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Status of Rare Isotope Science Project in Korea

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Abstract The Rare Isotope Science Project (RISP) is launched in Korea to build the IF and ISOL facilities. Current status of RISP is introduced.

1 Introduction

As the major research facility of the International Science Business Belt (ISBB) in Korea, construction of the accelerator complex for the rare isotope science was approved by the Korean government in 2009. In November 2011, the Institute for Basic Science (IBS) was established as the main institution of ISBB to host about 50 research centers and other affiliated Institutes. In order to carry out the technical design and the construction of the accelerator complex, the Rare Isotope Science Project (RISP) was established in December 2011, in the IBS.

The goal of the accelerator complex is to produce variety of stable and rare isotopes to be used for researches in basic science and various applications. The complex consists of a heavy ion linear accelerator as the driver, called as Driver Linac, for the in-flight fragment (IF) system, a proton cyclotron as the driver for the isotope separation on-line (ISOL) system and a post-accelerator for the ISOL system. The ISOL and the IF systems will be operated separately and independently. In addition, the rare isotopes produced in ISOL can be injected into the Driver Linac for accelerating the RI beam even higher energies or for use in IF system to produce even more exotic rare isotopes. In the future stage, the proton beam in the Driver Linac can be used for the ISOL system with higher power. A large number of rare isotopes with high intensity and with various beam energies will be available. The schematic diagram of the complex is shown in Fig. 1.

Sciences with rare isotopes have been well described by numerous previous studies [1,2]. The number of rare isotope accelerator facilities in operation or under construction demonstrating the importance of rare isotope sciences in the world. By using low and high energy RI beams, the basic science, nuclear physics, astrophysics and atomic physics will be studied. The programs include the study of nuclear structure of very neutron rich nuclei near the drip line, the properties of exotic nuclei and the equation of state (EoS) of nuclear matter, and the attempt to understand the origin of the universe and the process of nucleosynthesis under the various stellar environments. In addition, one of the aims of the RISP is to discover a new super-heavy element with $Z > 119$. For the applied science, finding new material, mutating the cell or DNA, constructing nuclear data, and developing new medical heavy ion therapy will be fulfilled. The material science with RI beams, whose scale is in femto (10^{-15}) meter, will give us chance to make new materials, to study their properties,

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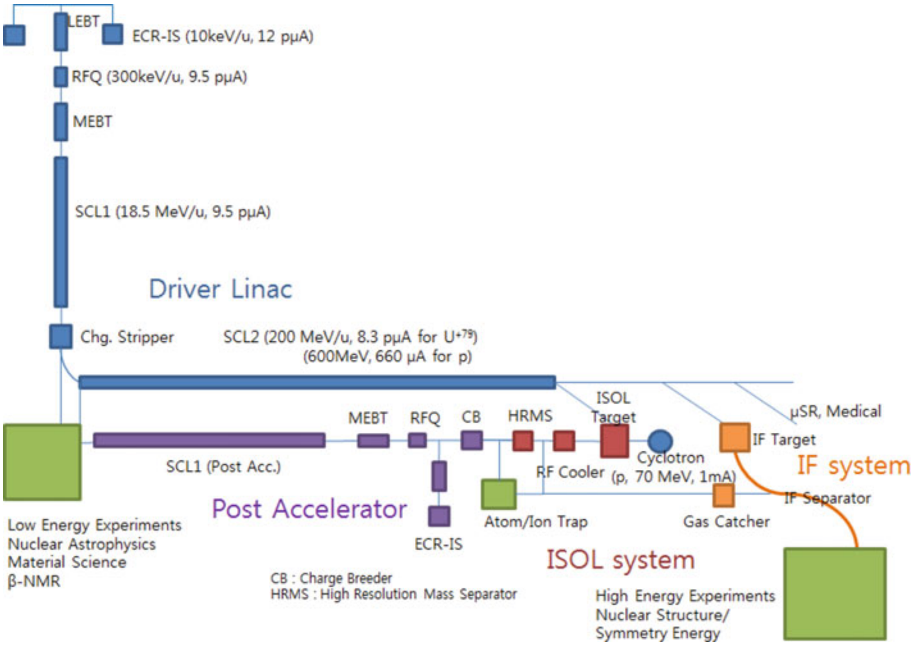

Fig. 1 Schematic diagram of the accelerator complex of RISP

and to see a dynamic image in the nano (10^{-9}) meter scale. For the medical and biological applications, there is a plan to develop the advanced treatment technology by using energetic RI beams and to study the mutation of DNA. A systematic nuclear data measurement using fast neutrons has been planned for the future nuclear energy development and radioactive waste transmutation research.

2 Accelerator System

2.1 The Driver Linac

The driver linac provides various ion beams from proton to uranium to the IF target with a beam power greater than 400 kW. For instance uranium (proton) beam is accelerated to 200 MeV/nucleon (600 MeV). The driver linac consists of the injector, low energy superconducting linac, charge stripper station, high energy superconducting linac and the beam transport line to various targets including the IF target.

Injector The injector consists of superconducting electron cyclotron resonance (ECR) ion source, low energy beam transport (LEBT), radio frequency quadrupole (RFQ) and medium energy beam transport (MEBT). The 28 GHz SC ECR ion source is employed to produce the highly charged heavy ions like $^{238}\mathrm{U}^{33+}$ with the kinetic energy of 10 keV/nucleon and normalized root-mean-square (rms) emittance of 0.1 π mm-mrad. Radio Frequency Quadrupole is to bunch and accelerate beams transported from the LEBT. It consists of a radial matching section, shaper, gentle buncher, and accelerating section. The RFQ is designed to accelerate two-charge state ($^{238}\mathrm{U}^{33+}$ and $^{238}\mathrm{U}^{34+}$ of 12pμ A) beams from 10 to 300 keV/nucleon.

Superconducting Linac The driver SCL for the IF facility is designed to accelerate high intensity heavy ion beams and to meet the needs of various users. Large cavity apertures (4 and 5 cm) are chosen to reduce the uncontrolled beam loss in the superconducting cavity due to the aperture scattering which is a serious problem in the high energy and high intensity heavy ion beam accelerators. Cavity types are chosen and optimization of the geometric betas of SC cavities is done and an optimum set of β_g = [0.047, 0.12, 0.30, 0.53] is obtained. The half wave resonator (HWR) is chosen to minimize the asymmetric field effects and to improve the quality. And for each type of SC cavities, optimization of the cavity geometry was conducted with respect to R/Q, QR_s, $\mathrm{E}_{peak}/\mathrm{E}_{acc}$ and $\mathrm{B}_{peak}/\mathrm{E}_{acc}$ etc. Figure 2 shows the electromagnetic fields of the optimized SC cavities.

It is known that the position of each component in a cryomodule changes by no less than a millimeter in a random fashion during the cool-down of a cryomodule and it is not trivial to accurately align superconducting

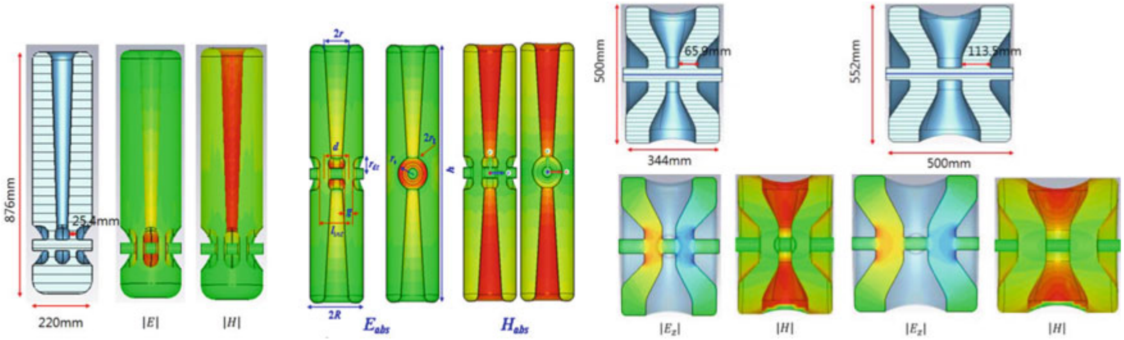

Fig. 2 *Plots* of optimized QWR/HWR (on the *left*) and SSR1/SSR2 (on the *right*) showing their electromagnetic fields

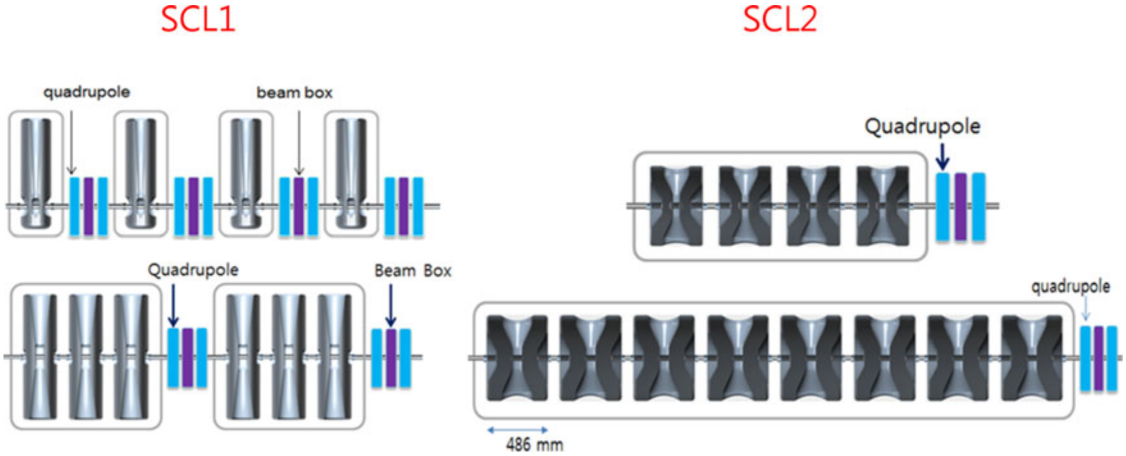

Fig. 3 *Plots* of the SCL layout for each SC cavity type

solenoids in a cryomodule after the cool-down. For high intensity operations, the lattice with normal conducting quadrupole doublet is adopted as shown in Fig. 3. The SPIRAL2 project also adopted quadrupole doublet focusing lattice for the high intensity ion beam acceleration (for instance 1 mA of heavy ion beams and 5 mA deuteron beam) [3].

The project can profit from the existing knowledge base, accelerating the learning process and minimizing the R& D workload and the project can concentrate on developing core design and technologies. Existing designs and products of cryomodules, couplers and tuners will be utilized as much as possible for the SCL design. It is planned to carry out R & D for couplers. The beam boxes located at every doublet are reserved for various diagnostics devices such as beam profile monitors, beam current monitors (BCM), Faraday cups, emittance scanners, bunch shape monitors (BSM), etc. Beam position monitors (BPM) will be installed with quadrupoles, providing beam position and phase data. At these beam boxes collimators can be installed at the beam boxes to improve beam quality. These collimators can minimize the uncontrolled beam loss to the superconducting cavities.

3 RI Production and Separation System

3.1 IF (In-Flight Fragment) system

The in-flight fragment separator is a device to separate isotope beam of interest and to purify the chosen isotope beam. The separator is divided into two sections: pre- and main separators as for the separators at the RIKEN, FRIB and FAIR, where the high primary beam power is removed in the front part of the separator. The layout of the separator chosen was namely S-shape for pre-separator, and C-shape for main separator as shown in Fig. 4. The C-shape for the main separator was also chosen by the FRIB as it has advantages in accepting higher rigidity beams and in simple configuration compared to different shapes.

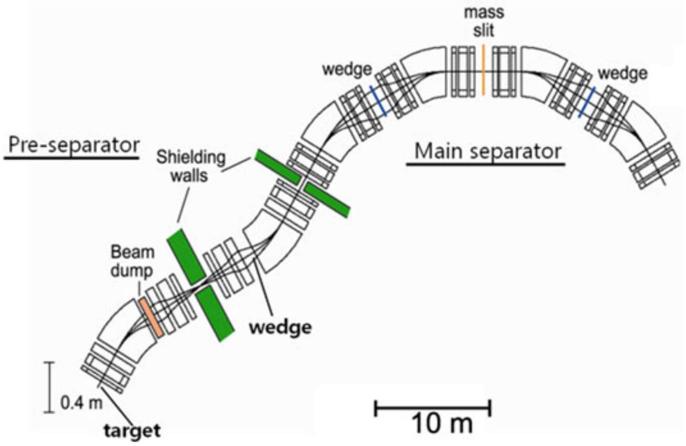

Fig. 4 Configuration of the IF separator with S-shape for the pre-separator and C-shape for the main separator

The wedge for the S-shape pre-separator is located in the mirror location of the beam dump, which can be used to compress momentum spread. The final selection of separator configuration will be made considering acceptance of rare isotope beam, mechanical convenience and so forth. The multipole magnets to correct high-order field components were initially considered to be independent magnets, by which interference with the main quadrupole fields can be reduced. However, the beam optics indicates the correction can be more efficiently done by incorporating the multipole coils with quadrupole magnets. These types of the magnet are also chosen for the FRIB. The prototype quadrupole magnet will include superconducting multiple coils wound on the cold bore tube. The field mapping will indicate more precisely the interference field effects for instance depending on the coil excitation.

3.2 ISOL (Isotope Separation On-Line) system

The RISP proposed the ISOL facility to provide the intense rare isotopes. The basic elements of the ISOL facility is comprised of the driver accelerator, the production target coupled to the ion source, the RF beam cooler, the high resolution mass separator (HRMS), the charge breeder, the beam transport system, and the post-accelerator. Two production target stations are proposed to produce various short-lived rare isotopes; one is a fission target station for the n-rich beams and the other spallation target station for the mainly proton-rich isotopes. Development of fission target is concentrated to produce the rare isotopes with masses in the range of A = 80–160 created through uranium fission reaction as its first priority by users requirement. Note that a Mega-Watt target station is also considered for a future beam line. To supply a various RI Beam, three types of ion sources: a surface ionization type ion source for ionization of alkali, alkaline earth, a FEBIAD plasma type ion source [4] for ionization of gaseous and volatile elements and a resonance ionization laser ion source to improve ionization selectivity are planned. To separate the isotopes neighboring A = 140, an RF-cooler and an HRMS with a resolving power of 45,000 are required. The another HRMS 10,000 will be prepared to reduce risk because the 45,000 is required the high technology and long R & Ds are needed. ECR-type and EBIS-type of two charge breeders are planned to development, which are having a limitation of beam quality and intensities respectively. The total fission rate are estimated to be about 10^{14} fission/s by a simulation study and the expected beam on experimental target hall will have a rate on the order of 10^8 pps for ^{132}Sn. Table 1 shows the design goal of development of RISP ISOL facility.

Table 1 Design goal of ISOL facility at RISP

Component	Design goal
Driver	Cyclotron, p, 70 MeV, 1 mA
Target	Direct fission target : UC_x
Ion source	SI, FEBIAD and RILIS
RF-cooler	Emittance : 3 π mm mrad, $\Delta E < 10$ eV
HRMS	R_m=10,000 and 45,000
Charge breeder	ECR and/or EBIS
A/q separator	B+E combination, $R_m = 3{,}000$

4 Experimental Systems

4.1 Nuclear Science Facilities

Recoil Spectrometer As a main facility for nuclear physics and nuclear astrophysics experiments with low energy (up to 18.5 MeV/nucleon) ion beams, the recoil spectrometer (RS) has been proposed. It is clear that experiments by using RI beams require not only high-quality beams of short-lived nuclei but also detection systems with high-efficiencies, high selectivity and high-resolutions, since in many cases these RI beams have rather low intensities. Typical beam intensities available at the present RIBs facilities in the world are $10^9 - 10^{11}$ particles/s or less. It is expected that recoil separators combined with appropriate detector systems provide highly selective and highly sensitive measurements suitable for the study of unstable nuclei far from the stability which are weakly populated in nuclear reactions. Main research topics and available experiments at the RS is listed in Table 2. Stable isotope (SI) beams up to 18.5 MeV/nucleon can be also delivered to the RS from main linac. Then we consider low energy in-flight separation with SI beams. With this method we expect that proton-rich RI beams up to A $\sim$80 can be produced and separated by the RS and we can study various research topics related with exotic nuclei of proton-rich side. And also the possibility of super heavy element (Z $>$ 119) search with hot fusion reaction such as ^{232} Th + ^{58} Fe, ^{64}Ni at the RS is being considered.

Large Acceptance Spectrometer Symmetry energy is the energy that requires converting a proton to a neutron inside a nucleus. Therefore, understanding the nature of symmetry energy will offer clues to fundamental questions about the asymmetric constitution of nucleons in heavy nuclei, isospin asymmetry in nucleon–nucleon interactions, their modifications in a nuclear medium, etc [5]. In addition, recent research shows that symmetry energy plays a critical role in the properties of a neutron star, such as its cooling rate, mass, and radius. The goal of the proposed investigation is to understand the nature of symmetry energy in nuclei and in nuclear matter with nuclei from stable ones to those far from the stability valley, and to apply our knowledge to related phenomena from a microscopic scale to stellar objects [6]. The Large Acceptance Multipurpose Spectrometer (LAMPS) is designed to explore the symmetry energy term in the equation of state (EOS) of nuclear matter in a wide range of neutron-proton asymmetry. In order to achieve the physics goal, the low-energy(LAMPS-L) and high-energy(LAMPS-H) nuclear facilities are proposed to perform the collision experiments with beam energy up to 250 MeV/nucleon for both stable and radioactivity beams. LAMPS will measure Pygmy and Giant dipole resonances, particle spectrum, yield, ratio and collective flow of pions, protons, neutrons, and intermediate fragments, e.g. t, ^{3} He, ^{7} Li, ^{7} Be, etc.

4.2 Applied Science Facilities

Material Science Facilities So far a number of nuclear experimental techniques have been introduced to material science, and then have produced remarkable achievements. RI beam is a very useful tool for looking at the inside nature of condensed matters. It can straightforwardly be used as tracer for diffusion studies. Moreover, due to its high sensitivity to electromagnetic feature within materials, it is capable of providing microscopic information on the structural and dynamical properties of solids by using the conventional nuclear techniques such as Mossbauer spectroscopy (MES), perturbed angular correlation (PAC), μ SR, β-NMR, emission channeling (EC), and conversion electron spectroscopy (CES). Among them, μ SR and β-NMR are very unique and promising techniques to investigate nano-scale electromagnetic structures and properties of material by using RI beams [7].

Both the μ SR and the β-NMR facilities will be installed at RISP as the main facilities for material science. Furthermore the μ SR facility will include beam lines for low-energy muon that can investigate thin films, multilayered structures and surfaces. If the β-NMR and the low-energy μ SR facilities are installed successfully,

Table 2 Main research topics and available experiments at the RS

Physics topics	Measurements
rp-process	Radiative capture, transfer reaction, scattering
r-process	Transfer reaction (d,p), decay measurement
Neutron drip line studies, halo nuclei	Transfer reaction, scattering
Proton drip line studies	Transfer reaction, fusion–evaporation reaction

the RIPS becomes the center for depth-resolved material science as the only one possessing both facilities in the world.

Atomic Physics Facility Atomic physics at accelerators has played a central role to study the behavior of nuclear matter including nuclear structure and the relevant nucleon interactions [8,9]. The main techniques include mass spectrometry, trapping, cooling, and laser spectroscopy. At the atomic physics facility at RISP, precise mass measurement and a range of laser spectroscopy projects are planned. Essential subsystems for the precise mass measurement are RFQ cooler buncher, multi-reflection time-of-flight mass separator, charge breeder ion trap, A/q selector, sympathetic cooler trap, measurement Penning trap, and TOF-ICR detector etc. High-precision mass measurements will be performed on the very short-lived nuclides and highly charged ions. Meanwhile, many laser spectroscopic techniques will be employed, including (1) In-beam laser spectroscopy, (2) In-source laser spectroscopy, and (3) In-trap laser spectroscopy. For in-beam laser spectroscopy, collinear laser spectroscopy of ions and atoms will be developed and performed. Polarized beams of atoms and ions produced by optical pumping would open the possibility of β-NMR. Neutralized atomic beam may utilize extended experiments such as collinear resonant ionization spectroscopy and spectroscopy in magneto-optical trap. For in-source laser spectroscopy, resonance ionization laser ion source (RILIS) system [10] will be developed to produce ion species which were not accessible by other methods. Lastly, we consider several interesting options for the in-trap laser spectroscopy, performed in a Paul trap and a magneto-optical trap.

5 Summary

The Rare Isotope Science Project (RISP) is going to establish RI accelerator, nuclear physics, application science facilities in Korea. Details of designs of these facilities are in progress for Technical Design Report (TDR) that will be published by the end of 2013.

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