OVERVIEW OF THE WORLD-WIDE RIB FACILITIES - STATUS AND CHALLENGES

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Abstract

An overview of radioactive isotope and rare isotope beam (RIB) facilities world-wide is given. Starting with the production methods of the RIBs, the present status of and technical challenges in several on-going projects of RIB facilities are reviewed.

INTRODUCTION

Since the 1980s, the rare isotope and radioactive ion beam (RIB) facilities have provided a means to access the unexplored region on the nuclear chart, far from the stability line. Unexpected characteristics have been revealed in unstable nuclei, such as the presence of dilute neutron distribution around the core, an unusual shell structure, and new excitation modes, which have motivated us to find a new comprehensive way to describe atomic nuclei. Moreover, detailed studies on unstable nuclei are expected to improve our understanding of how heavy elements were formed in the universe through the so-called r-process during stellar explosions.

It should be emphasized that to study the different regions of the nuclear chart, a wide variety of RIBs are required; the ion species, intensity, and quality of the beam required strongly depend on the scientific objective. Another important point is that a wide variety of technologies are required for constructing RIB facilities, as discussed in the next section. Therefore, well-organized collaborations among the facilities are important to study a wide range of R&D subjects.

This paper reviews the RIB facilities in the world. In the next section, production methods for RIBs are briefly discussed, and important components of the facilities are highlighted. The complementary nature of the RIB facilities is clearly stated. In the third section, the present status of and R&D challenges at several RIB facilities are outlined, focusing on the facilities recently started, and those under construction.

RI BEAM PRODUCTION

There are two main schemes in the RIB production. The first one is the so-called "in-flight method"[1] schematically shown in Fig. 1, where radioactive ions are obtained through fragmentation or fission reactions induced by energetic heavy ions colliding with a thin target made of light elements such as carbon and beryllium. The reaction fragments, ejected in the forward direction with almost the same speed as that of the incident beam, are separated with an in-flight fragment separator and transferred to the experimental apparatus as the RIB.

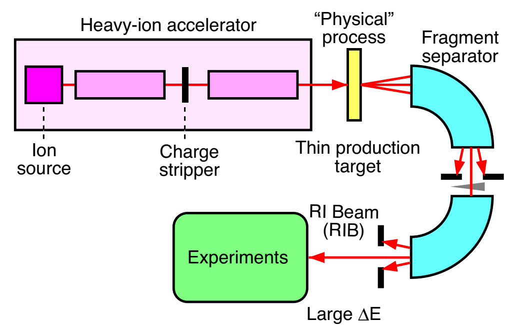

Figure 1: Schematic drawing of the in-flight production method.

An advantage of this method is that the production of the RIBs is independent of the chemical properties of the element. Moreover, isotopes with very short half-lives and even isomers are available as RIBs. On the other hand, the quality of the RIBs is poor due to the kinematic energy spread and their divergence that results from the production process.

From a technological viewpoint, the most important component is the high-intensity accelerator of heavy ions; a beam energy larger than 100 MeV/u ($\beta \geq 0.4$) is required. On the other hand, the production targets are essential as well for effective RIB production. The charge strippers are also crucial for high-power heavy-ion beams. Therefore, R&D of these components are challenging issues in the in-flight RIB facilities.

The second method is the ISotope On-Line (ISOL) scheme[2], which is illustrated in Fig. 2. This method is based on light-ion induced spallation or fission of thick targets made of heavy elements such as tantalum or uranium (uranium carbide), where intense protons and deuterons of 20 – 1000 MeV/u are used as the driving beams. The radioactive fragments diffuse out of the target and effuse to an ion source to become singly charged ions. After passing through a high-resolution magnetic separator, the charge state is boosted by a charge breeder to achieve a high acceleration efficiency in the post-accelerator.

An advantage of this method is that the quality of the reaccelerated beam is excellent and suitable for detailed studies of nuclear reactions and structures. It is also use-

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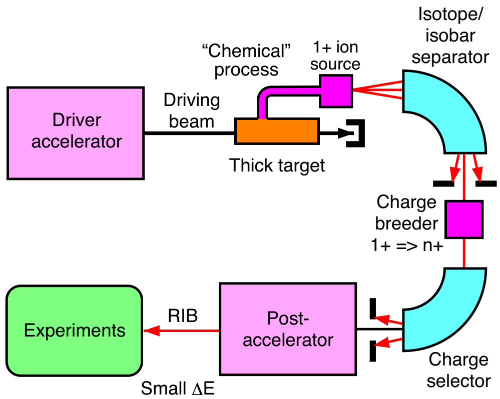

Figure 2: Schematic drawing of the ISOL production method.

ful for stopped-beam experiments such as the experiments involving the use of ion traps and laser spectroscopy. On the other hand, the production process strongly depends on the chemical properties of the produced isotopes, and it is generally difficult to provide chemically active elements as RIBs. Short-lived isotopes cannot be obtained because of the time required for diffusion and effusion. In this sense, the ISOL method is complementary to the in-flight method.

The most crucial component in this method is the driver accelerator that is capable of providing high-power beams. For high-efficiency production of RIBs, however, the R&D of the targets, ion sources, and charge-breeders are essential as well.

PRESENT STATUS OF RIB FACILITIES

Based on the success of the first generation RIB facilities in the 1980s, various upgrade programs and new construction plans have been proposed since the late 1990s, such as FAIR[3] in Germany, FRIB in the US, Spiral2 in France, HIRFL[4] in China, RIBF in Japan, and so on, which aim at expansion of the nuclear chart by enhancing the RIB species and intensities. Some of them have been already commissioned, and some of them are under construction at present. It is also remarkable that the activities are rapidly growing in Asian countries. Some facilities have started construction, such as VECC-RIB[5] in India and BRIF[6] in China. A number of big projects have been proposed so far, such as RISP[7] in Korea, ANURIB[8] in India, CARIF[9] and HIAF[10] in China.

In this section, several on-going projects are selected, and their present status will be illustrated, that are not presented in the other oral presentations of this conference. Basic parameters of the RIB facilities discussed in this section are included in Table 1.

RIBF

The RIKEN RI Beam Factory (RIBF)[11], which started commissioning in 2006, has now three injectors (two heavy ion linacs, RILAC and RILAC2, and AVF cyclotron) and four booster cyclotrons (RRC, fRC, IRC, and SRC), as shown in Fig. 3. Combining these accelerators in three acceleration modes, all types of ions from protons (H_2^+) to uranium ions can be accelerated up to 70% of the light speed in the cw mode. The accelerated beams are transferred to BigRIPS spectrometer, where the RIBs are generated through the in-flight method. Owing to the continuous efforts since the commissioning, the beam intensities for the light and medium-mass ions have been greatly improved by 2012. For instance, 1000 pnA of ^{18}O and 415 pnA of ^{48}Ca were extracted from the SRC at the beam energy of 345 MeV/u[12].

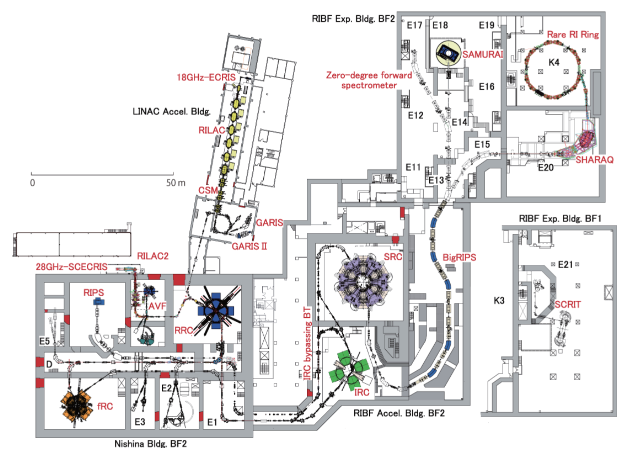

Figure 3: Layout of RIKEN RIBF.

The main accelerator of RIBF is the first superconducting ring cyclotron in the world, SRC[13]. The SRC consists of six superconducting sector magnets and generates the maximum magnetic field of 3.8 T, corresponding to the K-value of 2600 MeV, which is the largest in the world. In the acceleration of the uranium beam to 345 MeV/u, this single machine provides the total accelerating voltage of 640 MV in the cw mode.

RIBF has recently made big efforts in the upgrades of the beam intensities of very heavy-ions such as xenon and uranium[14]. The new injector, RILAC2, was constructed, which consists of a superconducting ECR ion source of 28 GHz, an RFQ and three drift-tube linacs. A new gas stripping system based on helium gas, which works for uranium beam at 11 MeV/u, was successfully developed[15]. The succeeding cyclotron, fRC, adopted a big modification on its bending power to accept the lower charge state (64+) of uranium beam; the K value has been increased from 570 MeV to 700 MeV[16]. Owing to these R&Ds, the intensity and stability of the uranium beam have been greatly improved since 2012. The intensity has exceeded 15 pnA at the exit of the SRC, which corresponds to 10^{11} pps.

Construction of experimental apparatus and new collaborations are under progress at RIBF. For example, a new spectrometer SAMURAI (Superconducting Analyzer for MUltiparticles from RAdio Isotope beams) was re-

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Table 1: RIB facilities recently commissioned and those under construction for facility upgrade. The beam energies and intensities in the in-flight facilities correspond to the designed values of the uranium beams.

In-flight facilities	**Driver**	**MeV/u**	**I (pps)**	**Separator**	**Exp.**
RIBF (RIKEN, Japan/2006 –)	SRC	345	6×10^{12}	BigRIPS	ZDS etc.
HIRFL (IMP, China/2006 –)	CSRm	500	10^{9}	RIBLL2	CSRe etc.
FRIB (USA/2017)	SC linac	200	5×10^{13}	A1900	ReA12 etc.
FAIR (2018)	SIS100	1500	2×10^{11}	SuperFRS	CR etc.
Catcher-reacc. facilities	**Driver (Beam)**	**MeV/u**	**Breeder**	**Post acc.**	**MeV/u**
ReA3 (MSU, USA/2011 –)	K1200 (HI)	170 - 80	EBIT	SC linac	3 - 6
CARIBU (ANL, USA/2011 –)	(^{252}Cf)	–	ECR	ATLAS	15
ISOL facilities	**Driver (Beam)**	**MeV**	**kW**	**Post acc.**	**MeV/u**
BRIF (CIAE, China/2013)	Cyclotron (p)	100	20	SC linac	2
ARIEL (TRIUMF, Canada/	Cyclotron (p)	500	50	ISAC	18
2013)	SC linac (e)	50	500	ISAC	18
Spiral2 (GANIL, France/2014)	SC linac (d)	40	200	CIME	2 - 25
SPES (INFN, Italy/2014)	Cyclotron (p)	40	8	ALPI	10
HIE-ISOLDE (CERN/2015)	PSB (p)	2000	10	REX upgrade	5.5 - 10

cently commissioned. The Rare-RI Ring for mass measurements will be commissioned soon. The EURICA (EUroball RIken Cluster Array) collaboration is carrying out various experiments using the intense RIBs. New results are foreseen at RIBF in the coming years.

FRIB

The Facility for Rare Isotope Beams (FRIB) is to be built at the Michigan State University under a corporate agreement with the US DOE[17]. The driver beam includes a 400 kW uranium beam of 200 MeV/u that is accelerated by a long superconducting (SC) linac and is based on the innovative concept of multi-charge acceleration[18]. The accelerator systems design has been assisted under work-for-others agreements by many national laboratories, and in collaboration with many institutes out of the US. The early commissioning is expected to start in 2017.

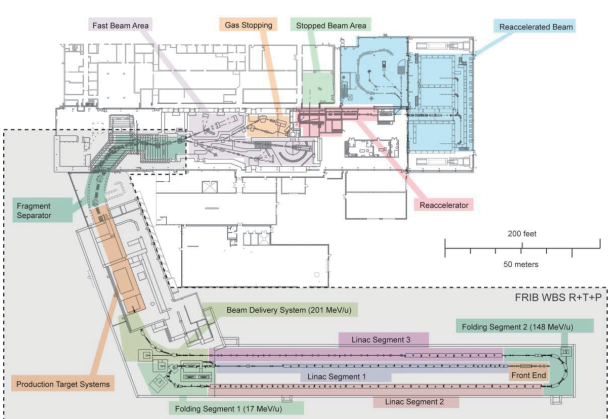

Figure 4: Layout of FRIB (hatched area) at MSU.

The FRIB accelerator design combines the complexity of heavy ion accelerators with the engineering challenges of high-power accelerators; it is carefully designed for attaining high availability, maintainability, reliability, tunability, and upgradability. Due to requirements of frequent longitudinal and transverse focusing in the superconducting acceleration structure, focusing solenoids are placed inside cryomodules adjacent to cavities. Requirements on beam halo prevention, detection and mitigation are stringent, because of the small beam apertures of the superconducting resonators and cold solenoids.

FRIB driver linac is the first full-size SC linac using a large quantity (340) of low-β cavities. All the cavities work with superfluid helium at 2 K, and the R&D of cavity prototypes underwent several modifications in these ten years. The cold tests recently performed for the prototypes of the QWR ($\beta = 0.085$) and HWR ($\beta = 0.53$) exhibited very good performances, qualifying the FRIB requirements.

The QWR prototypes ($\beta = 0.045$ and 0.085) are already working in the ReA3 facility at NSCL of MSU. Recently an RIB of ^{76}Ga was produced and accelerated in the ReA3 accelerator[19]. This means that the basic idea of the re-acceleration scheme, including the gas stopper and EBIT charge breeder, works as expected.

The FRIB baseline design of charge stripping system[20] selected a liquid lithium film which is under development in collaboration with the ANL Physics Division. Very recently, the liquid lithium film was tested at ANL with a 65 keV, 4 mA proton beam provided by the LEDA ion source developed at LANL in the 1990s. The result was successful; the film sustained under the heavy beam power[21].

ARIEL

Since the 1990s, the ISOL-based facility ISAC has been developed at TRIUMF and now the SC linac is providing RIBs such as ^{11}Li beams with remarkable intensities. The driver beam currently used is 50 kW protons provided by the 500 MeV TRIUMF cyclotron.

TRIUMF proposed the Advanced Rare IsotopE Laboratory (ARIEL) in 2010 under their 10-year vision[22], with the goal to significantly expand the RIB program for nuclear physics and astrophysics, nuclear medicine, and materials science. ARIEL will use proton-induced spallation and electron-driven photo-fission of ISOL targets for the production of short-lived rare isotopes that are delivered to experiments at the existing ISAC facility. Combined with ISAC, ARIEL will support delivery of three simultaneous RIBs, up to two accelerated, new beam species and increased beam development capabilities.

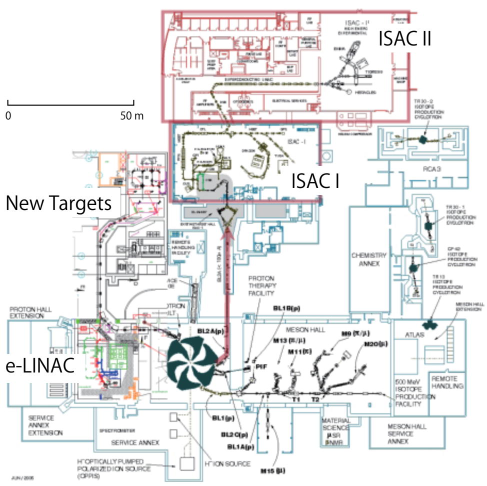

Figure 5: New and existing facilities at the TRIUMF site.

The ARIEL complex comprises a new electron linac, a beamline to the targets, one new proton beamline from the 500 MeV cyclotron to the targets, two new high power target stations, and mass separators and ion transport to the ISAC accelerator complexes. The layout of the facility is shown in Fig. 5. This project is being carried out based on a staged installation plan. In the first stage, the injector part of the electron linac and a new building for the full components are under construction.

The electron linac uses the 1.3 GHz, superconducting rf technology. The goal of this linac is to provide 50 MeV, 10 mA electron beam in the cw mode for the photo-fission production of the RIBs at the maximum fission rate of 10^{14}[23]. In the first stage, the electron gun, injector cryomodule, and one accelerator cryomodule will be completed by 2015. The multicell cavities for these cryomodules are under fabrication. High power tests of various rf components such as IOT and coupler are under progress.

As pointed out in the first section, the production target system is one of the most crucial components. The ISAC target has been operated at the maximum beam power of 50 kW, which is the highest in the world. New designs for the uranium carbide targets for the photo-fission are under discussion based on their expertise[24].

Spiral2

In addition to the in-flight facility LISE, GANIL has been operating the ISOL facility Spiral1 since 2001, where the driver beam is provided by the coupled cyclotron system. Spiral2 is a plan to increase intensity of the driver beam by constructing a powerful SC linac. The 20 MeV/u, 200 kW deuteron beam will be converted into a neutron flux by a carbon converter so that the uranium carbide target could have a designed fission rate of 10^{14}/s.

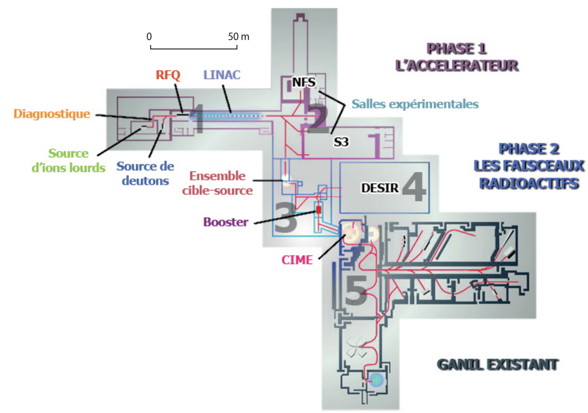

Figure 6: New and existing facilities at the GANIL site.

The Spiral2 complex is under construction in two phases, as shown in Fig. 6[25]. The first phase includes the complete accelerator and two new experimental halls, the Super Separator Spectrometer (S3) and the Neutron-based research area (NFS), all to be installed in a new dedicated building which is close to completion. On the other hand, the second phase includes the RIB production process and building, the low energy RIB experimental hall (DESIR) and the transfer line connection to the present GANIL facility for RIBs post-acceleration by means of the existing Spiral1 cyclotron (CIME).

The Spiral2 injector has two ECR ion sources; one is for heavy ions with $m/q \leq 3$, and the other is for deuterons and protons. The 18 GHz ECR heavy ion source (Phoenix-V2) has been tested successfully at LPSC/Grenoble for a few years. Its LEBT was recently transported to GANIL, and is presently under installation underground in the Spiral2 building. The deuteron/proton ECR source was fully tested with beams at IRFU/SACLAY. A 12 mA cw deuteron beam has been measured with an emittance of 0.22 (π) mm·mrad (rms, normalized).

The driver linac uses quarter-wavelength superconducting cavities of 88.05 MHz. The 12 low-β ($\beta = 0.07$) cavities were all qualified in vertical cryostat at IRFU/Saclay. The 14 high-β ($\beta = 0.12$) cavities were already success-

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fully tested at IPNO/Orsay. LPSC/Grenoble is in charge of the development, production and ongoing commissioning of the 12kW power couplers. Now the assembly and tests of the cryomodules are proceeding smoothly. The beam commissioning is expected to start in 2014.

HIE-ISOLDE

The ISOLDE collaboration at CERN has been running since 45 years, providing more than 700 nucleids over 70 chemical elements, which is the largest selection in the world. The present reaccelerator REX provides RIBs with a maximum energy of 3 MeV/u; the reaccelerator consists of an ion trap, EBIS breeder, and normal conducting linac.

A three-stage upgrade plan, HIE-ISOLDE, is under progress to increase the RIB intensities and energies. The goal of the energy-upgrade program is to boost the RIBs up to 10 MeV/u by adding an SC linac, which will comprise 32 QWRs working at 101.28 MHz in 6 cryomodules of 4.5 K[26]. The prototypes of the high-β cavity have been designed and fabricated at CERN, based on the Nb sputtering technique. They are being tested intensively to achieve the designed performance of $Q_0 = 5 \times 10^8$ at 6 MV/m with the rf power of 10 W.

The civil engineering for the helium compressor and cold box building was already finished in 2012. The first two cryomodules, which will boost RIBs to 5.5 MeV/u, is to be installed during the long shutdown of CERN, and the commissioning is expected to start in 2015.

SPES

The SPES project[27], to be built at INFN-Legnaro, is an ISOL facility based on a cyclotron driver. The SC linac ALPI[28] will be used for the reacceleration of the RIBs. The driver cyclotron, under construction at BEST Cyclotron Systems Inc., will provide 40 MeV protons of 0.2 mA on the uranium carbide target system. The layout of SPES is shown in Fig. 7.

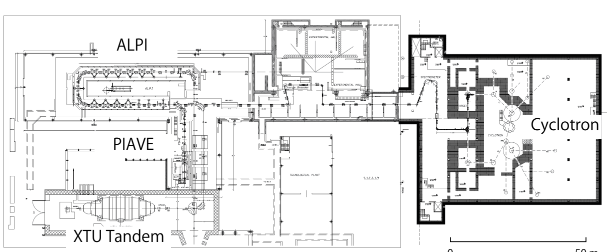

Figure 7: Schematic Layout of the SPES project.

The working core of SPES is constituted of the production target and the ion source. The R&D activities pertaining to a uranium-carbide target is a collaboration among the INFN laboratories and Italian universities. The target configuration is carefully designed to keep the fission rate as high as 10^{13}/s with moderate heat deposition, as well as to release the produced ions in a short time. The isotope in-target production for some interesting isotopes (Ag, Sn, Cs) reaches values up to 10^{11} atoms/s. The ^{132}Sn isotope, being a double-magic nucleus, is one of the radioactive nuclei of interest and the in-target production yield is here estimated to be 10^{10} atoms/s.

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