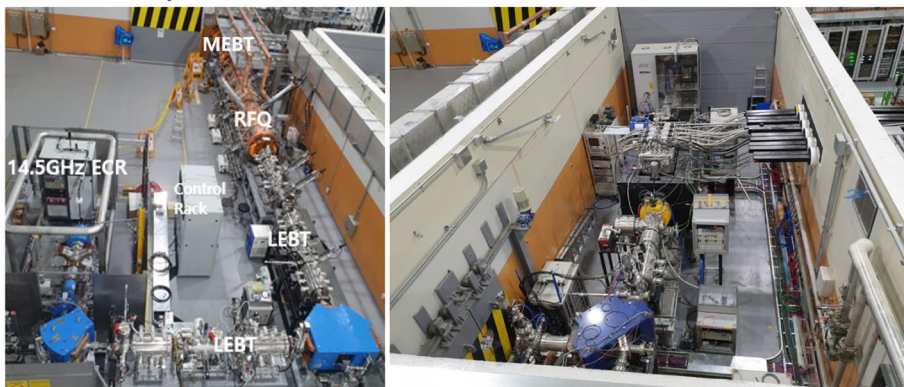
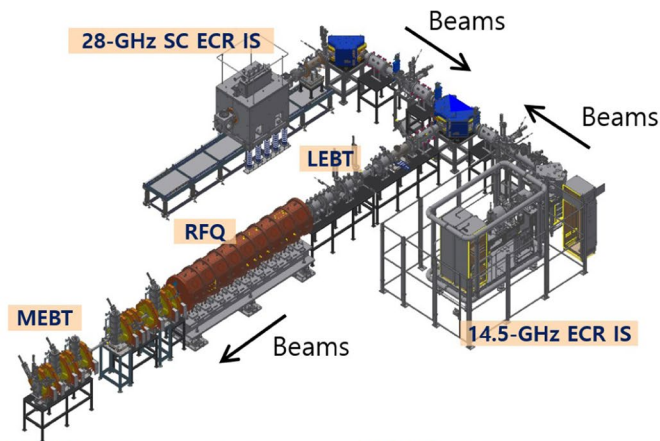
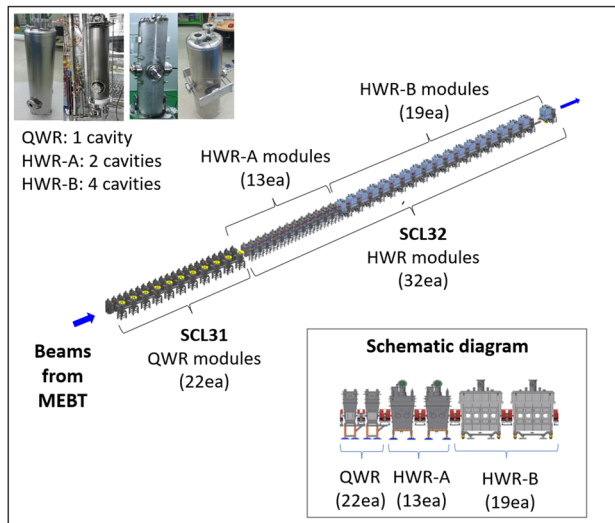


Fig. 3 Schematic (top) and images (bottom) of the injector system. The bottom-right panel shows the 28-GHz superconducting ECR ion source

SCL3 (Phase 1)



SCL2 (Phase 2)

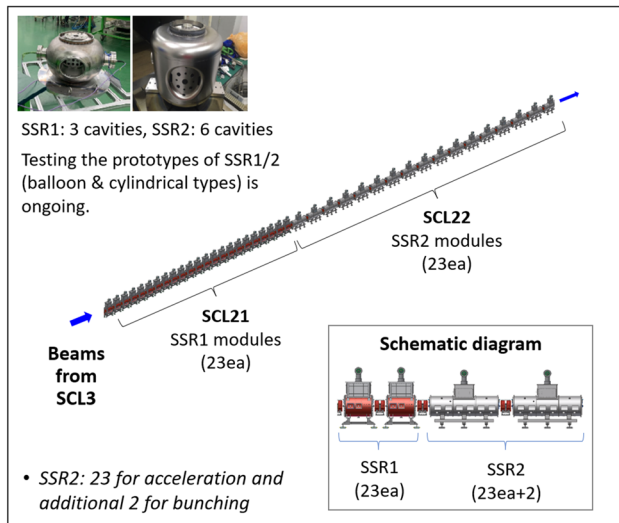


Fig. 4 Overview of the superconducting linac systems. The left panel shows the SCL3 system that is completed in Phase 1, and the right panel shows the SCL2 system that is under development as Phase 2

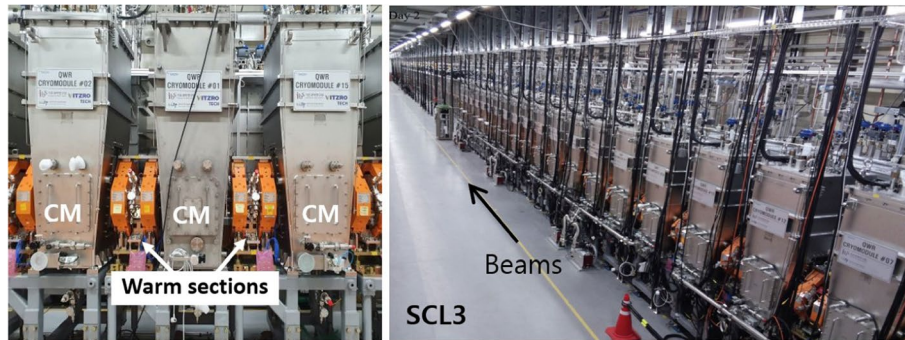


Fig. 5 Assembly of the cryomodules (CM) and warm sections (left) and the completed low-energy superconducting linac SCL3 (right)



Fig. 6 Images of the cryoplant system. From left to right, a cold box, warm compressors, and the liquid-He distribution system along with a cold box are shown

warm sections, and the right panel displays the SCL3 system completely installed in 2021.

The operation of the superconducting linac requires the cryoplant system. The two cryoplant systems and the cryogenic distribution system for liquid helium (LHe) were installed. Figure 6 shows a cold box, warm compressors, and the liquid-He distribution system for the cryoplant system. The SCL3 cryoplant has a cooling capacity of 4.2 kW as the equivalent heat load at 4.5 K. The larger SCL2 cryoplant for SCL2 and the IF separator has a cooling capacity of 13.5 kW as the equivalent heat load at 4.5 K. The installation of the cryoplants was completed in 2021. The Site Acceptance Test (SAT) for the SCL3 cryoplant was completed at the end of July 2022. Cooling down of the SCL3 cryoplant and conditioning of RF started at the beginning of September 2022. The first beam extraction of the $^{40}\text{Ar}^{9+}$ beam through the first six QWR cavities was successfully performed in October 2022. Beam commissioning for the entire SCL3 with the $^{40}\text{Ar}^{9+}$ beam is in progress.

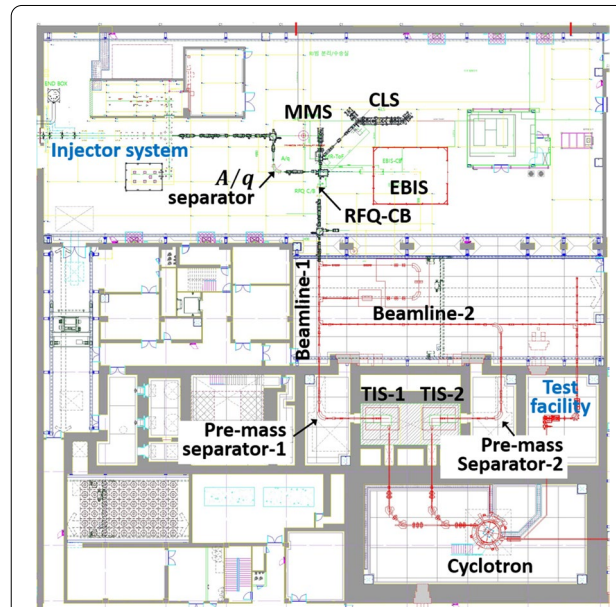


Fig. 7 Schematic of the ISOL system

3 RIB production system

3.1 ISOL

Figure 7 shows the schematic of the ISOL system and beamlines for RAON. The ISOL system consists of the driver cyclotron, TIS, pre-mass separator, RFQ cooler buncher (RFQ-CB), electron beam ion source (EBIS), and A/q separator. The installation of the cyclotron was performed in April 2022, and SAT is expected shortly. The cyclotron accelerates the protons up to 70 MeV with a maximum beam current of 0.75 mA. As an ISOL target, SiC, BN, MgO, LaC₂, and UC_x have been prepared for producing various RIB species. At the beginning stage of the ISOL operation, SiC will be used. The UC_x target will be used in 2025 or later.

In addition, the surface ion source, resonant ionization laser ion source (RILIS), and plasma ion sources are available for TIS. To avoid any radiation hazard a full remote handling system is installed for changing the targets in the TIS module. The ISOL system will provide RIBs with $6 \leq A \leq 250$ and $10 \leq K \leq 80$ keV. The purity of the beam species is expected to be higher than 90% for experiments.

While waiting for the cyclotron to supply proton beams for ISOL, the Cs ion source in TIS was used to test the ISOL system and beamlines. For this exercise the Cs source was placed in a hot-cavity Ta heater, as shown in the left panel of Fig. 8. The $^{133}\text{Cs}^+$ ion beams with a current of 4.0 nA were extracted and transported down to the A/q separator. From the measurement of the horizontal beam size in the pre-mass separator, the mass resolving power was determined to be approximately 1000 in 2σ . At RFQ-CB, the Cs ions were bunched into 1.66×10^8 /s, and subsequently, EBIS measured 5.0×10^7 $^{133}\text{Cs}^{27+}$ ions with a breeding efficiency of approximately 44%. The measured A/q spectrum of the Cs beam is shown on the right panel of Fig. 8, demonstrating an excellent

charge separation capability of the current ISOL beamlines. Accordingly, the mass resolving power of the A/q separator was determined to be approximately 250 in 2σ . However, the mass resolving power can be improved significantly to ~ 400 with more careful tuning of the system. In April 2022, Sn ions were also extracted by using RILIS and the natural abundances of the Sn isotopes were successfully reproduced. Figure 9 shows the mass spectrum of the pre-mass separator for the Sn isotopes extracted by RILIS at TIS and the measured A/q spectrum.

3.2 IF

The RAON IF separator consists of two parts: (1) the pre-separator (PS), following the beam delivery system (BDS), for the production and separation of RIBs of interest and (2) the main separator (MS) for identification and supply of the selected isotope for experimentations, as shown in the top panel in Fig. 10. IF was designed with a maximum rigidity of 9.6 Tm, the angular acceptance of ± 40 mrad, and the momentum acceptance of $\pm 3\%$ for the fragments and in-flight fission products, considering the future upgrade of 400 MeV/ u for uranium beams in SCL2.

PS consists of a high-power target, beam dump, and high-temperature superconducting quadrupole and hexapole magnets in large vacuum chambers for radiation protection and maintenance. The high-power target and beam dump that could handle up to 80 kW were manufactured using graphite. The offline test of the target and beam dump was completed, and the heat loading test using induction heating is being prepared. The production of the magnets for IF was completed, and the performance test of the low-temperature superconducting (LTS) quadrupole-magnet triplets is underway. The particle identification system, consisting of parallel plate avalanche counters (PPACs),

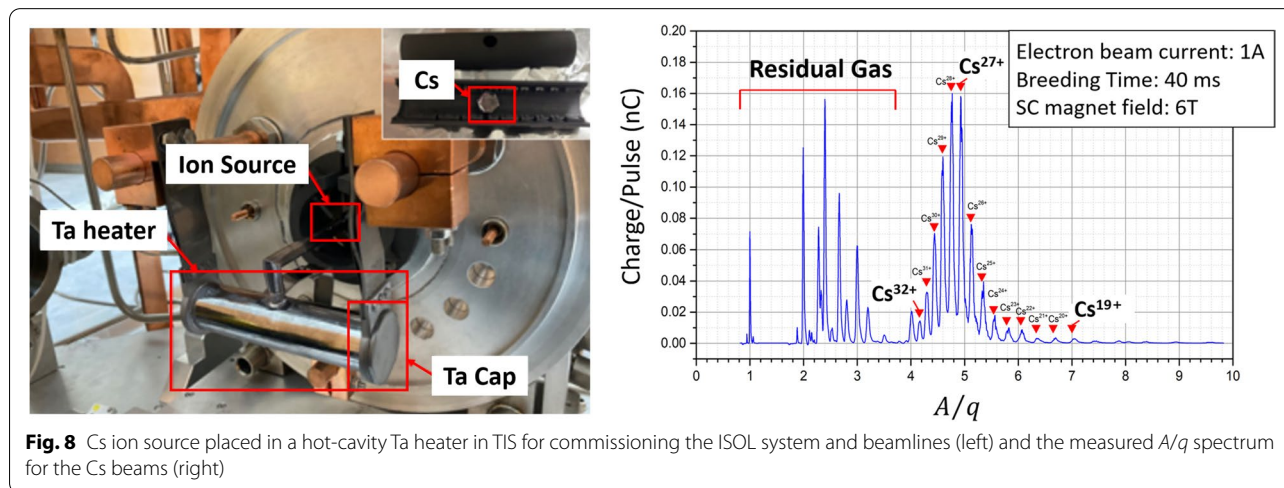
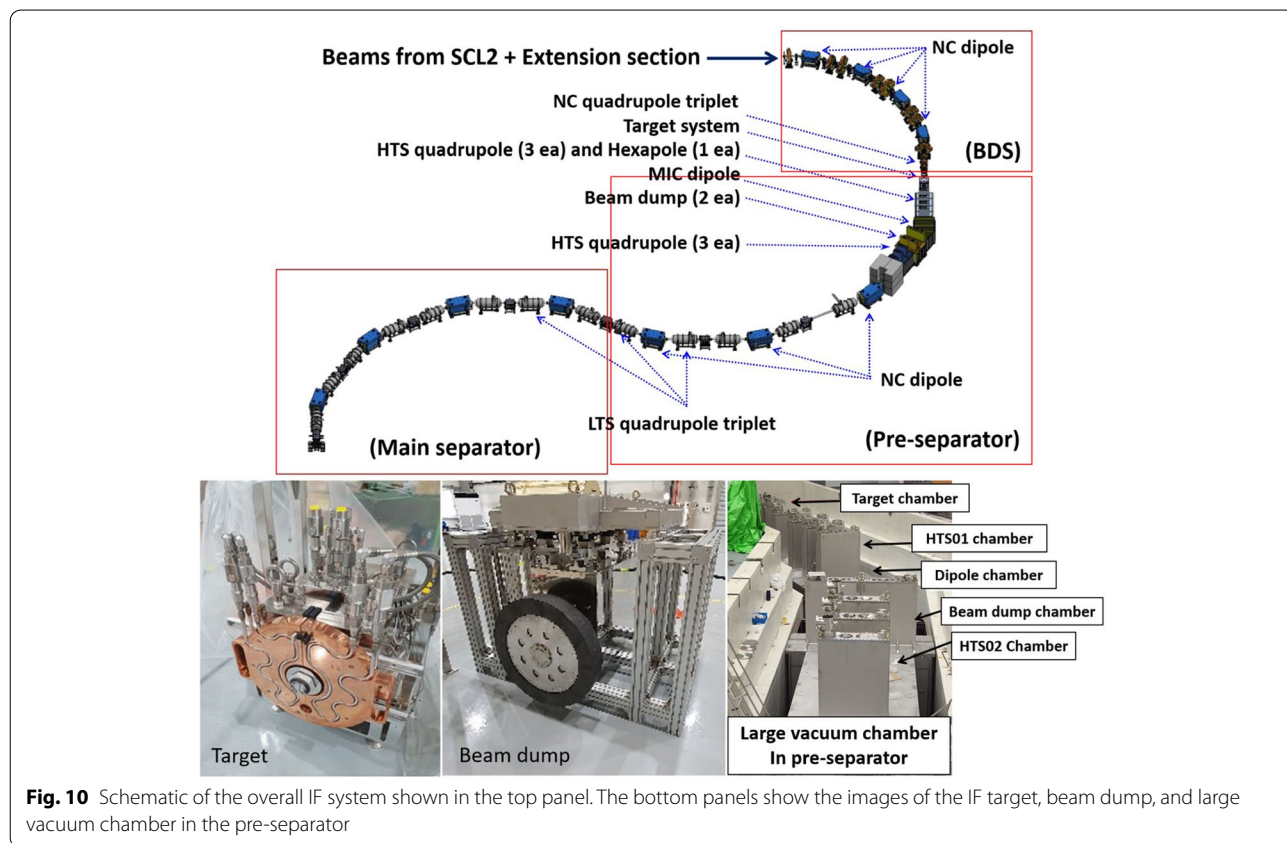
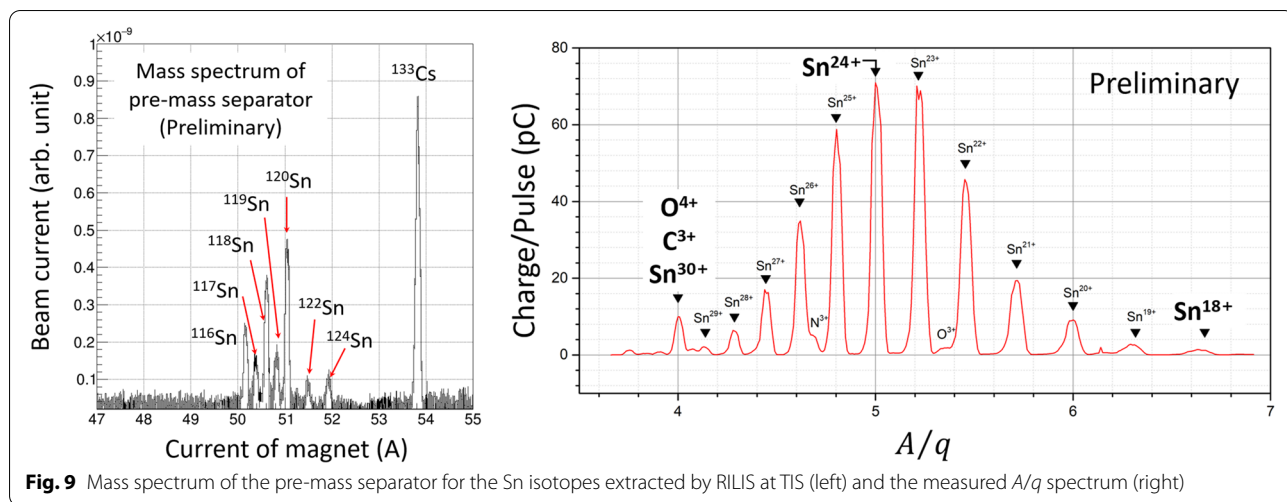


Fig. 8 Cs ion source placed in a hot-cavity Ta heater in TIS for commissioning the ISOL system and beamlines (left) and the measured A/q spectrum for the Cs beams (right)



plastic scintillators, and silicon detectors, is being prepared. The images of the IF target system, beam dump, and large vacuum chamber in PS are displayed in the bottom panels of Fig. 10. The installation of all magnets and subsystems for IF is expected to be completed by the end of 2022.

4 Experimental systems

4.1 KoBRA

KoBRA is a dedicated spectrometer for studying nuclear structure and astrophysics at low energies below ~ 40 MeV/ u [5, 6]. Figure 11 shows the low-energy experimental halls. Presently, the two rooms are used for setting

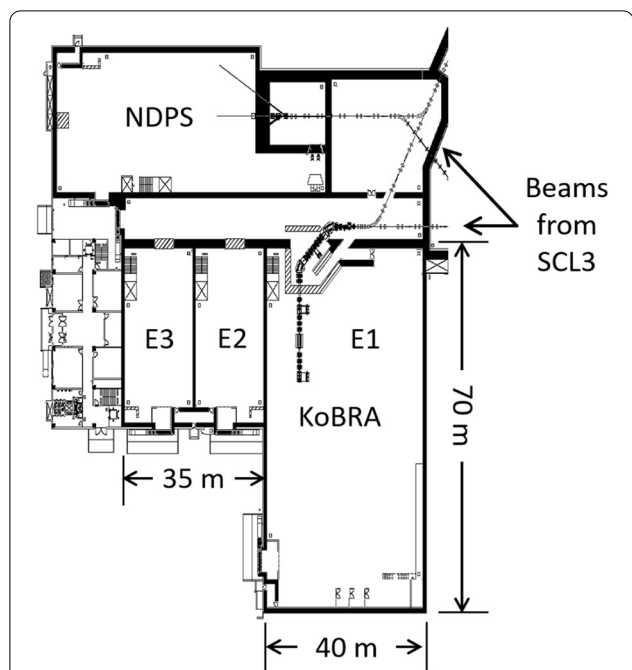


Fig. 11 Layout of the low-energy experimental halls at RAON. Presently, the two rooms are used for KoBRA and NDPS, respectively, and the other two rooms are reserved for future experiments

up the KoBRA and NDPS systems, respectively, and the other two rooms (E2 and E3) are reserved for future experiments. The schematic of the KoBRA setup is displayed in the left panel of Fig. 12. The right side of Fig. 12 shows two recent images for the production-target-chamber (F0) area on top and the dispersive focus (F1) area at the bottom. KoBRA consists of a swinger magnet right before the production target chamber, the two curved-edge bending magnets (D1 and D2) to minimize

the high-order aberrations up to the fourth order with two hexapole magnets, and fifteen quadrupole magnets. The swinger magnet bends the beam direction up to 12° for the rigidity of 3 Tm. The horizontal and vertical angular acceptances are 80 and 200 mrad, respectively, and the momentum acceptance is 8%.

The magnetic rigidity of RIBs can be analyzed at F1. The momentum and maximum mass resolving powers are 2100 and 750, respectively, for the horizontal beam size of 2 mm. Either homogeneous or curved degrader can be inserted at F1 to increase the beam purification. There are two double achromatic foci (F2 and F3) located downstream of F1. The installation of the KoBRA components was completed in June 2021 except for the Wien filter, which will be installed between F2 and F3 in 2023 to cause a mass dispersion at F3.

The beam transportation test was performed by installing the ²⁴¹Am α source at F0. The magnetic rigidities of α particles emitted from the source were analyzed by using the position information at F1 for each particle. The position at F1 was measured by the large area PPAC. The relative abundances of α's at three different energies (5.388, 5.442, and 5.486 MeV) and the transversal distributions at F1, F2, and F3 were consistent with the Monte–Carlo simulations, confirming the momentum resolving power at F1.

The startup plan for KoBRA is to experiment with the first commissioning ⁴⁰Ar beams at 25 MeV/u in 2023. RIBs, e.g., ³²Mg, will be produced by bombarding the ⁴⁰Ar beams on a graphite production target at F0, and the subsequent part of the magnetic spectrometer will select the desired RIBs for the experiments. However, the true strength of KoBRA can be recognized when ISOL provides exotic nuclei with high purity. For the experiments at KoBRA, several detector systems, such as the

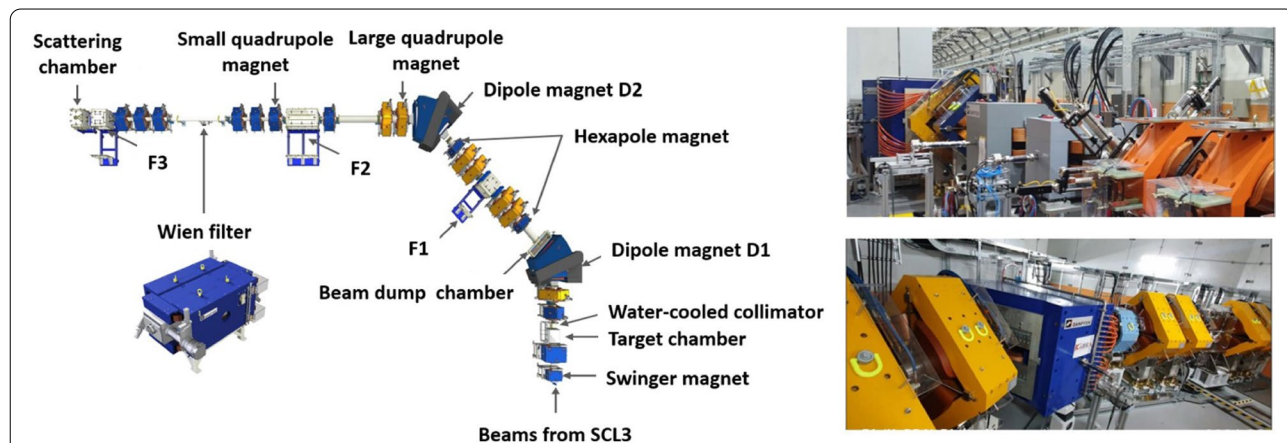
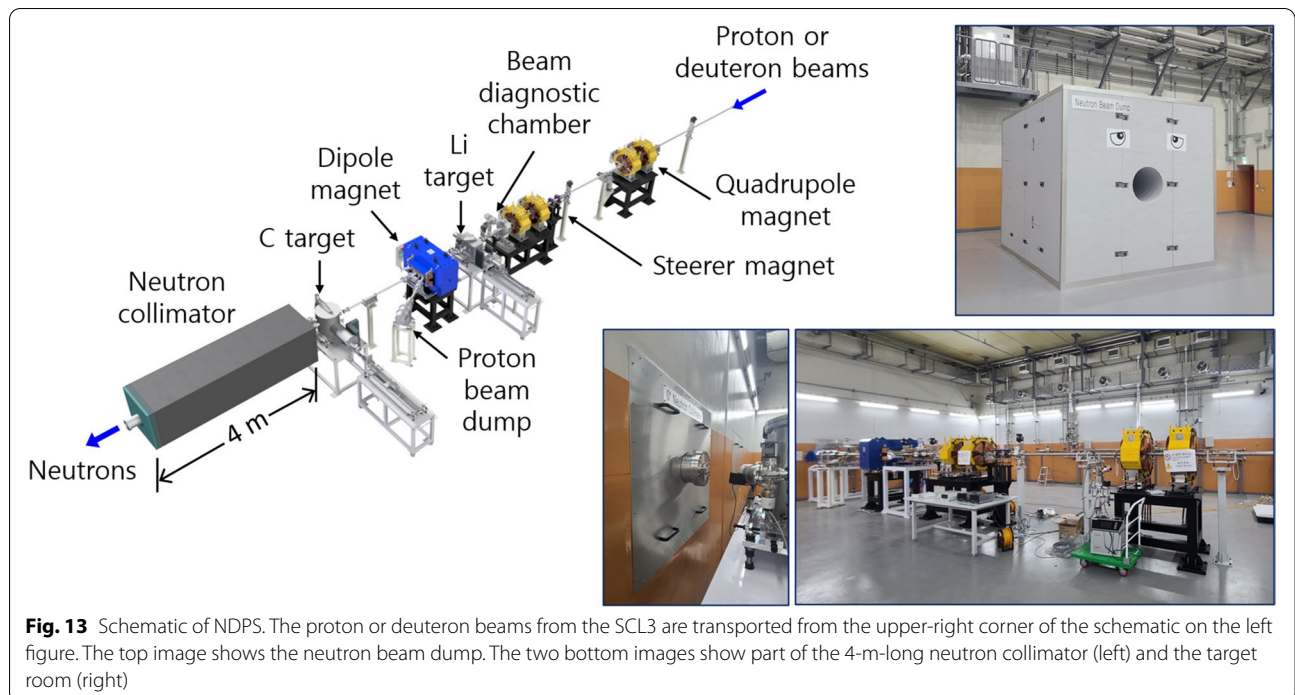


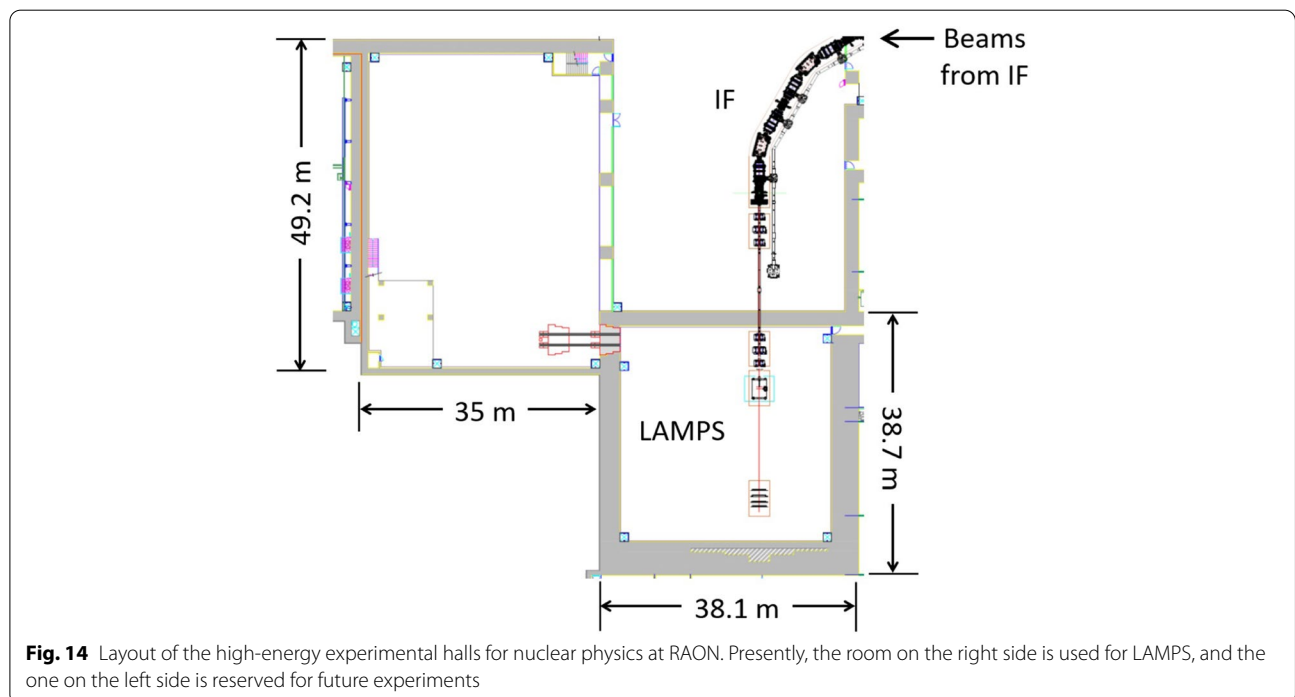
Fig. 12 Schematic of KoBRA on the left. The two images on the right show the production-target-chamber (F0) area (top) and the dispersive-focus (F1) area (bottom)



high-resolution γ detector system, Si detectors, and active-target time-projection chamber (AT-TPC), are being prepared.

In the early operational stage of RAON, these detectors will be used for several nuclear astrophysics and structure experiments, for example, the proton-induced fusion

evaporation of neutron-deficient nuclei, fusion reactions related to stellar evolution, a lifetime of isotopes near doubly magic $N = Z$ nuclei, fusion-evaporation reactions of three neutrons for mirror energy differences (MEDs) for $T = 3/2$ mirror pair nuclei, optical model potential studies using stable beams, spectroscopy of proton,



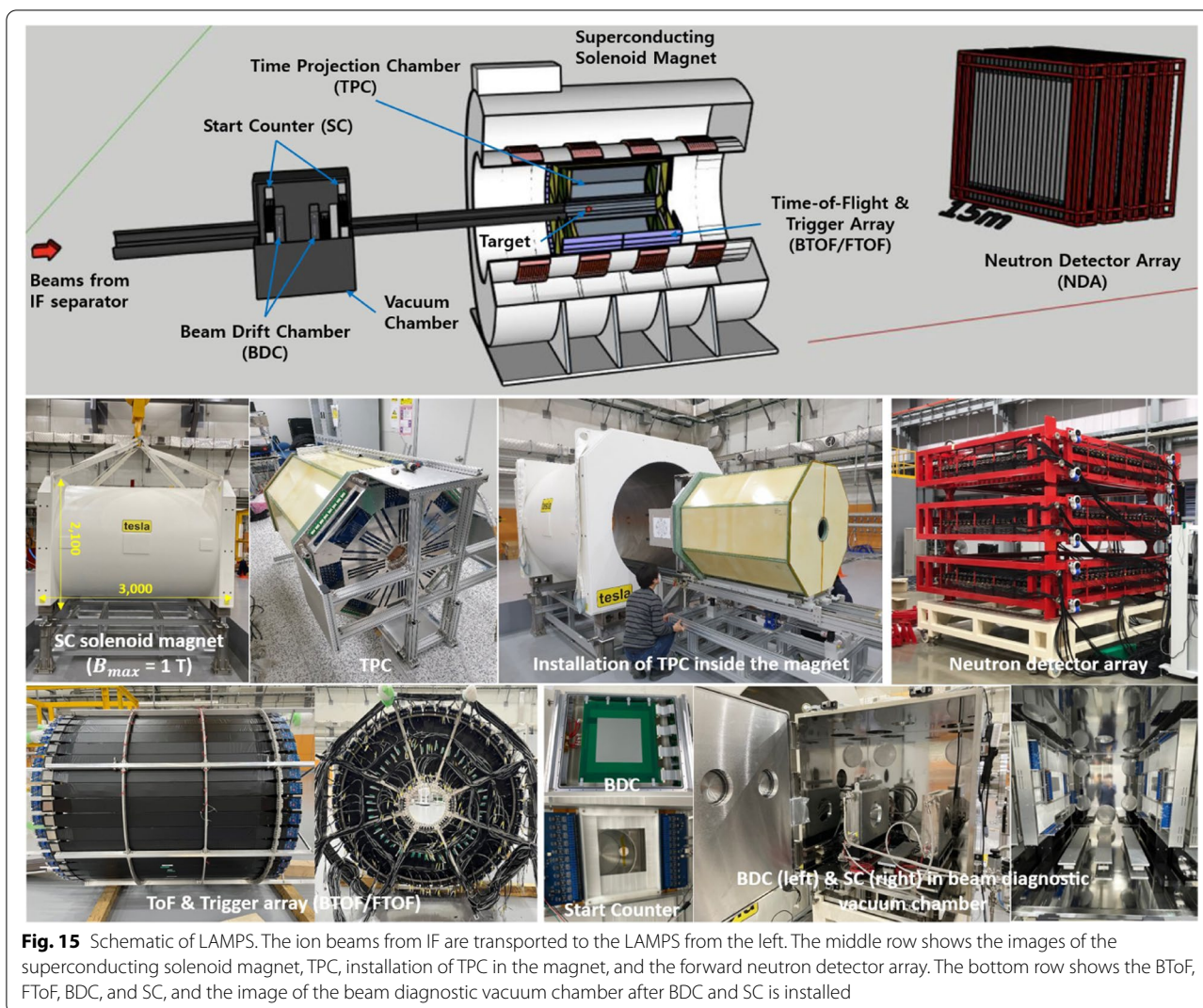


Fig. 15 Schematic of LAMPS. The ion beams from IF are transported to the LAMPS from the left. The middle row shows the images of the superconducting solenoid magnet, TPC, installation of TPC in the magnet, and the forward neutron detector array. The bottom row shows the BTOF, FTof, BDC, and SC, and the image of the beam diagnostic vacuum chamber after BDC and SC is installed

neutron and α emitters, measurement of RI production cross-section, and decay spectroscopy using fast-timing measurement.

4.2 NDPS

NDPS is a dedicated system for nuclear data production and other industrial applications. NDPS provides both white neutrons and monoenergetic pulsed neutrons. For white neutrons, the deuteron beams at 49 MeV/u bombard a thick graphite target. For monoenergetic neutrons, the proton beams at 83 MeV bombard a thin Li target. The NDPS system consists of two production target chambers, four quadrupoles and one dipole magnet, a proton beam dump for monoenergetic neutrons, and a 4-m-long neutron collimator. Figure 13 shows the schematic of the NDPS system with two images of the target room and neutron collimator. The neutron beam dump, which is only a concrete block with a thickness of ~ 1 m,

is placed approximately 35 m downstream from the exit of the neutron collimator.

4.3 LAMPS

Figure 14 shows the high-energy experimental halls at RAON. One of the rooms is used for LAMPS, which is presently the only detector system for nuclear physics in high-energy experimental halls, and another room is reserved for future experiments, such as the zero-degree spectrometer (ZDS). LAMPS was originally designed to investigate the nuclear equation of state (EoS) and the symmetry energy at the supra-saturation baryon densities; nonetheless, it can also be useful for studying the nuclear structure. LAMPS accepts high-intensity and high-energy RIBs, for example, ^{132}Sn beams at 250 MeV/u with intensity as large as 10^8 pps.

The top panel of Fig. 15 shows the schematic of the LAMPS system [7, 8]. It consists of a beam diagnostic

chamber and an almost azimuthally symmetric charged particle tracking system surrounded by a superconducting solenoid with a maximum field strength of 1 T. In addition, the neutron detector array is located in the forward region. In the beam diagnostic vacuum chamber, the starting counter (SC) coupled with movable veto paddles and beam drift chambers (BDC) are placed. For the charged particle tracking system, the time-projection chamber (TPC) consisting of eight octant sectors and the barrel and forward Time-of-Flight arrays (BToF and FToF, respectively) are used. Most of the detector components and a magnet are developed, fabricated, and assembled. The machine commissioning of the integrated LAMPS system including the LAMPS trigger and data acquisition system is foreseen by the end of 2022.

Although the development and construction of SCL2 have been postponed to the second phase, the LAMPS Collaboration is planning the physics program, for example, the isospin transport phenomenon and nuclear symmetry energy, the skin structure of the neutron-rich nuclei, and the measurement of the quasi-free scattering cross sections with the neutron-rich beams.

5 Summary

Since the construction project of RAON was launched in 2011, there have been many achievements, including the completion of the SCL3 superconducting linac, installation, and operation of the SCL3 and SCL2 cryoplants, installation of the ISOL system with successful transportation of the Cs beams, and machine commissioning of the KoBRA system in the low-energy experimental hall. RAON is preparing the SiC target for the ISOL system to extract certain rare isotope beams by the end of 2022. Thereafter, it will be able to deliver ^{26}Al beams to MMS and CLS in 2023. These beams will be useful for the investigation of isomer separation using the ground and isomer states of ^{26}Al in MMS and also the isomeric properties through the isotopic shifts of ^{26m}Al in CLS. RAON also plans to use the non-fissile ISOL targets, such as BN, MgO, and LaC_2 in addition to SiC in 2024 for more RIB species for the experiments. The UC_x target will be commissioned in 2025.

As per the plan, the R&D of the high-energy superconducting linac SCL2 will be completed to be finished by ~ 2025 , and the construction of SCL2 needs to be followed at the earliest. After the completion of SCL2, RAON will aim at the stable operation of uranium beams at 200 MeV/ u up to 80 kW, gradually increasing the beam power to the design goal of 400 kW. Finally, RAON plans to combine the ISOL and IF systems to provide more neutron-rich radioactive ion beams for experiments.

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Authors' contributions

The author wrote the manuscript. The author read and approved the final manuscript.

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Availability of data and materials

All data and figures presented in this article are based on the materials available in public through the corresponding references with the permissions by RISP.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The author declares that he has no competing interests.

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References

1. J.K. Ahn et al., Overview of the KoRIA facility for rare isotope beams. *Few Body Syst.* **54**, 197–204 (2013)
2. S.C. Jeong, P. Papakonstantinou, H. Ishiyama, Y. Kim, A brief overview of RAON physics. *J. Korean Phys. Soc.* **73**, 516–523 (2018)
3. B. Hong, Prospects of nuclear physics research using rare isotope beams at RAON in Korea. *Nucl. Sci. Tech.* **26**, S20505 (2015)
4. J.W. Shin, K.J. Min, C. Ham, T.-S. Park, S.-W. Hong, Yield estimation of neutron-rich rare isotopes induced by 200 MeV/ u ^{132}Sn beams by using GEANT4. *Nucl. Instrum. Methods B.* **349**, 221–229 (2015)
5. K. Tshoo, Y.K. Kim, Y.K. Kwon, H.J. Woo, G.D. Kim, Y.J. Kim, B.H. Kang, S.J. Park, Y.-H. Park, J.W. Yoon, J.C. Kim, J.H. Lee, C.S. Seo, W. Hwang, C.C. Yun, D. Jeon, S.K. Kim, Experimental systems overview of the Rare Isotope Science Project in Korea. *Nucl. Instrum. Methods B.* **317**, 242–247 (2013)
6. J.Y. Moon, J. Park, C.C. Yun, Y.K. Kwon, T. Komatsubara, T. Hashimoto, K. Tshoo, K. Lee, I.-I. Jung, Y.H. Kim, Y.-K. Kim, Development of the RAON recoil spectrometer (KOBRA) and its applications for nuclear astrophysics. *JPS Conf. Proc.* **6**, 030121 (2015)
7. B. Hong, J.K. Ahn, Y. Go, G. Jhang, E. Joo, D.G. Kim, E.J. Kim, H.H. Kim, Y.H. Kim, Y.J. Kim, Y.-J. Kim, Y.K. Kim, H.S. Lee, J.W. Lee, K. Lee, K.S. Lee, S.H. Lee, S.K. Lee, B. Mulilo, H. Shim, C.C. Yun, Plan for nuclear symmetry energy experiments using the LAMPS system at the RIB facility RAON in Korea. *Eur. Phys. J. A.* **50**, 49 (2014)
8. H. Shim, J. Lee, B. Hong, J.K. Ahn, G. Bak, J. Jo, M. Kim, Y.J. Kim, Y.J. Kim, H. Lee, H.S. Lee, K.S. Lee, B. Mulilo, D.H. Moon, M.S. Ryu, Performance of prototype neutron detectors for Large Acceptance Multi-Purpose Spectrometer at RAON. *Nucl. Instrum. Methods A.* **927**, 280–286 (2019)

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