

RARE-ISOTOPE BEAM FACILITIES IN ASIA

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Abstract

Growing activities in the rare-isotope beam (RIB) facilities in Asian countries are reviewed herein. The status of and planned developments are presented for several RIB facilities in Japan, China, India, and Korea.

INTRODUCTION

Recent research fields of the nuclear physics are widely spread on the nuclear chart. Studies in these fields require the use of a wide variety of rare-isotope beams (RIBs); the ion species, intensity, and quality of the RIBs strongly depend on the scientific objectives of the study. In other words, the accelerator technologies required for rare-isotope studies need to fulfill diverse requirements. These requirements cannot be fulfilled by a single RIB facility. Therefore, a number of facilities that are complementary to each other have either been constructed or are being planned worldwide[1, 2].

In Asian countries, the number of activities at RIB facilities is rapidly growing. This paper presents a brief review of the present status and future plans of several RIB facilities that are located in Japan, China, India, and Korea.

JAPAN

RIKEN RIBF

The RIKEN Radioactive-Isotope Beam Factory (RIBF)[3], which was started in 2006, is based on the in-flight fragmentation scheme. Figure 1 shows a schematic layout of RIBF. The main accelerator of RIBF is the superconducting ring cyclotron (SRC)[4]. In 2010, a new injector known as RILAC2 was commissioned, which is dedicatedly used for the acceleration of very heavy ions such as xenon and uranium[5]. While this acceleration mode is being used at RIBF, the original linac injector can be used independently, for the production of super-heavy elements, for instance.

Figure 2 shows a schematic drawing of the RILAC2 injector. It accelerates heavy ions with $M/q < 7$, that are produced by a 28-GHz superconducting ECR ion source, up to 680 keV/u with an RFQ and three DTLs. The accelerated beams are injected into the RIKEN Ring Cyclotron (RRC: $K = 540$ MeV) without charge-stripping. A major portion of the rf system of RILAC2 operates at a fixed frequency of 36.5 MHz, where the maximum power consumption of each rf resonator is designed to be below 20 kW. It has been operating very stably since the beam commissioning.

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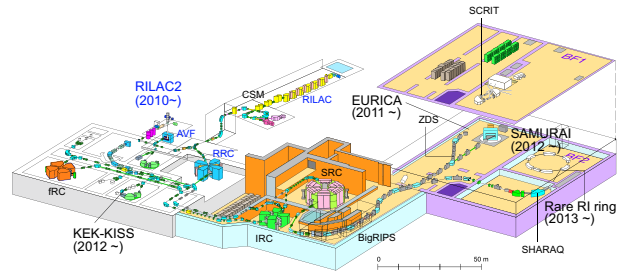


Figure 1: Layout of the RIKEN RIBF.

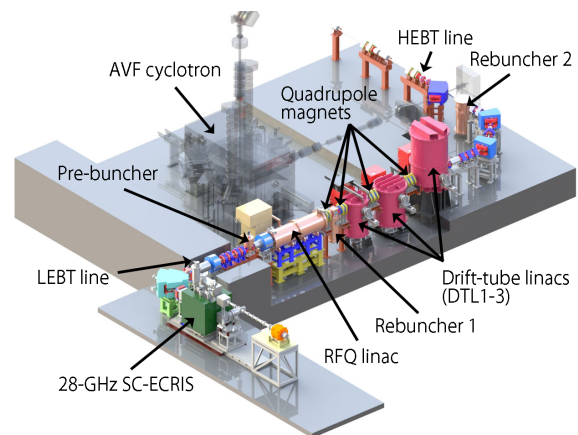


Figure 2: Schematic drawing of RILAC2 injector.

The evolution of maximum beam intensities for beams accelerated at RIBF is summarized in Fig. 3. Owing to the continuous efforts, the intensities are gradually becoming improved[6, 7]. It should be noted that the intensities of light ions such as deuterons and ^{18}O have already reached $1 \text{ p}\mu\text{A}$. On the other hand, the maximum currents in the RILAC2 injection mode are $3.5 \text{ p}\mu\text{A}$ for ^{238}U , $15 \text{ p}\mu\text{A}$ for ^{124}Xe ; the heavy-ion intensities remain to be improved.

One of the major obstacles in increasing the intensity of uranium and xenon beams is the limited lifetime of the carbon-foil strippers currently used. In order to overcome this difficulty, a gas-stripper system employing helium is being developed[8, 9]. An actual structure of the stripper has already been constructed based on several test results, and the beam commissioning has recently been started. A drawback of the gas stripper is that the available charge state becomes smaller compared to that obtained in the carbon-foil stripper. Therefore, the magnet power supplies of the fRC cyclotron have been upgraded in order to accommodate the lower charge states. Acceleration tests with the

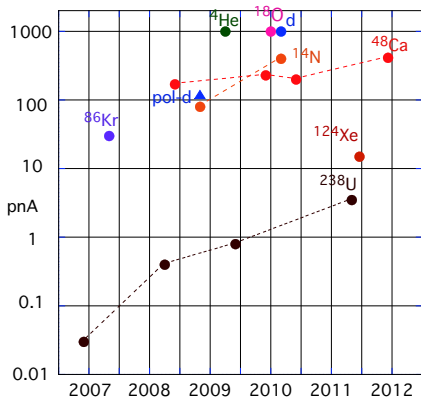


Figure 3: Evolution of maximum beam intensities at RIKEN RIBF.

upgraded fRC will be carried out in the near future.

At RIBF, the operation of a variety of experimental equipments has recently been commenced. For example, the Euroball-RIKEN Cluster Array (EURICA) collaboration for gamma ray spectroscopy was started last year[10]. A new superconducting analyzer with a large acceptance, which is known as SAMURAI, has been commissioned[11]. Moreover, the construction budget of the Rare-RI Ring[12] has been approved, and this ring will be used for performing precise mass measurements of rare isotopes. The number of papers published in scientific journals is also steadily increasing[13].

KEK KISS at RIBF

After the recent shutdown of the TRIAC facility[14] in Tokai, the RNB group members of KEK started the construction of the new apparatus which is named KEK Isotope Separation System (KISS) at RIKEN RIBF[15]. The layout of this system is shown in Fig. 4.

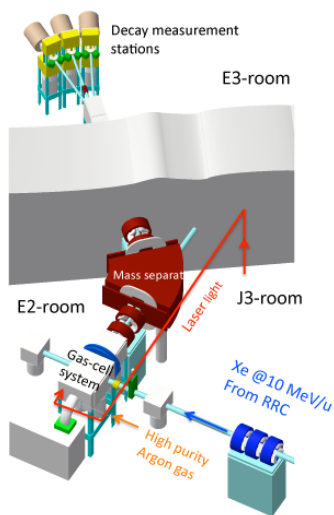


Figure 4: KEK KISS project at RIBF (Courtesy Prof. Miyatake).

KISS has been designed to investigate the origin of the third peak in the element distribution through measurements of the β -decay properties of neutron-rich isotopes having $N \approx 126$. These unstable nuclei can be produced by multi-nucleon transfer reactions induced by the ¹³⁶Xe beam accelerated by RRC. Among the reaction products collected in the gas cell, the unstable nuclei used for the investigation, such as tungsten isotopes, are ionized by the laser resonance ionization technique. The ions are mass-analyzed by an electromagnetic separator and transported to the next room for the decay measurements performed with a low background. The system construction is nearing completion and beam commissioning will be carried out this year.

CHINA

IMP HIRFL

The accelerator complex of the Heavy Ion Research Facility in Lanzhou (HIRFL)[16] is shown in Fig. 5. The injector is a coupled cyclotron system consisting of a sector focusing cyclotron (SFC: K = 69 MeV) and separated-sector cyclotron (SSC: K = 450 MeV). Rare isotope research was started here in the 1990s using the heavy ion beams from the SSC and based on the in-flight fragmentation scheme. In 2006, two cooler-storage rings, CSR-m and CSR-e, were constructed in order to expand the scientific opportunities provided by the RIBs; the high energy heavy-ion beams accelerated by the CSR-m produce more intense RIBs in a larger fragment separator placed after the ring. These RIBs are used for fixed-target experiments as well as mass measurements in CSR-e. The heavy-ion beams from CSR-m are used also for cancer therapy with a dedicated beam line.

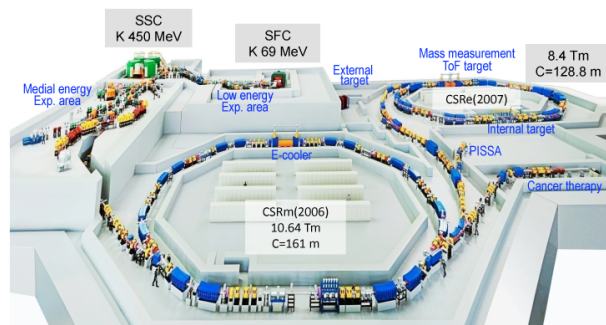


Figure 5: Layout of HIRFL (Courtesy Prof. Zhao).

Since 2011, three new beams, including those of uranium and hydrogen, have been successfully accelerated and accumulated in the CSR-m, and this will provide new scientific opportunities. In addition, very slow extraction from CSR-m that lasted almost three hours was achieved by improving the control system[17]. The mass-measurement program using CSR-e is rapidly progressing; measured masses of astrophysical interest, for four nuclei around the proton drip line, were recently published[18]. The mass

resolution in the isochronous mass spectrometry for CSR-e is as high as 10^{-6} .

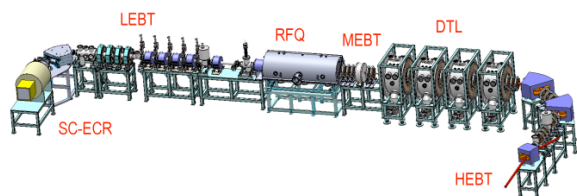


Figure 6: Layout of linac injector for SSC under construction at IMP (Courtesy Prof. Zhao).

In order to increase the beam intensities of the heavy-ion beams, a new linac injector is being constructed for the SSC[19]. As shown in Fig. 6, it consists of a superconducting ECR ion source, an RFQ, and four DTLs operated at 54 MHz. The SSC will be operated in two modes with this injector. One mode is for the injection to CSR-m and the other is for stand-alone use for the synthesis of super-heavy elements. The accelerator components of the injector are under fabrication in the indigenous companies, and they will become operational within three years. Another plan in the short term is constructing a pulsed-mode linac for direct injection into the CSR-m. The uranium beam intensity will be greatly improved by this injector, and parallel operation of the cyclotron facility and synchrotron facility will become possible. The construction is expected to be completed in five years.

More details of the recent achievements and future plans of HIRFL are reviewed in the proceedings[20].

CIAE BRIF

There is a second RIB project being run in China by CIAE. The project is referred to as the Beijing Rare Ion beam Facility (BRIF)[21], which is intended to accelerate rare-isotope beams based on the ISOL scheme, as shown Fig. 7. The driver accelerator is a 100 MeV, 200 μ A H^- cyclotron[22]. A superconducting linac will be added as a Tandem booster. This project was proposed in 1997, and the upgraded scheme currently under operation was approved in 2009.

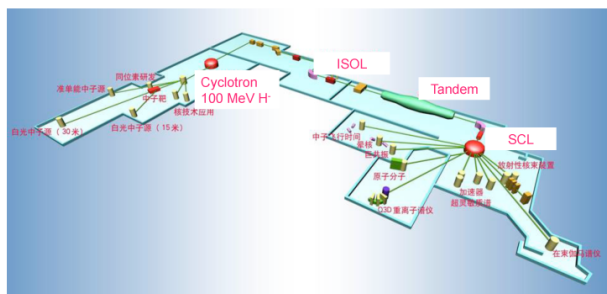


Figure 7: Layout of BRIF (Courtesy Prof. Liu).

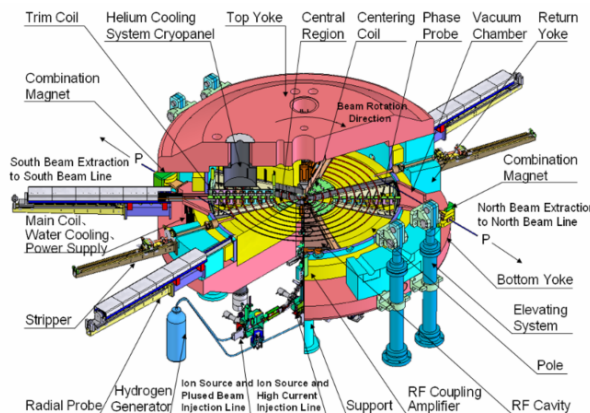


Figure 8: Schematic drawing of BRIF cyclotron (Courtesy Prof. Liu).

Figure 8 shows a schematic layout of the driver cyclotron. It is based on a four-sector AVF cyclotron, equipped with two double-gap resonators and two extraction ports with stripper foils. The construction of the cyclotron has almost been completed[23]. The superconducting cavities are also under fabrication at CIAE, by employing the sputtering technique. The BRIF project will be commissioned in 2014.

CIAE has planned a large future project for the RIB facility known as the China Advanced Rare Ion beam Facility (CARIF)[21]. This project aims to achieve the production of rare isotopes that are very far from the stability line with in-flight fragmentation of unstable nuclei accelerated by a post-accelerator with an ISOL. An interesting fact about this project is that the driver is not an accelerator, but the research reactor known as the China Advanced Research Reactor (CARR) of 60 MW, which recently entered a critical stage. The estimated fission rate in the ^{235}U target is as high as 10^{15} per second when using the powerful neutron flux from the reactor. Rare isotope beams such as ^{132}Sn are accelerated up to 150 MeV/u with an intensity of 5×10^{10} , and the secondary fragmentation reaction is expected to produce ^{78}Ni at 250 pps. The construction is slated for completion by around 2020.

INDIA

VECC

VECC, Kolkata, is executing their RIB project based on the ISOL scheme[24]. Figure 9 shows a schematic drawing of their post accelerator consisting of an RFQ (RFQ2) and six DTLs (LINAC1–6). The final energy of the post acceleration is set at 1.3 MeV/u. In 2011, they commissioned LINAC3, and the LINAC4 cavity is almost ready for operation. The low-energy beams from the smaller RFQ (RFQ1) are also used for the material science programs.

This year they succeeded in the production and transfer of radioactive isotopes that were produced in the He-jet multiple target system irradiated by alpha-particle beams

Table 1: RI-beam facilities that are in operation or under construction in Asian countries.

In-flight facilities	Driver	Mass	MeV/u	I (pps)	Separator	Exp.
RIBF (RIKEN, Japan)	SRC	- 238	440–345	6×10^{12}	BigRIPS (PF)	ZDS etc.
HIRFL (IMP, China)	CSRm	- 238	2800–500	10^9	RIBLL2 (PF)	CSRc
IUAC (India)	SC-Linac	- 238	~ 5	$\sim 10^{12}$	HIRA, HYRA (p,n),(d,n)	(PSSD)
ISOL facilities	Driver	Mass	MeV/u	kW	Post Acc.	MeV/u
RIB (VECC, India)	Cyclotron/e-Linac	4/(e)	16 / (10)	1.2 / 20	Linac	1.3
BRIF (CIAE, China)	Cyclotron	1	100	20	SC-Linac	2

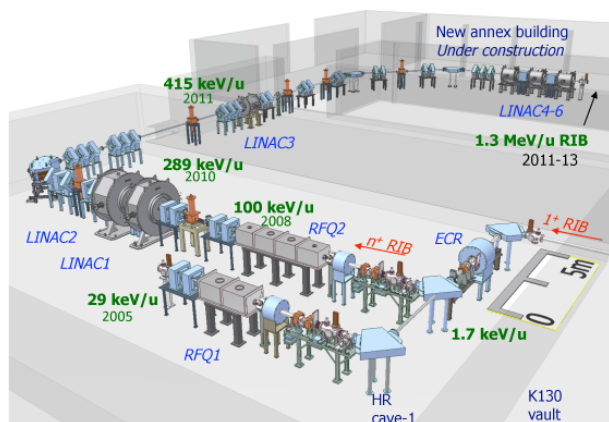


Figure 9: Layout of VECC-RIB (Courtesy Prof. Chakrabarti).

from the K-130 cyclotron. Gamma-ray spectra from the transported isotopes such as ^{14}O and ^{41}Ar were clearly measured in front of RFQ2[25].

On the other hand, the production efficiency of rare isotopes is expected to be enhanced by the photo-fission of the uranium target. For achieving this goal, VECC and TRIUMF are collaborating to develop a superconducting electron linac operating at 1.3 GHz for use as a new ISOL driver[26]. The first module, 10MeV-2mA linac, is expected to be ready in 2013.

VECC has recently proposed their future project known as ANURIB, which is an acronym for A National Facility for Unstable and Rare Isotope Beams[27]. This project is divided into two phases. The first phase, which will be completed in 2017, consists of the ISOL-post accelerator combination. The second phase is aimed at achieving the secondary fragmentation of unstable nuclei. In order to further accelerate the rare isotope beams from the first-phase accelerators, the construction of a superconducting ring cyclotron is planned. The second phase is expected to start in 2017.

IUAC

IUAC, New Delhi, has developed a low-energy beam of ^7Be using their Heavy-Ion Reaction Analyzer (HIRA)[28],

through (p,n) or (d,n) reactions with inverse kinematics. A beam energy of about 20 MeV has been produced with very high purity by operating the analyzer in a new beam optics.

Recently, they constructed the HYbrid Recoil mass Analyzer (HYRA)[29], as shown in Fig. 10, to fully exploit the heavy-ion beams provided by the ECR ion source and the superconducting linac. The primary purpose of this device is to efficiently collect the fusion evaporation residues with its gas-filled mode operation. However, it is also possible to operate it in the achromatic mode in order to produce radioactive beams. Ion species such as ^7Be and ^{18}F will be available at 20–50 MeV with a 10^3 – 10^4 pps.

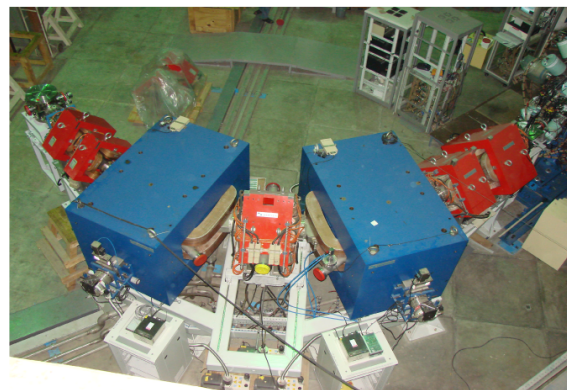


Figure 10: Photograph of the first stage of the HYbrid Recoil mass Analyzer (HYRA) at IUAC (Courtesy Prof. Roy).

KOREA

RISP

A large RIB project is known to have been proposed in Korea several years ago. Recently, the project was reopened with the name Rare Isotope Science Project (RISP) under the newly established Institute of Basic Science (IBS) in Daejeong[30].

Figure 11 shows the redesigned accelerator complex of RISP[31]. The main accelerator is a superconducting heavy-ion linac, which accelerates high-power uranium beam up to 200 MeV/u for a fragment separator. This linac can be also used as a driver accelerator for light ions

Concept of the Accelerator Complex

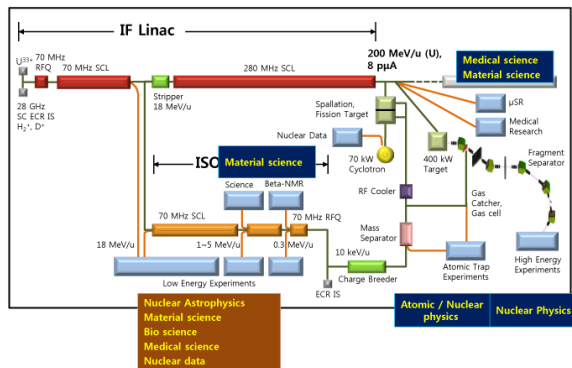


Figure 11: Conceptual drawing of accelerator complex of RISP (Courtesy Prof. Kim).

impinging on the spallation and fission target. The construction of a post-accelerator is planned for this ISOL scheme. Moreover, according to the plans, a 70-kW proton cyclotron will be added as an alternative driver for the fission target. The rare-isotope beam in the third mode can be finally accelerated through the main linac up to 200 MeV/u to produce secondary fragmentation with the RIBs. Beam commissioning of the initial part of the project is expected to start in 2017.

SUMMARY

A list of the facilities that are in operation and under construction in Asian countries is given in Table 1. Facilities that are still in the design stage have been omitted. International collaborations will gain increased importance for further progress.

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