Journal of the Korean Physical Society (2023) 82:613–621
https://doi.org/10.1007/s40042-023-00715-y

Online ISSN 1976-8524
Print ISSN 0374-4884

ORIGINAL PAPER - PARTICLES AND NUCLEI

Commissioning preparation of RAON rare isotope accelerator facility

Yeon-Sei Chung[1] · **Seung-Woo Hong**[1] · **Hyun-Man Jang**[1] · **Tae-Kyung Ki**[1] · **Hyoung-Jin Kim**[1] · **Young Jin Kim**[1] · **Myeun Kwon**[1] · **Jinho Lee**[1] · **Kyoungho Tshoo**[1] · **Taeksu Shin**[1]

Received: 29 August 2022 / Revised: 9 November 2022 / Accepted: 11 November 2022 / Published online: 12 January 2023

Abstract

RAON (Rare isotope Accelerator complex for ON-line experiments), started by the Rare Isotope Science Project (RISP) in Dec 2011, is the flagship rare isotope accelerator facility in Korea to promote the fundamental science of rare isotopes and the application. The construction of facility buildings and installation of the low-energy superconducting linac (SCL3) including injector system, ISOL (Isotope Separation On-Line) for the rare isotope production, a recoil spectrometer KoBRA, and MR-TOF for the mass measurement system were finished in 2021. Expecting the completion of the first phase of the RAON construction project in 2022, the beam commissioning experiments of low-energy superconducting linac (SCL3) and the ISOL system are underway. The status and overview of the RAON accelerator facility are reported in this paper.

Keywords RAON · Superconducting linac · Injector · Beam commissioning · ISOL · KoBRA · MR-TOF

1 Introduction

RAON is the flagship rare isotope accelerator facility for fundamental research and applications under construction in Korea. The Rare Isotope Science Project (RISP) was launched in 2011 as a large-scale basic science research facility under the Institute for Basic Science (IBS) within International Science Business Belt (ISBB).

RAON was designed to produce a variety of stable and rare isotope beams. It consists of a heavy ion superconducting linear accelerator (linac) as the driver of IF (In-flight Fragmentation) separator system, a proton cyclotron as the driver for the ISOL system, and a superconducting post-accelerator linac, to accelerate rare isotopes from the ISOL system. The ISOL and IF systems can be operated independently. In addition, the rare isotopes produced by the ISOL system can be injected into the superconducting linac for further acceleration to higher energies to produce even more exotic rare isotopes by using the IF system. This combined scheme of the ISOL and IF may be referred to as ISOLIF.

The construction of buildings and supporting facilities were finished in 2021 as shown in Fig. 1. The low-energy superconducting linac section SCL3 including an injector, ISOL, and all experimental systems is to be completed in phase 1 in 2022. The high-energy superconducting linac SCL2 will be constructed as the next phase. The R & D for the SCL2 is launched in 2022. Developments of major instruments for superconducting linear accelerator SCL3, cryoplant systems, ISOL facilities with cyclotron, experimental facilities are mostly done. Currently, the first phase of the SCL3 beam commissioning experiment from the RAON injector system using Argon beam is under preparation. ISOL facility with a 70 MeV proton cyclotron, and low-energy experimental facilities such as KoBRA (Korea Broad acceptance Recoil Spectrometer and Apparatus) are also under preparation for beam commissioning experiments.

2 Accelerator facility

The RAON accelerator is being constructed to deliver a wide range of heavy ion beams, e.g. uranium beams of 200 MeV/u and proton beams of 600 MeV with a beam current of 8.3 pμA for uraniums and 660 pμA for protons [4]. To accelerate heavy ions with high power, superconducting RF technology is used. [5] RAON adopted four

---

Work supported by the IBS/RISP funded by the Ministry of Science and ICT and the National Research Foundation of the Republic of Korea under Contract 2013M7A1A1075764.

✉ Taeksu Shin
tsshin@ibs.re.kr

[1] Institute for Basic Science, Daejeon 34126, Korea

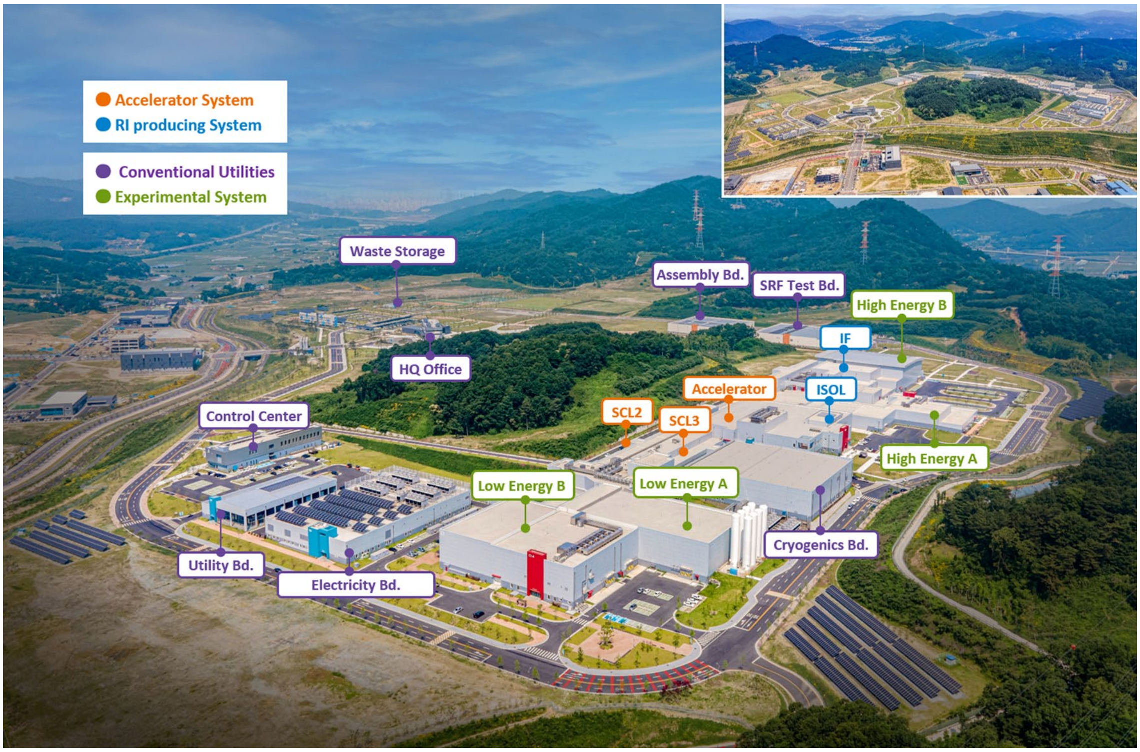


Fig. 1 A bird's eye view of RAON facility at Shindong of Daejeon

superconducting cavities which are independently phased and operated at 81.25, 162.5, and 325 MHz [6].

The injector system of RAON accelerates a heavy ion beam to 500 keV/u and creates the desired bunch structure of beams to be injected into the superconducting linac SCL3. It comprises electron cyclotron resonance ion sources (ECR-IS), a low energy beam transport (LEBT), a radio frequency quadrupole (RFQ), and a medium energy beam transport (MEBT) system. The superconducting linear accelerator is divided into two sections, the low-energy superconducting linac (SCL3) and the high-energy superconducting linac (SCL2). Two superconducting linac sections are connected by a Post-accelerator to Driver Linac (P2DT) which includes a charge stripper and a 180-degree bending system. The scheme of the accelerator systems including the ISOL connected to LEBT of the injector system is shown in Fig. 2.

The injector system for SCL3 has two ion sources: a 28 GHz superconducting ECR-IS for high-intensity stable ion beams and a 14.5 GHz permanent magnet ECR-IS for the early-stage experiments using stable light ion beams with relatively low beam intensities. The 28 GHz superconducting ECR-IS is in the process of improving its performance and the 14.5 GHz ECR-IS, manufactured by the Pantechnik of France [7], has been operational since its commissioning in October 2020. LEBT is designed to transport and match ion beams extracted from the ECR-IS to the radiofrequency quadrupoles(RFQ). Electrostatic quadrupoles were chosen for transport and focusing as these are more suitable for low-velocity beams at LEBT. About 5 m long RFQ with a

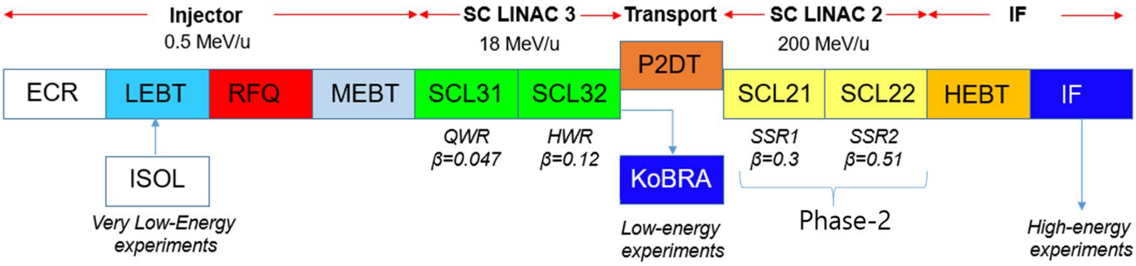


Fig. 2 The main configuration of RAON heavy ion accelerator system

4-vane structure is designed to accelerate ion beams from 10 to 500 keV/u at 81.25 MHz of the resonance frequency. MEBT is to transport and match ion beams accelerated from the RFQ to the low-energy superconducting linac, SCL3. A total of eleven room-temperature quadrupole magnets are chosen to transport and focus beams at MEBT. Four bunching cavities operating at 81.25 MHz of resonance frequency are also arranged to match the longitudinal beam size to the SCL3 [8].

The 14.5 GHz ECR-IS has been commissioned with Argon, Oxygen, and proton beams, and has provided ion beams to the injector system from 2022. The beam commissioning of the injector system has been done since October 2020. The $^{40}\mathrm{Ar}^{9+}$ beam was successfully transmitted through LEBT, accelerated by RFQ, and transported to the end of MEBT. During the beam commissioning, a peak current of 30 eμA continuous beam at LEBT was transported and an electrostatic chopper in the LEBT was used to generate a pulsed beam with a pulse length of 100 μs, and a repetition rate of 1 Hz.

The post-accelerator SCL3 uses two different families of superconducting resonators, i.e., a quarter wave resonator (QWR) and a half wave resonator (HWR). The SCL31 consists of 22 QWRs whose geometrical β is 0.047 at 81.25 MHz of the resonant frequency. Each QWR cryomodule bears one superconducting cavity. SCL32 consists of 102 HWRs with β=0.12 and 162.5 MHz. All 102 HWRs of the same cavities are installed in two different cryomodules A and B, where 13 Type-A cryomodules bear two cavities while 19 Type-B four cavities. The injector and SCL3 systems with cryoplants are shown in Fig. 3.

For testing and operating superconducting accelerator systems, Two cryoplants are built for SCL3 and SCL2 together with cryogenic distribution systems to ensure stable supplies and distribution of liquid helium (LHe) to each superconducting system. The SCL3 cryoplant has a cooling capacity of 4.2 kW as the equivalent heat load at 4.5 K. The SCL2 cryoplant is for cooling SCL2 and IF separator superconducting magnets and has a cooling capacity of 13.5 kW as the equivalent heat load at 4.5 K. For SCL3 commissioning, the mechanical installation and commissioning of SCL3 cryoplant were successfully finished in August 2022, and the cold box was connected to the main LHe distribution box.

For beam commissioning of SCL3, the helium distribution system and cryomodules are cooled down to 4.5 K. With all the cavities cooled down to 4.5 K, the RF parameters verification and RF conditioning of the couplers and cavities are performed. The first phase of the SCL3 beam commissioning experiment was completed by using $^{40}\mathrm{Ar}^{9+}$ in October 2022 by operating 5 QWRs and cryomodules to the designed RF amplitudes and phases to successfully extract accelerated beams.

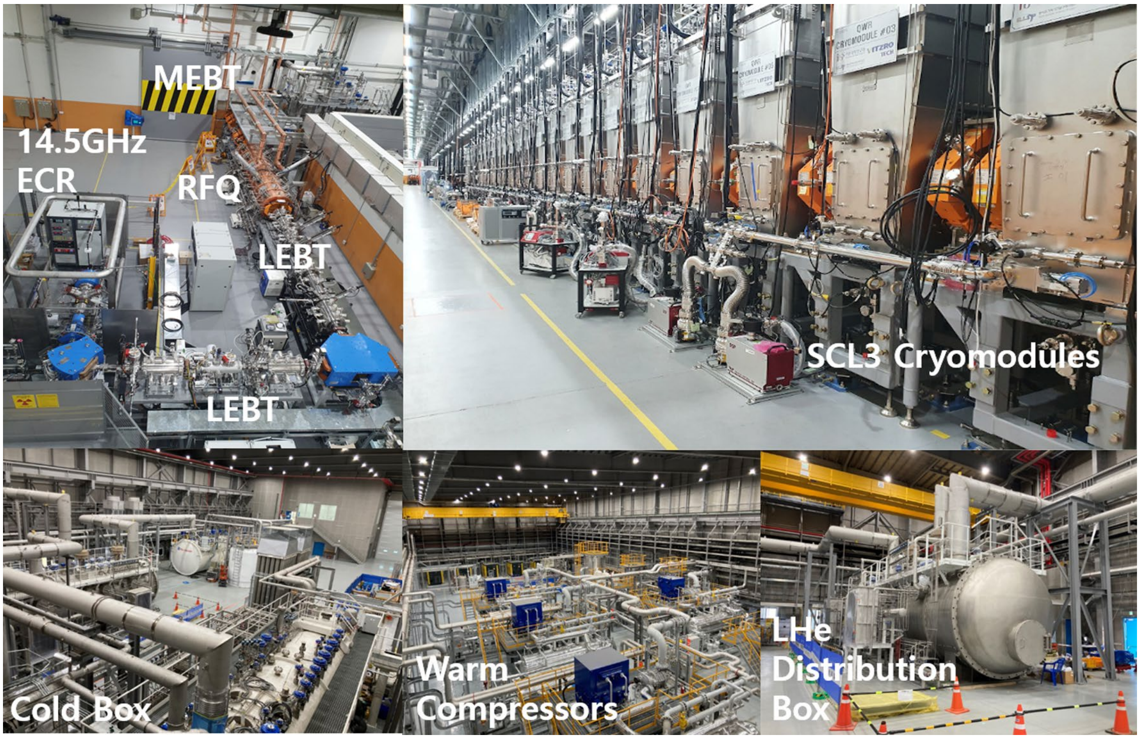


Fig. 3 Injector and SCL3 cryomodules in SCL3 tunnel and Cryoplants

3 Rare isotope production facility

The ultimate goal of RAON is to access unexplored regions of nuclear landscapes. As the first kind of rare isotope production facility in the world, RAON is designed to combine the ISOL as the first step and the IF system as the second step to produce more exotic RI beams, namely 80% of all isotopes predicted to exist for elements below uranium and to be studied at various experimental facilities of RAON [9–11].

The ISOL uses the proton-induced fission of a fissile target to produce rare isotope beams (RIBs) [12]. The ISOL system is equipped with a target ion source (TIS) module capable of a full remote handling system for target replacement with radiation protection. As the ISOL target driver, a 70 MeV proton cyclotron with a maximum current of 0.75 mA is purchased from the IBA and is ready to deliver the proton beams. The pre-mass separators with the 70 MeV proton cyclotron and beam lines to transport ion beams with the beam diagnostic chambers, RFQ Cooler Buncher (RFQ-CB), and EBIS charge breeder in the ISOL system are shown in Fig. 4.

The $^{133}Cs^{1+}$ ion beams were produced from the target ion source inside the TIS module by using a hot-cavity Ta heater, as was demonstrated on the ISOL offline test bench [13], and subsequently transported to the downstream of the A/q separator in the ISOL beam line as shown in Fig. 5. The ISOL beamline optics elements are grouped into two for RFQ-CB and EBIS charge breeder, where ion beams are manipulated for slowing down and charge breeding, respectively. The 4.0 nA $^{133}Cs^{1+}$ ion beams from the TIS were extracted with 30 % ionization efficiency and applied to 20 keV, and the mass resolving power was about 1000 in

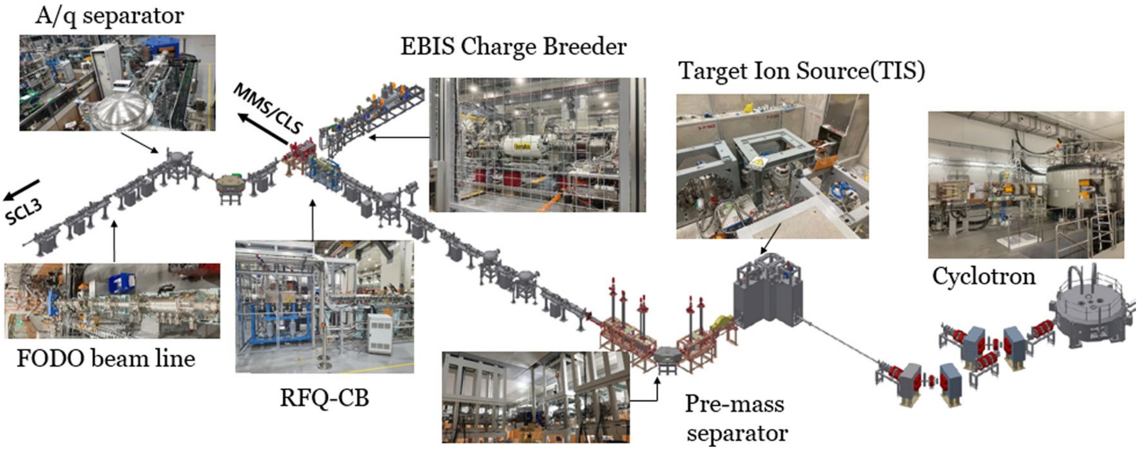


Fig. 4 The ISOL beamline scheme and photos of key components of the beamline

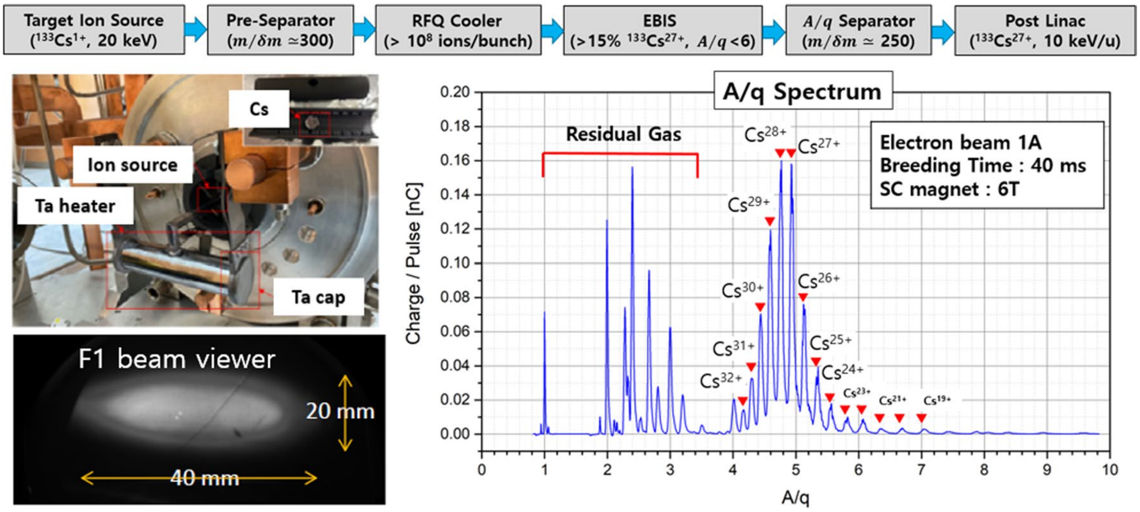


Fig. 5 Results of the Cs^{27+} ion beam commissioning of the ISOL beamline performed in 2021

2σ. The Cs ion beams were bunched to 1.66×10^8/s by the RFQ-CB and the EBIS charge breeder produced 5.0×10^7 of Cs^{27+} with 44 % breeding efficiency as shown in Fig. 5. Furthermore, Sn ion beams were extracted by using the laser ion source technique with a hot cavity TIS and all the natural isotopes were observed in the same method as in Ref. [14]. For commissioning the ISOL system, non-fissile target materials such as SiC and BN are to be used initially for producing isotopes with the 70 MeV proton cyclotron.

The IF separator consists of two parts; the pre-separator(PS) for producing radioactive isotopes and separating isotopes of interest and the main separator(MS) for identification and experiments with a selected isotope. The uranium beam of 200 MeV/u would have the average charge state of 79+, but by considering the energy upgrade to 400 MeV/u of the SCL2 in the future, the separator is designed to have a maximum rigidity of 9.6 Tm, ± 40 mrad of angular acceptance, ± 3% of momentum acceptance for fragmentation and in-flight fission processes. The PS consists of a high-power target, a beam dump, high-temperature superconducting quadrupole, and hexapole magnets in large vacuum chambers for radiation protection and maintenance purpose as such remote handling of components as shown in Fig. 6. The high-power target and beam dump of 80 kW were fabricated with graphite, and a heat loading test using RF induction is being prepared for further testing. The magnets for the IF system are produced and installed, and the performance test of the low-temperature superconducting (LTS) quadrupole magnet triplets is underway. The particle identification system to employ the TOF-Bρ-ΔE by using parallel plate avalanche counters (PPAC) [15], plastic scintillators, and silicon detectors are prepared for measuring the position, timing, and energy-loss of the isotopes produced by the separator. All the magnets and subsystems including particle identification detectors with chambers are being installed and are expected to be finished in 2022.

4 Experiment facilities

Experimental facilities are designed for pure and applied sciences using RIB of a few keV to hundreds of MeV. They consist of a recoil spectrometer called KoBRA for the study of nuclear reactions of astrophysics interest [16], the nuclear structure of neutron and proton-rich nuclei, production of rare isotopes, and super heavy elements; NDPS(Nuclear Data Production System) for neutron time-of-flight experannts; MR-TOF for high precision mass measurement system (MMS); collinear laser spectroscopy (CLS) for studying various properties of rare isotopes using the RIB from ISOL; a large acceptance multi-purpose spectrometer LAMPS to investigate the equation of state (EoS) of nuclear matter in a

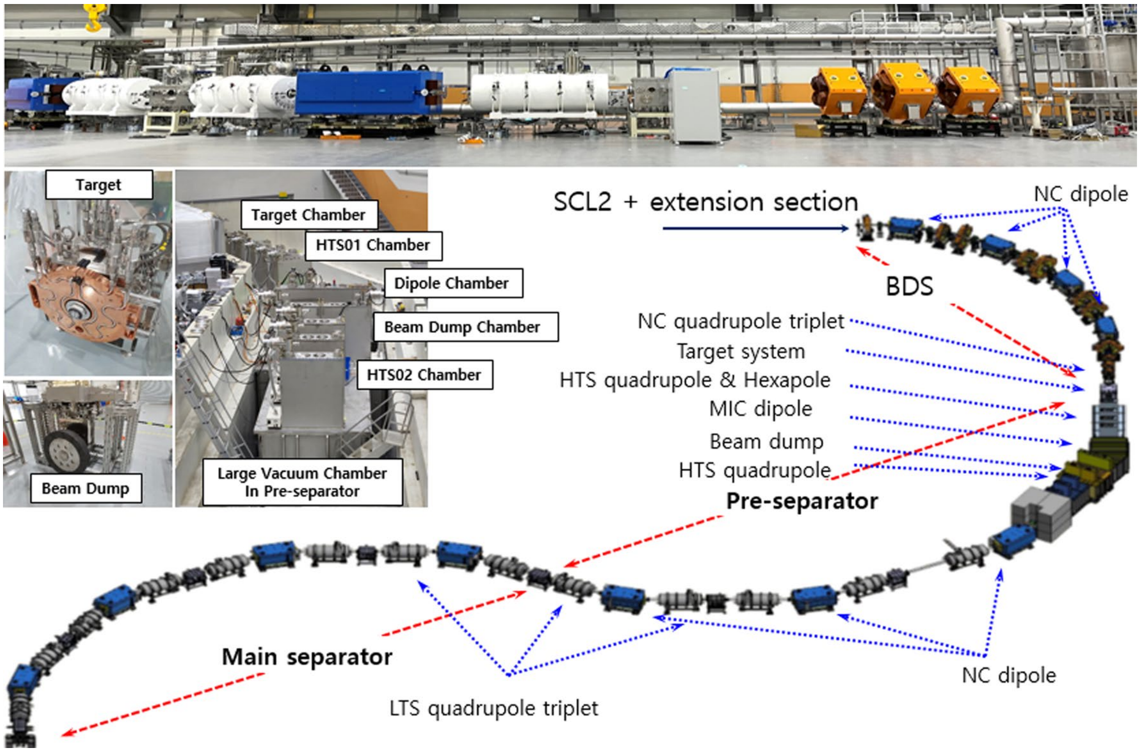


Fig. 6 RAON IF separator

wide range of neutron-proton asymmetry with intermediate energy of a few hundreds of MeV/nucleon; μSR for material science, and BIS(Beam Irradiation System) for a biomedical science research facility. The KoBRA and MR-TOF were commissioned in 2021 and all others to follow in 2022.

KoBRA will be utilized not only to produce rare isotopes using a stable ion beam at energies less than 40 MeV/u for studies of nuclear structure and reactions but also to provide high suppression of beam-induced background for studies of direct capture reactions of astrophysical interest with an additional extension of KoBRA.

As shown in Fig. 7, KoBRA consists of a swinger magnet located just upstream of a target chamber, two curved-edge bending magnets for minimizing the high order aberrations up to 4th order along with two hexapole magnets, fifteen quadrupole magnets, and a Wien filter. A target is placed at the focal point F0. The magnetic rigidity of produced rare isotope is analyzed at a dispersive focus (F1) with a momentum dispersion of 4.1 cm/%. A homogeneous or curved degrader can be inserted at F1 in order to increase the purification of rare isotope beams. Two double achromatic focuses (F2 and F3) are positioned downstream of F1, and the Wien filter is located between F2 and F3 so as to make a mass dispersion at F3.

The installation of KoBRA was completed in June 2021, except for the Wien filter. The Wien filter is being manufactured by the Center for Exotic Nuclear Studies (CENS) of IBS, and its installation will be completed by the end of 2023 [18, 19]. A beam transport test was performed using an ^{241}Am α-source placed at F0. The magnetic rigidities of α-particles emitted from ^{241}Am were analyzed particle-by-particle by measuring the position at F1 with a large area PPAC reported in Ref. [17]. The test results are consistent with those of Monte Carlo simulation, confirming the momentum resolving power at F1. In 2023, the commissioning beam experiment by using a graphite production target at F0 and about 25 MeV/u ^{40}Ar primary beam from SCL3 is planned to produce rare isotopes as a secondary.

A small silicon detector array, named SNACK (Silicon detector array for Nuclear AstrophysiCs study at KoBRA), consisting of three double-sided silicon strip detectors was developed in the last year, which can be installed at F3 for the (*d*,*p*) transfer reaction measurements along with a deuterated polyethylene (CD_2) target. A high-purity germanium detector array is also being tested for gamma-ray spectroscopy. Specific topics for the commissioning experiment are now under discussion together with domestic user groups.

A fast neutron production facility NDPS is constructed for nuclear data experiments and other industrial applications using neutron beams. NDPS will provide both white and mono-energetic pulsed neutrons, by using 49 MeV/u of deuteron and 20~83 MeV of proton beams with thick graphite and thin lithium target, respectively.

NDPS consists of four quadrupole and one dipole magnets, two production target chambers, a proton beam dump used for the production of a mono-energetic neutron, a neutron beam dump consisting of 1 m-thick concrete blocks, and a 4 m long neutron collimator. Figure 8 represents a schematic view of NDPS, where the proton beam dump will be surrounded by 10 cm-thick lead blocks for the radiation shielding. The neutron beam dump is placed at about 35 m away from the exit of the neutron collimator. A transverse

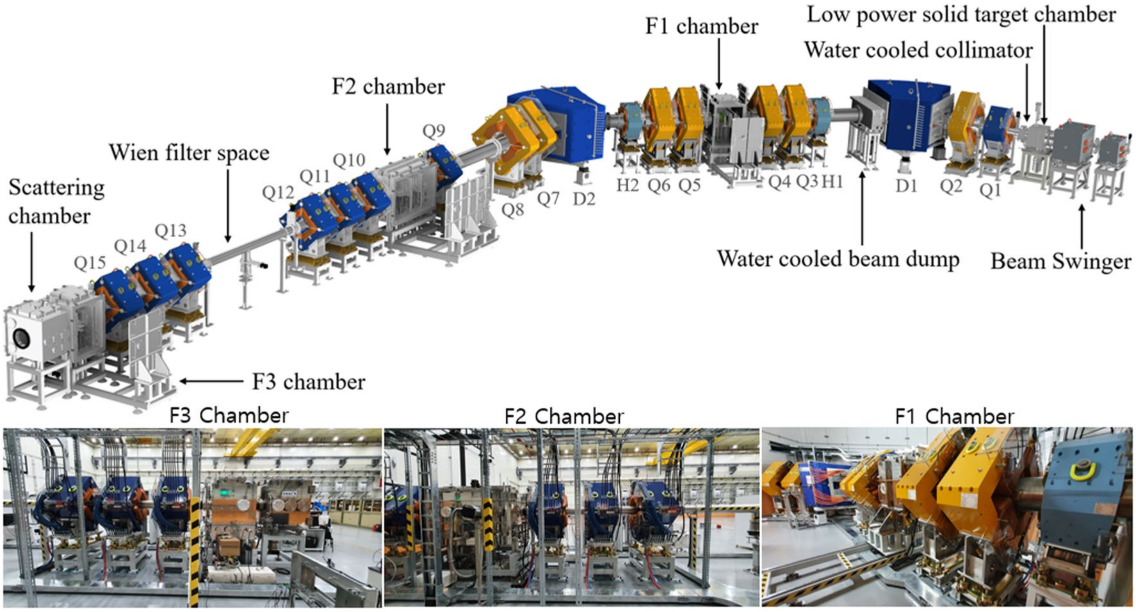


Fig. 7 The schematic view and installation of KoBRA in 2021

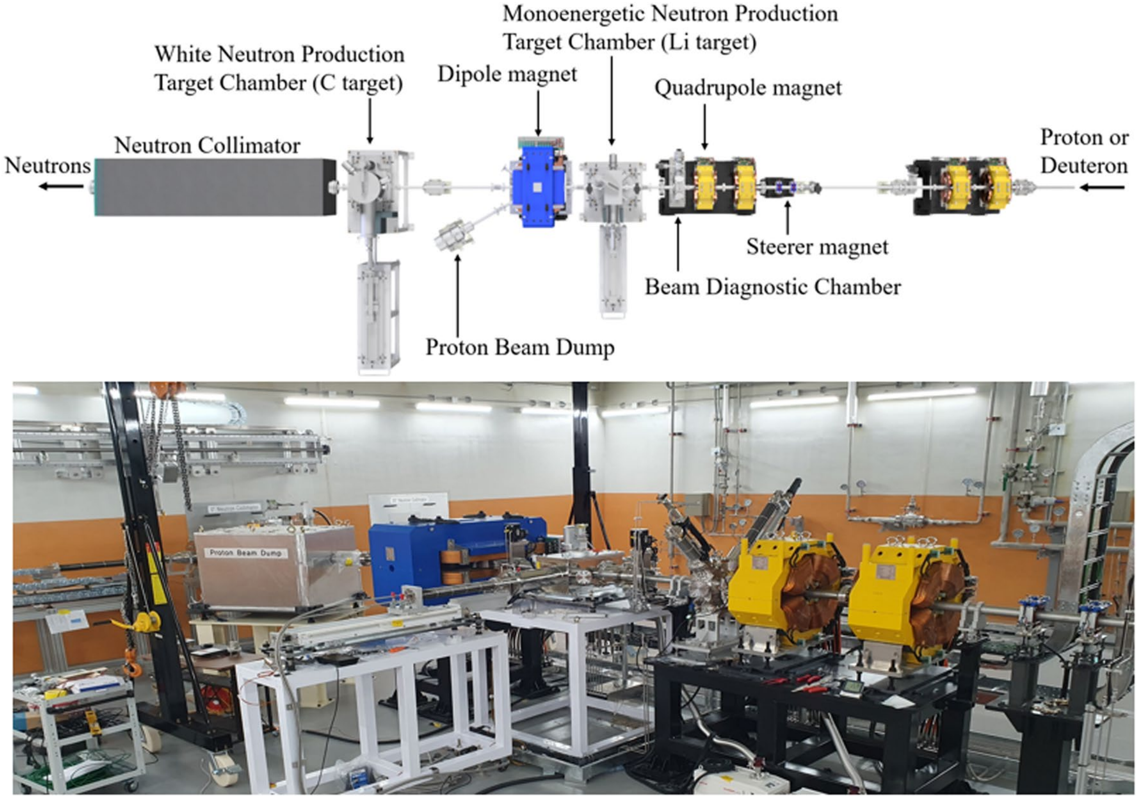


Fig. 8 The schematic view and installation of NDPS

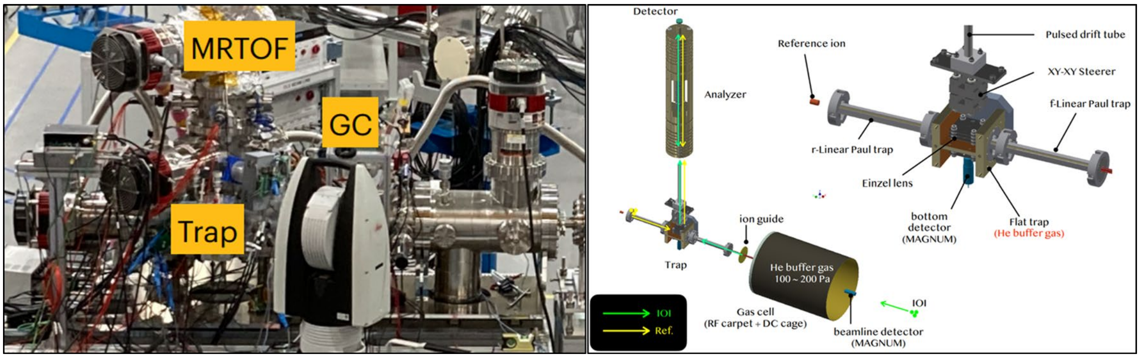


Fig. 9 The picture and schematic view of the MR-TOF

position and energy of the neutron beam are measured using a PPAC located downstream of the neutron collimator with a thorium foil converting neutrons to charged particles. The neutron energy is determined by employing the time-of-flight (TOF) technique.

The main components of NDPS were installed in April 2022. A remote handling system to replace a used graphite target is being manufactured, as well as ion beam diagnostics, which will be installed by the end of 2022. A fast chopper and a double gap buncher were also installed in the low-energy beam transport line of the injector system to provide pulsed ion beams with a repetition rate of fewer than 0.2 MHz, to generate pulsed neutrons. The beam commissioning for NDPS is scheduled for the year 2024. A detector array, consisting of a microchannel plate detector and passivated implanted planar silicon detectors, is being developed for nuclear fission measurements, where the mass of the fission fragment is determined by employing the TOF technique as reported in Ref. [20]. NDPS will give opportunities not only to obtain nuclear data in the neutron energy

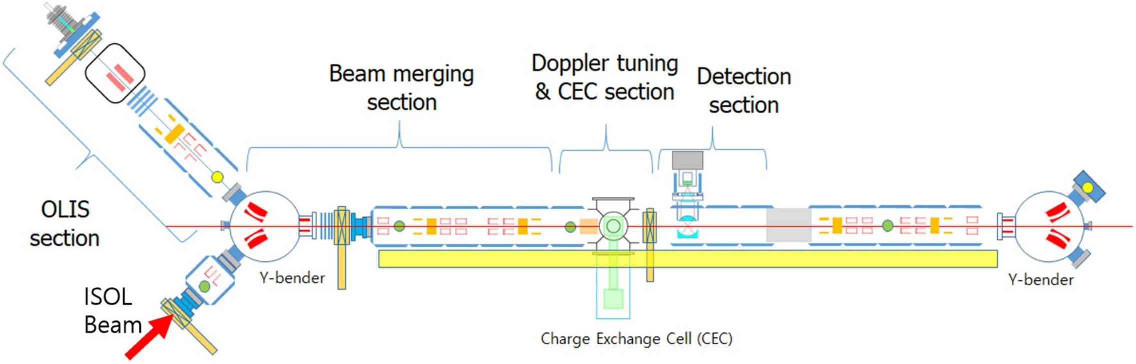
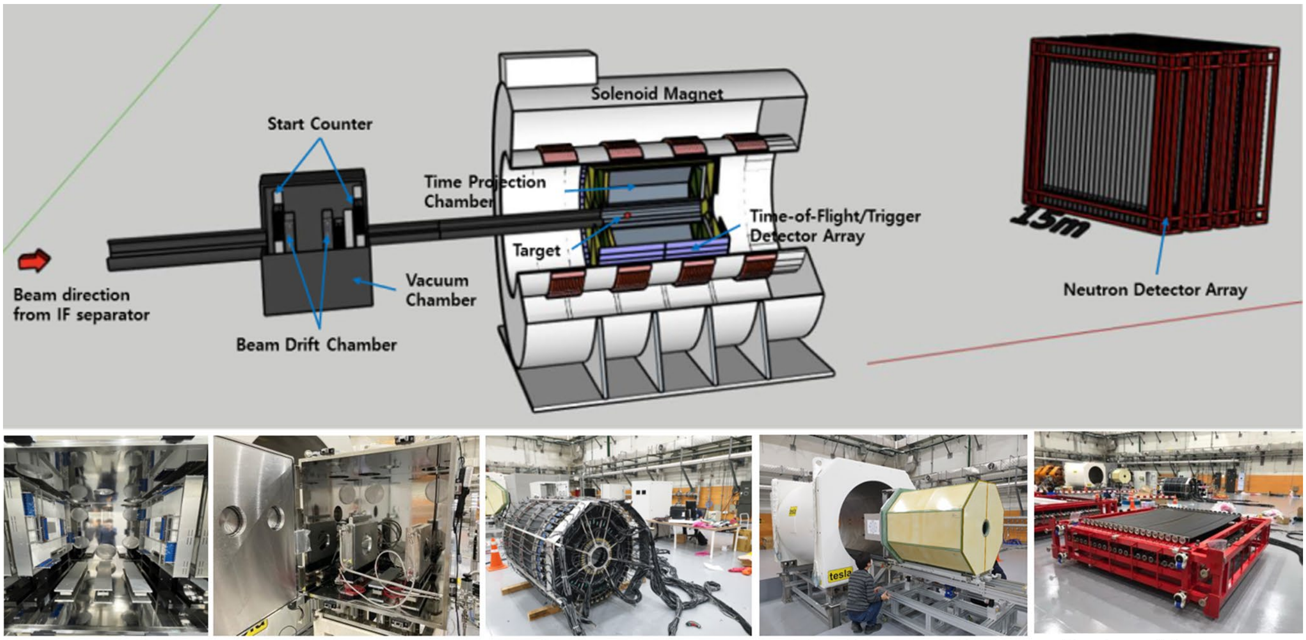


Fig. 10 The schematic drawing of CLS



Start counter BDC ToF/Trigger Detector Solenoid magnet/TPC Neutron detector array

Fig. 11 The schematic view and pictures of LAMPS facility

range of 20~83 MeV but also to study various industrial applications in the near future.

The MR-TOF for high-precision mass measurement system in the ISOL experiment hall was installed as in Fig. 9 and commissioned in 2021. The development of MR-TOF was carried out in collaboration with the KEK/WNSC(Wako Nuclear Science Center) at RIKEN. MR-TOF consists of a gas cell (or a catcher), trap, and mass analyzer. Beam commissioning of MR-TOF using 40~1700 pA of ^{133}Cs thermal ion beam was conducted and the mass resolving power of over 110,000 has been achieved in 2021.

CLS, yet another beam-sharing experimental system nearby MR-TOF in the ISOL hall, is assembled in TRIUMF of Canada and will be installed by the end of 2022. As shown in Fig. 10, CLS consists of a beam line with a beam emerging entrance switchyard that allows the installation of an off-line ion source (OLIS), laser access, and connection to the RIBs from ISOL.

LAMPS is a nuclear physics experimental facility that measures charged particles and neutrons produced by colliding high-energy stable isotopes and rare isotope beams onto stable nuclear solid targets [21]. LAMPS is equipped with a time projection detector to track the trajectory of charged particles generated in a collision, a detector system to measure the center of the collision, and a neutron detector array to the front of the solenoid to measure the neutrons generated in the collision. There are a start counter system and a beam drift chamber system that measure the arrival time and position of beams incident on LAMPS solid targets. All LAMPS instruments are currently manufactured and installation is in progress in the experiment hall as shown in Fig. 11. Integration of all detectors, after the performance test of each detector, will be carried out in 2022.

5 Summary

RAON has been constructed since 2011 and the building and supporting facility construction project was finished in 2021. However, the accelerator and experimental system installation project was staged into two in 2021, and the phase-1 project for installation of low energy superconducting linear accelerator SCL3, RI production systems, and experimental system will end in 2022. As part of the beam commissioning of the SCL3, the first acceleration of stable ^{40}Ar ion beams on low-energy superconducting accelerator SCL3 is successfully done by cooling down the cryomodules. In 2023, as the next beam commissioning experiment, about 25 MeV/u of ^{40}Ar beams from the SCL3 will be available on the KoBRA production target to carry out RI productions via quasi-projectile-like fragmentation process for the beam commissioning experiment. Also, the ISOL will make use of the SiC target to extract rare isotopes in 2023. In 2023, MR-TOF and CLS in the ISOL experimental hall are expected to use ^{26}Al isotope beams to study isomer separation using ^{26gs}Al and ^{26m}Al beams and isomeric property through isotope shifts of ^{26m}Al, respectively.

Acknowledgements At the time of submitting this paper, RISP extracted the first accelerated Ar beam by using 5 QWR cryomodules as the first phase of the beam commissioning experiment of the SCL3. The authors are grateful to the entire RISP team for their dedication. Also, the authors appreciate the support from RAON Users Associations (RUA), collaborators of universities and research institutions, the National Research Foundation, and the Ministry of Science and ICT of Korea.

References

1. Y.K. Kwon et al., Few-Body Syst. **54**, 961 (2013)
2. K. Tshoo et al., Nucl. Instr. Meth. B **317**, 242 (2013)
3. C.B. Moon, AIP Adv. **4**, 041001 (2014)
4. RAON Accelerator and Experimental System Technical Design Report (2013)
5. J. Wei *et al.*, in Proc. LINAC, Tel-Aviv, Israel, 2012, TU1A04
6. D. Jeon et al., J. Korean Phys. Soc. **65**, 1010 (2014)
7. PANTECHNIK, France; https://www.pantechnik.com/
8. H.J. Kim *et al.*, 13th Int. Particle Acc. Conf., IPAC2022, Bangkok, Thailand
9. EURISOL web page, https://www.eurisol.org
10. H. Suzuki et al., Phys. Rev. C **102**, 064615 (2020)
11. L. Neufcourt et al., Phys. Rev. C **101**, 044307 (2020)
12. H.J. Woo et al., J. Korean Phys. Soc. **66**, 443 (2015)
13. S.J. Park et al., Nucl. Instr. Meth. B **410**, 108 (2017)
14. J. H. Lee *et al.*, EMIS2022, Daejeon, Korea, to be published in Nucl. Instr. Meth. B, (2023)
15. C. Akers et al., J. Korean Phys. Soc. **70**, 682 (2017)
16. K. Tshoo et al., Nucl. Instr. Meth. B **376**, 188 (2016)
17. C. Akers et al., Nucl. Instr. Meth. A **910**, 49 (2018)
18. K. Tshoo *et al.*, EMIS2022, Daejeon, Korea, to be published in Nucl. Instr. Meth. B, (2023)
19. J.W. Hwang *et al.*, EMIS2022, Daejeon, Korea, to be published in Nucl. Instr. Meth. B, (2023)
20. M.O. Frégeau et al., Nucl. Instr. Meth. A **817**, 34 (2016)
21. Y.J. Kim, Nucl. Instr. Meth. A **463**, 15 (2018)